Efficacy of Different Rule Based Fuzzy Logic Controllers for Induction Motor Drive

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Abstract— **Performance of an electric drive is paramount for crucial motion applications and greatly influenced by the controller capabilities. Vector control technique is normally applied with the induction motor drive for high performance applications. For such applications fuzzy logic controller (FLC) has been widely used instead of conventional PID controller. However, size of rule-base of FLC is directly influencing the real time computational burden, which subsequently restricts its application with the processors of limited speed & memory. The number of rule base and performance of drive are inversely related with each other as it is evident that all the rules don't participate equally in the response and can be reduced for simplicity which utilizing less computational resources. In this paper the performance of vector controlled induction motor drive is presented for three different FLC rule bases namely 49, 25 and 9 rules. The drive performance has been investigated for these cases for speed control, disturbance rejection control ability. Moreover, sensitivity of the drive is evaluated for stator resistance control. The performance of drive system using larger FLC rule base is found superior as compared to the performance with lesser rules at the cost of large computational resources and speed.**

Index Terms—**Fuzzy logic controller, high performance drive, Induction motor, vector control.**

I. Introduction

Despite of various advantages speed control of induction motor is quite complex due to the complex mathematical model, nonlinearities such as core saturation, coupling of variables and unpredictable load disturbances. Sometimes these factors make the precise speed control impossible with the conventional controllers making them inefficient and inaccurate for the speed control applications where high performance is needed such as robotics, aircrafts and surgical appliances [1]

In recent years, FLC (fuzzy logic controller) is distinguished and captured the attention of researchers for its superior performance in the speed control applications. The superior performance of FLC has been proved by many authors using simulated results and some of them has subsequently verified experimentally in the recent past [2], [3]. In fact, FLC's have the merit to handle the system nonlinearities, and their control performance is not as much affected by system parameter variations. Moreover, they don't require a precise mathematical model of the plant which is to be controlled, therefore make the system design simpler and easy to implement. Adding to its features it utilizes a linguistic rule base that is designed by involving expert knowledge [4]-[5].

Numerous researchers have proposed the different aspects of designing of FLC rule base. In most of studies, the performance of the designed FLC is compared with PI controller in terms of the speed control performance. The superior performance of the FLC has been noticed from the results presented by many researchers [2]-[4], [6], [9]. In most of the studies authors have used the fix and distinctive parameters for the FLC designing. Standard rule base of 49 rules with triangular membership functions is the first choice for the simpler FLC designing. As all the rules from the rule base doesn't contribute significantly in the decision making and can be eliminated leading to a less computational burden and reduced memory requirement [7]. The References [7] - [8] have proposed the FLC's with reduced rule base. In Reference [9], a single input and single output FLC is proposed. However, the speed control performance may deviate due to the oscillations in hard situations leading to system failure. To the best of authors knowledge, extensive performance comparison among different rule based FLC is still to be done.

The objective of this paper is to provide a detailed comparative analysis of FLC with different rule base sizes, employed in an indirect vector control scheme for an induction motor drive. Performance evaluation was carried out for different loading conditions through simulation results. The system is dynamically simulated using Simulink/MATLAB Software.

The paper is organized in five sections. The section I present the introduction. In Section II, the aspects of the fuzzy-controlled system structure and the principle elements of the Simulink/MATLAB model are presented. In Section III, the proposed simplified embedded fuzzy system is described. In Section IV, the simulated results of the fuzzy speed-control performance as well as a comparative analysis are discussed. Finally, the conclusions are outlined in Section V.

II. System Description and Control

The schematic diagram of the FLC based induction motor drive system under analysis is shown in Fig.1. The basic configuration of the drive consists of an IM fed by a current-controlled voltage-source inverter. For high performance the indirect vector control technique is incorporated in this work. The actual rotor speed ω_r is

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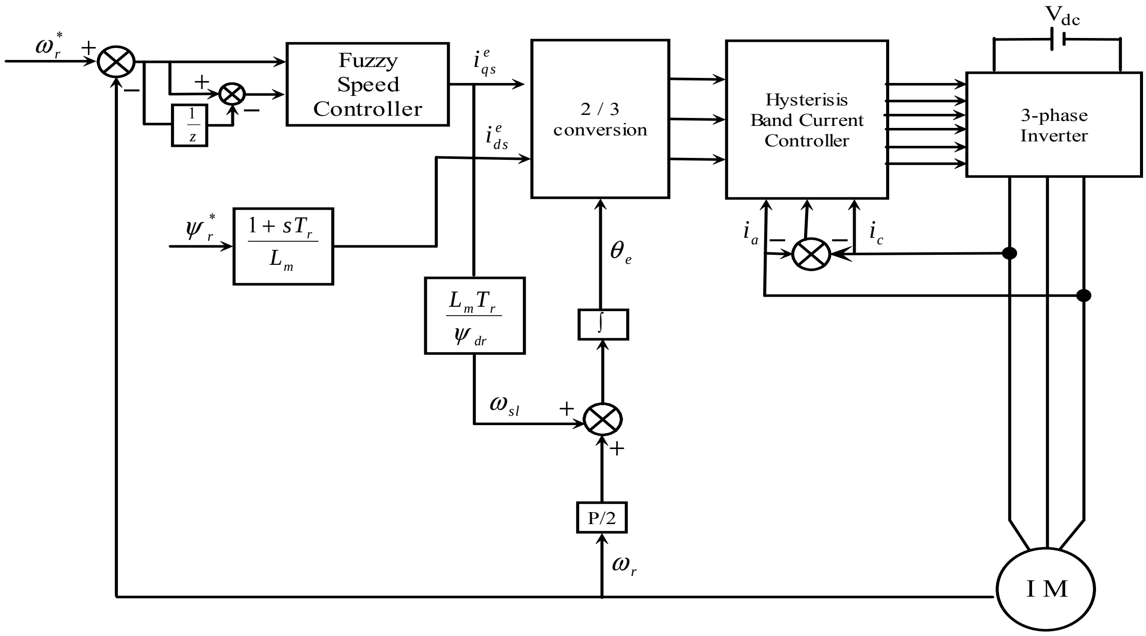


Fig.1. Schematic diagram of indirect vector control induction motor drive.

measured and compared with the reference speed ω_r^*. The resulting error generated from the comparison of two speeds is processed in the controller and the reference torque T_e^* is concluded as the output. The reference torque T_e^* is limited by a limiter in order to generate the q-axis reference current i_{qs}^{e*}. The d-axis reference current is set to zero. Both d-axis and q-axis stator currents generate three phase reference currents (i_a^* , i_b^* and i_c^*) through Park's Transformation which are compared with sensed winding currents (i_a , i_b and i_c) of the IM. The control signals generated after comparing the sensed current and the reference current will fire the power semiconductor devices of the three-phase voltage source inverter (VSI) to produce the actual voltages to be fed to the induction motor.

In synchronously rotating reference frame -the mathematical model for a three-phase y-connected squirrel-cage induction motor under steady state condition and the load is given as [10],[11]

$$\begin{bmatrix} I_{qs}^e \\ I_{ds}^e \\ I_{qr}^e \\ I_{dr}^e \end{bmatrix} = \begin{bmatrix} R_s & \omega_e L_s & 0 & \omega_e L_m \\ -\omega_e L_s & R_s & -\omega_e L_m & 0 \\ 0 & \omega_{sl} L_m & R_r & \omega_{sl} L_r \\ -\omega_{sl} L_m & 0 & -\omega_{sl} L_r & R_r \end{bmatrix}^{-1} \begin{bmatrix} V_{qs}^e \\ V_{ds}^e \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

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

$$T_e - T_L = J\frac{d\omega_r}{dt} + B\omega_r \tag{3}$$

$$\frac{d\theta_r}{dt} = \omega_r \tag{4}$$

where i_{ds}^e , i_{qs}^e are d , q -axis stator currents respectively, are v_{ds}^e , v_{qs}^e are d , q -axis stator voltages respectively, i_{dr}^e , i_{qr}^e are d , q -axis rotor currents respectively 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 inductance, ω_e is the speed of the rotating magnetic field, ω_r is the rotor speed, P is the number of poles, T_e is the developed electromagnetic torque, T_L is the load torque, J is the rotor inertia, B is the rotor damping coefficient, and θ_r is the rotor position.

The key feature of the vector control is to keep the magnetizing current at a constant rated value by setting $i_{dr}^e = 0$. Thus, by adjusting only the torque-producing current component the torque demand can be controlled. With this assumption, the mathematical formulations can be rewritten as

$$\omega_{sl} = \frac{R_r}{L_r}\frac{i_{qs}^e}{i_{ds}^e} \tag{5}$$

$$i_{qs}^e = \frac{L_m}{L_r} i_{qr}^e \tag{6}$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\psi_{dr}^e i_{qs}^e \tag{7}$$

where ω_{sl} is the slip speed and ψ_{dr}^e is the d -axis rotor flux linkage. The indirect vector controlled drive system with FLC assisted speed controller model is represented from equation no. (1) to equation no. (7).

III. FLC DESIGNING

The general block diagram of FLC is shown in Fig. 2. The main objective of the designed FLC is to maintain the performance obtained by 'standard design' while reducing the complexity of fuzzy rule base design. FLC has mainly four internal components from which input has to be processed to come out as output. Fig. 2 shows these components that are fuzzification, rule base, inference engine, and defuzzification. Mamdani type fuzzy inference engine is used for this particular work. In, defuzzification process the combined output fuzzy set produced from the inference engine is translated into a crisp output value of real-world meaning. Among the various defuzzification techniques centre of gravity (COG) is chosen for this work because of its known merits [12].

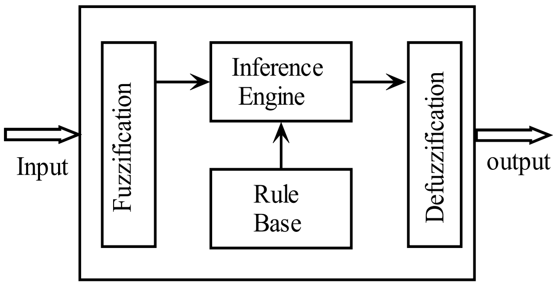


Fig. 2. Block diagram of FLC.

A. Scaling Factor Calculation

The role of scaling factor is similar to gain coefficients in a conventional controller, and affects the stability, oscillations and damping of the system, hence needs to be chosen with utmost care [13]. Three scaling factors represented by Gse, Gcse and Gcu for fuzzification as well as for obtaining the actual output of the command current are calculated using known motor data. All the linguistic variables of the fuzzy-control system (speed error, speed-error variation) were scaled into a common discourse universe with values between [−1, 1]. As a consequence, it was possible to map all the variables simultaneously with a unique set of membership functions.

Rated speed of the motor is 149 rad/s and an assumption is made that this value is the maximum speed of operation of the motor. Thus, maximum speed error is 149 for start-up from standstill and the scaling factor for the speed error is obtained as [13]:

$$Gse = 1/149 \approx 0.00671 \tag{8}$$

Scaling factor for the change in speed error is calculated on the basis of rated inertia and maximum torque that the motor is allowed to develop, taking sampling time 20µs.

$$Te\ max = Jn/P(\Delta\omega/Ts) \rightarrow \Delta\omega = 0.0487 \text{ rad/s}$$
$$Gcse = 1/cse = 1/(e(Ts) - e(0)) = 1/\Delta\omega = 20.5 \tag{9}$$

Output scaling factor is set to Gcu = 2.

B. Rule Base Designing

In this paper, in order to compare the performance of the FLC's with different Rule base sizes the rule base with the sizes of 49, 25 and 9 rules are designed for speed control of induction motor drive. Rule base is basically a matrix used for determining the controller output from their input(s) as it holds the input/output relationships.

The rules used in the rule base of 49, 25 and 9 rules with the different FLC's are given in tables shown in Tab. I, II, and III respectively. The linguistic terms used for input and output variables are described as: "Z" is "Zero"; "N" is "Negative"; and "P" is "Positive", NL is Negative Large , NM is Negative Medium, NS is Negative Small, PL is Positive Large, PM is Positive Medium and PS is Positive Small. The rules are in general format of "*if* anticedent[1] *and* antecedent[2] *then* consiquent".

TABLE I: RULE BASE ARRAY FOR FLC (49)

SE/CSE	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NM	NM	NS	Z
NM	NL	NL	NM	NM	NS	Z	PS
NS	NL	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PL
PM	NS	Z	PS	PM	PM	PL	PL
PL	Z	PS	PM	PM	PL	PL	PL

TABLE II: RULE BASE ARRAY FOR FLC (25)

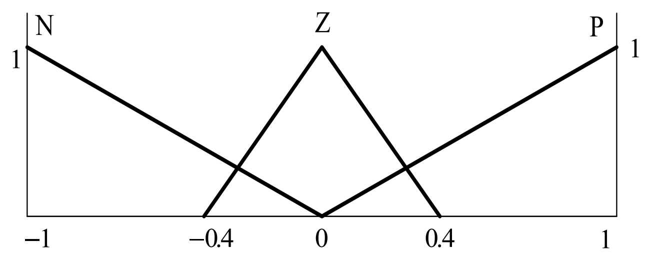
SE/CSE	NL	NS	Z	PS	PL
NL	NL	NL	NL	NS	Z
NS	NL	NL	NS	Z	PS
Z	NL	NS	Z	PS	PL
PS	NS	Z	PS	PL	PL
PL	Z	PS	PL	PL	PL

TABLE III: RULE BASE ARRAY FOR FLC (09)

SE/CSE	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

C. Membership Functions

In order to have unbiased comparison between the FLC's triangular membership function are used for designing the rule base in the work. The common input output membership functions are used for a particular FLC as shown in Fig. 3. All the membership functions are symmetrically spaced over the universe of discourse.



(a)

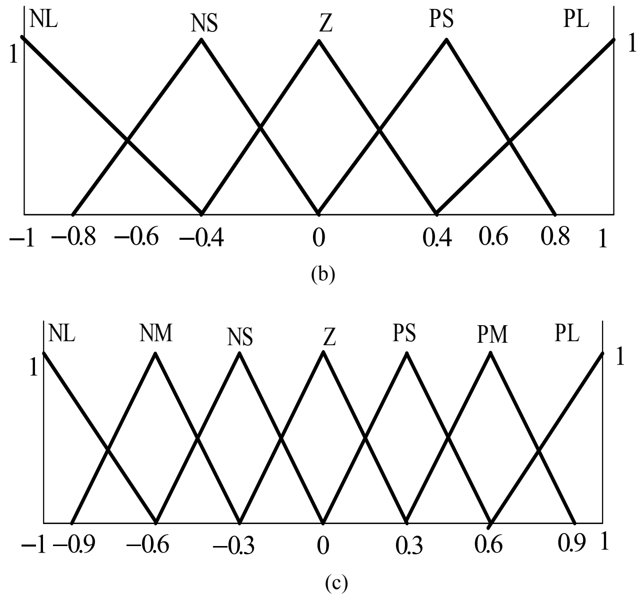


Fig. 3. Membership functions for FLC with (a) 9 rules (b) 25 rules (c) 49

IV. Results & Discussion

For the performance evaluation of the proposed fuzzy logic controller based indirect vector control induction motor drive, detailed study has been carried out for which drive was simulated under different operating conditions such as sudden change in command speed, step change in load. The parameters of the 4KW, 3phase, 415 V squirrel cage induction motor used for this work are given in Tab. IV.

For the performance comparison between the FLC's of different rule base sizes, three phase induction motor drive incorporating indirect vector control technique is implemented in the MATLAB/Simulink environment.

TABLE IV: Induction Motor Parameters

Parameter	*Value*
Stator Resistance (R_s)	1.405 Ω
Rotor Resistance (R_r)	1.395 Ω
Stator Inductance (L_s)	0.005839 H
Rotor Inductance (L_r)	0.005839 H
Mutual Inductance (L_m)	0.1722 H
Inertia (J)	0.0131 Kg.m^2
Pole Pair (P)	2
Friction Factor (F)	0.002985 N.m.s

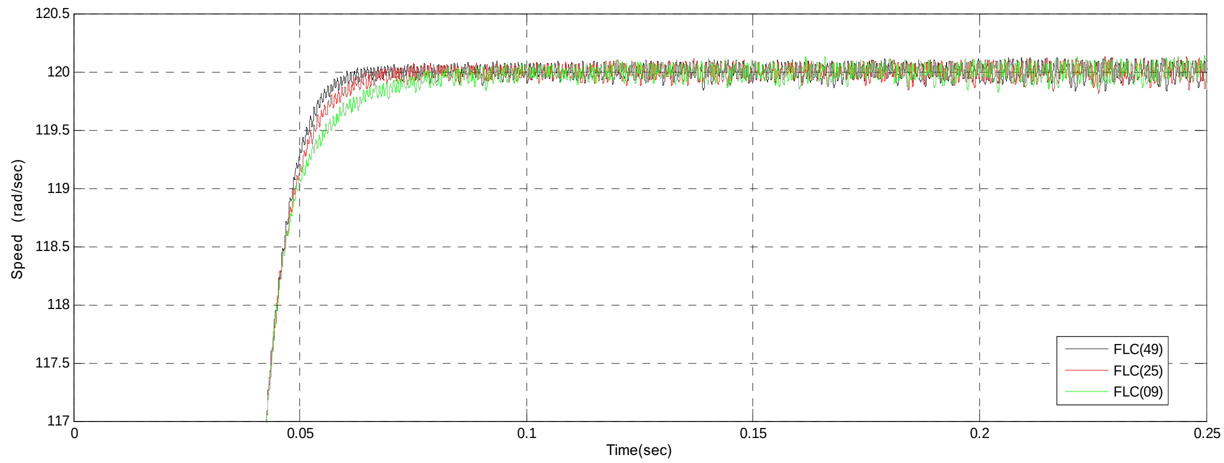


Fig. 4(a). Speed tracking capability of drive for three FLC rule base at higher speed of 120 rad/sec.

Fig. 4 (a) and 4 (b) shows the results of 49, 25 and 9 rules FLC for reference speed tracking of drive at higher speed of 120 rad/sec. and at lower speed 60 rad/sec. respectively. It is evident from these figures that undershoot in the responses leads to increase in settling time when changing from 49, 25, 9 rule base FLC system respectively. It is further observed that speed tracking of the drive system is excellent which shows the correctness of developed system.

The load rejection capability of the three FLC under consideration with discussed drive system is shown in Fig. 5 (a) and 5 (b) at higher speed of 120 rad/sec. and at lower speed of 60 rad/sec. respectively. The step rated torque load is suddenly applied at time t=0.6 sec when the drive is running at no load steadily. It is shown in the figures that the load rejection capability is improved in terms of steady state error and settling time when moving from lower rule base to higher rule base.

The performance of FLC drive system with rule base of 49, 25 and 9 rules under no load is also tested for increase in speed from 60 rad/sec. to 100 rad/sec. and decrease in speed from 100 rad/sec. to 60 rad/sec. is shown in Fig. 6 (a) and Fig. 6 (b) respectively at no load condition. These figures exhibit that the performance of the drive system is getting improved when rule base is increased from lower to higher in terms of steady state error and settling time.

The performance of FLC drive system with rule base of 49, 25 and 9 rules under load is also tested for increase in speed from 60 rad/sec. to 100 rad/sec. and decrease in speed from 100 rad/sec. to 60 rad/sec. is shown in Fig. 7 (a) and Fig. 7 (b) respectively. It is shown from these figures that drive possesses good dynamics even at full load condition for different rule base.

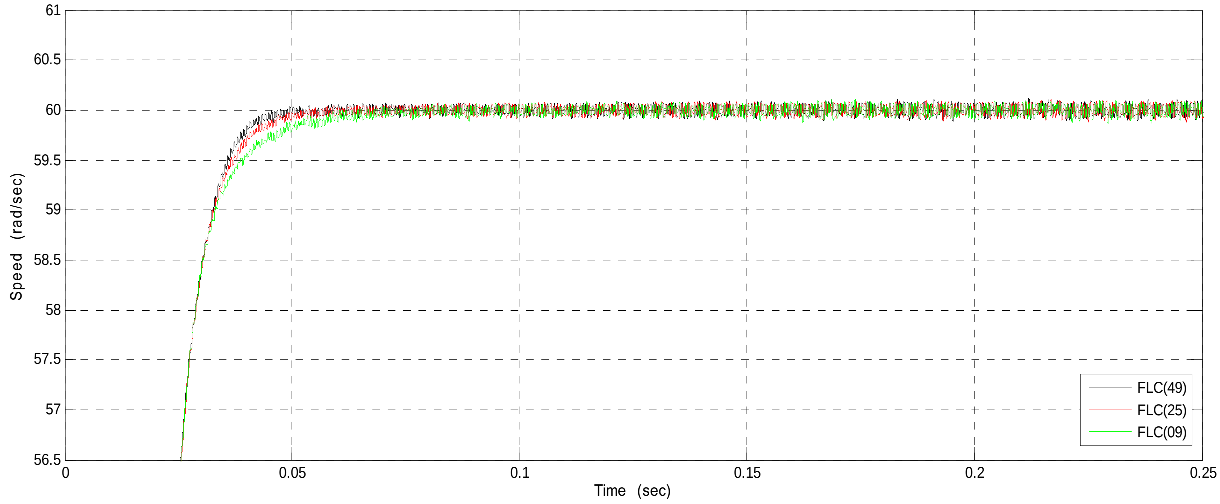


Fig. 4(b). Speed tracking capability of drive for three FLC rule base at lower speed of 60 rad/sec.

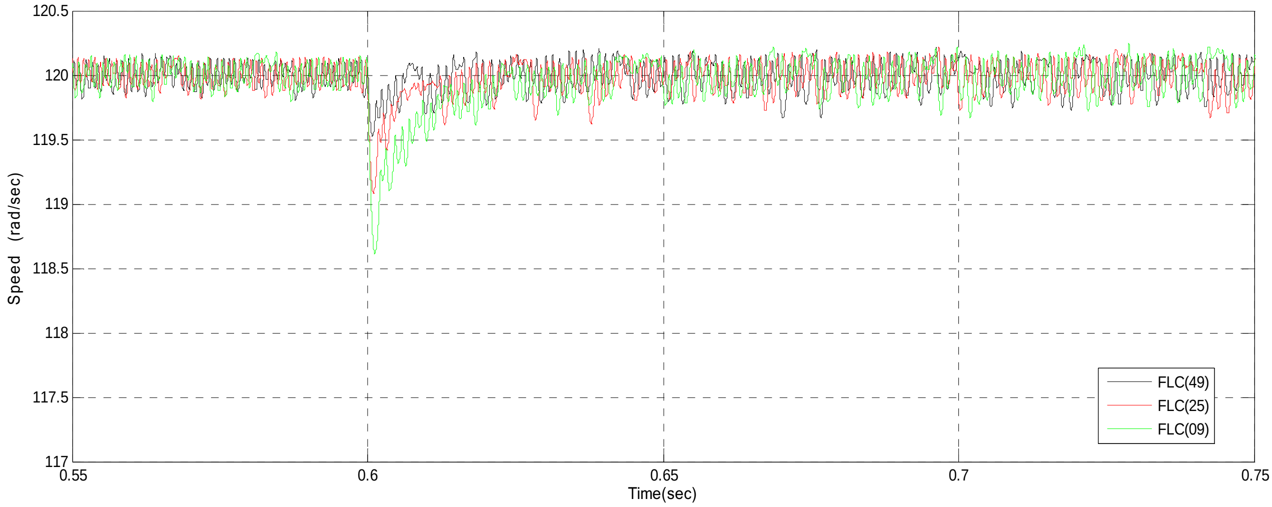


Fig. 5(a). Load rejection capability of drive for three FLC rule base at higher speed of 120 rad/sec.

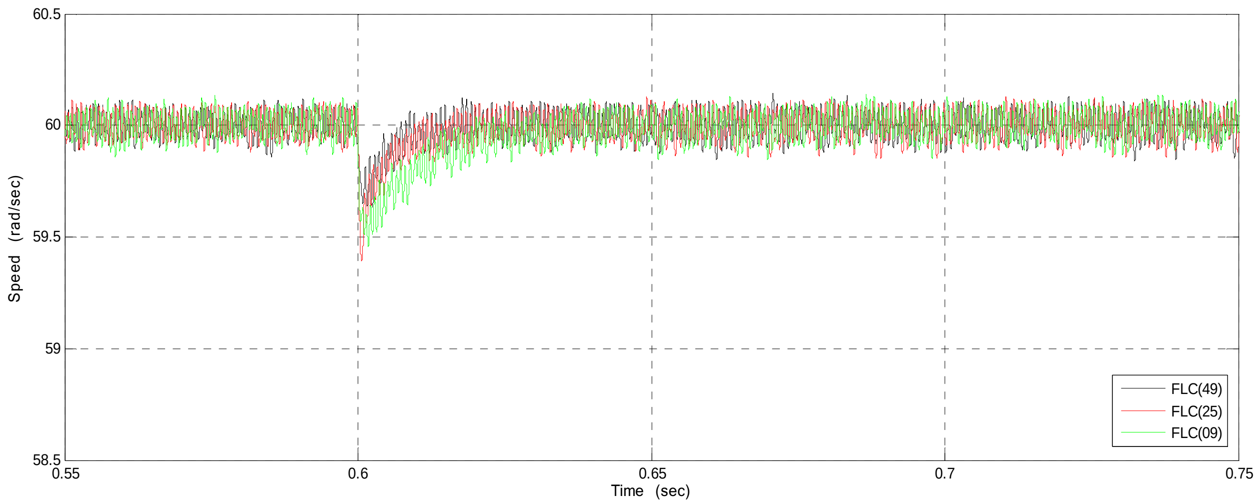
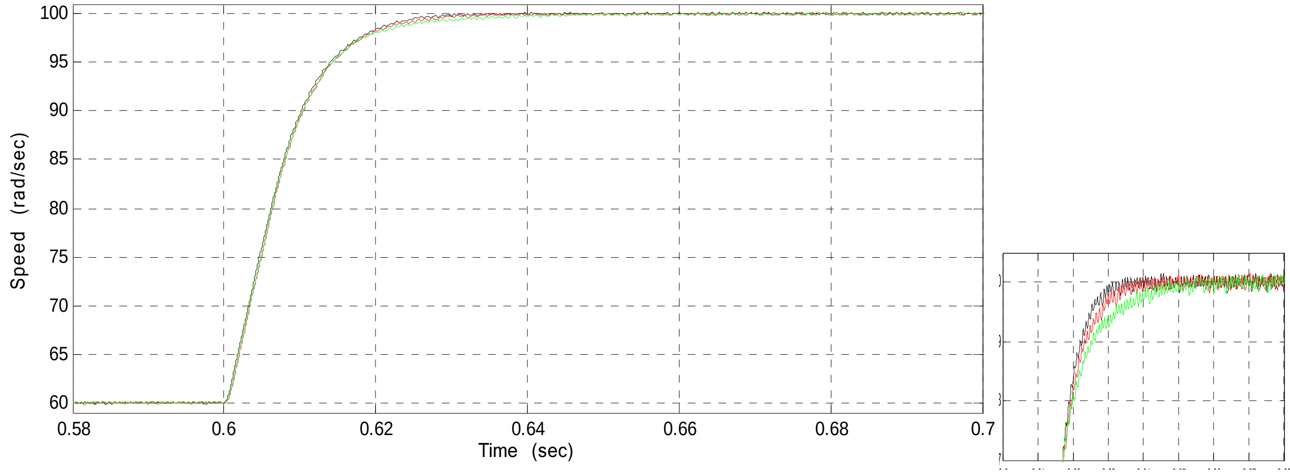
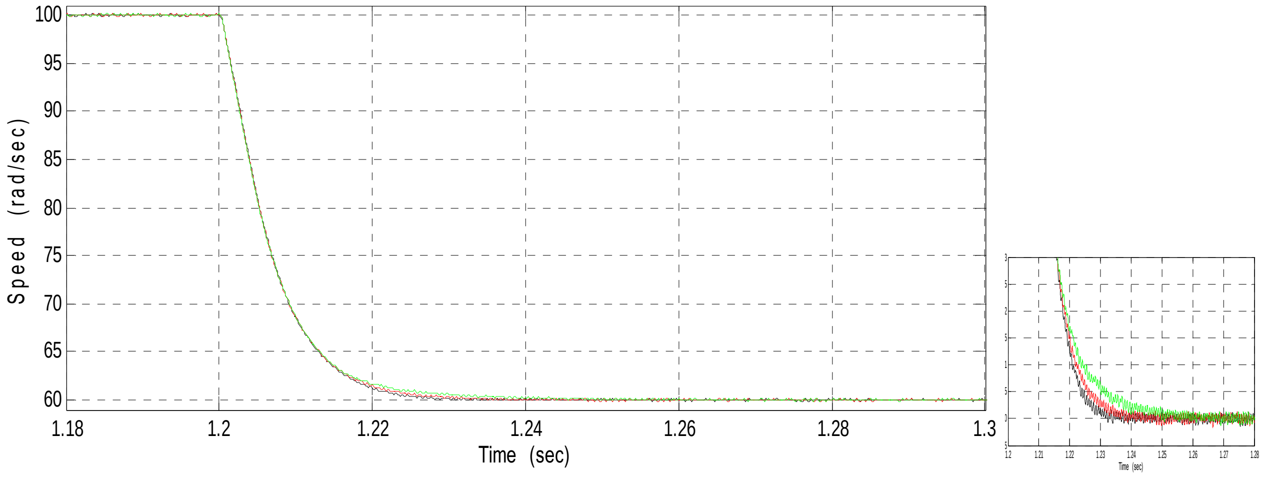


Fig. 5 (b). Load rejection capability of drive for three FLC rule base at lower speed of 60 rad/sec.



(Enlarge view of at knee point)

Fig. 6 (a). Performance of drive for three FLC rule base for increase in speed from 60 rad/sec. to 100 rad/sec at no load.



(Enlarge view of at knee point)

Fig. 6 (b). Performance of drive for three FLC rule base for decrease in speed from 100 rad/sec. to 60 rad/sec at no load.

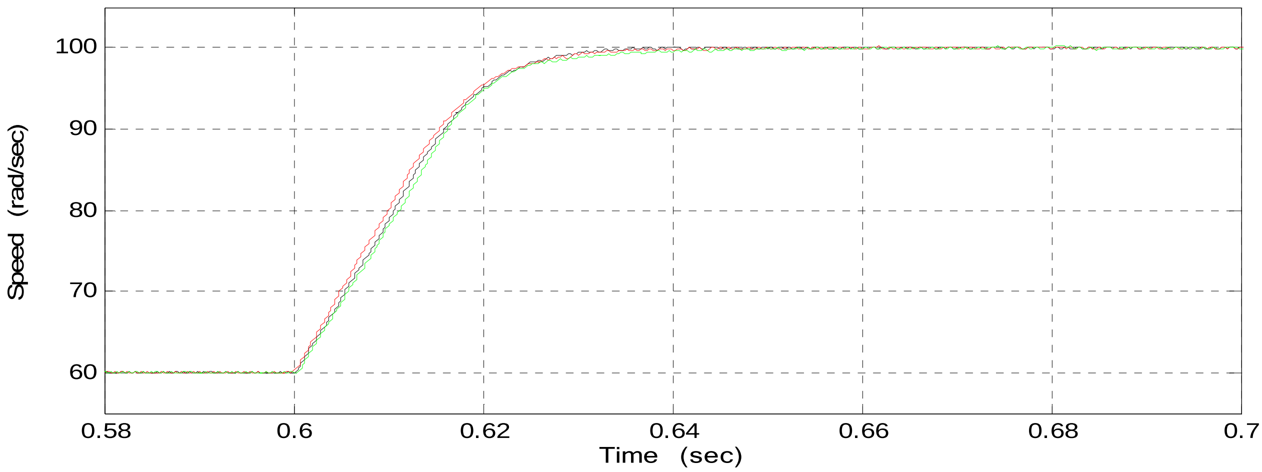


Fig. 7 (a). Performance of drive for three FLC rule base for increase in speed from 60 rad/sec. to 100 rad/sec at full load

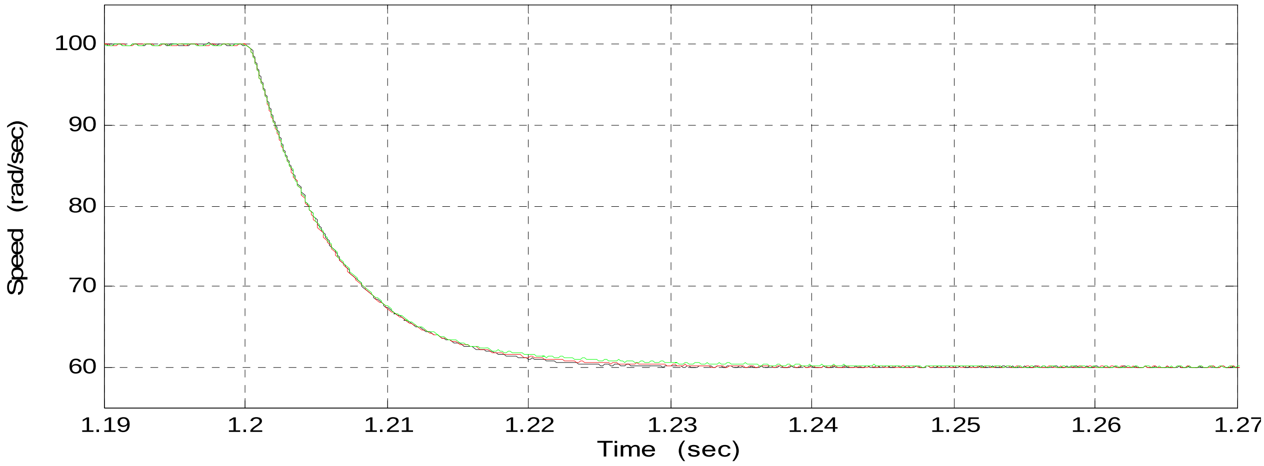


Fig. 7(b). Performance of drive for three FLC rule base for decrease in speed from 100 rad/sec. to 60 rad/sec at full load.

V. CONCLUSION

In this paper the performance of indirect vector controlled technique with proposed FLC for speed control loop has been presented for three different FLC rule bases namely 49, 25 and 9 rules. The dynamic model of drive system has been developed in Simulink/MATLAB. The drive performance has been evaluated for reference speed tracking, disturbance rejection control capability and speed changing case for no load and at full load. It has been observed that the performance of drive system using larger FLC rule base has been found excellent as far as performance indices have been concerned in comparison with the performance with lesser rules but at the cost of large computational resources and speed.

REFERENCES

[1] B. K. Bose, *Modern Power Electronics and AC Drives*, Eaglewood Cliffs, New Jersey: Prentice hall, 1986.

[2] M. N. Uddin, T. S. Radwan, and M. A. Rahman, "Performances of Fuzzy-Logic-Based Indirect Vector Control for Induction Motor Drive," *IEEE Trans. Industry Applications*, vol. 38, no. 5, pp. 1219-1225, Sep./Oct. 2002.

[3] T. S. Radwan, M. N. Uddin, and M. A. Rahman, "A new and simple Structure of fuzzy logic based Indirect Field Oriented Control of Induction Motor Drive," in *Proc.35th Annual IEEE Power Electronics Specialists Conference*, Germany, 2004, pp. 3290-3294.

[4] Z. Ibrahim and E. Levi, "A Comparative Analysis of Fuzzy Logic and PI Speed Control in High-Performance AC Drives Using Experimental Approach," *IEEE Trans. on Industry applications*, vol. 38, no. 5, pp. 1210-1218, Sep./Oct. 2002.

[5] C. Shanmei, W. Shuyun, and D. Zhengeheng, "A Fuzzy Speed Controller of Induction Motors," in *Proc. International Conference on Intelligent Mechatronics and Automation*, China, 2004, pp. 747-750.

[6] B. Sahu, K. B. Mohanty, and S. Pati, "A Comparative Study on Fuzzy and PI Speed Controllers for Field-Oriented Induction Motor Drive," in *Proc. International Conference on Industrial Electronics, Control and Robotics*, India, 2010, pp. 191-196.

[7] B. Kumar, Y. K. Chauhan, and V. Shrivastava, "Performance Evaluation of Reduced Rule Base Fuzzy Logic Controller for Indirect Vector *Controlled Induction Motor Drive," in Proc. 4th International Conference on Computer Simulation and Modeling,* Hong Kong, 2012, pp. 81-86.

[8] M. Masiala, B. Vafakhah, A. Knight, and J. Salmon, "Performances of PI and Fuzzy–Logic Speed Control of Field–Oriented Induction Machine Drives," in *Proc. Canadian Conference on Electrical and Computer Engineering,* 2007, Canada, pp. 397-400.

[9] C. B. Butt, M. A. Hoque, and M. A. Rahman, "Simplified Fuzzy-Logic-Based MTPA Speed Control of IPMSM Drive," *IEEE Trans. Industry Applications,* vol. 40, no. 6, pp. 1529-1535 Nov./Dec. 2004.

[10] M. N. Marwali, "Implementation of Indirect Vector Control on an Integrated Digital Signal Processor - Based System," *IEEE Trans. Energy Conversion*, vol. 14, no. 2, pp. 139-146, June1999.

[11] N. Mariun, S. B. M. Noor, J. Jasni, and O. S. Bennanes, "A fuzzy logic based controller for an indirect vector controlled three phase induction motor," in *Proc. IEEE Region 10 conference TENCON*, Bangkok 2004, pp. 1-4.

[12] C. Zang, "Vector controlled PMSM drive based on fuzzy speed controller," in *Proc. International Conference on Industrial mechatronics and Automation*, China, 2010, pp. 199-202.

[13] B. N. Kar, K. B. Mohanty, and M. Singh, "Indirect vector control of induction motor using fuzzy logic controller," in *Proc. International conference on Environment and Electrical Engineering*, Rome, 2011, pp. 1-4.

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