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Investigation of the Computational Burden Effects of Self-Tuning Fuzzy Logic Speed Controller of Induction Motor Drives With Different Rules Sizes

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ABSTRACT Fuzzy Logic Controller (FLC) as speed controller is preferred in many AC machine drives, due to its ability to handle model non-linearity, speed variations and parameters change. Additionally, Self-Tuning FLC (ST-FLC) is a modified FLC controller to overcome the issues associated with a fixed parameter FLC and to avoid performance degradation of the machine drive. It can update the FLC parameters in accordance to any variation, changes or disturbances that may occur to the drive system. However, FLC system requires huge computation capacity which increases the computational burden of the overall machine drive system and may result in poor performance. This research proposed a simple ST-FLC mechanism to tune the main FLC speed controller. Three different rule-size of FLC (9, 25, and 49) rules are implemented with ST-FLC mechanism based Induction Motor (IM) drive. Performance comparison of the three different rule-size based ST-FLC is conducted based on simulation and experimental analysis. In addition, a computational effort is technically analyzed and compared for the three different rule-size. In the experiment, ST-FLC with less number of rules (9-rules) shows superior performance, lower sampling and lower computational efforts compared to ST-FLC with higher rule-size (25, 49) rules.

INDEX TERMS Fuzzy, FLC, IM drives, self-tuning, computational complexity, computational efforts, fuzzy rules.

I. INTRODUCTION

Induction Motor (IM) is an electrical motor that produces a mechanical rotation of a shaft attached to its rotor, due to the generated rotating magnetic field on its stator windings [1]. The features of ruggedness, cheapness and easy maintenance of the IMs made them the most commonly used motors compared to other alternative motors [2], [3].

In the past, high performance applications were limited to DC motor drives, due the complexity and inefficiency of the scalar Voltage/Frequency (V/F) control methods of the IM drives [4], [5]. However, with the development of vector control method, IM drives become preferred in various domestic and industrial applications [6], [7]. Vector method enables decoupling between dq current components (magnetic flux and electromagnetic torque), thus, flux and torque of IM can be independently controlled resembling the operation of separately Excited DC motor [8], [9]. The most commonly used vector control techniques of IM drives are Field Oriented Control (FOC) and Direct Torque Control (DTC), which incorporate the concept of independent flux, and torque control [10]–[12]. These techniques have replaced the conventional scalar control and become the standard control of high performance IM drives with good transient and steady state performance [13]. Besides FOC and DTC, Model Predictive Control (MPC) has been recently proposed as a powerful control method with a simple design, multi variables control, fast transient behavior and handling non-linearity

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restrictions [14], [15]. But, despite of these MPC's merits, it requires a big computation capacity, which increases the sampling frequency and/or hardware cost [16]. However, with the development of powerful Digital Signal Processing (DSP) controllers at affordable cost, MPC can be applied for high performance IM drives. It has a big tendency to replace the FOC and DTC control techniques, since it, uses less control loops compared to FOC and selects the best suitable voltage vector based on cost function instead heuristically selecting voltage vector based on switching table as in DTC [17], [18]. Further literatures and recent advancements on MPC can be found on [19]–[24].

Apart from that, among of the control variables of IM drives is the speed, which requires crucial and efficient control mechanism to achieve satisfactory performance [25]. In the past, Proportional Integral (PI) controller has been employed as speed controller, which featured with design simplicity and good performance at optimum conditions [26], [27]. However, speed variations, parameters change, and external model disturbance can detune the PI controller, hence degrading the system performance [28]. As solution to overcome the issues associated with PI controller, Fuzzy Logic Controller (FLC) was proposed as intelligent speed controller of IM drives system [29]. The features of model independency, less parameters sensitivity and the ability to handle, non-linearity, load disturbance and speed variations have made FLC a dominant and preferred speed controller of the IM drives for decades [30]–[32]. Ever since the first incorporating FLC in the IM drives, various literatures have been introduced covering different aspects of FLC [33]–[37]. Membership Functions (MFs), rules and Scaling Factors (SFs) are the main parameters of FLC [38], [39]. Normally, these parameters are obtained based on heuristic technique and expert knowledge of the behavioral aspects of the IM drives system [40]–[42]. According to the literatures, there are three different standard FLC rules size have proven to obtain satisfactory performance, which are 9-rules, 25-rules and 49-rules [43]–[45]. Bigger rules size of these have proven not to show any performance improvement as reported in [46], where 81-rules were applied to control stepper motor. In addition, FLC has different shapes of MFs like, triangular, trapezoidal, Sigmoid, Gaussian and singleton [47], [48], but triangular and trapezoidal shapes are the most commonly used MFs due to their simplicity and computational effectiveness [49], [50]. Moreover, FLC variables can be assigned based on the controlled system which referred as linguistic variables. For instant, IM drives FLC speed controller has two inputs variables, error (e) and change of error (Δe) and one output variable of change of output (Δu) [51], [52].

The FLC rules, MFs and SFs are normally designed at nominal and rated speed conditions of the IM drives. However, operating at speed far away from the rated speed, the drive performance might be degraded since the FLC parameters are fixed and selected based on nominal conditions [53]–[55]. To solve this issue, Self-Tuning FLC (ST-FLC) methods have been proposed as an adaptive mechanism to update the FLC parameters accordingly [55]–[57]. Different ST-FLCs methods have been proposed in the literatures, focusing on MFs tuning [58], rules tuning [59] or SFs tuning [60]. A study in [61], proposed a self-tuning mechanism based on Model Reference Adaptive System (MRAS) to automatically update the SFs of main speed FLC of IM drives. The proposed self-tuning mechanism designed with fuzzy system as well based on Takagi-Sugeno (TS) fuzzy sets, where (5×5) input MFs and singleton output MFs are used and the fuzzy output (Δu) was determined using offline lookup table generated based on trial and error method. This study has shown a good drive performance with the proposed self-tuning mechanism in both simulation and experimental testing. However, complexity and additional fuzzy system of the self-tuning mechanism produce bigger computational burden of the overall drive system, thus increasing the sampling frequency and/or hardware cost. In addition, the fuzzy system for the self-tuning mechanism requires parameters tuning and empirical offline lookup table generation, which are time consuming and the tendency to select inaccurate values is high. Finally, the author only considered (5×5) MFs with 25-rules for both main speed FLC and self-tuning FLC, and did not discuss the effects of different, rules size and MFs numbers. In same context, study in [62] has proposed a self-tuning fuzzy logic to tune the output SF of the main FLC of speed controller of the IM drives. The proposed self-tuning fuzzy logic as well as the main FLC were based on simplified 7-rules fuzzy, where a 25-rules fuzzy of (5×5) MFs was simplified into 7-rules. The proposed method showed good transient and steady state performance at rated speed operations based on simulation analysis. Even though, the study has employed a simplified fuzzy rules which contributed to reduce the computation requirement. However, the two fuzzy systems used still potential sources which require a big computational capability. Moreover, different rules size was not covered in this study and only simplified 7-rules with (5×5) MFs was considered.

Most of the ST-FLC methods reported in the literatures have mainly focused on tuning one or all of the SFs of the main speed FLCs. This is because SFs has crucial impacts on the overall drive performance and fixed SFs of the FLCs might lead to performance degradation in case of speed variations, load disturbance and/or parameters change [63], [64]. In addition, the critical issue associated with many of the ST-FLCs proposed to tune SFs is their design complexity, in which some methods in order tune one or all SFs of main FLC utilize an additional FLC, complex mathematical model or other high computational mechanism [55], [56], [61], [63]. Thus, producing big computational burden of the overall drive system, which requires bigger processer capabilities, higher sampling frequency and/or increases the overall drive hardware cost. The simplicity as well as variety of ST-FLC based on experimental investigations have not been covered in the literatures. Simplicity, where a simple and effective self-tuning mechanism is used and variety, where different rules sizes are employed. In addition, many studies have pointed out that the computational capacity of the system or part of it can degrade the overall system performance and the system computational burden has a direct relationship to the system complexity [61], [65]. However, no technical analysis of the effects of computational burden on the system performance have been proposed. In other words, no study has technically investigates the computational effects of IM drive system in order to recognize which part of the system is generating big computational burden.

This study aims to investigate the performance of IM drives system based on Indirect Field Oriented Control (IFOC) with simple self-tuning mechanism to tune the output SF of the main FLC by considering different rules size of the FLC. Analyses of the effects of the rules size on the drive performance as well as on the computational burden of the system are presented. A computational time measurement is conducted for overall drive system with ST-FLC method considering 49-rules, 25-rules and 9-rules. This includes, technical analysis of the effects of computational burden on the overall drive system. In addition, a performance comparisons of these rules sizes are conducted based on simulation and experimental approach. The obtained results showed that, ST-FLC with 9-rules sizes has the lowest computational burden and produced superior experimental performance. Moreover, all the different rules sizes have shown almost similar simulation performance. The reset of the paper is organized as follow: section 2 discusses the dynamic modelling of IM drive incorporating IFOC, section 3 discusses the FLCs and ST-FLC design, section 4 presents the simulation testing, experimental setup, computational time analysis and investigations and finally section 5 summarizes what have been achieved in the paper and highlights the findings.

II. INDIRECT FIELD OREINTED CONTROL (IFOC) OF IM

IM drive system incorporating vector control principle (FOC) is shown in Fig. 1. The system mainly consists of IM model, phase-transformations, speed controller, hysteresis current controller and three-phase Voltage Source Inverter (VSI).

In order to design an efficient IM drive system, an accurate mathematical model of the motor is required. The performance of the drive system is dependent of the IM model and crucially degraded due to modelling error and or model parameters variation. The IM can be mathematically modelled in various reference frames depending on the application requirements such as stationary reference frame, rotary reference frame and synchronous reference frame. In this research, stationary reference-frame is employed to model the IM. The real three-phase induction machine can be represented by a three ideal windings as depicted in Fig. 2 (a). From these windings, an equivalent circuit of the machine can be obtained as shown in Fig. 2 (b) [66], [67].

Refereeing to the equivalent circuit, the stator equations of the machine can be expressed as follow:

$$V_{sa} = R_s I_{sa} + \frac{d\varphi_{sa}}{dt} \tag{1}$$

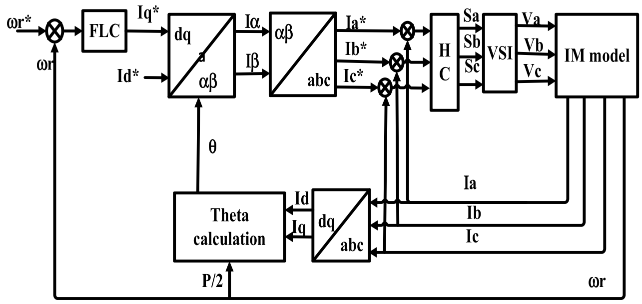

FIGURE 1. Field oriented control (FOC) of induction motor drives.

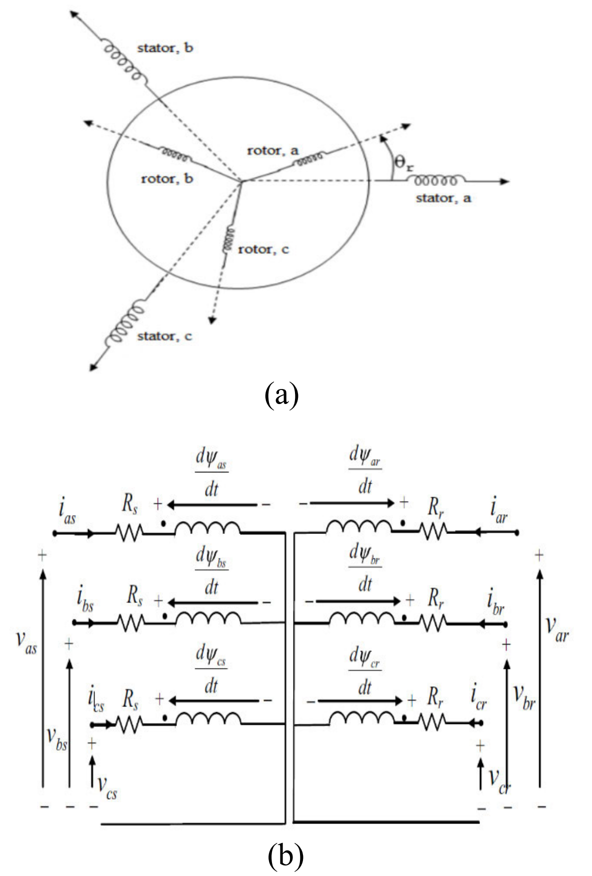

FIGURE 2. Three-phase induction motor, (a) three-phase windings, (b) three-phase equivalent circuit.

$$V_{sb} = R_s I_{sb} + \frac{d\varphi_{sb}}{dt} \tag{2}$$

$$V_{sc} = R_s I_{sc} + \frac{d\varphi_{sc}}{dt} \tag{3}$$

Similarly, the rotor equations of the machine can be expressed as follow:

$$V_{ra} = R_r I_{ra} + \frac{d\varphi_{ra}}{dt} \tag{4}$$

$$V_{rb} = R_r I_{rb} + \frac{d\varphi_{rb}}{dt} \tag{5}$$

$$V_{rc} = R_r I_{rc} + \frac{d\varphi_{rc}}{dt} \tag{6}$$

where, (V_{sa}, V_{sb}, V_{sc}) and (V_{ra}, V_{rb}, V_{rc}) are the stator and rotor voltages respectively at phases a, b, and c. (I_{sa}, I_{sa}, I_{sa}) and (I_{ra}, I_{ra}, I_{ra}) are the stator and rotor currents respectively at phases a, b, and c. R_s and R_r are the stator and rotor resistances. $(\varphi_{sa}, \varphi_{sb}, \varphi_{sc})$ and $(\varphi_{ra}, \varphi_{rb}, \varphi_{rc})$ are the stator and rotor fluxes respectively. The machine equations can be represented in space vector form ($\alpha\beta$-model) by using the following equation:

$$\bar{V} = \frac{2}{3}\left(V_a + \bar{a}V_b + \bar{a}^2 V_c\right) \tag{7}$$

where, a, a^2 are expressed as:

$$a = e^{j120^\circ} = cos\ 120^\circ + j\ sin\ 120^\circ = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \tag{8}$$

$$a^2 = e^{j240^\circ} = cos\ 240^\circ + j\ sin\ 240^\circ = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \tag{9}$$

Substituting equations (1), (2), (3), (8) and (9) in equation (7), the stator voltage in space vector form is expressed as:

$$\bar{V}_s = R_s\bar{I}_s + \frac{d\bar{\varphi}_s}{dt} \tag{10}$$

Similarly, substituting equations (4), (5), (6), (8) and (9) in equation (7), the rotor voltage in space vector form is expressed as:

$$\bar{V}_r = R_r\bar{I}_r + \frac{d\bar{\varphi}_r}{dt} \tag{11}$$

Moreover, the stator and rotor fluxes in space vector form can be expressed in the following equations:

$$\bar{\varphi}_s = L_s\bar{I}_s + L_m\bar{I}_r \tag{12}$$

$$\bar{\varphi}_r = L_r\bar{I}_r + L_m\bar{I}_s \tag{13}$$

A representation of the ab model in state-space equations is very useful for computer based simulation purposes. Rearranging Equations (10)–(13) and taking the currents as state-space variable, the model of the IM is expressed in a matrix form as in (14), which can be expanded into ($\alpha\beta$-model) as in (15).

$$\frac{d}{dt}\begin{bmatrix}\bar{I}_s\\ \bar{I}_r\end{bmatrix} = \frac{1}{\sigma LsLr} \times \begin{bmatrix} -R_sLr - j\omega_m Lm^2 & R_rLm - j\omega_m LmLr \\ R_sLm + j\omega_m LmLs & -R_rLs + j\omega_m LsLr \end{bmatrix} \times \begin{bmatrix}\bar{I}_s\\ \bar{I}_r\end{bmatrix} + \frac{1}{\sigma LsLr}\begin{bmatrix} Lr & -Lm \\ -Lm & Lr\end{bmatrix}\begin{bmatrix}\bar{V}_s\\ \bar{V}_r\end{bmatrix} \tag{14}$$

$$\frac{d}{dt}\begin{bmatrix} \mathrm{i}_{\alpha s}\\ \mathrm{i}_{\beta s}\\ \mathrm{i}_{\alpha r}\\ \mathrm{i}_{\beta r}\end{bmatrix} = \frac{1}{\sigma LsLr} \times \begin{bmatrix} -R_sL_r & \omega_r L_m^2 & R_rL_m & \omega_r L_m L_r \\ -\omega_r L_m^2 & -R_sL_r & -\omega_r L_m L_r & R_rL_m \\ R_sL_m & -\omega_r L_m L_s & -R_rL_s & -\omega_r L_r L_s \\ \omega_r L_m L_s & R_sL_m & \omega_r L_r L_s & -R_rL_s \end{bmatrix} \times \begin{bmatrix} \mathrm{i}_{\alpha s}\\ \mathrm{i}_{\beta s}\\ \mathrm{i}_{\alpha r}\\ \mathrm{i}_{\beta r}\end{bmatrix} + \frac{1}{\sigma LsLr}\begin{bmatrix} -L_r & 0 \\ 0 & L_r \\ L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix} v_{\alpha s}\\ v_{\beta s}\end{bmatrix} \tag{15}$$

where σ is sigma and equal to $\sigma = 1 - \frac{L_m^2}{LsLr}$

Based on the equation in (15), a dynamic model of IM can be designed considered current as the state space variables as well as can be modelled with other variables such as flux. In addition, the output torque of the machine can be expressed in two forms mechanically and electrically as follow:

Mechanical torque:

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_L = \frac{J}{P}\frac{d\omega_r}{dt} + \frac{B}{P}\omega_r + T_L \tag{16}$$

Electric Torque:

$$T_e = \frac{3}{2}PL_m\left(i_{r\alpha}i_{\beta s} - i_{s\alpha}i_{r\beta}\right) \tag{17}$$

III. SPEED CONTROLLER DESIGN

This section deals with the design methodology of speed controller of IM drives including main speed controller FLC and self-tuning controller ST-FLC. The rule-base, MFs and SFs of main FLC will be designed covering different rules sizes and different MFs numbers. In addition, the design of the proposed ST-FLC method will be discussed in detail and illustrating the way of a simple mathematical algorithm can tune and automatically update the output SF of the main FLC based on the current trends of process (e, Δe).

A. FLCs DESIGN

FLC speed controller has great interests in the area of AC motor drives, particularly IM drives. This is due the features of FLC in terms of non-linearity constrains, speed variations robustness, model parameters independency and load disturbance rejection. Based on the literatures, there are three standard FLC rules sizes, thus a three different number of MFs. A (3 × 3), (5 × 5) and (7 × 7) MFs results in a 9, 25 and 49 rules size respectively. The FLC system considering Mamdani type has fuzzification, rule-base and defuzzification processes. The fuzzification process convert linguistic inputs variables into fuzzy variables represented with inputs MFs labels. Rule-base process forms the fuzzy output based on IF-THEN rules. Finally, defuzzification process convert the fuzzy output variable into a linguistic variable [68], [69].

FLC is a feedback speed controller, in which the actual motor speed is compared with a reference speed and the resultant error is fed into the speed controller. In most of feedback speed control systems, there are two inputs and one output speed controller, where the inputs are speed error (e) and change of speed error (Δe), while the output is change of control output (Δu). Based on these, the FLC speed control model can be designed as shown in Fig. 3.

From the block diagram of the FLC, it has three parts which are pre-processing, FLC interface engine and post-processing. In the pre-processing, the fuzzy controller input variables are speed error e and change of speed error Δe.

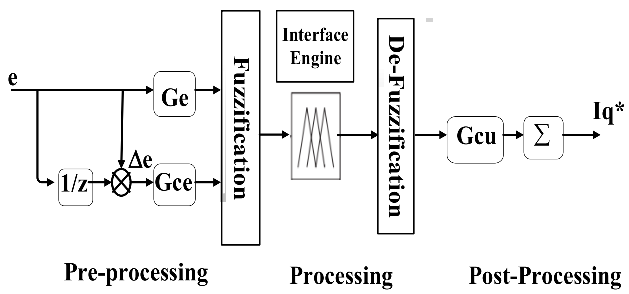

FIGURE 3. FLC speed control model.

The inputs scaling factors of error and change of error are Ge and Gce respectively, the input error e and change of speed error Δe can be expressed as follow:

$$e(k) = G_e\left(\omega_r^*(k)\right) - \omega_r(k) = G_e(k) \quad (18)$$

$$\Delta e(k) = G_{ce}\frac{(e(k) - e(k-1))}{T_{samp}} \quad (19)$$

While, in the last step of the FLC system post-processing, the output signal ΔIq is multiplied by the output scaling factors Gcu at time instant k and expressed as follow:

$$i_{sq}^*(k) = i_{sq}^*(k-1) + G_{cu}(\Delta i_{sq}^*(k) \quad (20)$$

where, $\omega^*{}_r$ and ω_r stand for the reference speed and actual speed respectively, while k and $k-1$ represent the current and past system state in order to get the change of speed error. Δe is the change of speed error, T_{samp} is the sampling time.

There are three different parameters of the FLC, which are Scaling Factors (SFs), Membership Functions (MFs) and Rule-base. The flowing sections discusses the design and calculations of these parameters.

1) SCALING FACTORS (SFs)

Scaling factors are one of the most essential parameters of the FLC due to their critical impacts in the overall system performance. Initially, the FLC scaling factors are computed in accordance to the maximum value of the speed reference when the motor is running at rated speed [70], [71]. The scaling factor for input speed error can be calculated as:

$$G_e = \frac{1}{|2\omega_{emax}|} \quad (21)$$

In which the ω_{emax} is the maximum speed error when the motor is operating at rated speed. The constant coefficient 2 is used to assure the maximum ranges within the forward to reverse speed operation. The rated speed of the induction motor is 149.7 rad/s, hence the input scaling factor of speed error can be calculated using equation 3.38 as follow where $\omega_{emax} = 149.7rad/s$:

$$G_e = \frac{1}{|2 \times 149.7|} = 0.00334$$

The SF of input change of error Gcu can be computed based on simulation tests to obtain the suitable value of *Gce* which was found to be 0.350.The output fuzzy SF Gcu is maintained as 1 for the standard fixed parameters FLC.

2) MEMBERSHIP FUNCTIONS (MFs)

Different type of MFs can be utilized to design the FLC. However, the most popular type of MFs are the triangular and trapezoidal shapes of MFs. They produce less computational burden in comparison to other MFs types [50], [72]. The notation for the MFs are represented as NL for Negative Large, ZE for Zero and PL for Positive Large. This project used trapezoidal shape 3 × 3 MFs with range of (−1 to 1) which is the speed error range after normalized by scaling factors. Three different triangular MFs are shown in Fig. 4.

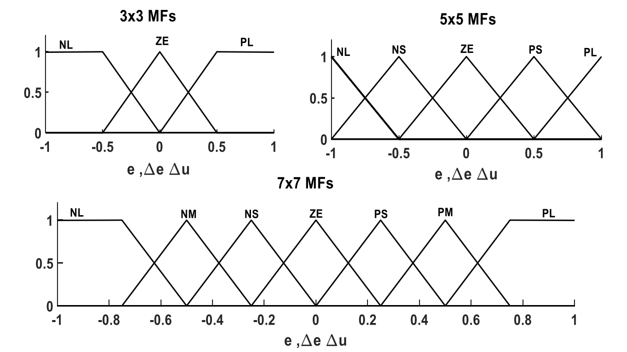

FIGURE 4. Three different inputs and outputs MFs of Error (e), change of error (Δe) and output control (Δu).

3) RULE-BASE

The qualitative relation between the inputs and output of FLC is illustrated by designed fuzzy rules sets. IF and THEN conditional states are utilized to represent the fuzzy rules in linguistic terms, where these linguistic terms are used to identify the output fuzzy set. In this research, a well-known min-max fuzzy interface is utilized due to its capabilities to obtain enhanced control performance [73]. The output performance is measured in accordance to the implication and aggregation of the fuzzy output set. The center of gravity (*CoG*) algorithm is utilized in order to obtain efficient control signal [74]. Table 1 presents the rule base of FLC.

B. PROPOSED ST-FLC

In order to automatically update the output SF of the main speed FLC, self-tuning mechanism is required. This research proposed a simple but effective ST-FLC which can tune the output SF of FLC based on the FLC inputs of speed error (e) and change of speed error (Δe). The ST-FLC is a simple

TABLE 1. Rule-base for FLC.

Δe e	NL	NM	NS	ZE	PS	PM	PL
PL	ZE	PS	PS	PL	PL	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PS	NS	NS	ZE	PS	PS	PL	PL
ZE	NL	NM	NS	ZE	PS	PM	PL
NS	NL	NL	NS	NS	ZE	PS	PS
NM	NL	NL	NL	NM	NS	ZE	PS
NL	NL	NL	NL	NL	NS	NS	ZE

mathematical algorithm that has been developed based on the relationship between FLC inputs (e, Δe) and the FLC output SF (Fig. 5). If α considered an updating gain of FLC output SF, the output fuzzy control (Δu) can be expressed as:

$$\Delta u = (G_{cu} \times \alpha)\Delta u_n$$

where, Δu is fuzzy output control, Gcu is the FLC output SF, α is the updating gain of output SF and Δu_n is the FLC output. Based on equation, a computing model or mathematical algorithm to obtain the desired value of updating gain α based on the inputs of e and Δe. In order to develop updating gain α computing model, the relationship between FLC inputs of speed error (e) and change of speed error (Δe) and FLC output SF gain α need to be investigated based on the knowledge of the behavioral aspects of the controlled system as follow:

i. When the speed error (e) is big (positive or negative) and the change of speed error (Δe) is zero, thus the FLC output SF gain α need to be very big in order to ensure faster rise time (Tr) of the drive system transient response.
ii. When the speed error (e) is small (positive or negative) and the change of speed error (Δe) is zero, thus the FLC output SF gain α need to be big in order to ensure faster settling time (Ts) and lower overshoot of the drive system transient response.
iii. When both speed error (e) and the change of speed error (Δe) are zero, the FLC output SF gain α need to be medium to prevent oscillation due to lower or zero gain, thus maintaining the stability of the drive system steady state response.

Based on these relationships, the FLC output SF gain α can be expressed in mathematical form as follow:

$$\alpha = [(|e| - |\Delta e| + 1)\, K \tag{22}$$

where |e| is the absolute value of speed error and |Δe | is the absolute value of change of speed error, K is a constant which used to make the required variation on α and the 1 term is used to ensure a medium value of α in the case both e and Δe are zero. The value of K is determined based on several tuning process and found to be 1.5, which achieves the best possible optimum drive performance.

IV. RESULT AND DISCUSSION

In the section, the performance evaluation of the proposed ST-FLC with different rules sizes based on simulation and experimental approach is discussed based 2hp-1400 rpm IM with parameters listed in Appendix A. In addition, the computational time measurement and investigations of the proposed ST-FLC with different rule sizes is presented in this section as well.

A. SIMULATION ANALYSIS

Induction motor drive system based on Indirect Field Oriented Control (IFOC) has been designed using Matlab/

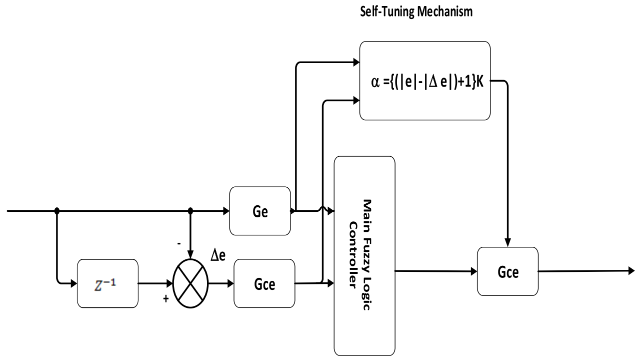

FIGURE 5. Proposed ST-FLC speed control model.

Simulink environment. First, the effectiveness and robustness of the proposed ST-FLC method, performance comparisons with standard FLC considering three different rules sizes (9,25,49) with nominal motor parameters and with 50% error in rotor inductance (R_r) as shown in Fig. 6. Based on the results shown in Fig. 6, ST-FLC is superior compared to standard FLC at nominal and mismatching parameters and with the three different rules sizes.

The proposed ST-FLC is applied for speed control and three different rules sizes are considered. The system performance at different operating conditions were obtained to show the impacts of rule sizes on the overall drive performance. Fig. 7 presents the performance comparison of step speed responses of the three rule sizes at 1400 rpm, 900 rpm and, 400 rpm. Based on the obtained results, ST-FLC with 49-rules shows faster transient and good steady state responses compared to ST-FLC with 25-rules and 9-rules. This is due to the big number of MFs used with 49-rules which increase the coverage of the input variables and improve the accuracy of the output variable of fuzzy system. Therefore, an improved performance is obtained with ST-FLC based 49-rules. In addition, less current and torque ripples are produced with ST-FLC-49 as shown in Fig. 8,9 and 10, for phase A current, q-component current (Iq) and electromagnetic Torque. Apart from this, 20N.M load disturbance is applied to the drive system at 2.5s to show the ST-FLC capability of load disturbance rejection with 9, 25 and 49 rule sizes. The speed response comparison at rated speed (1400rpm) with load disturbance for ST-FLC (9, 25, and 49) rules is presented in Fig. 11. ST-FLC with 49-rules shows the lowest speed drop with faster recovery time compared to ST-FLC with 25-rules and 9-rules.

B. EXPERIMENTAL ANALYSIS

Mm The experimental setup was done based 2HP induction motor with specification as in Appendix A. The hardware structure of the control system consists of two interconnected module which are dSPACE DS 1104 and interface drive board. The dSPACE DS 1104 reads the feedback signals from the current sensors, speed encoder, and fed them back to the control model to generate the switching pulses for VSI-fed IM drive. In addition, the whole drive system consists

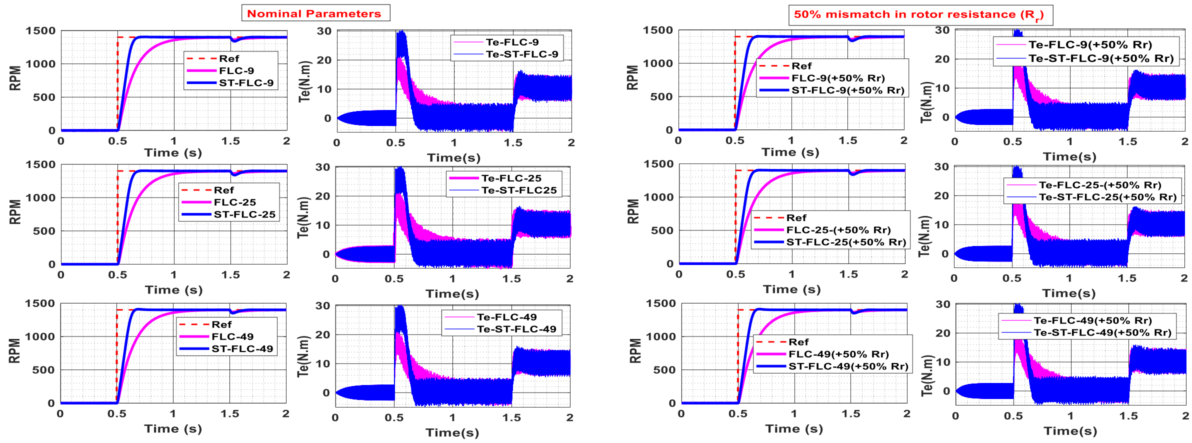

FIGURE 6. Performance comparisons of standard FLCs and ST-FLCs with nominal parameters and 50% error in rotor resistance.

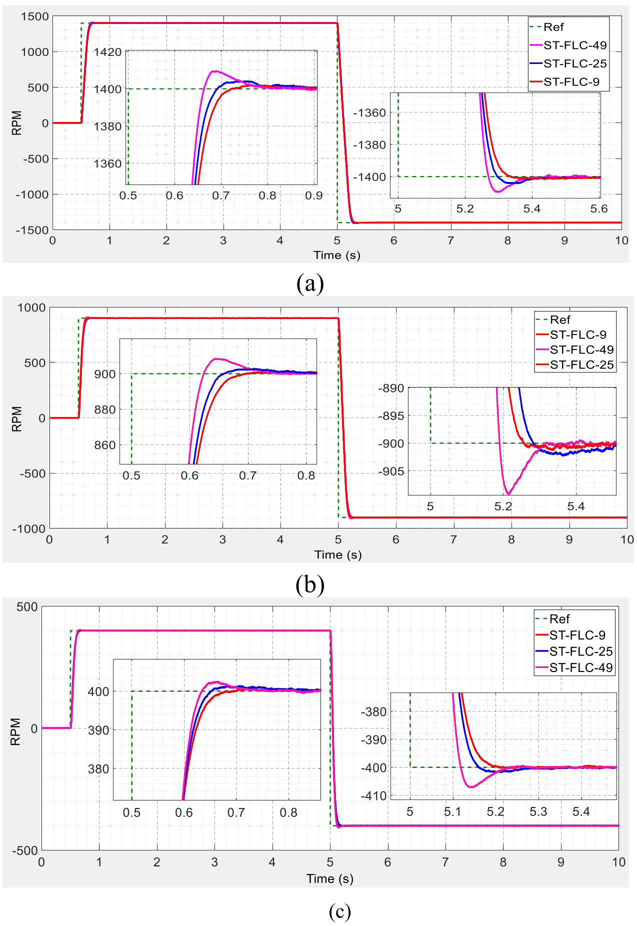

FIGURE 7. Speed performance comparison of ST-FLC with (9, 25, 49) rules at (a) 1400 rpm, (b) 900rpm and (c) 400 rpm.

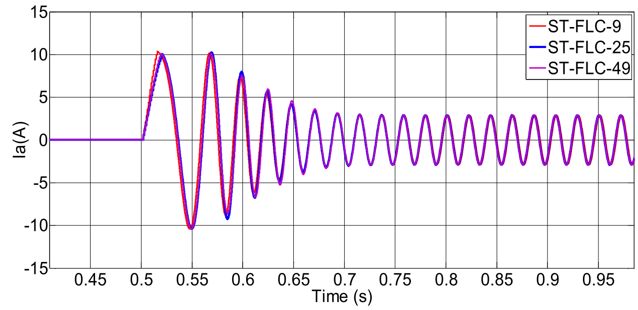

FIGURE 8. Stator current (Ia) performance comparison of ST-FLC with (9, 25, 49) rules at 1400 rpm.

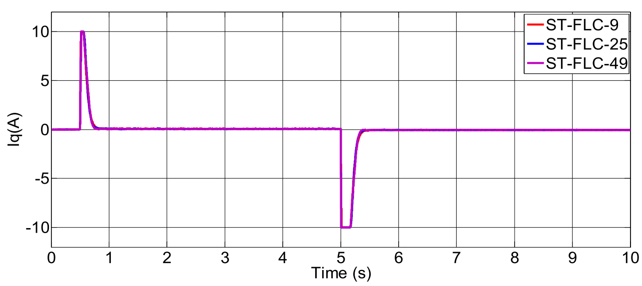

FIGURE 9. Reference torque current (Iq∗) performance comparison of ST-FLC with (9, 25, 49) rules at 1400 rpm.

of PC, dSPACE DS 1104, FPGA module, gate drives, VSI, current sensor, DC-link capacitor, rectifier, encoder, IM and DC machine as shown in Fig. 12.

The hardware results are obtained with the help of dSPACE ControlDesk. The performance comparison of ST-FLC-9, ST-FLC-25 and ST-FLC-49 are done experimentally in order to investigate the drive response with different rule-size. Fig. 13 shows the comparison performance of speed operation during forward and reverse at 1400 rpm. To verify the controller robustness at different speed operations, Fig. 14 shows the speed performance comparison of ST-FLC methods at lower speed operations (900,400) rpm. In addition, the stator current Ia performance comparison of ST-FLC methods is presented in Fig. 15, while the torque current Iq performance is presented in Fig. 16. Based on the results, it clearly shown that the ST-FLC-9 have superior performance compared to ST-FLC-25 and ST-FLC-49. It shows fast transient response and stable steady state error with less

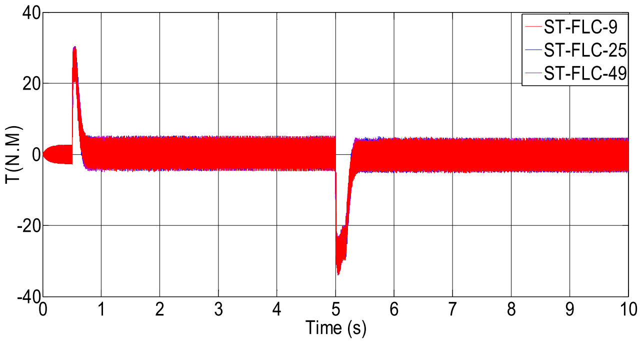

FIGURE 10. Electromagnetic torque (Te) performance comparison of ST-FLC with (9, 25, 49) rules at 1400 rpm.

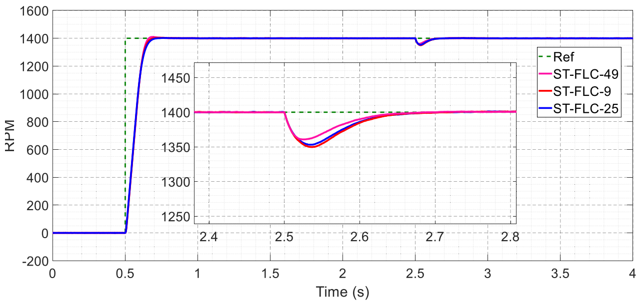

FIGURE 11. Speed performance comparison of ST-FLC with (9, 25, 49) rules at 1400 rpm with load disturbance.

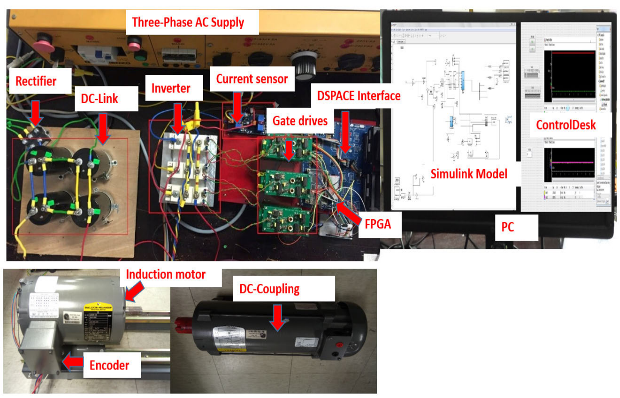

FIGURE 12. Experimental setup of the drive system.

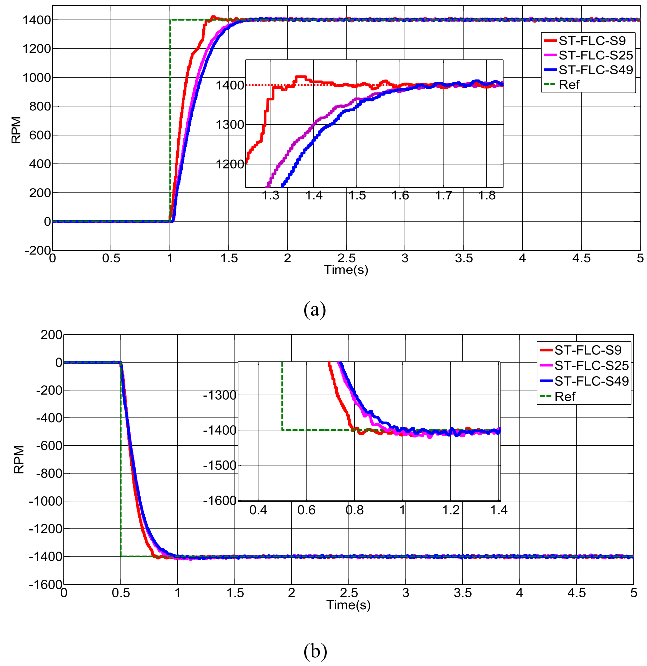

FIGURE 13. Speed performance comparison of ST-FLC at rated speed 1400 rpm (a) forward, (b) reverse.

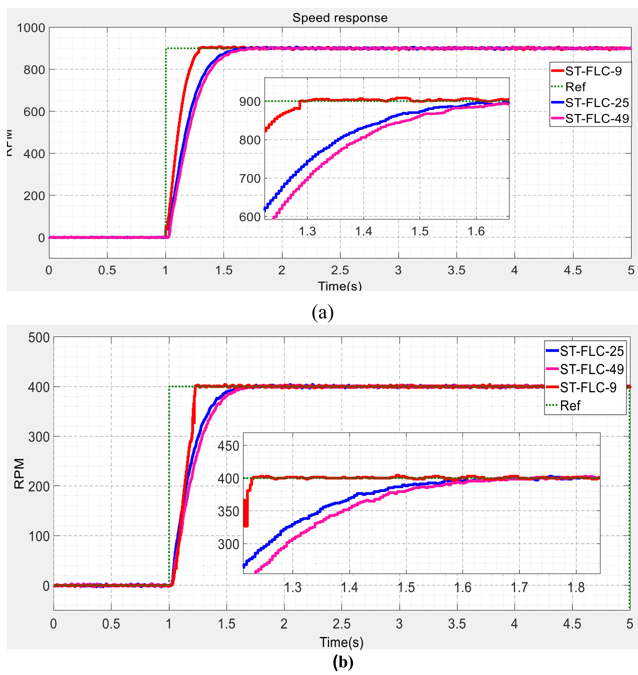

FIGURE 14. Speed performance comparison of ST-FLC at forward (a) 900 rpm, (b) 400 rpm.

current ripple. This is because ST-FLC-9 utilize less fuzzy rules, which result in low computation efforts, thus enhanced performance was obtained.

In addition, load disturbance is applied to the system to test the rejection capabilities of each ST-FLC method. Fig. 17 shows the speed performance comparison of ST-FLC methods with load disturbance applied at 2.5 seconds. ST-FLC-9 has shown excellent load disturbance rejection capabilities with less speed drop and fast recovery time compared to ST-FLC-25 and ST-FLC-49. Unlike simulation testing, ST-FLC has superior performance during experimental testing, this is due to the fact that, ST-FLC-9 has only 9 fuzzy rules with 3 × 3 membership function, while ST-FLC-25 has 25 fuzzy rules with 5 × 5 membership functions and ST-FLC-49 has 49 fuzzy rules with 7 × 7 membership function. Thus, 25 and 49 rules tend to produce high computational efforts compared to the 9 rules which impact the performance during experimental testing.

Qualitative analysis of ST-FLC methods performance might be inadequate to make effective comparison since it is based on transient response. Therefore, numerical analysis

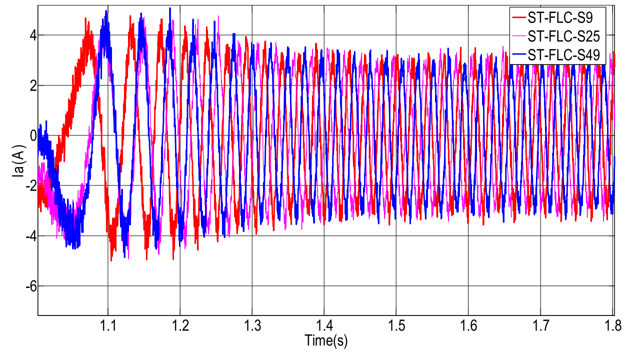

FIGURE 15. Stator current (Ia) performance comparison of ST-FLC at rated speed of 1400 rpm.

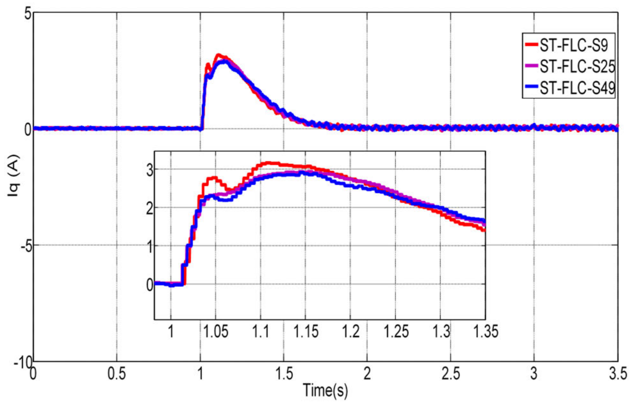

FIGURE 16. Iq performance comparison of ST-FLC at forward 1400 rpm.

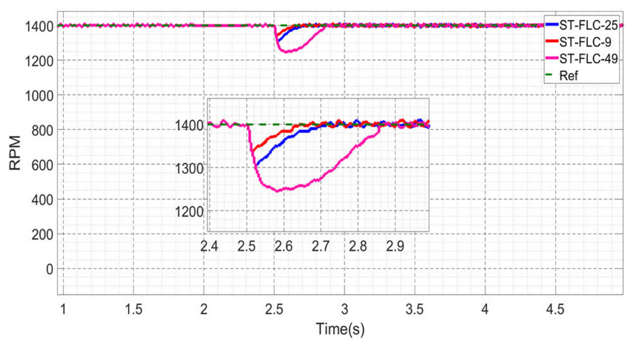

FIGURE 17. Speed performance comparison of ST-FLC at forward 1400 rpm with load disturbance.

based on steady state response is conducted. Speed characteristics of ST-FLC (9, 25, and 49) at simulation and experimental is presented in Table 2. As can be seen from the data obtained, ST-FLC-49 has superior performance during simulation testing due to the high output accuracy with 49 fuzzy rules and 7 × 7 membership function, also the performance is not affected by the computational effort during simulation testing. However, ST-FLC-9 has superior performance during experimental testing due to the lower computation effort produced with lower fuzzy rules and membership functions. Thus, it is clear that, fuzzy rules have direct relationship with

TABLE 2. Speed characteristics comparison of ST-FLC (9, 25, 49) at simulation and experimental.

Index / ST-FLC	Settling time (s)		Rise time (s)		Overshoot (%)	
	Sim	Exp	Sim	Exp	Sim	Exp
ST-FLC-9	0.301	0.35	0.107	0.25	0.14%	1.5%
ST-FLC-25	0.289	0.61	0.104	0.31	0.28%	0.5%
ST-FLC-49	0.279	0.65	0.102	0.34	0.64%	0.43%

the computational effort of the system. This indicate that, lower fuzzy rules can enhance the drive performance during experimental testing due to the lower computational efforts produced, while higher fuzzy rules can degrade the drive performance due to the huge computational efforts produced.

Further simulation analysis based on the Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE). These two performance measures provide evaluation for the quality of the dynamic performance with numerical values based on integration of the control error [75]. The mathematical expression of IAE and ITAE are presented in equations 23 and 24.

$$IAE = \int_{0}^{\infty} |e(t)| \, .dt \tag{23}$$

$$ITAE = \int_{0}^{\infty} t \, |e(t)| \, .dt \tag{24}$$

where, dt is the error deviation between the actual and reference speed.

Performance comparison of ITAE and IAE of ST-FLC (9, 25,49) at rated speed 1400 rpm during simulation and hardware results is presented in Table 3. Based on the values of IAE and ITAE recorded, ST-FLC-9 produces lower index values compared to the ST-FLC-25 and ST-FLC-49. A big difference in ITAE and IAE values between simulation and experimental results due to the accumulated error due to encoder accuracy during experimental results which produce ±15 rpm error while it is ideal in simulation and produce zero error.

TABLE 3. ITAE and IAE comparison during simulation and experimental.

Index / ST-FLC	ITAE		IAE	
	Sim	Exp	Sim	Exp
ST-FLC-9	6.57	136.3	10.29	176.6
ST-FLC-25	6.73	158.2	10.38	205.6
ST-FLC-49	6.35	180.5	10.15	235.9

C. COMPUTATIONAL TIME ANALYSIS

The computational time of a model (task) is the time required to execute the model in real time, in which each step is computed within the model sampling time. Fig. 18 shows the block diagram of real-time execution time of a model, which

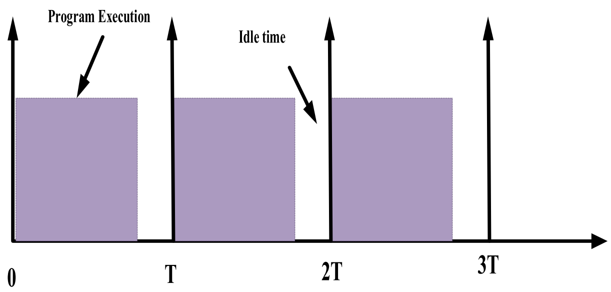

FIGURE 18. Execution time of a model in real time (similar tasks).

is executed in identical steps of time with a sampling time for each step.

The sampling time has crucial influence on the system performance, the faster the sampling time the optimum system performance is achieved. This is because the sampling time is directly proportional to the execution time, the longer the execution time a big sampling time is required. A model with tasks having similar computational requirements can be executed with a faster sampling time, normally the base sampling time of the model. An example of this has been shown in Figure18. However, a model with multi-rate tasks which have different computational requirements, such that at a given sampling time, a task has finished its execution and needs to start execution again, while other task is requested to start again, but has not finished its previous execution. Therefore, for this case the sampling time must be increased till all the model tasks can be executed at a sampling time step. For instance, considering a model with two tasks having big computational requirement (Tbig) and small computational requirement (T_{small}) with an adequate sampling time, the Tsmall will be executed every sampling step, while Tbig will be executed every second sampling step. The diagram of a model execution time that have Tbig and Tsmall is presented in Fig. 19.

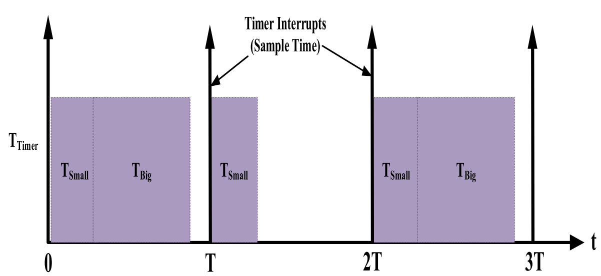

FIGURE 19. Execution time of a model in real time (different tasks).

As can be seen in Figure19, a longer sampling time has been used to ensure the execution of both tasks in a sampling step. This is because a shorter sampling time will cause overrun condition, in which the Tsmall has started new execution step, but Tbig has not finished its current execution. If overrun condition occurred, the model cannot be implemented in real time, Fig. 20 shows the overrun conditions of two different tasks with shorter sampling time.

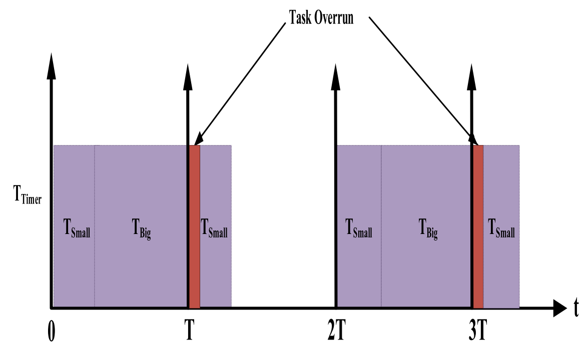

FIGURE 20. Execution time of a model with two different tasks (overrun condition).

Besides the increase of sampling time, the overrun condition can be avoided by using multiple timer task instead using single timer task as in previous diagrams. The multiple task timer enables using different sampling time for different tasks, thus the execution of tasks with big computational requirements can be interrupted for the tasks with small computational requirements (high-priority). Considering the Tbig and Tsmall tasks have been executed with a single timer task, they can be executed using multiple timer task by assigning Tsmall to timer1 and Tbig to timer2, the execution sequence of the two timers can be presented as shown in Fig. 21.

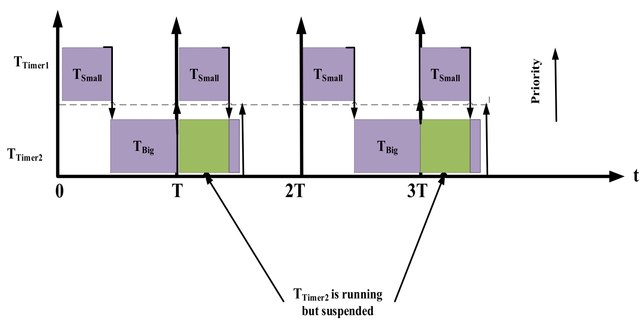

FIGURE 21. Execution time of a model with different tasks (multiple timer task).

From Fig. 21 the operations of multiple timer task can be explained as that, timer1 has started execution till has finished, then timer 2 starts execution till timer1 ready for next execution, then timer 2 is interrupted and timer1 is executed till finished, then timer 2 resume its execution. In general, the model execution with multiple timer task can behave in a similar way to the single timer execution, if all the model tasks are executed within the time range of the sampling time.

Induction motor drive with fuzzy logic system requires a big sampling time in order to be executed in single timer task due to the high computation capability associated with the fuzzy logic system. However, the multiple timer operation can be utilized for the system, where a timer with big sampling time is used for fuzzy system block and another timer with small sampling time is used for the rest of the system. Thus, executing the system with a sufficient sampling time that ensure better performance of the drive. In this research

TABLE 4. Computational time of different ST-FLCs methods.

Controller	Sampling time	Computational time
ST-FLC(S9)	200μ	175μ
ST-FLC(S25)	600μ	530μ
ST-FLC(S49)	1000μ	975μ

a proposed ST-FLC method with three different rule sizes is implemented for IM drives. The execution time of the drive based ST-FLC with each rule-size is computed. In order to prove the ability and simplicity of the proposed ST-FLC in terms of reducing the computational burden, the execution time of two different ST-FLC methods was computed and compared with the proposed ST-FLC.

The proposed ST-FLC method considering different rules sizes have been applied to control the speed of IM drives based on IFOC method. With the help of dSPACE DS 1104 controller, the execution time as well as the possible sampling time of each methods have been obtained based on dSPACE Control Desk and simulation studies. Table 4 shows the computational times and sampling times of ST-FLC with different fuzzy rule-size. The obtained values have fairly verified the above principals about the execution time of a model.

From Table 4, it can be seen that the proposed ST-FLC with 9-rules has the lowest computational time and faster sampling time. This is due to the simplicity and computation efficiency of the proposed self-tuning mechanism and the smaller number of fuzzy rules of the main FLC. In addition, our proposed ST-FLC with 25-rules and 49-rules have produced very big execution time with a longer sampling time. This is because the large computational requirements associated with big number of fuzzy rules and MFs. Moreover, ST-FLC methods with big computational requirements and longer sampling time have a high tendency to produce ineffective and degraded drive performances.

By referring to the execution time diagrams in Fig. 19 and 21, the bigger computational task in the IM drive model is the speed controller including main FLC and ST-FLC, while the small computational task is the rest of the IM drive system. Considering the speed controller as a task (represented by ST-FLC for simplicity) and the IM drive system as another task (represented by IM for simplicity), the execution time of IM drives model with single timer task and multiple timer task are depicted in Fig. 22 and 23.

The ST-FLC task (speed controller block) is executed every second step, while the IM task (rest of the IM drives model) is executed every time step.

This due the high priority interruption in multiple timer task (IM task has faster sampling time) and the computation efficiency in single timer task (IM task requires less computational capabilities). Apart from this, ST-FLC methods with a big computational requirements can be executed with shorter sampling time if they have been implemented with higher capabilities processors than dSPACE DS 1104. However, this is will contributes to increase the cost of the hardware

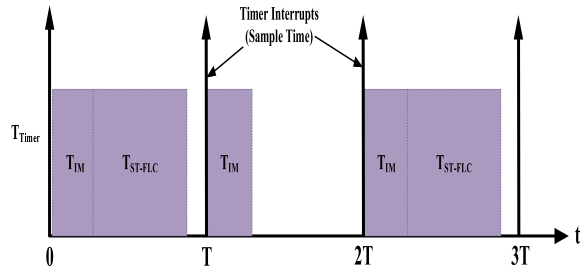

FIGURE 22. Execution time of IM drives model with single timer task.

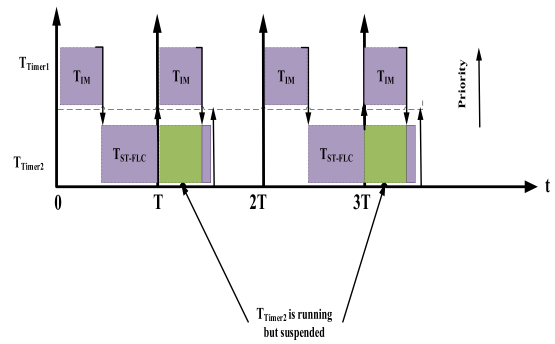

FIGURE 23. Execution time of IM drives model with multiple timer task.

implementation of the IM drive system. Thus, this paper has focused in designing a ST-FLC method that can produce the minimum computational time and maximum sampling time based on dSPACE DS 1104 controller.

V. CONCLUSION

Fuzzy Logic Controller (FLC) has attained many features in high performance Induction motor drives including parameters independency, robustness and handling non-linearity. In order to make FLC more robust and adaptive, Self-tuning mechanisms are introduced to adjust FLC parameters automatically during operations, thus avoiding performance degradation due to the fixed parameters of FLC. In addition, FLC with big number of fuzzy rules might produce accurate output with good performance during simulation testing. However, it might require huge calculation and degrade the performance during experimental testing. In this paper, a simple self-Tuning FLC (ST-FLC) mechanism was employed to tune the output-scaling factor of main FLC based on the inputs of error (e) and change of error (Δe) of the main FLC. Three different FLC rule sizes were used with ST-FLC to investigate the performance of drive system with different fuzzy rule-size. Based on simulation results, ST-FLC with 49 rules showed superior performance over 25 and 9 rules. However, experimental testing showed ST-FLC with 9 rules is superior over 25 and 49 rules. This implies the effects of computational effects during experimental testing where 49 rules require intensive calculations and produce huge computational effects to the system which result in degraded performance. To validate the relation between computational effects with the number of fuzzy rules, a technical analysis of computational time was performed. It was observed that, as the number of fuzzy rules increased a huge computational burden is produced and slow sampling time is required. Therefore, it is obvious that, less number of fuzzy rules is less computational to the system, while, big number of fuzzy rules is highly computational which can degrade the drive performance, require bigger processing memory and increase the hardware cost.

APPENDIX

TABLE 5. Induction motor parameter.

Parameter	Value
Rated power	2hp
Rated voltage	500Vdc
Rated frequency	50Hz
Rated Speed	1500 rpm
Number of poles	4
Stator resistance	3.4Ω
Stator inductance	320mH
Rotor resistance	3.6Ω
Rotor inductance	325mH
Inertia	0.01 kgm^2

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