System Analysis and Controllers Performance Comparison for D.C. Motor

Ayad E. Korial
Computer Engineering, University of Technology, Baghdad, Iraq
Email: ayad.e.korial@uotechnology.edu.iq

Ivan Isho Gorial
Control and Systems Engineering, University of Technology, Baghdad, Iraq
Email: Ivan.I.Gorial@uotechnology.edu.iq

***Abstract*—Due to their great efficiency in converting mechanical energy in manufacturing as well as energy recovery, Direct Current (D.C.) motors have been utilized for a long time. This sort of motor's machinery is extremely powerful and capable of delivering maximum torque. In this work, three controllers are designed and sought to establish the impact of these three types of controllers in the control performance of D.C. motor in terms addressed to control the position. The first one is Linear Proportional-Integral-Derivative (LPID) controller, second one Nonlinear Proportional-Integral-Derivative controller (NPID) and then third Fuzzy Logic Controller (FLC). The control's results yielded an appropriate answer for the applications. The outcomes of simulations run in the MATLAB environment are compared. According to the findings, fuzzy position-controlled D.C. motors have a faster settling time and higher performance parameters than LPID and NPID position-controlled D.C. motors, in addition, FLC provides an accurate controller for controlling the systems.**

***Index Terms*—position, D.C. motor, controllers, FLC, fuzzification, defuzzification, COG, mamdani, LPID, NPID**

Nomenclature

NM	Negative Medium
PM	Positive Medium
NS	Negative Small
PS	Positive Small
Z	Zero
x_i	In the final universe, there is a point $(i = 1, 2, 3, \cdots)$
$\mu_c(x_i)$	Conclusion set result membership value
γ	Design parameter
V	Voltage source
$\dot{\theta}$	Speed of rotation of the shaft
J	Moment of inertia of the rotor
b	On the motor, there is always viscous friction.
K_e	Electromotive force constant factor
K_t	Constant motor torque
R	Resistor
L	Induction
FIS	Fuzzy Inference System
KVL	Kirchhoff's Voltage Law

I. Introduction

Because of their benefits, D.C. motors have been utilized in high-performance drive systems in recent years [1]. D.C. motors are frequently utilized in industrial applications, robot manipulators, and household appliances that require motor position control due to their high reliabilities, flexibility, and low prices [2].

An actuator that transforms electrical energy into rotating mechanical energy is known as a D.C. motor. D.C. motors are frequently employed in industry and a variety of other control systems, such as robots and home appliances, where precision is required. Controlling the position of motors is crucial, and this necessitates the employment of different controllers in industries [3].

Industry's increasing desire for better productivity is putting additional strains on electric motor-related systems. Due to the rapid dynamics and instability, this causes a variety of issues in work processes. The system's stability is required to achieve the intended set of goals. Because of the non-linear effects generated by motors, the controller's ability to hold position at specified points is often harmed. As a result, a variety of industrial applications necessitate D.C. motor position control. The D.C. motor's position control allows it to move to a precise location and stay there even if an external force attempts to move it. D.C. motor position control is widely utilized in robotic arm control, aerospace automation, mechatronics, and cranes, among other applications. PID Controller and FLC [4] are two approaches that may be used to regulate the position of D.C. motors.

The need to improve dynamic system performance, reduce production costs, and reduce repetitiveness in manual industrial control operations. However, non-linearity and uncertainty, which are common in real-world control issues, presented complications for these

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traditional control methods created for the regulation of dynamic systems. Because of its capacity to manage imprecise and inconsistent real-world situations, the fuzzy logic controller is well suited for a wide range of applications [5].

Efficacious control is essential to enhancing the quality of industrial production operations. D.C. motor businesses have had difficulty operating successfully due to a variety of factors, including fluctuations in motor load demand, non-linearity, disturbances, and so on [6]. With FLCs, it is possible to overcome non-linearity and imprecision in D.C. motor position control by using a heuristic understanding of real-life dynamic systems via an intuitive user interface [7].

D.C. motors function as actuators in control systems when they are used for position control. It may provide rotational motion and translational motion when used in conjunction with drums and wheels. A D.C. motor converts DC electricity to rotational motion. For industrial purposes, D.C. motors are commonly utilized. Because of their simple designs and extensive functions, PID controllers are often employed for position control. However, the PID for D.C. motor position control may not be designed and tuned properly to obtain the required results. FLC has become one of the most active study fields in industrial processes, relying on logical systems that are more similar to human reasoning [4].

Fuzzy control may be used to control a system even if the system's information is unavailable [8]. It may also deal with a certain amount of imprecision, ambiguity, and even uncertainty. Furthermore, several methods of control had been proposed to D.C. motor position: Manikandan and Arulmozhiyal [1] developed fuzzy PI controller to control D.C. servo motor position.

Moreover, Usoro *et al*. [9] investigated the control performance of an industrial type D.C. motor using an PID and FLC. However, Kaur and Singh [4] used MATLAB/SIMULINK to perform D.C. motor position control.

Furthermore, sailan and Kuhnert [10] designed PID controller for a D.C. motor angular position control.

Manasa *et al*. [11] utilized PID algorithm to control a D.C. motor position. Yadav [2] controlled the position of D.C. Motor by using FLC.

Dange and Pawar [12] utilized the possibility of Fuzzy justification for position control, using D.C. servomotor. Using a PID controller, Maung *et al*. [13] observed that they could enhance the angular position control precision for a geared motor. Pandey and Pandey [14] demonstrated the design of a FLC system to torque control of a D.C. motor.

The major goal of this article is to use three separate controllers to regulate the position of a D.C. motor and attempt to rectify the discrepancy between the measured and intended positions by estimating the error i.e. system requirements steady state error equal zero. These details are clarified in next sections.

In this paper, system analysis and controllers performance comparison for D.C. motor position. The remainder of the paper is laid out as follows: section two describes methods of controllers design, section three shows simulation results and discussion, finally, section four concludes the findings of this work.

II. METHODS OF CONTROLLERS DESIGN

The rotor free-body diagram [15] is clarified in Fig. 1.

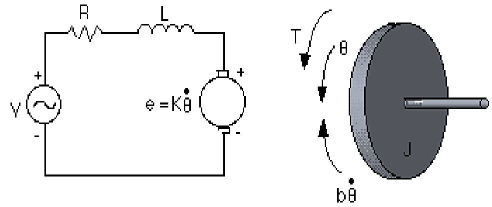


Figure 1. Separately excited D.C. motor
(DC motor equivalent circuit and free-body diagram of the rotor)

As shown in the following equation. An armature-driven motor is what it's called.

$$T = K_t\, i \tag{1}$$

e, back emf, is proportional to $\dot{\theta}$ by a constant factor

$$K_e.e = K_e\, \dot{\theta} \tag{2}$$

In SI units, $K_t = K_e$ (constants). On the basis of KVL and Newton's 2nd Law, the governing equations shown in Fig. 1 may be constructed.

$$J\ddot{\theta} + b\dot{\theta} = Ki \tag{3}$$

$$L\frac{di}{dt} + Ri = V - K\dot{\theta} \tag{4}$$

Applying the Laplace transform:

$$s(Js + b)\theta(s) = KI(s) \tag{5}$$

$$(Ls + R)I(s) = V(s) - Ks\theta(s) \tag{6}$$

By removing $I(s)$ between (5) and (6) equations, where armature voltage is the input and rotational speed is the output.

$$P(s) = \frac{\dot{\theta}(s)}{V(s)} = \frac{K}{(Js+b)(Ls+R)+K^2}\left[\frac{rad/sec}{V}\right] \tag{7}$$

This is the D.C. motor transfer function. Take the following physical parameter values in Table I [16].

TABLE I. SYSTEM PARAMETERS VALUES

Symbol	Value	Unit
J	0.5	$\mathrm{kg.m^2}$
b	0.01	$\mathrm{N.m.s}$
K_e	1	$\mathrm{V/rad/s}$
K_t	1	$\mathrm{N.m/Amp}$
R	0.4	Ω
L	0.05	H

With the use of a model framework, simulation is a cost-effective and safe method. It's a useful technique for dealing with a wide range of issues.

However, we will be looking at the position as the output in this case. By integrating the speed, we can obtain the position, eq. (8).

$$\frac{\theta(s)}{V(s)} = \frac{K}{s((Js+b)(Ls+R)+K^2)} \left[\frac{\text{rad}}{\text{V}}\right] \tag{8}$$

The state variables of motor position, motor speed, and armature current may be used to write the aforementioned differential equations in state-space form.

$$\frac{d}{dt}\begin{bmatrix}\theta\\ \dot{\theta}\\ i\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & -\frac{b}{J} & \frac{K}{J}\\ 0 & -\frac{K}{L} & -\frac{R}{L}\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\\ i\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{1}{L}\end{bmatrix} V \tag{9}$$

$$y = \begin{bmatrix}1 & 0 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\\ i\end{bmatrix} \tag{10}$$

III. System Methodology and the Three Types of Controller

A comparison investigation of three distinct controllers is performed on a D.C. motor that is separately excited. (DC motor equivalent circuit and free-body diagram of the rotor) for model derived in the above equations. These suggested controllers are designed independently from each other. **The first controller** is FLC, in terms of tracking performance, the FLC is clearly the most important controller. It was built to meet the demand for a controller like this. Fuzzy inference system Error and change of error of DC motor equivalent circuit system was taken as inputs to FLC and control was output.

Whereas, FLC system is used in nonlinear control system. Human heuristic knowledge on how to control systems can be formalized, represented, manipulated, and implemented using this method [17]. Fig. 2 is a block schematic of an FLC.

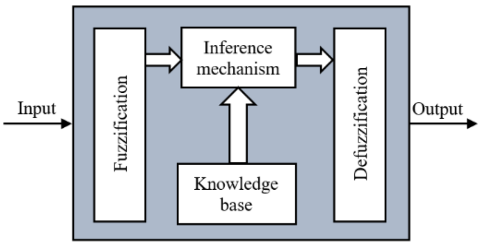


Figure 2. The FLC block diagram

Normalization of [-1, 1] is used to represent the fuzzy membership function created for the error and the change in the error. With the following in mind, the linguistic values for the error and the change in error are designed:

The error linguistic values are designed with five linguistic terms as illustrated in Fig. 7. While the linguistic values of the change of error are designed with seven linguistic terms as clarified in Fig. 8.

The linguistic terms of the output (control) are designed with five linguistic terms as shown in Fig. 9. A triangle membership function is used to signify each linguistic value. The Mamdani system, which uses fuzzy sets, is used by FLC. The initial stage in creating an FLC (Mamdani controller) is to identify the linguistic variables that will be used, as well as the issue statement for this function. As shown in Fig. 6-Fig. 12.

The FLC, which was based on 35 rules, was supplied the system's errors and changes in errors as inputs. Singletons' Center of Gravity for Discrete Sets is computed as follows:

$$u_{COGS} = \frac{\sum_i \mu_c(x_i) x_i}{\sum_i \mu_c(x_i)} \tag{11}$$

LPID is **the second controller.** It is mostly employed in industrial control systems as a feedback control loop. PID control uses proportional, integral, and derivative terms to calculate an error value and provide corrective [18]-[21]. The following formula yields the best PID controller for continuous-time PID controllers: (12).

$$u_{PID} = k_p e + k_i \int e dt + k_d \dot{e} \tag{12}$$

In this paper, values of k_p, k_i and k_d equal to 7.8, 1 and 0.5 respectively.

NPID is **the third controller** in the chain. Taking as its basis [22], an error function integral is substituted for an error saturation function integral in the proposed law, and then changing various parameters of the saturation function. NPID is the third controller in the chain. Taking as its basis [22], the suggested law consists in substituting an integral of the error function for an integral of the error saturation function, and then changing various parameters of the saturation function.

$$u_{NPID} = k_p e + k_i \int_0^t sat_\gamma e\, dt + k_d \dot{e} \tag{13}$$

where, Sat_γ: The saturation function given by:

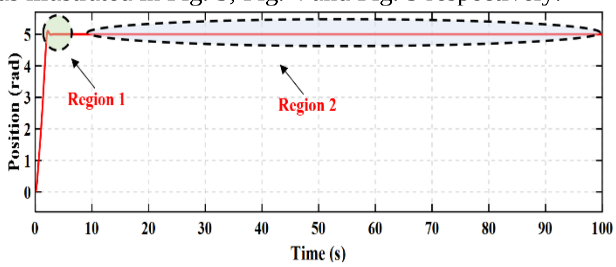
$$Sat_\gamma(e) = \gamma * sign(e) \tag{14}$$

Aside from that, the design parameter γ for the NPID controller is equal to 200.

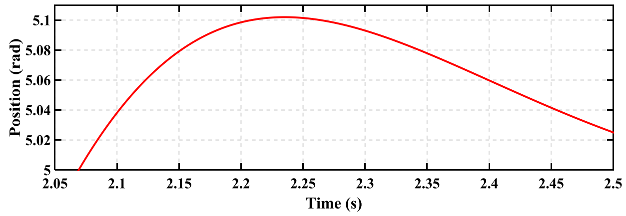
IV. Simulation Results and Discussion

For D.C. motor position control, the required (desired) 'Step' input signal is adjusted to around 5 rad. According to the answer, when FLC is employed, the output signal is very rapid, reaching the required position in 3.656 seconds, with zero steady state error and no oscillation, indicating the best outcomes.

Moreover, LPID reached the desired position but after 39.536 seconds. While NPID always oscillated and rippled as illustrated in Fig. 3, Fig. 4 and Fig. 5 respectively.



(a)



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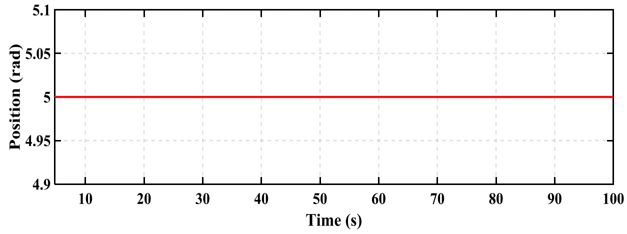
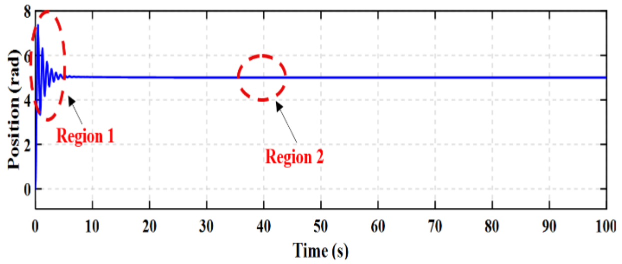
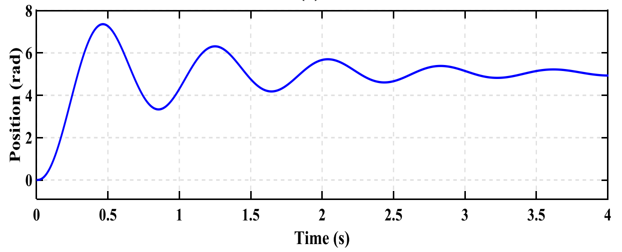


(c)

Figure 3. System step refence: (a) System step refence based on FLC (b) Close view of Region 1 (c) Close view of Region 2



(a)



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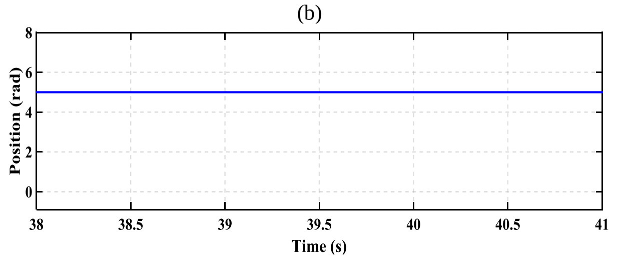

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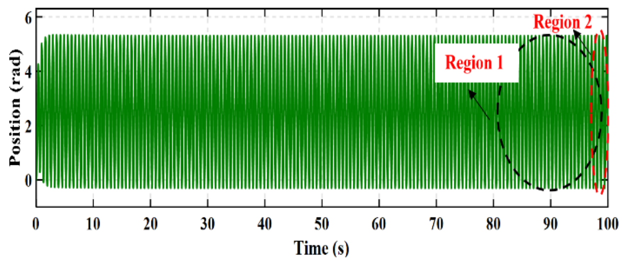
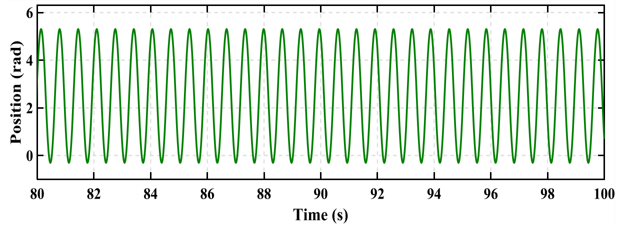
Figure 4. System step refence: (a) System step refence based on FLC (b) Close view of Region 1 (c) Close view of Region 2



(a)



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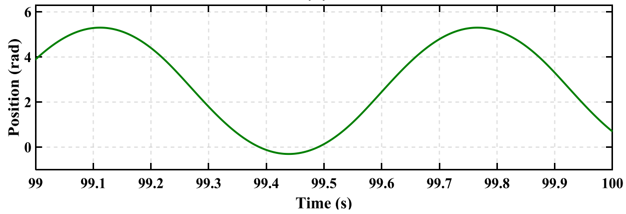
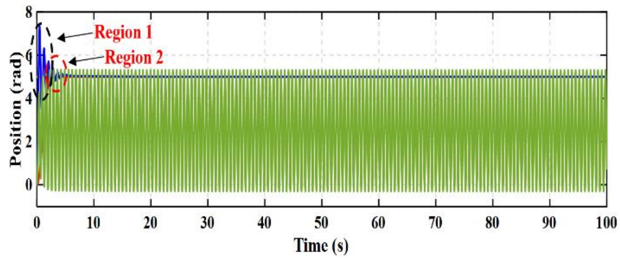


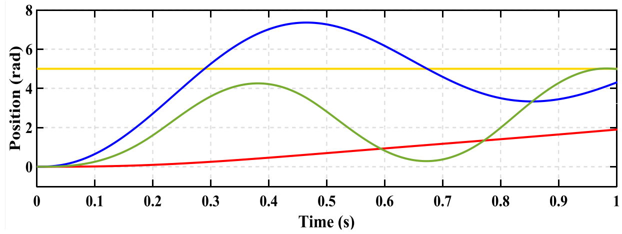
(c)

Figure 5. System step refence: (a) System step refence based on FLC (b) Close view of Region 1 (c) Close view of Region 2

Moreover, Fig. 6 shows the comparison of these three controllers. Where, (Yellow: reference; red:FLC; green: LPID; blue: NPID)



(a)



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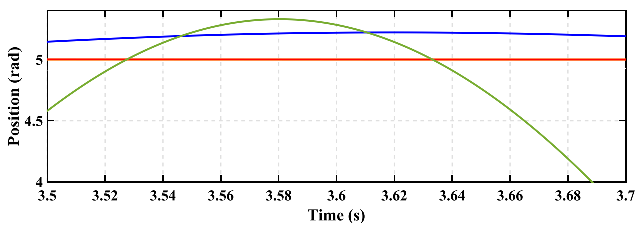

(c)

Figure 6. System step refence: (a) System step refence based on FLC (b) Close view of Region 1 (c) Close view of Region 2

For more details, fuzzy membership function for inputs (error and change of error) in addition to output (voltage) are shown in Fig. 7, Fig. 8 and Fig. 9.

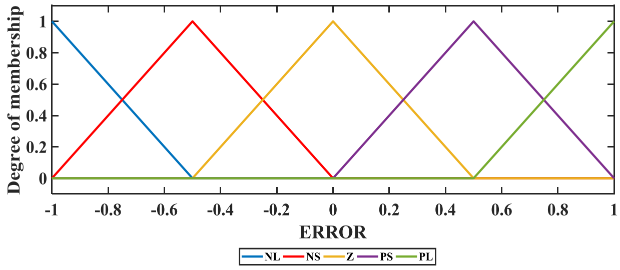

Figure 7. Membership func tions for fuzzy input variables (error)

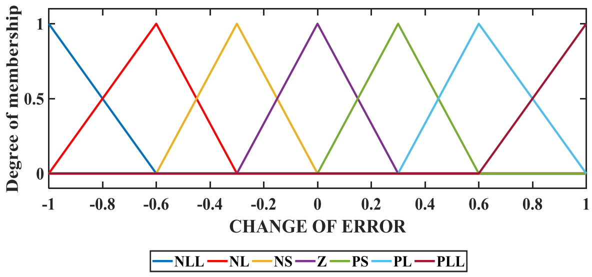

Figure 8. Membership functions for fuzzy input variables (change of error)

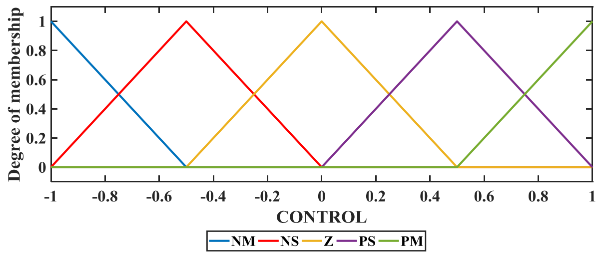

Figure 9. Membership functions for fuzzy output variables.

However, Fig. 10 shows Fuzzy Inference System (FIS), surface view and rule viewer FLC in Fig. 11 and Fig. 12 respectively and Table II shows FLC rule base.

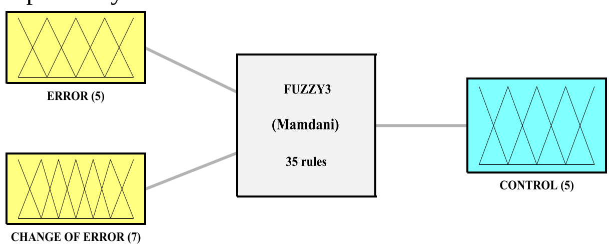

Figure 10. FIS

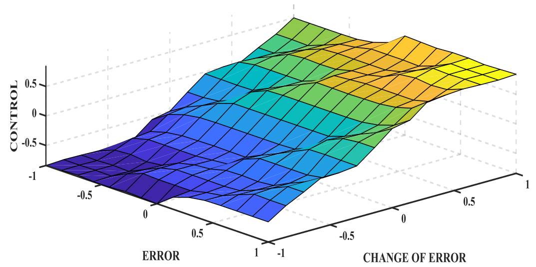

Figure 11. Surface view

TABLE II. FLC RULE BASE

1	If ERROR == NL & ΔERROR == NNL ⇒ CONTROL = NM
2	If ERROR == NL & ΔERROR == NL ⇒ CONTROL = NM
3	If ERROR == NL & ΔERROR == NS ⇒ CONTROL = NM
4	If ERROR == NL & ΔERROR == Z ⇒ CONTROL = NS
5	If ERROR == NL & ΔERROR == PS ⇒ CONTROL = Z
6	If ERROR == NL & ΔERROR == PL ⇒ CONTROL = Z
7	If ERROR == NL & ΔERROR == PLL ⇒ CONTROL = PS
8	If ERROR == NS & ΔERROR == NLL ⇒ CONTROL = NM
9	If ERROR == NS & ΔERROR == NL ⇒ CONTROL = NM
10	If ERROR == NS & ΔERROR == NS ⇒ CONTROL = NS
11	If ERROR == NS & ΔERROR == Z ⇒ CONTROL = Z
12	If ERROR == NS & ΔERROR == PS ⇒ CONTROL = Z
13	If ERROR == NS & ΔERROR == PL ⇒ CONTROL = PS
14	If ERROR == NS & ΔERROR == PLL ⇒ CONTROL = PS
15	If ERROR == Z & ΔERROR == NLL ⇒ CONTROL = NM
16	If ERROR == Z & ΔERROR == NL ⇒ CONTROL = NS
17	If ERROR == Z & ΔERROR == NS ⇒ CONTROL = NS
18	If ERROR == Z & ΔERROR == Z ⇒ CONTROL = Z
19	If ERROR == Z & ΔERROR == PS ⇒ CONTROL = PS
20	If ERROR == Z & ΔERROR == PL ⇒ CONTROL = PS
21	If ERROR == Z & ΔERROR == PLL ⇒ CONTROL = PM
22	If ERROR == PS & ΔERROR == NLL ⇒ CONTROL = NS
23	If ERROR == PS & ΔERROR == NL ⇒ CONTROL = NS
24	If ERROR == PS & ΔERROR == NS ⇒ CONTROL = Z
25	If ERROR == PS & ΔERROR == Z ⇒ CONTROL = Z
26	If ERROR == PS & ΔERROR == PS ⇒ CONTROL = PS
27	If ERROR == PS & ΔERROR == PL ⇒ CONTROL = PM
28	If ERROR == PS & ΔERROR == PLL ⇒ CONTROL = PM
29	If ERROR == PL & ΔERROR == NLL ⇒ CONTROL = NS
30	If ERROR == PL & ΔERROR == NL ⇒ CONTROL = Z
31	If ERROR == PL & ΔERROR == NS ⇒ CONTROL = Z
32	If ERROR == PL & ΔERROR == Z ⇒ CONTROL = PS
33	If ERROR == PL & ΔERROR == PS ⇒ CONTROL = PM
34	If ERROR == PL & ΔERROR == PL ⇒ CONTROL = PM
35	If ERROR == PL & ΔERROR == PLL ⇒ CONTROL = PM

TABLE III. TYPES OF CONTROLLERS AND RESULTS: SUMMARY OF SYSTEM ANALYSIS RESULTS

FLC		
Rise Time	Peak Position	Peak Time
1.4498	**5**	2.2351
LPID		
Rise Time	Peak Position	Peak Time
0.1809	**7.3592**	0.4652
NPID		
Rise Time	Peak Position	Peak Time
0.1687	**10.6543**	3.5793

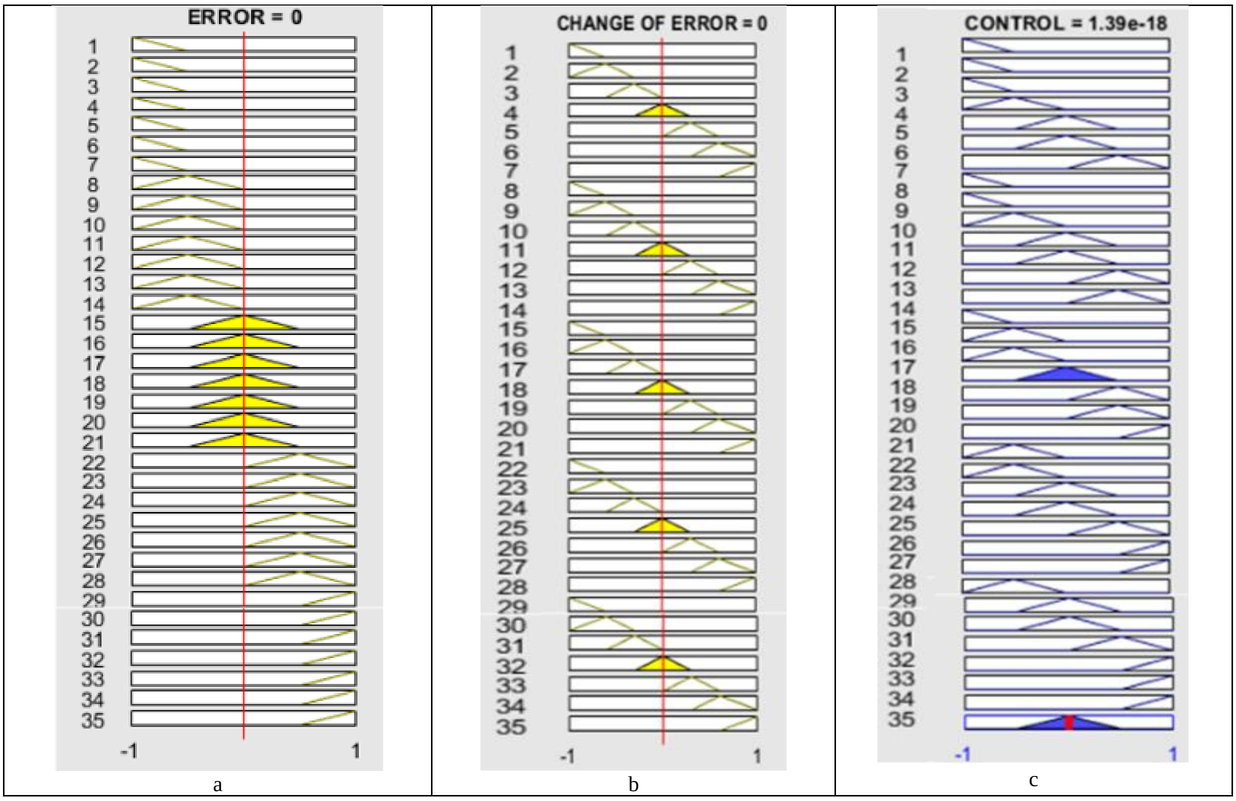

Figure 12. Rule viewer FLC: (a) Error (b) Change of error (c) Control

The simulation results of these three types of controllers illustrated in details in Table III and in Fig. 13 and also, peak position value is shown in Fig. 14.

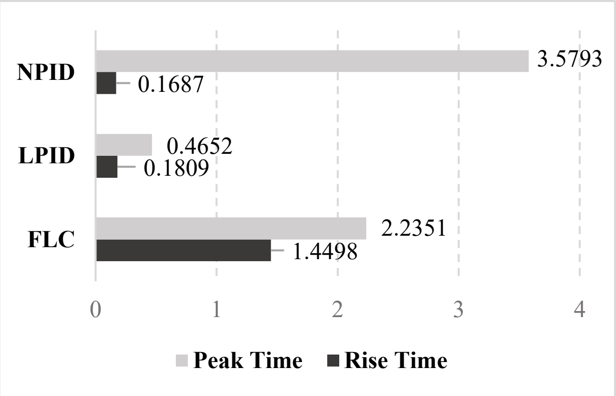

Figure 13. Summary analysis results chart

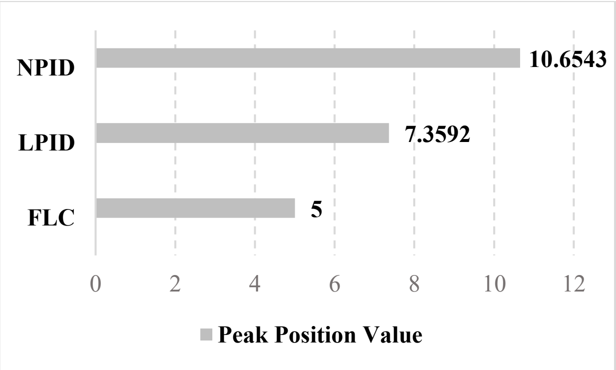

Figure 14. Peak position value

V. Conclusion

FLC has the best dynamic response and the best ability to follow the reference input signal. FLC provides greater flexibility and smooth control when applying position in D.C. to reduce position error. The conclude from the simulation results is that FLC is faster than the two other controllers where reach actual peak position value equals 5 rad at 3.656 s when used FLC that matches the desired peak position value i.e. zero steady state error, no oscillation in addition to an improved look, performance parameters have improved, and the system's overshoot, rising time, peak time, settling time, and delay time have all decreased. While when applying LPID also reached the desired peak position but after 39. 536 s and this is too late. Quite the opposite, so find NPID not achieve the desired value of position moreover, oscillation and ripple. FLC provided excellent results while also reducing computing time by eliminating unneeded sophisticated mathematical models of nonlinear systems. This research may be used to the robot arm model and the selection of a robust controller to get the optimum performance for the stability system. The findings show that by employing FLC, the system responsiveness has actually improved. Sequel to the foregoing findings, concluded that FLC is easily applied in local industry to increase precision and performance in D.C. motor operations.

Conflict of Interest

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors performed the conceptualization, methodology, software and implementation, validation and formal analysis, writing original draft preparation, and writing were performed by all authors in addition to editing. Moreover, all authors read and approved the final manuscript.

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Ayad E. Korial was born in Baghdad, Iraq in 1991. He received the BSc. degree in Computer Engineering from the University of Technology-Baghdad, Iraq in 2014 and the MSc. degree in computer engineering from the University of Technology-Baghdad, Iraq in 2016. From 2016 till now he was an assistant lecturer computer engineering in the same university to graduate from it. His research interests include software development, cloud computing, data science, biomedical image/signal processing, deep learning and machine learning.

Ivan Isho Gorial From the University of Technology, Baghdad, Iraq in 2006 she obtained a B.Sc. in Control and Systems Engineering and a Master's degree in Mechatronics Engineering in 2013. She presently serves as an assistant professor in the department of Control and Systems Engineering. She has published numerous publications in academic journals and conferences. Aside from vibration control, her current study focuses on intelligent systems.