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EXPERIMENTAL INVESTIGATION OF DIFFERENT RULES SIZE OF FUZZY LOGIC CONTROLLER FOR VECTOR CONTROL OF INDUCTION MOTOR DRIVES

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ABSTRACT

There is lack of performance comparison investigation between 49, 25 and 9 rules sizefor the speed controller of Induction Motor (IM) drives. Thus, it is difficult to understand the effect of the rules size toward the motor performance. Furthermore, no study was conducted based on the computation burden time affects by the rules experimentally. This paper compares the fuzzy rules sizes in terms of performance based on simulations and experimental analysis as well as the execution time. MATLAB/SIMULINK and dSPACE DSl104 controller platform are used for the analysis. Variation in performance with different rule size may occur due to the shape and number of membership functions. Based on the experimental results, it can be concluded that, higher number of rules increase the Computational Time (CT), hence bigger sampling time is required which will affect the performance.

Keywords: fuzzy logic; IM drives; FLCs; performance; computational time (CT).

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1. INTRODUCTION

The use of induction motor involves in most applications ranging from simple electric fan to large factory applications [1-4]. The robustness, easy to make, less maintenance as well as cheaper costs make the induction motors preferred in most of applications [5-6]. The most actual obstacles with induction motor are the control mechanisms, different approaches and algorithms have been introduced to control the inductions motor [7]. V/F method was first proposed to control the induction motor [8-10].However, due the shortcomings and less efficiency of V/F control, vector control was proposed in order to drive the motor efficiently [11]. Vector control can provide effective and efficient method to control the induction motor similar to controlling DC motor. The most two popular method of vector control of induction motor are Field Oriented Control (FOC) [12] and Direct Torque Control (DTC) [13].

For the last decades proportional integral controllers (PI, PID, and PD) were usually integrated with FOC to drive the AC motors. However, these controllers depends on the motor parameters accuracy and load disturbance and changes, hence any variation may affect the overall system performance [14-16]. In order to eliminate the drawbacks of proportional integral controllers, fuzzy logic controllers were introduced as promising controller that can overcome the non-linearity issues presented in AC motor drives [17].Recently, most of researchers [18-19] are focusing in implementing fuzzy logic as effective controller of vector control of AC drives. The reason behind the intensive interests of using fuzzy logic controller in AC drives is due to due to its capabilities of handling non-linear systems, robustness performance under load disturbances and changes and parameters dependency [20-21].

Many researchers have discussed the superiority of fuzzy logic controller compared to the conventional controllers. In [30, 15] Introduced a comparison between fuzzy logic and PI controllers based on AC motor drives in which the superiority of fuzzy logic is verified with experimental approaches.

Based on the work reports, three are three common sizes of rules are used in AC drive application known as 49, 25 and 9 [23, 14]. Different rules size can produce an effect in the performance of motor drives [24] in which the variations in the number of rules does not produce instability to the controller, but it cause changes to the system performances.

Different study [25] introduced by Betin which investigates the impacts of size of rules based on the stepper motor drive. Four sizes of rules discussed with addition 81 rules set. The system performance was limited to rated speed and the conclusion was that utilizing the addition 81 rules does not produce any improvement,hence the 49 rules was chosen as the best rules size selection which make noticeable improvement.

In case of AC motor drives, study introduced by [26] which investigate different rules size based on induction motor drives. The study compares the 49, 25 and 9 rules with better performance for 49 rules and concluded that the large computational burden presented as the number of rules increase. However, the analysis is limited to the simulation study without computational time measurement for hardware implementation.

This paper presents comparisons study between different FLC rules sizes along with comparisons of computational time effects for each rules selection. The standard number of rules (49, 25 and 9) is implemented with hardware set based DSPACE 1104. The comparison is done to observe the effects of rules size in the speed, torque and current performance of the drive. The unique part about this study is that it investigates the effects of rules sizes on the computational times based on experimental approach.

2. MATHEMATICAL MODEL INDUCTION MOTOR

There are many different drives system for induction motor. Fig. 1 shows the block diagram of Field Oriented Control (FOC) of induction motor. In the FOC method, the stators currents are controlled which is represented by two orthogonal current component vector. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque current component (aligned with the q co-ordinate) and the flux current component (aligned with d co-ordinate). As FOC is simply based on projections, the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient). The block diagram in Fig. 1 presents the FOC of induction motor with hysteresis current control in which the system includes the induction motor model, inverter, phase transformations, theta calculation, hysteresis current controller and speed (FLC) controller and [27-28].

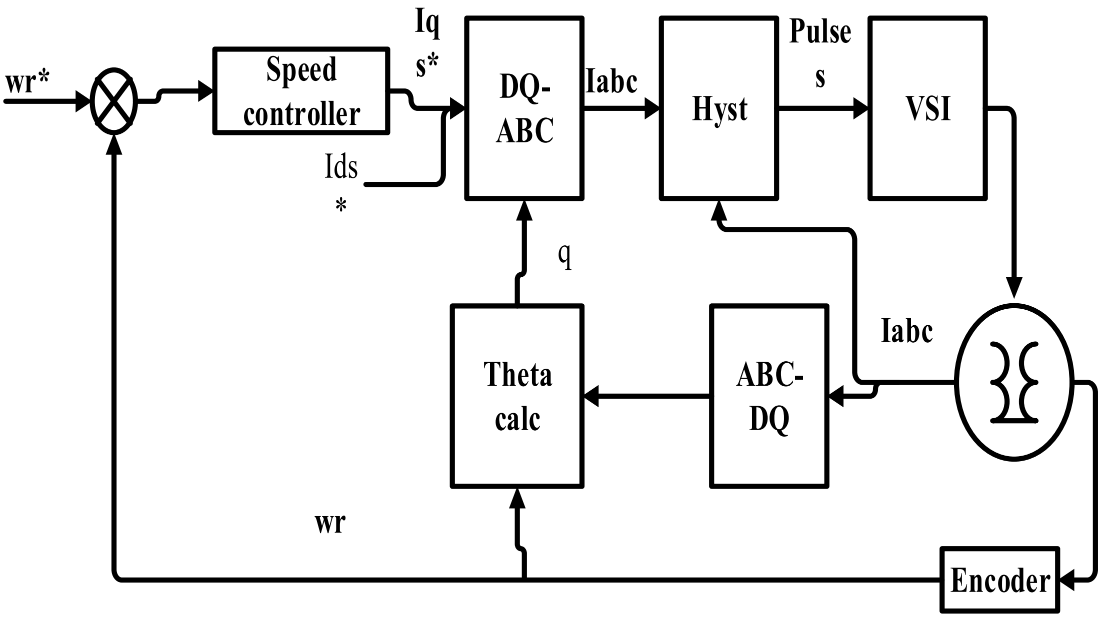


Fig.1. FOC of induction motor with hysteresis current controller

The speed reference is compared with the actual speed produced from the motor. The error signal is fed into the fuzzy logic controller, which produced the torque current, iq reference. The iq and id currents component is converted into three phase current reference to be compared with actual three phase currents in the hysteresis current block and produce the control signals for the inverter.

In accordance to the induction motor model represented in rotary reference frame, the voltage quantities can be expressed as follow [24]:

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \tag{1}$$

$$V_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds} \tag{2}$$

$$V_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} + \omega_e \psi_{ds} \tag{3}$$

$$V_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr} \tag{4}$$

$$V_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} + (\omega_e - \omega_r)\psi_{qr} \tag{5}$$

and V_{qr}, V_{dr}=0 and the flux equation as follow:

$$\psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \tag{6}$$

$$\psi_{qr} = L_{lr} i_r + L_m (i_{qs} + i_{qr}) \tag{7}$$

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \tag{8}$$

The electromagnetic torque can be expressed as follow:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \tag{9}$$

All the motor parameters and nomenclature are given in Table 1. When the vector control is accomplished, the d frame of the rotor field can be zero. So, that the torque is driven by q frame of stator current as expressed in Equation (10).

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

Table 1. Induction motor parameters

Vs(rated)	380V	**Fs(rated)**	50Hz
P(poles)	4	**ω(reference speed)**	1400rpm
Rs(stator resistance)	3.45Ω	**Rr(rotor resistance)**	3.6141Ω
Ls (stator inductance)	0.3252H	**Lr(rotor inductance)**	0.3252H
Lm (magnetic inductance)	0.3117H	**J**	0.02kgm^2

3. HYSTERSIS CURRENT CONTROLLER

Fig. 2 explains the operation principle of Hysteresis band PWM for an inverter. The control circuit generates the sine reference current wave of desired magnitude and frequency and it is compared with the actual phase current wave. As the current exceeds a prescribed hysteresis band, the output was set to high. However, when the current starts to decay, the output goes to low. The actual current wave was forced to track the sine reference wave within the hysteresis band by back and-forth (or bang-bang) switching of the upper and lower switches. The inverter then essentially becomes a current source with peak to peak current ripple, which was controlled within the hysteresis band.

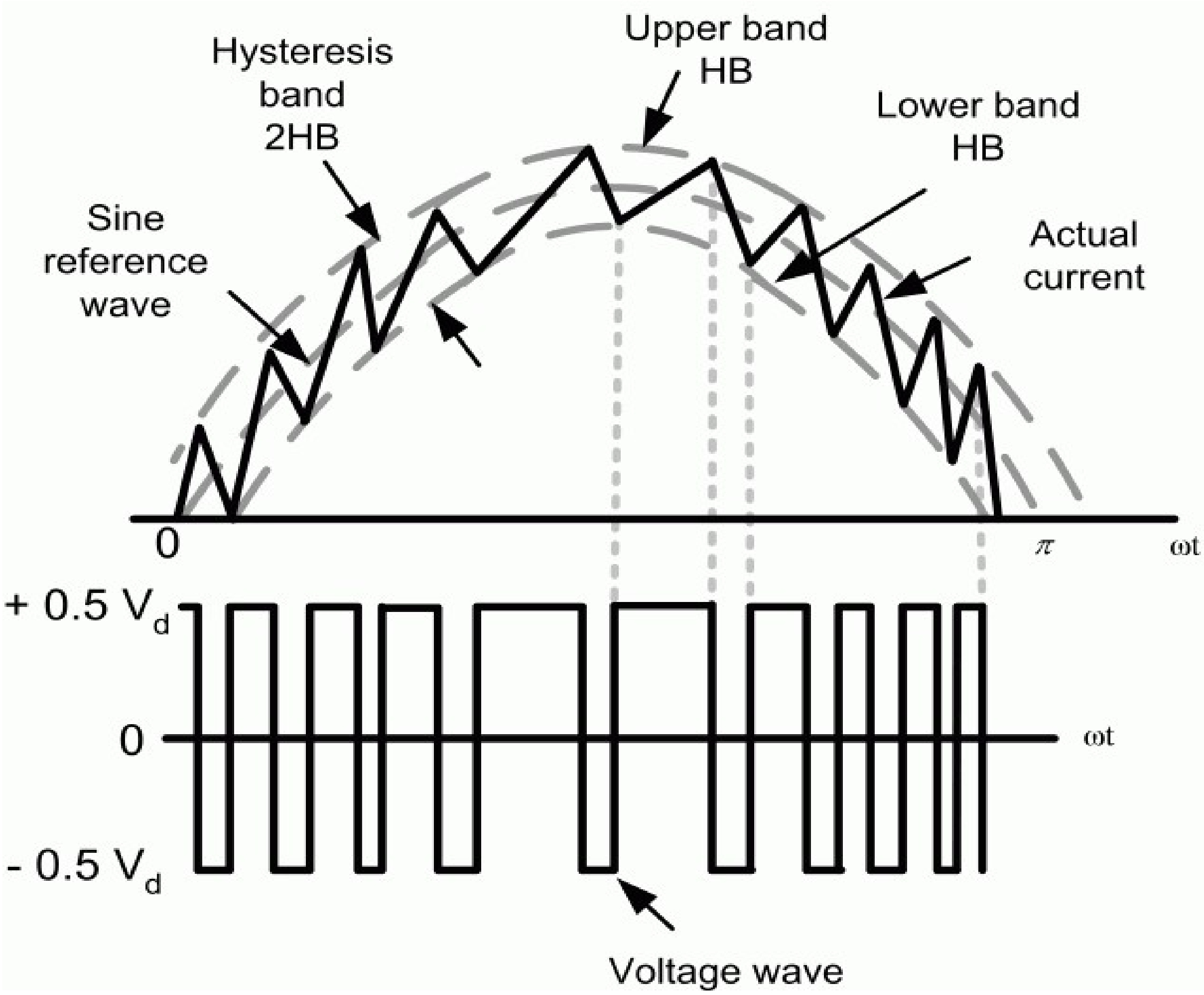


Fig.2. The hysteresis band control technique

4. FLCS DESIGN

This section discussed on the Fuzzy Logic speed control (FLSC) designed. The working principle of the speed control is based on speed error between the actual speeds of the motor with reference speed. The produced error is fed into the controller to generate the reference based on the error. The proportional controller (PI), FLC or Hybrid PI-FLC can be utilized as speed controller to compensate the error and produce the appropriate reference torque current component. Fuzzy controllers however proved to have the superiority in terms of performance and flexibility to parameters variation. Thus, various studies as well as industries prefer the FLC over other conventional controllers.The standard block diagram of fuzzy logic controller has two inputs signal and one output signal is presented in Fig. 3. The fuzzy system consists of four process stages which are fuzzifier, inference engine, knowledge based and fuzzifier process.

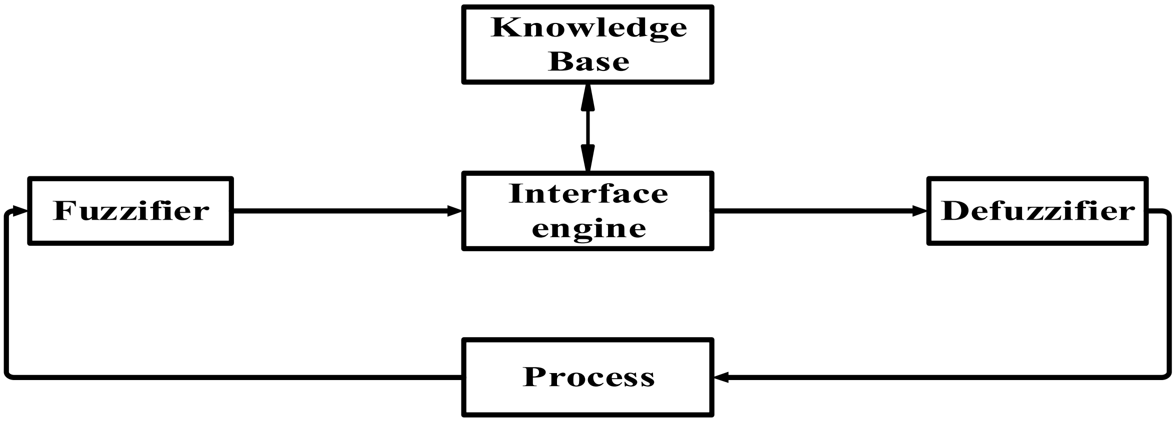


Fig.3. Fuzzy logic block diagram

The speed error and the change of the speed error are used as the inputs signals for the speed controller and having a gain scaling factor respectively. As these normalized quantities are crisp in nature, they need to be first converted to their corresponding fuzzy variables by fuzzification procedure. After fuzzification, the fuzzified inputs are given to the fuzzy inference mechanism. For implementing the fuzzy inference engine, the "min" operator for connecting multiple antecedents in a rule, the "min" implication operator, and the "max" aggregation operator have been used. The fuzzy inference engine uses the appropriately designed knowledge rules base to evaluate the fuzzy rules and produce an output for each rule. The outputs from the inference mechanism are fuzzy in nature and hence to determine the crisp output, the centroid defuzzification scheme has been used. Finally, the incremental crisp output can be tuned by the output scaling gain factor.

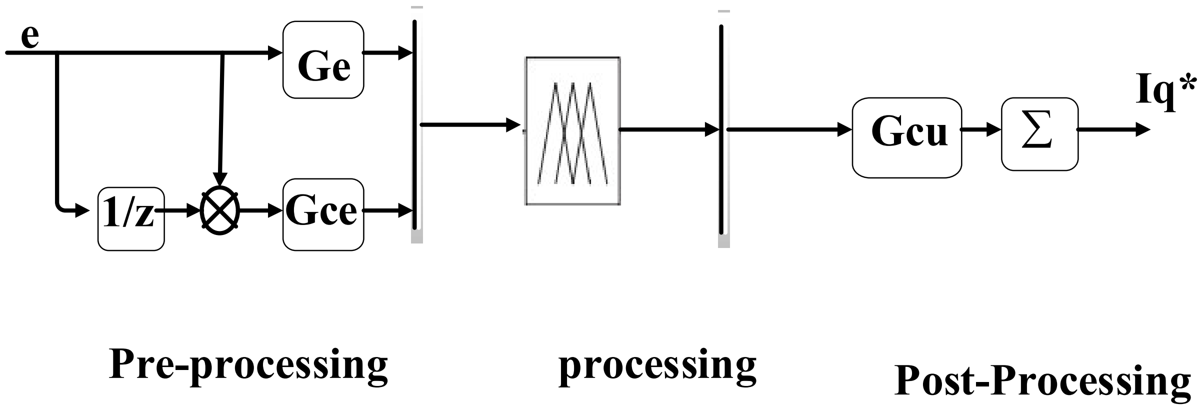


Fig.4. standard FLC for IM drive

4.1.Scaling Factor

In the preprocessing part, the crisp inputs of the speed error, e and its change of speed error Δe are converted into to their corresponding fuzzy variable and defined as:

$$e(k) = G_e\big(\omega_r{}^*(k) - \omega_r(k)\big) = G_e(k)$$

$$\Delta e(k) = G_{ce}\frac{(e(k) - e(k-1)}{T_s}$$

From the above equation, ωr * and ωr stand for reference and actual speed respectively. Meanwhile, (k) and (k-1) represent the current and previous state of the error. Ts represents for the sampling time. The Ge and Gce denote the error and the change of error gain scaling factor where ωr * and ωr are speed reference and actual speed respectively. The maximum Ge gain is determined to cover the rated speed using the following equation.

$$G_e = \frac{1}{|\omega_{e\,max}|}$$

where$\omega_{e\,max}$is the maximum error for the rated speed operation to ensure high enough gain applied to cover the rated speed operation and normalized the input value. The Ge is keep constant based on this maximum speed error .For the change of error gain, Gce and output gain, Gcu the membership function range opted to fit the rated speed operation. The Gce values are tuned to get zero overshoot with faster rise time and the Gcu it set to 1.

.Through defuzzification, the output current $\Delta Iq*$ is computed using the center of gravity (COG) algorithms. For post-processing part, the final crisp output for the torque current Iq* is obtained by the following equation:

$$I^*{}_q(k) = I *_q (k-1) + Gcu(\Delta Iq(k))$$

4.2.Membership Function

The membership function for error (e) and change of error Δe and incremental output gain, cu are presented in Fig. 5. Three are three type of membership function used in this analysis which are 3, 5 and 7. Similar MFs number and shape applied for the inputs and output variable. Triangular and trapezoid membership function shape is used for the designed for all the input and output variable with normalized value of -1 to 1 domain. The membership function shapes are set to be equally overlapped between the next membership function. This paper used this uniformly distributed triangular membership function shape.

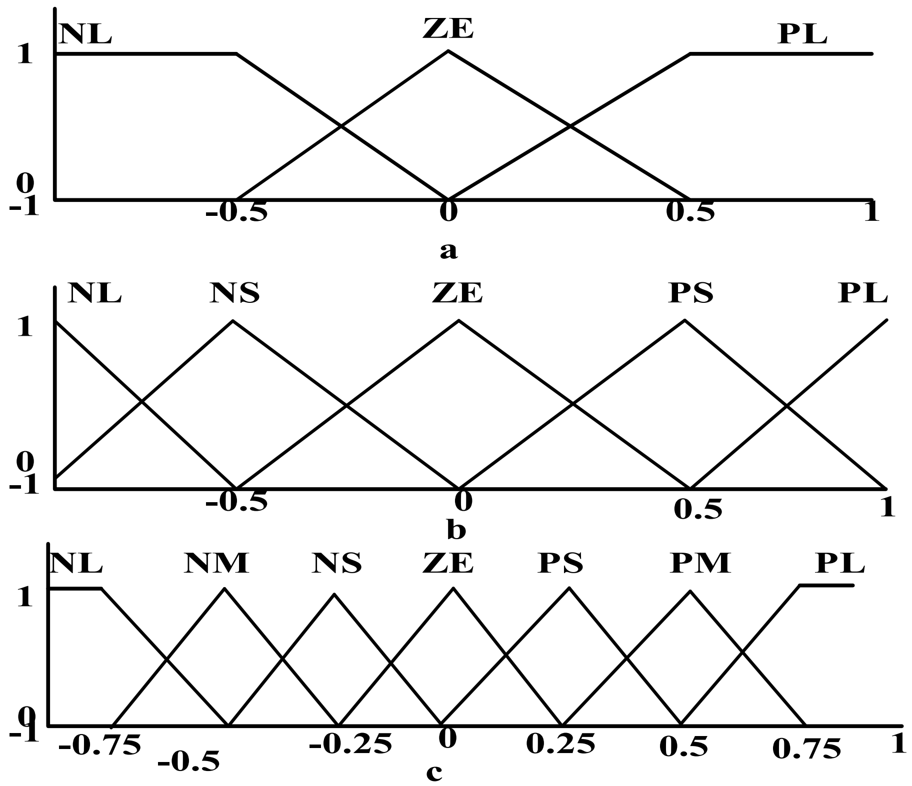


Fig.5. Inputs and output membership functions variable design (a) 9 rules, (b) 25 rules and (c) 49 rules

4.3. Fuzzy Rules Design

The fuzzy rule designed is related to the number of membership function input. The fuzzy rules designed based on the knowledge based to relate between inputs and output control. Based on the three different fuzzy logic membership functions set, three different fuzzy rule set is developed. The fuzzy rules sets designed are presented in Table 2, 3 and 4 for 9, 25 and 49 rules respectively. The rules are developed using Mamdani-type fuzzy inference. Appropriated rules are interpreted based on the decision tables for the rules design using Fuzzy Logic Tools MATLAB.

Table 2. Fuzzy rule (9)

e / ∇e	NL	ZE	PL
NL	NL	NL	ZE
ZE	NL	ZE	PL
PL	ZE	PL	PL

Table 3. Fuzzy rule (25)

∇e \ e	**NL**	**NS**	**ZE**	**PS**	**PL**
NL	NL	NL	PS	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NL	NS	NS	PS	PL
PS	NS	ZE	ZE	PS	PL
PL	ZE	PS	PS	PL	PL

Table 4. Fuzzy rule (49)

∇e \ e	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	NL	PL	PL	PL

5. SIMULATION RESULTS

MATLAB/SIMULINK environment was utilized to perform the simulation of the IM drive system with three different fuzzy rules size of speed control. Both fuzzy sets designed to achieve almost zero overshoot.However, as can be seen from the speed response, there is a slight difference in performance between the three different rules size during forward and reverse speed operation. Table 5 summarizes the rise time (Tr) and settling time (Ts) of the 9, 25 and 49 rules at 1400rpm. In addition, different speed ranges were considered in order to investigate the motor performance at high, medium and low speed operations. The performance of the speed operations is depended on the distribution and gradient of the membership function shape. The simulation results demonstrate the workability of the three different rules under forward and reverse speed operation.

Table 5. Speed response characteristics

Term	Ts(s)		Tr(s)	
Rules	Forward	Reverse	Forward	Reverse
9	0.446	0.487	0.257	0.237
25	0.4926	0.522	0.288	0.239
49	0.48	0.482	0.311	0.261

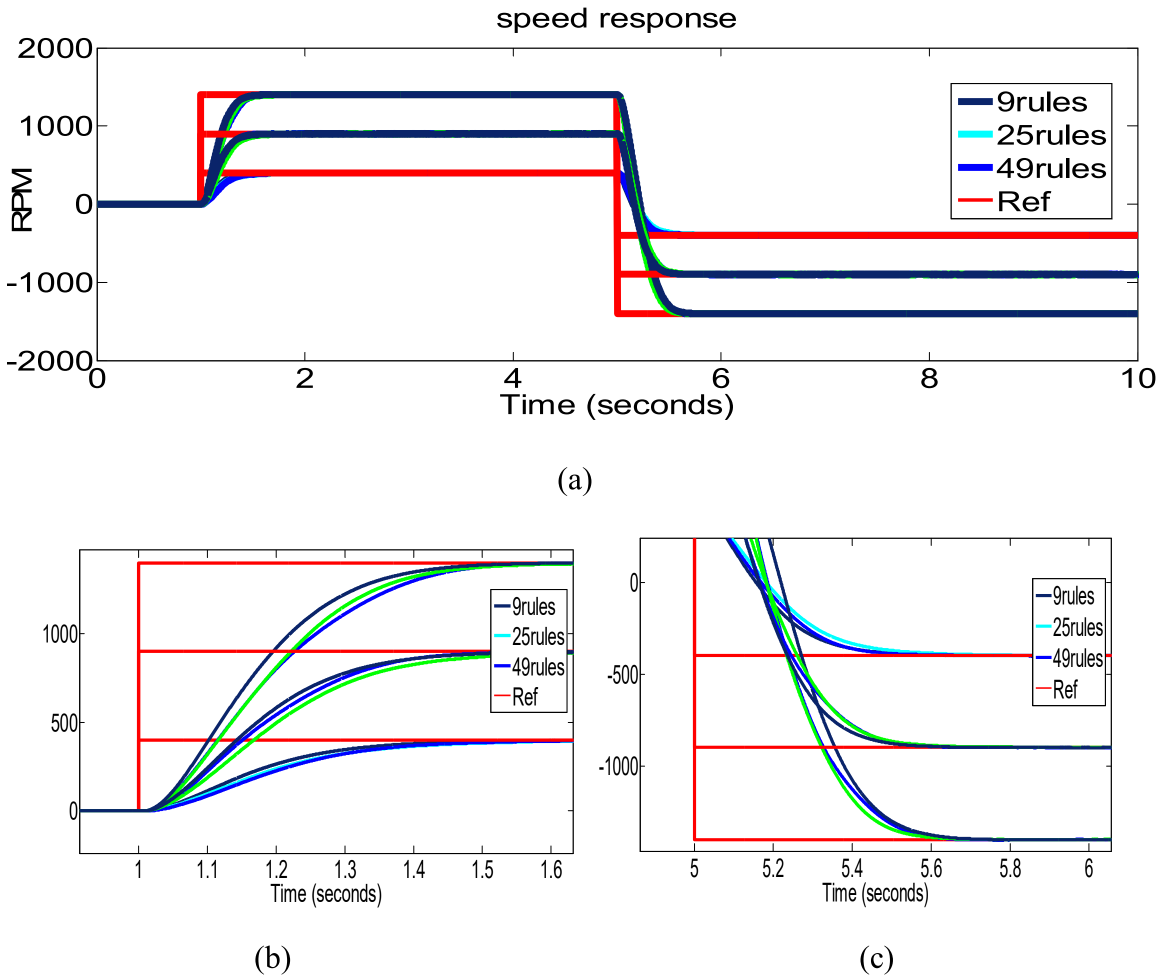
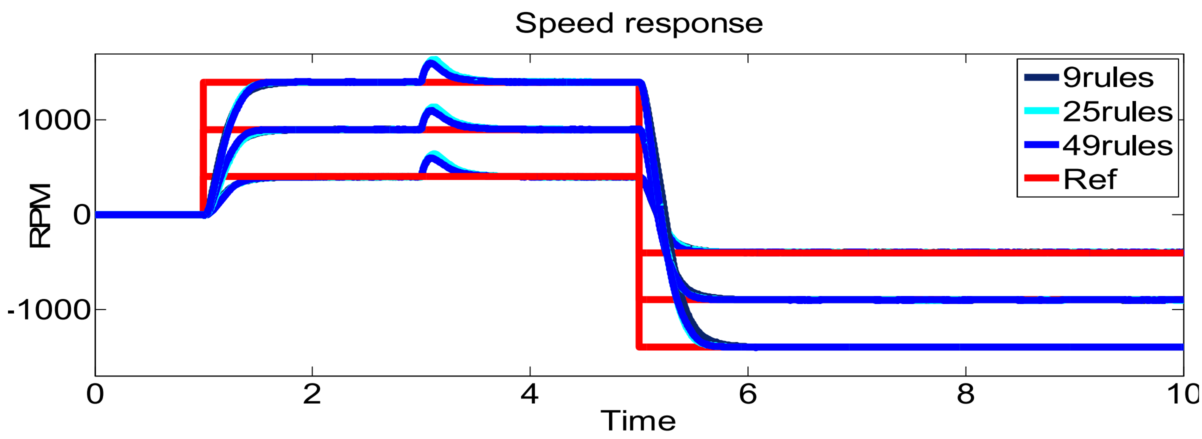
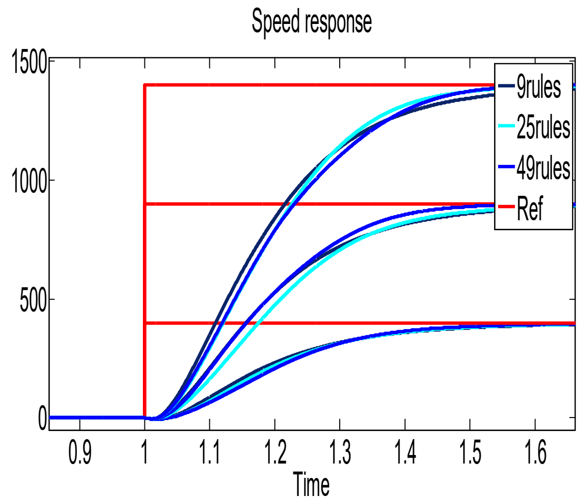


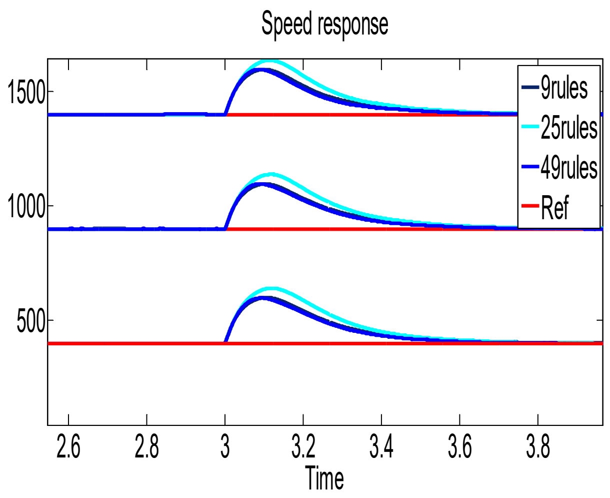
Fig.6. Speeds response without load at 1400, 900and400 rpm (a) full range speed, (b) close up view forward speed, (c) close up view reverse speed



(a)



(b)



(c)

Fig.7. Speeds response with load at 1400, 900and400 rpm (a) full range speed, (b) close up view forward speed, (c) close up view load applied

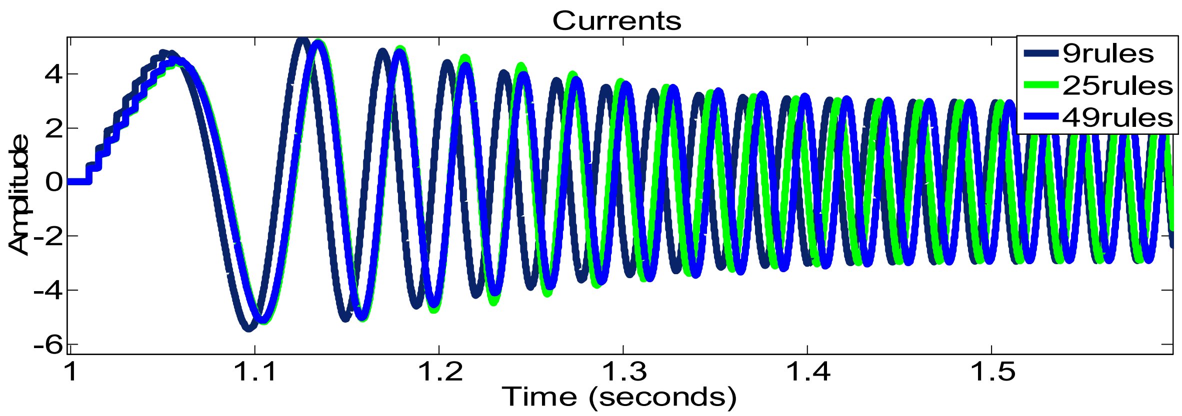


Fig.8. Currents response at 1400 for different rules sizes

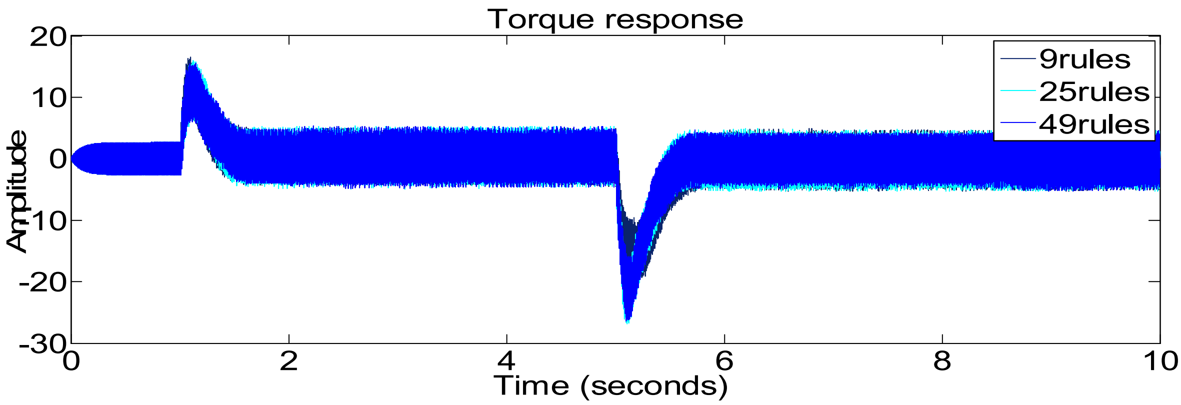


Fig.9. Torque response at 1400 for different rules sizes

6. EXPERIMENTAL RESULTS

6.1. Speed Performance

Experiment analysis also conducted to validate the performance of FLSC drive. In addition, this test is conducted to investigate the effect of the number of rules size towards the computation time burden. The hardware setup is configured with Dspace 1104 and 2Hp, 4 poles, 380V three phase inductions motor and the motor parameters are given in Table 1. The hardware setup is presented in Fig.10 which comprises MATLAB/SIMULINK environment, Dspace1104, inverter and motor.

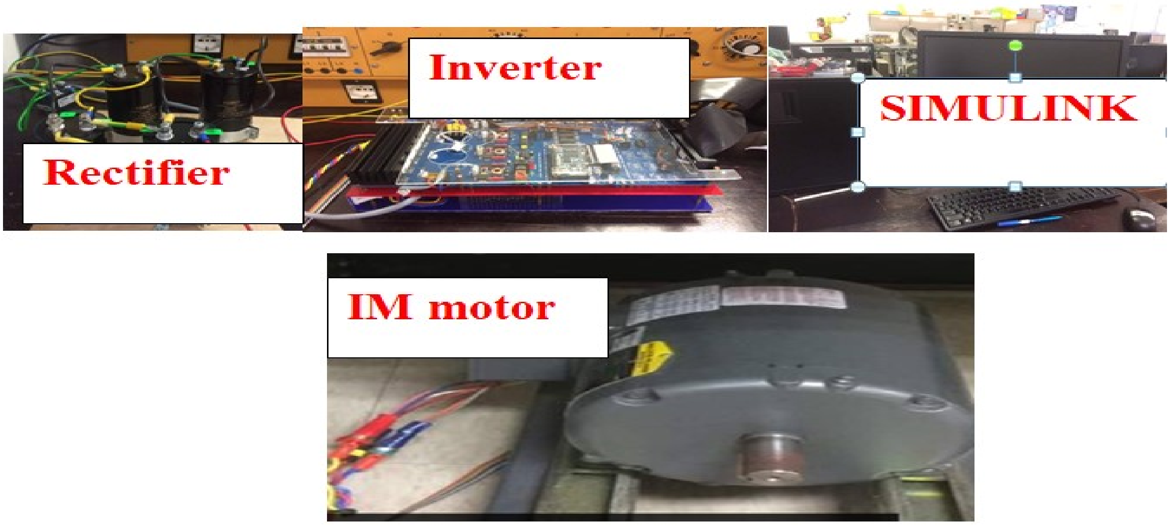


Fig.10. Hardware setup

Similar tests procedure are repeated as the simution parts. All the FLC parameter are keep unchanged and the test result are shown in Fig. 11, 12 and 13 for 400, 900 and 1400 rpm respectively.The expermintal results are almost similar to the simulation results in terms of speed peformance, torque and currents for each fuzzy rule size. From the expermintal results, it can be noticed that 9 rules obviously perform better than 25 and 49 rules in terms of speed response characteristics as shown in Table 6.The settling time as well as rise time of 9 rules is better than the 25 and 49 rules .

The reason behind this is, as the number of rules increase the computational time on the hardware also increase, hence decrease the performance. The big impacts of big size of fuzzy rules is the corresponding computational time produced. Nine rules fuzzy perform faster in reverse and forward speed due to its membership function shapes, as well as the small computational time which produce that can be operated at small sampling time. The comparison of Ts, Tr between 9, 25 and 49 is presented in Table 6. Over the different operations speed,9 rules has the lowest value of settling as well as rising time which emphasize that in experimental testing, the performance is affected by the size of the fuzzy rules.These effects are due to the shape of membership functions of each rules sets and due to the big Computional Time (CT) produced with big number of rules.

Table 6. Speed characterstics of different rules size at different speed operations

Term / **Rules**	**Ts (s)**	**(Tr) (s)**
	400 rpm	
9	0.524	0.324
25	0.548	0.326
49	0.560	0.332
	900 rpm	
9	0.541	0.315
25	0.564	0.325
49	0.594	0.34
	1400 rpm	
9	0.575	0.311
25	0.587	0.335
49	0.596	0.351

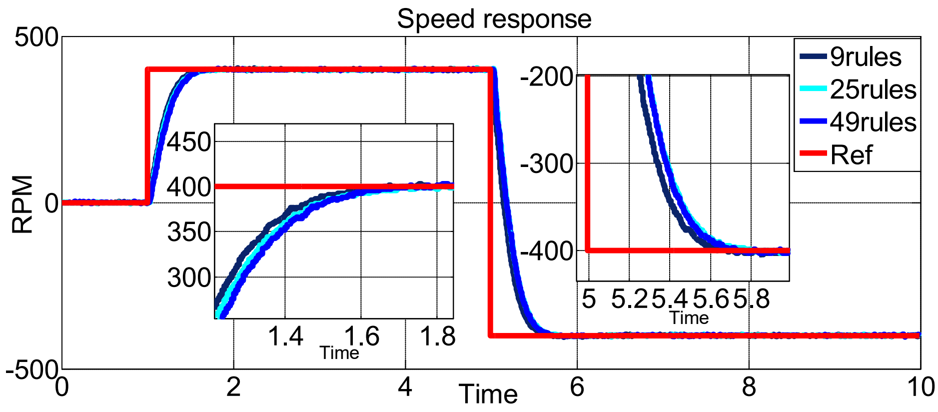


Fig.11. Actual speed response at 400 rpm for different fuzzy rules with close up view of forward and reverse speed

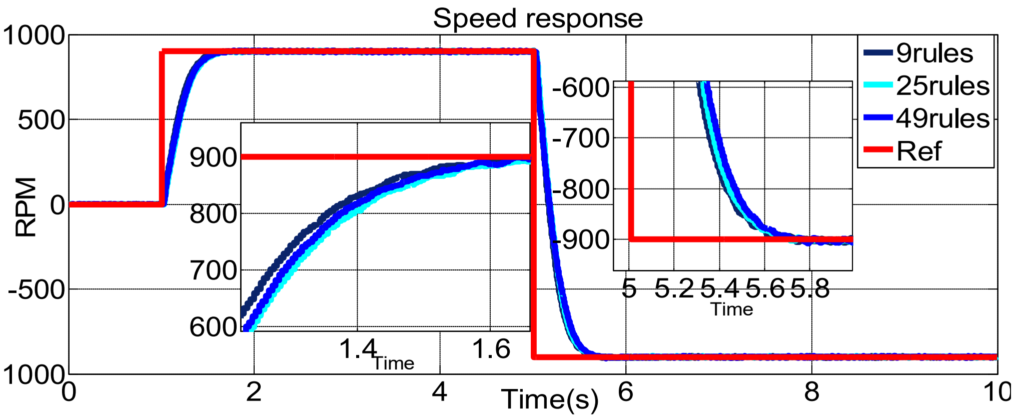


Fig.12. Actual speed response at 900 rpm for different fuzzy rules with close up view of forward and reverse speed

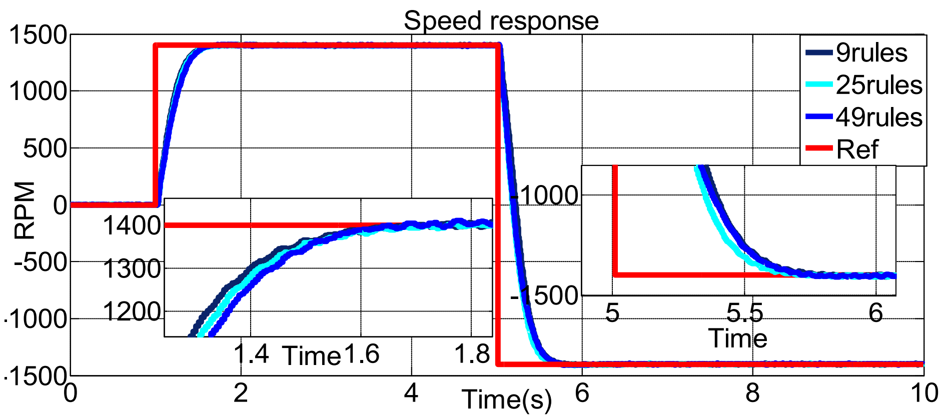


Fig.13. Actual speed response at 1400 rpm for different fuzzy rules with close up view of forward and reverse speed

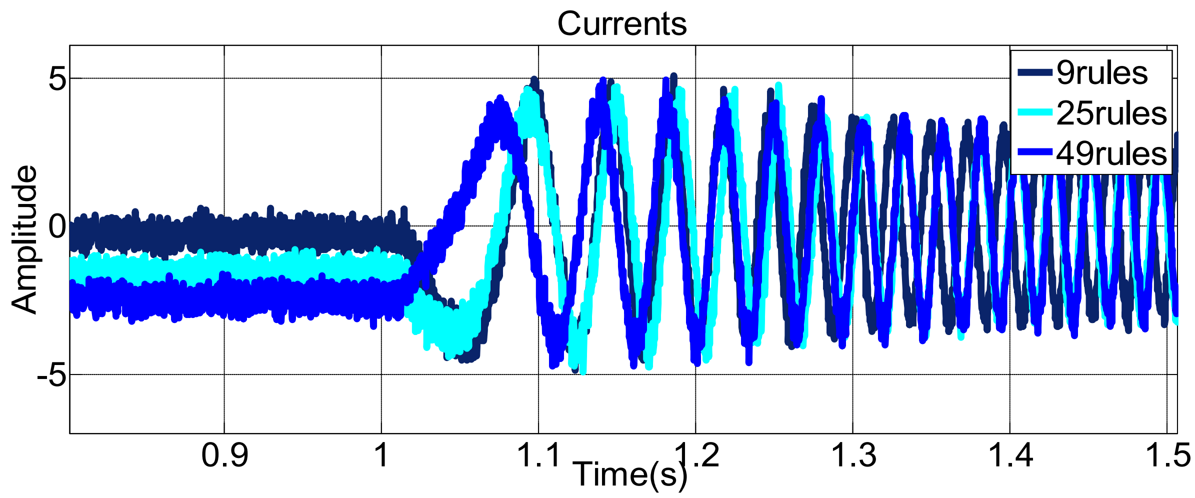


Fig.14. Actual currents response at 1400 for different rules sizes

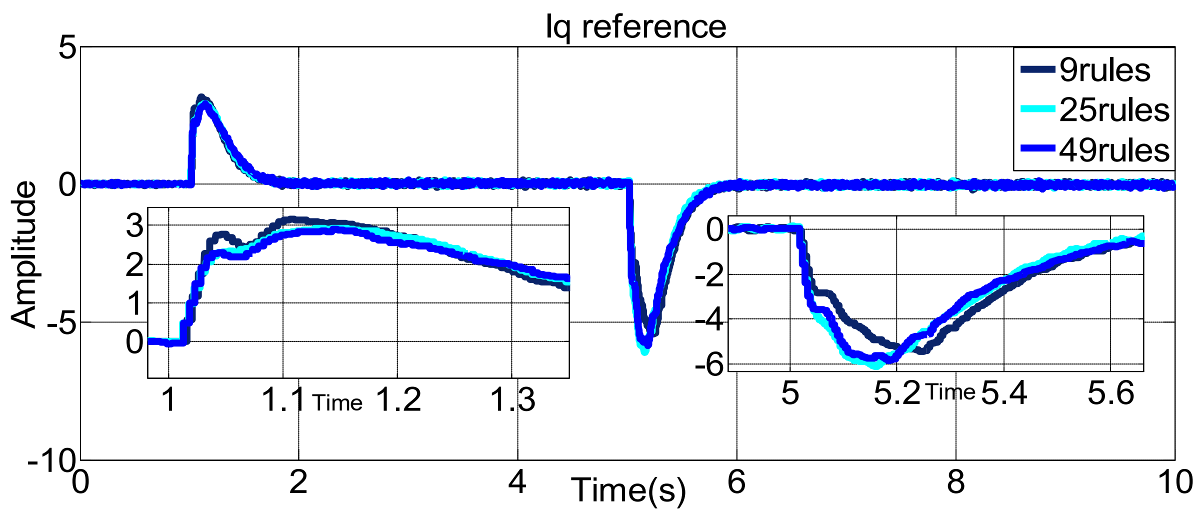


Fig.15. Actual Iq reference at 1400 for different rules sizes

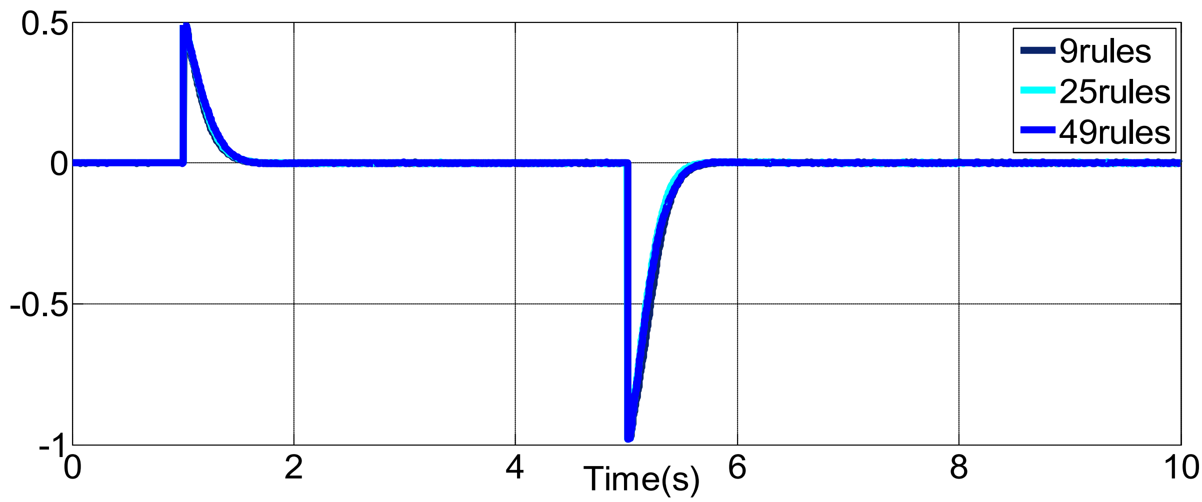


Fig.16. Gce range for different rules size

6.2. Execution Time

Computational Time (CT) has been addressed by many researchers their effects in the system performance by simply mentioning that the big size of fuzzy rules increase the computational time (CT) burden. Control Desk Dspace is utilized to compute the CT of the MATLAB/SIMULINK model used for the experiment. Applying different rules size and measuring the CT and plot it as in Fig.17, 18 and 19 for 9, 25 and 49 rules respectivly. The computational time of 9 rules is the smallest value, which means it execute faster and less burden to the hardware.

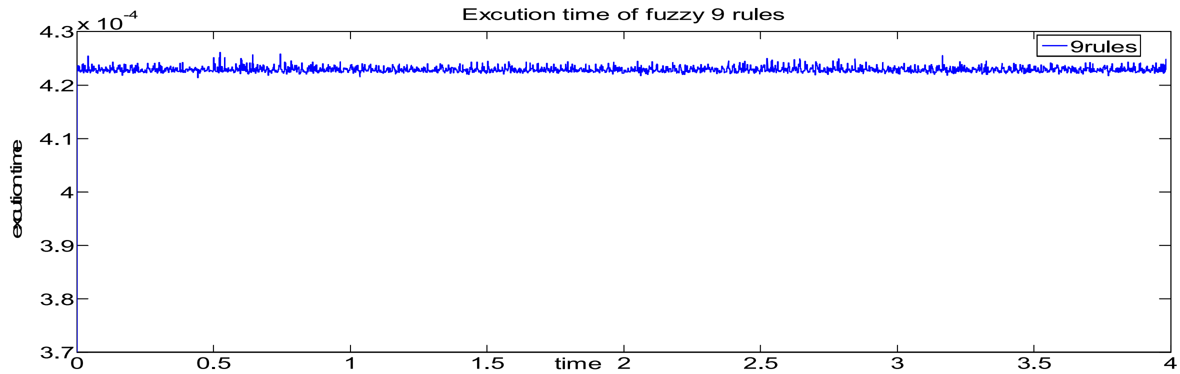


Fig.17. Execution time of fuzzy 9 rules

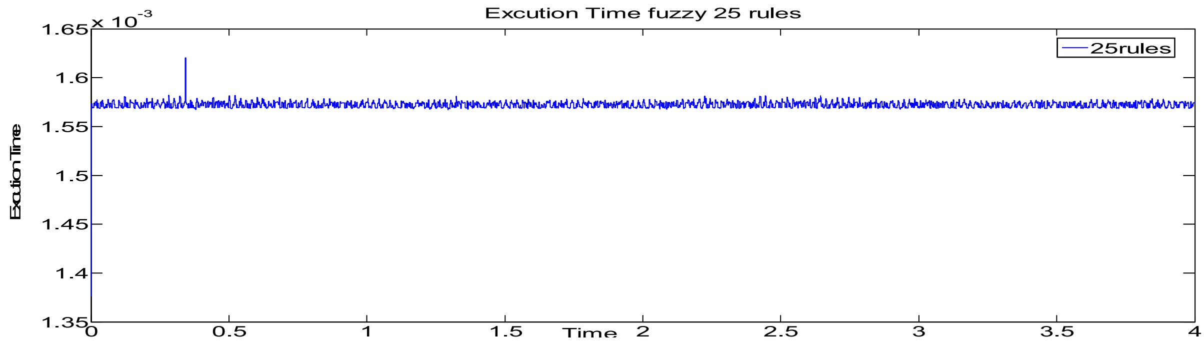
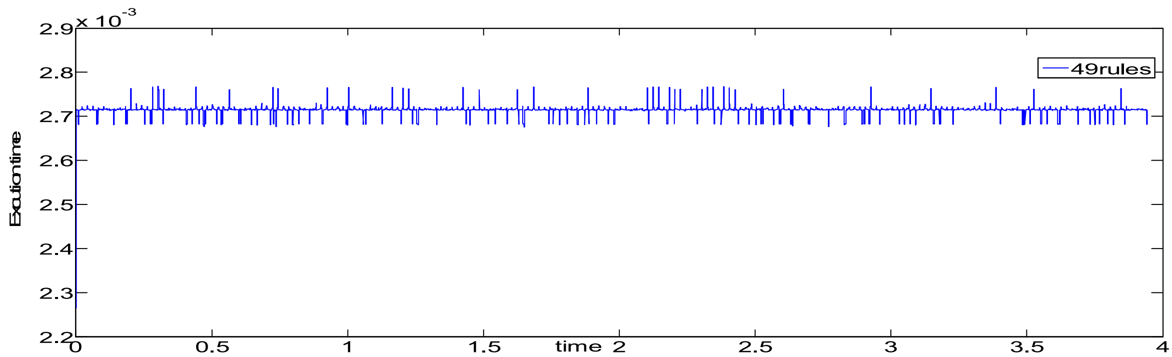


Fig.18. Execution time of fuzzy 25 rules



(c)

Fig.19. Execution time of fuzzy 49 rules

The comparison between execution time of different rule size is presented in Fig. 20. Also, the chart of relationship of number of rules and CT is presented in Fig. 21 which shows almost direct relationship between CT and the number of rules.

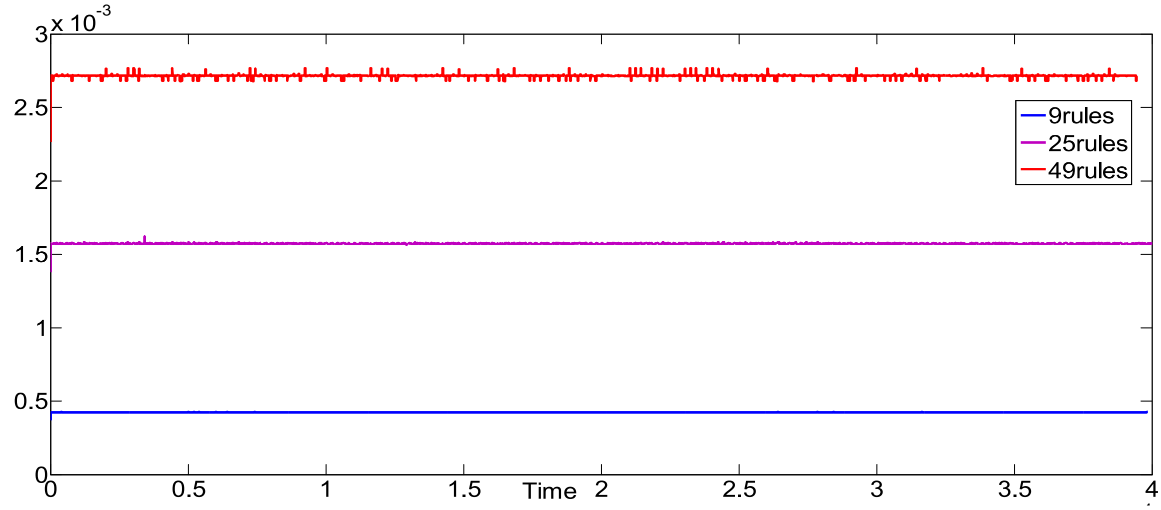


Fig.20. Comparison of execution time of fuzzy rule sets

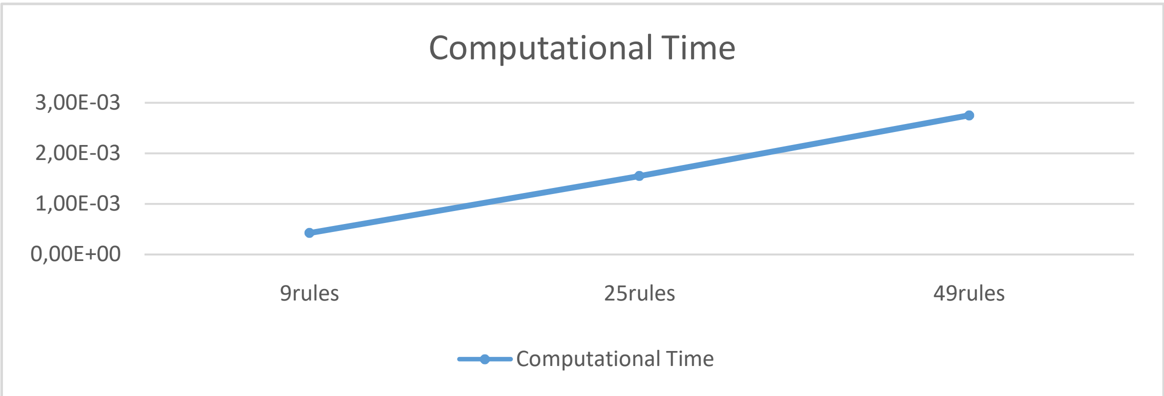


Fig.21. Computational time chart of fuzzy sets

As can be seen from chart presented in Fig. 15, proportional relationship between the number of rules and the computational time. The computational time difference between 9 and 25 rules is 1.12ms, which means 70us for each rule. Also the CT difference between 9 and 49 rules is 2.33ms which means 60us for each rule, CT difference between 25 and 49 1.2ms with 50 us for each rules. Thus, the average CT for each fuzzy rule can be calculated to be 60us.

7. CONCLUSION

This study presented a comparative experimental analysis of fuzzy speed control rules sizes. Three different rules categories were considered 9, 25 and 49 rules as speed controllers of

Induction motor drive system. Two important aspects were concern for the comparison, the first one is the effects of rule number on system performance such as settling time, rise time and overshoot. While, the second aspect focused on the Computational time (CT) with respect to the number of rules. In accordance to the results obtained, small size of fuzzy rules (9) can produce fast CT and the performance will not be affected significantly. In contrast, the big size of rules (49) produces big CT which will affect the hardware and require big sampling time, hence degrading the performance. Thus, it was concluded that an average 60us computational time for each fuzzy rule.

8. ACKNOWLEDGEMENTS

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