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A COMPARATIVE ANALYSIS OF PI, FUZZY LOGIC AND ANFIS SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

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Abstract—The conventional Proportional-Integral (PI) speed control has been widely used in industrial motor controls due to its capabilities in controlling linear plants. However, motor behaves as non-linear plant where the PI speed control may not be able to provide precise speed responses. With the fast growing of artificial intelligent in motor controls, the fuzzy logic and adaptive network fuzzy inference system (ANFIS) are available in more precise motor controls. Nevertheless, there are still many disputes on the superiority of PI and fuzzy logic controls. The fuzzy logic controller with rules-based is limited to a particular load torque due to its output membership functions. This incurs a larger steady-state error of the fuzzy logic controller when the load torque is varied. On the other hand, PI controller has better adaptability over load torque variation and has a smaller steady-state error even though it incurs the overshoot and has longer settling time. In this paper, a comparative analysis of PI, fuzzy logic and ANFIS was done in the Matlab Simulink environment. The object of study is permanent magnet synchronous motor (PMSM).

Keywords: PMSM, PI, Fuzzy Logic, ANFIS, speed control

1. INTRODUCTION

Electrical machines with permanent magnet (PM) rotor excitation become popular in various applications due to its brushless and low power-loss operation. The improvement in flux density

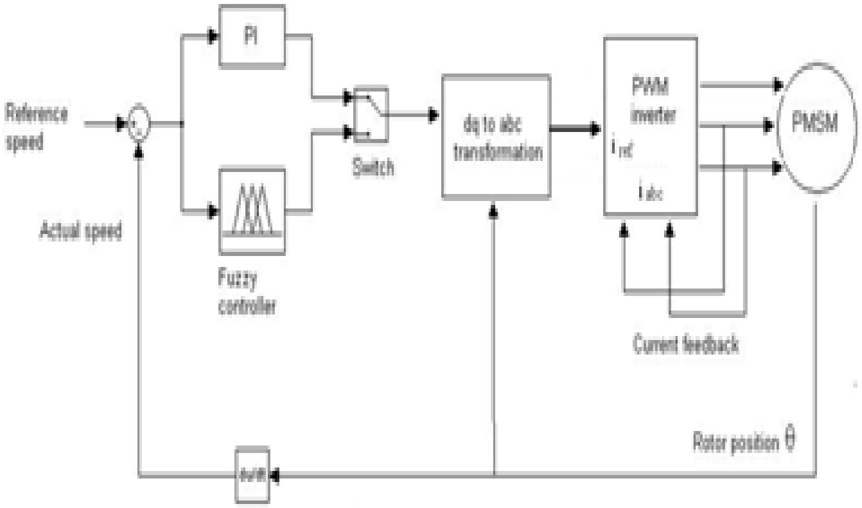


Figure 1: Simulation block diagram of PMSM

of rare-earth permanent magnets created the opportunities for novel machine topologies with substantially improved performance such as efficiency and higher torque-to-weight ratio [1].

A conventional PI speed control method is capable of controlling linear plants successfully, but it is not able to control nonlinear plants with the same success. Machines drives might behave as a nonlinear system, where non-linearities may appear due to armature current limitations, change of load and drive inertia [2]. The system step response for a given reference speed is one of the performance indicator of the speed controller. It is desired that the step response of the system has minimal rise time and without overshoot. However, conventional PD (proportional-derivative) or PI (proportional-integral) controllers cannot be tuned in such way that the optimum step response is achieved for different inertia, load and speed reference. This is the reason why a nonlinear controller is needed, like the fuzzy logic controller [3].

During the past decade, fuzzy control has emerged as one of the most active areas for machines speed control. The researcher found that incorporating human intelligence into the process control application would be an efficient solution and this led to development of fuzzy control algorithms. The invention of fuzzy set theory by Zadeh [4] in the year of 1965 also provides a large contribution especially in the process control applications and the power electronic systems due to complex, nonlinear and precise control is required. In the year of 1989, a lot of researches have been done by Li and Lau [5]. Their applications were applying the fuzzy control theory to a microprocessor-based servo motor controller. The comparison was done between the PID control and Model References Adaptive Control (MRAC). Others approaches also have been developed and the superiority of fuzzy logic controller was reported in [6] and [7]. Of all indicated that the present of fuzzy logic control provides an opportunity to improve the performance of PI control through fuzzy PI controller (FPIC) and the superiority of fuzzy control based fuzzy algorithms is proven as one of the most effective measures [8]. However, the fuzzy control algorithm is a complex nonlinear model, whereby there is no systematic procedure for the design of fuzzy logic controller. Thus, designing a good fuzzy inference system is very time consuming [9]. Nevertheless, the time of designing fuzzy logic controller can be reduced using the adaptive network fuzzy inference system (ANFIS).

The adaptive network fuzzy inference system (ANFIS) is a method of representation of fuzzy systems that enables fuzzy system parameter optimization and training. This learning method works similarly to that of neural networks [10] and [11]. ANFIS provides a method for the fuzzy modeling procedure to learn information about data set and computes the membership function parameters that best allow the associated fuzzy inference system to track the given input and output data. The ANFIS controller is composed of a pattern set, an off-line learning algorithm with back propagation and neuro-fuzzy network. ANFIS implements a First or zero order Takagi-Sugeno fuzzy system, because it is a more compact and computationally efficient representation than a Mamdani system. Only single output fuzzy system ANFIS training can be done, because the output is obtained using weighted average defuzzification which is linear or constant output membership functions [12]. In this paper, the speed control of Permanent Magnet Synchronous Motor (PMSM) is compared among three controllers, PI, fuzzy logic and ANFIS. A speed response based on the steady-state error, settling time and overshoot were compared among PI, fuzzy logic and ANFIS. Figure 1 shows the Matlab Simulink simulation block diagram of PMSM.

2. THE DYNAMIC D-Q MODELLING OF PMSM

A dynamic performance of PMSM can be achieved by the d-q current control system. Figure 2 shows the d- and q-axis equivalent circuits of the sinusoidal PMSM brushless machine where R_s is the stator resistance, l_s is the stator leakage reactance, V_q and V_d are the d- and q- axis stator voltage, i_d and i_q are the d- and q- axis stator current, L_{md} and L_{mq} are the armature mutual inductances in the d- and q-axis, ω_0 is the motor angular frequency. The rotor magnet can be considered as a loop of constant current source, i_m located at the stator direct axis. Any change in the magnetic flux of the rotor magnet will cause an induced electromagnetic force, resulting in a circulating current in the magnet.

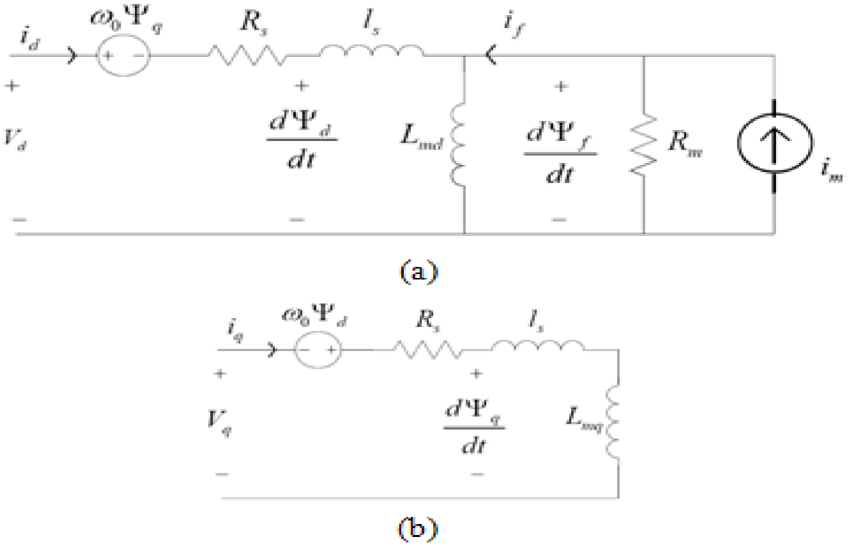


Figure 2: d- and q-axis equivalent circuits of the sinusoidal PMSM brushless machine (a)d-axis;(b)q-axis

The stator voltage equations can be expressed as:

$$v_d = R_s i_d + \frac{d\psi_d}{dt} + \omega\psi_q \tag{1}$$

$$v_q = R_s i_q + \frac{d\psi_q}{dt} - \omega\psi_d \tag{2}$$

The instantaneous power to the motor input terminals is:

$$P_{in} = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \tag{3}$$

The electromagnetic power of a three-phase machine is:

$$P_{elm} = \frac{3}{2}\omega\left[\psi_f + \left(L_d - L_q\right) i_d\right] i_q \tag{4}$$

The electromagnetic torque of a three-phase motor with p-pole pairs is:

$$T_e = p\frac{P_{elm}}{\omega} = \frac{3}{2}p\left[\psi_f + \left(L_d - L_q\right) i_d\right] i_q \tag{5}$$

The electrical and mechanical torque balance equations are as follow:

$$J\frac{d\omega}{dt} = p\left(T_e - T_m\right) - B_\omega \tag{6}$$

where J is the inertia of the PMSM, T_m is the load torque, B is the approximated mechanical damping to friction. The motor angular speed ω is $\omega = \frac{d\theta}{dt}$ where θ is rotor angle. The relationship between i_d, i_q and phase currents i_{aA}, i_{aB} and i_{aC} are:

$$i_d = \frac{2}{3}\left[i_{aA}cos\omega t + i_{aB}cos\left(\omega t - \frac{2\pi}{3}\right) + i_{aC}cos\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{7}$$

$$i_q = \frac{2}{3}\left[i_{aA}sin\omega t + i_{aB}sin\left(\omega t - \frac{2\pi}{3}\right) + i_{aC}sin\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{8}$$

The reverse relations in conjunction with $i_{aA} + i_{aB} + i_{aC} = 0$ are:

$$i_{aA} = i_d cos\omega t - i_q sin\omega t \tag{9}$$

$$i_{aB} = i_d cos\left(\omega t - \frac{2\pi}{3}\right) - i_q sin\left(\omega t - \frac{2\pi}{3}\right) \tag{10}$$

$$i_{aC} = i_d cos\left(\omega t + \frac{2\pi}{3}\right) - i_q sin\left(\omega t + \frac{2\pi}{3}\right) \tag{11}$$

The dynamic model of PMSM is simulated using Matlab simulink. The simulation model is divided into two parts, namely electrical part and mechanical part. The electrical part execute the calculation of three phase current, i and electrical torque produced, T_e. The mechanical part executes the calculation of motor angular speed and rotor angle. The details of the model are shown in Figure 3.

3. PWM INVERTER MODEL

The instantaneous three phase currents, i_{abc} of the PMSM motor is feedback to the PWM inverter model and compare with the reference current, i_{ref} obtained from the d-q to a-b-c transformation module (refer to Figure 4). The currents will then be converted into the equivalent three phase voltage via a voltage controlled source block to drive the PMSM motor.

4. PI CONTROLLER

The gains of the PI controller are tuned using the simulink response optimization tools. Figure 5 shows the block parameters of the optimization tool. The Kp and Ki gains obtained from the optimization are 10 and 1.5 each respectively.

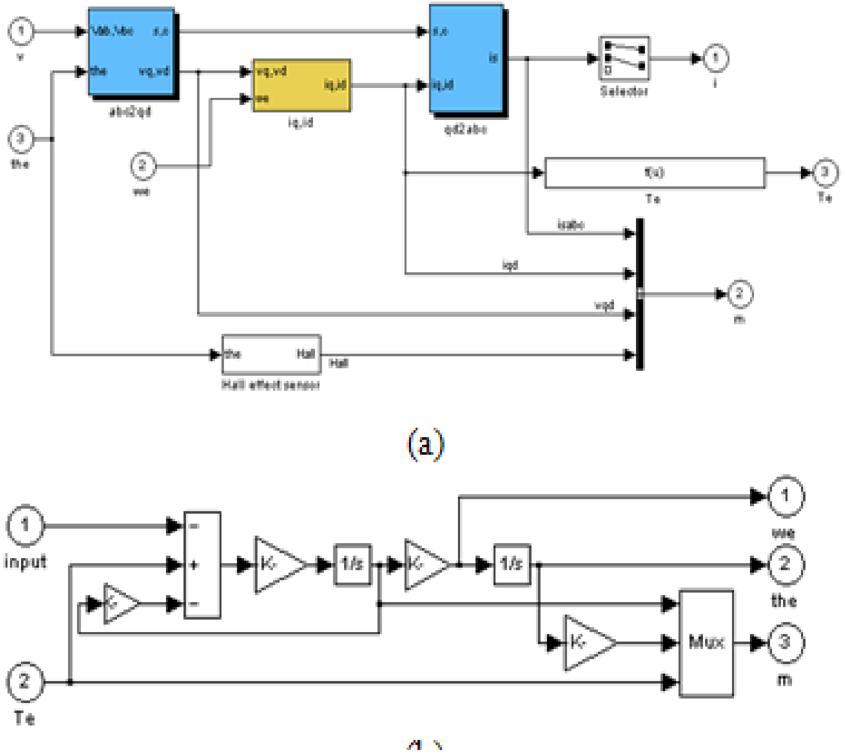


Figure 3: Simulation model of PMSM in Matlab simulink (a) Electrical part; (b) Mechanical part

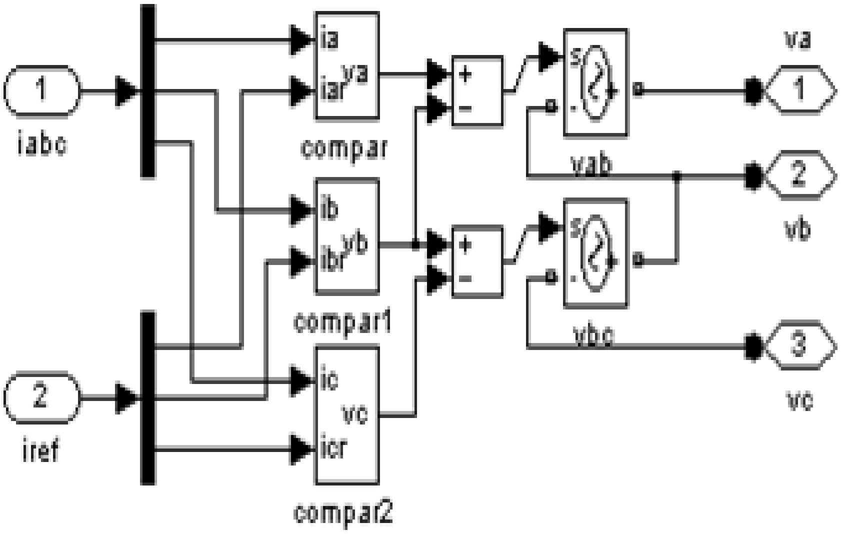
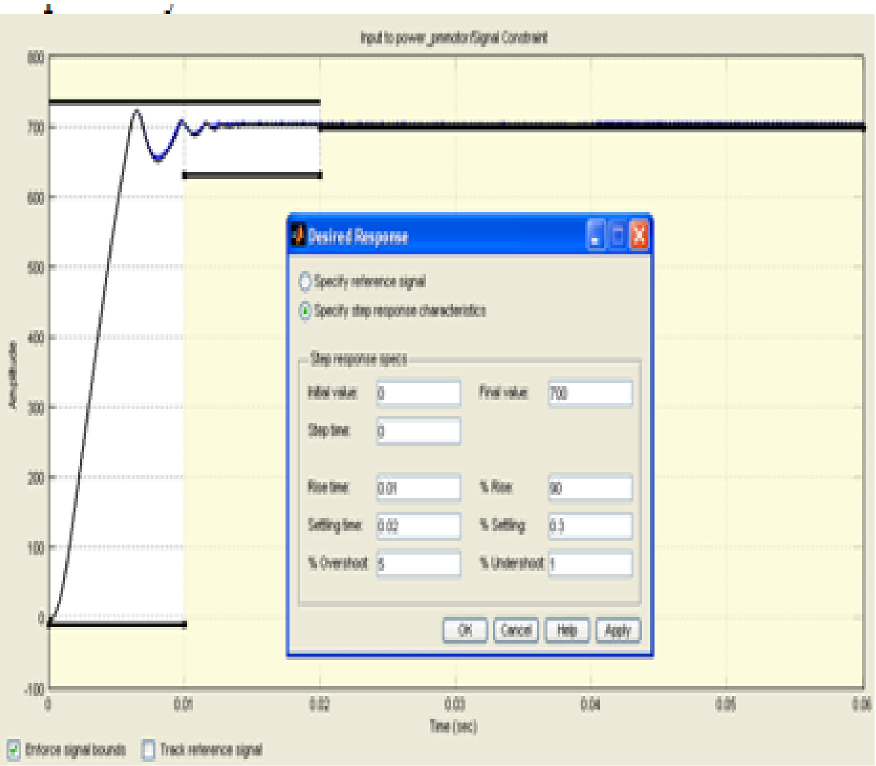


Figure 4: PWM inverter model

5. FUZZY LOGIC CONTROLLER

5.1. Input variables

The fuzzy logic controller is adopted in speed loop in the PMSM control model. The fuzzy logic controller consists of three stages: the fuzzification, rule execution, and defuzzification. The input



Desired Response

○ Specify reference signal
● Specify step response characteristics

Step response specs

Initial value: 0
Final value: 700
Step time: 0
Rise time: 0.01
% Rise: 90
Settling time: 0.02
% Settling: 0.3
% Overshoot: 5
% Undershoot: 1

☑ Enforce signal bounds ☐ Track reference signal

Figure 5: Simulink response optimization tool

variables for fuzzy logic are speed error, $e_r(m)$, and change in speed error, $e(m)$. The expressions are shown below:

$$\begin{aligned} e_r(m) &= w_r^*(m) - w_r(m) \quad (12) \\ e_r(m) &= e_r(m) - e_r(m-1) \quad (13) \end{aligned}$$

where w_r^* and w_r are the speed command and the actual speed of the PMSM. The output signal (CU), is the desired current for the motor speed control. In order to permits flexibility in the design, the variables can be normalized as follow:

$$\begin{aligned} E &= e_r(pu) = \frac{e(m)}{GE} \quad (14) \\ CE &= e(pu) = \frac{e(m)}{GCE} \quad (15) \end{aligned}$$

where GE is scaling factor for speed error and GCE is scaling factor for change in speed error.

5.2. Fuzzy variables, membership functions and rules

Each universe of discourse is divided into seven fuzzy sets:

NL: Negative large
NM: Negative medium
NS: Negative small
ZE: Approximately zero

PL: Positive large
PM: Positive medium
PS: Positive small

Two additional fuzzy variables are used for the output signals, namely (PVL) "Positive very large" and (NVL) "Negative very large". These two additional fuzzy variables optimized the output signals. Figure 6 shows the membership functions of E, CE and CU variables. In practice, one or two types of membership functions are more than enough to solve most of the problems. For simplicity, triangular and trapezoidal shapes are used here. The next step is to define the control rules. There are no special criteria to formulate the fuzzy logic rules. However, the step responses of a PI controller provide an opportunity for rule justification. This can be achieved through examining the condition of each reference points and related it to the E, CE, and CU as shown in Figure 7.

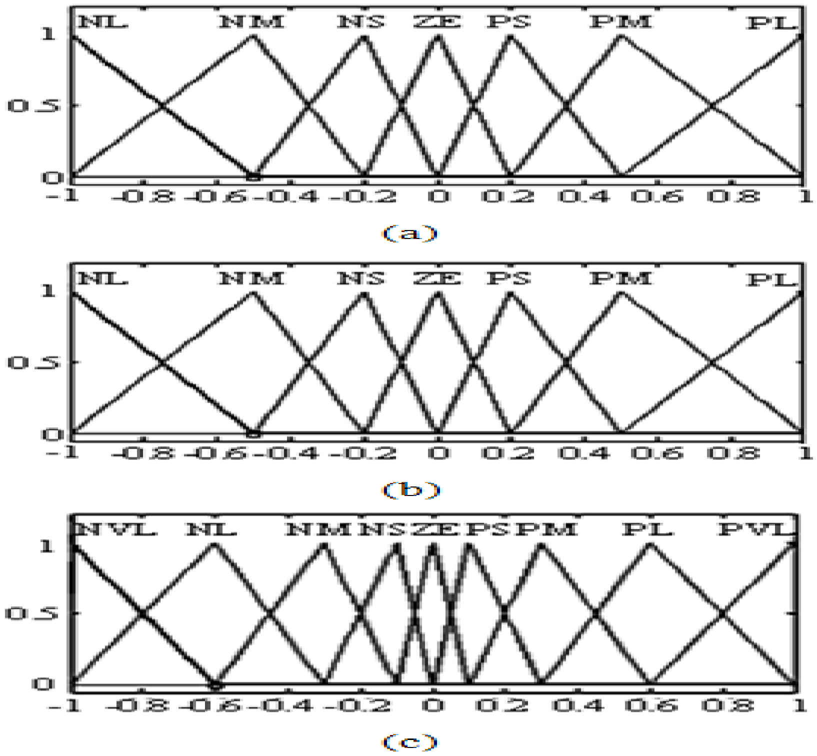


Figure 6: Membership functions (a)Speed error (E) (b)Change in speed error (CE) (c)Current output signal (CU)

Therefore, throughout careful analysis the total 49 rules can be split into nine regions corresponding to each condition until reach the desire speed at "I" as shown in the Table 1.

6. ANFIS CONTROLLER

The network is trained using off-line learning algorithm in Matlab Simulink. Firstly, the simulation results (input and output data) of fuzzy logic controller were collected as training data set. Then the input and output data obtained is modified into the desired data based on the desired output. The desired output will be trained using the Matlab toolbox function 'ANFIS'. From the training, a Fuzzy Inference System with adjusted membership functions as shown in Figure 8, Figure 9, Figure 10 and Figure 11 were obtained.

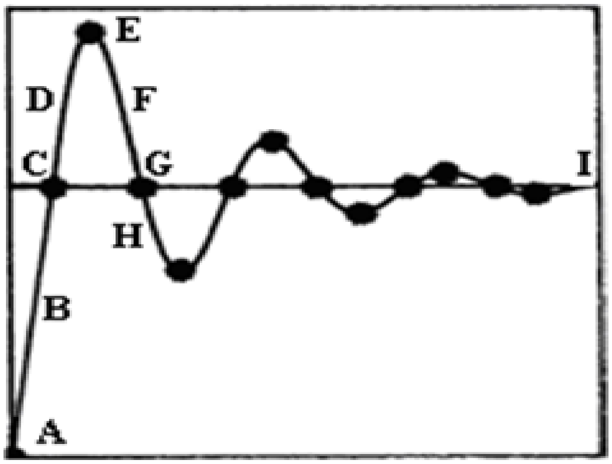
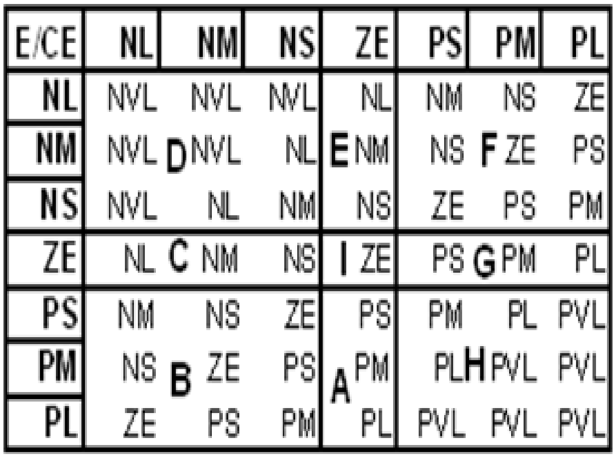


Figure 7: System step response

Table 1: Rule matrix for fuzzy Speed Control



E/CE	NL	NM	NS	ZE	PS	PM	PL
NL	NVL	NVL	NVL	NL	NM	NS	ZE
NM	NVL	D NVL	NL	E NM	NS	F ZE	PS
NS	NVL	NL	NM	NS	ZE	PS	PM
ZE	NL	C NM	NS	I ZE	PS	G PM	PL
PS	NM	NS	ZE	PS	PM	PL	PVL
PM	NS	B ZE	PS	A PM	PL	H PVL	PVL
PL	ZE	PS	PM	PL	PVL	PVL	PVL

7. RESULTS AND DISCUSSIONS

Figure 12 below shows the simulation results for step speed response of PMSM at the speed of 700 rad/s. The fuzzy logic controller has faster rise time, smaller overshoot, settling time and steady-state error compared to PI controller. Figure 13 shows the speed responses with variation of torque at time of 0.03s from 3 N.m to 7 N.m. From the observations, during the torque change duration, the fuzzy logic controller has smaller undershoot and faster settling time. Figure 14 shows the step speed response of PMSM from speed of 700 rad/s to 300 rad/s. Again, the fuzzy logic controller is outperforming compared to the PI controller.

Figure 15, 16 and 17 show the comparison between ANFIS controller and PI controller for the step speed response for 700 rad/s, variation of torque at time of 0.03s from 3 N.m to 7 N.m, and step speed response of speed from 700rad/s to 300 rad/s. Finally, the speed responses are compared between fuzzy logic and ANFIS controller. Figure 18 shows the comparison of step speed response between ANFIS and fuzzy logic controller. From the observation, there is no significant difference between the speed responses of fuzzy logic controller and ANFIS controller.

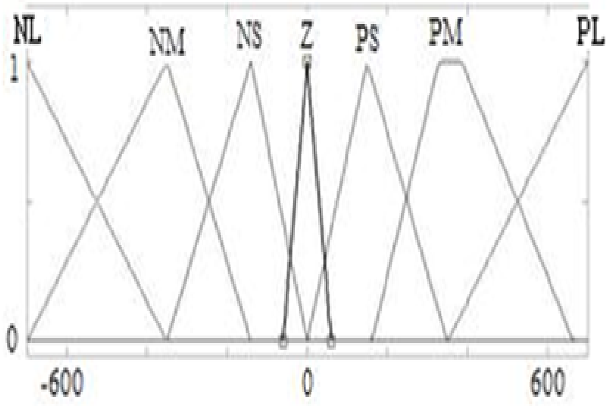


Figure 8: Input Error Membership Function before ANFIS training

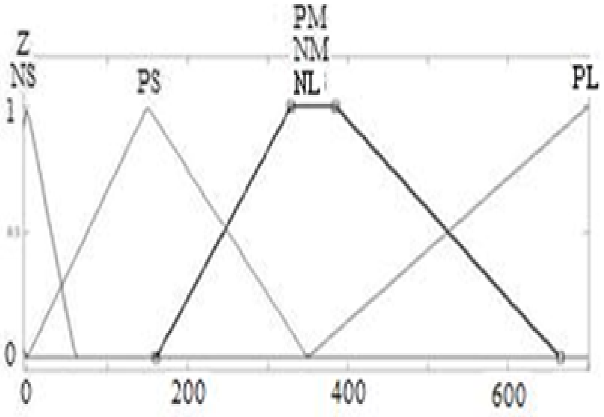


Figure 9: Input Error Membership Function after ANFIS Training

8. CONCLUSION

From the simulation results, it is found that the fuzzy logic and ANFIS controller produce better speed responses than PI in terms of rise time, overshoot, settling time and steady-state for step speed response as well as variation of load torque. Fuzzy logic and ANFIS controller have significantly reduced the overshoot as well as the settling time compared to PI controller. They also successfully cancelled the disturbance effects (load torque change) and maintained steady-state accuracy. From the comparison between ANFIS and fuzzy logic controller, it is shown that there is no significant difference in speed response. The used of ANFIS controller has significantly reduce the time for designing an optimal fuzzy logic controller. As a conclusion, the ANFIS method can be used in obtaining the optimal fuzzy logic controller with faster time.

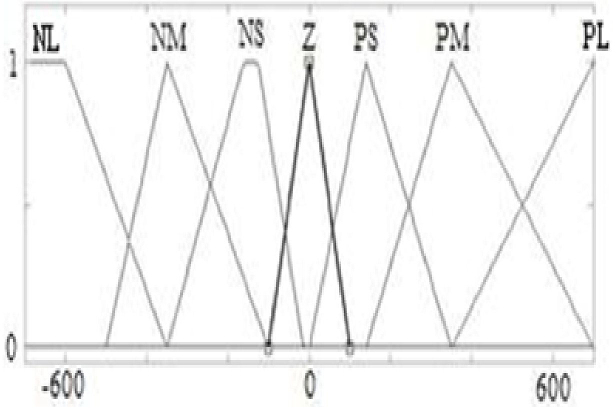


Figure 10: Input Change of Error Membership Function before ANFIS training

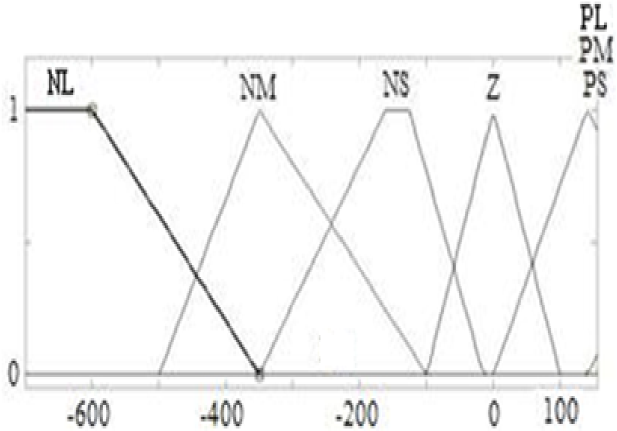


Figure 11: Input Change of Error Membership Function after ANFIS Training

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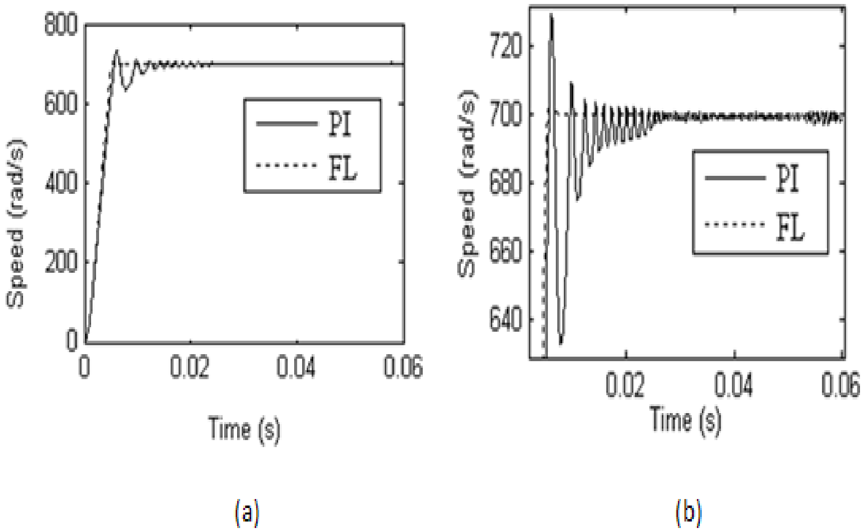
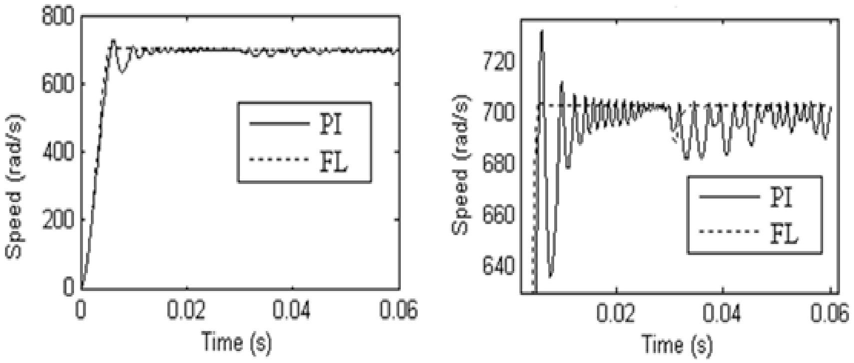


Figure 12: Step response at speed of 700 rad/s (a)Normal scale (b)Enlarged scale

APPENDIX A.

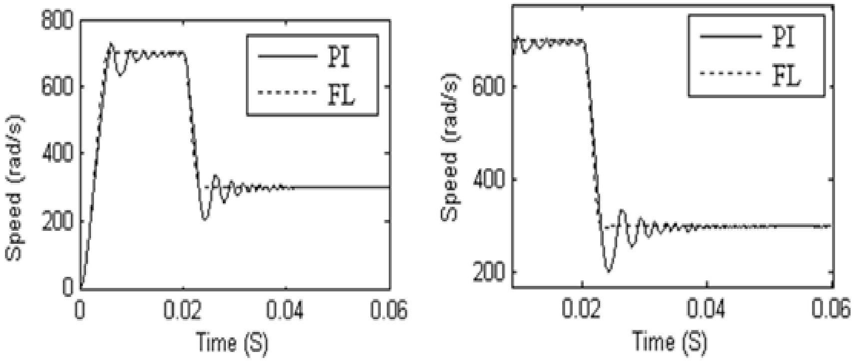
PMSM motor parameters:

Rated Power	1.1 kW
Rated Voltage	220 V
Rated Speed	3000 rpm
Rated Torque	3.5 Nm
Inertia	8.0×10^{-3} Jkgm^2
Stator phase resistance	2.875 Ω
Inductance ($L_d = l_q$)	8.5 mH



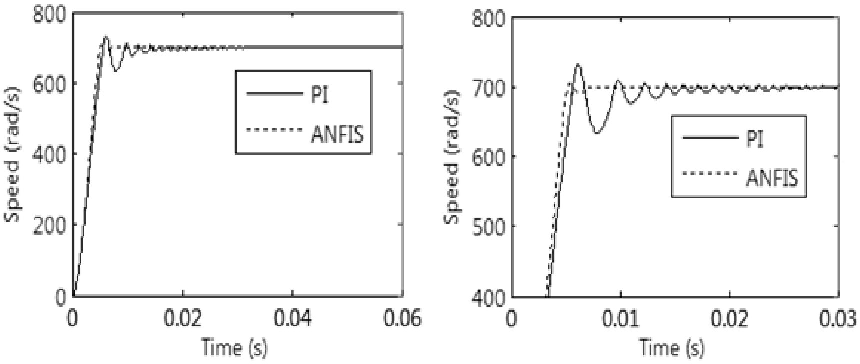
(a) (b)

Figure 13: Variation of torque from 3 N.m to 7 N.m at time of 0.03s (a)Normal scale (b)Enlarged scale



(a) (b)

Figure 14: Step speed response from 700 rad/s to 300 rad/s (a)Normal scale (b)Enlarged scale



(a) (b)

Figure 15: Step response at speed of 700 rad/s (a)Normal scale (b)Enlarged scale

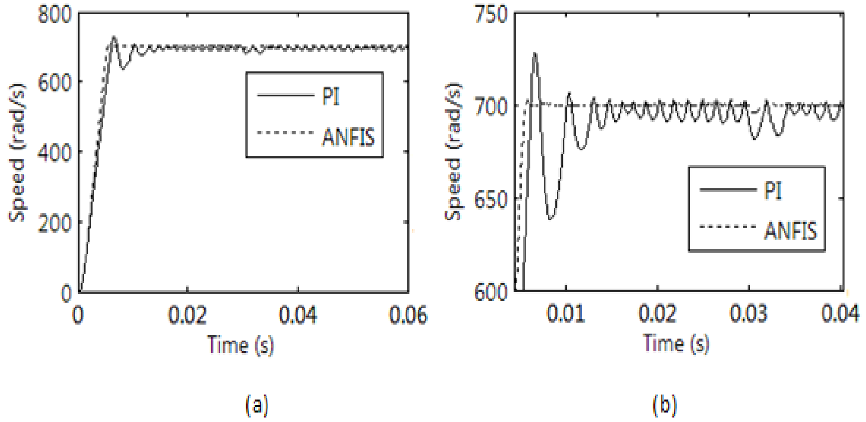


Figure 16: Variation of torque from 3 N.m to 7 N.m at time of 0.03s (a)Normal scale (b)Enlarged scale

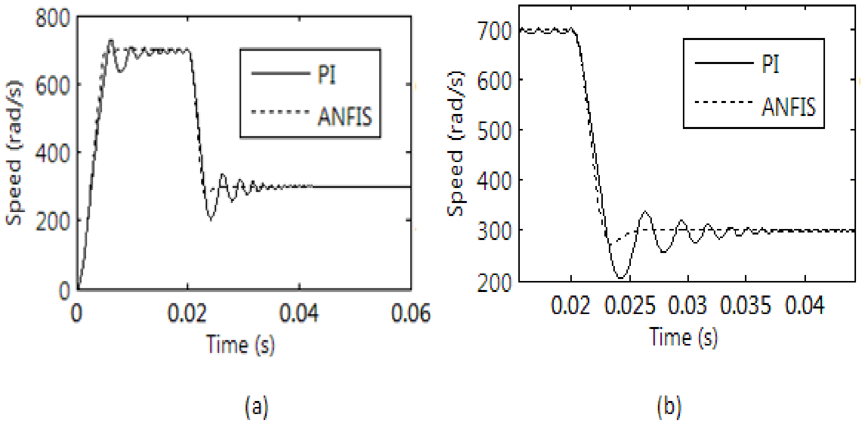


Figure 17: Step speed response from 700 rad/s to 300 rad/s (a)Normal scale (b)Enlarged scale

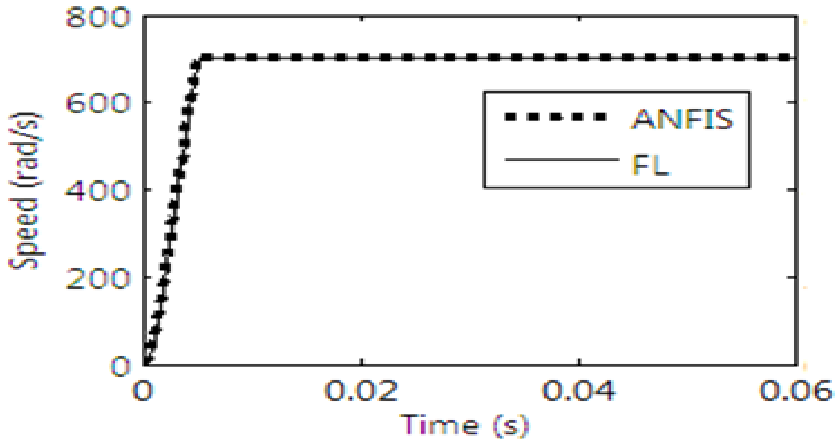


Figure 18: Step response for fuzzy logic and ANFIS controller