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# Fuzzy Logic Speed Regulator for D.C. Motor Tuning

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## ABSTRACT

A D.C. motor's rotational speed is regulated in this study using a PID controller and a fuzzy logic controller. In contrast to the fuzzy logic controller, which uses rules based on knowledge and experience, the proportional-integral-derivative (PID) controller requires a mathematical system model. This study investigates the regulation of a DC motor's velocity using PID and fuzzy logic controllers. The PID controller utilizes a mathematical model and parameter tuning by trial and error. Still, the fuzzy logic controller (FLC) operates on rule-based knowledge, enabling it to handle the nonlinear features of the DC motor effectively. The FLC design entails intricate determinations, including the establishment of a rule base and the process of fuzzification. A total of 49 fuzzy rules have been devised to achieve precise control. Based on MATLAB/SIMULINK simulations, the study concludes that the Fuzzy Logic Controller (FLC) beats the Proportional-Integral-Derivative (PID) controller. The FLC exhibits superior transient and steady-state responses, shorter response times, reduced steady-state errors, and higher precision. This study emphasizes the efficacy of the FLC (Fuzzy Logic Controller) in dealing with the difficulties associated with DC motor control. It presents a strong argument for the suitability and efficiency of FLCs in industrial environments compared to conventional PID (Proportional-Integral-Derivative) controllers. There are a wide variety of ways to construct a fuzzy logic controller. The speed error and the rate of change in the speed error are two inputs to the FLC. Defuzzification is done by focusing on the core of the problem. The results show that FLC is superior to PID controllers in efficiency and effectiveness due to its reduced transient and steady-state factors.

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## A. INTRODUCTION

Almost all of the mechanical actions we observe in the world are driven by electric motors. Energy can be transformed through the use of electric machinery. Electrical energy is converted into mechanical energy by engines. Electric motors power numerous commonplace items. Direct Current (D.C.) and Alternating Current (A.C.) electric motors are the main types. There is a wide variety of the kinds inside these umbrella categories, each with its characteristics and strengths. Electric motors rely on the magnetic flux and electric current interaction between the stator (the stationary field) and the rotor (the rotating field or armature) to generate rotational speed and torque. (Maarif & Setiawan, 2021; Mandal & Sikdar, 2019) (Hambley, 2011).

Almatheel & Abdelrahman (2017) A recent study examined the regulation of a DC motor's speed using both PID and Fuzzy Logic Controllers (FLC). The comparison study in the relevant research demonstrated that the FLC outperformed other systems regarding time characteristics. The FLC demonstrated superior performance compared to the typical PID controller in terms of rising time (0.8600 vs. 0.9727), settling time (2.6821 vs. 2.9848), and overshoot (0.008264% vs 0.120000%). In addition, the PID controller reached its peak value at time 1, but the FLC reached its peak value at time 2. This thorough assessment establishes a standard for our research, in which the goal is to exceed these accuracy criteria by further refining the Fuzzy Logic Controller to achieve greater precision and efficiency in the regulation of DC motor speed.

Controllers ensure that the system operates in a predetermined, desirable manner over an extended period. The fuzzy logic controller is one example. Using a nonlinear defuzzification technique, it was shown analytically that a Fuzzy Logic Controller (FLC) is comparable to a nonlinear controller. Fuzzy logic can mitigate nonlinear effects in a D.C. motor and boost controller performance, as evidenced by comparing traditional control methods and the FLC and fuzzy compensator (El-Shimy & Zaid, 2016; Wang et al., 2022; Xin et al., 2010) (Shaker & Al-Khashab, 2010). The fuzzy logic toolbox is fantastic for use with a fuzzy controller. This opens up the possibility of using fuzzy logic to create truly intelligent systems. The fuzzy logic toolkit is simple to learn and implement. Last, but not least, it gives an accessible and contemporary overview of the fuzzy logic technique and its many uses. (Jang & Gulley, 2015).

Various methods exist for regulating speed, first the field can be held constant while the armature voltage is changed in a separately stimulated motor. Then, varying the voltage produces a range of mechanical c/s with similar slopes but different intercepts (no-load speeds). The cheapest and most convenient way to generate changeable D.C. voltage is via a voltage divider (Hilal et al., 2023). Still, this setup could be more efficient, so it's rarely utilized outside the testing phase. In contemporary applications, the field is often fed by an uncontrolled rectifier while the armature is supplied with changing D.C. voltage by a solid-state controlled rectifier. The Ward Leonard technique is another reliable approach for achieving steady voltage regulation. A prime mover (such as an ac motor or diesel engine) powers a dc generator, which supplies power to the dc motor (Al-Khaykan et al., 2023). The motor's armature voltage was changed (and even stored) by adjusting the generator's field excitation. An exciter (small D.C. generator) or rectifier supplies a steady current to the motor field. However, there are situations in which the Ward-Leonard system's higher cost is justified by its benefits.

By decreasing the field current and the main field, raising the resistance of the field circuit causes the speed to increase. The c/s curve flattens, and the intercept and slope rise with increasing field resistance. Infinitely decreasing the flow risks damaging the engine due to the excessively low rate. If the main field is sufficiently weak, the demagnetizing effect of the armature reaction could become noticeable (very large), perhaps leading to instability (García-Martínez et al., 2020) (Maldonado & Castillo, 2012).

PID controllers are a common solution to various issues such as motor drive, automotive, aviation control, and instrumentation. It is challenging to tune the PID controller's parameters, the controller could be more durable, and it is hard to reach an optimal state in actual production when operating in the field (Rahmati & Ghorbani, 2018; Somwanshi et al., 2019) (Kaur & Patel, 2019; Nishat et al., 2019) ("Marks' Standard Handbook for Mechanical Engineers," 1997).

Conventional controllers may suffer from performance degradation due to the nonlinear features of a D.C. motor. Due to the constraints and difficulties traditional controllers face in dealing with the nonlinear properties of a D.C. motor, it is crucial to conduct immediate research to investigate alternate control methods. The rigidity of conventional controllers with predetermined parameters requires a transition towards inventive alternatives. Using a fuzzy logic controller (FLC) arises as an appealing substitute, providing the ability to simulate imprecise and nonlinear systems. The FLC offers a more adaptable and efficient approach, delivering a more straightforward, quicker, and dependable solution than traditional approaches. This research is crucial in tackling the urgent demand for controllers that can promptly and precisely adapt to the changing demands of industrial applications while limiting excessive response, decreasing errors, and improving the time it takes to stabilize and reach desired levels.

## B. METHODOLOGY

The purpose of modeling is to find the governing differential equations that relate input voltage to torque or rotor speed (Hameed, 2012). In Figure.1, we see a model of a generic automated system that considers the mechanical characteristics of the motor and the mechanism to which it is coupled. The armature voltage-controlled equivalent circuit is depicted here. The effect of armature reactions should be mentioned in the motor's description. The constant voltage results in a stable field current when applied to the field. The linear model of a fundamental D.C. motor consists of two mechanical and one electrical equation. (Li et al., 2021), as shown in Figure 1.

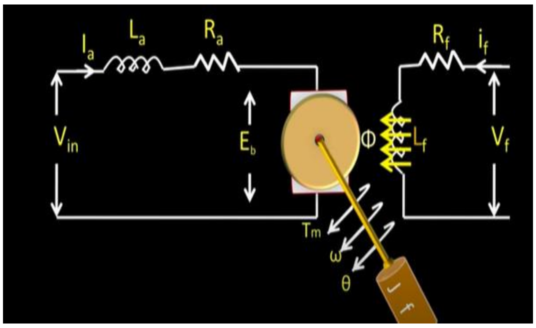

**Figure 1**. D.C. motor equivalent circuit for a non-commutated excitation system

Parameters Explanation: $E_b$ = (Back emf, (volt)); $R_a$ = (Resistance of armature, (in Ohm)); $R_f$ = (Resistance of field); $L_a$ = Inductance of armature winding; $I_a$ = (Armature Current); Various parameters in figure are described as $T_m$ is the motor torque; $\omega$ is the resulting angular velocity. Using the schematic in Figure (1), we can apply Kirchhoff's Voltage Law (KVL) to the circuit. All of these are writable.

$$E_a(t) = R_a . I_a + L_a \frac{di_a}{dt} + K_b . w(t) \tag{1}$$

The armature's voltage $(E_a)$, the current $(I_a)$, the resistance $(R_a)$, the inductance $(L_a)$, and the back EMF $(e_b)$ are all denoted in volts. The electrical equation in (1) can be written as where $e_b$(t) is set equal to $K_b . w(t)$. The produced torque must be greater than the sum of the load torque and the friction and inertia forces for the system to function normally.

$$T_m(t) = J_m . \frac{dw(t)}{dt} + B_m . w(t) + T_L \tag{2}$$

where $T_m$motor torque in Newton is meters, $J_m$ is rotor inertia in kilograms per square meter, $w$ is the angular velocity in degrees per second, $B_m$ is viscous friction coefficient in Newton meters per degree per second, and $T_L$ is load torque in Newton meters. Setting $T_m(t)$ equal to $K_T .\ I_a$ and $T_L\ =\ 0$ yields; Taking the Laplace transforms yields.

$$E_a(s) = R_a(s) . I_a(s) + L_a I_a(s) + K_b . w(s) \tag{3}$$

$$K_T .\ I_a(s) = J_m . w(s) + B_m . w(s) \tag{4}$$

current obtained form as

$$I_a(s) = J_m . w(s) . s + B_m . w(s) \tag{5}$$

And then substituted in (3) get.

$$E_a(s) = \frac{w(s)}{K_T} [(R_a . J_m . s + R_a . B_m) + (L_a . J_m . s^2 + L_a . B_m . s) + K_b . K_T] \tag{6}$$

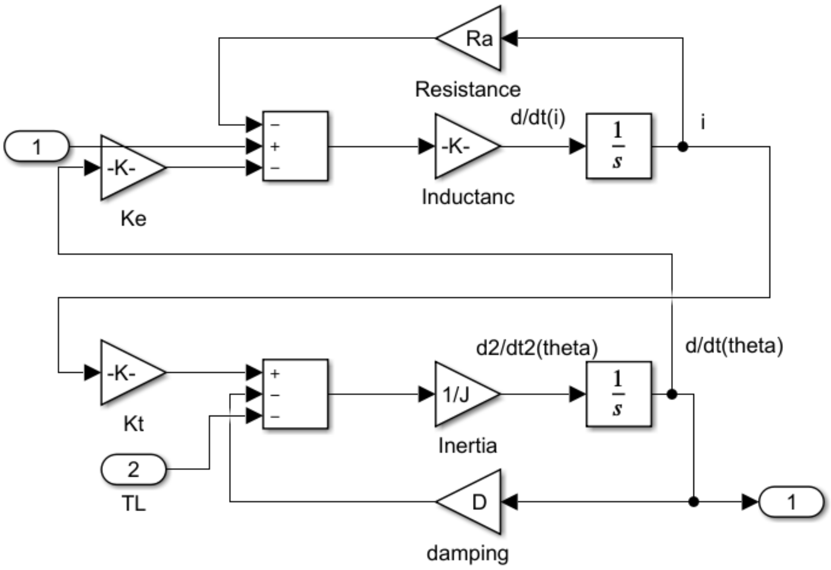

**Figure 2**. D.C. motor with two sets of exciters.

Parameters: Armature Resistance ($R$): Ohms ($\Omega$); Armature Inductance ($L$): Henrys ($H$); Inertia ($J$): Kilogram-Meters squared ($kg \cdot m^2$); Back EMF Constant ($E_b$): Volts per Rad/Sec ($V/(rad/s)$); Torque Constant ($k_\mathrm{t}$): Newton-Meters per Ampere ($Nm/A$); Damping Coefficient ($b$): Newton-Meters per Rad/Sec ($Nm/(rad/s)$); Load Torque ($TL$): Newton-Meters ($Nm$); Angular Speed ($\omega$): Rad/Sec; Voltage Input: Volts ($V$); Current ($I$): Amperes ($A$)Step Input (for Simulation): Unit Step (dimensionless); Time ($t$): Seconds ($s$). Therefore, the transfer function in Figure 2 illustrates the connection between rotor shaft speed and applied armature voltage.

$$\frac{w(s)}{E_a(s)} = \frac{K_T}{L_a.J_m.s^2((R_a.J_m + L_a.B_m).s + (R_a.B_m + K_b.K_T)} \tag{7}$$

The table below details the specifications of the separately excited D.C. motor utilized in the study 1 (Shravan Kumar Yadav, 2015), as shown in Table 1.

**Table 1.** Parameters for D.C. motors

| Parameter | Its value |
|---|---|
| (Armature resistance) $R_a$ | 0.4 Ω |
| (Armature inductance) $L_a$ | 2.7 H |
| (Rotor inertia) $J_m$ | 0.0004 kgm |
| (Frictional resistance due to viscosity) $B_m$ | 0.0022 Nms/rad |
| (constant of Torque) $K_T$ | 0.015 Nm/A |
| (Back emf constant) $K_b$ | 0.05Vs/rad |

A Fuzzy Inference System (FIS) defines the input/output mapping. Fuzzy inference systems have been useful in many fields, including automatic control, data classification, decision analysis, and computer vision. Fuzzy inference systems of the Mamdani and Sugeno varieties are two viable options. The two types of inference have subtle distinctions in the methods used to determine their results. By integrating over a continuously differentiating function, the Mamdani inference method finds the centre of a two-dimensional shape. A single spike, or singleton, was proposed by Michio Sugeno as the membership function for the rule consequent. A singleton fuzzy set has a membership function of unity at a single point in the discourse universe and zero everywhere else. "The need to employ an FLC typically arises when: the technical process is described merely in words rather than analytically," (Jang & Gulley, 2015) states. The process's parameters cannot be determined with any degree of accuracy. There is no way to specify these requirements accurately; the process description must be simplified and expressed in technical terms (Mahmud et al., 2020; Shuraiji & Shneen, 2022) (Sung et al., 2009).

An automatic control method, fuzzy logic control employs a control algorithm derived from a language control strategy based on domain expertise. A typical fuzzy control system's block diagram is depicted in Figure 3. The fuzzy controller consists of these four sub-components: "Controller architecture utilizing Fuzzy Logic" delineates the methodical configuration of constituents and the process of decision-making within a control system, wherein the controller employs principles of Fuzzy Logic. This strategy enables greater adaptability and subtle decision-making, especially in scenarios where conventional control approaches may encounter difficulties due to imprecise or ambiguous data, as shown in Fugure 3.

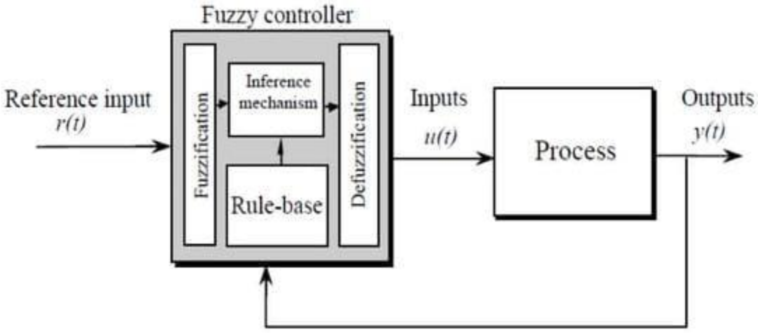

**Figure 3.** Controller architecture using Fuzzy Logic

Establishing which of the system's state variables characterize its dynamic performance will be used as the controller's input signal is the first stage in developing a fuzzy controller. In fuzzy logic, the variables are words rather than numbers. Fuzzification is changing a quantitative variable (such as an exact number or set of discrete values) into a linguistic one (an ambiguous number). This is possible thanks to the numerous fuzzified. There are generally three types of fuzzification that can be used: (1) singleton fuzzier; (2) a gaussian fuzzy maker; (3) a fuzzy triangle or trapezoidal shape. Both the speed error and the variation in the speed error are illustrated in Figures 4 and Figures 5, with the former spanning a range of -4.75 to 4.75 and the latter -1.65 to 1.65. Output is the control action, varying from 7 to +7, as seen in Figure 6; input was a Gaussian fuzzify, and the triangle was utilized.

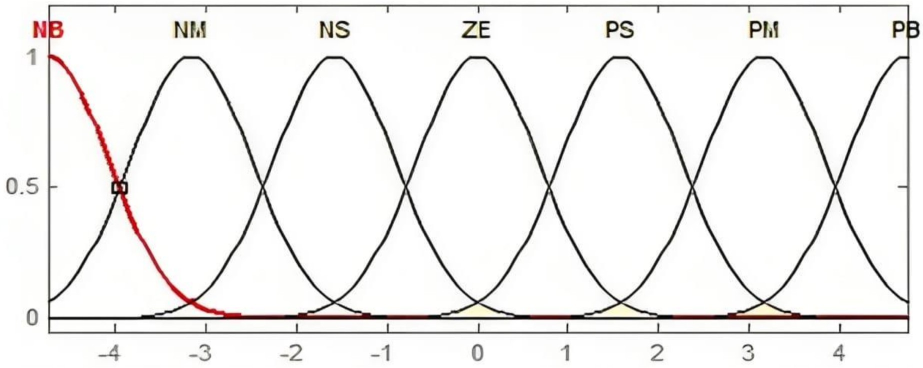

**Figure 4.** Speed-Error Variable

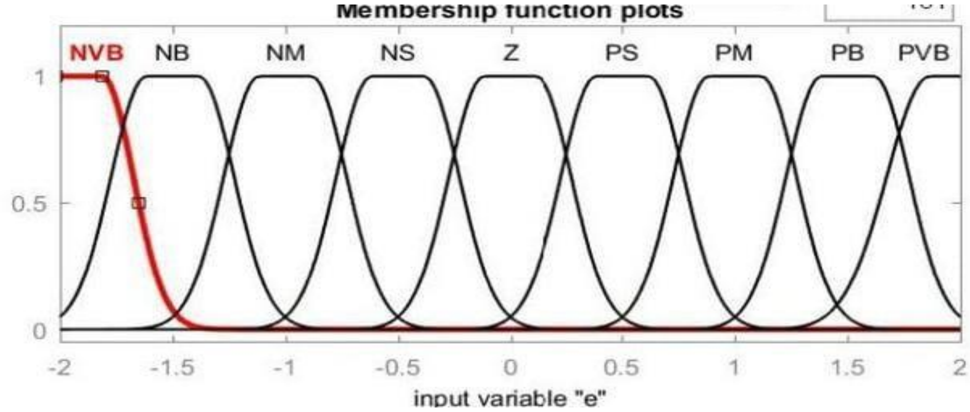

**Figure 5**. Error Due to Varying Speed Due to Evolution

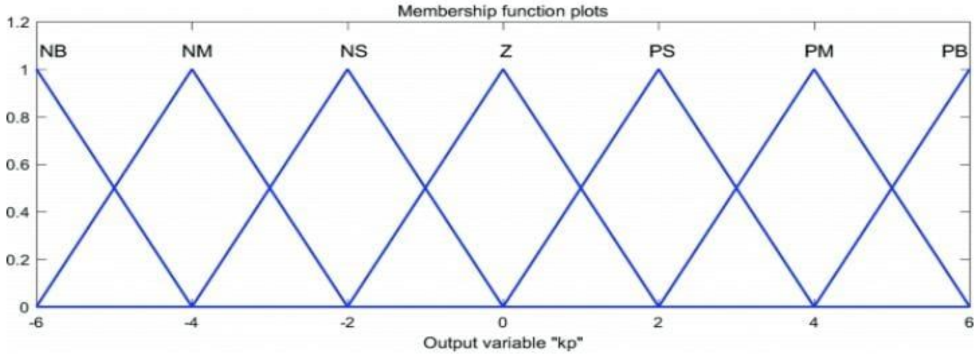

**Figure 6.** Resulting Variable

Like human decision-making, fuzzy control is based on a comprehension of control rules and the definitions of linguistic variables (Astrom, 2002). The rules are expressed in an "If-Then" structure, where the "If" part represents the "conditions," and the "Then" part represents the "conclusion." The armature voltage is the control function that the fuzzy controller outputs based on the inputs of error (e), the "difference between the output speed and the set point," and the error variation. The control strategy of a rule-based controller is written down in something approximating natural language. A rule basis controller can be understood and maintained by a non-specialist end user, and a traditional implementation of a similarly effective controller is possible (Benson OGUNDARE, 2013). Table 2 summarizes the rules (77=49) with examples. Language-specific rules variables include: (1) Large Negative (L.N.); (2) Medium Negative (MN); (3) Small Negative (S.N.); (4) ZE Zero; (5) Small Positive (S.P.); (6) Medium Positive (MP); and (7) Large Positive (L.P.), as shown in Table 2.

**Table2.** Separated excited D.C. motor speed regulation, based on established rule**s**

| **CEE** | **NL** | **NM** | **NS** | **ZE** | **SP** | **MP** | **LP** |
|---|---|---|---|---|---|---|---|
| NL | NL | NL | NL | NL | NM | NS | ZE |
| NM | NL | NL | NL | NM | NS | ZE | SP |
| NS | NL | NL | NM | NS | ZE | SP | MP |
| ZE | NL | NM | NS | ZE | SP | MP | LP |
| SP | NM | NS | ZE | SP | MP | LP | LP |
| MP | NS | ZE | SP | MP | LP | LP | LP |
| LP | ZE | SP | MP | LP | LP | LP | LP |

An inference engine is a software that analyzes the data in a certain context and draws conclusions about the state of affairs based on those conclusions. Deduction, association, identification, and decision-making are some of the inference processes we use when confronted with an issue that calls for reasoning rather than fencing abilities to solve. An inference engine is a computer software or other information processing system that uses logical deduction like a human brain. Although the max-min and the max-product approaches are frequently employed, the former was chosen for this paper. Defuzzification is the process by which Fuzzification is undone. Fuzzy Logic Controllers (FLCs) generate results as a linguistic variable (unclear number). Real-world standards necessitate a transformation of the linguistic variables into clean output. The most often used defuzzification technique is as follows (Nafeh et al., 2022). In contrast to the fuzzy set, which has a crisp control value as its abscissa, discrete groups have a center of gravity for singletons (COGS).

$$u_{COGS} = \frac{\sum_i \mu_c(x_i) x_i}{\sum_i \mu_c(x_i)}$$

The set of conclusions that result has a membership value represented by and$\mu_c(x_i)$, where $x_i$ represents a location in the universe of the conclusion$(i = 1, 2, 3...)$. Instead of using sums, integrals are utilized for continuous sets.

## C. RESULTS AND DISCUSSION

The system model may be safely and cheaply tested through simulation. But the accuracy of the system model is crucial to the accuracy of the simulation findings. It's a powerful method for addressing numerous issues. As a simulation tool, MATLAB will be used. Figures 7 and 8 show the PID and FLC-controlled DC motor operating at full load. The parameters of a fuzzy controller are tuned by trial and error to operate an independently stimulated D.C. motor. Gain1 = 20, Gain7 = 10, Gain6 = 0.08, Gain4 = 10, and Gain5 = 1.5 are the values for the gains. Figure 7 depicts a simulation model of a DC motor driven by a PID controller. The model has three gains, with initial values at 1/1500 and 1500.

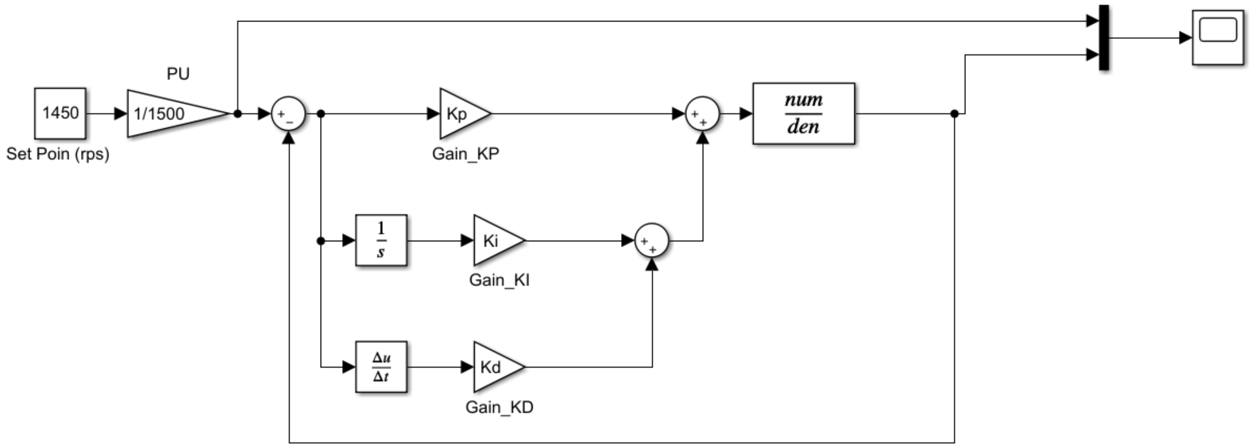

**Figure 7**. PID-controlled DC motor operating at full load

The performance is displayed to demonstrate the motor's reaction under particular circumstances. Figure 8 depicts the performance of the model under no load conditions. The curve on the x-axis ranges from 0 to 10, while the curve on the y-axis ranges from 0.8 to 1. This offers a deeper understanding of the motor's performance when no external load is present. Figure 9 expands the study to a situation when the system operates at maximum capacity. It assesses how well the PID controller achieves specific performance criteria, such as peak time, as outlined in the following table.

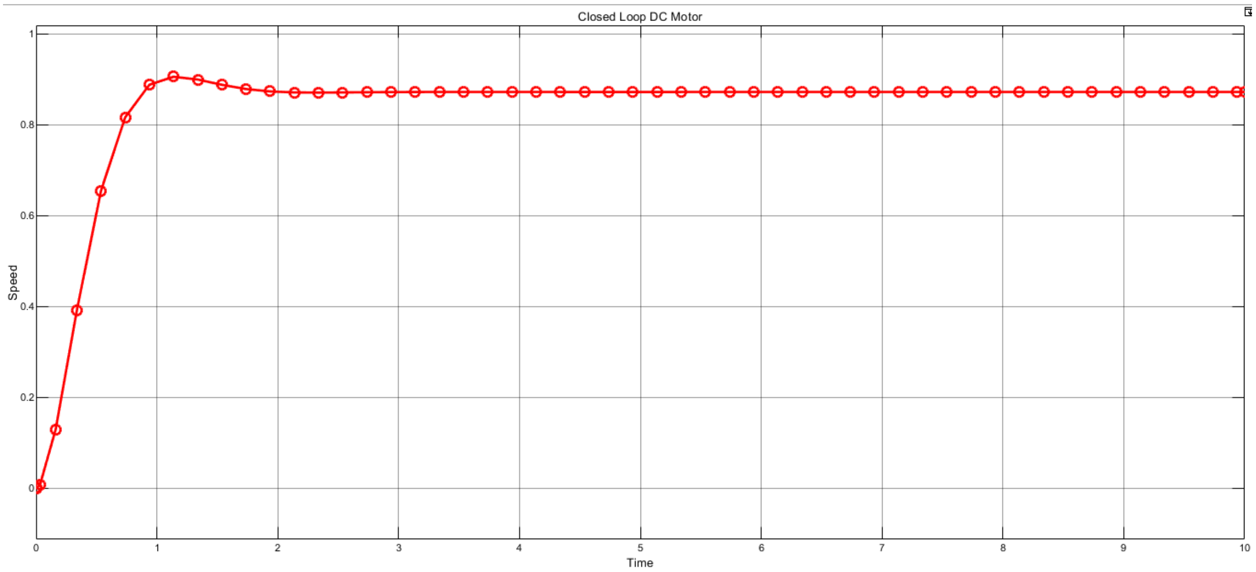

**Figure 8.** D.C. motor operating without a PID controller at full load

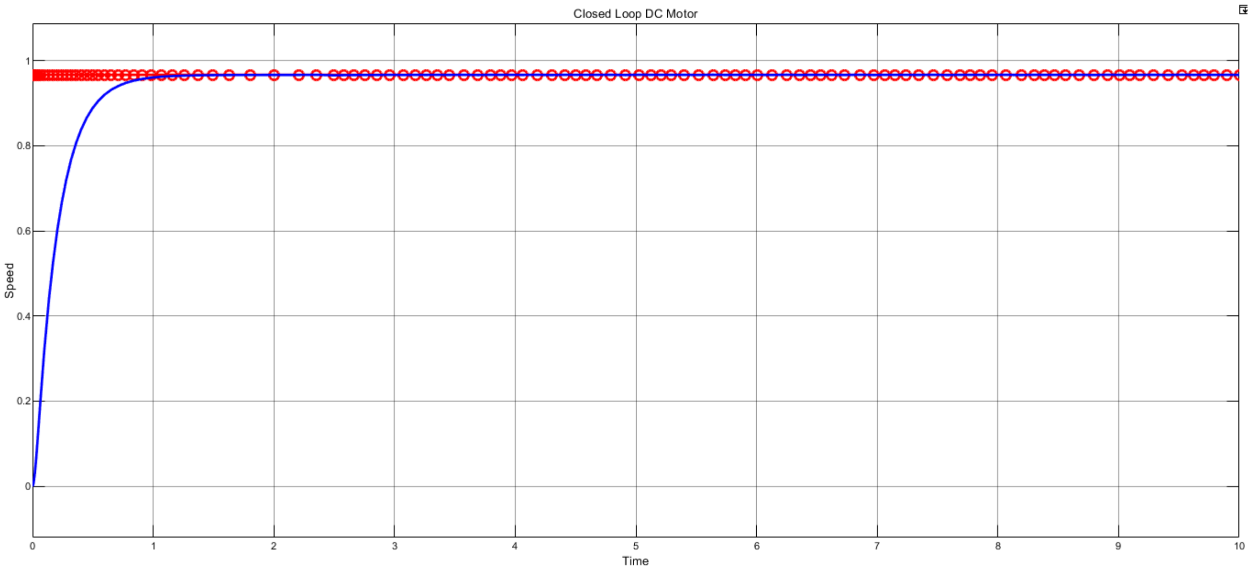

**Figure 9.** PID-controlled DC motor operating at full load

Transitioning to Figure 10, the attention is redirected toward the Fuzzy Logic Controller (FLC) model, including the DC motor. Like Figure 8, it showcases the motor's performance when operating without any external load, emphasizing the fluctuations in the curve. Figure 11 and Figure 12 illustrate the performance of the DC motor controlled by a Fuzzy Logic Controller (FLC), both under full load and without load. The table below outlines the performance parameters, enabling a thorough comparison with the PID controller. The provided data and figures collectively contribute to the assessment of PID and FLC controllers, providing a visual representation and quantitative study of their effectiveness in regulating the speed of DC motors. These findings provide a foundation for comprehending the relative advantages and disadvantages of the controllers, which can then be used to direct the creation of more efficient control techniques for DC motor applications, as shown in Figure 10.

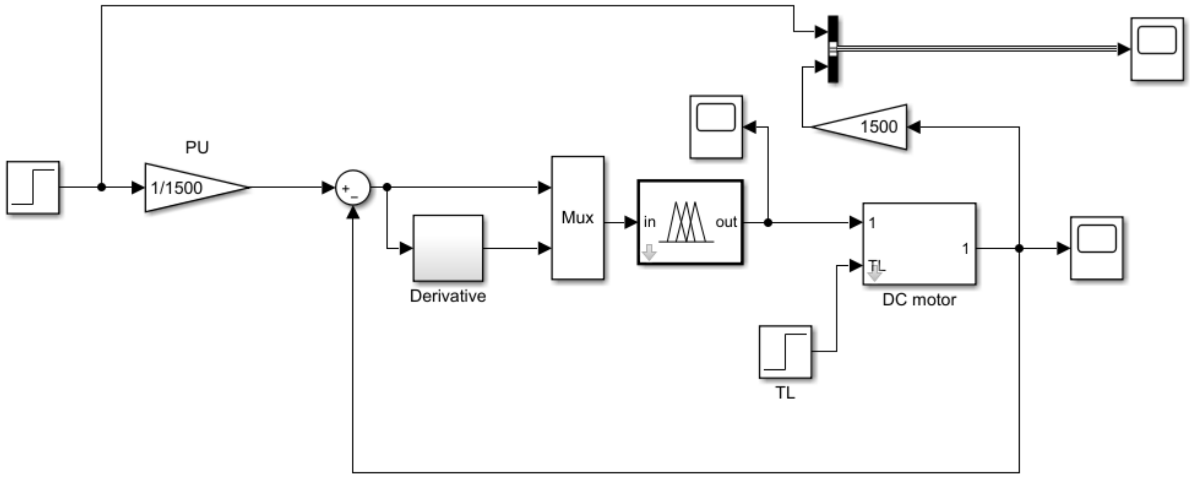

**Figure10.** For a fully loaded D.C. motor with an FLC

This research aimed to find a way to regulate the speed of a D.C. motor by simulating the system's operation in a computer program called MATLAB. Table 3 and Figure 9 compare the numerical operating results with PID, FLC, and no controller. The simulation results provide a detailed overview of the performance of a PID-controlled DC motor and its comparison with an FLC-controlled counterpart. Figures 7 to 12 display this information. Figure 7 illustrates the DC motor controlled by a PID controller while operating under full load conditions. The specific gains have been adjusted to get the best possible performance. Figure 8 highlights the behaviour of the DC motor when operating at full load without a PID controller, demonstrating the effects of not using this control method. Figure 9 continues to focus on the PID controller, assessing its effectiveness in controlling the DC motor's speed when operating at maximum capacity. Figure 10, including a Fuzzy Logic Controller (FLC), introduces a novel aspect, examining the effectiveness of fuzzy logic compared to PID in attaining speed control. Figures 11 and 12 explore situations where the DC motor functions without an FLC controller, offering valuable information about its performance when subjected to full load circumstances. Table 3 presents a quantitative and comparative analysis of essential time parameters for PID and FLC controllers, including rise time and settling time. This analysis offers vital insights to researchers and practitioners seeking the most effective control methods for DC motor applications.

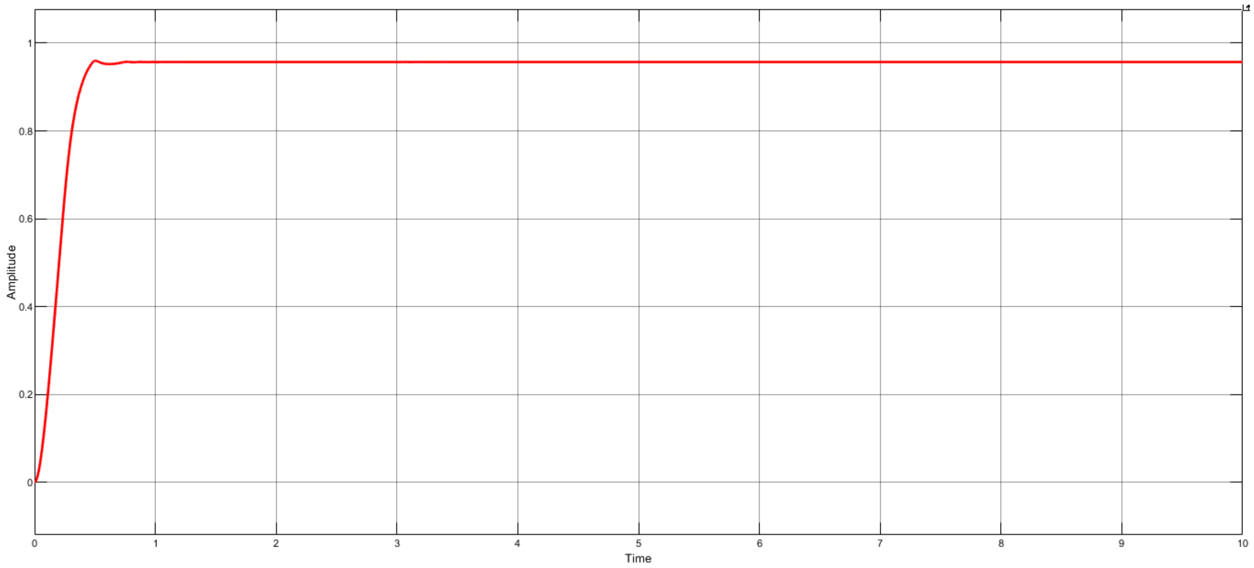

**Figure11.** D.C. motor without FLC controller operating at full load.

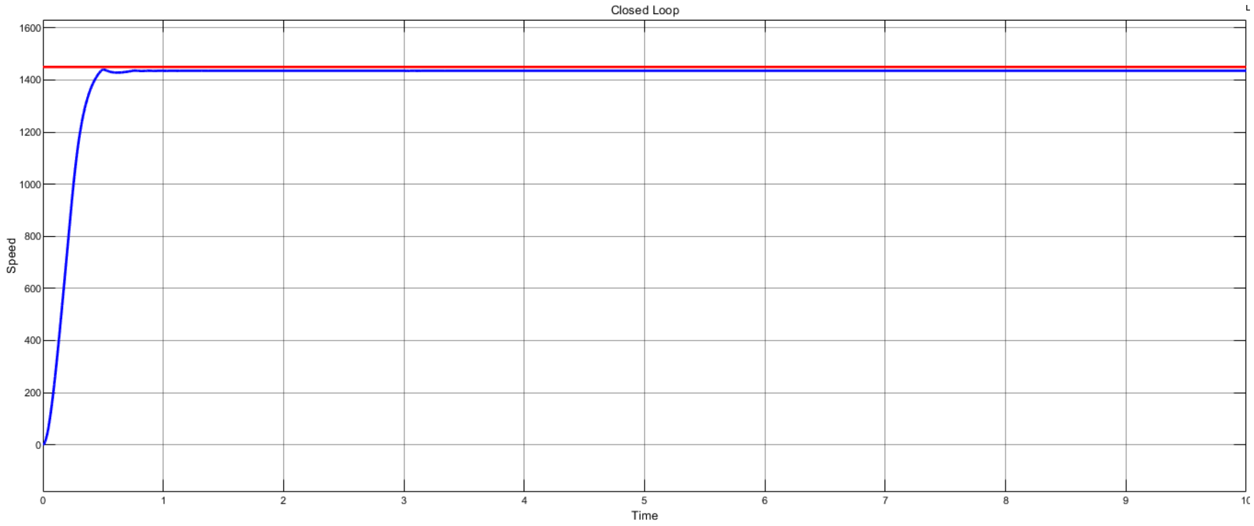

**Figure12**. D.C. motor operating without an FLC controller at full load.

**Table 3.** The results of comparing the PID controller and the fuzzy controller

| **Controller Time Characteristics** | **PID** | **Fuzzy controller** |
|---|---|---|
| Rise time | 0.8 | 0.7 |
| Settling time | 2.9641 | 2.6421 |
| Overshoot | 0.130000% | 0.009353% |
| Peak time | 0.5 | 1 |

The table thoroughly compares PID and Fuzzy Logic Controllers (FLC) for DC motor speed control, explicitly focusing on important time aspects. The PID controller demonstrates a rise time of 0.8, a settling time of 2.9641, an overshoot of 0.130000%, and a peak time of 0.5. On the other hand, the FLC exhibits improved performance with a faster rise time of 0.7, a shorter settling time of 2.6421, and a significantly reduced overshoot of 0.009353%, although with a slightly longer peak time of 1. The FLC's improved efficiency and precision in obtaining the desired speed control for the DC motor are demonstrated by these characteristics compared to the PID controller. The values act as quantitative benchmarks from a prior research study, offering significant insights for researchers and practitioners looking for the most effective control solutions for DC motor applications.

Our research intends to exceed the stated accuracy standards shown in the comparison analysis, in contrast to a recent study investigating DC motor speed control utilizing PID and Fuzzy Logic Controllers (FLC). The previous investigation (Almatheel & Abdelrahman, 2017) showed that the FLC outperformed the PID controller in terms of essential time features, with a quicker rise time (0.8600 vs. 0.9727), shorter settling time (2.6821 vs. 2.9848), and significantly lower overshoot (0.008264% vs. 0.120000%). In addition, the PID controller reached its maximum value at time 1, but the FLC obtained this maximum at time 2. Based on these findings, our research aims to enhance the Fuzzy Logic Controller to achieve higher accuracy and efficiency in controlling the speed of DC motors. Our goal is to improve the area by surpassing these defined accuracy criteria. This will demonstrate enhanced control tactics for DC motor applications.

## D. CONCLUSION AND SUGGESTIONS

PID and fuzzy controllers were developed in MATLAB to regulate the rotational speed of a DC motor subjected to asymmetrical excitation. The system's effectiveness was enhanced by adding fuzzy and PID controllers. The fuzzy controller outperformed the conventional PID controller in all tested categories, including transient and steady-state responsiveness, the dynamic response curve quality, reaction time, steady-state error (SSE) magnitude, and precision. To summarize, this research provides a thorough investigation into the regulation of speed in a separately stimulated DC motor utilizing PID and fuzzy logic controllers (FLC). The comparison research demonstrates that, although the FLC has a more complex design process, it surpasses the PID controller in terms of efficiency and effectiveness, exhibiting greater performance. The statistical analysis highlights the following advantages of the FLC over the PID controller: a reduced rise time of 0.7 (compared to 0.8 for PID), a shorter settling time of 2.6421 (compared to 2.9641 for PID), a significantly lower overshoot of 0.009% (compared to 0.13% for PID), and an improved peak time of 1 (compared to 0.5 for PID). The results emphasize that the FLC is well-suited for dealing with the non-linear properties of DC motors, making it a preferable option for industrial applications where reducing transient and steady-state factors is essential.

This research intends to investigate the ongoing and extensive utilization of Direct Current (DC) motors in many applications, with a specific focus on Separately Excited DC Motors. The study will use MATLAB and Simulink to compare classical Proportional Integral (PI) Controllers with advanced soft computing Intelligent Controllers such as Fuzzy Logic Controllers (FLC), Adaptive Neuro Fuzzy Inference System (ANFIS) Based Controllers, and Artificial Neural Network (ANN) Based Controllers for the purpose of achieving efficient speed control. The analysis will provide useful insights for the development of precise and cost-efficient speed controllers for Separately Excited DC Motors, assisting engineers and researchers in making well-informed decisions.

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