A Comparative Study on Fuzzy and PI Speed Controllers for Field-Oriented Induction Motor Drive

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Abstract—**This paper presents simulation results obtained from a feedforward vector controlled induction motor drive under varying operating conditions like step change in speed command and step change in torque command. Here fuzzy logic controller is used for controlling the speed. The performance of fuzzy logic controller has been investigated and compared with the conventional PI controller based drive. The simulation results show that fuzzy controller is superior to PI controller under dynamic condition.**

Keywords- feedforward vector control (FVC), induction motor (IM) , fuzzy logic controller (FLC)

I. INTRODUCTION

AC motor drives are used in a multitude of industrial and process applications requiring high performances. In high performance drives systems, the motor speed should closely follow a specified reference trajectory regardless of any load disturbances, parameter variations, and model uncertainties [1].

Induction motor is one of the ac motor having simple and rugged structure; moreover, they are economical and immune to heavy overloads. However the use of induction motor also has its disadvantages, mainly the controllability, due to its complex mathematical model and its nonlinear behavior. In order to achieve high performance and better controllability, vector control or field oriented control of induction motor drive is employed. By this method the induction motor can be controlled like a separately excited dc motor. This method enables the control of field and torque of the induction machine independently (decoupling) by manipulating the corresponding field oriented quantities.

The motor is traditionally controlled by fixed-gain proportional-derivative (PD), proportional-integral (PI) and proportional-integral-derivative (PID) controllers. But when there are occur parameter variations, load disturbances or environmental disturbances, the fixed-gain controllers do not give satisfactory response. Thus the controller parameters have to be continually adapted. The problem can be solved by several adaptive control techniques such as model reference adaptive control (MARC), sliding-mode control (SMC), variable structure control (VSC), and self tuning PI controllers, etc. The design of all of the above controllers depends on the exact system mathematical model, but it is difficult to develop an accurate system mathematical model due to unknown load variation, unknown and unavoidable parameter variations due to saturation, temperature variations and system disturbances. In order to overcome the above problems, the fuzzy logic controller (FLC) is used for controlling the motor. The mathematical tool for the FLC is the fuzzy set theory introduced by Zadeh. Recently fuzzy logic has been found application in many domains of control problem. The main advantages of fuzzy logic control method as compared to the conventional control techniques resides in the fact that it does not require any exact mathematical model of a system, it can handle nonlinearity of arbitrary complexity and it is based on the linguistic rules with an IF-THEN general structure, which is the basis of human logic.

In this paper the application of FLC for controlling the speed of induction motor is investigated. The complete feed forward vector control scheme of IM using FLC is simulated. The performance of fuzzy logic controller has been investigated and compared with the conventional PI controller based drive.

II. DYNAMIC OF INDUCTION MOTOR AND ITS CONTROL STRUCTURE

The dynamics behavior of an induction machine is described by the following equations written in the d^e - q^e synchronously rotating frame:

$$\frac{d\Psi_{dr}}{dt} = \frac{L_m}{T_r} i_{ds} - \frac{\Psi_{dr}}{T_r} + (\omega_e - \omega_r)\Psi_{qr} \tag{1}$$

$$\frac{d\Psi_{qr}}{dt} = \frac{L_m}{T_r} i_{qs} - \frac{\Psi_{qr}}{T_r} - (\omega_e - \omega_r)\Psi_{dr} \tag{2}$$

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

$$T_e = T_L + J\frac{d\omega_r}{dt} + B\omega_r \tag{4}$$

where i_{ds} and i_{qs} are d, q-axis stator currents respectively; i_{dr} and i_{qr} are d, q-axis rotor currents respectively; Ψ_{dr} and Ψ_{qr} are d,q-axis rotor flux linkages; R_s , R_r are the stator and rotor resistances per phase respectively; L_s, L_r are the self inductances of the stator and rotor respectively; L_m is the mutual or magnetizing inductance; $T_r=L_r/R_r$ is the rotor time constant; ω_e is the speed of rotating magnetic field; ω_r is the rotor speed; P is the number of poles; T_e is the electromagnetic developed torque; T_l is the load torque; J_m is the rotor inertia; B_m is the rotor damping coefficient.

The axis transformation from two-phase stationary stator voltages and currents to three-phase are related as

$$\begin{bmatrix} x_{as} \\ x_{bs} \\ x_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120^\circ) & \sin(\theta-120^\circ) & 1 \\ \cos(\theta+120^\circ) & \sin(\theta+120^\circ) & 1 \end{bmatrix} \begin{bmatrix} x_{qs}^s \\ x_{ds}^s \\ x_{0s}^s \end{bmatrix} \quad (5)$$

The corresponding inverse relation is

$$\begin{bmatrix} x_{qs}^s \\ x_{ds}^s \\ x_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120^\circ) & \cos(\theta+120^\circ) \\ \sin\theta & \sin(\theta-120^\circ) & \sin(\theta+120^\circ) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} x_{as} \\ x_{bs} \\ x_{cs} \end{bmatrix} \quad (6)$$

where x may be voltage or current. There are two ways to determine the θ_e : the direct vector control uses flux sensors or motor input currents/voltages to synthesize θ_e and the indirect field orientation uses the rotor slip to calculate θ_e . In this paper indirect vector control is adopted

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl} \quad (7)$$

In indirect field oriented vector control for decoupling, the rotor flux is oriented to the d-axis so that $\Psi_{qr} = 0$.

So we have

$$\frac{L_r}{R_r}\frac{d\psi_r}{dt} + \Psi r = L_m i_{ds} \quad (8)$$

At steady state the slip angular frequency can be expressed as

$$\omega_{sl} = \frac{L_m R_r}{\psi_r L_r} i_{qs} = \frac{R_r i_{qs}}{L_r i_{ds}} \quad (9)$$

Again the torque equation can be written as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\Psi_{dr} i_{qs} \quad (10)$$

Equations (1)-(10) are used to simulate the whole drive system. The schematic diagram of the FLC-based indirect vector control of induction motor is shown in Fig. 1. The IM drive is fed by a current-controlled voltage-source inverter.

Here hysteresis current controller is used and it consists of compares current error (the difference between measured and reference currents) with a fixed hysteresis band. When the error falls below the lower hysteresis limit, the inverter phase-leg is switched on and when the error rises the upper hysteresis limit, it is switched off. The actual speed is compared with the reference speed and the speed error and the rate of change of speed error are processed by the FLC to generate the torque producing current component command i_{qs}^*.The instantaneous three-phase reference current $(i_{as}^*, i_{bs}^*, i_{cs}^*)$ is obtained from the dq stator current (i_{ds}^*, i_{qs}^*) by applying equation (5). The reference three-phase current is compared with the actual machine terminal current and the error is processed through hysteresis current controller.

III. PRINCIPLE AND DESIGN OF FLC FOR IM

Fig. 2 shows block diagram of a FLC. It consists of fuzzification, inferencing mechanism, knowledge base and a defuzzification block. In this proposed FLC the input linguistic variables are the speed error (e) and rate of change of speed error (ce) and the output linguistic variable is the torque producing current component.

$$e(t_s) = \omega_r^*(t_s) - \omega_r(t_s) \quad (11)$$

$$ce(t_S) = e(t_S) - e(t_S - 1) \quad (12)$$

where $\omega_r(t_s)$ is the actual rotor speed and $\omega_r{}^*(t_s)$ is the reference speed at current sampling time t_s, $e(t_s\text{-}1)$ is the error at previous sampling time, $e(t_s)$ is the speed error at current sampling time t_s. The inputs and the output are related as:

$$i_q(t_s) = f(e(t_s), ce(t_s)) \quad (13)$$

In the next step the scaling factors G_1, G_2 and G_3 are chosen for normalization. The factors G1 and G_2 are used to normalized speed error $e(t_s)$ and change of speed error $ce(t_s)$ respectively, so that these remain within the limit of -1 to +1. This process of converting crisp variables into fuzzy variables is called fuzzification. After selecting the scaling factors, the next step is to choose the membership function for e, ce and i_q*. The membership function used for the input and output fuzzy set are shown in Fig. 3. Here triangular membership functions are used and are labeled as: Z=Zero, PS=Positive small, PM=Positive Medium, PB=Positive Big, NS=Negative Small, NM=Negative Medium, NB= Negative Big, PVS=Positive Very small and NVS= Negative Very Small. All the membership functions have asymmetrical shape with more crowding near the origin for higher precision at steady state. The knowledge base involves defining the rules represented as IF -THEN rules statements governing the

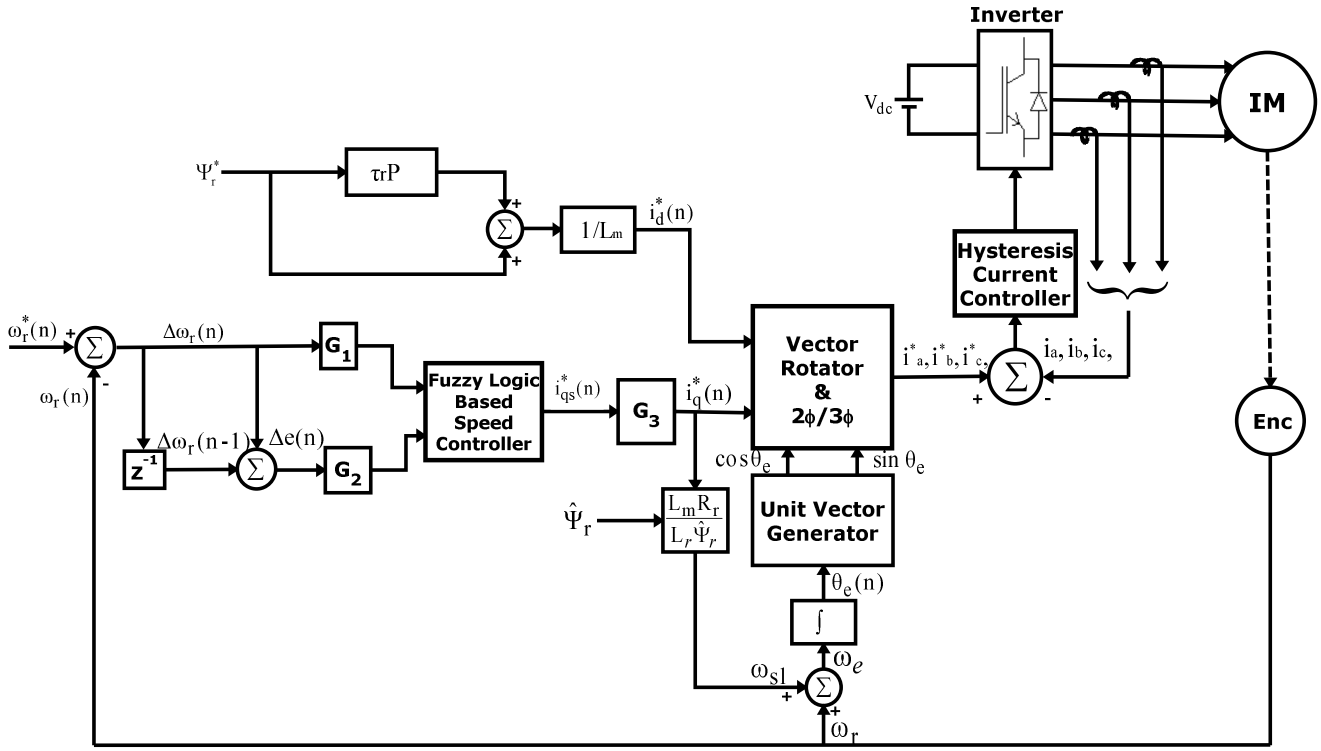


Fig. 1 Fuzzy Logic Controller based Feed forward Vector Control of Induction Motor Drive

relationship between inputs and output variables in terms of membership functions. In this stage the input variables $e(t_s)$ and $ce(t_s)$ are processed by the inference engine that executes 7×7 rules shown in rule Table I. A typical rule can be written as follows.

If e is a_k and ce is b_k then output is c_k

where a_k , b_k , c_k are the labels of linguistic variables of error (e), change of error (ce) and output (i_q*) respectively. Inferencing mechanism includes application of fuzzy operator AND (∩), OR (U) and NOT (-).

AND → Intersection: $\mu_{a \cap b} = \min[\mu_a(x), \mu_b(x)]$

OR → Union: $\mu_{a \cup b} = \max[\mu_a(x), \mu_b(x)]$

NOT → Complement: $\mu_a = 1 - \mu_a(x)$

After processing the inputs through knowledge base and inferencing mechanism the next stage is defuzzification. In this stage the fuzzy variables are converted into a crisp variable. This stage introduces different inference methods that can be used to produce the fuzzy set value for the output fuzzy variable i_q*. In this, the center of gravity (COA) or centroid method is used to calculate the final fuzzy value i_q*. The output function is given as:

$$i_q^* = \frac{\sum_{k=1}^{n} i_{q(k)} \mu(i_{q(k)})}{\sum_{k=1}^{n} \mu(i_{q(k)})} \quad (14)$$

where n is the total number of rules and $\mu(i_{q(k)})$ denotes the output membership value for kth rule.

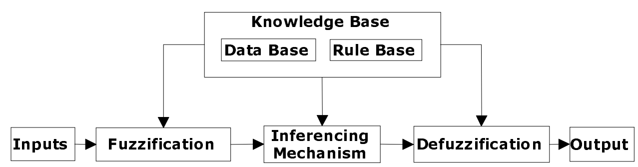


Fig. 2. Block diagram of FLC

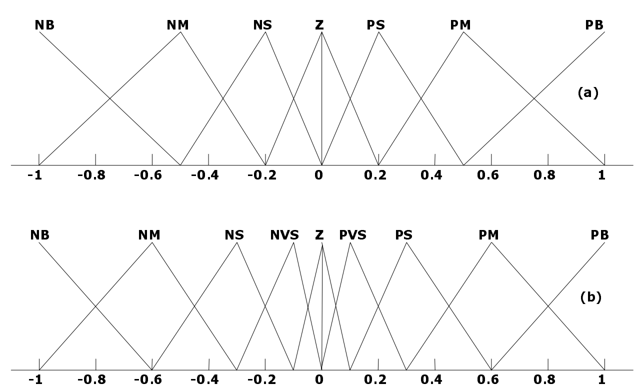


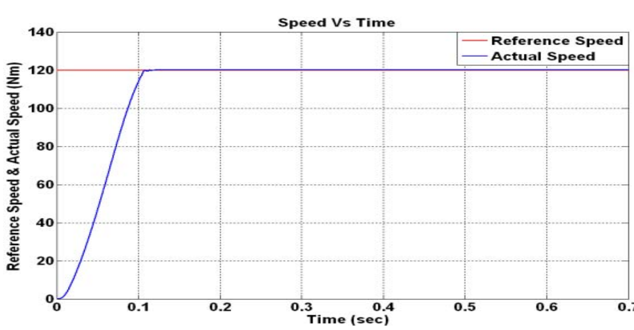
Fig. 3 Membership functions for: (a) speed error-e and change of speed error -ce and (b) command current -i_q*.

TABLE I
FUZZY RULE BASED MATRIX

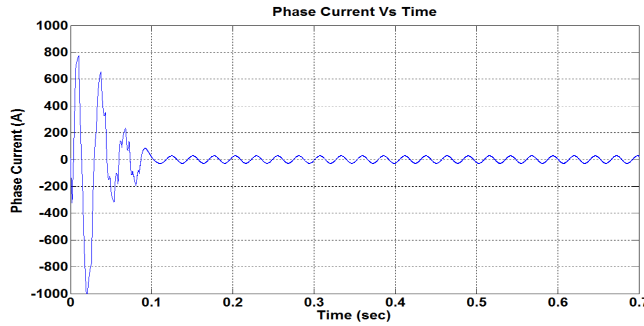
ce \ e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NVS	Z
NM	NB	NM	NM	NS	NVS	Z	PVS
NS	NB	NM	NS	NVS	Z	PVS	PS
Z	NM	NS	NVS	Z	PVS	PS	PM
PS	NS	NVS	Z	PVS	PS	PM	PB
PM	NVS	Z	PVS	PS	PM	PM	PB
PB	Z	PVS	PS	PM	PB	PB	PB

IV. SIMULATION RESULTS AND DISCUSSIONS

Several simulation tests for feedforward vector control of IM were carried out using both PI controller and fuzzy logic controller. The speed responses under different operating conditions such as step change in command speed or sudden change in load were observed. Figs. 4 and 7 shows the PI and FLC response speed at no load and the current drawn by the motor respectively. The FLC performance is better with respect to rise time and steady state errors. Figs. 5 and 8 shows the speed tracking performance while changing the speed from 120 rad/sec to 100 rad/sec at 0.8 sec and again to previous state at 1.6 sec, and phase current using PI and FLC respectively. It is evident from Figs. 5 and 8 that the FLC based IM drive follow the command speed without any overshoot and steady state error. Figs. 6 and 9 shows load disturbance rejection capabilities and phase current of both controller with a step change of load torque from 0 to 200 Nm and then again to 0. The load disturbance doesn't have any effect on speed response by using both the controller but FLC has better transient response. It is evident from the results that the fuzzy controller gives better responses in terms of overshoot, steady-state error and fast response.

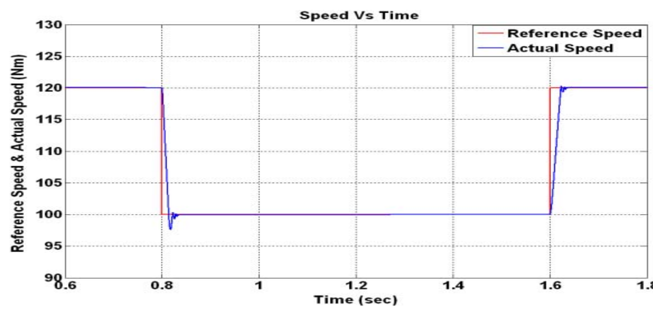


(a)



(b)

Fig.4. Starting responses of the drive using PI controller with no load(a) Speed (b) Phase current



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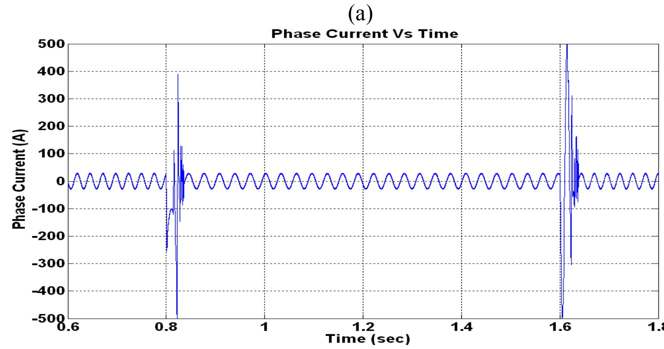
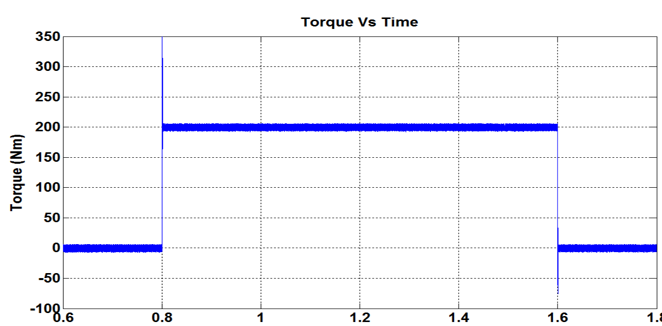


(b)

Fig.5. Simulation responses of the drive using PI controller with step change in reference speed (a) Speed (b) Phase current



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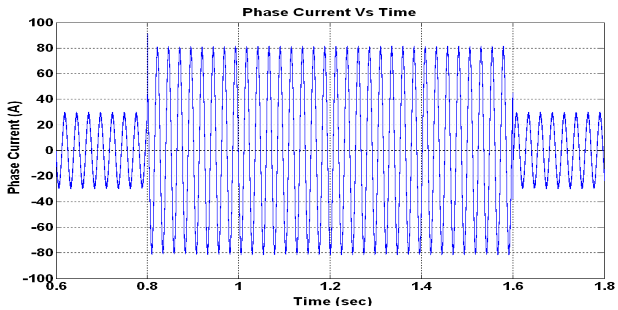

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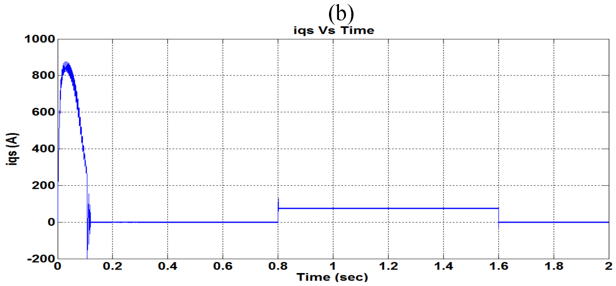

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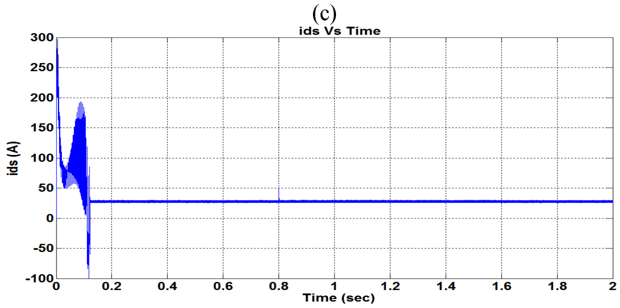
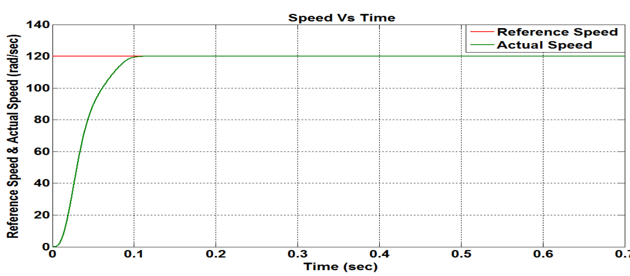
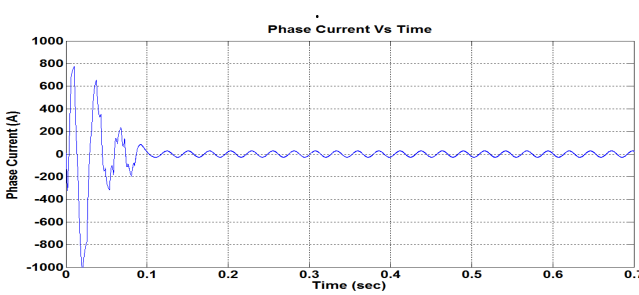


(d)

Fig. 6. Simulation responses of the drive using PI controller with sudden change in load torque (a) Torque (b) Phase current (c) Stator q-axis current component (d) Stator d-axis current component

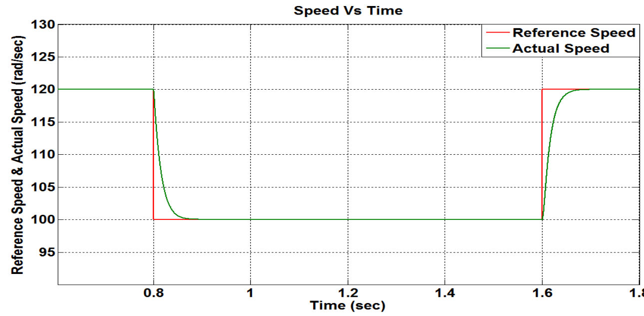


(a)

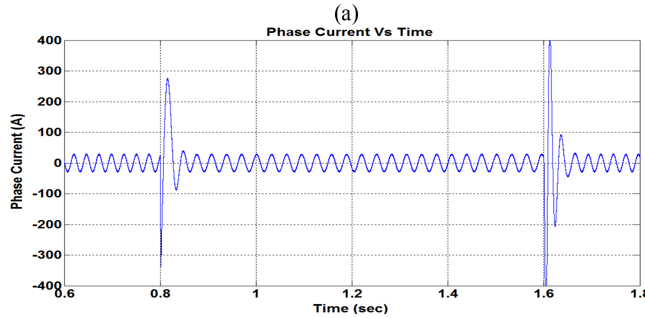


(b)

Fig. 7. Starting responses of the drive using FLC with no load(a) Speed (b) Phase current

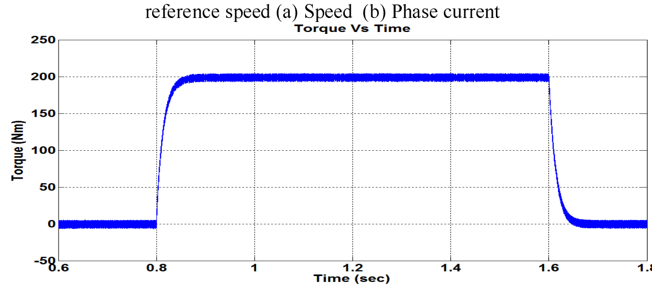


(a)



(b)

Fig. 8. Simulation responses of the drive using FLC with step change in reference speed (a) Speed (b) Phase current



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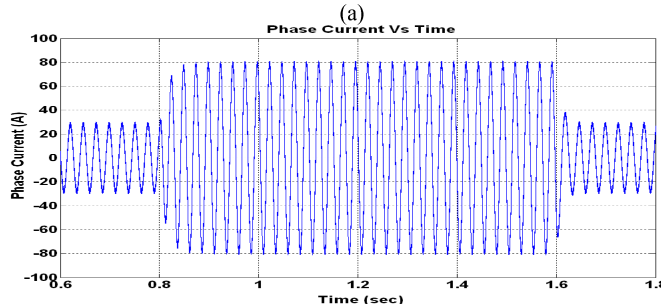

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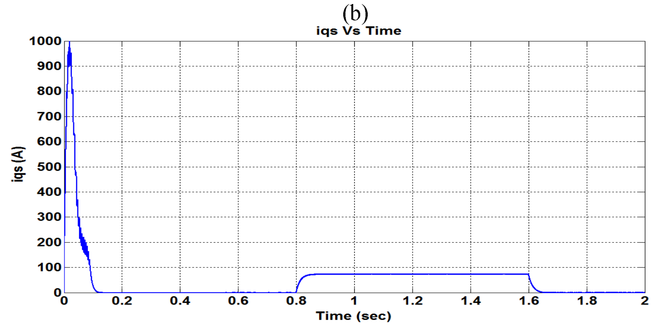

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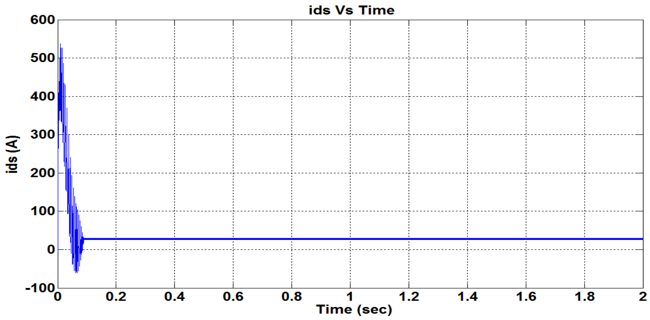

(d)

Fig. 9. Simulation responses of the drive using FLC with sudden change in load torque (a) Torque (b) Phase current (c) Stator q-axis current component (d) Stator d-axis current component

CONCLUSION

A FLC-based feedforward vector control of an induction motor drive has been presented in this paper. The drive system was simulated using both PI and fuzzy logic controller and their performances with respect to change in command speed and load disturbance were compared. It is concluded that the FLC has shown superior performances over the PI controller.

APPENDIX

MOTOR SPECIFICATION

$50\text{hp}, 3\Phi, 460\text{V}, 60\text{Hz}, P=4, R_s=0.087\Omega, R_r=0.228\Omega,$
$L_s=0.8\text{mH}, L_r=0.8\text{mH}, L_m=34.7\text{mH}, J=1.662\text{Kg.m}^2, F=0.12\text{N.m.s}$

REFERENCES

[1] M. Nasir Uddin, Tawfik S. Radwan, and M. Azizur Rahman, "Performances of Fuzzy-Logic- Based Indirect Vector Control of Induction Motor Drive", IEEE Trans. Industry Application ,vol.38, no.5 September/October 2002, pp.1219-1225.

[2] Bimal K. Bose. "Modern Power Electronics and AC Drives", New Delhi, Pearson Education, 2002.

[3] Durval de Almeida Souza, Wilson C. P. De Aragao Filho, and Gilberto Costa Drumond Sousa, "Adaptive Fuzzy Controller for Efficiency Optimazation of Induction Motor", IEEE Trans. on Industrial Electronics,vol.54, no.4, August 2007, pp. 2157-2164.

[4] Bahram-Kimiaghalam, Meisam-Rahmani and Hassan-Halleh, "Speed & Vector Control of Induction Motors with Fuzzy Logic Controller", International Conf. On Control, Automation and Systems 2008 Oct. 14-17, 2008 in COEX, Seoul, Korea, pp. 360-365.

[5] Bimal K. Bose, "An Adaptive Hysteresis-Band Current Control Technique of a Voltage-Fed PWM Inverter for Machine Drive System", IEEE Trans. Industrial Electronics,vol.37,no.5,October 1990, pp. 402-408.

[6] Chuen Chien Lee , "Fuzzy Logic in Control Systems: Fuzzy Logic Controller", (Part I and II), IEEE Trans. On Systems, Man, and Cybernetics,vol.20,no.2,March/April 1990, pp. 404-435.

[7] P.S. Bimbhra. "Generalized Theory of Electrical Machines". New Delhi, Khanna Publishers, 2008.

[8] P.S. Bimbhra. "Power Electronics". New Delhi, Khanna Publishers, 2007.

[9] Zulkifilie Ibrahim and Emil Levi , " A Comparative Analysis of Fuzzy Logic and PI Speed Control in High-Performance AC Drives Using Experimental Approach", IEEE Trans. Industry Application ,vol.38, no.5 September/October 2002, pp. 1210-1217.

[10] Mavungu Masiala, Behzad Vafakhah, John Salmon , Andrew M. Knight, "Fuzzy Self-Tuning Speed Control of an Indirect Field-Oriented Control Induction Motor Drive ", IEEE Trans. Industry Application ,vol.44, no.6, November/December 2008, pp. 1732-1740.

[11] P.C.Krause, Oleg Wasynczuk, Scott D.Sudhoff "Analysis of electrical machinery and drive systems" Wiley Interscience, 2004.

[12] J. C. Basilio and S. R. Matos, "Design of PI and PID Controllers With Transient Performance Specification", IEEE Trans. On Education,vol.45.no.4,November 2002, pp. 364-370.

[13] K. M. Rahman, M. Rezwan Khan, M. A. Choudhury, and M. A. Rahman,"Variable-Band Hysteresis Current Controllers for PWM Voltage-Source Inverters" IEEE Trans. On Power Electronics,vol.12, no.6, November 1997, pp.964-970.

[14] Ying-Yu Tzou and Shiu-Yung Lin, "Fuzzy-Tuning Current-Vector Control of a Three-Phase PWM Inverter for High-Performance AC Drives", IEEE Trans. on Industrial Electronics,vol.45, no.5, October 1998, pp. 782-791.

[15] Hwi-Beom Shin, "New Antiwindup PI Controller for Variable-Speed Motor Drives" IEEE Trans. on Industrial Electronics,vol.45, no.3, June 1998, pp. 445-450.

[16] P. C. Krause and C. S. Thomas, "Simulation of symmetrical induction machinery," IEEE Trans. on Power Apparatus & Systems, vol. 84, no. 11, 1965, pp. 1038- 1053.

[17] T. L. Chern and Y. C. Wu, "Design of integral variable structure controller and application to electrohydraulic velocity servo systems," Proc. Inst. Elect. Eng., vol. 138, no. 5, Sept. 1991, pp. 439–444.

[18] E. Cerruto, A. Consoli, A. Raciti, and A. Testa, " Fuzzy adaptive vector control of induction motor drives," IEEE Trans. Power Electron., vol. 12, Nov. 1997, pp. 1028– 1039.

[19] L. A. Zadeh, "Fuzzy sets," Inform. Control, vol. 8, 1965, pp. 338–353.