A Concise Evaluation of Auto-tuned PID and Fuzzy Logic Controllers for Speed Control of a DC-Motor

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Abstract. This paper presents the dynamic performance evaluation of the auto tuned conventional PID controller and fuzzy logic based speed control of a permanent magnet dc (PMDC) motor. Analytically designed PID controllers and fuzzy logic based controllers need final tuning until the response of the plant to be controlled meets the performance specifications set during design stage. Usually, fuzzy logic based controllers need more tuning activities than analytically designed conventional PID based controllers. The alarming advancement in automation tools provided a number offers to simplify the manual activities to be solved automatically within a short period of time. In this regard, MATLAB software provided automatic tuning features for conventional PID controllers by which the trial and error tuning period can be shorten. In this research, a conventional PID controller for a PMDC motor speed control application is tuned using one of auto tuning feature of MATLAB, i.e., SISOtool. And also, fuzzy logic based controllers is also designed using the fuzzy control system design approach. The performance of both controllers is evaluated for the conditions of no load and loaded conditions of the PMDC motor. The results reveal that application of fuzzy logic based controller has better response than PID based system response.

Keywords: Fuzzy Logic controller · PID controller · SISOtool · Dynamic performance

1 Introduction

Dc motors are widely in use in different industries that require high starting torque such as electric transportations, electric vehicles, and electric trains. And also applicable in areas that may require adjustable speed drives such as in printers, paper industry and floppy drives [1–5]. Among different Dc motor permanent magnet Dc motors are widely in use for different industrial applications that may require adjustable speed drives using power electronics converters. To provide adjustable speed drives, control of the current loop in addition to the outer speed control loop may be required. Usually, the control algorithm may use conventional PID controllers [1, 2]. However, conventional PID controllers may not give whenever parameter changes such as load changes mainly due to nonlinearity of the system to be controlled. To overcome such

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problems a number of controllers that are appropriate for non-linearity cases are devised. Among the number of controllers, fuzzy logic based controllers are appropriate for systems with no models since the main idea behind fuzzy logic based controllers is to model expert's knowledge for a particular application [4–7]. Usually, conventional PID controllers are designed analytically and followed by tuning tasks. However, advancement in automation application tools such as MATLAB provided offers of automatic tuning tasks for linear and nonlinear controllers [5, 8].

In this paper performance evaluation of auto tuned conventional PID controller and fuzzy logic based controllers for speed control application of a PMDC motor is proposed. The overall system architecture and descriptions are presented in the second section. Dynamic models of the power processing unit, the motor, the mechanical load and MATLAB/Simulink model of the open-loop system are presented in third section. Section four described the controller design procedures bot of the PI and fuzzy logic based systems. The MATLAB/Simulink model of the closed-loop system for implementation, simulation results and discussions are presented in section five of the paper. Summary of the findings in this paper is presented in section six.

2 System Description

The system given in Fig. 1 comprises of the controller, power processing unit (PPU), the dc motor and mechanical load. The controller consists of error amplifier and controller (PI or fuzzy logic based). The output speed is sensed and feedback to be compared with the reference speed. The difference between the feedback and reference input (error) signal is amplified and fed to controller by which output of the controller (PWM signal) will be input to the power processing unit [1, 2].

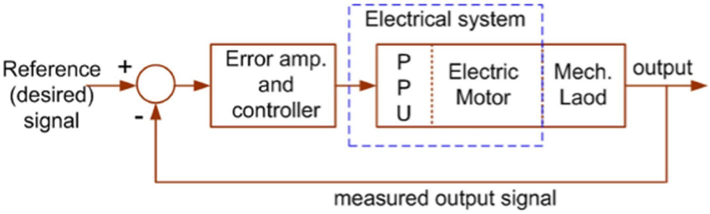


Fig. 1. Basic structure of the proposed system [1]

The speed controller responds to the inputs, disturbances and other changes that may arise due uncertainty. Due to mechanical load in general, the system is non-linear [1, 2]. To design the controller, the most common procedures can be summarised as:

- Linearization of the non-linear system (small-signal modelling).
- Controller design, further tuning, large signal simulation and evaluation.

3 Mathematical Model of the System

Developing mathematical model of the system helps to perform the required dynamic performance evaluation of the controller for the system to be controlled. In this research, Dc motor is considered as a system to be controlled. The Dc motor comprises of electrical and mechanical characteristics and to model these physical laws using energy balance principle are applied [2, 3].

The schematic diagram in Fig. 2 shows the basic electrical components of the Dc motor considered. The variables: V_a is voltage source across the coil of the armature, L_a represents equivalent inductance of armature coil, R_a is the series armature resistance and V_C represents induced voltage that opposes the voltage source generated by the rotation of the electrical coil through magnetic field due to the permanent magnet and this voltage usually known as back-emf or electromotive force [2–5].

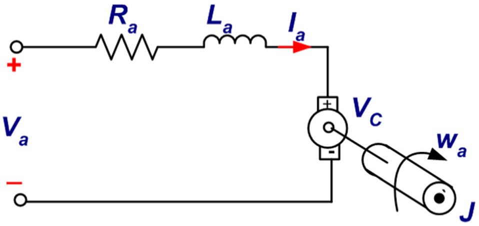


Fig. 2. Electrical diagram of a dc motor [3]

Applying Kirchhoff's voltage law around the electrical loop of schematic diagram in Fig. 2, we can get the Eq. (1).

$$V_a - V_{Ra} - V_{La} - V_c = 0 \tag{1}$$

Applying ohm's law, we can develop the relations for voltage across armature resistance, R_a (V_{Ra}), voltage across the armature inductance, L_a (V_{La}) considering the relation that voltage across inductor is proportional to time rate of change in current and back-emf (V_C) can be represented by expressions in Eq. (2) respectively.

$$\begin{cases} V_{Ra} = i_a R_a \\ V_{La} = L_a \dfrac{d}{dt} i_a \\ V_C = k_v \omega_a \end{cases} \tag{2}$$

where i_a is the armature current, L_a is the inductance of the armature coil, k_v is the velocity constant (determined by the flux density of the permanent magnets, the reluctance of the iron core of the armature, and the number of turns of the armature winding) and ω_a is the rotational velocity of the armature. Substituting, expressions in

Eq. (2) to electrical Eq. (1) derived by applying Kirchhoff's voltage law, we can get the differential Eq. (3) representation of electrical characteristics of the motor.

$$V_a - i_a R_a - L_a \frac{d}{dt} i_a - k_v \omega_a = 0 \tag{3}$$

Mechanical characteristic can be developed from energy balance that the sum of torques of the motor is zero. Thus, Eq. (4) torque equations of the motor.

$$T_e - T_{\omega'} - T_\omega - T_L = 0 \tag{4}$$

where T_e is the electromagnetic torque, $T_{\omega'}$ is the torque due to rotational acceleration of the rotor, T_ω is the torque produced from the velocity of the rotor, and T_L is the torque of the mechanical load. Considering the proportional relation between the electromagnetic torque and armature current we can develop expression for electromagnetic torque (T_e), the relation of torque due to rotational acceleration ($T_{\omega'}$) with inertia of the motor, and the relation between torque and velocity can be given by expressions in Eq. (5) respectively.

$$\begin{cases} T_e = k_t i_a \\ T_{\omega'} = J \dfrac{d}{dt} \omega_a \\ T_\omega = B \omega_a \end{cases} \tag{5}$$

where k_t is the torque constant, where J is inertia of the motor equivalent to mechanical load and where B is the damping coefficient associated with mechanical rotation of the machine. Substituting the torque Eqs. (5) to torque Eq. (4) for balance of energy we can get the differential Eq. (6) representation of the mechanical system.

$$k_t i_a - J \frac{d}{dt} \omega_a - B \omega_a - T_L = 0 \tag{6}$$

Expressions in Eq. (6) are differential equations given in Eq. (7) for armature current and angular velocity to describe the dc-motor system respectively.

$$\begin{cases} \dfrac{d}{dt} i_a = -\dfrac{R_a}{L_a} i_a - \dfrac{k_v}{L_a} \omega_a + \dfrac{V_a}{L_a} \\ \dfrac{d}{dt} \omega_a = \dfrac{k_t}{J} i_a - \dfrac{B}{J} \omega_a - \dfrac{T_L}{J} \end{cases} \tag{7}$$

Arranging the differential expressions in Eq. (7) in state space form can be represented using Eq. (8).

$$\frac{d}{dt} \begin{bmatrix} i_a \\ \omega_a \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{k_v}{L_a} \\ \frac{k_t}{J} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega_a \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J} \end{bmatrix} \begin{bmatrix} V_a \\ T_L \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega_a \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_a \\ T_L \end{bmatrix}$$

Symbolically can be represented using Eq. (9) where, $\bar{x}$ and $\bar{u}$ represent input vector and $\bar{y}$ is the output vector.

$$\begin{aligned} \frac{d}{dt}\bar{x} &= A\bar{x} + B\bar{u} \\ \bar{y} &= C\bar{x} + D\bar{u} \end{aligned} \tag{9}$$

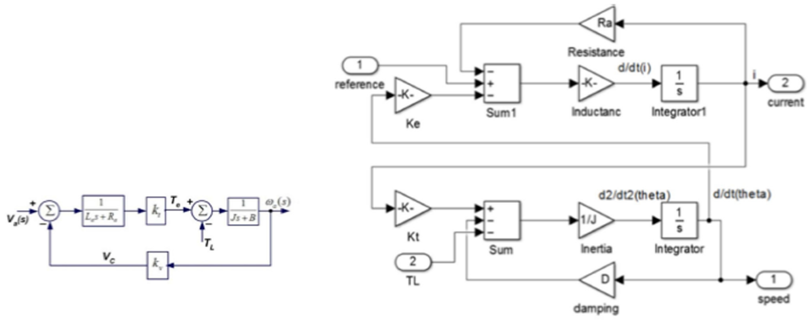
Block diagram can be developed using differential expressions above. Taking Laplace transform of these differential expressions we can get expressions in Eq. (10).

$$\begin{cases} sI_a(s) - i_a(0) = -\dfrac{R_a}{L_a} I_a(s) - \dfrac{k_v}{L_a} \omega_a(s) + \dfrac{1}{L_a} V_a(s) \\ s\omega_a(s) - \omega_a(0) = \dfrac{k_t}{J} I_a(s) - \dfrac{B}{J} \omega_a(s) - \dfrac{1}{J} T_L(s) \end{cases} \tag{10}$$

Consider small perturbations around steady-state condition, initial conditions will be approximated to zero and small changes around the reference state for other variables expressions in Eq. (10) can be represented using Eq. (11).

$$\begin{cases} I_a(s) = \dfrac{-k_v\omega_a(s) + V_a(s)}{L_a S + R_a} \\ \omega_a(s) = \dfrac{-k_t I_a(s) - T_L(s)}{Js + B} \end{cases} \tag{11}$$

The block diagram of the motor can be easily developed using transfer functions given in Eq. (11). Figure 3 shows the block diagram representation of the motor considered. Thus, based on dynamic characteristics of electrical and mechanical



(a) Block diagram of the motor (b) MATLAB/simulink model of the system

Fig. 3. Block diagram representation and MATLAB/Simulink model of the open-loop system

characteristic of the dc-motor, simulation model for the proposed system is developed in MATLAB/Simulink. Figure 3(b) shows the Simulink model of the dc-motor.

4 Design of Speed Controllers

The objective of controller is to achieve system performance of:

- Fast response – (large bandwidth)
- Minimum overshoot, good gain margin (>60^0)
- Zero steady state error – very large DC gain

The power processing unit, the dc-motor and mechanical load considered have parameter values given in Table 1.

Table 1. System parameter values.

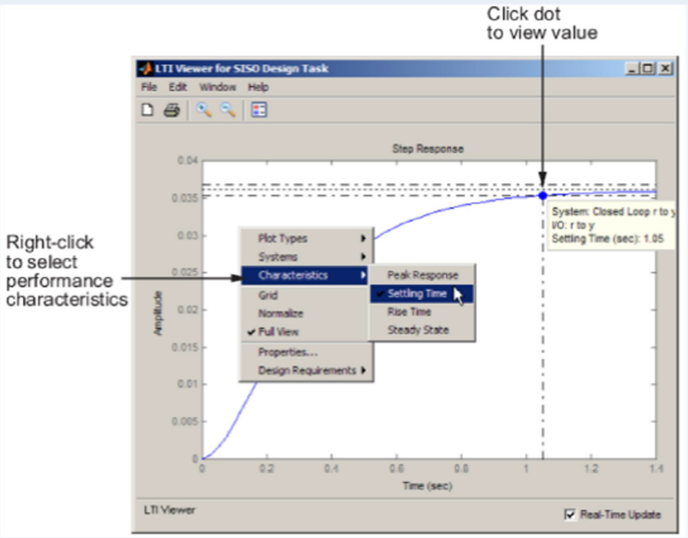
System parameter	Value
R_a	2Ω
L_a	5.2 mH
B	1×10^{-4} kg.m^2/sec
J	152×10^{-6} kg.m^2
K_E	0.1 V/(rad/s)
k_T	0.1 Nm/A
V_d	60 V
V_{tri}	5 V
f_S	33 kHz

Based on the design objectives (specifications) and given parameter values of the system controllers of PI and fuzzy logic based are designed and presented in the following sections.

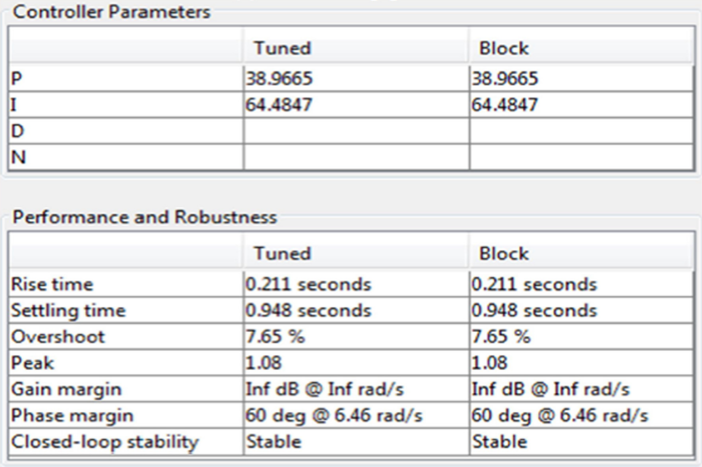
4.1 PI Controller Design

Summary of related works in motion control systems generalizes that PI controller is enough for systems involving Dc motor for motion control application. The controller acts on the error signal and compensates the system response until the required response is achieved [1, 4–7].

In this research, the PI controller is designed using control system designer tool box (SISO) of MATLAB/Simulink [8]. Based on the basic procedures and requirements the controller is designed. Requirements include the model of plant in MATLAB work space and design specifications. Accordingly, the PI controller is designed using automated tuning option of control and estimation tools manager. The closed loop performance of the system, controller parameters, performance and robustness are given in Fig. 4. Following the procedures of automated PID tuning technique, the closed loop response given in Fig. 4(a) is tuned until the performance parameters are within the limits of design specifications.



(a) closed-loop performance



Controller Parameters

	Tuned	Block
P	38.9665	38.9665
I	64.4847	64.4847
D		
N		

Performance and Robustness

	Tuned	Block
Rise time	0.211 seconds	0.211 seconds
Settling time	0.948 seconds	0.948 seconds
Overshoot	7.65 %	7.65 %
Peak	1.08	1.08
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	60 deg @ 6.46 rad/s	60 deg @ 6.46 rad/s
Closed-loop stability	Stable	Stable

(b) controller parameters and their performance

Fig. 4. Feedback structure and closed loop performance

4.2 Fuzzy Logic Controller Design

System non-linearity and systems with no accurate mathematical model can be better handled using artificial intelligent algorithms like fuzzy logic and neural network.

Fuzzy logic models operator's taught and the process of control system can be interpreted and widely used. Fuzzy logic for control application comprises of procedures of fuzzification, rule execution, inference and defuzzification [9–15] where all these procedures can be described in Fig. 5.

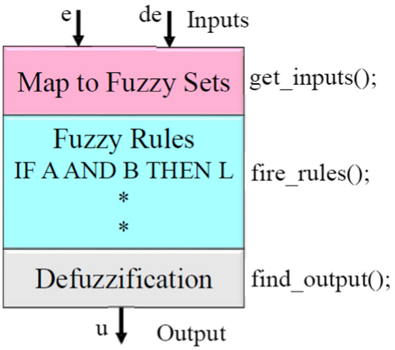


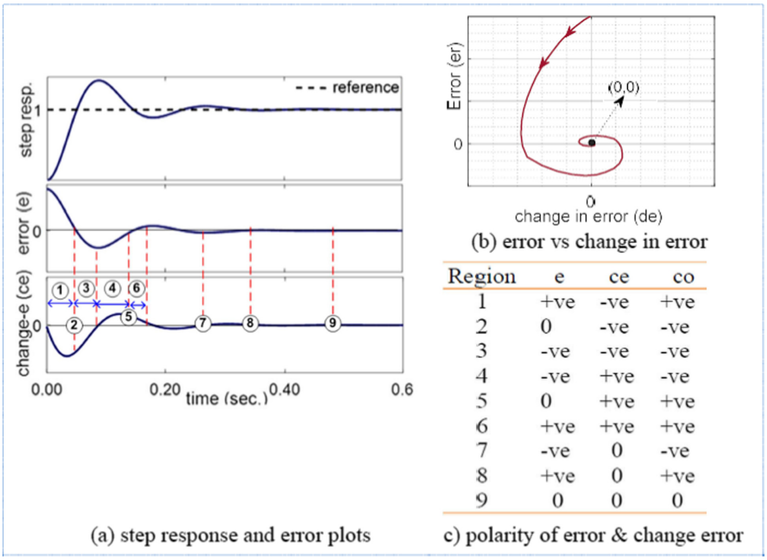
Fig. 5. Schematic diagram of basic tasks in fuzzy logic controller

Centre of gravity technique is widely applied defuzzification technique [9, 10]. Mathematically, the approach can be represented by Eq. (12).

$$y_{out} = \frac{\sum_{i=1}^{n} y_i(x_i) * x_i}{\sum_{i=1}^{n} y_i(x_i)} \tag{12}$$

The general rules for Dc motor speed control is that if motor speed is less than desired speed then speed up the motor and if motor speed is more than reference speed then slows it speed. If we consider a general unit step response of under damped case given in Fig. 6(a), we can have nine possible conditions as given in table form in Fig. 6 (c) from which based on the magnitude and polarity of error and change in error, it is possible to determine the fuzzy output. The error versus change in error plot given in Fig. 6(b) can give the active regions (range) of the universe of discourse for the fuzzy membership functions.

Following similar procedure, we can fill the possible fuzzy controller output for the error and change in error combinations. This concept can be used to set the rule table for the fuzzy logic controller. In this paper, triangular membership functions for the inputs and the output having each seven linguistic variables of negative large (nl), negative medium (nm), negative small (ns), zero (ze), positive small (ps), positive medium (pm) and positive large (pl) are designed. Accordingly, the corresponding membership functions and the rule table are given in Fig. 7.



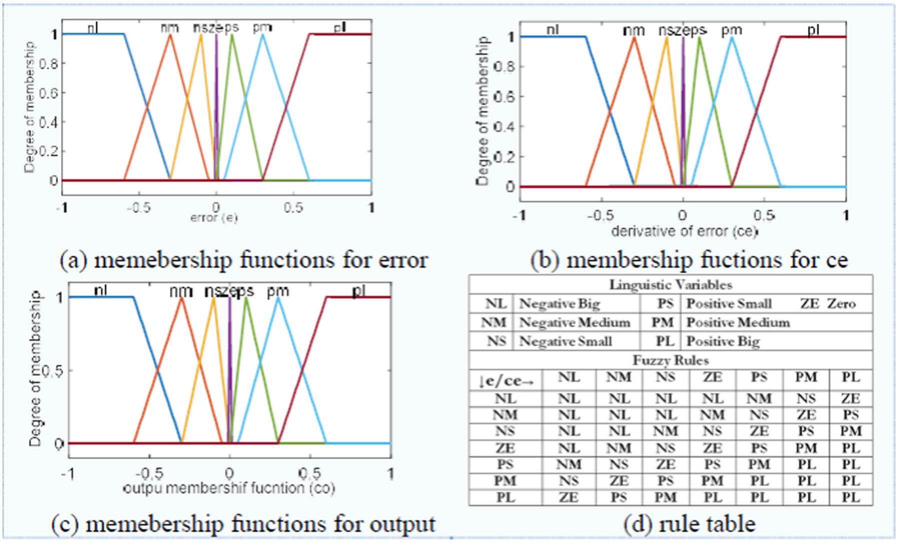
(a) step response and error plots

(b) error vs change in error

Region	e	ce	co
1	+ve	-ve	+ve
2	0	-ve	-ve
3	-ve	-ve	-ve
4	-ve	+ve	-ve
5	0	+ve	+ve
6	+ve	+ve	+ve
7	-ve	0	-ve
8	+ve	0	+ve
9	0	0	0

c) polarity of error & change error

Fig. 6. Step-response and error signal plots and analysis table



(a) memebership functions for error

(b) membership fuctions for ce

(c) memebership functions for output

Linguistic Variables					
NL	Negative Big	PS	Positive Small	ZE	Zero
NM	Negative Medium	PM	Positive Medium		
NS	Negative Small	PL	Positive Big		

Fuzzy Rules

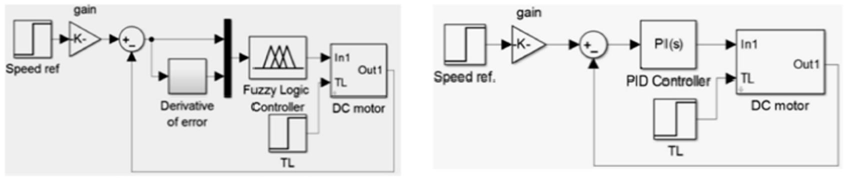
↓e/ce→	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

(d) rule table

Fig. 7. Fuzzy membership functions and rule table

5 Results and Discussions

Performance evaluation of the proposed controllers is done using MATLAB/Simulink simulation for the test conditions of no load and loaded conditions. The complete MATLAB/Simulink model of the closed-loop system using PI and fuzzy logic controllers is given in Fig. 8.

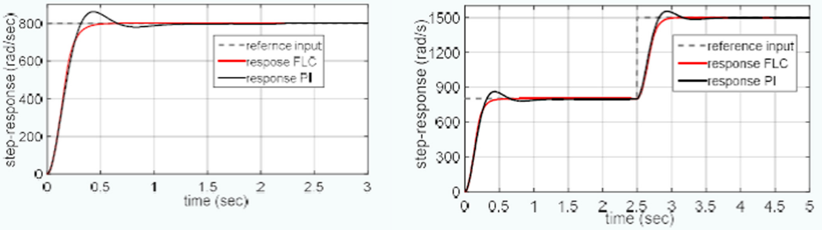


(a) FLC control model (b) pi control model

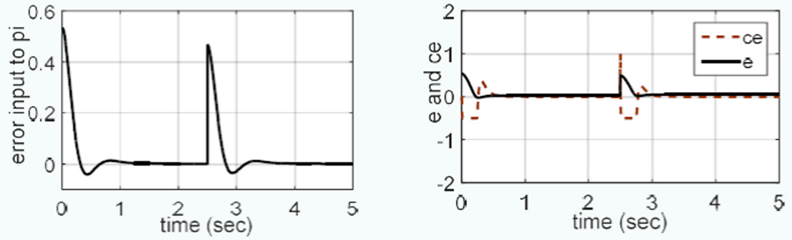
Fig. 8. MATLAB/Simulink Models for speed control of a DC motor

5.1 Responses at No-Load Condition

Step-input of reference speed 800 and 1500 rad/sec are applied for both cases: PI and fuzzy logic based control systems. Figure 9 shows the step-response plots at no-load conditions.



(a) step-input (b) step-change input



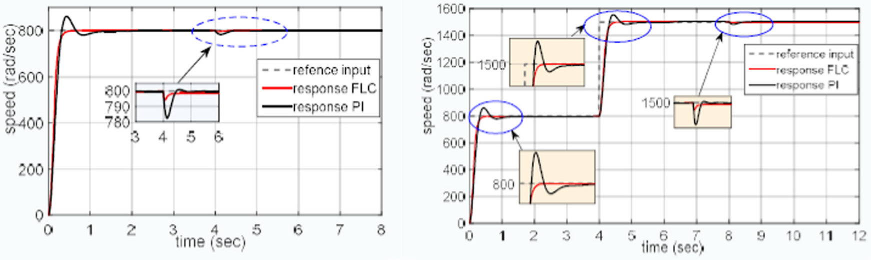
(c) error input to pi controller (d) error and change inputs

Fig. 9. Step responses at no-load and error/change in error signals

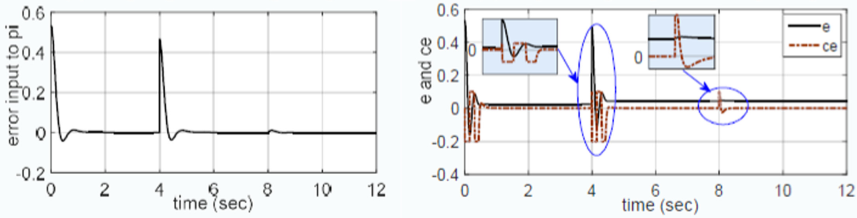
The broken line shows the reference (step-input) plot and the black curve shows the response using PI controller and the red curve with no-overshoot shows the response using fuzzy logic controller. From the responses, fuzzy logic controller based system has zero steady state error; zero percentage overshoot compared with PI based system. Figures 9(c) and (d) show the error plots for the corresponding controllers.

5.2 Response at Loaded Condition

At loaded condition, a reference speed of 800 and 1500 rad/sec and torque of load of 5 Nm is applied at time t = 4 s of the simulation time. The response plot with overshoot and black colour is the response using PI controller and the response with no overshoot and red colour is using fuzzy logic controller. Accordingly, the response plot for a loaded case, step reference input of 800 rad/sec and step-change in reference input from 800 rad/sec to 1500 rad/sec is given in Fig. 10.



(a) step-input and step-torque (b) step-change input and step-torque



(c) error input to pi controller (d) error and change error inputs

Fig. 10. Response for a step-change input/applied torque and the corresponding error

The results reveal that performance parameter values of using both controllers are within the specified limits. But using fuzzy logic has short settling time (≈0.61 s) where as using PI has settling time of ≈1.4 s. For both conditions of loaded and no-load, fuzzy logic based controller has almost zero percentage overshoot compared 7.3% of overshoot using PI controller. This is because, fuzzy based controller has slow rise time compared to PI controller that may result in increasing peak over reference speed value. From performance parameters value for step reference speed input of 800rad/sec, the system takes short time to settle compared to using PI controller. And also the system using FLC has almost zero overshoot where as using PI has some overshoot even though it is within the limit specified. The result verifies that using FLC for the specified system has better dynamic performance and zero steady-state error compared to PI based system under the no-load and loaded conditions of the system.

6 Conclusions

Dynamic performance evaluation of the conventional PID controller and the intelligent fuzzy logic controllers based speed control of a permanent magnet DC motor using MATLAB/Simulink tool has been done. To evaluate their performance, measuring parameter values of rise-time, settling time, percentage overshoot and peak speed have been evaluated for the corresponding controllers. Controller having system performances of reduced percentage overshoot, short settling time and zero steady state-error are the required performances. From the performance evaluations done, the results shows that using fuzzy logic controller has small rise time which cause to reduce the peak speed and percentage overshoot and small settling time compared to using PI controller.

In summary, using fuzzy logic controllers as speed controller of dc motor has superior dynamic performance than using PID controllers.

References

1. Mohan, N., Undeland, T.M., Robbins, W.P.: Power Electronics: Converter, Applications and Design. Wiley and Sons
2. Lakshmi, G.R.P., Puttalakshmi, G.R., Paramasivam, S.: Speed control of brushless Dc motor using fuzzy controller. Indian Journal Appl. Res. (3)(11), 1–5 (2013)
3. Zhang, R., Song, L., Yang, J., Hoffman, T.: DC motor speed control system simulation based on fuzzy self-tuning PID. Fuzzy Info. Eng. **2**, AISC 62, 967–975 (2009)
4. Dökmetaş, B., Akçam, N., Faris, M.: Speed control of DC motor using fuzzy logic application. In: 4th International Symposium on Innovative Technologies in Engineering and Science 3–5, pp. 734–740, November 2016
5. Bitara, Z., Al Jabia, S., Khamisb, I.: Modeling and simulation of series DC motors in electric car. Energy Procedia **50**, 460–470 (2014)
6. Jilani, A., Murawwat, S., Jilani, S.O.: Controlling speed of DC motor with fuzzy controller in comparison with ANFIS controller. Intell. Control Autom. **6**, 64–74 (2015)
7. Guillemin, P.: Fuzzy logic applied to motor control. IEEE Trans. Ind. Appl. **32**(1), 51–56 (1996)
8. MATLAB Documentation “SISO Design Tool” (2017)
9. Orlowska-Kowalska, T., Szabat, K.: Optimization of fuzzy-logic speed controller for DC drive system with elastic joints. IEEE Trans. Ind. Appl. **40**(4), 1138–1144 (2004)
10. Gupta, R.A., Kumar, R., Bansal, A.K.: Artificial intelligence applications in Permanent Magnet Brushless DC motor drives. Artif. Intell. Rev. **33**, 175–186 (2010)
11. Jamali, N., Amlashi, S.: Design and implementation of fuzzy position control system for tracking applications and performance comparison with conventional PID. IAES Int. J. Artif. Intell. (IJ-AI) **1**(1), 31–44 (2012)
12. Sun, X., Koh, K., Yu, B., Matsui, M.: Fuzzy-logic-based *V*/*f* control of an induction motor for a DC grid power-leveling system using flywheel energy storage equipment. IEEE Trans. Industr. Electron. **56**(8), 3161–3168 (2009)

13. Ramya, A., Balaji, M., Kamaraj, V.: Adaptive MF tuned fuzzy logic speed controller for BLDC motor drive using ANN and PSO technique. J. Eng. **2019**(17), 3947–3950 (2019)
14. Kahveci, H., Okumus, H.I., Ekici, M.: Improved brushless DC motor speed controller with digital signal processor. Electron. Lett. **50**(12), 864–866 (2014)
15. Nag, T., Santra, S.B., Chatterjee, A., Chatterjee, D.: Fuzzy logic-based loss minimisation scheme for brushless DC motor drive system. IET Power Electron. **9**(8), 6 29, 1581–1589 (2016)