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RESEARCH ARTICLE

Fuzzy-PID based control scheme for PMDC series motor speed control

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Abstract

Abstract Background/Objectives: PID controllers are widely used in different industrial appliations especially in achieving stable speed control of DC motors. Hower, due to their limitations, most often other methods like Sliding Mode controller, or fuzzy based controller are used. Since the Fuzzy controlers are more adaptive to non-linearity. This study is to analyse a fuzzy-based speed control scheme for tuning/adusting the performance of PID controller for the purpose of speed control of DC motor under the load condition. **Methods/Statistical Analysis:** Because of low precision and slow response in different control schemes, a performance comparison is shown between three different control approaches for the DC motor speed control. MATLAB's Simulink platform is used to realize DC Motor and to implement the PID, Fuzzy and Fuzzy-based PID controllers to run the DC motor on the desired speed. Fuzzy controller is based on very few rule & performance is analyzed considering the load. **Findings:** The performance of three controllers is evaluated in terms of transient domain characteristics like Percentage overshoot, settling and rise times and percentage error under load (2000 rpm). The PID controller has the highest overshoot and hence a faster rise time while FLC has significantly reduced the overshoot, therefore causing rise time to increase. For the Fuzzy-PID controller the percentage overshoot has almost vanished. The rise time also decreased as compared to the FLC. The simulated controller's responses confirm that Fuzzy-based PID controller has better performance comparing to independent PID and FLC controllers. **Novel/Applications:** In this work, the design of an intelligent Fuzzy-PID controller for the speed control of the DC motor with reduced complexity and a faster response using with minimum number of Fuzzy rules producing more optimized performance is presented. The design of a control strategy that has capability to control nonlinear behaviors and to stabilize the performance of linear systems specially to provide optimized performance for speed tracking system which is an important aspect in real time system design.

Keywords: PMDC motor; PID Controller; fuzzy controller; fuzzy-based PID controller; transient response

1 Introduction

PMDC (Permanent Magnet Direct Current) motors have been widely employed since years in a vast range of applications because of their constant torque characteristic [1]. DC motor is particularly used in railway engines, electric cars, elevators, appliances and complex processes, where torque has a vital importance [1,2]. The DC motors are more utilized than AC (Alternating Current) motors due to their lower cost, heat-sustaining capacity, simplest structure, variable speed and full torque at zero rpm, ease of maintenance and many other features [3]. Applications like conveyors and turntables which require adjustable speed and torque extensively use DC motors [4]. Industrial processes where in situations of emergency dynamic braking or in sanding application where reversing action is needed, also employ DC motors [5]. For all types of DC motor applications, require the control of motor speed. These applications may require either low or high speed with high torque. Hence to provide a robust speed control of DC motor is highly challengeable.

Almost 95% process industries are still equipped with proportional-integral-derivative (PID) controllers [6,7]. Therefore, PID (Proportional-Integral-Derivative) control is generally considered the best control scheme for indusial processes. However, nonlinear behavior of load and other disturbances greatly influence the tuning of the loop and hence performance of PID controller which cause the controller to behaves nonlinearly. Proper tuning of PID coefficients helps obtain an optimal performance of the process. There are several other method to deal with such nonlinearitties [8,9]. Fuzzy logic control (FLC) is a nonlinear control scheme which provides a way of computing uncertain values. FLC is derived from the Fuzzy set theory which employs a way of estimated reasoning similar to human-like decisions. FLC has an advantage over conventional PID controller that it can perform nonlinear control actions [9,10]. It consists of linguistics terms and IF-THEN type of rules that define a certain control action. It has a faster response and minimum error value compared to conventional PID controller. Fuzzy controller is most suitable for crucial speed control applications. Since nonlinear FLC outdoes the performance of conventional linear PID controllers due to dealing with uncertainties, the combination of both types of controllers can comprehensively improve the performance of PID controller as FLC will be performing the tuning of PID coefficients [11–17]. Many schemes are developed using fuzzy controllers for the Speed control of DC motors [18–25]. In this work, these three types of controllers i.e. PID, Fuzzy and Fuzzy-PID controllers are separately used to control the speed of DC motor to compare the transient and steady state performance of each controllers. The Fuzzy-controller is based on few rules. The transient performance (i.e. maximum overshoot, rise time, settling time) and the steady-state error are compared with each controller.

1.1 PID controller

The classical PID controller is based on three basic control actions, namely proportional, integral and derivative. Figure 1 depicts the basic classical blocks of PID control, which are actually gains of the controller. Generally, the

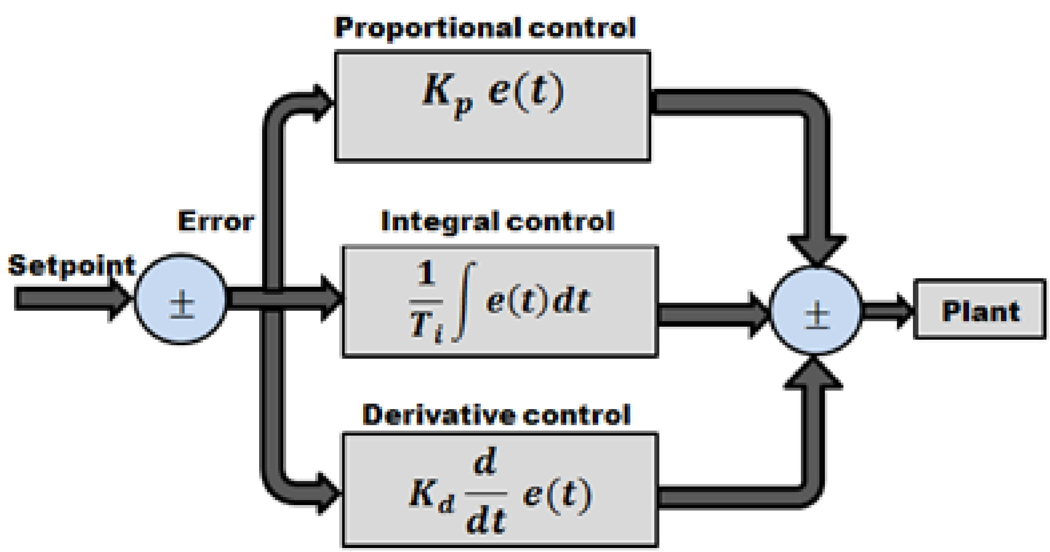


Fig 1. Structure of Classical PID controller.

proportional gain (K_p) improves rising time i.e. makes control response faster, integral gain (K_i) reduces error and derivative gain (K_d) minimizes overshoot occurred by integral gain ($K_i = 1/T_i$). In overall, classical PID helps to improve transient performance of a system. The output of the PID controller is determined by adding these three gains.

$$PID_{out} = K_p\, e(t) + 1/T_i \int e(t)\, dt + K_d \frac{d}{dt} e(t) \quad (1)$$

1.2 Fuzzy controller

To overcome the limitations of PID controller, Lotfi A. Zadeh introduced Fuzzy logic controller (FLC) in 1965 using the Fuzzy set theory. FLC provides a way to represent human knowledge in linguistic terms to get a control variable that can be applied as to act in the process control. FLC is an effective control strategy to cover a broader control range of operating conditions in nonlinear and complex systems in the vicinity of noise and disturbances [13]. Figure 2 portrays the block diagram of Fuzzy logic controller. There are five building blocks of the Fuzzy logic controller which are necessary for constructing Fuzzy inference system (FIS). The Fuzzifier unit converts inputted crisp quantities into Fuzzy values. Rule-base block comprises IF-THEN rules. The database has Fuzzy membership functions contained in Fuzzy rules. Inference Engine is the operational block that processes Fuzzy rules. Lastly defuzzifier block converts Fuzzy values back to crisp quantities.

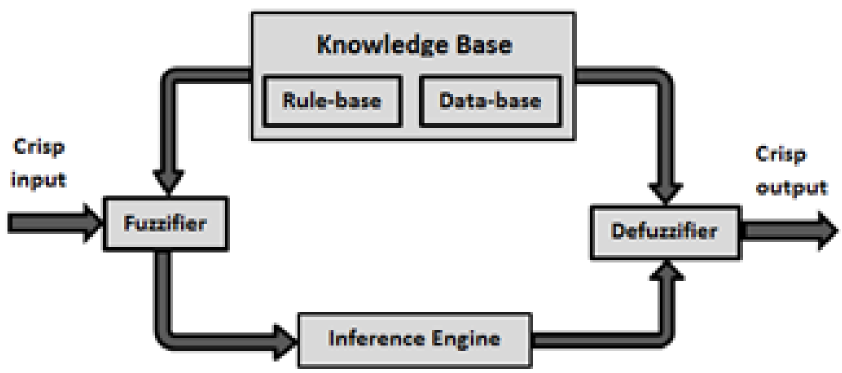


Fig 2. Structure of Fuzzylogic Controller (FLC).

1.3 Fuzzy-PID controller

The architecture of Fuzzy-PID controller (as shown in Figure 3), also known as self-tuning controller, describes that the FLC is working as supervisor in which Fuzzy controller is actually tuning the PID gains (K_p, K_i and K_d).

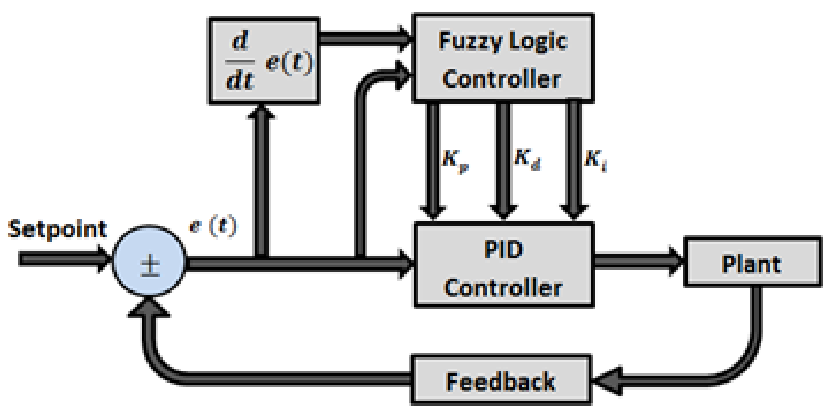


Fig 3. Fuzzy-PID controller structure

The Fuzzy controller required two inputs; i.e. error e(t) and the rate of error d/dt (et). After processing the Fuzzy rules, fuzzy controller generates the suitable values of the PID gains necessary for fine-tuning. This strategy of the online tuning enables the PID controller to effectively react to sudden dynamic changes occuring in the process thereby giving the finest performance of the system.

2 Modeling of PMDC series motor

The DC motor model as shown in Figure 4 is realized by adding up the torques acting on the inertia of the rotor and obtaining velocity by the integration of the acceleration[14].

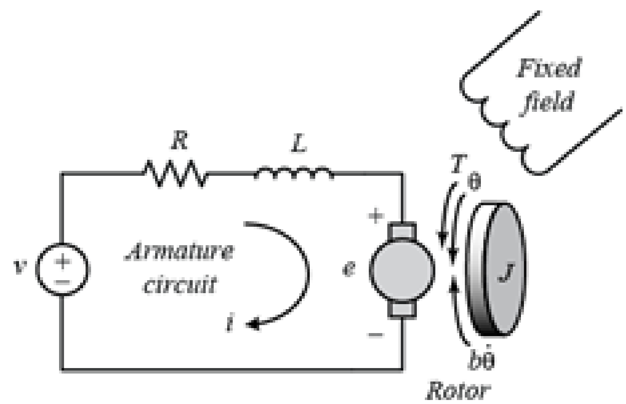


Fig 4. Model of series DC motor

$$\int \frac{d^2\theta}{dt^2}dt = \frac{d\theta}{dt} \tag{2}$$

$$\int \frac{di}{dt}dt = i \tag{3}$$

Supposing the magnetic field constant makes the motor torque is proportional only to the armature current by a factor K_t as given in (3).

$$T = K_t i \tag{4}$$

The back EMF (Electromotive Force), **e** is given in equation which is proportional to the motor shaft's velocity by a factor K_e .

$$e = K_e \frac{d\theta}{dt} \tag{5}$$

Applying Kirchhoff's Voltage Law to the electrical part of the DC motor, we get:

$$V = Ri + L\frac{di}{dt} + e \tag{6}$$

or

$$L\frac{di}{dt} = -Ri + V - e \tag{7}$$

$$\frac{di}{dt} = \frac{1}{2}\left(-Ri + V - K_e\frac{d\theta}{dt}\right) \tag{8}$$

And we apply Newton's second law on mechanical system,

$$T = J\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} + T_L \tag{9}$$

$$J\frac{d^2\theta}{dt^2} = T - b\frac{d\theta}{dt} \quad (T_L \text{can } be \text{ neglected}) \tag{10}$$

$$\frac{d^2\theta}{dt^2} = \frac{1}{j}\left(K_t i - b\frac{d\theta}{dt}\right) \tag{11}$$

The definition of different parameters used in this model is as under:

Parmaeters	**Units**
Input voltage (V)	V
Armature resistance (R)	Ω
Armature current (i)	A
Inductance (L)	H
Back EMF (e)	V
Moment of inertia (J)	kg//m2
Torque developed (T)	N.m
Load torque (TL)	N.m
Torque Constant (Kt)	N.m/A
Viscous Friction coeeficient (b)	N.m.s/rad
Back EMF constant (KE)	V.s/rad
Angular displacement (θ)	radians

Equations (7) and (10) are transformed to realize the complete model using SIMULINK as shown in Figure 5. Table 1 lists the parameters that are to be used for the operation of DC motor.

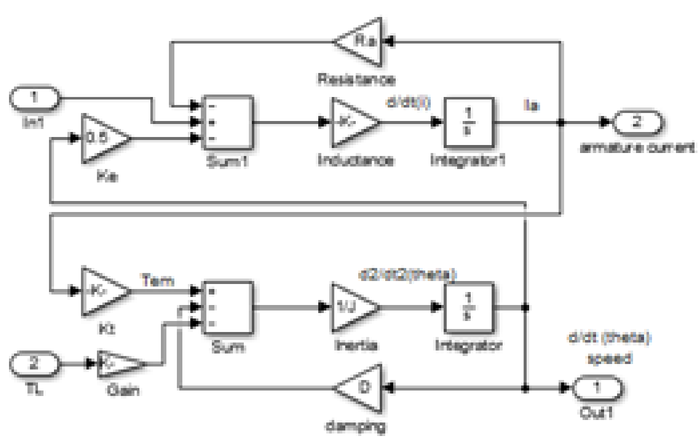


Fig 5. Simulink based model of DC series motor

Table 1. PMDC series motor design parameters

Parameters	Value
V	10 V
R	0.5 Ω
L	0.02 H
J	0.1 Kg/m2
	0.008 N.m.s
KE	0.01 V.s/rad
Rated voltage	12 V
Rated current	70 Amp
Rated torque	10 N.m
d speed	1872 RPM
Rated power	1 hp

3 Modeling of PID, Fuzzy and Fuzzy-PID Controllers using SIMULINK

3.1 PID Controller Design

The PID controller can be realized using Simulink's built-in PID controller function blocks. The PID controller gains are adjusted by PID auto tuner application. The DC motor model connected with PID controller as shown in Figure 6 where motor speed is feedback to compare with the set point to generate an error value to be controlled by PID controller.

3.2 Modeling of FLC

Fuzzy logic controller has been designed using SIMULINK. The FLC with rule viewer has been taken as controller selected from fuzzy tool box. It employs if-else form of program of the various conditions to control the motor speed. The Mamdani fuzzy inference system is employed in creating fuzzy controller. The controller has two fuzzy inputs, error (E) and rate of change of error (CE) and single output. Fuzzy inputs and output are described by five linguistic variables each. For input variable error (E) has five membership functions with two trapezoidal functions VS (very small) and VB

(very big) and three triangular MFs, S (small), M (medium) and B (big) are employed. The second Fuzzy input, change of error (CE) contains two triangular membership functions P (positive) and N (negative). The range of both Fuzzy inputs is normalized that is standard range is taken from -1 to 1.Fuzzy output variable (CONTROL) conatins five triangular membership functions VLOW (very low), LOW (low), MED (medium), LARGE and VL (very large).Range of output is taken from -30 to 30. Ranges of all the membership functions of error, rate of error and output are taken on personal experience and trial method. Membership functions of Fuzzy input and output variable are given in Figures 7 and 8 . Fuzzy rule-base contains seven rules as shown in Figure 9 .The FLC based motor speed control can be realized as shown in Figure 10 .

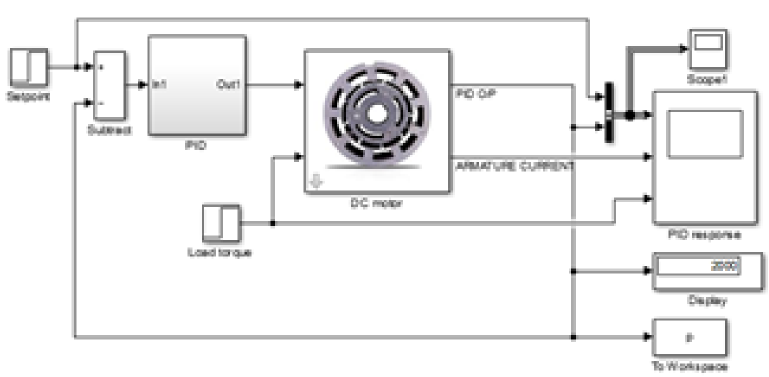


Fig 6. The model of PID controller realized in SIMULINK

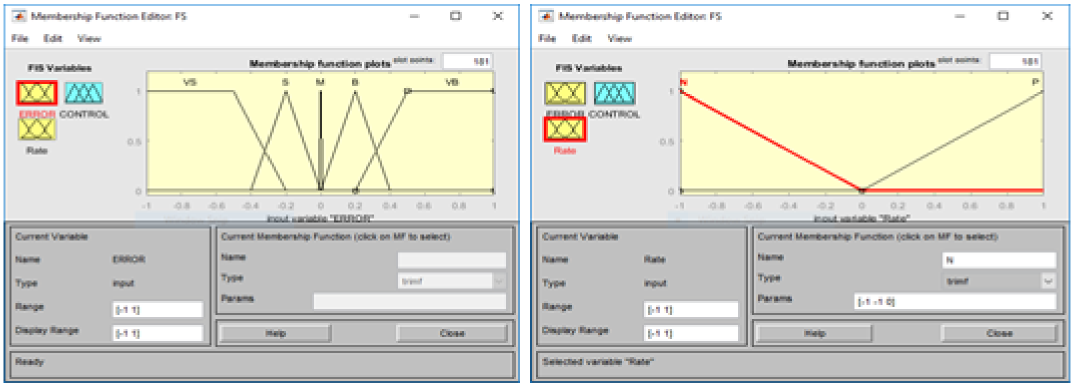


Fig 7. Membership functions of Fuzzy inputs; error and rate of error

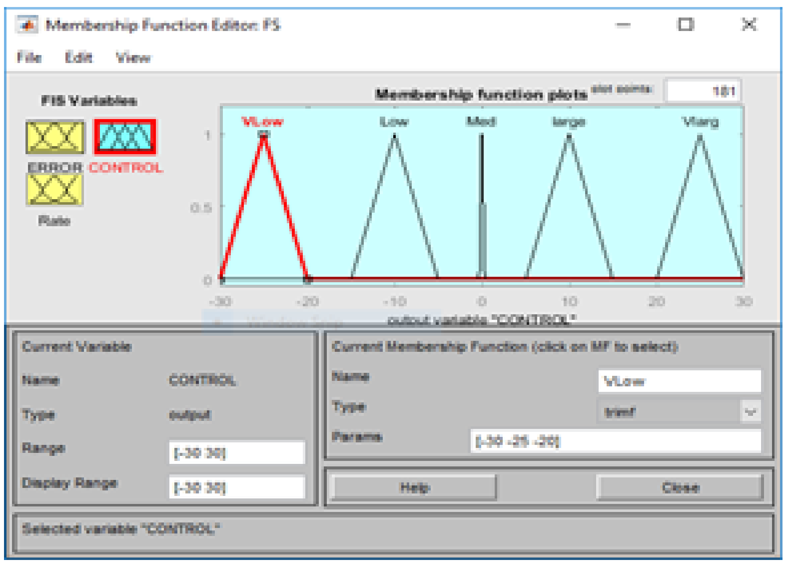


Fig 8. Membership functions of Fuzzy output 'CONTROL'

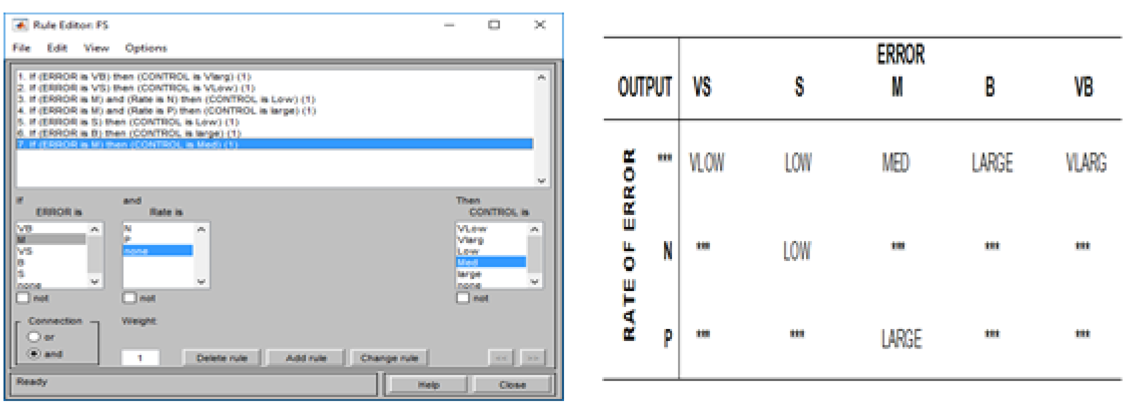


Fig 9. Representation of Ffuzzy logic controller rules.

3.2.1 Tuning Fuzzy Controller

Linear fuzzy approach is used to tune the fuzzy controller; means to select the membership functions ranges and design the rule base which is the engine of fuzzy inference system. Linear fuzzy approach gives the linear surface view by using expertise in control design we can tune it easily or simply using trial method and noticing the surface view until it becomes approximately linear surface. Such control design offer less number of rules and occupies less memory that is, a less complex system.

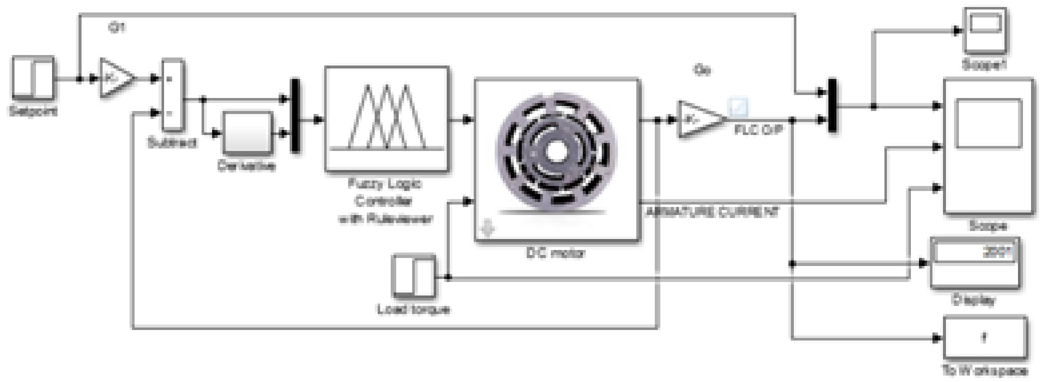


Fig 10. Model of Fuzzy Logic Control developed in Simulink.

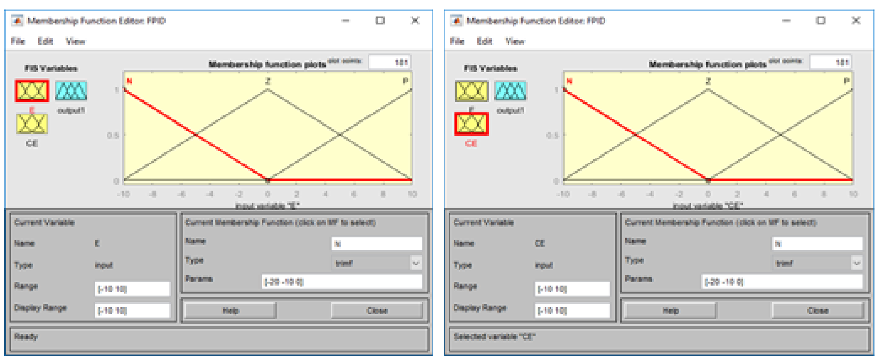


Fig 11. Membership functions of Fuzzy-PID input variables

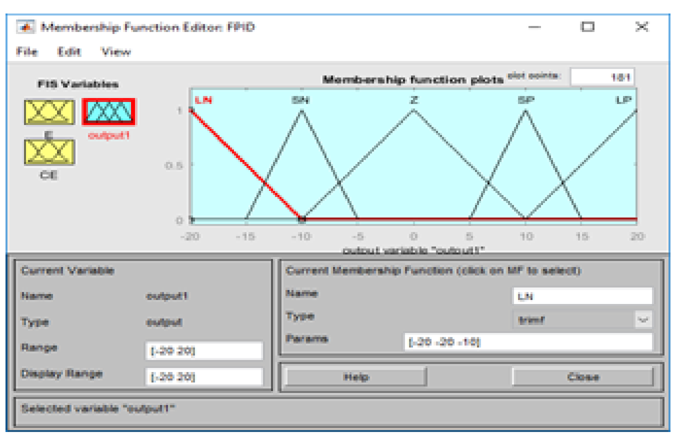
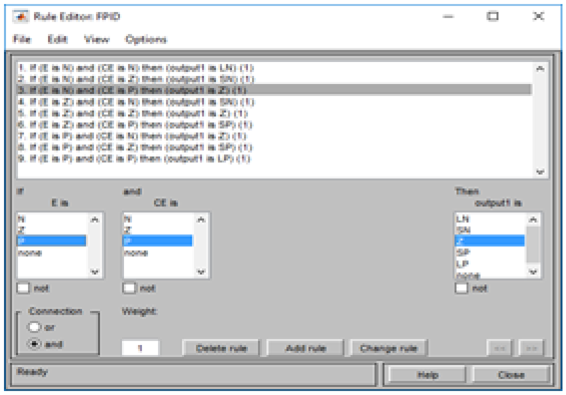


Fig 12. Membership functions of Fuzzy-PID output variable 'output1'



OUTPUT		ERROR		
		N	Z	P
RATE OF ERROR	N	LN	SN	Z
	Z	SN	Z	SP
	P	Z	SP	LP

Fig 13. Rules of Fuzzy-PID controller

3.3 Fuzzy-PID Controller

The Fuzzy-PID controller is realized in Simulink as shown on Figure 14. Fuzzy-PID scheme combines the characteristics of both of PID and Fuzzy controllers. Like Fuzzy controller, it takes two inputs that is, error (E) and rate of error (CE) and a single output. Each input has three membership functions that are N (negative), Z (zero) and P (positive). The ranges of both inputs Eand CE are normalized to the range [-10 10]. The input sets are triangular and cross neighbor sets at membership value of 0.5. Te Fuzzy-PID output variable (OUTPUT1) has five membership functions; LN (large negative), SN (small negative), Z (zero), SP (small positive) and LP (large positive) with the range [-20 20]. Membership functions of Fuzzy-PID input and output variables and rules are shown in Figures 11, 12 and 13 respectively. The Fuzzy-PID controller is designed with nine rules to obtain a better controller than PID and FLC.

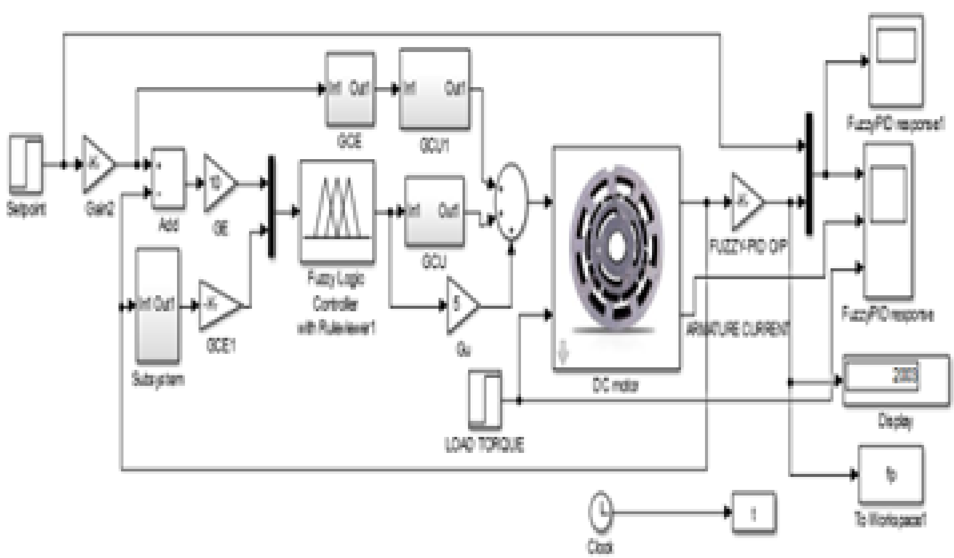


Fig 14. The Fuzzy-PID controller realized in Simulink

4 Simulation Results

The three controllers i.e. PID, Fuzzy and Fuzzy-PID are tested on PMDC series motor model by applying load on different intervals of time. The amount of load applied on the motor has been selected as 10 N-m. There are two reference inputs applied to controllers which are 1000 rpm and 2000 rpm. All these two controllers step responses on 1000 rpm are shown From Figures 15, 16 and 17 individually and the combined response of three controllers at 2000 rpm is shown in Figure 18 . A comparison of simulation results of all controllers performance parameters is given in Table 2. The simulation results of the three controllers are discussed below for both reference points.

4.1 Three Controllers response at reference point 1000 rpm

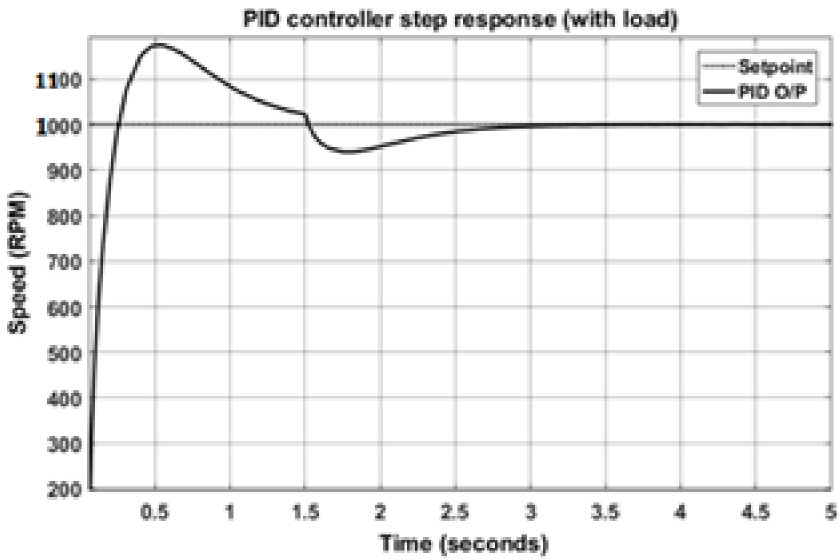


Fig 15. PID controller step response at 1000 RPM.

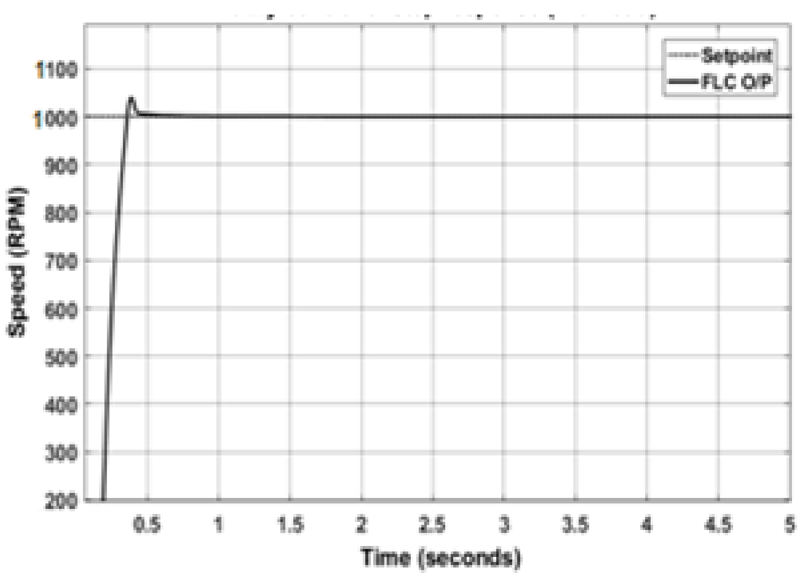


Fig 16. Fuzzy controller step response at 1000 RPM

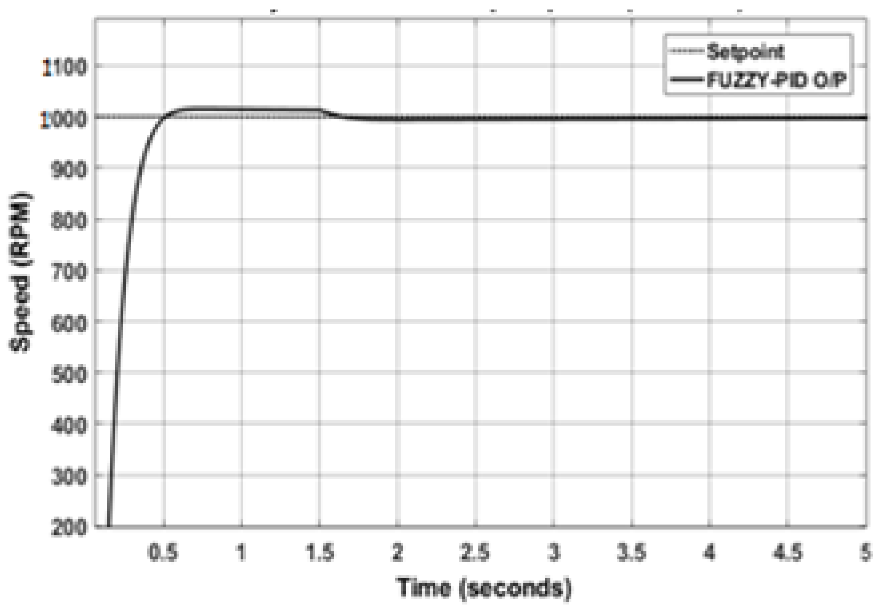


Fig 17. Fuzzy-PID controller step response at 1000 RPM.

In this simulated work, the reference was set as 1000 rpm. The PID controller response is shown in Figure 15, for similar set point, the response of FLC and Fuzzy PID are shown in Figures 16 and 17. The simulation results show that PID controller has a faster response with the highest overshoot (Mp) with 16.25% than other two controllers, as overshoot (Mp) of 3.646 % with FLC and overshoot (Mp) of 2.54% is obtained with Fuzzy-PID controller. It takes longer time to settle with PID controller (i.e. t_s = 1.149s) comparing FLC (i.e. t_s = 0.180s) and Fuzzy-PID (i.e. t_s = 0.310s). The steady-sate error is obtained as zero with PID. However steadt state is not zero with FLC and Fuzzy-PID controllers. Fuzzy controller is designed with minimum number of rules so that controller response is faster with more optimized results than the PID controller. Fuzzy-PID controller is set to be designed with nine (9) rules to obtain a better control strategy than PID and FLC. The loading time greatly influences the settling and rise times of the controller.

4.2 Three Controllers response at reference point 2000 rpm

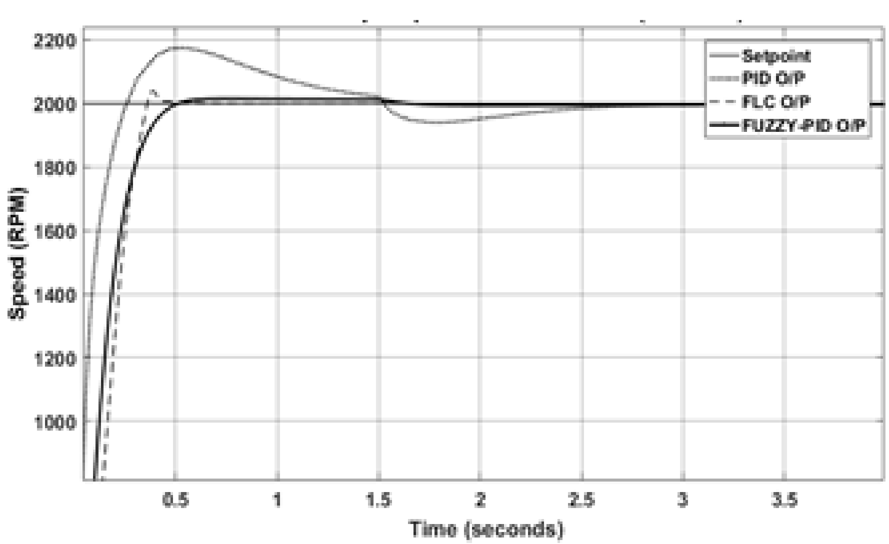


Fig 18. Combined step responses of controllers with load at setpoint 2000 RPM.

By setting set point to 2000 rpm, the simulation were performed. The step response of the system with all three controller configuration is shown in Figure 18 . It can observed that Fuzzy-PID has relatively good response then FLC considering the maximum overshoot, rise time, settling time. The steady-state error is very smaller within the acceptable range (0.5%). The performance paramater achieved by all three controllers are given in Table 2. The Simulation results noticeably show that Fuzzy-PID controller has proven to be a better control scheme than PID and Fuzzy control strategies with optimized performance parameters for PMDC series motor speed control time are minimum. Percentage steady-state error (Ess) is equally optimized by the three controllers. In this work, it is obvious that Fuzzy-PID is more suitable in terms of optimizing/adjusting the controller response.

Table 2. Comparing thetransient performance of all three controllers.

CONTROLLER	SETPOINT (RPM)	%OVER SHOOT	t_r (s)	t_s (s)	% E_{ss}
PID	1000	16.25	0.161	1.149	0
	2000	8.152	0.161	1.149	0
FLC	1000	3.646	0.169	0.180	0.1
	2000	1.531	0.244	0.183	0
FLC-PID	1000	2.54	0.263	0.310	0.5
	2000	0.454	0.263	0.310	0.5

5 Conclusion

In this study, the performance of three different controllers for the application of speed control of DC motor to be used as an engine starter under varying load has been presented. A starter motor requires a constant torque within the range 1000-2000 RPM (Revolutions per minute) [15,16].TheSimulation results validates that the Fuzzy-PID combined approach is more suitable and better improves the transient domain performance of DC motor. The Fuzzy-PID control provides robust speed control, better active response and steady-state domain performance of DC motor (than Ref.[1,2,16]). It can be concluded that Fuzzy-PID combined approach is a better strategy than any single configuration or any conventional controller. The results of FLC are much better than presented in[25], however, the motor parameters are not the same. Consequently, this work presents much better performance using fewer rules in Fuzzy controller. It can be concluded that Fuzzy-PID combined approach is an efficient linear control strategy than any single configuration or any conventional controller.

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