DEVELOPMENT OF A FUZZY LOGIC–INTEGRATED PID MODEL FOR DC MOTOR SPEED CONTROL

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ABSTRACT
A fuzzy logic–assisted PID controller has been designed in this work to achieve effective speed control of a DC motor. The proportional, integral, and derivative gains (Kp, Ki, Kd) of the PID controller are tuned using a fuzzy logic mechanism. The fuzzy logic controller (FLC) is constructed with rule sets to enable self-adjustment of each PID parameter. The controller uses two input signals: the speed deviation, defined as the difference between the desired and actual motor speed, and the derivative of this error. and the rate of change of error. The outputs of the FLC are the tuned PID gains, which are then applied for precise motor speed regulation.

Keywords: *Fuzzy Logic, PID Controller, Fuzzy logic controller (FLC)*

INTRODUCTION

DC motors are widely used because they offer high starting torque, smooth speed control over a broad range (both below and above the rated speed), and precise, stepless control at constant torque. They also provide quick starting, stopping, reversing, and acceleration, along with high reliability. Furthermore, they enable excellent speed regulation during both acceleration and braking, making them suitable for applications requiring precise dynamic control.

To regulate the speed of a DC motor for various tasks, several control strategies have been developed, among which PID control remains one of the most widely used. However, conventional PID controllers often exhibit steady-state errors or reduced performance if the parameters are not tuned properly. The objective of this paper is to enhance the performance of traditional PID control by employing a fuzzy logic–based tuning approach.
PID controllers are popular due to their simplicity, robustness, and reliable performance of
A controller. [1]
when the proportional, integral, and derivative gains are appropriately adjusted. In recent years, fuzzy logic–based techniques have gained significant attention in research and industrial applications. Introduced by Lotfi A. Zadeh in 1965 and later developed for control applications by Mamdani in 1975, fuzzy logic control (FLC) has proven to be an effective tool in handling nonlinear and uncertain systems. In a fuzzy logic PID controller, the error and the change in error are typically used as inputs for generating adaptive control actions.[2]

Related Works

Control of speed can be achieved using different methods

Armature Voltage Control

In a separately excited DC motor, the armature voltage can be adjusted while keeping the field current constant. Changing the applied voltage alters the no-load speed, producing a family of speed–torque curves that are parallel to each other. The most basic way to obtain a variable DC voltage is by using a voltage divider, but this approach is inefficient and only suitable for laboratory testing. In practical applications, controlled rectifiers are commonly employed to supply variable DC voltage to the armature, while the field winding is powered by an uncontrolled rectifier. For smoother and more flexible speed regulation, the Ward-Leonard system is also widely used. A DC motor can be supplied by a DC generator that is driven by a prime mover, such as an AC motor or a diesel engine. By adjusting the excitation of the generator field, the motor's armature voltage can be controlled and even reversed if required. The motor's field winding is typically energized from an exciter (a smaller DC generator) or a rectifier operating at constant voltage. Although the Ward–Leonard system is costlier compared to modern solid-state drives, it offers unique advantages that make it suitable for specific applications.

Field Control

When resistance is added to the field circuit, the field current decreases, resulting in a weaker main field. As the flux reduces, the motor speed increases. Increasing the field resistance raises the no-load speed and makes the speed–torque characteristic steeper. However, the field strength cannot be weakened indefinitely, as excessive speed may damage the motor. In addition, if the field becomes too weak, the armature reaction produces a stronger demagnetizing effect, which can cause instability in motor operation.[3}

Proportional-Integral-Derivative (PID) Controller

The PID controller is a vital element in embedded systems and is extensively utilized in diverse applications, including motor drives, automotive systems, flight navigation, and instrumentation. Despite its popularity, tuning the controller parameters remains a complex task, often leading to inadequate robustness and difficulty in attaining optimal performance under real production environments.[2]

Proposed Solution

The nonlinear behaviour of a DC motor, such as magnetic saturation and friction, can reduce the effectiveness of conventional controllers. Since traditional controllers are designed with fixed structures and constant parameters, they often face challenges in tuning and optimization, especially under varying operating conditions. To address these limitations, fuzzy logic controllers (FLCs) have been introduced. Unlike classical logic systems, fuzzy logic can handle uncertainty and imprecision in system modelling.

The fuzzy control approach provides a simpler, faster, and more robust solution compared to conventional methods. In practice, FLCs are widely employed for higher-level control tasks that are difficult to achieve with traditional techniques. They enable the system to produce accurate outputs in a shorter response time, with reduced overshoot, minimal steady-state error, shorter settling time, and faster rise time—features that are highly valuable in industrial applications.

Separately Excited Dc Motor Modeling

In motor modeling, the objective is to derive the governing differential equations that connect the applied voltage with the resulting torque or rotor speed. Figure 1 illustrates the equivalent circuit under armature voltage control along with the mechanical system model, which represents both the motor's mechanical parameters and the load coupled to it. For simplicity, the effect of armature reaction is neglected in this analysis. The field winding is supplied with a constant voltage V_f causing the field current to stabilize at a fixed value. Thus, a simplified linear model of a DC motor can be represented by two equations: an electrical equation and a mechanical equation. The motor is coupled to a mechanical load defined by a moment of inertia J and a viscous friction coefficient B. A variable voltage is supplied to the armature, and the following parameters are considered for the subsequent calculations.

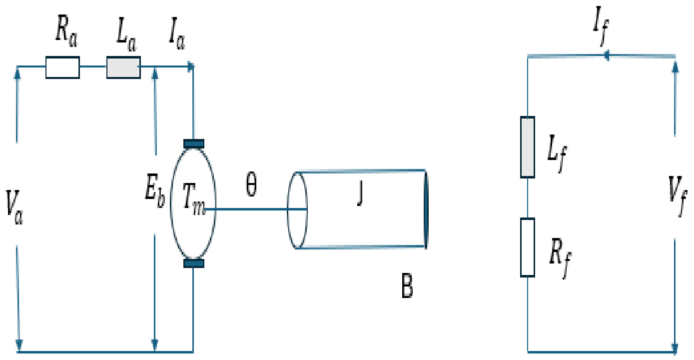

Figure 1. Diagram of DC motor model for speed control

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

$$T_m = K_1 K_f i_f i_a \quad (1)$$

The electromagnetic torque developed in the air gap is given by

$$T_m = K i_a \quad (2)$$

Back emf is given by

$$e_b = K_b \frac{d\theta}{dt} \quad (3)$$

Applying KVL equation in the armature loop

$$L\frac{di_a}{dt} + R i_a + e_b - e_a = 0 \quad (4)$$

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

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

Applying the Laplace Transform on the above equation transfer function is derived as equation (6)

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

V Proportional-Integral -Derivative (PID) Controller

A PID Controller produces an output signal consisting of three: one proportional to the error signal. One term is proportional to the integral of the error signal, while another term is proportional to its derivative."

The combination of proportional controller action, integral controller action, and derivative control action is called PID control action. Combined action has the advantage of three Individual control actions.

The proportional controller helps stabilize the system gain; however, it results in a steady-state error. The Integral controller reduces and eliminates Steady-state error. The derivative controller reduces the rate of Change of error. The main advantages of the PID controller are higher stability, no offset, and reduced overshoot. The PID controller's acquitting signal or output signal is higher stable, has no offset, and has diminished overshoot.

PID controllers are used in process control industries. The actuating signal or output signal from a PID controller in the time domain is given by

$$e_a = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de}{dt} \quad (7)$$

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

$$E_a(s) = \left(K_P + \frac{K_I}{s} + K_D s\right) E(s) \quad (8)$$

Figure 2 show Speed control of a DC motor by using a PID controller

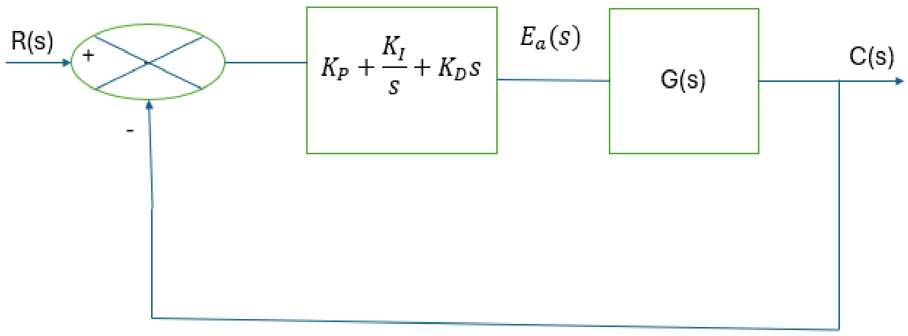

Figure 2. Block diagram of a PID Controller for speed control of DC Motor

As a core component of embedded systems, the PID controller governs a wide spectrum of control processes, ranging from motor drives and automotive applications to flight control and precision instrumentation. Nonetheless, parameter tuning is inherently difficult, resulting in challenges related to robustness and optimal operation in practical production settings.

Fuzzy Inference System

A Fuzzy Inference System (FIS) represents the process of mapping inputs to outputs using the principles of fuzzy logic. These systems have found extensive applications in areas such as automatic control, pattern classification, decision-making, expert systems, and computer vision. There are two commonly used types of FIS: Mamdani-type and Sugeno-type.

In the Mamdani approach, the output is determined by computing the centroid of a two-dimensional membership function, which requires integration over a continuous domain.

In the Sugeno approach (proposed by Michio Sugeno), the consequent of each rule is represented by a fuzzy singleton. A singleton is essentially a fuzzy set that takes a membership value of one at a single point in the universe of discourse and zero elsewhere.

The use of a fuzzy logic controller (FLC) becomes particularly useful in situations where:

The system or process can only be described linguistically rather than analytically.

1. The process parameters cannot be precisely identified.
2. The system is too complex for a precise mathematical model, making a verbal description more practical.

The control objective is better defined using qualitative rather than quantitative terms.

Fuzzy Controller

Fuzzy logic control is a technique that applies a rule-based, linguistic strategy—developed from expert knowledge—to automatically regulate a system. Instead of relying solely on mathematical models, it uses human-like reasoning expressed in terms of fuzzy rules.

A general block diagram of a fuzzy control system (Figure 3) shows that the fuzzy controller is composed of four main components:

1. Fuzzification Module – Converts crisp input values into fuzzy sets using membership functions.
2. Rule Base – Stores the collection of fuzzy IF–THEN rules derived from expert knowledge or system behavior.
3. Inference Engine – Performs reasoning using the rules and the fuzzified inputs to determine the fuzzy output.
4. Defuzzification Module – Transforms the fuzzy output of the inference engine back into a crisp (numerical) control signal to drive the system.

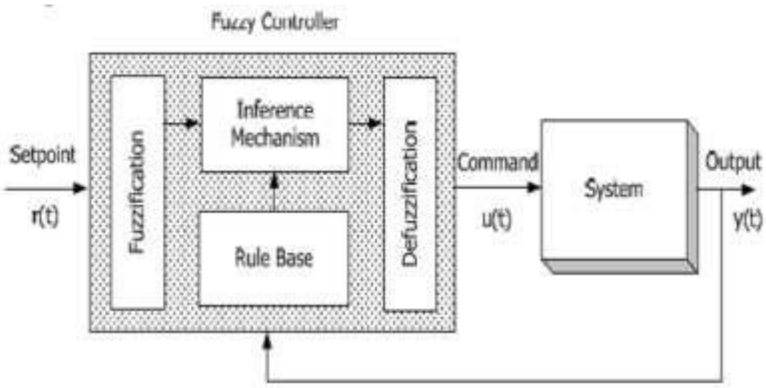

Figure 3. Structure of Fuzzy Logic controller

Rule-based designed

The rule base represents the decision-making logic of a fuzzy controller, mimicking human reasoning by applying a set of control rules defined through linguistic variables. These rules are generally expressed in the IF–THEN format, where the IF part specifies the condition and the THEN part specifies the resulting action.

In operation, the controller evaluates the measured inputs—such as the error (eee), which is the difference between the reference (set point) and the actual output speed, and the change in error Δe to determine the control output, which typically adjusts the armature voltage.

The control strategy in a rule-based fuzzy controller is stored in a form that closely resembles natural language, making it intuitive, easy to understand, and simple to modify even by non-specialist users. Although a similar control strategy could be designed using conventional methods, the fuzzy approach offers greater flexibility and clarity.

In this work, a 7×7 rule table (49 rules) is employed, where the rules use linguistic variables such as:

1. Negative Big (NB)
2. Negative Medium (NM)
3. Negative Small (NS)
4. Zero (Z)
5. Positive Small (PS)
6. Positive Medium (PM)
7. Positive Big (PB)

The full 49-rule base for 7×7 fuzzy speed controller with 5 possible outputs (VL, L, M, H, VH).

Rows = Error (e), Columns = Change of Error (Δe)

Row 1 (e = NB):

1. IF (e = NB) AND (Δe = NB) THEN Output = VL
2. IF (e = NB) AND (Δe = NM) THEN Output = VL
3. IF (e = NB) AND (Δe = NS) THEN Output = L
4. IF (e = NB) AND (Δe = Z) THEN Output = L
5. IF (e = NB) AND (Δe = PS) THEN Output = M
6. IF (e = NB) AND (Δe = PM) THEN Output = H
7. IF (e = NB) AND (Δe = PB) THEN Output = VH

Row 2 (e = NM):

8. IF (e = NM) AND (Δe = NB) THEN Output = VL
9. IF (e = NM) AND (Δe = NM) THEN Output = L
10. IF (e = NM) AND (Δe = NS) THEN Output = L

11. IF (e = NM) AND (Δe = Z) THEN Output = M

12. IF (e = NM) AND (Δe = PS) THEN Output = M
13. IF (e = NM) AND (Δe = PM) THEN Output = H
14. IF (e = NM) AND (Δe = PB) THEN Output = VH

Similarly, all seven rows are designed, and the table I is designed

Table 1. 7×7 Fuzzy Rule Table for DC Motor Speed Control

Δe ⇒ / e ⇓	NB	NM	NS	Z	PS	PM	PB
NB	VL	VL	L	L	M	H	VH
NM	VL	L	L	M	M	H	VH
NS	L	L	M	M	H	H	VH
Z	L	M	M	M	H	H	VH
PS	M	M	H	H	H	VH	VH
PM	M	H	H	H	VH	VH	VH
PS	H	H	H	VH	VH	VH	VH

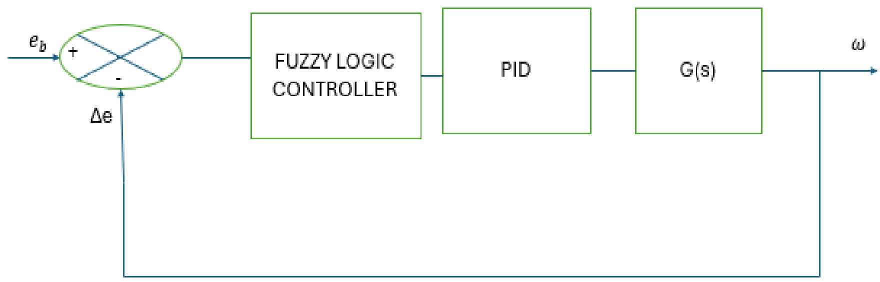

Figure 3. Block diagram of the System with FLPID

RESULTS AND DISCUSSION

To achieve the objective of this study, which focuses on the speed control of a DC motor, the system will first be represented through its mathematical model to describe its dynamic characteristics. Based on this model, a suitable control strategy will be designed and implemented using MATLAB simulations, allowing for performance analysis and verification of the proposed approach

CONCLUSION

In this study, PID and fuzzy controllers were developed for the speed regulation of a separately excited DC motor. A rule-based model was formulated to implement the fuzzy control approach, ensuring effective decision-making in the control process.

REFERENCES

1. Shaker Mm, Al-Khashab Ym. Design And Implementation Of Fuzzy Logic System For Dc Motor Speed Control. In2010 1st International Conference On Energy, Power And Control (Epc-Iq) 2010 Nov 30 (Pp. 123-130). Ieee.
2. Natick, Fuzzy Logic Toolbox User's Guide, 1995 – 1999.
3. Almatheel, Yasser Ali, And Ahmed Abdelrahman. "Speed Control Of Dc Motor Using Fuzzy Logic Controller." 2017 International Conference On Communication, Control, Computing And Electronics Engineering (Iccccee). Ieee, 2017.
4. Y. A. Almatheel And A. Abdelrahman, "Speed Control Of Dc Motor Using Fuzzy Logic Controller," 2017 International Conference On Communication, Control, Computing And Electronics Engineering (Iccccee), Khartoum, Sudan, 2017, Pp. 1-8, Doi: 10.1109/Iccccee.2017.7867673.

5. Hameed, W.I. And Mohamad, K.A., 2012. Speed Control Of Separately Excited Dc Motor Using Fuzzy Neural Model Reference Controller. International Journal Of Instrumentation And Control Systems (Ijics), 2(4), Pp.27-39.