Intelligent Speed Control of DC Motor using Fuzzy Algorithm

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Abstract - *In this paper, an overview of intelligent control technique for the speed control of a direct current (DC) motor has been discussed. Considering the non-linear characteristics of the DC motor and its mechanical variations due to operating conditions, the traditional controllers alone are not enough to give precise control. A more adaptive controller using fuzzy logic is built in this study to realize a better control compared with the current PID controller. It is a technique that auto tunes the PID parameters according to the response of plant. In this the outputs of the fuzzy logic controller are used as dynamic parameters of PID. Simulation results illustrate the practicability of this technique. This article presents a comparative study between Proportional-Integral-Derivative (PID), a modified PID structure called I-PD, Fuzzy Logic Controller (FLC) and Fuzzy PID (F-PID) controllers based on time domain characteristics. The results indicate the supremacy of F-PID over the classical controllers grounded on the transient response analysis.*

Key Words: **PID controller, fuzzy logic controller, I-PD, fuzzy PID, speed control**

1.INTRODUCTION

The principal purpose of control is to increase the reliability and to enhance the performance of plants and this can be achieved by employing engineering concepts to plan the control process. The standard PID controllers are still widely used even after development of numerous control theories due to its simple implementation and good performance.

The high precision and accuracy in movement dynamics of direct current motors result in extensive use in a variety of applications like robotics, industrial and home application, etc., which require high-speed control accuracy and reliable effective dynamic response. It provides a wide range of speed control and requires manual or automatic control. So, often designers try to find the best control method which can help in controlling the motor output (position or speed) to a predefined set point.

The speed of a DC motor is directly proportional to armature voltage and inversely proportional to the magnetic flux produced by the poles of the motor. Some conventional methods of speed control of DC motor are:

- By varying the flux per pole- flux control method
- By varying the resistance in the armature circuit-armature control method
- By varying the applied voltage V- voltage control method [1]

Previous studies have presented several controllers to enhance the performance of the DC motor. The PID controllers are the best-known controllers used in the industrial control processes due to their simple structure, ease of design, and robust performance in a wide range of operating conditions. The first PID was developed in 1911 by Elmer Sperry for the US navy but the PID control method that we use today was introduced in 1922 by Minorsky [2]. Several modifications were made to it in the 1930s and these have been in industrial use for various process control works ever since the 1940s [3].

The performance of a PID controller mostly depends on the precision of system models and their parameters. It is essential to obtain a fine-tuning of parameters to achieve the desired control action. As manual tuning can prove to be a tedious task so, numerous efforts were made for tuning the PID. Ziegler and Nichols gave the well-known Ziegler-Nichols tuning method in 1942-1943 [4,5]. Further Cohen and Coon gave the alternative for tuning in the 1950s which was accepted by certain types of plants [6]. Several other tuning methods and strategies like fractional order PID [7], DSP-based self-tuning IP [8], etc. were introduced to improve the performance of PIDs, some of which are discussed in [9-11]. However, PIDs are often inefficient for a system with undefined complexities like time delays, oscillatory behavior, nonlinearities, or for multiple-input multiple-output (MIMO) systems. Additionally, a kick or spike called set-point kick is experienced in the output due to proportional and derivative action of the PID whenever there is a change in the setpoint. This action can cause serious damage to the system receiving the control signal from the controller like motor, control valve, etc. These effects are avoided by modifying the PID controller structure to I-PD controller [12].

Recently, intelligent process control has drawn the attention of many. Fuzzy control, neural networks, genetic algorithms and expert systems, and many more techniques have gained a lot of importance today, of which fuzzy and neural control are coming as the fastest growing areas. Fuzzy logic control (FLC) gives an intelligent tuning that uses linguistic control algorithm based on rules which use general statements instead of mathematical equations [13]. It has been suggested as a better control than the conventional control algorithms for complex systems with uncertain dynamics and those with nonlinearities [14].

The fuzzy logic was proposed by Lotfi A. Zadeh in 1965 which was based on fuzzy sets. The first successful application of fuzzy logic in control was reported by Mamdani and Assilian. Also, Kingt and Mamdani suggested the application of fuzzy logic control systems to industrial processes in [15]. Although systematic analysis and design for FLC are still considered premature in general, significant progress has been added recently in the search of this technology. The most popular reasoning method used in fuzzy is the compositional rule of interface (CRI). Still, the traditional CRI is not very satisfactory due to the presence of error in the robust control [16].

The success of fuzzy logic inspired work in the field of developing autotuned fuzzy-based PID controllers. It has been used to improve the performance of PID controllers by developing fuzzy-based PI/PID controllers [17], ANFIS based hybrid PID [18], a fuzzy logic-based pre-compensation approach for PID controllers [19], and many others. The results indicated the superiority of such controllers over the conventional ones. An improved genetic algorithm to regulate fuzzy controller parameters has been discussed for the control of a series DC motor in [20].

Considering the points outlined above, several studies on the control of DC motors have been performed. It has been demonstrated in preceding studies how fuzzy logic control can provide suitable procedures to find the best control. In the meantime, there are some inefficiencies in the previous techniques. For instance, the motive of studies is to minimize the transient response parameters, but we can often find aberrations from this target.

In contribution to the existing studies, this work presents a technique to control speed of DC motor by monitoring the armature voltage using 4 closed loop controllers known as PID, I-PD, FLC, and F-PID. A control method for manipulating PID parameters using fuzzy logic is presented. The schemes are discussed in detail, tested with simulation model of DC motor, and their results are compared.

The paper is organized as follows: Section 2 describes the mathematical model of the DC motor in which all the mathematical equations related to speed control are detailed, Section 3 discusses the classical PID and tuning approach followed by brief description of I-PD controller, Section 4 describes the fuzzy logic controller and fuzzy-based PID used in this study, Section 5 consists of the results and discussion, and Section 6 discusses the conclusions drawn.

2. MATHEMATICAL MODELLING OF DC MOTOR

The DC motor is a common actuator used in most control systems. It converts electrical energy into rotary motion, and if coupled with elements like wheels and cables, it can provide translational motion too. Fig- 1 shows the electrical circuit and free body diagram of the rotor system of the DC motor. The parameters and their values are given in Table 1

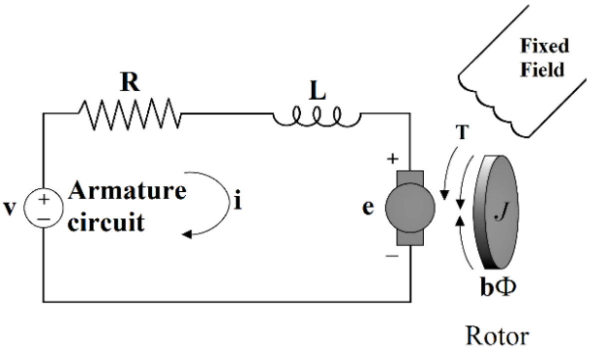

Fig-1: Electrical circuit and free body diagram of DC motor

Table-1: Motor parameters

Parameter	Description	Value
R	Armature resistance	0.5 Ω
L	Armature inductance	0.02 H
J	Moment of inertia of the rotor	0.1 Kg.m^2
B	Damping ratio of the mechanical system	0.008 Nm/rad/sec
K_b	Back emf constant	1.25 V/rad/sec
K_t	Motor torque constant	0.5 Nm/A

The input to the system is the supply voltage (V) and it is translated to output as the shaft rotational speed (w). The motor torque T, and the armature current i are related by armature constant factor K_t and the back emf (e) is related to the rotational velocity by motor constant K_b as given by the following equations:

$$T = K_t * i \quad (1)$$

$$e = K_b * \frac{d\theta}{dt} \quad (2)$$

By applying KVL and Newton's law in the circuit, we get,

$$J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = K_t i \quad (3)$$

$$L\frac{di}{dt} + Ri = V - K_b\frac{d\theta}{dt} \quad (4)$$

Applying Laplace transform, we get,

$$s(Js + B)\theta(s) = K_t i(s) \quad (5)$$

$$(Ls + R)i(s) = V - sK_b\theta(s)$$

Solving and eliminating i(s) we get open-loop transfer function, where the angle is the output, and the voltage is the input.

$$\frac{\theta}{V} = \frac{K_t}{s[(Ls + R)(Js + B) + K_b K_t]} \quad (7)$$

The input voltage to output speed (w) transfer function will be:

$$\frac{w}{V} = \frac{K_t}{(Ls + R)(Js + B) + K_b K_t} \quad (8)$$

The equivalent block diagram of armature-controlled DC motor based on (8) is shown in Fig- 2.

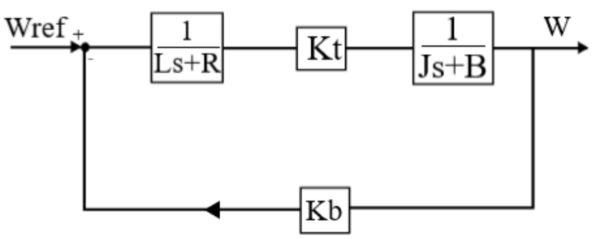

Fig-2: Equivalent block diagram of DC motor.

3. PID AND I-PD CONTROLLERS

A combination of proportional, integral, and derivative action in parallel makes a traditional PID controller. The structure of a PID controller is shown in Fig- 3.

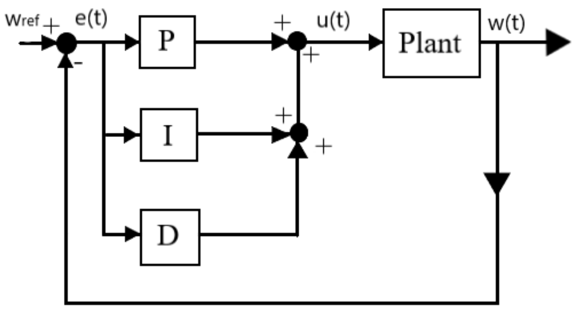

Fig-3: Closed loop system using a PID

These controllers incline towards decreasing the error i.e., the difference between the process variable and setpoint, by comparing the response with the desired value. Its design requires the specification of three parameters: proportional P, integral I, and derivative D parameters. The parameters and their actions associated with these can be described as: (6)

- Proportional gain K_p - reduces the rise time and steady-state error
- Integral gain K_i - maintains minimum error
- Derivative gain K_d- decreases overshoot.

Here, K_p is related to present error, K_i is related to past error and K_d is related to the future behavior of error [13]. The equation of the PID controller is (9).

$$u(t)|_{PID} = K_p e(t) + K_i \int e(t)\,dt + K_d\frac{de}{dt} \quad (9)$$

The transfer function of the PID controller is given as-

$$\frac{U(s)}{E(S)} = G_{PID}(s) = K_p + K_i\frac{1}{S} + K_d s \quad (10)$$

In terms of integral time T_i and derivative time T_d:

$$G_{PID}(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \quad (11)$$

Here,

$$K_i = \frac{K_p}{T_i} \quad (12)$$

$$K_d = K_p * T_d \quad (13)$$

These parameters can be tuned by manual tuning, tuning heuristics, or automated methods. The automatic tuning or self-tuning method uses a mathematical model to process the input-output relationship. Ziegler-Nichols rule is the best and most famous tuning heuristic method.

This paper uses the Zeigler Nichols method for tuning the PID parameters as described in Table 3. It is performed by keeping K_i and K_d zero and gradually increasing K_p from zero until sustained oscillations are received. The maximum gain of these oscillations is the ultimate gain K_u and the oscillation period is T_u.

Table-2: Ziegler-Nichols method

Controller type	K_p	T_i	T_d
P	0.5 K_u	-	-
PI	0.45 K_u	$\frac{T_u}{1.2}$	-
Classical PID	0.6 K_u	0.5 T_u	0.125 T_u

Considering the kicking effect of proportional and derivative action on the output of a PID controllers, it is advantageous to shift these actions to the feedback (so that only the feedback signal is affected) while retaining the integral action in the feedforward path. This rearrangement of PID gives the I-PD control. The block diagram of the closed loop control using I-PD is shown in Fig- 4.

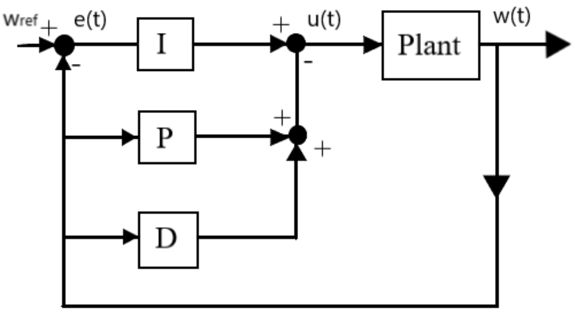

Fig-4: Closed loop system using I-PD

In this structure, only the integral (I) action is performed on the error whereas the proportional plus derivative (PD) action is applied on the output. The output of the I-PD is given by (14)

$$u(t)|_{I-PD} = K_i \int e(t)dt - \{K_p w(t) + K_d \frac{dw}{dt}\} \quad (14)$$

In this structure, the proportional, K_p, and derivative, K_d action will depend solely on output and any abrupt change in the set point or input will not affect these terms.

4. FUZZY LOGIC CONTROLLER AND FPID

Fuzzy Logic Control (FLC) is often used as an alternate method for designing any dynamic controller. It is based on fuzzy logic which is a linguistic control algorithm that uses general statements rather than mathematical equations.

The design of FLC consists of a control structure comprising rules and gains, and the fuzzy reasoning method. It can utilize human proficiency and experience for designing a controller [20]. The rules adjusted for designing fuzzy control are not mathematical equations rather they are simple "IF-THEN" statements. The structure of a fuzzy control system is shown in Fig- 5. The blocks of the fuzzy control system are:

- *Pre-processing:* It is the first step in which conditioning of input is done before entering the controller.
- *Fuzzification:* In this block crisp inputs are transformed into the setting of linguistic values viz. fuzzy sets.
- *Rule base:* The fuzzy adaptive rules are like human decision-making. The fuzzy output is interpreted based on fuzzy rules that are in form of conditional "IF-THEN" statements. The rule base is the collection of fuzzy rules upon which the FLC makes decisions. The 'If' side is called antecedent or premise and the 'Then' side is called consequence. An example of a fuzzy rule is: If the temperature is high, then the fan speed is high.
- *Inference:* Under inference, the truth value for the antecedent is calculated, and applied to the conclusion of each rule. As a result, for each rule, every output variable has a fuzzy subset assigned to it. Mostly MIN or PRODUCT operation is used for inference. In MIN inference, the output membership function is trimmed off at a certain height. For the rule bases, a classic interpretation of Mamdani was used in this paper. A two-input single-output Mamdani fuzzy model is illustrated in Fig- 6 in which x and y are inputs and z is the output of the fuzzy logic controller.
- *Defuzzification:* It is the reverse process of fuzzification. In this fuzzy output is converted into crisp values or real number output [1, 13, 19]. In this paper, defuzzification was done by the CENTROID method.
- *Post-processing:* It is the last step of fuzzy logic control in which output scaling is done.

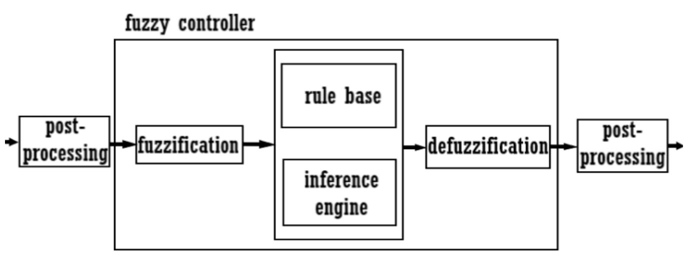

Fig-5: Fuzzy logic modules

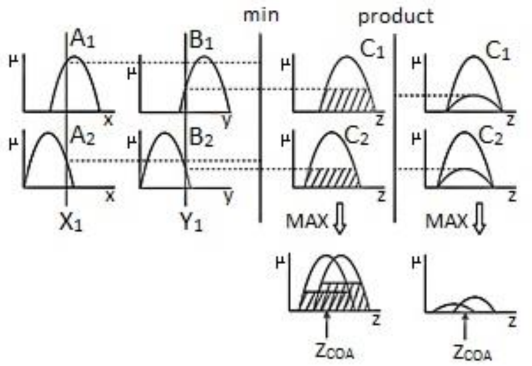

Fig-6: Mamdani fuzzy model

A. Fuzzy Logic Controller (FLC)

The inputs to the fuzzy logic controller are error (e) and change in error (ce), and the output is taken as o. It is required to set a reasonable domain for effective speed control which is selected based on simulation experiments and practice. The domain for e is [-0.2, 0.2], ce with [0, 0.8] and o with [0, 2.515]. The input space of e and ce, and the output space of o are defined by linguistic variables. The fuzzy sets of input and output contain these variables. The input e is defined by {low error (LE), medium error (ME), high error (HE)}, ce by {low change (LC), medium change (MC), high change (HC)} and the output o by {low output (LO), medium output (MO), high output (HO)}. Triangular membership functions were used for sensitivity and robustness. Rules of the fuzzy logic are constructed on the basis of experimental experience. The rules of FLC are described in Table 3.

These rules can be defined as: *if (e is LE) and (ce is LC) then (o is LO).* All the other rules can be explained similarly. The membership functions of e, ce and o are shown in Fig- 7, Fig- 8, and Fig- 9 respectively. The rule viewer of the FLC can be seen in Fig- 10.

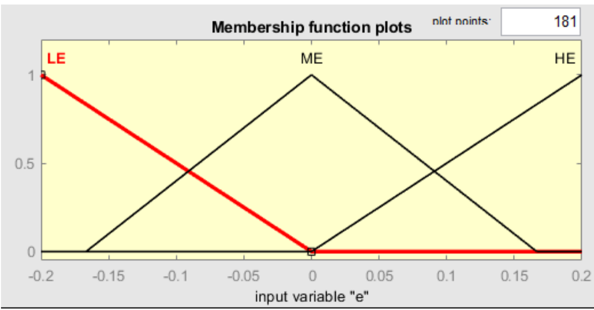

Fig-7: Membership functions of e in FLC

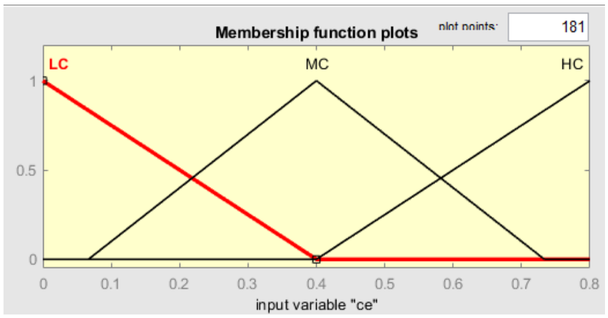

Fig-8: Membership functions of ce in FLC

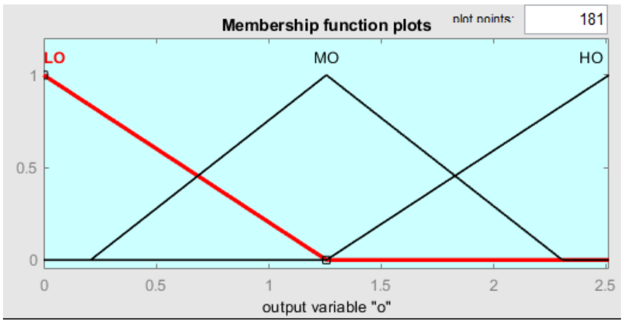

Fig-9: Membership functions of o in FLC

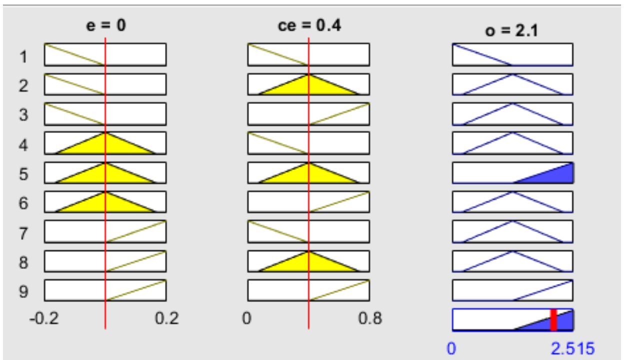

Fig-10: Rule viewer of FLC

Table-3: Rules for FLC

ce	e		
	LE	**ME**	**HE**
LC	LO	MO	MO
MC	MO	HO	MO
HC	MO	MO	HO

B. F-PID controller

The block diagram of Fuzzy PID (F-PID) controller is shown in Fig- 11. The proposed F-PID, controls the system with dynamic gains (ΔK_p, ΔK_i and ΔK_d in Fig- 11) for automatic tuning of the PID. These dynamic values are added to a fixed value of K_p, K_i, and K_d of the PID controller, which are determined by experience and practice.

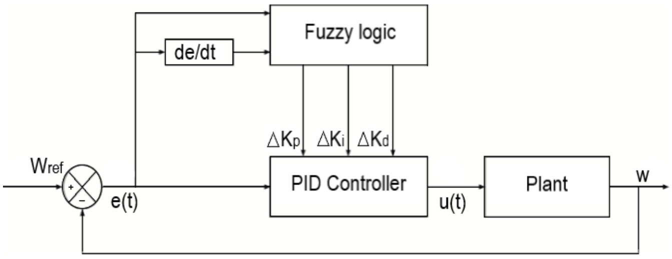

Fig-11: Closed loop control using Fuzzy PID

For the F-PID, the fuzzy logic is the main element, and it requires the design of input and output range, membership functions, and rule base for decision making. So, it is essential to build proper fuzzy logic to realize better control. The designed F-PID is a two-input, three-output fuzzy PID controller. The parameters of the PID are modified by fuzzy output as:

$$K_p' = dp + K_p \qquad (15)$$

$$K_i' = di + K_i \qquad (16)$$

$$K_d' = dd + K_d \qquad (17)$$

Here,

K_p', K_i', and K_d' are the final values, dp, di and dd are dynamic values obtained from fuzzy logic controller, and K_p, K_i, and K_d are the initial values of PID. The initial parameters K_p, K_i, and K_d have values 0.24, 0.75, and 0.025 respectively.

i. Membership functions

The inputs to the fuzzy logic are error (e) and change in error (ce) and the outputs are dp (dynamic proportional), di (dynamic integral), and dd (dynamic derivative). The domain of e is [-0.2, 0.2], ce with [0, 0.8], dp with [0, 7.2], di with [0, 14.4] and dd with [0, 1]. The input space of e and ce, is given as e by {low error (LE), medium error (ME), high error (HE)}, ce by {low change (LC), medium change (MC), high change (HC)}, and the output space of dp, di and dd is defined as: {low gain (LG), medium gain (MG), high gain (HG)}.

ii. Fuzzy adaptive Rules

The rule base for F-PID used in this paper is shown in Table 4. These rules can be defined as: *if (e is LE) and (ce is LC) then (*dp (or di/dd) *is LG).*

The membership functions of e, ce, dp, di, and dd are shown in Fig- 12, Fig- 13, Fig- 14, Fig- 15, and Fig- 16 respectively. The rule viewer for the F-PID is shown in Fig- 17.

Table-4: Rules for F-PID

ce	e								
	dp			di			dd		
	LE	ME	HE	LE	ME	HE	LE	ME	HE
LC	LG	MG	MG	LG	MG	MG	LG	MG	MG
MC	MG	HG	MG	MG	HG	MG	MG	HG	MG
HC	MG	MG	HG	MG	MG	HG	MG	MG	HG

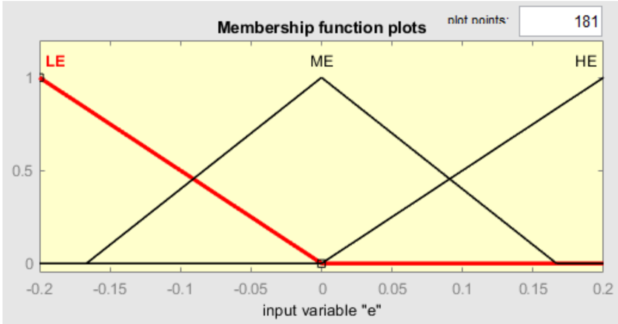

Fig-12: Membership functions of e in F-PID

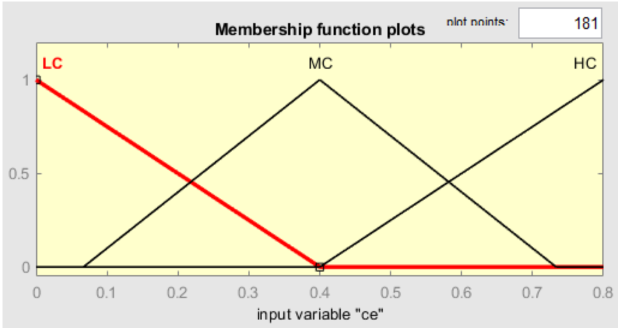

Fig-13: Membership functions of ce in F-PID

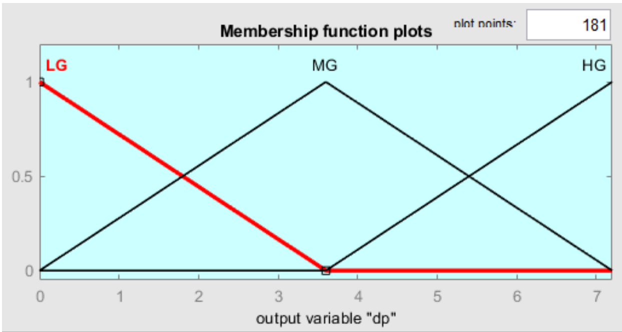

Fig-14: Membership functions of dp

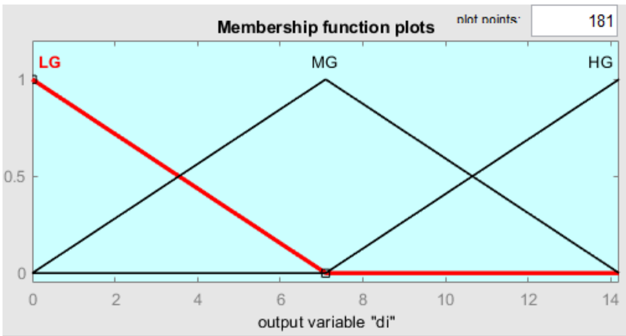

Fig-15: Membership functions of di

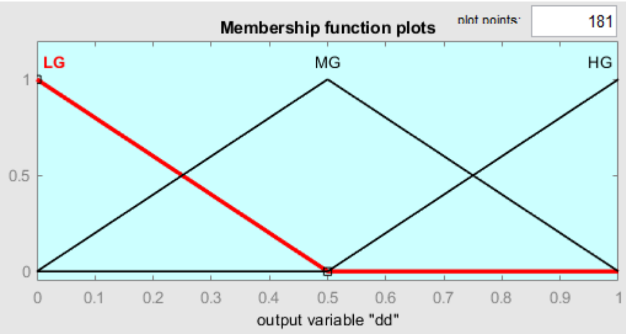

Fig-16: Membership functions of dd

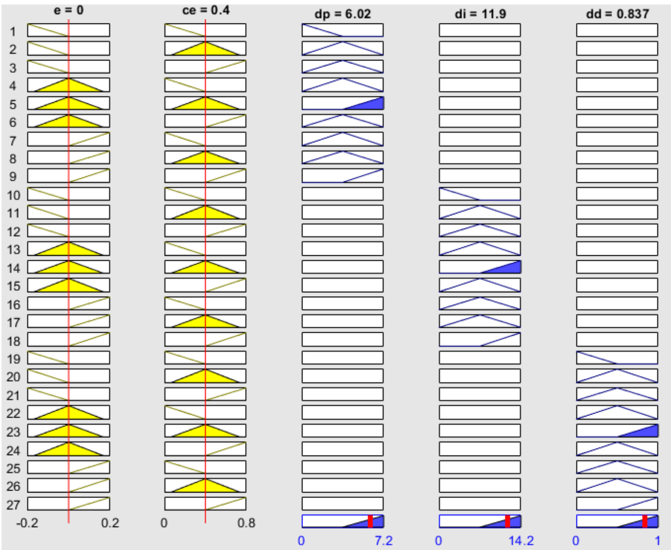

Fig-17: Rule viewer of F-PID

5. RESULTS AND DISCUSSION

For effective comparison the system is simulated at two different set speeds of 1 rad/sec and 100 rad/sec and their simulation result has been shown in Fig- 18 and Fig- 19 respectively.

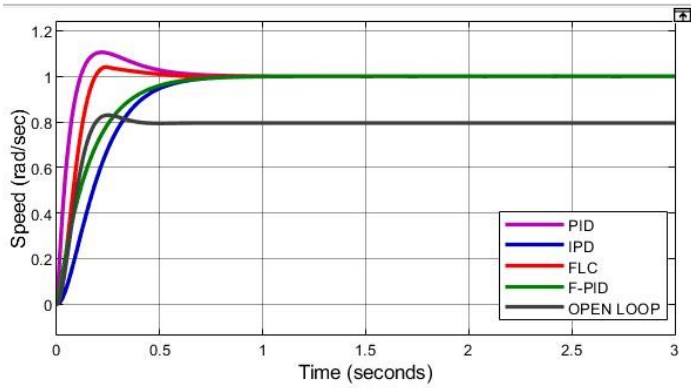

Fig-18: Simulation results at set speed 1 rad/sec.

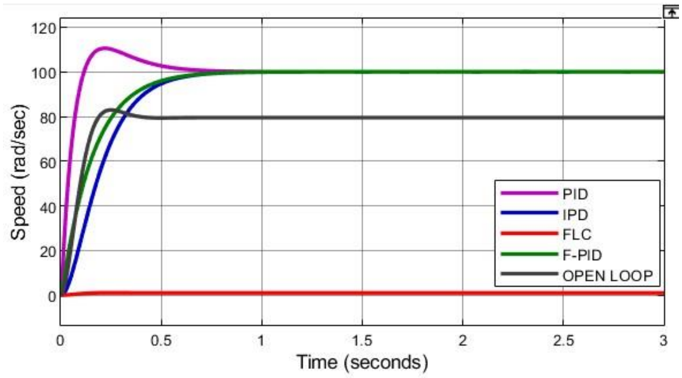

Fig-19: Simulation results at set speed 100 rad/sec.

- **At set speed 1 rad/sec**

As it can be seen from the result in Fig- 18 when the motor is running in an open-loop (depicted by the black line), about 20% offset error is present as the response is limited to around 80%. This problem is resolved when motor is operated in closed loop system having different controllers. A tuned PID helps in stabilizing the system and steady-state error is also removed but there is an overshoot of around 10%. When an I-PD with the same parameters as PID is used the overshoot is minimized (0.1 %) and steady-state error is also minimized. A fuzzy logic controller gives a lesser overshoot (4%) than the PID controller and steady-state error is also removed. The designed F-PID shows no overshoot, and the error is also eradicated.

- **At set speed 100 rad/sec**

From Fig- 19 we can observe that, when the set point is increased, all the controllers except FLC had the same performance as in case of set speed 1 rad/sec. An offset error of 99% is produced by FLC when reference signal is 100 rad/sec. The open loop performance and closed loop performance using PID, I-PD, and F-PID are adjusted accordingly and give the same percentage of overshoot and error as for 1 rad/sec reference speed. The results indicate the incompetence of FLC in giving optimal control for different reference with same fuzzy logic. Thus, the logic of this FLC needs to be adjusted according to the set point.

Comparison of these controllers based on different time response characteristics is done in Table 5 and Table 6. Out of the four closed loop control methods, F-PID gives supreme response with zero overshoot, excellent set point tracking and relatively better speed of response. A summary of performance analysis for all the closed loop controllers is shown in Table 7.

Table-5: Response of controllers at set speed 1 rad/sec

Control method	Maximum overshoot (%)	Rise time (sec)	Settling time (sec)	Steady state value (rad/sec)
Open loop	4.315	0.150	0.318	0.795
Closed loop control				
PID	10.5	0.090	0.543	1
I-PD	0.1	0.415	0.629	1
FLC	4.3	0.150	0.391	1
F-PID	0	0.363	0.605	1

Table-6: Response of controllers at set speed 100 rad/sec

Control method	Maximum overshoot (%)	Rise time (sec)	Settling time (sec)	Steady state value (rad/sec)
Open loop	4.315	0.150	0.318	79.5
Closed loop control				
PID	10.5	0.090	0.543	100
I-PD	0.1	0.415	0.629	100
FLC	4.3	0.150	0.391	1
F-PID	0	0.363	0.605	100

Table-7: Result analysis for different controllers

Controller	Strengths	Drawbacks
PID	Low settling time	Highest overshoot
I-PD	No overshoot	Slowest response
FLC	Fastest response at 1 rad/sec	Significant overshoot at 1 rad/sec, unstable at higher set point, and logic needs to be manipulated for every set point.
F-PID	No overshoot	Higher settling time

6. CONCLUSIONS

A total of five different methods using one open loop control and four closed loop control including PID, I-PD, FLC, and F-PID were tried to optimize the speed of the DC motor. On the basis of the results and performance obtained, it can be concluded that closed loop control using F-PID, analyzed in this work, is more flexible and gives better dynamic and static response. It adapts the PID parameters according to the speed response of motor, removes the overshoot completely, and gives optimal set point tracking. However, a little compromise can be done with the settling time if a faster response is not the sole purpose.

A PID controller though reduces the steady-state error, it gives maximum overshoot which is not desirable in many situations. At 1 rad/sec, the FLC gives lesser overshoot than the PID and it takes the lowest time to settle but when the set point is changed then it fails to give the desired response. So, the drawback of FLC is that for every specified set point the logic needs to be manipulated. Another control characteristic like F-PID is showcased by I-PD, but it has maximum settling time, thus being the slowest of all.

Since, the performance of a PID controller can be improved when it is tuned using fuzzy reasoning, it can be concluded that the F-PID can be a better alternative for process control than the PIDs. Furthermore, for this purpose it is important to formulate proper modeling of fuzzy algorithm.

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