Indonesian Journal of Electrical Engineering and Computer Science
Vol. 20, No. 3, December 2020, pp. 1653~1664
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v20.i3.pp1653-1664

Experimental simplified rule of self tuning fuzzy logic-model reference adaptive speed controller for induction motor drive

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Article Info

Article history:

Received Feb 2, 2020
Revised May 4, 2020
Accepted May 25, 2020

Keywords:

Fuzzy Logic
Fuzzy Logic Controller
Model Reference Adaptive Controller

ABSTRACT

Fuzzy logic controller (FLC) has shown excellent performance in dealing with the non-linearity and complex dynamic model of the induction motor. However, a conventional constant parameter FLC (CPFL) will not be able to provide–good coverage performance for a wide speed range operation with a single tuning parameter. Therefore, this paper proposed a self tuning mechanism FLC approach by model reference adaptive controller (ST-MRAC) to continuously allow to adjust the parameters. Due to real time hardware application, the dominant rules selection method for simplified rules has been implemented as part of the reducing computational burden. Experiment results validate a good performance of the ST-MRAC compared to the CPFL for the speed performance in terms of the wide range of operations and disturbance showed remarkable performance.

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1. INTRODUCTION

Two types of AC and DC electric motors have been introduced since the 1930s. The advantages of the AC motor are simple structure, low environmental dependence and easier to maintenance compared to the DC motor [1]. AC motors are generally is induction motor (IM), which are used routinely used in various fields such as agriculture, transport, manufacturing and other daily life [2]. With the high development of power electronics and microelectronics technology, more advanced control strategies can be used. For the high-performance drive system, the vector control technique provides excellent dynamic response and good controllability for IM drive. Besides, it offers a simple design and implementation [3]. By providing decoupling of torque and flux control demands, vector control can execute an AC similar to a separately DC motor drive. It operates without sacrificing the quality of dynamic performance [4].

The speed controller plays an important role in the performance of the IMs drive. Conventional speed controllers in IMs drive system have been controlled by proportional integral (PI) and proportional integral derivative (PID) for a long time ago. Several researchers claim this controller has simple structures, low computation, and satisfactory performance for a wide range of operating conditions [5, 6]. However, this controller is very much influence by the plant parameters and may difficult to get the right tuning values [7-9]. This is due to the limited ability to handle the non-linearities behaviour and complex dynamic model, especially when dealing with the three phase induction motor [10, 11]. Fuzzy logic controller (FLC) was proposed as an alternative and become a successful solution to the IM drive [12, 13]. Over the last few decades, FLC has received great attention for IM drive application because to its robustness, less parameter sensitivity and performance improvement compared to the conventional PI controller [10, 14].

FLC is a heuristic control method that will be able to embed the key elements of human knowledge in designing a nonlinear controller. The crisps speed error signal will become the inputs signal converted into a fuzzy set. Three main parameters groups such as scaling factors, membership function and fuzzy rules are tuned and will effectively reduce the error and achieve the optimum performance [15]. However, for the constant parameters FL CPFL, the optimum performance can be achieved at the rated design operation only. Yet, when difference speed demand or disturbance existed, its performance will be degraded [16].

The self tuning mechanism has been introduced to address these issues. Fuzzy parameters are continuously tuned to adapt with any changes or disturbances occurred [17, 18]. The tuning parameters such as rules, membership functions (MF) and scaling factors (SF) can be tuned in a self-tuning fuzzy controller [19-21]. In the drive field, there are various Self-tuning FLC configurations and design structure. Self-tuning proposed in [12] is the simpler self-tuning method. This method only operates through the FLC tuner to update the output scaling factor of the main FLC. In overall, 49 x 2 number of fuzzy rules are used to determine the decision of the main controller and the output SF controller [13]. This research has been continued by [22], which covers on the different number of rules. As conclusion, the different size of the rules directly affects drive performance. By increasing the size of the fuzzy rules, the accuracy of the output results increases [23]. However, it will cause difficulties in realizing real-time implementation.

Efforts to realize self-tuning in real-time implementation has been continuously invented. The simplification rule method is one of the popular techniques that have been proposed in order to reduce computational requirements FLC. As a result, this technique reduces the number of fuzzy rules with minimum effect for fuzzy variables coverage and output decisions [22-24]. Another technique to reduce computerize burden to realize self-tuning in real-time implementation by using a different type of fuzzy from Mamdani to Takagi Sugeno (TS) [25]. The main characteristic of the TS is that singleton output MFs. A different method of self-tuning TS fuzzy type was proposed in [14] with model reference adaptive controller (MRAC) approach. The method was being tested by simulation and experimental setup; the outstanding results of this proposed method provide online tuning for all SF inputs and outputs.

This paper proposes simplified Mamdani self-tuning FLC with MRAC approach (ST-MRAC) for speed control induction motor drive. The proposed methods implement two FLC controllers with only 7 fuzzy rules for the main output control and 7 rules for the tuning mechanism through the simplification method's results. The output SF gain tuning mechanism is able to tune the value of change of error and output scaling factor simultaneously. In overall, only 14 numbers of rules are used for the proposed controller to reduce the computational burden for real-time implementation significantly. The overall drive system performances are compared between ST-MRAC and constant parameter FLC based on simulation and hardware for the variation of speed and load disturbance operations.

This paper is divided into five sections as follows: section 2 gives an overview of IM drive system. Section 3 describes the speed controller modeling. Evaluate the comparison of the results between STFL and the ST- MRAC in section 4. Finally, in section 5 summarize the findings and conclusions.

2. FIELD ORIENTED CONTROL FOR INDUCTION MOTOR DRIVE

Field Oriented Control (FOC) system is one of the most commonly controlled strategies used in high performance IM drive due to its robustness and high-performance [26]. The structure of the indirect field-oriented control (FOC) fed hysteresis current control (HCC) is shown in Figure 1. The AC motor drive can be performed likes a separately excited DC motor in vector control with the aid of feedback controllers [27]. The three-phase motor equations are transformed into a two-component coordinate system (dq axis) through Park or Clarke transformation [28-30]. It can be controlled separately the flux and torque as a DC motor. The mathematical model of the IM follows the discussion in [20, 31]. The electromagnetic torque is identical to the DC motor expression and can be interpreted as below when ids is zero.

$$Te = \frac{3}{2}\frac{P}{2}\frac{Lm}{Lr}(\Psi drIqs) \quad (1)$$

Refer the model in Figure 1, just torque q component is controlled, while flux d component is constant value $isq *=$ 2.9A according to the datasheet of IM. Through inverse Park and Clarke transformation, the components of the current transform from $isq *$ and $isd *$ to $iabc *$ respectively. HCC works as a switching signal generator for inverter by different current demands ($iabc *$)and actual current ($iabc$). HCC is used to control the inverter output voltage because of its simple and fast response characteristics [32, 33]. Lastly, the inverter provides a voltage demand for IM.

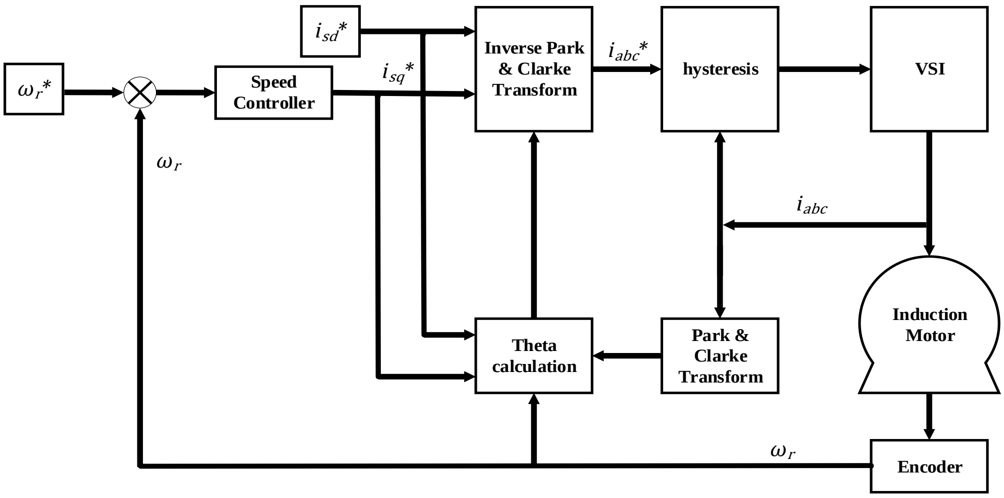


Figure 1. IFOC system fed by HCC

3. FUZZY LOGIC SPEED CONTROLLER DESIGN

Figure 2 shows an internal structure FLSC with one time tuning parameters or constant parameter (CPFL). The internal structure of FLC is divided into three parts: Pre-processing, Fuzzy logic and Post-processing. The normalized input is processed in Pre-processing parts. Here, inputs SF gain value-speed error, Ge and change of speed error, Gce are determined as the (1) and (2) accordingly [34]. Where ωemax and $\triangle\,\omega$cemax with coefficient 2 is the maximum error and change of error for the rated speed to cover-up forward to reverse operations. The membership function and rule of fuzzy are designed in the second part. Range -2 to 2 MF error is designed to cover wider speed operation [24], while the MF change of error and output are designed in range -1 to 1. A combination between the trapezoid and triangular shapes with 50% overlap is used to design the MF[12] as shown in Figure 3 for error (e) and Figure 4 for change of error (ce) and output (cu). The 5x5 MF was designed and labeled as Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS) and Positive Big (PB). The relationship rules between error, change of error and output are states in Table 1, all the rules and MF design processes via knowledge-based experience, phase plane method [35, 36].

$$Ge = \frac{1}{|2\omega\text{emax}|} \tag{2}$$

$$Gce = \frac{1}{|2\triangle\omega\text{emax}|} \tag{3}$$

Table 1. Rules of FLSC

E \ CE	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
ZE	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

*Note : Simplified Rules

The output torque current, $Iq*$ compute by the center of gravity (COG) technique. The denormalized output is operated in the last part, which is Post-processing and the output SF factor, Gcu set as 1.

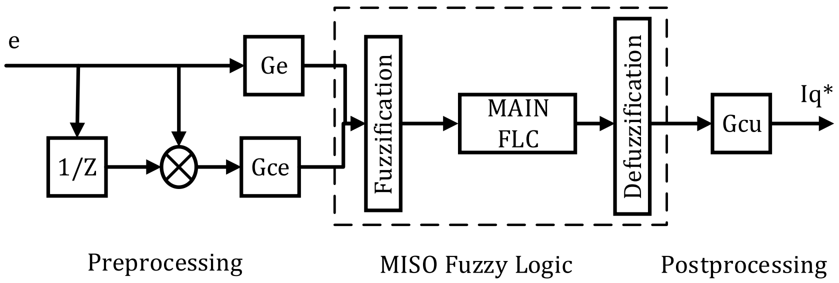


Figure 2. The internal structure of FLSC

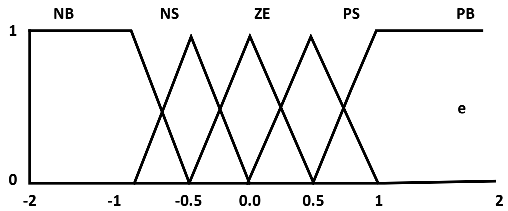


Figure 3. Error membership function

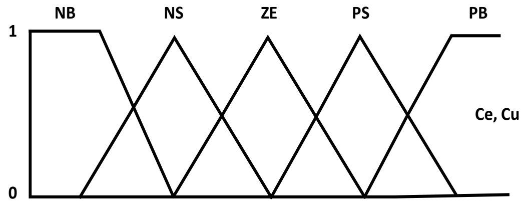


Figure 4. Change of error and output membership function

3.1. Simplified rules of FLSC

FLC faced a huge challenge to implement for real-time hardware due to high numbers of fuzzy rules that affect the computational burden [25]. However, the successful operation of FLC is highly dependent on the ability of the fuzzy rules to interact with the properties. Simplified rules are one of the techniques to a realization hardware implementation by reducing the number of rules. Therefore, the computational burden decreased automatically. In this paper, fuzzy rules are simplified based on the dominant rules selection method [24]. Thus, from 25 rules, only 7 rules were given the most significant. The blue box highlight in Table 1 state the number of rules as the result of the simplified selected rules method [24]

3.2. Proposed ST-MRAC

The general structure of the MRAC shown in Figure 5 is proposed for a self-tuning mechanism controller consisting of a reference model, an adjustment mechanism, a controller and a plant. Differences were added between the MRAC and the normal control loop model with two additional blocks. First, the reference model is used to provide the idealized response of the adaptive control system to the reference input. Second, the adjustment mechanism is used to modify the parameters of the controller [37]. The error signal from the deviation between model reference output and actual speed is computed in the Auxiliary FLC block. Then, the ouput of this Auxiliary FLC block is fed to the main FLC controller. While Figure 6 shows the overall model of the ST-MRAC controller applied to the IM drive system based on the general structure of the MRAC.

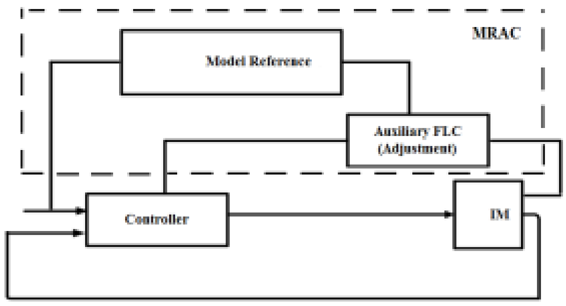


Figure 5. The general structure of MRAC [37]

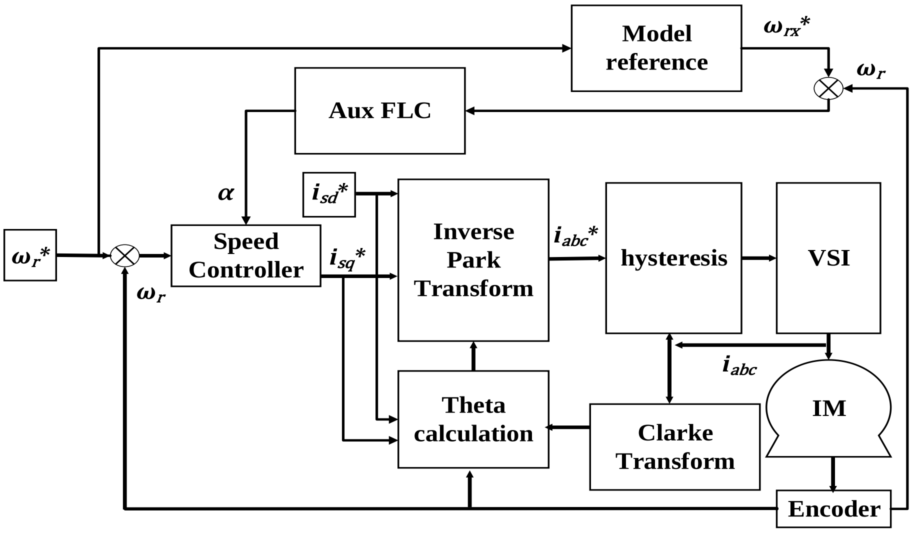


Figure 6. IFOC fed by ST-MRAC

The conceptual of ST-MRAC is tuning FL through MRAC fundamental in order to produce excellent high-performance speed control. The second-order general equation is formulated to be a reference model block and the parameters selected based on the optimum in wide range speed performance. The second order parameters are designed based on the actual motor parameter used than can produce optimum performance. The general equation for the second order system is shown in the following equation [38].

$$G(s) = \frac{\omega n2}{s2+2\xi\omega ns+\omega n2} \quad (4)$$

Where ωn, ξ is the natural frequency and damping ratio respectively. After the calculation process, the parameter of the reference model is determined as in (4),

$$G(s) = \frac{1600}{s2+72s+1600} \quad (5)$$

Figure 7 presents the internal structure ST-MRAC, the error between speed demand and reference model will be the input for auxiliary FLC in the adjustment block.

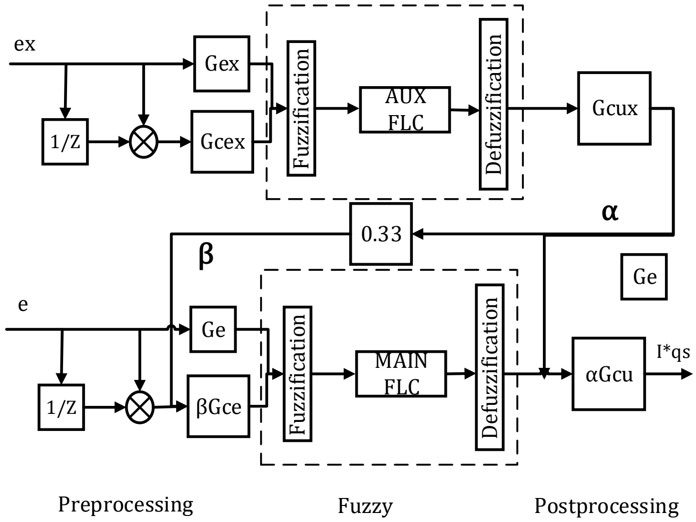


Figure 7. Internal ST-MRAC speed controller

Here, Multi Inputs Single Output (MISO) type FLC is functions to tune SF gains for the output, α and change of error, β scalling factor. The SF gain is continuously tuned based on the input error and change of error. All the scaling factors and membership functions for the main and auxiliary FCL remain unchanged as discussed in the previous part. Only the output, α MF tuned are added for the auxiliary FLC for the tuner, as shown in Figure 8. The overall operation utilized by 14 numbers rule of FLC; 7 rules for main FLC speed controller and 7 rules for auxiliary FLC for tuning SFs as listed below.

a) Rule 1 and 2 : If E is NB/PB and CE is ZE then α is XS/XL
b) Rule 2 and 3 : If E is NS/PS and CE is ZE then α is /L
c) Rule 3 and 4 : If E is ZE and CE is NS/PS then α is S/L
d) Rule 7 : If E is ZE and CE is M then α is M

The following equation presented the torque current and tuner for the change of error SF. Value of β following α coefficient by constant value 0.33.

$$I * qs(n) = i * qs(n-1) + \triangle i * qs(n) * Gcu * \alpha \quad (6)$$

$$\beta = \alpha * 0.33 \quad (7)$$

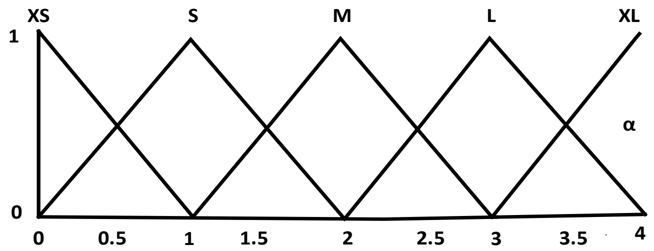


Figure 8. Tuner for Output SF, α

4. DISCUSSION AND RESULTS

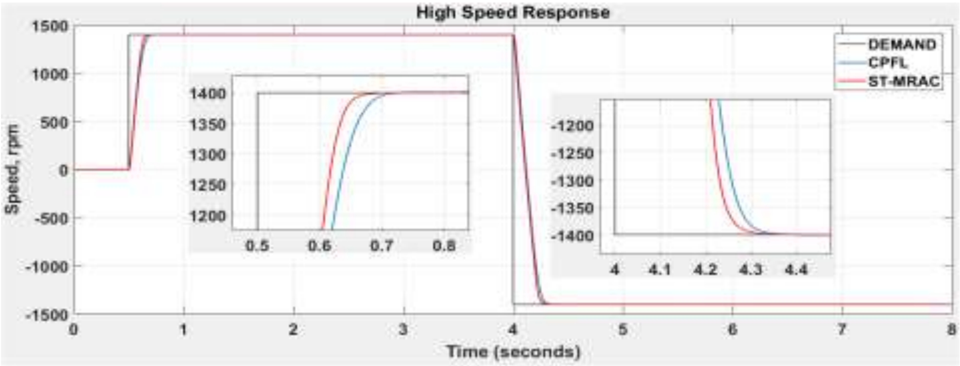
In this section, the performance of each speed controller technique is recorded. The CPFL and ST-MRAC of the IFOC speed controller model in the Simulink / Matlab software to connect to 3 phase, 4 poles, 2HP IM powered by HCC. To evaluate a comparison of performance between STFL and ST-MRAC in a wide range of low, medium and high-speed operations and load disturbance tested. Details IM as follows rated voltage = 380V, stator resistance = 3.45Ω, rotor resistance 3.6141Ω, stator inductance = 0.3246H, rotor inductance = 0.3252H, magnetizing inductance = 0.3117H and inertia = 0.02kgm2.

4.1. Simulation results

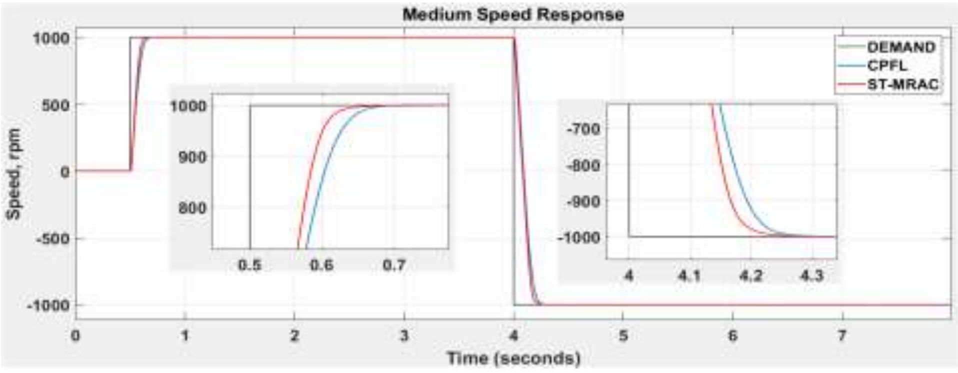
Speed performance under no load condition is conducted in both forward and reverse operations. Speed demand is set at 0.5s for forward speed operation from the initial standstill condition and then reverses its operation at 4s. In contrast, load interruption is applied at time 1.5s to 3s in all low, medium and high-speed range conditions respectively. Figure 9 and Figure 10 captured the simulation performance results. The performance comparisons are made in terms of overshoot or undershoot, rise time, settling time and speed drops. In the analysis, the rise time in speed response was determined to exceed 90% of speed command in 0% OS. Table 2 and Table 3 summarized the observation from the simulation speed response. Based on the result, ST-MRAC has shown that it is better to achieve demand for speed in increasing time. ST-MRAC recorded 0.1153s, 0.0892s and 0.0646s at different speeds, high, medium and low. It takes 0.0196s, 0.0213s and 0.0429s faster than CPFL. While for load interruption, the CPFL recorded average speed drops of 34 rpm lower than the ST-MRAC.

Table 2. Rising time comparison with 0% OS different speed operation

Demand of speed (rpm)	ST-MRAC (s)	CPFL (s)	Different
1400	0.1153	0.1349	0.0196s
1000	0.0892	0.1105	0.0213s
600	0.0646	0.1075	0.0429s



(a)



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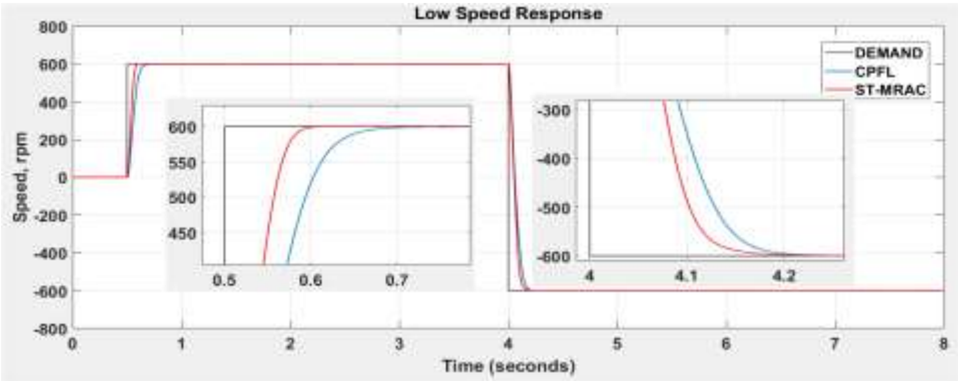
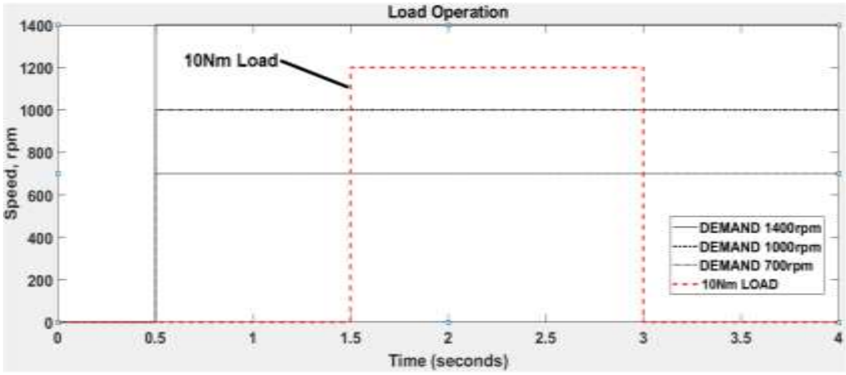


(c)

Figure 9. Speed performance response (a) high speed 1400 rpm, (b) medium speed 1000rpm, (c) low speed 600rpm

Table 3. Speed drop when interruption load to the system

Demand for speed (rpm)	Loaded			Unloaded		
	ST-MRAC (rpm)	CPFL (rpm)	Different (rpm)	ST-MRAC (rpm)	CPFL (rpm)	Different (rpm)
1400	1362.0	1328.0	34.0	1453.0	1477.0	24.0
1000	963.0	929.7	33.3	1052.0	1076.0	24.0
600	562.4	527.5	34.9	650.9	673.2	22.3



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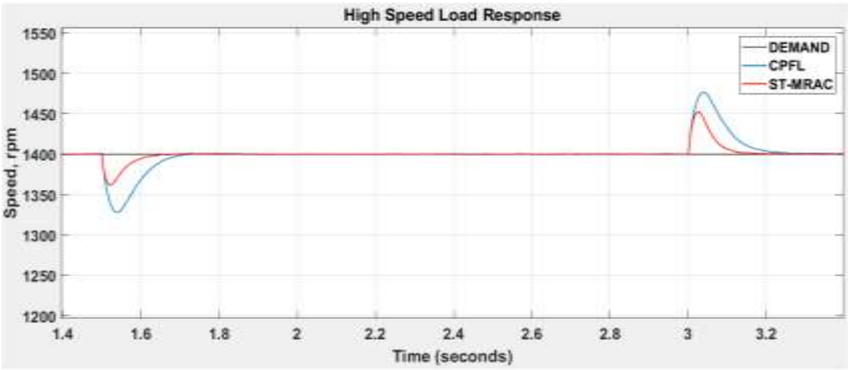

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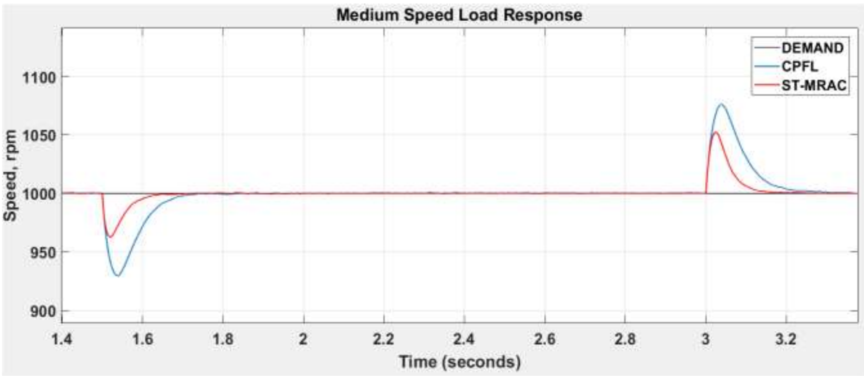

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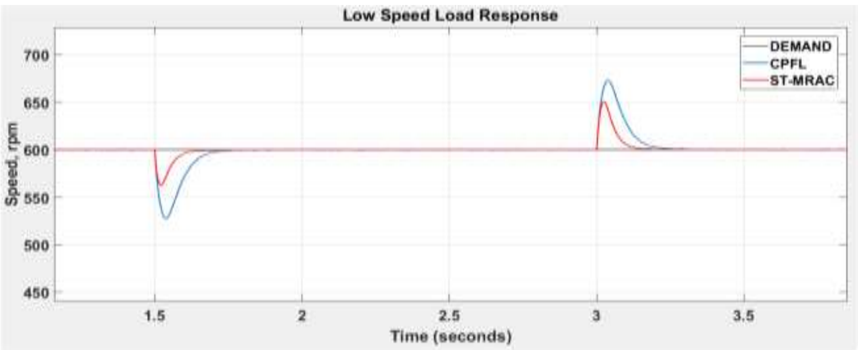
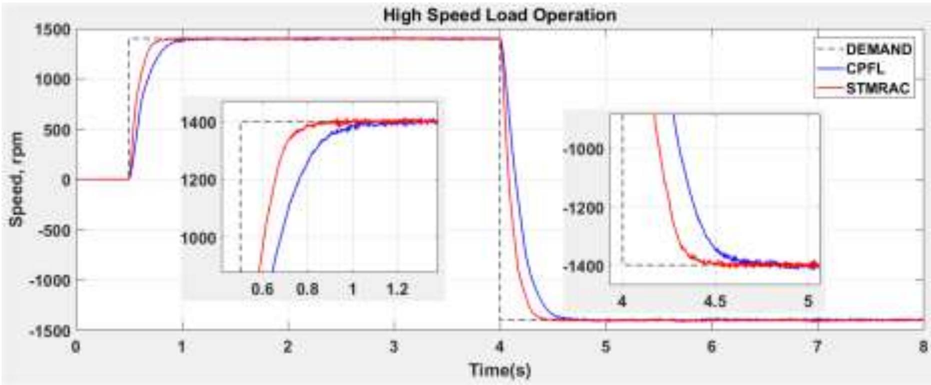


(d)

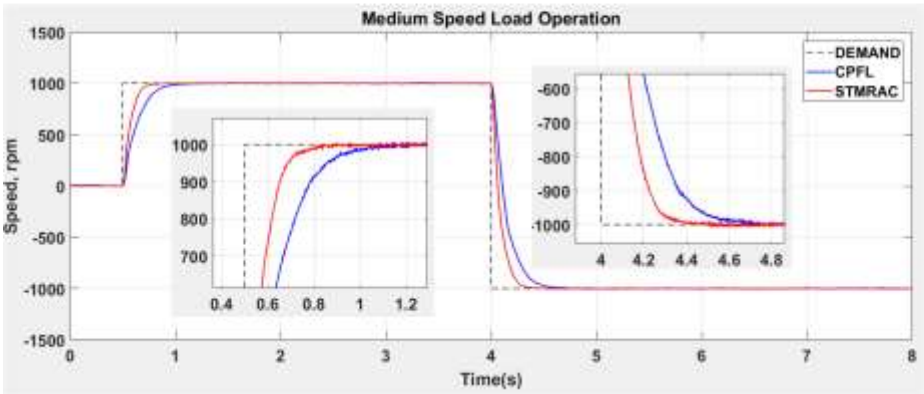
Figure 10. Speed performance load response (a) flow operation load disturbance (b) high speed 1400 rpm, (c) medium speed 1000rpm, (d) low speed 600rpm

4.2. Hardware Experimental Results

The experimental test validated the effectiveness and robustness of the proposed ST-MRAC for IM drive at different operating conditions. The drive has been tested in real-time implementation using MATLAB/Simulink and ControlDesk programs interface with hardware equipment by dSPACE 1103 controller. By interfacing, the closed-loop system can be obtained. The IM, speed sensor, VSI, 3 phase AC power supply, rectifier, gate drivers and current sensor are parts of the hardware for inverter supplied by 537 Vdc. All the testing procedures and parameters of fuzzy such as SF, MF and rules are set as in simulation setup. The hardware speed performance results are shown in Figure 11 and Figure 12 for no load and loaded conditions.



(a)



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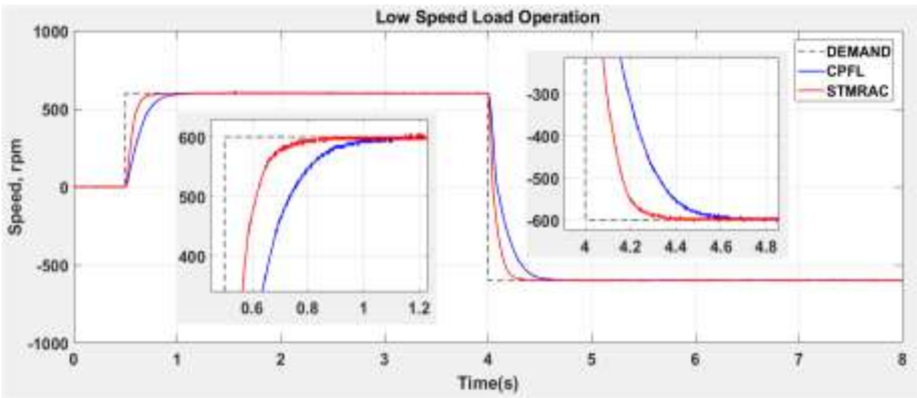
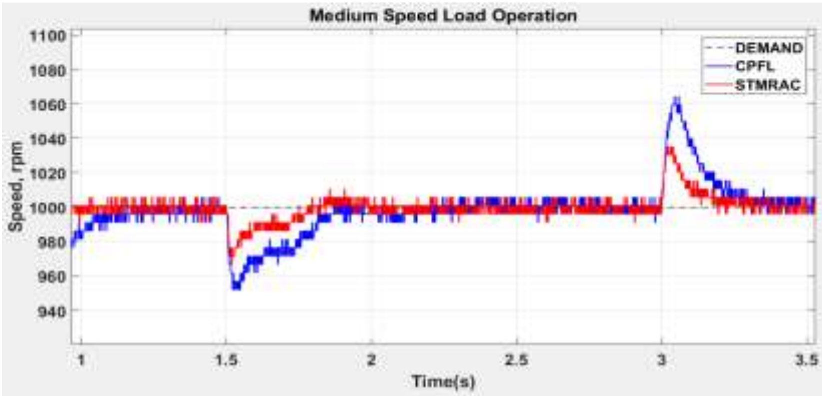


(c)

Figure 11.Speed performance hardware response (a) high speed 1400 rpm, (b) medium speed 1000rpm, (c) low speed 600rpm

Table 4 summarizes the speed performance result. Based on the comparison data, the ST-MRAC gives better speed performance compare to the CPFL in the drive of IM in all test conditions. For forward operation ST-MRAC show 0.1257s, 0.1336s and 0.1472s faster than CPFL in high, medium and low speed operation respectively. It shows the same performance in suddenly changing direction operation from forward to reverse. ST-MRAC recorded 0.141s, 0.138s and 0.188s faster in high, medium and low speed operation respectively. For load disturbance tests, ST-MRAS showed improvement compared to CPFL 2.07 per cent at high, 1.47 per cent at medium and 4.06 per cent at low speed operation.

(a)



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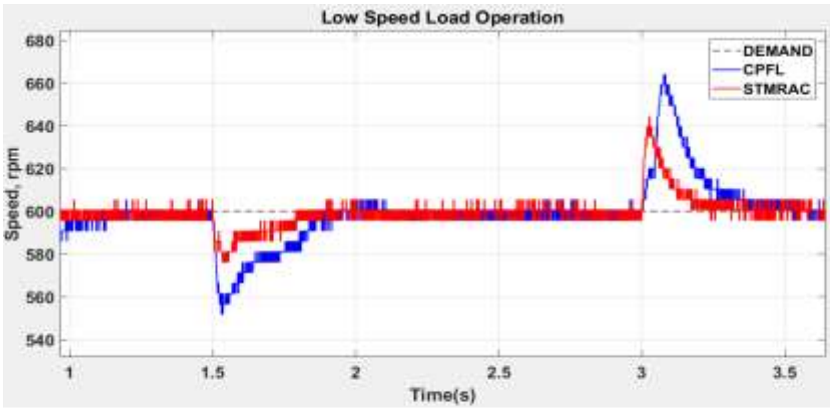

(c)

Figure 12. Speed performance hardware response (a) high speed 1400 rpm, (b) medium speed 1000rpm, (c) low speed 600rpm

Table 4. Summarize experiment speed performance

	ST-MRAC			CPFL		
Demand for speed (rpm)	Rise time (s)	load	unload	Rise time (s)	load	unload
1400 Forward	0.1763	1362.0	1421.0	0.3020	1333.0 rpm	1431.0 rpm
1400 Reverse	0.2770	rpm	rpm	0.4180		
1000 Forward	0.1512	966.8	1035.0	0.2848	952.1 rpm	1064.0 rpm
1000 Reverse	0.2270	rpm	rpm	0.3650		
600 Forward	0.1405	576.2	644.5	0.2877	551.8 rpm	664.1 rpm
600 Reverse	0.1880	rpm	rpm	0.3760		

5. CONCLUSION

In this paper, self tuning fuzzy logic - model reference adaptive speed controller for Induction Motor Drive is proposed. This proposed mechanism is to tuning output scaling factor and change of error scaling factor simultaneously. The dominant rules selection method for simplified rules applied 7 rules of each FLC tuning FLC mechanism to realized real-time implementation. This method proved the robustness of speed performance compare to constant parameter fuzzy logic controller in low, medium and high speed operations based on simulation and hardware.

ACKNOWLEDGEMENT

The authors would like to acknowledge their gratitude to Electric Vehicle Drive Lab, Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for providing the resources and support in this study.

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