International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869 (O) 2454-4698 (P) Volume-8, Issue-11, November 2018

Improvement of Transient Response of a DC Motor Controller Based on Non-Linear Optimization Techniques

Shameem Hasan

***Abstract*— In this study, various precise and appropriate control systems that use a DC motor, have been simulated for improved transient response. Three controllers: lead-lag compensator, conventional Proportional-Integral-Derivative (PID) and Fuzzy logic controller were designed and simulated in order to analyse the performance. Among them, Fuzzy logic algorithm tuning for PID controller exhibits better transient response for DC motor actuators.**

***Index Terms*— DC motor, Fuzzy logic, Lead compensator, Lead Lag compensator, Proportional-Integral-Derivative controller, Transient response**

I. INTRODUCTION

Owing to their high reliabilities, flexibilities, and low costs, DC motors are widely used in industrial applications, robot manipulators and home appliances. There are several types of applications where the load on the DC motor varies over a speed range. These applications demand speed control accuracy and good dynamic responses [1,13]. So, it is important to introduce a controller to control the speed and transient behavior of a DC motor in the desired manner.

Today, more than 95% of control design applications utilize Proportional-Integral-Derivative(PID) [2,14]. The PID controllers are commonly used for motor control applications because of their simple structures and comprehensible control algorithms [3,4]. Two main problems encountered in motor control are the time-varying nature of motor parameters under operating conditions and the existence of noise in a system loop. Analysis and control of complex, nonlinear and time-varying systems is a challenging task using conventional methods because of uncertainties. The fuzzy set theory which led to a new control method called Fuzzy Control is able to cope with system uncertainties [5,6]. One of the most important advantages of fuzzy control is that it can be successfully applied to control nonlinear complex systems. Moreover, PID controller requires a mathematical model of the system while Fuzzy logic controller (FLC) provides an alternative to PID controller, especially when data are not available or partly available for the system [6,7].

In this paper, a conventional PID controller, a lead-lag compensator filter and a Fuzzy logic controller for DC motor actuators have been designed. The simulation was performed to show the response for each proposed design. The research tool for this work was MATLAB and Simulink where simulations were done and appropriate behaviors regarding each controller were observed.

A linear differential equation describing the properties of a DC motor to model the relation between input (V) and output ($\dot{\theta}$) was first developed. From that, a transfer function was derived. This transfer function was then used to analyze the performance of the system and to design proper controllers to meet the design criteria. For the compensator design, the locations of the desired poles were found out from the proposed values of settling time, rise time and percentage overshoot [8,9]. Using root locus, it was found that a lead compensator is required to place poles in the desired locations. A lag compensator was also designed and added to meet the steady-state requirement of the problem. Further, a PID controller was designed and tuned based on the conventional methods [10,14]. To achieve smoother control, a fuzzy logic controller with two inputs and one output including several rules was also designed [11]. All the four controllers were implemented in the simulation. In fine, the controllers were compared against each other based on their performance and control.

II. DYNAMICS OF A DC MOTOR

The most common device used as an actuator in mechanical control is the DC motor. The physical parameters of the motors are:

TABLE I
MOTOR DYNAMICS

Parameters	**Selected Values**
Moment of inertia of the rotor, J	42.6×10^{-6} Kgm^2
Viscous friction coefficient, b	47.8×10^{-6} Nms
Torque constant, k_t	14.5×10^{-3} Nm/A
Back emf, k_e	14.5×10^{-3} Vs/rad
Terminal resistance, R	4.57 Ω
Electric inductance, L	171×10^{-3} H

The motor speed for a given voltage is given by the law of physics described by the open-loop transfer function (1) in Laplace domain with voltage V(s) as input and shaft speed $\omega=\dot{\theta}(s)$ as output. The relationship between the reference speed $\dot{\theta}_{ref}$ and the output speed $\dot{\theta}(t)$ with a constant gain of K is given by the closed loop transfer function (2). The Routh-Hurwitz MATLAB program was used to check the stability of the system. The state space representation of the plant dynamic as given in (3) was used to confirm that the system is stable, controllable and observable.

$$\frac{\dot{\theta}(s)}{V(s)} = \frac{\frac{K_t}{JL}}{s^2 + \frac{(JR+bL)}{JL}s + \frac{bR+k_ek_t}{JL}} \quad (1)$$

$$\frac{\dot{\theta}_{out}}{\dot{\theta}_{ref}} = \frac{\frac{K.K_t}{JL}}{s^2 + \frac{(JR+bL)}{JL}s + \frac{K.K_t+bR+k_ek_t}{JL}} \quad (2)$$

$$\begin{bmatrix} \dot{i} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} -R/L & -k_e/L \\ k_t/J & -b/J \end{bmatrix} \begin{bmatrix} i \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V(t) \quad \text{and}$$

$$\dot{\theta} = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i \\ \dot{\theta} \end{bmatrix} \quad (3)$$

III. LEAD-LAG COMPENSATOR DESIGN

It is observed from the root locus of the open loop transfer function (Fig. 1) that the system has two real open loop poles at P_1 = -25.2 and P_2 = -2.1 which repel each other at -14.5, one going to the positive infinity and other going to the negative infinity. The desired damping ratio (ξ = 0.69) and desired natural frequency (ω_n = 57.962 rad/s) were calculated through the available equations for settling time and percentage overshoot and were then used in determining the desired characteristic equation as described in (6). Since the desired poles $S_{1,2}$ = - 40.1 ± 41.9476i do not satisfy the angle condition for the actual characteristic equation as shown in (7), the root locus will not go through the desired poles.

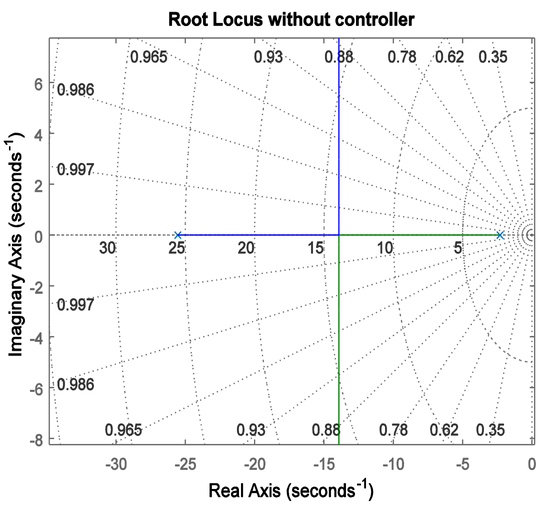

Fig. 1 *Root locus of the DC motor system without any controller*

Hence a lead compensator filter was required to shift the root locus to the left half plane to meet the desired poles location. The closed loop poles were placed at the desired location by multiplying the lead compensator transfer function

$$G_1(s) = \frac{K_1(s+a_1)}{(s+b_1)}, (|b_1| > |a_1|) \quad (4)$$

to the open loop transfer function of the system and then performing coefficient matching which yields a system of three equations with four unknowns (a_1, b_1, c_1, K_1), where c_1 is the added pole to the desired characteristic equation. The one degree of design flexibility was satisfied by assuming a_1 = 16, which results in K_1=1.2754, b_1 = 65.3889, c_1= 20.41. The performance of the designed lead compensator was evaluated for a step input through final value theorem. The limit showed convergence to 0.7% which is larger than the desired SSE of 0.1%, hence a lag compensator with transfer function

$$G_2(s) = \frac{K_2(s+a_2)}{(s+b_2)}, (|b_2| < |a_2|) \quad (5)$$

was added by assuming a_2 = 5 resulting b_2=0.0578. The final transfer function of the complete lead-lag compensator filter is

$$G_{lead-lag}(s) = G_1(s)G_2(s)$$

$$\Delta_D = s^2 + 2\xi\omega_n s + \omega_n^2$$

$$= s^2 + 79.999s + 3359.59 \quad (6)$$

$$\Delta_D = (s + 40.1 + 41.9476i)(s + 40.1 - 41.9476i) \quad (7)$$

$$G_{lead-lag}(s) = \frac{1.275s^2 + 26.78s + 102}{s^2 + 65.45s + 3.778} \quad (8)$$

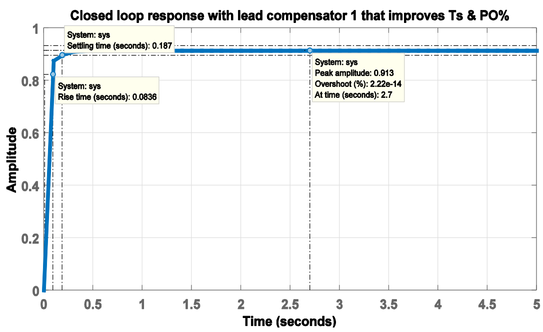

Fig. 2 *Closed loop response of lead compensator*

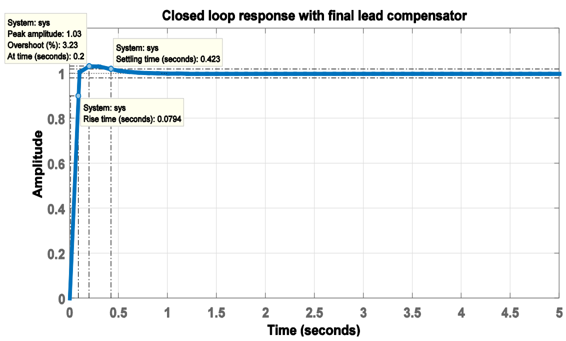

Fig. 3 *Closed loop response of final lead-lag compensator*

IV. PID Controller Design

The general transfer function for a PID controller in Laplace domain can be written as shown in (9) where K_P *is* the proportional gain, K_I is the integral gain and K_D is the derivative gain [12]**.** Considering the effect of each term in the PID controller the PID gains were selected through a trial and error approach and were then tuned by simulation with final values of: K_P= 0.67, K_I = 0.55 and K_D= 0.01

The open loop and closed loop transfer function of the system with PID controller is given by (10) and (11) respectively:

$$PID(s) = K_p + \frac{K_I}{s} + K_D s \qquad (9)$$

$$G_{open\_loop\_PID}(s) = \frac{19.91s^2 + 1334s + 1095}{s^3 + 27.85s^2 + 58.85s} \qquad (10)$$

$$G_{closed\_loop\_PID}(s) = \frac{19.91s^2 + 1334s + 1095}{s^3 + 47.75s^2 + 1392s + 1095} \qquad (11)$$

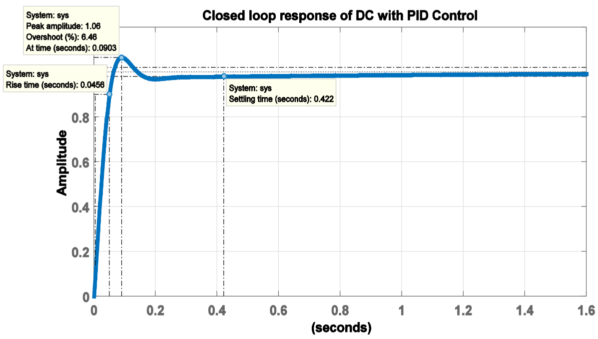

Fig. 4 *Closed loop response of PID controller*

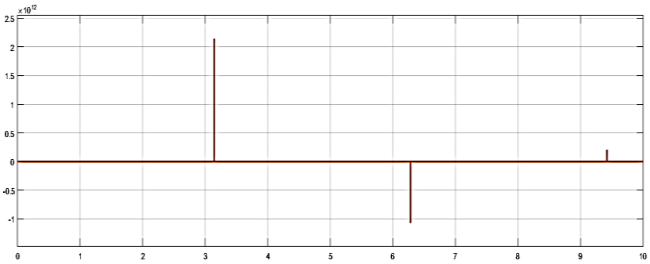

Fig. 5 *Plot of control signal for the PID controller for step input*

V. Fuzzy Logic Controller Design

Fuzzy Inference System (FIS) is the process of formulating the mapping from a given input to an output using Fuzzy logic. Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. There are two types of Fuzzy inference systems that can be implemented.

- Mamdani-type and
- Sugeno-type.

These two types of inference systems vary somewhat in the way outputs are determined [10,11]. Mamdani-type inference requires finding the centroid of a two-dimensional shape by integrating across a continuously varying function.

Principal Elements to a Fuzzy logic controller are

- Fuzzification
- Rule base and Inference engine
- Defuzzification

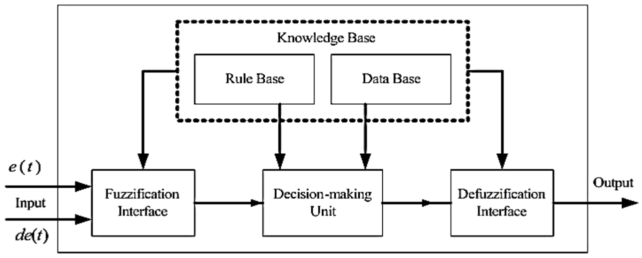

Fig. 6 *Fuzzy Logic Controller block diagram*

TABLE II FUZZY LOGIC CONTROLLER RULE TABLE

De/e	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
NVB	PVB	PVB	PVB	PB	PM	PM	PS	Z	Z
NB	PVB	PVB	PB	PM	PS	PS	PS	Z	Z
NM	PVB	PB	PM	PS	PS	Z	Z	Z	NS
NS	PB	PM	PM	PS	PS	Z	Z	NS	NS
Z	PM	PM	PS	Z	Z	Z	NS	NS	NM
PS	PM	PS	PS	Z	NS	NS	NM	NM	NB
PM	PS	PS	Z	NS	NS	NM	NB	NB	NB
PB	PS	Z	Z	NS	NM	NM	NB	NVB	NVB
PVB	Z	Z	NS	NM	NM	NB	NB	NVB	NVB

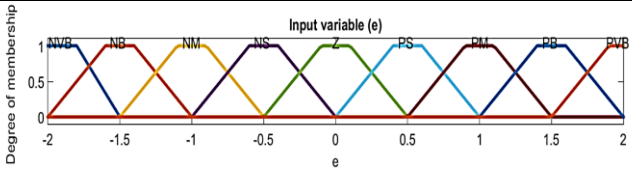

Fig. 7 *Fuzzy logic first input variable, error*

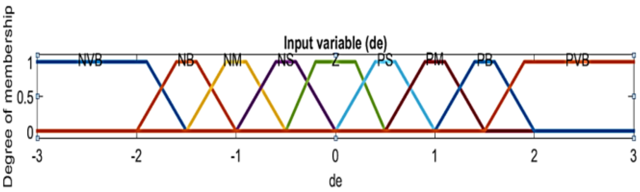

Fig. 8 *Fuzzy logic second input variable, change of error*

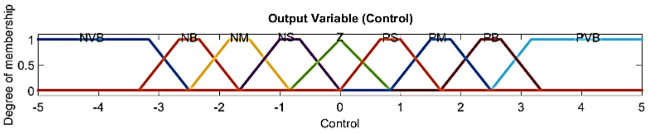

Fig. 9 *Fuzzy logic output variable, control*

A typical structure of a fuzzy logic controller is shown in Fig. 6. Using a pre-processor, the inputs that were in the form of crisp values generated from feedback error (e) and change of error (de) were conditioned in terms of multiplying by constant gains before entering into the main control block. The fuzzification block converts input data to degrees of membership functions and matches data with conditions of rules. From the rule based commands, the Mamdani type inference engine determined the capability of degree of employed rules and returned a Fuzzy set for defuzzification block where the Fuzzy output data were taken and crisp values were returned. The outputs of the Fuzzy sets were converted to crisp values through centroid defuzzification method. The post processing block then converted these crisp values into standard control signals.

The rule table (TABLE II) is designed and used with a triangular membership function input-output in the fuzzy logic controller and was implemented in the simulation. These rules make control efforts based on several if-then statements about (e) and (de), i.e., if the error is equal Negative Big (NB) and change of error is equal to negative medium (NM), then the change in control (c) is positive big (PB). The numbers of these if-then statements were determined based on experiment and tuning of the system. Plots of fuzzy logic membership function for the two input variables (e) and (de) and the output (c) are shown in Fig. 7 to Fig. 9.

A. Advantages of Fuzzy Logic Controller

- Fuzzy Logic Controller (FLC) is an attractive choice when precise mathematical formulations are not possible.
- Allows imprecise or contradictory inputs. For example, it uses linguistic variables.
- Rule base or fuzzy sets can be easily modified.
- Relates input to output in linguistic terms, so easily understood.
- Cheaper because they are easier to design and increased robustness than other non-linear controller.
- Can achieve less overshoot and oscillation and doesn't require fast processors.
- It requires less data storage in the form of membership functions and rules than conventional look up table for non-linear controllers.

VI. SIMULATIONS AND RESULTS

. The performances of the three designed controllers were simulated in Simulink with block diagram as shown in Fig. 10. A signal generator produces input references of step and sinusoidal function for each control blocks. The lead-lag and PID controller transfer function were implemented in the simulation followed by the DC motor dynamic model. The Fuzzy logic controller block process the inputs and output of Fuzzy inference engine and generate control signal.

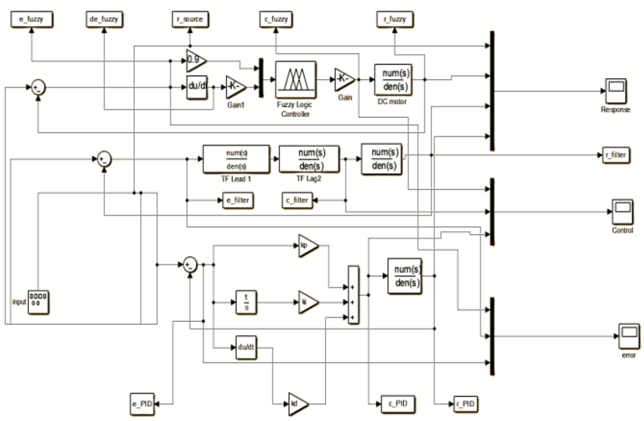

Fig. 10 *Simulation diagram of PID, lead lag compensator and Fuzzy controllers for DC motor speed control*

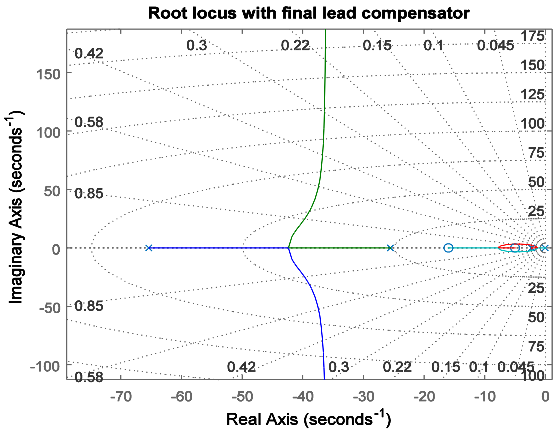

Fig. 11 *Root locus of the DC motor system with lead compensator*

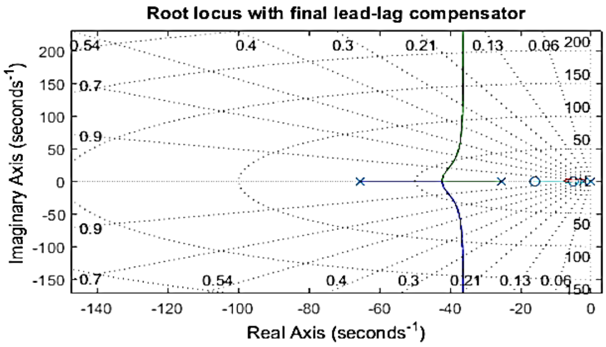

Fig. 12 *Root locus of the DC motor system with final lead-lag compensator*

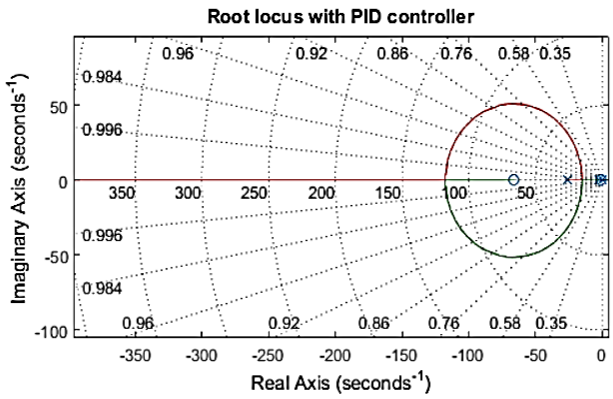

Fig. 13 *Root locus of the DC motor system with PID controller*

The root locus plot of the system with PID controller is also shown in Fig. 13 which proves that the design criteria with the desired poles locations have been satisfied.

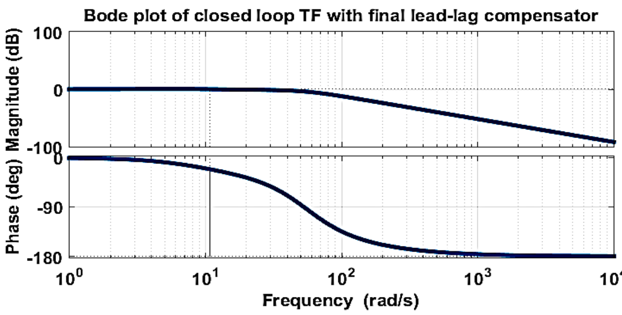

Fig. 14 *Bode plot of closed loop TF with final lead-lag compensator, Gm = inf dB, Pm =158 degree (at 10.8 rad/sec)*

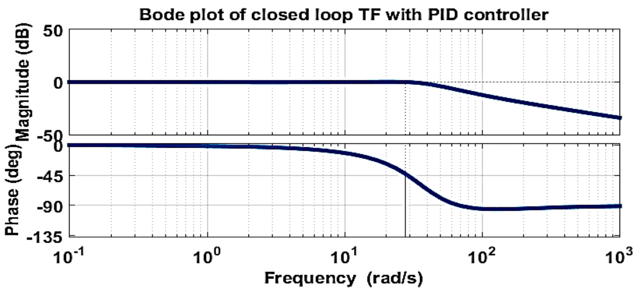

Fig. 15 *Bode plot of closed loop TF with PID controller, Gm = inf dB, Pm = 153 degree (at 23.6 rad/sec)*

According to the infinite gain and phase margin observed from the bode plots of the closed loop system in the presence of these controllers as shown in Fig. 14 and Fig. 15, the system will not become unstable with increasing gain.

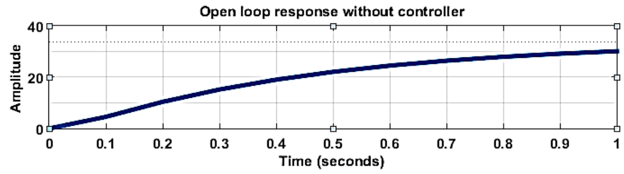

Fig. 16 *Open loop step response without controller*

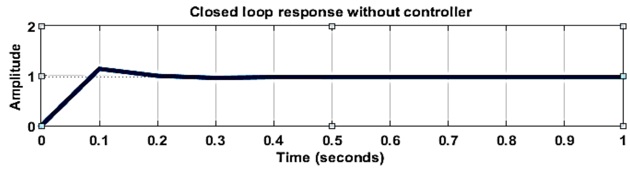

Fig. 17 *Closed loop step response of DC motor without controller*

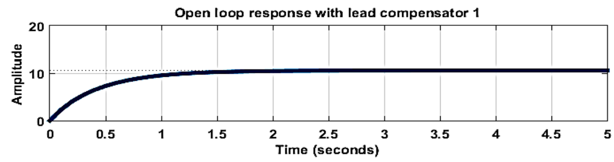

Fig. 18 *Open loop step response of DC motor with first lead compensator*

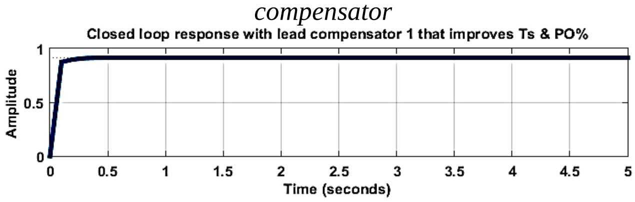

Fig. 19 *Closed loop step response of DC motor with lead compensator*

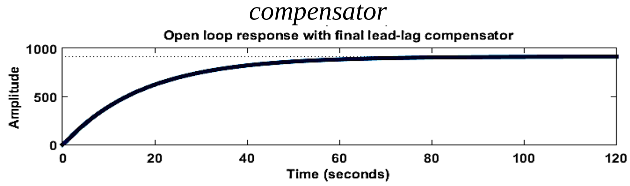

Fig. 20 *Open loop step response of DC motor with final lead-lag compensator*

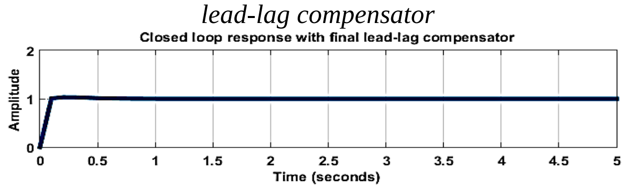

Fig. 21 *Closed loop response of DC motor with final lead-lag compensator*

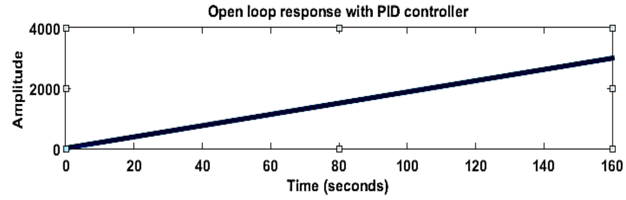

Fig. 22 *Open loop step response of DC motor with PID controller*

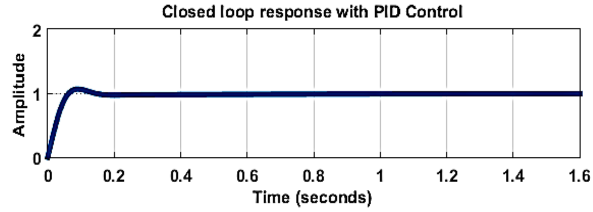

Fig. 23 *Closed loop step response of DC motor with PID controller*

The behavior of the open loop and closed loop response and the performance of the controllers were evaluated by input step functions and the plots are shown from Fig. 16 to Fig. 23.

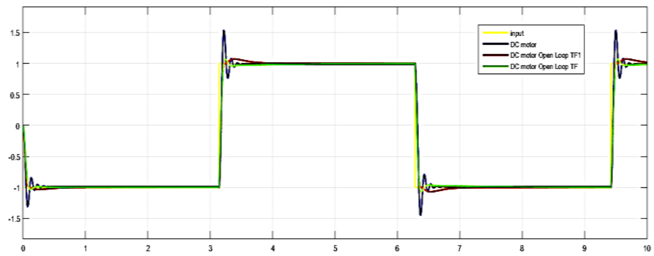

Fig. 24 *For step response the performance comparison of the designed PID, lead-lag compensator and Fuzzy controllers*

Plots of system responses and control signals are provided for the three controllers (lead lag compensator, PID and Fuzzy logic) design in Fig. 24.

Although the open loop system shows stability in nature, but the initial closed loop step response indicates a demand for a controller to improve rise time, settling time, overshoot and steady state error. All these performances were improved in the final closed loop response with lead-lag compensator, Fuzzy logic algorithm and PID controller with the results summarized in Table IV.

TABLE IV
PERFORMANCE OF CONTROLLERS

Controller	Rise time(s)	Overshoot(%)	Settling time(s)
Lead Compensator	0.083	0	0.187
Final Lead-lag Compensator	0.0794	3.23	0.423
Conventional PID Controller	0.0456	6.46	0.422
Fuzzy Logic Controller	0.04	10.2	0.36

VII. CONCLUSION

In this paper, a PID controller, a lead-lag compensator filter, a lead compensator and a fuzzy logic controller for DC motor actuators have been designed. Simulation was performed to show the controllers' response for each proposed design. The research tool for this work was MATLAB and Simulink. The results showed that for step input, Fuzzy logic controller has better performance over conventional PID, lead compensator and lead-lag compensator design in terms of rise time, settling time and producing desired transient response.

REFERENCES

[1] Shashi Bhushan Kumar, Mohammed Hasmat Ali and Anshu Sinha, "Design and Simulation of Speed Control of DC Motor by Fuzzy Logic Technique with Matlab/Simulink", *International Journal of Scientific and Research Publications*, July 2014, 4, (7), pp. 255-299.

[2] Zhang, J., N. Wang and S. Wang, "A developed method of tuning PID controllers with fuzzy rules for integrating process", *Proceeding of the American Control Conference*., 2004, pp. 1109-1114.

[3] O. J. Oguntoyinbo, "PID control of brushless DC motor and robot trajectory planning and simulation with matlab/Simulink", *Degree Thesis, University of Applied Sciences*, 2009.

[4] K. Ogata, "Modern Control Engineering, 4^{th} Edition", 2015, Dorling Kindersley Pvt. Ltd., India.

[5] Zadeh L.A., "Fuzzy sets. Inform. Cont.", 1965, 8, (3), pp. 338-353.

[6] Aiping Shi, Maoli Yan, Jiangyong Li, 'The research of fuzzy PID control application in DC motor of automatic doors", *International Conference on Electrical and Control Engineering(ICECE*), 2011, pp. 1354-1358.

[7] Ch. Chengaiah and K. Venkateswarlu, "Comparative study on dc motor speed control using various controllers", *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, January 2014, 3, (1).

[8] Niu, J.J., Wang, Y.J. and Tang, J, "Research on Parameter Optimization of PID Controller Based on Genetic Algorithm", *Computer Simulation*, 2010, 27, pp. 180-182.

[9] P. Mhaskar, H. Nael El-Farra and D. Christofidest, "A Method for PID Controller Tuning Using Nonlinear Control Techniques", in Proc. of the *2004 American Control Conf.* Boston, Massachusetts, June 30 - July 2, 2004.

[10] Venugopal P, "Design of tuning methods of PID controller using fuzzy logic", *International Journal of Emerging trends in Engineering and Development*, September 2013, 3, (5).

[11] Rayapakse, A., Furuta, K., And Kondo, S., "Evolutionary learning of fuzzy logic controllers and their adaptation through perpetual evolution", *IEEE Trans. Fuzzy Syst.*, 2002, 10, (3).

[12] Ang, K.H., G. Chong and Y. Li, "PID control system analysis: Design and technology", *IEEE T. Contr. Syst. T.*, 2004, 13, (4), pp: 559-576.

[13] Reynoso-Meza, G., Blasco, X., Sanchis, J., et al., "Controller tuning using evolutionary multi-objective optimization: current trends and applications", *Control Eng. Pract.*, 2014, 28, (1), pp. 58–63.

[14] Padula, F., Visioli, A., "Optimal tuning rules for proportional-integer derivative and fractional-order proportional-integer-derivative controllers for integral and unstable processes", *IET Control Theory Appl*., 2012, 6, (6), pp. 776