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Comparison of Proportional Integral Derivative and Fuzzy Logic Controllers: A Literature Review on the Best Method for Controlling Direct Current Motor Speed

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ABSTRACT

Control systems, particularly for DC motors, are a continually evolving field with various methods and techniques aimed at improving control system performance. Common issues in DC motor control, such as high overshoot and inadequate response times, highlight the need for further research into more effective tuning techniques. This study compares conventional PID and FLC methods in controlling DC motor speed, while also exploring optimization potential through new approaches like hybrid methods and the use of neural networks. The contributions of this research include a comprehensive analysis of previous studies on DC motor control performance and an in-depth assessment of the effectiveness of PID and FLC methods in addressing rise time, settling time, and overshoot issues. The methodology used in this study is a literature review, which involves collecting and analyzing various studies related to the application of both methods in DC motor control. Literature selection criteria include relevance, methodology used, and contributions to scientific advancements in motor control. The analysis shows that FLC performs better in handling overshoot, with previous studies indicating its ability to completely eliminate overshoot. Although the PID method is simpler and easier to apply in systems with linear characteristics, FLC offers better flexibility and adaptability for managing uncertainty and non-linear systems. Recommendations for further research are also presented, including a deeper exploration of integrating the two methods in a hybrid control system to enhance motor control performance.

1. Introduction

A control system is a mechanism designed to regulate, control, or direct the behavior of a system to achieve a desired outcome [1]-[3]. Essentially, a control system consists of input, process, and output components, which interact to ensure effective performance [4]. Control systems can be categorized into two main types: open-loop and closed-loop systems [5]-[8]. Open-loop systems operate based on initial input without using feedback, making them unable to adjust output based on changing conditions. In contrast, closed-loop systems use feedback to monitor and dynamically adjust the output, thereby enhancing accuracy and stability. In this context, controlling a DC (Direct Current) motor is an example of a closed-loop control application [9]-[11], where feedback from the motor's speed or position is used to adjust the control signal, ensuring the motor operates according to the desired objective.

DC motor control is crucial in control system applications, especially in various industries such as automotive, robotics, and manufacturing [12]-[14]. The widespread use of DC motors is due to their ability to produce strong torque at low speeds and respond quickly to load changes. In operation, controlling the speed of a DC motor is a critical factor that can determine the efficiency and performance of the system. Two main methods commonly used to control DC motor speed are Proportional-Integral-Derivative (PID) [15]-[17] and Fuzzy Logic Controller [18]-[20]. These two approaches offer different solutions, each with its own advantages and limitations.

The main challenge in controlling DC motors lies in the need for precise and stable control under various operational conditions, such as load variations, external disturbances, or changes in system characteristics [21], [22]. While the PID controller has been widely used and is known to provide good response in linear systems, it often faces limitations when applied to nonlinear or complex conditions [23]. PID's inability to adapt to rapidly changing dynamics or load uncertainties can lead to performance issues, such as excessive overshoot or slow recovery times. On the other hand, FLC has emerged as a more adaptive alternative, capable of handling uncertainties and load variations without requiring an exact mathematical model [24], [25]. However, the complexity of implementing FLC presents its own challenges [26]-[28]. Therefore, a comprehensive review comparing these two methods is needed to determine the most effective control method across various situations, particularly in DC motor speed control applications.

The primary objective of this review is to outline the advantages and disadvantages of two control methods, PID and FLC, in the context of DC motor speed control. Through this analysis, we aim to critically evaluate previous studies to identify the method that delivers the best performance across different situations. The main focus is to understand how these two methods behave in motor control, particularly regarding stability, accuracy, and response to load changes or external conditions. Additionally, this review seeks to explore the practical limitations still faced in implementing PID and FLC, as well as to identify research gaps that hinder further advancements in more sophisticated DC motor control.

The main contribution of this research is to present a comprehensive literature analysis with a systematic approach that enables researchers to identify current research gaps. We aim to provide a clear perspective on how each of these control methods can be applied more effectively, as well as areas where further innovation or development is needed. In this review, we also offer recommendations for future research, including the potential to combine PID and FLC methods in a hybrid model that could deliver superior control performance. This article is expected to provide valuable insights for practitioners, engineers, and researchers in selecting the most appropriate control method for specific applications and to encourage new innovations that can enhance the efficiency, accuracy, and reliability of DC motor control in the future.

2. Method

2.1. Research Stage

The initial stage of this research begins with topic exploration. In this phase, the researcher undertakes various actions such as reading relevant literature, reflecting on existing findings, posing critical questions, and narrowing the scope of the topic to be discussed. The outcome of this stage is a promising topic for further investigation. Once the topic is selected, the next step is literature search. The researcher conducts a literature search through various academic sources, checks the relevance of studies, downloads the necessary articles, and performs screening to identify relevant studies. At this stage, the result is a pool of literature or studies aligned with the chosen topic.

The next stage is study selection. The researcher carefully examines each study in the collected pool, assessing its quality, considering the strengths and weaknesses of each study, and selecting the most relevant and credible ones. The result of this process is a final sample of studies to be used in the research. After that, the researcher enters the literature synthesis stage, where key information from the selected studies is extracted, analyzed, and synthesized to build a comprehensive understanding of the topic under investigation. The outcome of this stage is a synthesis of studies that reflects integrated findings and understanding.

The final stage is organizing the structure of the literature review. In this stage, the researcher outlines the framework of the paper, writes a draft manuscript, integrates the findings and synthesis produced, and gathers feedback to improve and strengthen the writing. The end result is a draft manuscript ready for revision or publication. All these stages work sequentially to produce a systematic and well-structured literature review. In general, these stages are shown in Fig. 1.

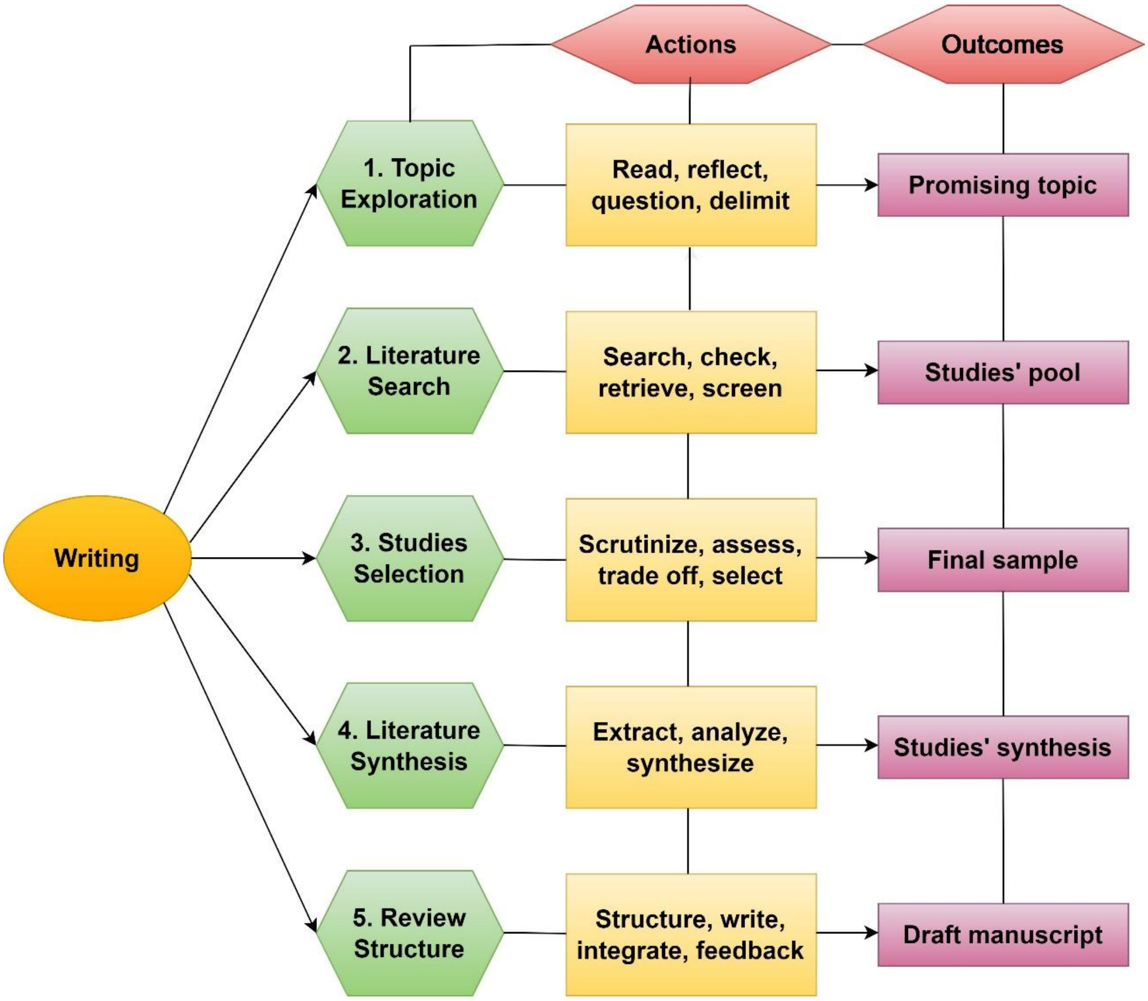


Fig. 1. Research stages

2.2. PID Controller

The PID controller is one of the most commonly used classical control techniques in industrial control systems [29]-[32]. Its popularity is based on its simplicity, effectiveness, and ability to provide stable and fast responses in various systems, both linear and nonlinear. The PID controller consists of three main components: Proportional (P), Integral (I), and Derivative (D) [33]-[37]. Each component plays a specific role in controlling the system, and the combination of these three components creates optimal control [38]-[41].

The P action regulates the control response proportional to the magnitude of the current error, which is the difference between the setpoint and the actual output of the system. This error $e(t)$ is defined as shown in Equation (1), [42].

$$e(t) = r(t) - y(t) \tag{1}$$

In Equation (1), $r(t)$ represents the reference value or setpoint, which is the desired target value of a system. This is the value the system aims to achieve during operation. On the other hand, $y(t)$ is the actual output of the system, which is the result or response produced by the system at a specific moment. The error $e(t)$ is calculated as the difference between $r(t)$ and $y(t)$, which is then used by the PID controller to correct the system's performance to approach the desired setpoint value. Therefore, the equation for the *P* action can be formulated as shown in Equation (2).

$$P = K_p e(t) \tag{2}$$

Here, K_p is the proportional gain constant that determines how much the control signal will respond to the error. The larger the value of K_p, the greater the influence of the error on the control signal [43]. This proportional action provides a correction proportional to the size of the error but may not always eliminate the error completely, especially in systems with steady-state error, where the output does not reach the setpoint even though the control signal has been applied.

Additionally, the *I* action is responsible for eliminating steady-state error, which cannot be addressed by the proportional action [44]-[47]. This component in the PID controller works by considering the accumulation of error over time, where K_i is the integral gain constant that determines the contribution of the accumulated error. The formula for the *I* action is shown in Equation (3).

$$I = K_i \int_0^t e(\tau)d\tau \tag{3}$$

Equation (3) describes the total error that occurs from the initial time until time *t*. With the integral action, the system not only corrects the current error but also addresses unresolved past errors. If small errors persist, the control signal generated by the integral action will continue to increase until the system output reaches the setpoint, thereby reducing the steady-state error. However, if the value of K_i is too large, it can lead to overshoot in the system's response or even oscillations, which may decrease the stability of the system.

On the other hand, the *D* component functions as a predictor by responding to the rate of change of the error, measuring how quickly the error changes over time [48]-[50]. This component takes into account the trend of error changes and attempts to anticipate the future behavior of the system. The formula for the *D* action is shown in Equation (4).

$$D = K_d \frac{de(t)}{dt} \tag{4}$$

K_d in Equation (4) is the derivative gain constant, and $\frac{de(t)}{dt}$ is the first derivative of the error with respect to time, indicating the rate of change of the error. The derivative action provides a significant control signal when there is a rapid change in the error, helping to dampen sudden changes and reduce system oscillations. By predicting error changes, this component assists the system in achieving stability more quickly. However, if the constant K_d is too large, the derivative response may make the system overly sensitive to small disturbances or noise, which can lead to unwanted oscillations.

By combining these three components proportional, integral, and derivative a PID controller is obtained, which is formulated as shown in Equation (5), [51].

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \tag{5}$$

This PID controller operates by combining the contributions of each component based on the tuning parameters K_p, K_i, and K_d [52]-[54]. Tuning must be done carefully, as each component impacts the system response differently. When K_p, K_i, and K_d are set correctly, the PID controller can provide a fast, stable, and accurate response for both linear and nonlinear systems [55]. In practical implementation, the PID controller is often used due to its flexibility. A system with a PID controller can be easily adapted to various applications by simply adjusting its gain parameters [56]. However, although the PID controller can deliver good responses in many scenarios, incorrect parameter tuning can lead to instability or overshoot, which requires careful adjustment and often involves trial-and-error or automatic tuning methods. The processing flow with the PID controller is shown in Fig. 2.

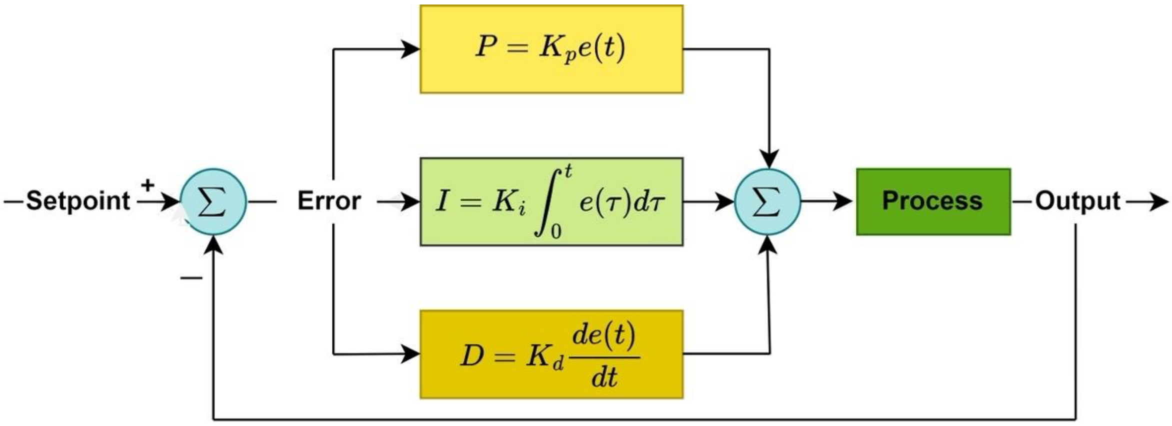


Fig. 2. Processing flow with a PID controller [57]

2.3. FLC

FLC is a control system approach that uses fuzzy logic, a concept introduced by Lotfi Zadeh in 1965 [58], [59]. Fuzzy logic allows variables to have membership values between 0 and 1, unlike conventional binary logic which only recognizes two absolute values, 0 and 1 [60]-[62]. This makes FLC very useful for handling complex, nonlinear systems, or when the system's mathematical model is difficult to formulate. With FLC, control can be based on knowledge-based or human experience rules translated into IF-THEN rules [63], [64]. For example, “IF temperature is high THEN fan runs fast.” These rules form the basis of the fuzzy inference process, where system inputs are converted to outputs based on fuzzy logic. The process in FLC consists of three main stages: fuzzification, fuzzy inference (which includes rule evaluation and aggregation), and defuzzification [65].

Fuzzification is the process of transforming numerical inputs into fuzzy variables with specific membership degrees [66]. Numerical inputs are typically mapped into several fuzzy sets based on membership functions. These membership functions can take shapes such as triangular, trapezoidal, or other forms that represent the degree of membership of the input within a fuzzy set, such as "low," “medium” or “high”. The degree of membership reflects how strongly the input belongs to a given fuzzy category. For instance, if an input x has a membership degree of 0.6 in the "low" set, this indicates that the input is between low and medium values. This fuzzification process provides flexibility to the control system, enabling it to handle uncertainties and variations that traditional binary logic cannot explain.

One of the commonly used membership function equations in fuzzification is the linear increasing membership function, which is formulated as shown in Equation (6).

$$\mu(x) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a < x < b \\ 1, & x \ge b \end{cases} \tag{6}$$

In Equation (6), $\mu(x)$ is the membership degree, and a and b are the boundary values of the interval for input x within the fuzzy set. This function is used to determine the degree of membership of an input within the fuzzy set, with values ranging from 0 to 1.

After fuzzification, the next stage is fuzzy inference, which consists of two main subprocesses: rule evaluation and aggregation. During rule evaluation, the system assesses predefined fuzzy rules, which are IF-THEN statements such as, "IF error is low AND change in error is low THEN control output is low." This evaluation uses fuzzy logic operators like AND (minimum) or OR (maximum). In cases where a rule uses the AND operator, the system selects the minimum membership degree of the fuzzy inputs. For example, if the error has a membership degree of 0.6 in the "low" category and the change in error has a membership degree of 0.8 in the same category, the fuzzy output for that rule will take the value 0.6, which is the minimum of the two inputs.

After rule evaluation, the next step in fuzzy inference is aggregation, where all fuzzy outputs from various rules are combined into a single composite fuzzy output. In the aggregation process, the system merges the evaluation results from multiple relevant rules to produce a set of fuzzy outputs that will be used in the defuzzification stage [67]. A common aggregation method is the maximum operator, where the fuzzy output from each rule is combined by taking the maximum value from all relevant fuzzy sets. For instance, if one rule's output has a membership degree of 0.6 and another rule's output has 0.4, the final aggregated output is 0.6, representing the highest value from the two rules. Aggregation enables the integration of contributions from multiple rules, thus reflecting the overall behavior of the system in a broader context.

The final stage in the FLC process is defuzzification, which converts the fuzzy output into a crisp or numerical value that can be used as an actual control signal within the system [68], [69]. This step is crucial as it allows the system to produce a concrete decision that can be directly applied to the real control system. Common defuzzification methods include the centroid method and the weighted average method.

The centroid method is one of the most popular defuzzification methods and is widely applied in Mamdani-based FLC systems. This method works by calculating the center of mass of the fuzzy set formed from the fuzzy output. The crisp output is generated by calculating the integral of the product between the fuzzy membership degree and the fuzzy output value, then dividing by the integral of the membership degree. Mathematically, the centroid method can be expressed by the formula shown in Equation (7).

$$z^* = \frac{\int \mu(z) \cdot u \, dz}{\int \mu(z) \, dz} \tag{7}$$

where z^* is the resulting crisp value, $\mu(z)$ is the membership degree of the fuzzy output set, and the integral bounds are the minimum and maximum values of the fuzzy set's domain. Using this method, the final result lies at the center of mass of the fuzzy set distribution, representing a balanced decision based on all involved fuzzy rules.

In addition to the centroid method, the weighted average method is also commonly used, especially in Sugeno and Tsukamoto fuzzy systems, where the fuzzy output is directly a crisp value [70], [71]. In the weighted average method, each crisp output is weighted based on the degree of membership of the triggered fuzzy rules. The final output is calculated as a weighted average of these crisp values. The formula representing this method is shown in Equation (8), [72].

$$z^* = \frac{\sum \mu_i z_i}{\sum \mu_i} \tag{8}$$

where μ_i is the membership degree of the i-th fuzzy set, indicating how strongly the rule is triggered, and z_i is the crisp value corresponding to the fuzzy output of the i-th rule. With this method, the crisp output is determined as a weighted average of all outputs generated by the active fuzzy rules. The weighted average method tends to be simpler than the centroid method, especially when the system output is already in crisp form. In general, the control process with FLC is shown in Fig. 3.

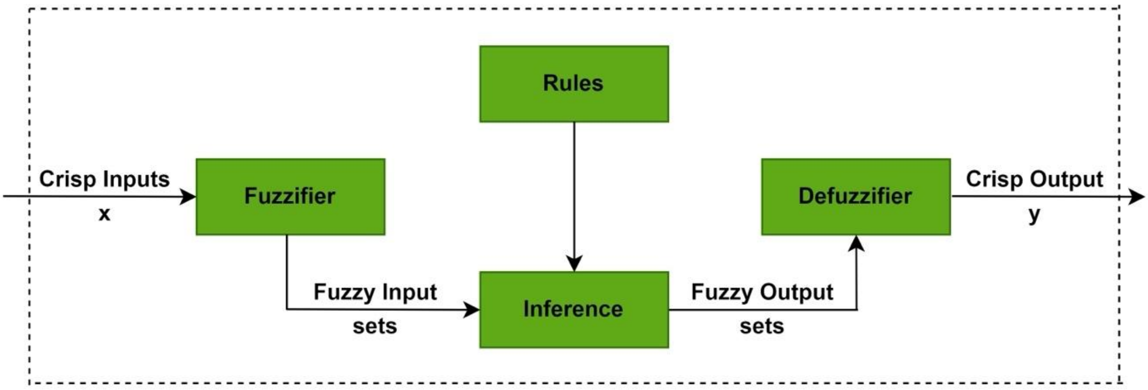


Fig. 3. Processing flow with FLC

2.4. DC Motor Performance Evaluation Parameters

The performance evaluation of a DC motor relies heavily on several key parameters, including rise time, settling time, and overshoot [73]. These three parameters help in understanding how quickly and stably the motor can reach the desired speed or position after an input or disturbance is applied. In DC motor control systems, these serve as primary indicators for assessing the efficiency and effectiveness of the system's response.

Rise time measures how quickly a DC motor can accelerate from a stationary position or low speed to reach 90% of the desired setpoint. For instance, when a DC motor is set to operate at 1000 RPM, the rise time indicates how quickly the motor can reach approximately 900 RPM. The equation commonly used to calculate rise time in a second-order system, particularly in a lightly damped system, is shown in Equation (9).

$$T_r \approx \frac{1.8}{\omega_n} \tag{9}$$

Where ω_n is the natural frequency of the system. The faster the rise time, the more responsive the motor is to input changes, which is crucial in applications requiring rapid speed adjustments, such as robotics or automated manufacturing systems. Slow rise time can result in the motor responding too slowly to changes, which can be detrimental in operating conditions that require high precision.

Next, the settling time is the time required for the motor to reach and remain within a certain tolerance range of the setpoint, usually 2% or 5%. This measures how quickly the motor stabilizes after oscillating or experiencing changes. The equation for settling time in a second-order system is shown in Equation (10).

$$T_s \approx \frac{4}{\zeta\omega_n} \tag{10}$$

Here, ζ is the damping ratio of the system, and $\zeta\omega_n$ is the natural frequency. A faster settling time indicates that the DC motor can achieve stability more efficiently after an input change. In applications such as robotic control or factory automation, a shorter settling time is crucial because the motor must quickly reach a stable condition to prevent disturbances in operation. If the settling time is too long, the motor will continue to oscillate around the setpoint, which can disrupt the overall system performance.

Overshoot refers to how far the motor's response exceeds the setpoint value before eventually stabilizing. It is often expressed as a percentage of the setpoint value. The formula for overshoot in a damped system is shown in Equation (11).

A large overshoot indicates that the DC motor reacts too quickly to the input and exceeds the desired setpoint value, which can lead to instability. In some applications, excessive overshoot can be dangerous as it may cause the motor to operate outside its operational limits. Therefore, one of the primary goals in control system design is to minimize overshoot so that the motor can reach the desired value without exceeding those limits. An illustration of rise time, settling time, and overshoot on a control response graph is shown in Fig. 4.

$$M_p = e^{-\frac{\zeta\pi}{\omega_n\sqrt{1-\zeta^2}}} \tag{11}$$

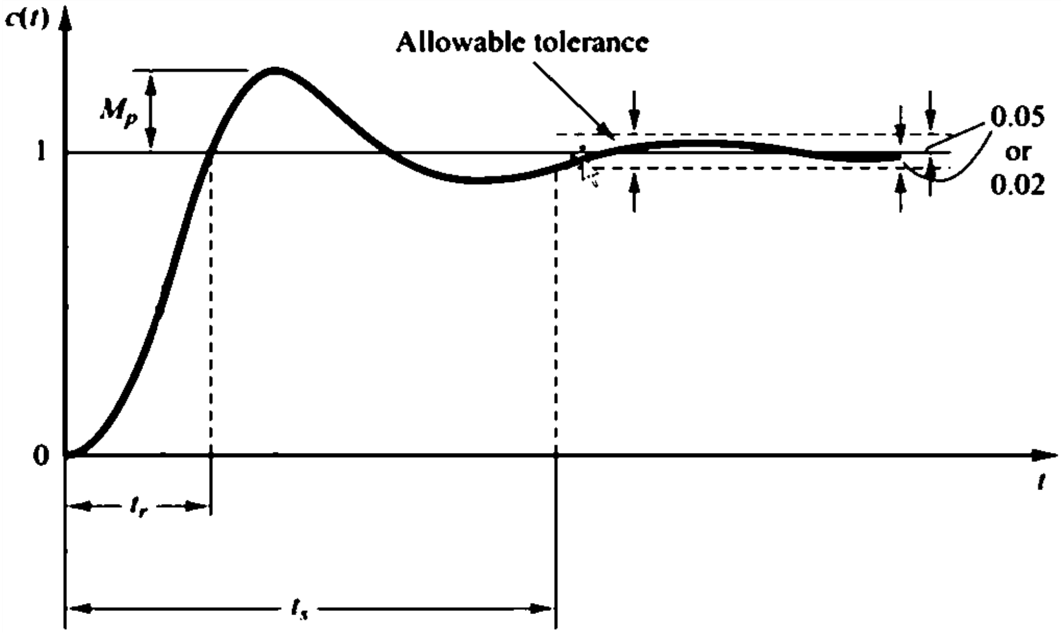


Fig. 4. Illustration of rise time (Tr), settling time (Ts), and overshoot (Mp) on the control response graph

3. Literature from Previous Research

In the field of system control, particularly in DC motors, previous research has played a crucial role in developing various methods and techniques to improve control system performance. Numerous studies have been conducted to compare the efficiency and effectiveness of different tuning approaches, focusing on key parameters such as response time, overshoot, and settling time. By understanding the various findings from prior research, we can better evaluate and select the most appropriate methods for specific applications in DC motor control.

In the control of DC motors with PID, Abdulameer et al. [74] compared two PID tuning methods, namely Ziegler-Nichols and Chien-Hrones-Reswick (C-H-R), for controlling a DC motor. In the Ziegler-Nichols method, the two formulas yield different PID parameter results, where the first formula produces a faster response with a rise time of 0.0451 seconds but has an overshoot of 26.3%. The second formula results in a larger overshoot of 42.2% but has a longer settling time of 1.25 seconds. The C-H-R method provides more stable results with an overshoot of 10.6% for the first formula and 13.1% for the second formula, although with relatively higher settling times compared to Ziegler-Nichols.

Another study by Li & Gong [75] showed that the conventional PID method provides satisfactory performance for DC motors, with a rise time of approximately 0.74 seconds, an overshoot of 9.7%, and a settling time of 0.86 seconds. Although the performance of conventional PID is adequate, overshoot remains an issue. This was also found in the study by Abdulameer et al. [74], which emphasized that conventional PID tuning often leads to significant overshoot, especially when using the Ziegler-Nichols method. Meanwhile, a study by Damilola Fajuke & Raji [76] in 2023 also showed similar results, with a relatively high overshoot of 22.94% and a commendable rise time of 0.5 seconds.

PID optimization using modern techniques such as Genetic Algorithms (GA) has shown significant performance improvements. Research [77] that utilized GA to optimize PID successfully eliminated overshoot; however, it still faced limitations with higher rise time and settling time, specifically 0.0763 and 0.116 seconds, respectively. These time values are worse compared to the results obtained from conventional PID, which had a rise time of 0.0062 seconds and a settling time of 0.0837 seconds, but with a larger overshoot of 47.4%.

On the other hand, FLC has also been used in many studies, such as the research by Putra et al. [78], which examined the use of FLC to control the speed of a DC motor in a fishing reel system. The results showed that the uncontrolled system resulted in a high overshoot of 60.6%, but with FLC, the overshoot significantly decreased to 19.5876%. FLC also improved the rise time (0.7 seconds) and settling time (0.8 seconds), although the response time was slower compared to the uncontrolled system. This study underscores the effectiveness of FLC in reducing overshoot and enhancing the stability of DC motor speed.

The same is supported by research conducted by Ismail et al. [79], who studied FLC for controlling DC motor speed in 2018. Their research focused on speed stability under load by comparing FLC and non-FLC methods. They successfully produced a response without experiencing overshoot when using FLC, while the previous uncontrolled system achieved an overshoot of 15.43%. However, unlike the study by Putra et al. [78], they were also able to optimize the system by generating better rise and settling times than without control (without FLC). Nevertheless, this does not come without challenges, as FLC can also potentially produce high overshoot, as evidenced by Rahman [80] in 2017 in his research on controlling the position of a DC motor, which had an overshoot of 40%. The motor model was developed using MATLAB/Simulink, and the FLC was designed with two inputs for error and change in error, and one output in the form of the applied voltage. The FLC used seven membership functions for error input and five for change in error, resulting in 35 fuzzy rules. The system recorded a rise time of 0.0921 seconds, peak time of 0.5 seconds, settling time of 2.373 seconds, and a delay time of 0.0563 seconds.

Meanwhile, research [81] and [82] demonstrate a clearer comparison between FLC methods and traditional control. The FLC resulted in a reduced response time of 0.0044 seconds and a steady-state time of 0.015 seconds. The overshoot decreased from 75% to 20%, and the speed error dropped from 1.5% to 0%. When a load of 4 Nm was applied, the system returned to the set point in 0.014 seconds [81]. Compared to PI Control, FLC also excelled in maintaining the stability of shunt DC motors, with a faster average steady-state time and lower overshoot [82]. This underscores that FLC provides better performance in various types of DC motors compared to conventional methods.

Additionally, several studies have compared PID and FLC within the same research, one of which is the study by Kushwah & Wadhwani aimed at controlling the speed of a separately excited DC motor [19] (more details can be found in Fig. 5). The methods employed included the application of FLC in a MATLAB/Simulink environment. The FLC was designed with 9 fuzzy rules derived from expert knowledge of the system. The system was then tested by providing a step input to the separately excited DC motor model. The simulation results showed that FLC provided better performance than PID, with a lower overshoot of 4.1997% and a faster settling time. However, FLC here still had a relatively higher rise time, measured at 0.124 seconds. A similar situation was experienced by Keshari Sahoo & Saha [88] in 2019, where the rise time for FLC (0.225 seconds) was greater compared to PID (0.027 seconds), although with smaller overshoot and settling time values.

Not stopping there, several other researchers experienced similar outcomes, including Kaloi (2020) [83], Akpama et al. (2021) [84], Awouda (2023) [85], and Ridzuan & Rahman (2024) [86]. Among these four studies, the lowest overshoot was achieved by Ridzuan & Rahman at 0.7746% with FLC, accompanied by a rise time of 0.1374 seconds. This rise time is greater compared to the PID control they produced, which was 0.0456 seconds. The poorer rise time of FLC compared to PID indicates a gap that needs to be updated and improved.

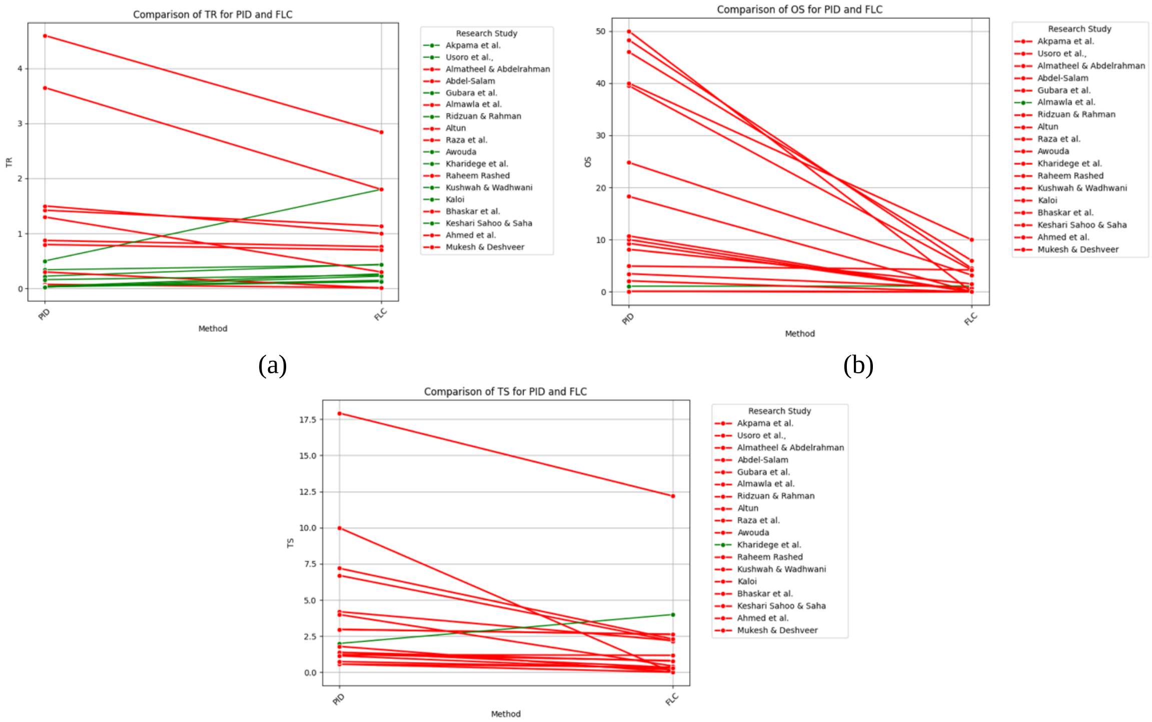
These results are also supported by Almatheel & Abdelrahman [87] in their 2017 study. In their research, FLC, designed with 49 fuzzy rules, successfully achieved a very low overshoot of 0.0083%, while PID had a higher overshoot of 0.12%. In this study, FLC outperformed PID in reducing overshoot and showed advantages in both rise time and settling time. This demonstrates a significant improvement compared to studies by Kushwah & Wadhwani [19], Keshari Sahoo & Saha [88], Kaloi [83], Akpama et al. [84], Awouda [85], and Ridzuan & Rahman [86], which only highlighted the benefits of FLC for overshoot and settling time (not for rise time). In addition to Almatheel & Abdelrahman, Altun's 2019 study [89] also highlighted FLC's superiority in terms of overshoot, rise time, and settling time compared to PID. They recorded an overshoot of 4.203%, a rise time of 2.8386 seconds, and a settling time of 12.1929 seconds with FLC. These values outperformed the PID controller's results, which had a higher overshoot, rise time, and settling time of 4.9408%, 4.5973 seconds, and 17.9273 seconds, respectively. Although this result is less optimal than Almatheel & Abdelrahman's, it reinforces that FLC has a stronger advantage over PID in DC motor control.

In this regard, Mukesh & Deshveer (2021) [90] also contributed by discussing speed control for a separately operated DC motor using both methods. In their tests, PID control parameters were tuned using the Ziegler-Nichols method, while FLC used a fuzzy rule-based system combining two inputs: speed error and error change. The results showed a rise time of 1.3 seconds for PID and only 0.3 seconds for FLC. Additionally, FLC demonstrated a 10% overshoot compared to 40% with PID, and a faster settling time of 0.3 seconds for FLC versus 0.75 seconds for PID. The steady-state error for both methods was 0%. In their study, the overshoot values remained relatively high for both PID and FLC. However, improvements were achieved by Abdel-Salam [91] in 2022 and Raza et al. [92] in 2023, who achieved much lower overshoot values for FLC at 0.024% [91] and 0.0094% [92]. Although the overshoot value by Raza et al. was significantly better, their control system tended to have a longer rise time and settling time compared to the studies by Mukesh & Deshveer and Abdel-Salam.

On the other hand, impressive results were demonstrated in several [93]-[97], [20] that highlighted FLC with zero overshoot (0%) as achieved by Ismail et al. [79]. One example is Ahmed et al.'s study [93] from 2003. Their simulation results showed that FLC delivered the best performance. With Ziegler-Nichols tuning, the simulation yielded an overshoot of 70%, a rise time of 2 seconds, and a settling time of 15 seconds. Manual tuning reduced the overshoot to 50%, with a rise time of 1.5 seconds and a settling time of 10 seconds. Soft tuning produced minimal overshoot (2%) and a rise time of 1 second but had a steady-state error of 2%. The best results were achieved with FLC, which eliminated overshoot (0%), had a rise time of 1 second, and achieved 0% steady-state error, indicating optimal and stable control.

The achievement of zero overshoot was also reported in the study by Gubara et al. (2016) [94], which used MATLAB Simulink for simulation. The results indicated that although PID provided a good response with a short rise time, it exhibited higher overshoot and settling time compared to FLC. However, the overshoot value they obtained for PID was still better (10%) than that reported by Ahmed et al. (50%). This overshoot value was almost identical to the results obtained by Kharidege et al. [95] in the same year, showing 10.72% for PID and 0% for FLC. In this case, however, the rise time and settling time varied slightly, as FLC had a longer rise time (0.2667 seconds) and settling time (4 seconds) compared to PID (0.04 and 2 seconds). Meanwhile, Bhaskar et al. [96] conducted another study that year, optimizing PID to reduce overshoot to a more optimal 2.1%. However, this was still insufficient to surpass FLC with its zero overshoot. Additionally, FLC's rise time and settling time aligned with its overshoot performance, proving FLC superior. In 2019, Raheem Rashed [20] achieved smoother control for FLC, with zero overshoot, and an impressive rise time and settling time of 0.008 and 0.016 seconds, respectively. The PID control also performed smoothly, with an overshoot of 0.1%, rise time of 0.3 seconds, and settling time of 1.8 seconds.

Additionally, a unique finding was presented in a study by Almawla et al. (2024) [98], which contrasted with other research. In their comparison paper, they highlighted that PID had a better response than FLC in managing overshoot. They recorded an overshoot of 1.09% for PID, while FLC had a slightly higher overshoot at 1.118%. Although the difference is minimal, this result contradicts findings from several previous studies, which showed FLC as superior in this aspect. On the other hand, despite falling behind in overshoot, FLC still excelled in rise time and settling time. Further details can be seen in Fig. 5.



(a) (b)

(c)

Fig. 5. Comparison of (a) rise time, (b) overshoot, and (c) settling time across all literature that studied and compared PID and FLC simultaneously

Fig. 5 shows a comparison of rise time, overshoot, and settling time from all literature that has investigated and compared PID and FLC simultaneously. A total of 18 studies conducted direct comparisons between the two methods. This comparison is highlighted with colors that indicate which method was superior: green for studies where PID performed better and red for those favoring FLC. In point (a), nine studies demonstrated that PID had a faster response in rise time, while the other nine studies favored FLC. This results in an even percentage—50% for PID and 50% for FLC. Meanwhile, in points (b) and (c), only one study favored PID in handling overshoot and settling time: Almawla et al. [98] for overshoot and Kharidege et al. [95] for settling time. The percentage favoring PID was only 5.56%, with the remaining 94.44% favoring FLC.

To understand the relationship between these three indicator variables, we present a heatmap illustrating the correlation levels among them. This heatmap allows us to observe potential patterns and relationships, identifying whether there is a positive, negative, or insignificant correlation among the analyzed variables. This visualization is highly useful in data analysis, as it provides a clear and concise depiction of interactions between the variables. The heatmap is shown in Fig. 6.

The correlation matrix in Fig. 6 reveals the relationships between three key attributes in the analysis of control system response: rise time, overshoot, and settling time. The correlation value between rise time and settling time is 0.81, indicating a strong positive relationship; this means an increase in rise time tends to correlate with an increase in settling time. In contrast, the correlation between rise time and overshoot is -0.18, indicating a weak negative relationship, suggesting that an increase in rise time may be slightly associated with a decrease in overshoot, though the effect is minimal. The correlation between overshoot and settling time is 0.03, showing no meaningful relationship between these variables, meaning that variations in overshoot do not significantly impact settling time. A summary of previous studies is shown in Table 1. Further, to examine the differences in control performance from the reviewed literature based on rise time, overshoot, and settling time, see Fig. 7, Fig. 8, Fig. 9.

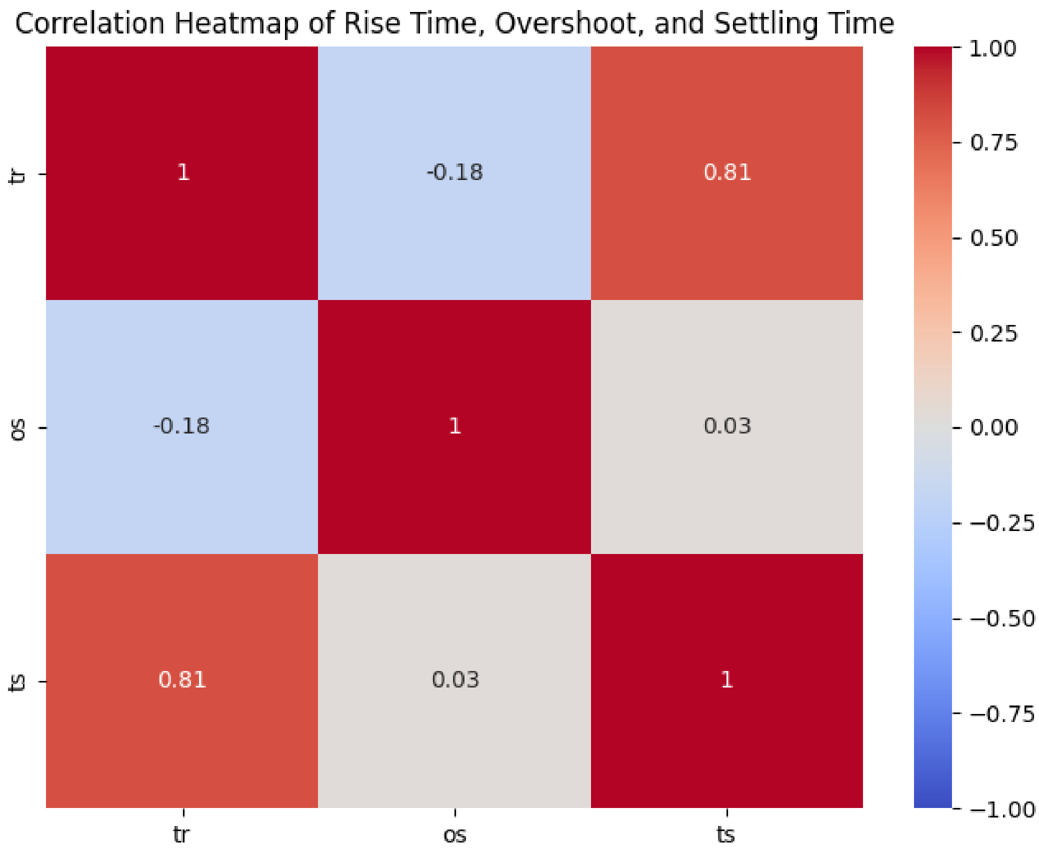


Fig. 6. Correlation heatmap of rise time, overshoot, and settling time

Fig. 7 shows the rise time obtained by previous researchers utilizing PID and FLC for DC motor control. Based on the figure, it can be seen that the longest rise times are dominated by PID-based control. Notably, in 2019, Altun [89] achieved a rise time of 4.597 seconds, which stands as the longest rise time compared to all referenced literature, followed by a study by Bhaskar et al. [96] from three years earlier (2016), with a rise time of 3.65 seconds. On the other hand, the smallest rise time is achieved by FLC, with the best time of 0.004 seconds, obtained by Ginola et al. in 2020. The previous year (2019), another researcher [20] also achieved an impressive value of 0.008 seconds. However, that result was not sufficient to compete with the time achieved by Ginola et al. [81]. In the following two years (2022), the best rise time for PID control was achieved by Chourasia [77], with a time of 0.006 seconds. However, when compared to FLC, this time is still less favorable, albeit by a very small margin.

In terms of overshoot shown in Fig. 8, the FLC method generally demonstrates more stable results compared to PID, with some studies even reporting no overshoot in FLC-based systems (e.g., Ahmed et al., 2013 [93]). This indicates that FLC is more reliable in maintaining system stability without exceeding the setpoint value, which is crucial in motor control applications to avoid vibrations or mechanical damage caused by excessive speed spikes. On the other hand, PID in some cases shows significant overshoot, as seen in the study by Ahmed et al. (2013) [93], which recorded an overshoot of 50%. This high overshoot can lead to reduced efficiency and increased risk of instability in DC motors. Although some studies note that PID can operate with minimal overshoot, such as 0.130% (Raza et al., 2024 [92]), the average overshoot of PID is still higher than that of FLC (see Fig. 10 b). In many studies, FLC shows very small overshoot, such as only 0.009% (Raza et al., 2024 [92]) or even zero in some cases. This supports the notion that FLC is more suitable for applications requiring high precision and stability without excessive oscillations after reaching the setpoint, particularly in sensitive settings like precision motor systems.

Table 1. Previous research on the use of PID and FLC in DC motor control

Ref.	Author	Year	Method	Performance		
				Rise Time	Over-shoot	Settling Time
[93]	Ahmed et al.	2013	PID	1.5000	50.0000	10.0000
[93]	Ahmed et al.	2013	FLC	1.0000	0.0000	0.0000
[19]	Kushwah & Wadhwani	2013	PID	0.0286	39.5190	1.3950
[19]	Kushwah & Wadhwani	2013	FLC	0.1240	4.1997	0.3405
[78]	Putra et al.	2015	FLC	0.7000	19.5876	0.8000
[74]	Abdulameer et al.	2016	PID	0.1910	10.6000	1.0800
[94]	Gubara et al.	2016	PID	0.5000	10.0000	4.2000
[94]	Gubara et al.	2016	FLC	1.8000	0.0000	2.2000
[95]	Kharidege et al.	2016	PID	0.0400	10.7200	2.0000
[95]	Kharidege et al.	2016	FLC	0.2667	0.0000	4.0000
[96]	Bhaskar et al.	2016	PID	3.6500	2.1000	7.2000
[96]	Bhaskar et al.	2016	FLC	1.8000	0.0000	2.3000
[97]	Usoro et al.,	2017	PID	0.2240	18.3000	1.3870
[97]	Usoro et al.,	2017	FLC	0.4400	0.0000	0.7810
[87]	Almatheel & Abdelrahman	2017	PID	0.8727	0.1200	2.9782
[87]	Almatheel & Abdelrahman	2017	FLC	0.7600	0.0083	2.6200
[80]	Rahman	2017	FLC	0.0921	40.0000	2.3730
[79]	Ismail et al.	2018	FLC	0.1000	0.0000	0.3800
[20]	Raheem Rashed	2019	PID	0.3000	0.1000	1.8000
[20]	Raheem Rashed	2019	FLC	0.0080	0.0000	0.0160
[89]	Altun	2019	PID	4.5973	4.9408	17.9273
[89]	Altun	2019	FLC	2.8386	4.2030	12.1929
[88]	Keshari Sahoo & Saha	2019	PID	0.0270	46.0000	4.0000
[88]	Keshari Sahoo & Saha	2019	FLC	0.2250	6.0000	0.4400
[83]	Kaloi	2020	PID	0.1610	8.1520	1.1490
[83]	Kaloi	2020	FLC	0.2440	1.5310	0.1830
[81]	Ginola et al.	2020	FLC	0.0044	20.0000	0.01500
[82]	Aliyya	2020	FLC	0.3424	0.5050	0.7526
[90]	Mukesh & Deshveer	2021	PID	1.3000	40.0000	0.7500
[90]	Mukesh & Deshveer	2021	FLC	0.3000	10.0000	0.3000
[84]	Akpama et al.	2021	PID	0.3400	24.8000	1.2300
[84]	Akpama et al.	2021	FLC	0.4300	3.2000	0.8200
[75]	Li & Gong	2022	PID	0.7400	9.7000	0.8600
[77]	Chourasia et al.	2022	PID	0.0062	47.4000	0.0837
[91]	Abdel-Salam	2022	PID	0.0750	9.3000	0.5680
[91]	Abdel-Salam	2022	FLC	0.0130	0.0240	0.0170
[85]	Awouda	2023	PID	0.0300	48.3000	0.5710
[85]	Awouda	2023	FLC	0.1500	4.5000	0.3600
[76]	Damilola Fajuke & Raji	2023	PID	0.5000	22.9400	6.1960
[92]	Raza et al.	2024	PID	0.8000	0.1300	2.9641
[92]	Raza et al.	2024	FLC	0.7000	0.0094	2.6421
[86]	Ridzuan & Rahman	2024	PID	0.0456	3.4619	1.2236
[86]	Ridzuan & Rahman	2024	FLC	0.1374	0.7746	1.1805
[98]	Almawla et al.	2024	PID	1.4220	1.0900	6.7070
[98]	Almawla et al.	2024	FLC	1.1350	1.1180	2.1650

In terms of settling time (Fig. 9), FLC also shows superiority in achieving system stability more quickly than PID. Several studies indicate very short settling times for FLC, such as 0 seconds (Ahmed et al., 2013 [93]) or 0.016 seconds (Raheem Rashed, 2019 [20]), indicating that systems controlled by FLC reach a stable condition faster after responding to input changes. This shorter settling time is particularly beneficial in DC motor control applications, where stability and accuracy are crucial to avoid prolonged fluctuations or instability. Conversely, the settling time for PID tends to be longer, with some studies showing settling times of up to 17.927 seconds (Altun, 2019 [89]). Although proper tuning can reduce PID settling time, as observed in several studies with settling times below 1 second (e.g., Mukesh & Deshveer, 2021 [90]; Awouda et al., 2023 [85]; Abdel-Salam, 2022 [91]; Chourasia et al., 2022 [77]), the average performance of PID is still slower compared to FLC (Fig. 10 c). Therefore, in the context of applications requiring fast response and good stability, FLC can be a superior choice compared to PID, especially in DC motor control where prolonged fluctuations can negatively impact the efficiency and durability of the system. To see the overall averages, see Fig. 10.

Based on the three key parameters in Fig. 10, which are rise time, overshoot, and settling time, there are significant differences in the performance of the two methods. In terms of rise time, the FLC method demonstrates better performance compared to PID. The average rise time for FLC is 0.591739 seconds, which is lower than the average of 0.788682 seconds for PID. This indicates that FLC can reach the transient state more quickly than PID. The minimum value for FLC is also lower, at 0.004 seconds compared to 0.006 seconds for PID, and the maximum rise time for FLC is 2.839 seconds, which is smaller than the 4.597 seconds achieved by PID.

For overshoot, FLC again excels with an average of 5.028739%, which is significantly lower than the average of 18.530636% for PID. This indicates that FLC tends to be more stable in avoiding excessive spikes after reaching the target. The minimum overshoot value for FLC is 0%, meaning there are conditions where no overshoot occurs, while PID still experiences a minimal overshoot of 0.1%. However, at the maximum value, FLC reaches 40%, which is slightly lower than PID's maximum overshoot of 50%.

In terms of settling time, FLC again shows better results with an average settling time of 1.603391 seconds, which is faster than PID's average of 3.466818 seconds. The minimum settling time for FLC is 0 seconds, indicating some conditions where the system can stabilize very quickly, while PID has a minimum settling time of 0.084 seconds. At the maximum value, FLC achieves a settling time of 12.193 seconds, which is lower than PID's requirement of up to 17.927 seconds to reach full stability.

4. Limitations and Gaps

In this review, several limitations and research gaps are identified, which offer opportunities for further studies in the future. Most research tends to focus on ideal models that do not always reflect the complexities of physical systems in the real world. This poses challenges to the validity of results when applied to more complex physical environments. The motor models used tend to overlook the effects of rotor friction and other nonlinearities that may arise in real applications. These factors reduce the validity of simulations when applied to more complex physical motors. Some studies also do not address variations in motor load that can affect controller performance [74], [95], [87], [98], nor do they consider external disturbances that could impact control reliability [83], [88], [20], [85], [91]. Additionally, gaps in analysis regarding how control techniques can be integrated or compared in broader industrial applications are also evident [83], [98], [92]. Some studies do not test the impact of load variations beyond established limits, which can significantly affect control performance [78]. Limited testing on a single type of DC motor and a specific set of load conditions [79], [82], [90], [96] highlights the need for further studies to explore optimization methods and intelligent control techniques to enhance system performance [76]. The nonlinear dynamics that arise in real applications, as well as the interactions between environmental factors and motor characteristics, have also not been sufficiently considered [80].

Furthermore, the conventional PID approach has major limitations, such as sensitivity to load changes and environmental disturbances, resulting in unwanted oscillations and reduced control performance. This weakness is compounded by the lack of adaptive capability to automatically adjust control parameters in dynamic environments. The reliance on manual tuning of PID parameters (Kp, Ki, Kd) presents a challenge, especially in more complex applications, as existing tuning methods are often not flexible enough to address real system dynamics [74], [94], [96], [75], [85]. Additionally, the use of classical tuning methods like Ziegler-Nichols can lead to significant overshoot, which limits the effectiveness of PID in dynamic applications that require real-time adjustments.

In FLC (Fuzzy Logic Control), although simulations show better results, this evaluation is limited to the simulation environment in MATLAB and has not yet been directly tested in the real world [93],

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[19], [74], [94], [95], [97], [91], [98]. This research has not included variations in motor types or more complex models [89], [81]. Additionally, FLC still relies on manual adjustment of fuzzy rules, which may reduce accuracy in physical applications. These limitations highlight the need for further testing under real conditions to validate the effectiveness of FLC [89]. Another gap is seen in the lack of in-depth analysis of the real-time response of fuzzy controllers compared to PID, as well as the optimality of the defuzzification strategy used [95]. Furthermore, the impact of FLC parameters and the selection of the number of membership functions on control results is not always analyzed optimally, indicating the need for further research to validate this method under various conditions [82], [97].

The fuzzy method used is still based on simple rule-based systems without more complex adaptations. This gap reveals an opportunity to develop hybrid control techniques or integrate with other advanced methods, such as Neural Networks or Model Predictive Control (MPC), to improve performance in responding to load changes and dynamic environmental conditions [19], [84], [20], [79].

5. Further Development Potential

Further development in the field of fuzzy logic control offers substantial opportunities to address various gaps identified in previous research. Most existing studies tend to focus on ideal models that do not fully reflect the complexity and dynamics of physical systems in the real world. This limitation poses significant challenges to the validity of obtained results, especially when applied to more complex physical environments, where factors such as rotor friction, nonlinearities, and variations in operational conditions can affect control performance. Therefore, it is necessary to develop more realistic models that take these effects into account to enhance the accuracy of simulations and the effectiveness of FLC applications in real-world scenarios. Additionally, many current studies do not consider motor load variations and external disturbances, which can have a significant impact on controller performance. In this context, the development of adaptive control systems becomes crucial. Such systems should be able to automatically adjust control parameters based on actual conditions encountered, including the effects of disturbances and load changes. Further research should explore the application of control techniques capable of handling load variations beyond established limits to ensure system reliability and stability in more dynamic situations.

Furthermore, the conventional PID approach has limitations, particularly in terms of sensitivity to load changes and environmental disturbances that can cause unwanted oscillations. This weakness can be addressed by implementing automatic tuning methods that utilize artificial intelligence (AI)-based optimization algorithms, such as particle swarm optimization (PSO), genetic algorithm (GA), bacteria foraging algorithm (BFA), and ant colony optimization (ACO). These methods have proven effective in various optimization problems and can be adapted for tuning FLC and PID control parameters, thereby enhancing system performance under varying conditions.

Although FLC performs well in simulations, direct evaluation in real-world settings remains limited. Therefore, testing FLC in physical environments is essential to validate its effectiveness and reliability, as well as to explore the impact of variations in motor types and more complex models. An in-depth analysis of the real-time response of fuzzy controllers compared to PID is also necessary to identify the optimality of the defuzzification strategy applied. Additionally, the influence of FLC parameters and the selection of the number of membership functions on control results should be analyzed more comprehensively.

To address gaps in existing research, the development of hybrid control techniques that integrate FLC with other advanced methods, such as Neural Networks [99] and Model Predictive Control (MPC), is essential. This approach is expected to enhance the system's ability to handle load variations, changing environmental dynamics, and interactions between environmental factors and motor characteristics. By conducting deeper exploration into the integration of these control techniques, research can yield more innovative and effective solutions to real-world complex challenges, while also contributing to the advancement of control technology in industrial and robotics applications.

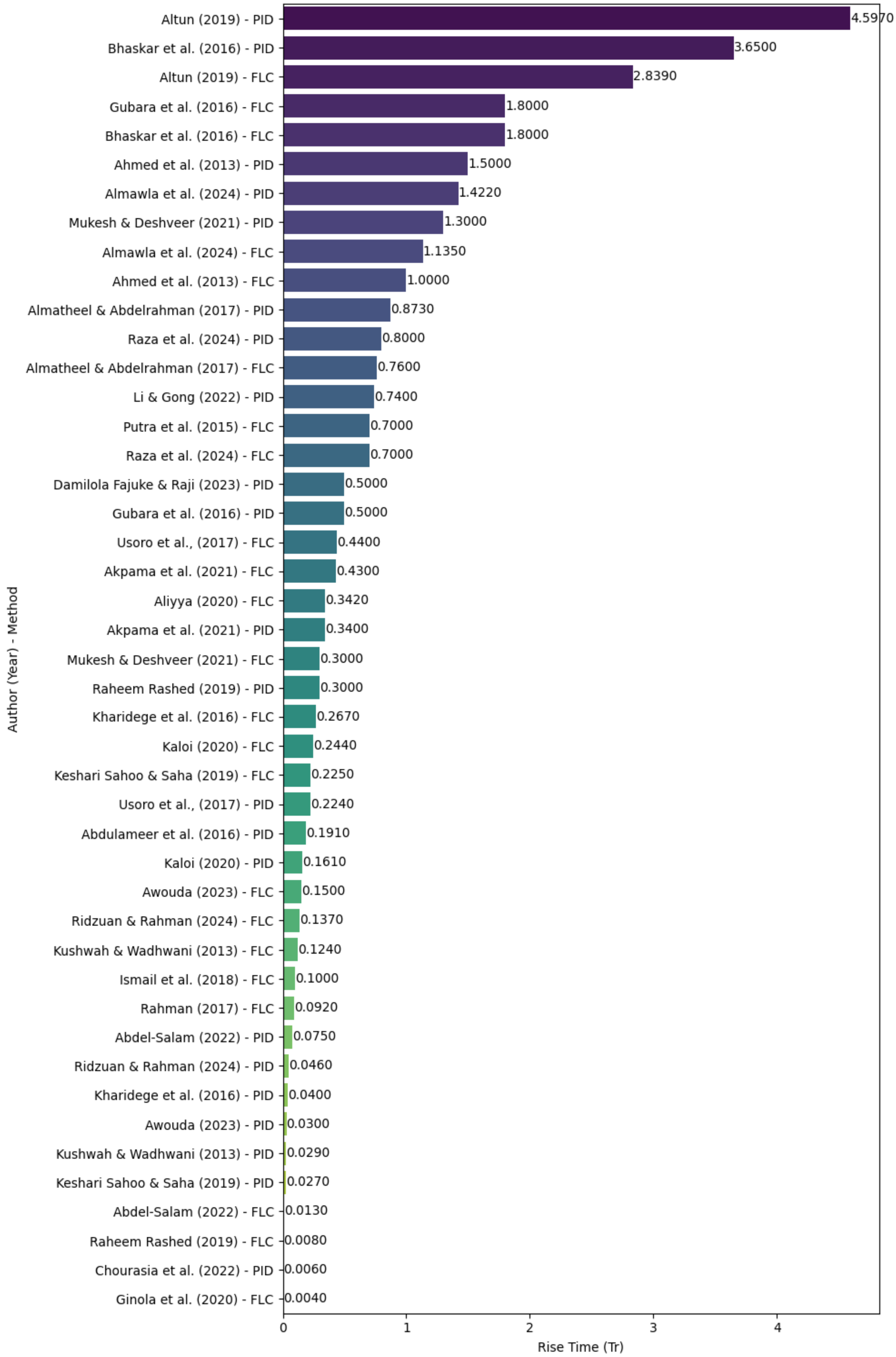


Fig. 7. Rise time by author (year) - method

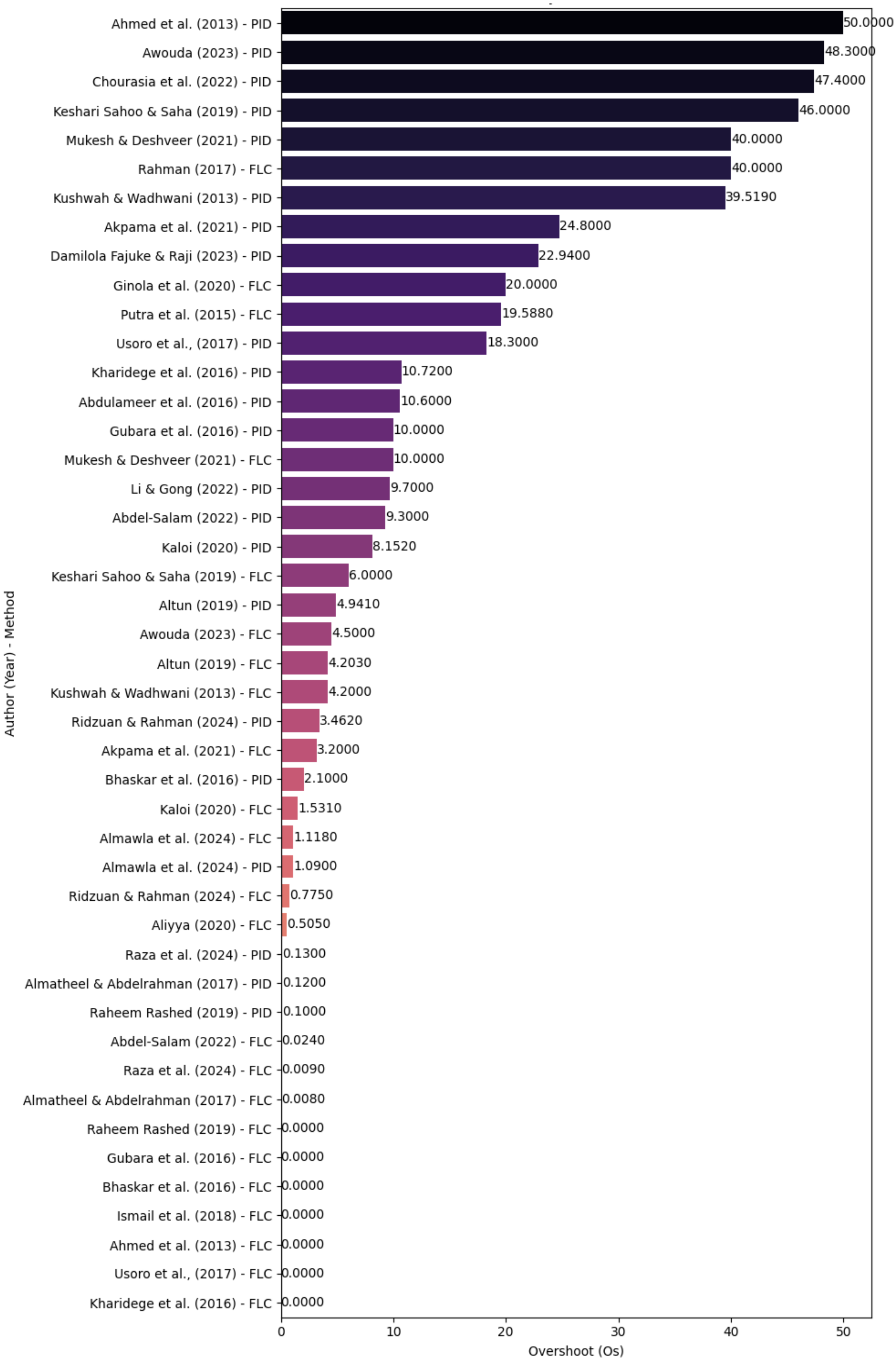


Fig. 8. Overshoot by author (year) - method

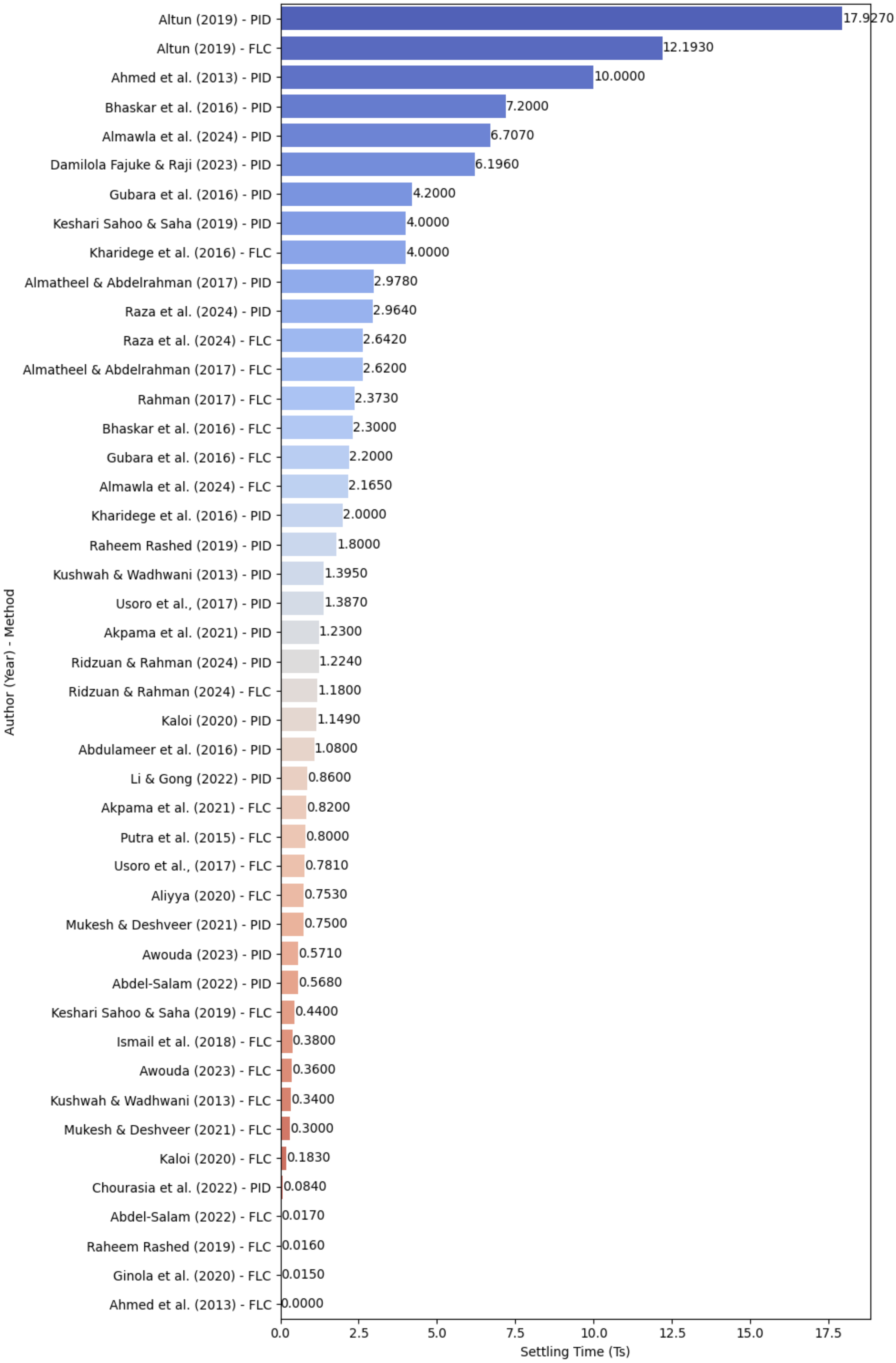
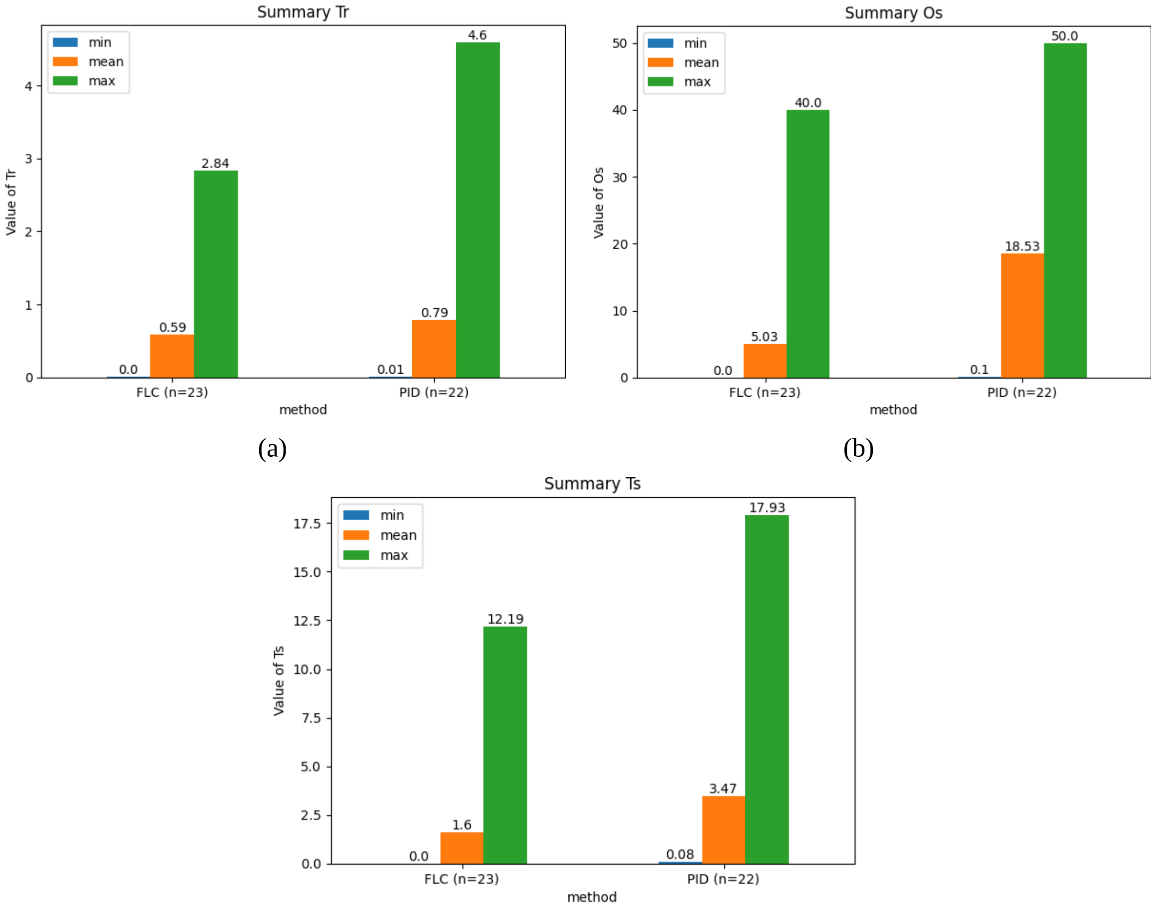


Fig. 9. Settling time by author (year) - method



(a) (b)

(c)

Fig. 10. Average (a) rise time, (b) overshoot, and (c) settling time of all literature based on their methods

6. Conclusion

Research in DC motor control shows that traditional methods like PID are still widely used due to their simplicity and ability to provide good performance in terms of rise time and settling time. However, issues such as significant overshoot are often encountered, especially when using tuning methods like Ziegler-Nichols. Studies also show that newer optimization methods, such as Genetic Algorithms (GA) and fuzzy logic control (FLC), can address the overshoot issue, albeit with the trade-off of increased rise or settling times. This indicates that no single method is entirely superior across all performance parameters, as each has its own strengths and weaknesses depending on the specific application and system requirements. Generally, further developments in DC motor control optimization focus on achieving a balance between fast response times, system stability, and minimized overshoot. FLC appears to offer a more reliable solution than PID in reducing overshoot, especially in applications requiring stability under variable load conditions. However, some challenges remain, particularly related to slower response times in FLC. Therefore, future research can continue to explore combinations and hybridization of these control techniques to achieve more optimal performance in DC motor control across various scenarios.

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Conflicts of Interest: The authors declare no conflict of interest.

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