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Advanced Speed Control of DC Motors by Tuning Classical PID Controllers, using Fuzzy Logic Technique

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Abstract
This study introduces a PID controller tuning approach that combines the Ziegler–Nichols method with fuzzy logic, aimed at regulating the speed of a DC motor. In this approach, the proportional, integral, and derivative gains (Kp, Ki, Kd) of the PID controller are adjusted based on fuzzy logic principles. The fuzzy logic-based PID (FLPID) controller is designed using a set of 25 self-tuning rules, which dynamically adjust the PID parameters. The controller takes two inputs: the speed error (difference between actual and desired speed) and the rate of change of the speed error. These inputs are used to regulate the PID parameters to achieve optimal speed control of the DC motor. The MATLAB model of the speed control system using fuzzy logic requires minimal calculations, making it efficient and straightforward to implement. Simulation results show that the self-tuned FLPID controller achieves superior speed control compared to the conventional PID controller, validating the effectiveness of this design.

Key words: *Classical PID controller, DC Motors, Tuning Fuzzy Logic.*

1. INTRODUCTION

A DC motor provides high starting torque and easy speed control. With a wide range. It has the capability of adjusting the speed. It can accelerate or reverse its direction. The torque speed characteristics are better than an A.C. machine; it is possible to get the desired speed in the case of a DC motor. It has a wide range of applications. It has various applications in industry, transportation. There are three main ways to control the speed of a DC motor. The first one is armature control, the second is field control, and the third is the PID controller.

The DC motor delivers high starting torque and easy speed control over any range. It has the capability of adjusting constant torque starting and accelerating. Reverse and fast acceleration are quickly done. The speed and torque characteristics of DC motors are superior to those of AC motors. They allow for excellent control of acceleration and deceleration in both accelerating and braking modes. To achieve desired speed control of DC motors for various applications, several techniques are used, with PID control being among the most common. The primary goal of this paper is to enhance the performance of conventional PID controllers etc. Main Techniques to Control the speed of a DC motor. The first one is armature control, the second is Field control third one is the PID controller.

The study introduces a PID controller tuning approach that combines the Ziegler–Nichol's method with fuzzy logic, aimed at regulating the speed of a DC motor**[2]**. In this approach, the proportional, integral, and derivative gains (Kp, Ki, Kd) of the PID controller are adjusted based on fuzzy logic principles. The fuzzy logic-based PID (FLPID) controller is designed using a set of 25 self-tuning rules, which dynamically adjust the PID parameters. The controller takes two inputs: the speed error (difference between actual and desired speed) and the rate of change of the speed error. These inputs are used to regulate the PID parameters to achieve optimal speed control of the DC motor. The MATLAB model of the speed control system using fuzzy logic requires minimal calculations, making it efficient and straightforward to implement. Simulation results show that the self-tuned FLPID controller achieves superior speed control compared to the conventional PID controller, validating the effectiveness of this design.**[2]**

1. INTRODUCTION

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The fuzzy logic technique, initially introduced by L.A. Zadeh in 1965 and further developed by Mamdani in 1975, has become a popular research tool and is widely used in industrial applications. In designing a fuzzy logic-based PID (FLPID) controller, the error and the rate of change of error are used as inputs to improve speed control precision.[3]

2. DC Motor

In Figure 1, a field-controlled DC motor is shown where the applied field voltage varies without affecting the armature voltage. The DC motor is connected to a mechanical load with moment of inertia J and viscous friction coefficient B. A variable voltage is applied to the armature, and the following parameters are considered for calculations.

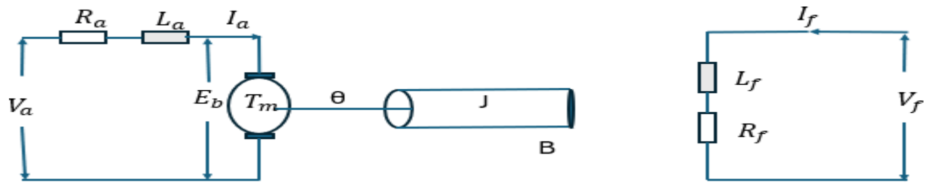


Fig. 1: Diagram of a DC motor

Notations

R= Resistance of armature winding (Ω)
L= Inductance of armature winding (H)
I_a =Armature current (ampere)
I_f = Field current (ampere)
e_a =Applied armature voltage (V)
e_b =back emf (V)
T_m =developed by motor (Nm)
θ = angular displacement of motor shaft (rad).
ω = angular speed of motor shaft (rad/sec.)
J = equivalent moment of inertia of motor and load referred to motor shaft (kg-m^2)
B = equivalent friction coefficient of motor and load referred to motor shaft (Nm/rad/sec)

In armature control of a separately excited DC motor, the voltage is changed by changing the applied voltage. Applying the torque equation and KVL in the loop of the DC motor

$$T_m = K_1 K_f i_f i_a \tag{1}$$

The electromagnetic torque developed in the air gap is given by

$$T_m = K i_a \tag{2}$$

Back emf is given by

$$e_b = K_b \frac{d\theta}{dt} \tag{3}$$

Applying KVL equation in the armature loop

$$L\frac{di_a}{dt} + Ri_a + e_b - e_a = 0 \tag{4}$$

During steady-state operation, the torque generated by the motor must balance the load torque along with the effects of friction and inertia.

$$J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = T_m \quad \textbf{(5)}$$

Applying the Laplace Transform on the above equation transfer function is derived as equation

$$G_1(s) = \frac{C(s)}{R(s)} = \frac{\omega(s)}{E_b(s)} = \frac{K_T}{[(R+LS)(Js+B)+K_T K_b)]} \quad \textbf{(6)}$$

As we know $\theta(s)=\frac{\omega(s)}{s}$ (7)

From (6) and (7)

$$\frac{\theta(s)}{E_b(s)} = \frac{K_T}{s\,[(R+LS)(Js+B)+K_T K_b)]} \quad \textbf{(8)}$$

The transfer function of the DC motor is taken as $G(s)=\frac{1}{(s^3+s^2+5s)}$ (9)

3. PID Controller

A PID controller combines three essential components: proportional, integral, and derivative control, as illustrated in Figure 2. The controller receives an input signal, which is compared with the feedback signal at a summing point to determine the error. This error signal is then processed by the PID controller, which adjusts the output sent to the plant's transfer function. If the output doesn't reach the desired value, the system continues to adjust based on the feedback error until the target output is achieved.

Determining the right parameters for the PID controller can be complex. The Ziegler-Nichols tuning method offers guidelines to help with this process. Using a table of Ziegler-Nichols rules, the proportional gain (Kp), integral time (Ti), and derivative time (Td) values are selected and calculated to achieve effective control.

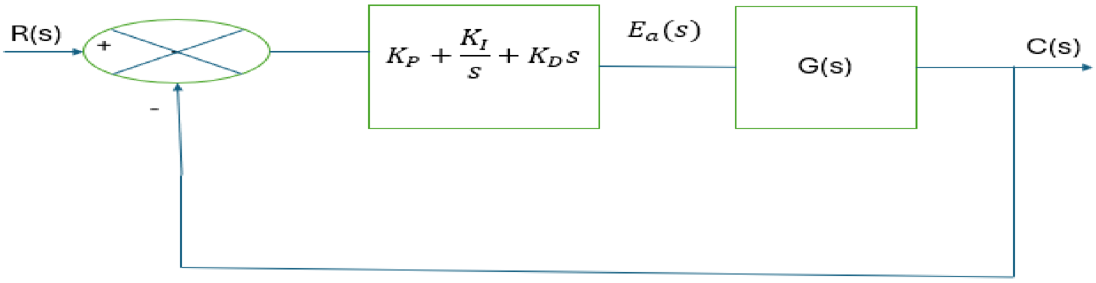


Fig. 2. PID Controller

The actuating signal or output signal from a PID controller in the time domain is given by

$$e_a = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de}{dt} \quad (10)$$

In the s-domain, the output signal from the controller is

$$E_a(s) = \left(K_P + \frac{K_I}{s} + K_D s\right) E(s) \quad (11)$$

When the transfer function of a system is known, traditional tuning methods like the Ziegler-Nichols (Z-N) approach can be applied to adjust PID controller parameters. This approach enables the determination of values that meet the closed-loop system's transient and steady-state requirements. However, for complex systems where the model is difficult to tune, finding suitable parameters (Kp, Ki, Kd) can be challenging. This paper presents a solution to this tuning difficulty by using a fuzzy logic technique, which effectively addresses the complexities of such systems.

4. Ziegler-Nichols Tuning Rule Based on Critical Gain K_{cr} and Critical Period P_{cr}

In the second method of Ziegler-Nichol's tuning, to solve the tuning problem, the integral time (Ti) is set to infinity, and the derivative time (Td) is set to zero. This means that only proportional control is applied. The proportional gain $K_p$is gradually increased from zero until the system output begins to oscillate continuously, indicating the critical gain Kcr. Once this critical gain and the corresponding oscillation period Pcr are determined, Ziegler and Nichols provide formulas to calculate the values of K_p,Ti, and Td, as shown in Table 1

Table 1 Ziegler Nichols Tuning Rule

Type of controller	Kp	T_i	T_d
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$\frac{1}{1.2}P_{cr}$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

$$G_s(s) = K_p(1 + \frac{1}{sT_i} + sT_d) \qquad (12)$$

By using Table 1 Transfer function is written as

$$G_s(s) = 0.6K_{cr}(1 + \frac{1}{0.5sP_{cr}} + 0.125sP_{cr}) \qquad (13)$$

By using Routh Harwitz stability criterion and solving, we get
K_P=39.4198 T_i=3.069 T_d = 0.7685

By using MATLAB Program for a unit step PID controller system, the response of the system after tuning is shown in the Figure 3

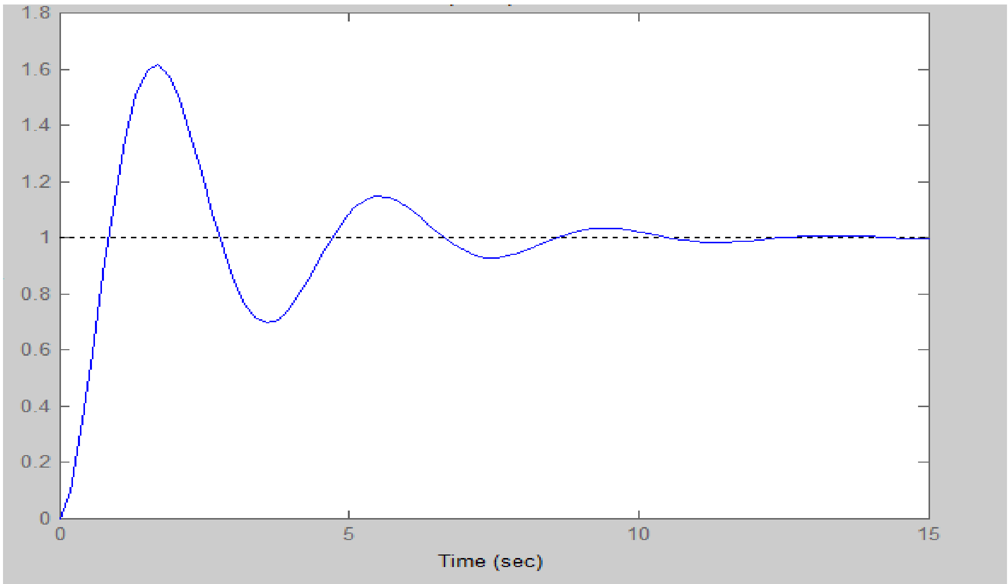


Fig. 3 : Response of the system after tuning by Ziegler-Nichols' method

The result of the graph is Maximum overshoot M_p=65%. Delay time T_d = 0.51sec.
Rise Time Tr = 0.852sec. Peak time T_P =1.65sec. Settling time T_s=12.6sec.
From Figure 3, after tuning with Ziegler-Nichols' method the response of the system gets stable after 12.6 sec. The graph is not satisfactory, so we need some other tuning techniques to improve the result. Ziegler-Nicholas tuning rules (and other tuning rules presented in the literature) have been widely used to tune PID controllers in process control systems where the plant dynamics are not precisely known. Over many years, such tuning rules proved to be very useful. Ziegler-Nicholas tuning rules can, of course, be applied to plants whose dynamics are known. If plant dynamics are known, many analytical and graphical approaches to the design of PID controllers are available, in addition to Ziegler-Nicholas tuning rules.

5. FUZZY LOGIC PROPORTIONAL INTEGRAL DERIVATIVE (FLPID) CONTROLLER DESIGN

Designing of FLPID Controller for the proposed modal. The FLPID controller in a closed-loop control system is shown below in Figure

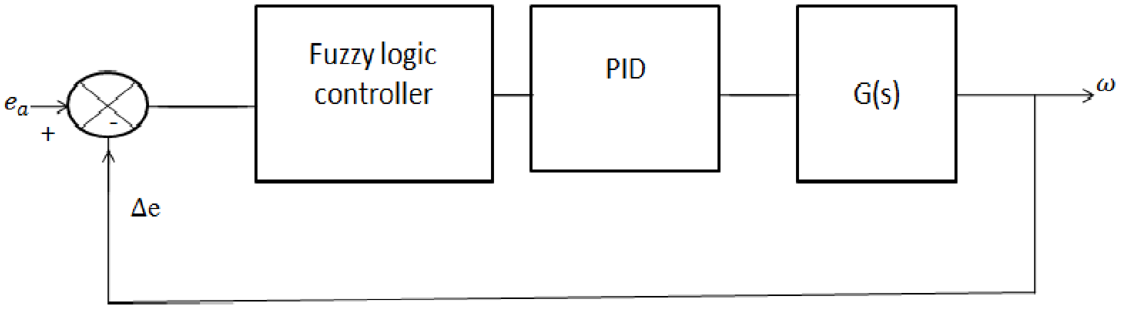


Fig 4: Block diagram of System with FLPID

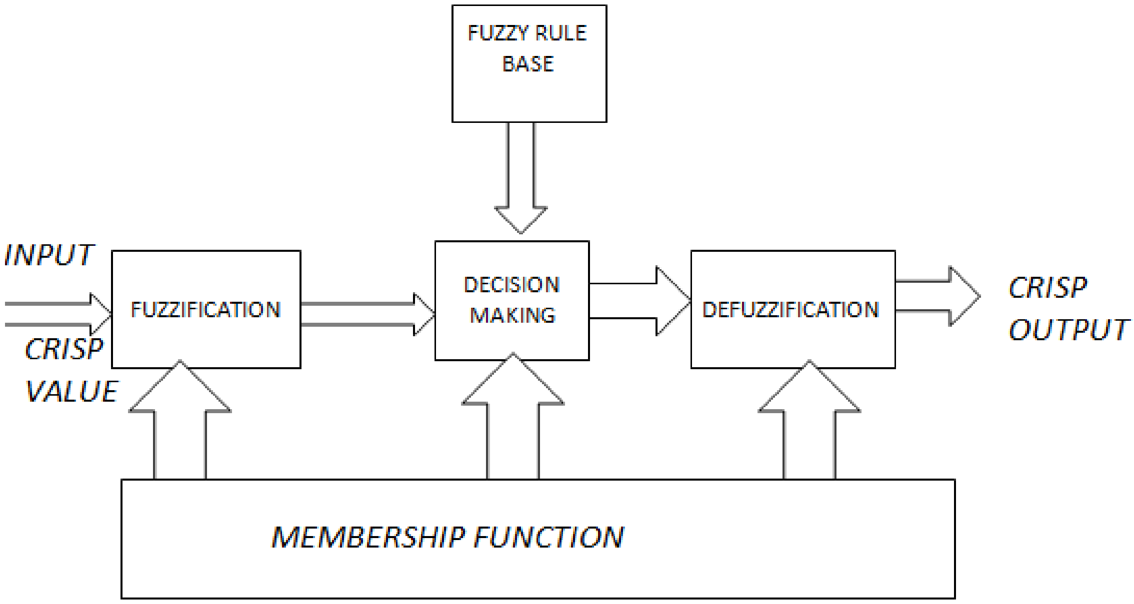


Fig. 5: Block diagram of Fuzzy inference unit (FIU)

Figure 5 shows a block diagram of Fuzzy inference. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made or patterns discerned. The process of fuzzy inference involves all of the pieces that are described in the membership function, logical operation, and if-then
rules.

5.1 Fuzzification

The process of fuzzification is to transformation of crisp input to the fuzzy input for example if anyone want to convert the height of human being which is a crisp value that may varies from 2 feet to 7 feet into a membership function which varies from 0 to 1, so the person below 2 feet and above 7 feet is not consider in this particular membership function. The maximum crisp value of this case is 7 feet, so the fuzzy value of this is 1 similarly the person whom height is 3.5 feet, the value of fuzzy is 0.5 in this way the membership may be framed so height may define as very high (VH), medium (ME), short (SH), and very short (VS), for the proposed.

FLPID controller the membership function is defined as fuzzy sets: NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), and PM (Positive Medium). Each fuzzy variable is a member of the subsets with a degree of membership μ varying between 0 (non-member) and 1 (full member). All the membership functions have an asymmetrical shape with more crowding near the origin (steady state). This permits higher precision at Steady State. Fuzzy rules for input voltage and change in voltage (Kp, Kd , Ki) is given in Tables 3, 4, and 5. Table 2 shows the fuzzy logic algorithm

5.2 Fuzzy logic algorithm

Table 2: Fuzzy logic algorithm

	Fuzzy Logic algorithm
1	Define linguistic variable and term
2	Build MF (Membership Function)
3	Configure rule base
4	Transform crisp data to fuzzy value with help of MF
5	Judge the rule in rule base
6	Merge the result of each rule
7	Transform output data to non-fuzzy values

1) Linguistic sets (for both inputs)

Use the same five terms for error e and change of error Δe:

- NM = Negative Medium
- NS = Negative Small
- ZO = Zero
- PS = Positive Small
- PM = Positive Medium

2) Design rule

Let the control action trend with the "sum" of e and Δe. Map NM=-2, NS=-1, ZO=0, PS=1, PM=2, then index(output)≈index(e)+index(Δe) clamped to [−2,2]

3) Inference & defuzzification

- Inference: Mamdani min–max.
- Defuzzification: Centroid (CoG).
- Tuning: adjust:(input scaling) and (output scaling).

4) If-then rule examples for column one

- IF e is NM AND Δe is NM THEN output is PM.
- IF e is NS AND Δe is NM THEN output is PM.
- IF e is ZO AND Δe is NM THEN output is PM.
- Similarly, **all column is developed for** K_P K_i K_d

Table 3: Fuzzy Rule defied for Kp

e ↓ Δe →	NM	NS	ZO	PS	PM
NM	PM	PM	PS	PS	ZO
NS	PM	PM	PS	ZO	NS
ZO	PM	PS	ZO	NS	NM
PS	PS	ZO	NS	NS	NM
PM	ZO	NS	NM	NM	NM

Table 4: Fuzzy Rule defied for Ki

e ↓ Δe →	NM	NS	ZO	PS	PM
NM	NM	NM	NS	NS	ZO
NS	NM	NS	NS	ZO	PS
ZO	NM	NS	ZO	PS	PM
PS	NS	ZO	PS	PS	PM
PM	ZO	PS	PS	PM	PM

Table 5: Fuzzy Rule defied for Kd

e ↓ Δe →	NM	NS	ZO	PS	PM
NM	NS	NM	NM	NM	NS
NS	NS	NM	NM	NS	NS
ZO	NS	NS	NS	NS	NS
PS	ZO	ZO	ZO	ZO	ZO
PM	PS	PS	PS	PS	PS

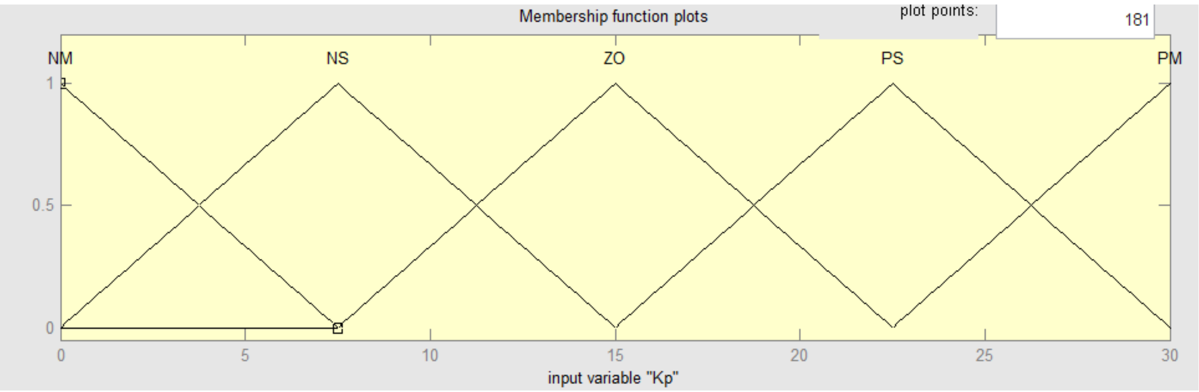


Fig. 6: Membership Function plots for input Kp.

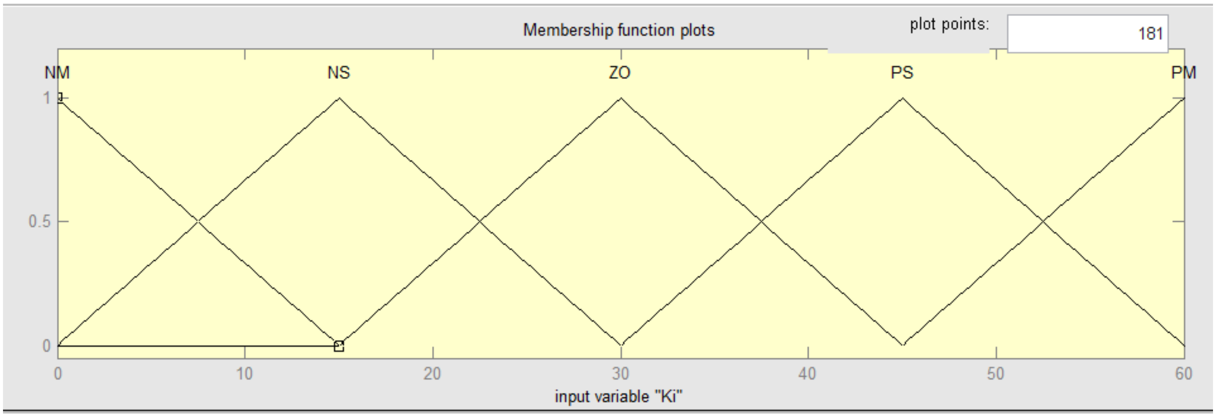


Fig. 7: Membership Function plots for input Ki

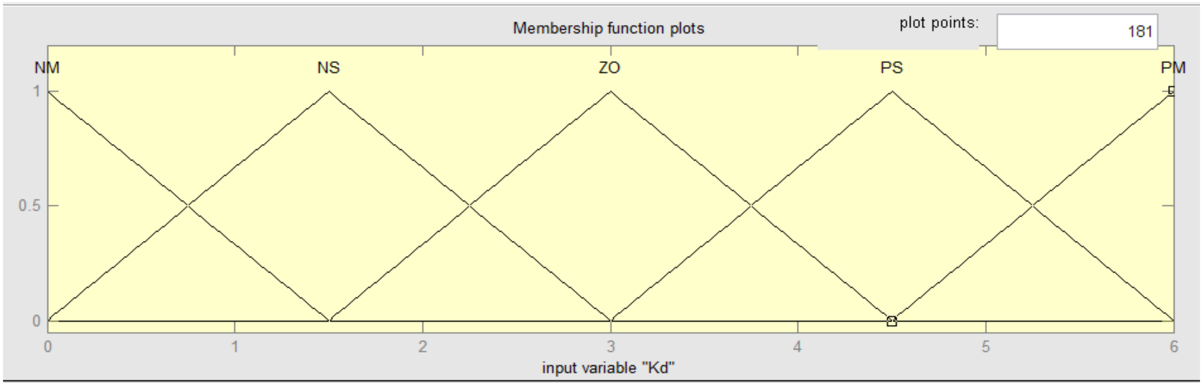
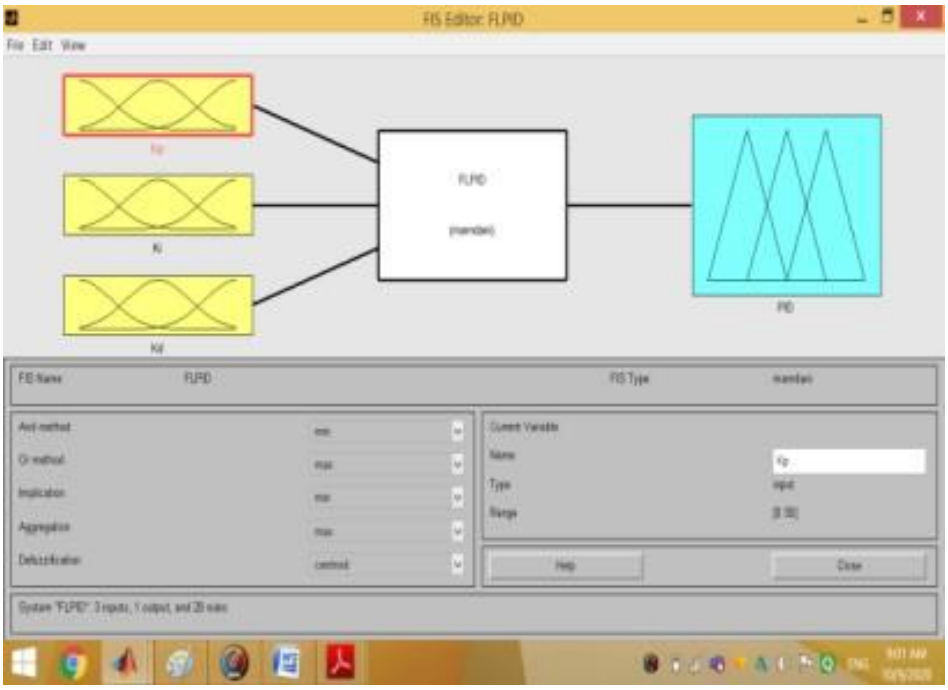


Fig. 8: Membership Function plots for input Kd

5.2 Determination of Rule for FLPID

The input variable and output variable is governed by certain rule which is defined in FIS editor for FLPID, as shown in Fig. 9. If the rule is fed in the Mamdani block shown in white colour in the FIS editor after defining 25 rules Table 3 the graph of the rule is observed in Figure 6 for **Kp,** and similarly, by using Table 4 and Table 5 graph of the membership function of Ki and Kd fig 7 and fig 8, Similarly, Membership Function plots for the output PID controller are plotted by using MATLAB Fig 10



FIS Name FLPID
FIS Type mamdani
And method min
Or method max
Implication min
Aggregation max
Defuzzification centroid
Current Variable
Name Kp
Type input

Fig 9: FIS Editor for FLPID.

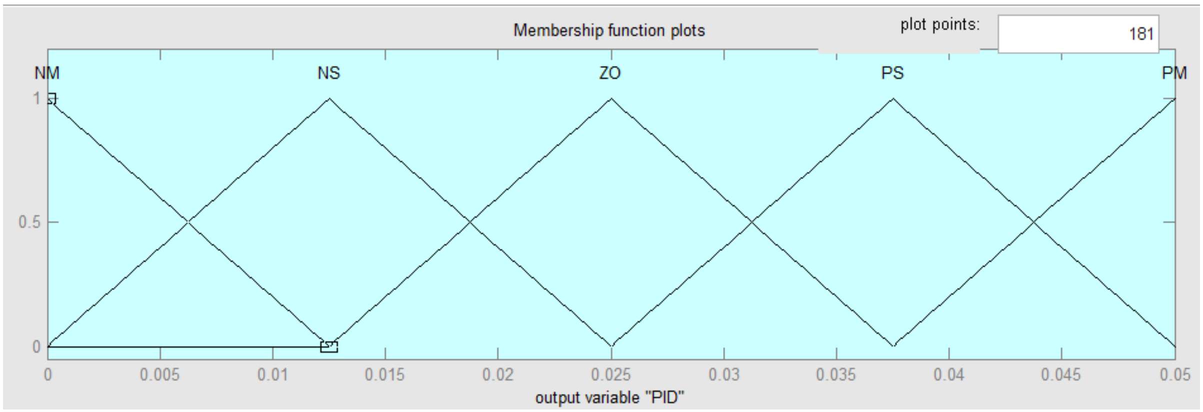


Fig. 10: Membership Function plots for output PID controller

5.3 Defuzzification

There are many defuzzification methods, but the most common methods are as follows:

- Mean of maximum (MOM) Technique
- Centre of gravity (COG) Technique
- Bisector of area (BOA) Technique
- Smallest of maximum (SOM) Technique

5.4 Advantages

There are many advantages of Fuzzy logic to controlling devices as compared to other control techniques. Some are: -

1. Fuzzy logic is an accurate problem-solving Technique
2. It can handle big numerical data and linguistic knowledge.
3. A technique that facilitates control of a complicated system without knowledge of its mathematical description.
4. Fuzzy logic differs from classical logic in that statements are no longer black or white, true or false, on or off.

In traditional logic, an object takes on a value of either zero or one. In fuzzy logic, a statement can assume any real value between
0 and 1, representing the degree to which an element belongs to a given set.

1. A computational paradigm that is based on how humans think
2. Fuzzy logic looks at the world in imprecise terms, in much the same way that our brain takes in information (e.g., temperature is hot, speed is slow), then responds with precise actions.
3. The human brain can reason with uncertainties, vagueness, and judgments. Computers can only manipulate precise valuation.

Fuzzy logic is an attempt to combine the two techniques.

6. SIMULINK IMPLEMENTATION GAIN INTEGRATAR

In this section, the **FLPDI** model is designed by using MATLAB, as shown in Figure 11. To design the model, the Integrator. Derivative, gain, fuzzy logic controller block is selected from Simulink library browser and drag to workspace and for testing unit step signal is applied, and summer is added to give feedback to summer with and output signal is observed in scope transfer function block differentiator gain summer is drag to workspace and model is formed as shown in the figure 11. The input test signal is given by using unit step test signal a summer is added to take the feedback signal.

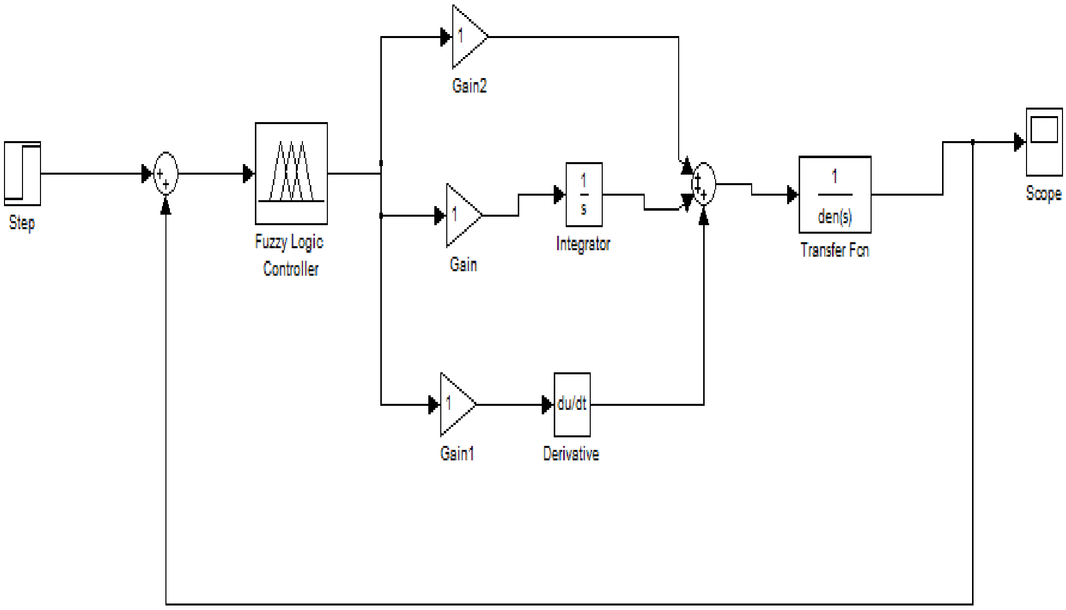


Fig. 12: Output of the scope

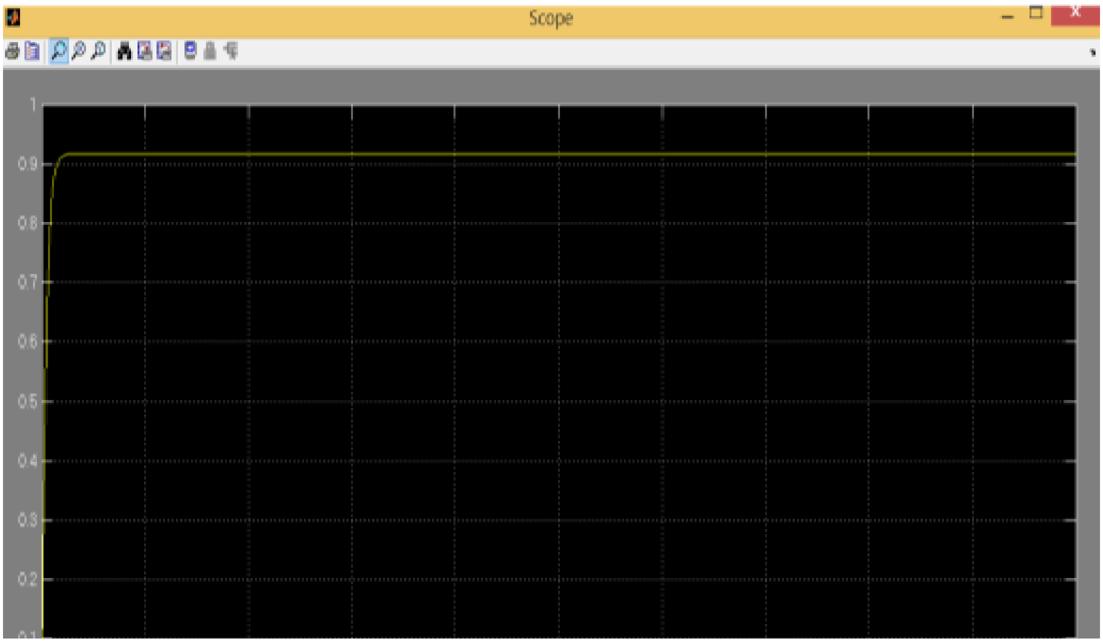


Fig. 11: FLPID control system

7. CONCLUSION

This study proposed a fuzzy logic-based approach for tuning PID controllers, aiming to enhance system performance. Comparative analysis between the fuzzy logic-tuned PID (FLPID) controller and a traditionally tuned PID controller (using the Ziegler-Nichols method) was conducted, with simulations modelled in MATLAB/Simulink. The fuzzy-tuned PID approach effectively addressed limitations associated with the Ziegler-Nichols method, resulting in a controller with improved gain (illustrated in Figure 12) over the conventional method (Figure 3). Key performance metrics, including rise time, peak time, delay time, settling time, and maximum overshoot, demonstrated significant improvement when using the FLPID controller. Overall, simulation results validate the superior performance and responsiveness achieved by the fuzzy logic-based tuning method.

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