Enhancement of Cruise Control System by Improving Transient Response of Motor Controller using Non-Linear Optimization Techniques

Golam Sarowar[1] and *Shameem Hasan[2],

Department of Electrical and Electronic Engineering, Islamic University of Technology, Gazipur-1704, Bangladesh.

Summary

In this study, for the enhancement of cruise control, various DC motor controller have been simulated for improved transient response. Four controllers: lead-lag compensator, Ziegler Nichols sustained oscillation method, conventional Proportional-Integral-Derivative (PID) and Fuzzy logic controller were designed and simulated in order to analyze the performance. Among them, Fuzzy logic algorithm for tuning PID controller exhibits better transient response for DC motor actuator installed in cruise control system.

Key words:

Cruise control, Fuzzy logic controller, Lead-Lag Compensator, Proportional-Integral-Derivative (PID) controller, Transient response, Ziegler-Nichols method.

1. Introduction

Cruise control system has become a familiar feature of the modern vehicles in long-distance travels [1]. Automobile cruise control system reduces the physical and the mental stress of drivers who are driving in highway by providing them solace from regularly stepping on the pedal for adjusting gas. It also adds to the safety [2] of the passengers by reducing the risks of accidents. DC motor is an integral part of cruise control. One of the important aspect of Cruise control is the improvement of transient performance of the automobile. The Proportional-Integral-Derivative (PID) controller takes the proportional (Kp), integral (Ki) and derivative (Kd) parameters and adjusts them in a manner which stabilizes the plant according to some preset values. It also works fine under closed loop control scheme for different sets of plants. So it provides a diverse field of controllers for the researchers to work upon. So, it is important to introduce a controller to improve the transient behaviour of a DC motor installed in a cruise control in desired manner.

Today, more than 90% of control design applications utilize Proportional-Integral-Derivative(PID) [2,15]. The PID controllers are commonly used for cruise control applications because of their simple structures and comprehensible control algorithms [3,4]. Two main problems encountered in cruise control are the time-varying nature of motor parameters under operating conditions and existence of noise in system loop. Analysis and control of complex, nonlinear and time-varying systems is a challenging task using conventional methods because of uncertainties. Taking the challenge under consideration, Ziegler-Nichols sustainable optimization method is applied in cruise control [5,6]. Fuzzy set theory which led to a new control method called Fuzzy Control, is able to cope with system uncertainties [7,8]. 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 [9-14]

The design criteria of the controller for improved transient response in order to maintain better cruise control can be mentioned as:

i. Minimize the rise time: Rise time to be less than

ii. 0.1 sec. Time required for system response to rise from 10% to 90% (over damped); 5% to 95%; 0% to 100% (Under damped) of the final steady state value of the desired response.

iii. Minimize the maximum overshoot: Overshoot to

iv. be less than 10%. Maximum overshoot is the maximum peak value of the response curve measured from the desired response of the system.

v. Minimize the settling time: Settling time to be less

vi. than 1 sec. Time required for response to reach and stay within 2% of final value.

In this paper, Ziegler-Nichols sustainable oscillation method for closed loop systems, a PID controller, a lead-lag compensator filter, a Fuzzy logic controller for cruise control have been designed. 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 behaviour regarding each controller was observed.

A linear differential equation describing the properties of a DC motor installed in cruise control 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

Manuscript received December 5, 2018
Manuscript revised December 20, 2018

the compensator design, the locations of the desired poles were found out from the proposed values of settling time, rise time and percentage overshoot [17]. 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. Ziegler-Nichols tuning method for sustained oscillation was used to find out the transient behaviour of cruise control system. Further, a PID controller was designed and tuned based on the conventional methods [15,16]. To achieve smoother control, a Fuzzy logic controller with two inputs and one output including several rules was also designed [12-14,18]. To obtain better transient response for cruise control, all the five controllers were implemented in the simulation. In fine, the controllers were compared against each other based on their performance and control.

2. 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 1: DC Motor dynamics

Parameters	Selected Values
Moment of inertia of the rotor, J	42.6 x 10-6 Kgm2
Viscous friction coefficient, b	47.8 x 10-6 Nms
Torque constant, kt	14.5 x 10-3 Nm/A
Back emf, ke	14.5 x 10-3 Vs/rad
Terminal resistance, R	4.57 Ω
Electric inductance, L	171 x 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.

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

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

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

and

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

3. 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 P1 = -25.2 and P2 = -2.1 which repel each other at -14.5, one going to the positive infinity and other going to the negative infinity.

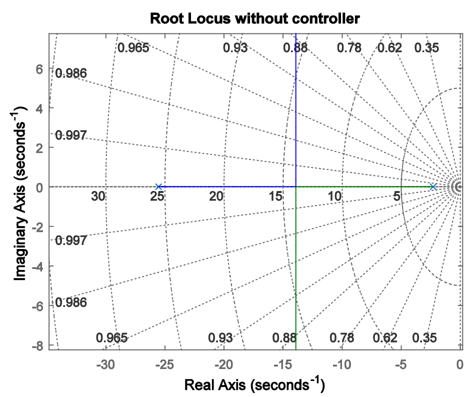

Fig. 1 Root locus of the DC motor system without any controller

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 (7). Since the desired poles S1,2 = - 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. 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 (a1, b1, c1, K1), where c1 is the added pole to the desired characteristic equation. The one degree of design flexibility was satisfied by assuming a1 = 16, which results in K1 = 1.2754, b1 = 65.3889, c1 = 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 Steady State Error (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 a2 = 5 resulting b2=0.0578. The final transfer function of the complete lead-lag compensator filter is

$$G_{lead-lag}(s) = G_1(s)G_2(s) \quad (6)$$

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

$$= s^2 + 79.999s + 3359.59$$

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

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

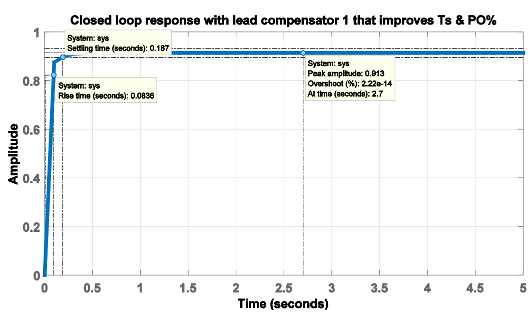

Fig. 2 Closed loop response of lead compensator

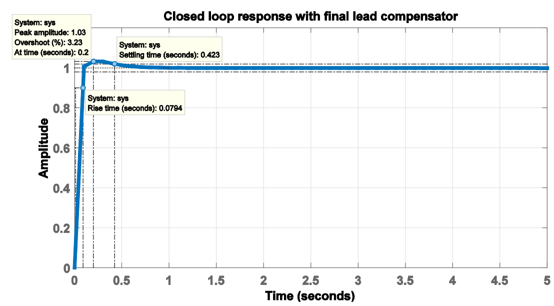

Fig. 3 Closed loop response of the final lead-lag compensator

4. Ziegler-Nichols Tuning Method for Sustained Oscillation

In 1942, Ziegler-Nichols presented a tuning formula, based on time response. The tuning of a PID controller consists of selecting gains KP, KI and KD so that performance specifications are satisfied. By employing Ziegler–Nichols's sustained oscillation method for PID tuning, [4,5] those gains are obtained through experiments with the process under control.

For the system under study, Ziegler-Nichols sustained oscillation method based on critical gain, Ker and ultimate or critical period, Per was used. In this method, the integral time Ti will be set to infinity and the derivative time Td to zero initially. This is used to get the initial PID setting of the system. According to Ziegler-Nichols method for PID controller, KP = 0.6 Ker, KI = 0.5 Per and KD = 0.125 Per.

$$G_C(s) = K_P \times [1 + \frac{1}{(T_i \times s)} + (T_d \times s)] \quad (9)$$

Here, Critical gain, Kcr = 0.82331 and ultimate period, Pcr = 0.81905 sec. By applying this tuning method, we found the parameters for this cruise control as Kp = 0.4858, Ti = 0.4095 sec and Td = 0.0983 sec for controller formulation as given in (9). The response of the PID controller tuning with Ziegler Nichols sustained oscillation method is shown in Fig. 4.

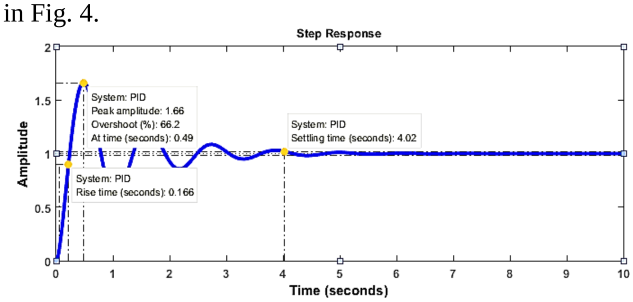

Fig. 4 Response of the system Using PID controller tuning with Ziegler Nichols method.

5. PID Controller Design

The general transfer function for a PID controller in Laplace domain can be written as shown in (10) where Kp is the proportional gain, KI is the integral gain and KD is the derivative gain. 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: KP= 0.67, KI = 0.55 and KD= 0.01

The open loop and closed loop transfer function of the system with PID controller is given by (11) and (12) respectively:

$$PID(s) = K_p + \frac{K_I}{s} + K_D s \quad (10)$$

$$G_{open\_loop\_PID}(s) = \frac{19.91s^2 + 1334s + 1095}{s^3 + 27.85s^2 + 58.85s} \quad (11)$$

$$G_{closed\_loop\_PID}(s) = \frac{19.91s^2 + 1334s + 1095}{s^3 + 47.75s^2 + 1392s + 1095} \quad (12)$$

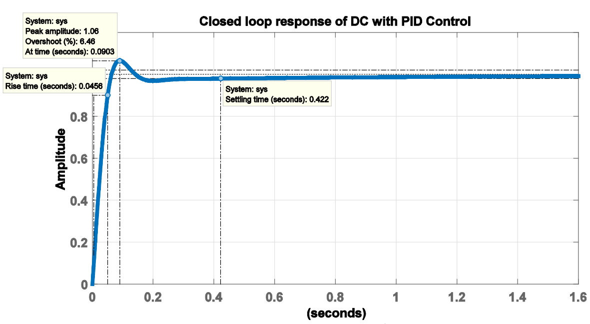

Fig. 5 Closed loop response of PID controller

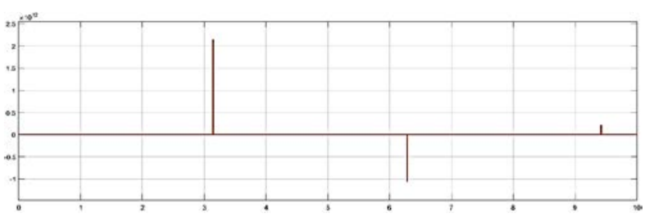

Fig. 6 Plot of control signal for the PID controller for step input

6. 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 [10-12]. 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

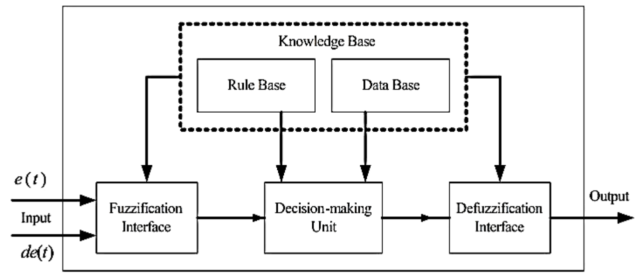

Fig. 7 Fuzzy Logic Controller block diagram

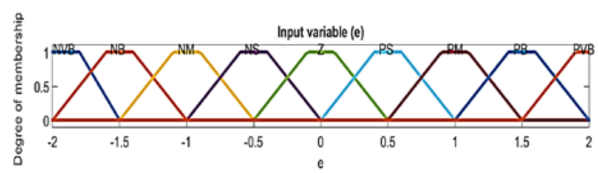

Fig. 8 Fuzzy Logic first input variable, error

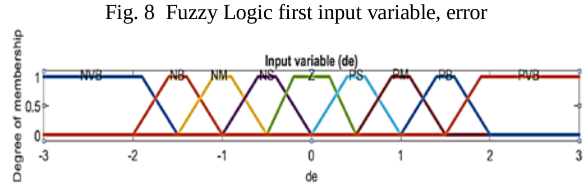

Fig. 9 Fuzzy Logic second input variable, change of error

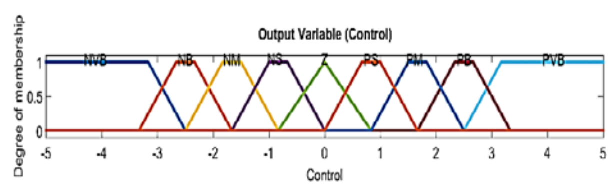

Fig. 10 Fuzzy Logic output variable, control

A typical structure of a Fuzzy Logic Controller is shown in Fig. 7. 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 2) 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. 8 to Fig. 10.

6.1 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 does not 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.

Table 2: 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

7. Simulations and Results

The performances of the three designed controllers were simulated in Simulink with block diagram as shown in Fig. 11. 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 processes the inputs and outputs of Fuzzy inference engine and generate control signal.

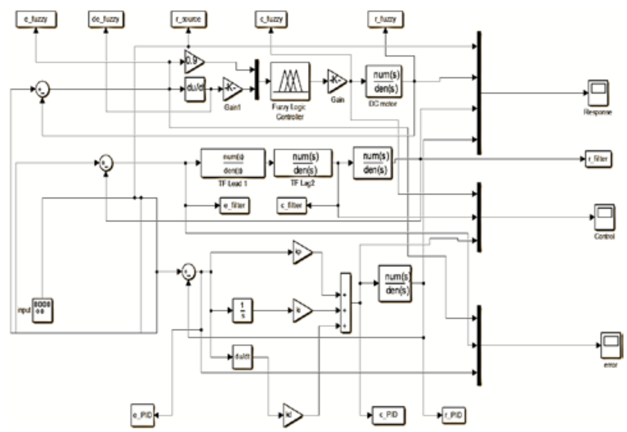

Fig. 11 Simulation diagram of PID, lead lag compensator and Fuzzy controllers for DC motor speed control

The Ziegler-Nichols algorithm-based PID controller tuning Simulink block diagram is shown in Fig. 12.

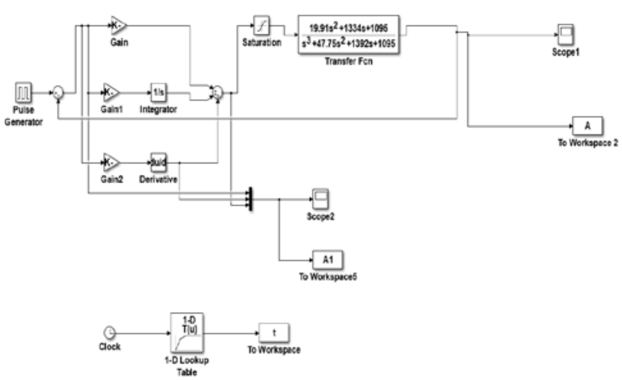

Fig. 12 Simulation diagram of Ziegler-Nichols sustained oscillation method.

The root locus plots of the system with lead compensator and final lead-lag compensator are shown in Fig. 13 and Fig. 14, respectively. From these two figures, position changing of poles are seen which is a vital aspect of stability analysis.

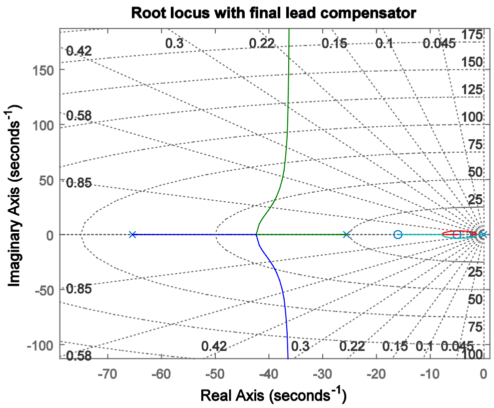

Fig. 13 Root locus of the DC motor system with lead compensator

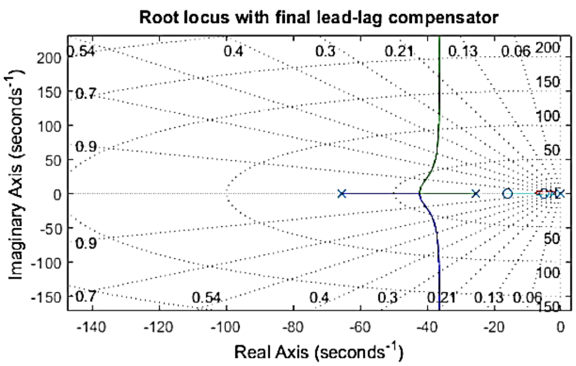

Fig. 14 Root locus of the DC motor system with final lead-lag compensator

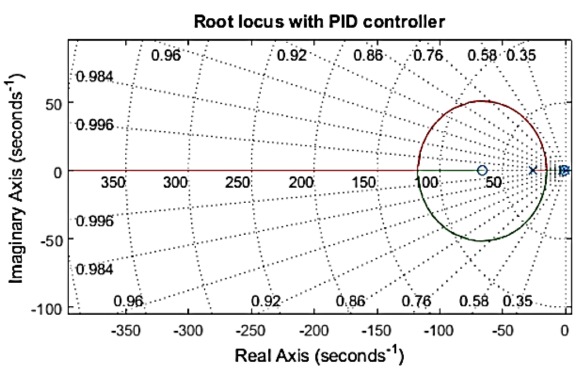

Fig. 15 Root locus of the DC motor system with PID controller

The root locus plot of the system with PID controller is also shown in Fig. 15 which proves that the design criteria with the desired pole locations have been satisfied.

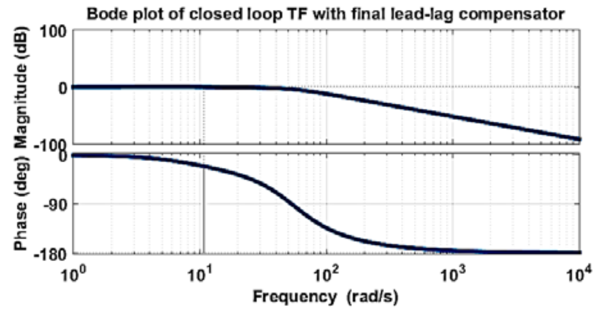

Fig. 16 Bode plot of closed loop TF with final lead-lag compensator, Gm = inf dB, Pm =158 degree (at 10.8 rad/sec)

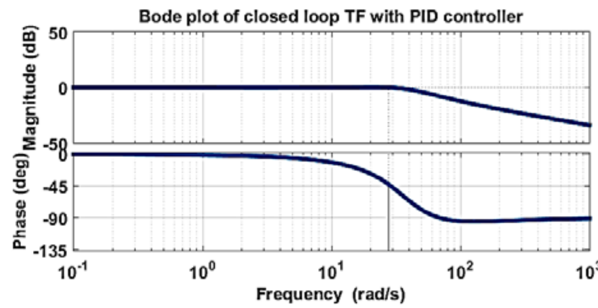

Fig. 17 Bode plot of closed loop TF with PID controller, Gm = inf dB, Pm = 153 degree (at 23.6 rad/sec)

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. 16 and Fig. 17, the system will not become unstable with increasing gain.

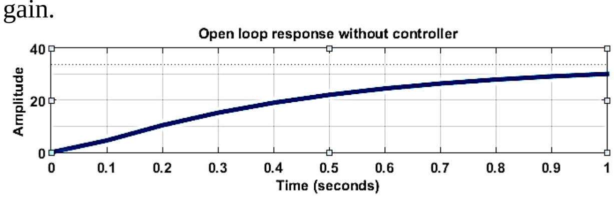

Fig. 18 Open loop step response without controller

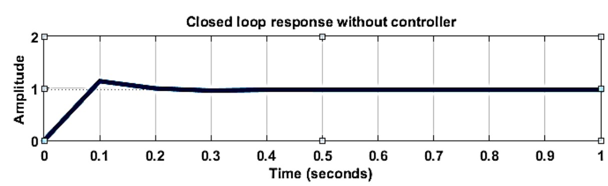

Fig. 19 Closed loop step response of DC motor without controller

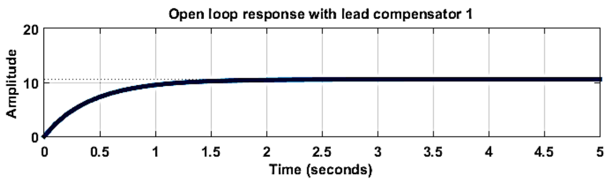

Fig. 20 Open loop step response of DC motor with first lead compensator

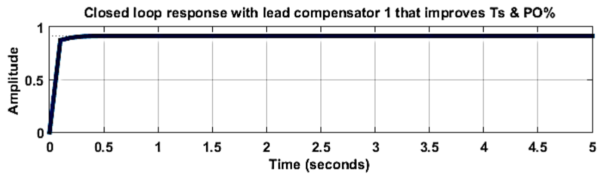

Fig. 21 Closed loop step response of DC motor with lead compensator

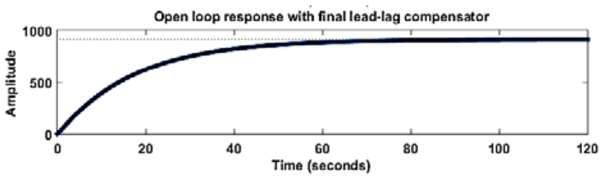

Fig. 22 Open loop step response of DC motor with final lead-lag compensator

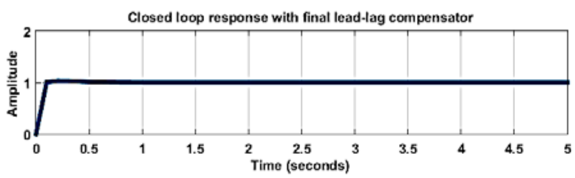

Fig. 23 Closed loop response of DC motor with final lead-lag compensator

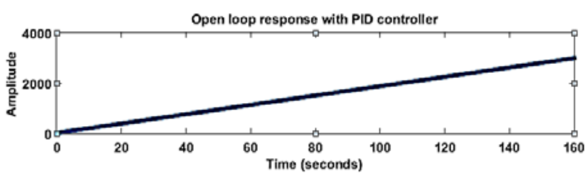

Fig. 24 Open loop step response of DC motor with PID controller

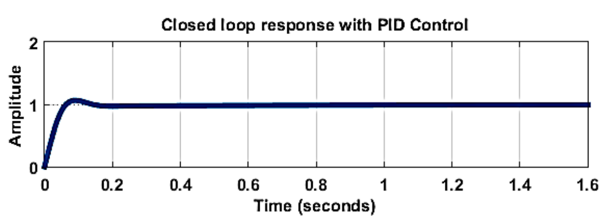

Fig. 25 Closed loop step response of DC motor with PID controller

The behaviour 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. 18 to Fig. 25.

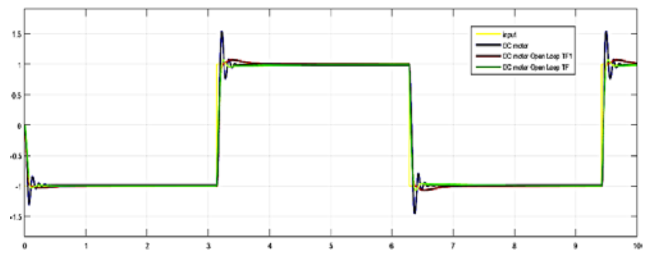

Fig. 26 For step response the performance comparison of the designed PID, lead-lag compensator and Fuzzy controllers

Although the open loop system shows stability in nature, yet 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, Ziegler-Nichols tuning method, Fuzzy logic algorithm and conventional PID controller with the results summarized in Table 3.

Table 3: Performance comparison 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
Ziegler-Nichols sustained oscillation method	0.166	66.2	4.02
Conventional PID Controller	0.0456	6.46	0.423
Fuzzy Logic controller	0.035	9.2	0.36

8. Conclusion

In this paper, Ziegler-Nichols tuning method for PID controller, a conventional PID controller, a lead-lag compensator filter, and a fuzzy logic controller for cruise control have been designed. Simulation was performed to show the controllers' response for each proposed design. Fuzzy logic controller produced 30.285% improved rise time and 17.5% better settling time than conventional PID controller which showed better result among other controller optimization techniques discussed earlier in this paper. The results showed that for step input, Fuzzy logic algorithm has better performance over Ziegler-Nichols sustained oscillation method, conventional PID and lead-lag compensator design in terms of rise time, settling time and producing desired transient response of cruise control system.

References

[1] Vedam, N., Diaz-Rodriguez, I., Bhattacharyya, S.P, "A novel approach to the design of controllers in an automotive cruise-control system", Industrial Electronics Society, IECON - 40th Annual Conference of the IEEE, 2014, pp: 2927- 2932.

[2] Khairuddin Osman, Mohd. Fuaad Rahmat, Mohd. Ashraf Ahmad, ‘‘Modelling and Controller Design for a Cruise Control System”, 5th International Colloquium on Signal Processing & Its Applications (CSPA), 2009.
[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, 4th Edition”, 2015, Dorling Kindersley Pvt. Ltd., India.
[5] Mallesham, G., Mishra, S., and Jha, “A.N. Ziegler-Nichols based controller parameters tuning for load frequency control in a micro grid”, International Conference on Energy, Automation, and Signal (ICEAS), 2011, pp. 1-8.
[6] Zadeh L.A., “Fuzzy sets. Inform. Cont.”, 1965, 8, (3), pp. 338-353.
[7] Abdulameer, A., Sulaiman, M., Aras, M., and Saleem, D., “Tuning Methods of PID Controller for DC Motor Speed Control”, Indonesian Journal of Electrical Engineering and Computer Science, 2016, 3, (2), pp. 343-349.
[8] 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.
[9] 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).
[10] 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., 2004.
[11] 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).
[12] 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.
[13] 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).
[14] 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.
[15] 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.
[16] Thomas, N., Poongodi, P., “Position control of DC motor using genetic algorithm based PID controller”, Proc. of the World Congress on Engineering, 2009, pp. 1–5.
[17] 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.
[18] 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.

Golam Sarowar received the B.Sc. Engineering, M.Sc. Engineering and PhD degrees from the department of Electrical and Electronic Engineering, Islamic University of Technology, Gazipur, Bangladesh. He has authored or co-authored over 25 scientific papers. He is currently working as Associate Professor in the department of Electrical & Electronic Engineering in Islamic University of Technology. His research interest includes Microcontroller based systems, Power Electronics and Control systems.

Shameem Hasan received B.Sc. Engineering degree in Electrical and Electronic Engineering in 2015 from Islamic University of Technology, Gazipur, Bangladesh. He is pursuing M.Sc. degree in Electrical and Electronic Engineering from Islamic University of Technology. Currently, he is working as Lecturer in department of Electrical and Electronic Engineering in Sonargaon University, Dhaka, Bangladesh. His research interest includes controller design with different optimization techniques, power system, machine learning and power electronics.