

Comparative Performance Analysis of PID and Fuzzy-PID Speed Controllers for Brushless DC Motor Drives

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ABSTRACT

Proportional-Integral-Derivative (PID) controllers are effectively and widely used in various industries due to their ease of use and versatility. The Brushless DC (BLDC) motor is a well-known motor that combines reliability and efficiency, but for optimal performance, speed control must be precise. Although useful and often treated as a 'black box', PID controllers require careful tuning to achieve optimal performance in applications. This study describes a comparative study of two PID controllers for BLDC motors. The first PID controller was tuned using the Ziegler-Nichols PID (ZN-PID) method, a classical empirical method that could yield poor performance in complex applications. The second PID controller utilizes a fuzzy inference system to dynamically adjust PID values (Fuzzy-PID). The performance of both controllers was evaluated in a MATLAB/Simulink model to demonstrate that the Fuzzy-PID controller significantly improves speed control accuracy and energy efficiency when controlling BLDC motors compared to the ZN-PID controller.

Keywords- BLDC motor; PID; Ziegler-Nichols method; fuzzy inference system; speed control; membership function; rule base

I. INTRODUCTION

The development of high energy permanent magnet materials, power semiconductors, and digital integrated circuits has led to the advancement of Brushless DC (BLDC) motors. The best option for any application needing an electric motor where weight and space are limited is a BLDC motor [1, 2]. A BLDC motor can operate at high speeds, has excellent heat characteristics, and a high power to mass ratio. BLDC motors eliminate several drawbacks of brushed DC motors, including reduced efficiency, susceptibility to commutator assembly wear, subsequent maintenance requirements, and noisy

performance. Although BLDC motors require more complex and costly control electronics, they offer improved reliability and durability. Due to their advantageous electrical and mechanical features, BLDC motors are widely used in servo applications across automotive, aerospace, medical, instrumentation, and electromechanical fields [2-6].

Several controllers have been developed for the speed control of BLDC motors, such as the Proportional-Integral-Derivative (PID), the fuzzy inference controller, and the Adaptive Neuro-Fuzzy Inference System (ANFIS) controller [7]. Conventional PID controllers are still used in most industrial processes due to their simplicity and robust design.

However, the challenge in conventional PID lies in adjusting the parameters [5, 8]. This complexity often leads to suboptimal performance and inaccurate control of the system.

These inaccuracies, in turn, can significantly compromise the efficiency of BLDC motors [8]. Many techniques have been proposed for the adjustment of PID controllers. The Ziegler-Nichols PID (ZN-PID) method is one of the most widely accepted classical methods. This approach is often effective for a wide range of real-world control processes, yielding satisfactory results in many cases [9, 10].

However, there are cases where this method is inadequate, resulting in a substantial overload of the system's response. Therefore, in practical control applications, it is common to require reassessment and adjustment of this method before implementation for process control [11-13].

Various intelligent techniques and meta-heuristics methods have been used by many researchers to fine-tune the parameters (K_p, K_I, K_D) and enhance the effectiveness and implementation of PID regulators; one such technique is the Fuzzy-PID system, which combines PID with fuzzy inference to adjust PID gains [14, 15].

The main purpose of this study is to make a comparison between two hybrid controllers. The first controller uses the fuzzy inference system with a conventional PID, whereas the second uses the ZN-PID method. The combination of the ZN-PID method and the conventional PID is not considered ideal and adequate for the BLDC motor, whereas the Fuzzy-PID controller is specially designed to better adjust PID gains. Combining the fuzzy inference system and the conventional PID, this configuration provides a robust means of control to significantly improve the performance of the BLDC motor.

The main objective of this research is to compare the ZN-PID controller with the Fuzzy-PID controller to control the speed of BLDC motor by keeping the motor speed variable without load or constant with load and to show the dynamic speed response. The user can increase or decrease the speed as needed, and the motor will run at that exact speed. This study also intends to determine the most robust control and assure that torque ripple is minimized by the Fuzzy-PID controller.

II. SYSTEM DYNAMICS

The conventional DC motor mathematical model served as the basis for the BLDC motor's mathematical structure, whereas the BLDC motor has three phases, as presented in Figure 1.

The motor winding shown in Figure 2 is specifically outlined in (1)-(2) [3, 16]:

$$V = Ri + L \frac{di}{dt} + e \tag{1}$$

which gives:

$$e = V - Ri - L \frac{di}{dt} \tag{2}$$

where:

- V is the applied DC voltage (V).

- L is the winding inductance (H).
- R is the winding resistance (Ω).
- e is the back Electromotive Force (EMF) of the motor.

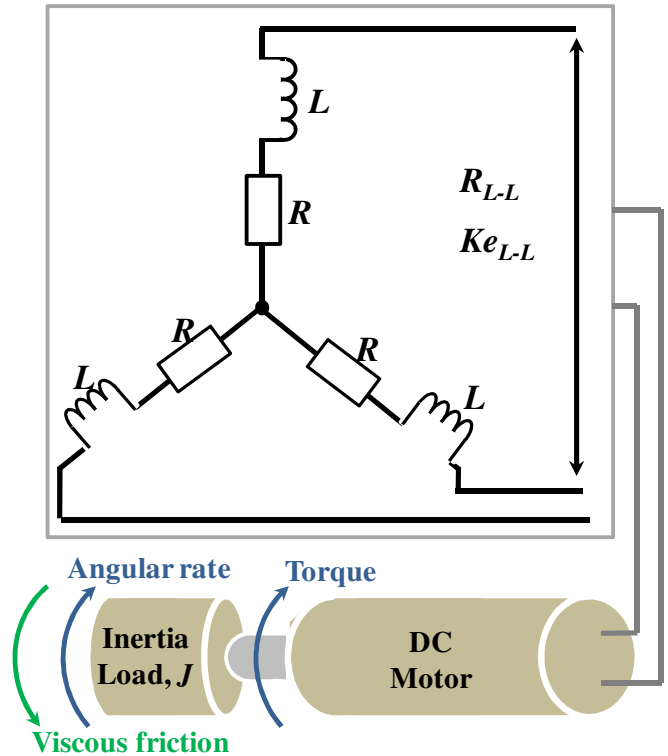


Fig. 1. Schematic diagram of the BLDC motor.

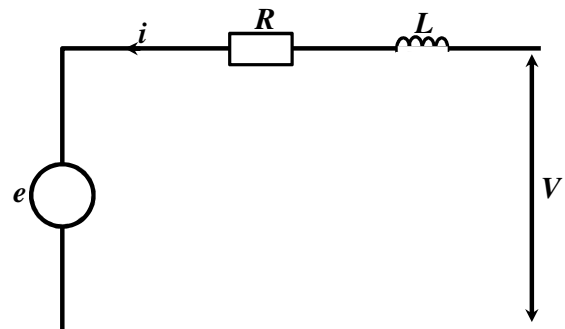


Fig. 2. One-phase model of the BLDC motor.

Finally, the mathematical model is written as:

$$G(s) = \frac{\frac{1}{K_e}}{\frac{JR}{K_e K_t} \cdot \frac{L}{R} \cdot s^2 + \frac{JR}{K_e K_t} \cdot s + 1} \tag{3}$$

where:

- K_e is the back-EMF constant (V·s/rad).
- J is the moment of inertia (kg·m²).
- R is the winding resistance (Ω).

- L is the winding inductance (H).

- K_t is the torque constant (N·m/A).

The following constants are acquired:

- Electrical constant:

$$\tau_e = \frac{L}{R} \quad (\text{One phase}) \quad (4)$$

- Mechanical constant:

$$\tau_m = \frac{J \cdot R}{K_e K_t} \quad (\text{One phase}) \quad (5)$$

For a three-phase BLDC motor, the mechanical and electrical constants are written as:

$$\tau_e = \frac{L}{3 \cdot R} \quad (\text{Three phases}) \quad (6)$$

$$\tau_m = \frac{J \cdot 3R}{K_e K_t} \quad (\text{Three phases}) \quad (7)$$

where:

- τ_m is the mechanical time constant (s).

- τ_e is the electrical time constant (s).

The transfer function equation for the BLDC motor is shown in (8):

$$G(s) = \frac{1}{\tau_m \tau_e s^2 + \tau_m s + 1} \quad (8)$$

The mathematical model of the BLDC motor is based on the parameters presented in Table I. The resulting transfer function is:

$$G(s) = \frac{11,76}{4.774 \cdot 10^{-6} s^2 + 0,005443 s + 1} \quad (9)$$

TABLE I. PARAMETERS OF THE BLDC MOTOR

| Parameter | Symbol | Value |
|----------------------|--------|---------------------------------------|
| Phase resistance | R | 0.57 Ω |
| Phase inductance | L | 1.5×10^{-3} H |
| Torque constant | K_t | 0.085 N·m/A |
| Back-EMF constant | K_e | 0.085 V·s/rad |
| Number of poles | P | 4 |
| Rated voltage | V | 36 V |
| Rotor inertia | J | 23×10^{-6} kg·m ² |
| Friction coefficient | B | 7.35×10^{-5} N·m·s/rad |

III. CONTROLLER DESIGN

In industrial control applications, the PID controller plays a key role in the feedback loop [17]. Using the basic equation, the output signal of the PID controller $u(t)$ can be expressed as:

$$u(t) = K_p \left[e(t) + K_I \int_0^t e(t) dt + K_D \frac{de(t)}{dt} \right] \quad (10)$$

where K_p represents the proportional gain, K_I denotes the integral gain, K_D denotes the differential gain, $u(t)$ is the output signal of the PID controller, and $e(t)$ is the error, calculated as the difference between the reference input $r(t)$ and the measured output.

Although implementing a PID controller is simple, determining its optimal parameters is challenging [18]. To control the speed of the BLDC motor, the PID parameters must be carefully tuned under various operating conditions. When using a conventional PID controller, achieving satisfactory results can be difficult [1, 6].

A. Ziegler–Nichols Method

The ZN-PID step response method is one of the classical techniques for PID controller tuning. Although first introduced in 1942, it remains widely used in the process industry. The method is based on an open-loop step response test, which requires a stable process.

The unit step response of the process is characterized by two parameters, L and T . These are determined by drawing a tangent line at the inflexion point, where the step response slope is maximum. The intersections of the tangent with the coordinate axes provide the process parameters, as shown in Figure 3, which are then used to calculate the PID controller gains. The controller parameters obtained from the ZN-PID step response method are given in Table II.

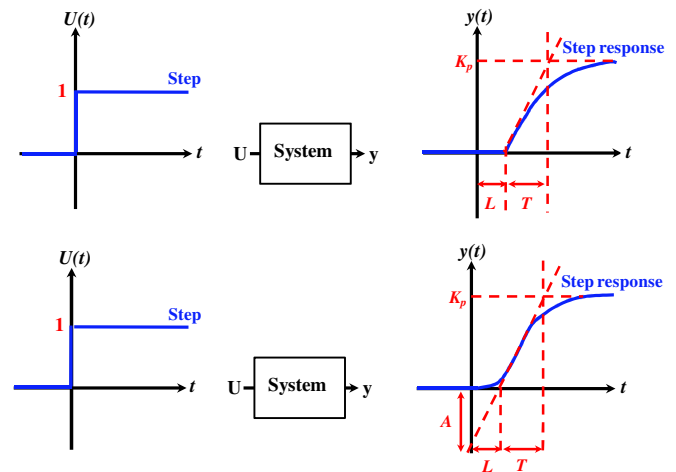


Fig. 3. Response curve used for ZN-PID tuning.

TABLE II. ZN-PID TUNING FORMULA (STEP RESPONSE METHOD)

| Parameter | K_p | T_I | T_D |
|-----------|-----------|-------|---------|
| Value | $1.2 T/L$ | $2 L$ | $0.5 L$ |

a. $K_D = K_p \cdot T_D$, $K_I = K_p \cdot T_I$.

B. Fuzzy PID Controller

The Fuzzy-PID controller is based on a fuzzy inference system that adaptively tunes the PID gains in real time. By adjusting the PID parameters using fuzzy rules, it is possible to achieve better performance than a conventional PID controller [18, 19]. The structure of the Fuzzy-PID controller is illustrated in Figure 4.

The membership functions and rule bases were designed to provide optimal tuning of the PID parameters (K_p, K_I, K_D) considering the BLDC motor's dynamic behavior. The input

variables, error (e), and change in error (de/dt), were divided into five fuzzy subsets (NL, NS, ZE, PS, PL) to handle a wide range of operating conditions (from large deviations to almost no adjustments near the setpoint).

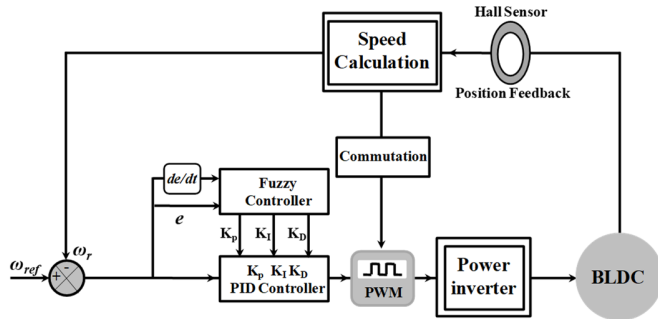


Fig. 4. Block diagram of the Fuzzy-PID controller.

The controller outputs (K_p, K_i, K_d) were divided into seven fuzzy subsets (ZE, PVS, PS, PM, PML, PL, PVL), enabling finer gain adjustment and smoother control action. The fuzzy rules were developed based on expert knowledge, with the goal of applying aggressive corrections for large errors, moderate corrections for small errors, and additional damping near the setpoint to minimize overshoot and oscillations.

Using this approach, the Fuzzy-PID controller is expected to provide improved speed regulation, faster settling time, reduced torque ripple, and better disturbance rejection compared to the ZN-PID controller.

The input and output subsets are summarized in (11) and (12):

$$e, \frac{de}{dt} = \{NL, NS, ZE, PS, PL\} \quad (11)$$

$$K_p, K_i, K_d = \{ZE, PVS, PS, PM, PML, PL, PVL\} \quad (12)$$

The control rules were developed based on the expertise of BLDC motor specialists. The membership functions of the Fuzzy-PID controller's inputs and outputs are shown in Figure 5, whereas the corresponding PID parameter adjustment rules are summarized in Tables III-V. The resulting gain surface is presented in Figure 6.

TABLE III. RULE BASE FOR K_p

| $e / \frac{de}{dt}$ | NL | NS | ZE | PS | PL |
|---------------------|-----|-----|-----|-----|-----|
| NL | PVL | PVL | PVL | PVL | PVL |
| NS | PML | PML | PML | PL | PVL |
| ZE | PVS | PVS | PS | PMS | PMS |
| PS | PML | PML | PML | PL | PVL |
| PL | PVL | PVL | PVL | PVL | PVL |

TABLE IV. RULE BASE FOR K_i

| $e / \frac{de}{dt}$ | NL | NS | ZE | PS | PL |
|---------------------|-----|-----|-----|-----|-----|
| NL | PM | PM | PM | PM | PM |
| NS | PMS | PMS | PMS | PMS | PMS |
| ZE | PS | PS | PVS | PS | PS |
| PS | PMS | PMS | PMS | PMS | PMS |
| PL | PM | PM | PM | PM | PM |

TABLE V. RULE BASE FOR K_d

| $e / \frac{de}{dt}$ | NL | NS | ZE | PS | PL |
|---------------------|-----|-----|-----|-----|-----|
| NL | PVS | PMS | PM | PL | PVL |
| NS | PMS | PML | PL | PVL | PVL |
| ZE | PM | PL | PL | PVL | PVL |
| PS | PML | PVL | PVL | PVL | PVL |
| PL | PVS | PMS | PM | PL | PVL |

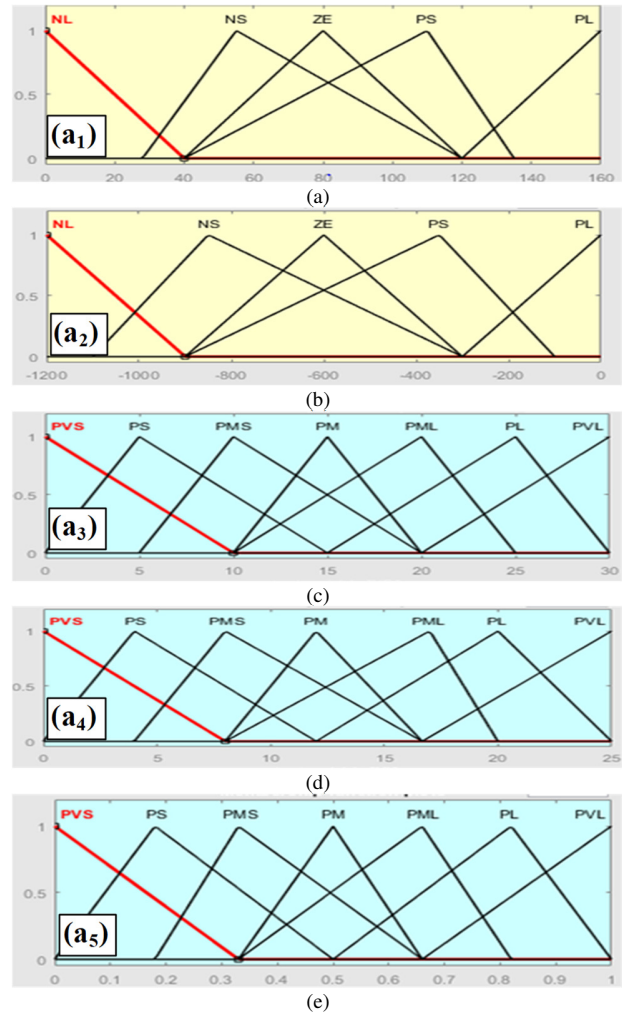
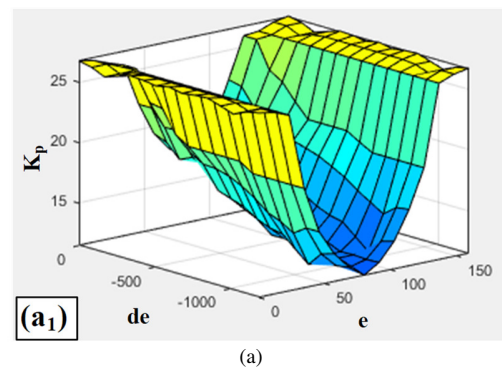


Fig. 5. Membership functions of the Fuzzy-PID controller: (a) input variable e , (b) input variable de/dt , (c) output variable K_p , (d) output variable K_i , (e) output variable K_d .



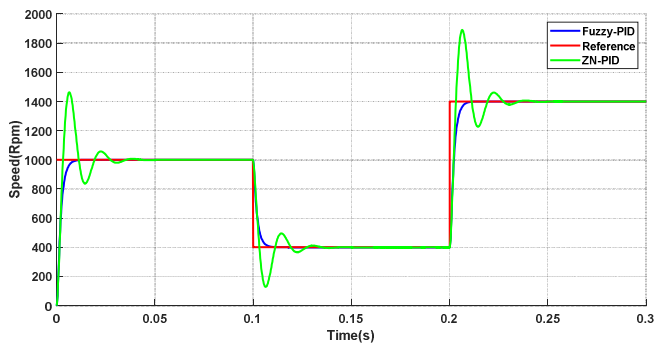


Fig. 8. BLDC motor speed response under ZN-PID and Fuzzy-PID control for variable-speed operation.

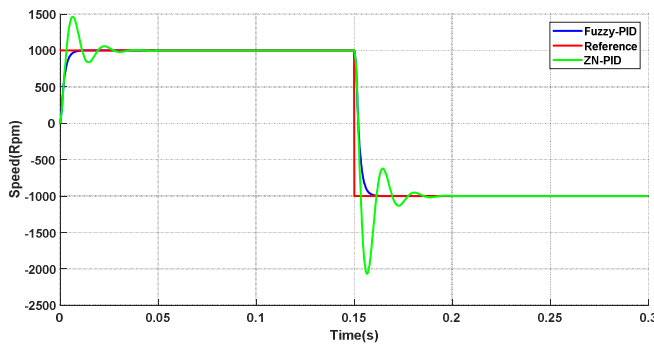


Fig. 9. BLDC motor speed response under ZN-PID and Fuzzy-PID control during speed reversal.

Table VI offers a quantitative assessment of the control performance for the Fuzzy-PID and ZN-PID controllers using three key error measures: ITAE, IAE, and ISE. The results indicate that the Fuzzy-PID controller outperformed the ZN-PID controller, achieving an 88% reduction in the ITAE (0.0056 compared to 0.0472), indicating better long-term error suppression and transient response; a 58% lower IAE (2.2546 compared to 5.354), implying improved overall tracking accuracy; and a 40% reduction in ISE (1346.5 compared to 2234), demonstrating enhanced control action and reduced oscillations. In summary, all three measures confirm that the Fuzzy-PID controller was adaptable, whereas the ZN-PID controller had fixed parameters, resulting in greater absolute and speed deviations. The robust results show that the Fuzzy-PID controller is well suited for precision applications, such as electric vehicles and industrial automation.

TABLE VI. PERFORMANCE INDICATORS FOR FUZZY-PID AND ZN-PID CONTROLLERS

| | Fuzzy-PID | ZN-PID |
|------|-----------|--------|
| ITAE | 0.0056 | 0.0472 |
| IAE | 2.2546 | 5.354 |
| ISE | 1346.5 | 2234 |

Figures 8 and 9 show the BLDC motor speed responses for the Fuzzy-PID and ZN-PID controllers. As summarized in Table VI, the Fuzzy-PID controller consistently achieved lower ITAE, IAE, and ISE values, confirming its superior efficiency and improved tracking performance compared to the ZN-PID controller.

B. Response of the Brushless DC Motor with Load

The simulation results of the BLDC motor speed with load using Fuzzy-PID and ZN-PID controllers are shown in Figures 10 and 11. Fuzzy-PID and ZN-PID were compared in this study. Both controllers follow the reference well; however, when a load is applied at $T = 0.15$ s, the ZN-PID controller shows a significant speed drop. In contrast, the Fuzzy-PID controller exhibits smaller deviations and faster recovery, highlighting its superior disturbance rejection capability. In addition, the ZN-PID controller shows ripple in steady state, whereas the Fuzzy-PID method reduces these fluctuations.

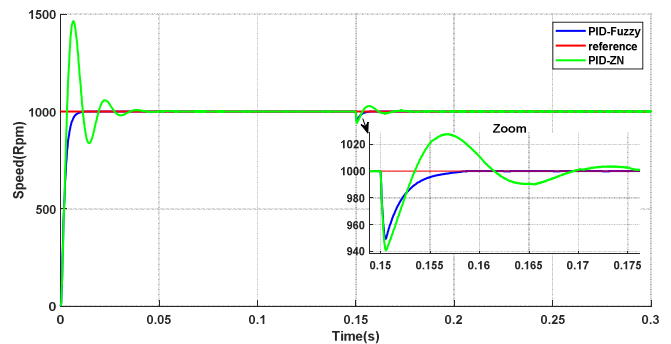


Fig. 10. BLDC motor speed under ZN-PID and Fuzzy-PID control with a 0.5 N·m load.

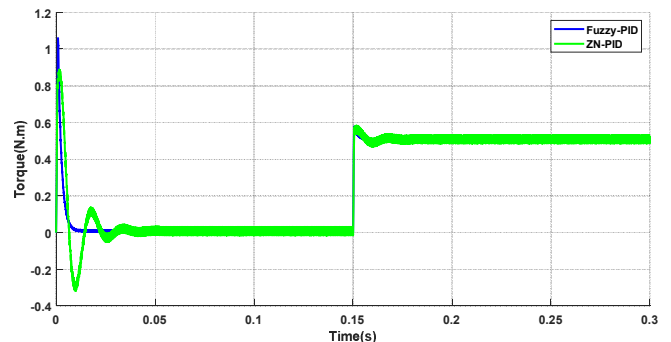


Fig. 11. BLDC motor torque under ZN-PID and Fuzzy-PID control with a 0.5 N·m load.

The rise time, settling time, overshoot, steady-state error, and torque ripple coefficient are summarized in Table VII, where T_{max} , T_{min} , T_{avg} are the maximum, minimum, and average torque values during steady-state operation. Lower values indicate smoother motor performance.

TABLE VII. STATISTICAL ANALYSIS OF BLDC MOTOR WITH PROPOSED CONTROLLERS UNDER LOAD

| Controller | Fuzzy-PID | ZN-PID |
|--|-----------|---------|
| Torque ripple coefficient $(\frac{T_{max}-T_{min}}{T_{avg}})100$ | 4.18% | 9.17% |
| Steady-state error | 0.0618 | 0.18 |
| Overshoot | 0.0057 | 46.3259 |
| Settling time (s) | 0.1522 | 0.1587 |
| Rise time (s) | 0.0040 | 0.0023 |

The results show that the Fuzzy-PID controller achieves superior performance compared to the N-Z-PID controller, with a lower settling time of 0.0067, steady-state error of 0.00618, torque ripple of 4.18%, and reduced overshoot of 0.0057, except for the rise time, which is 0.0040 s compared to 0.0023 s for the ZN-PID controller.

A comparative analysis of the Fuzzy-PID and ZN-PID controllers for BLDC motor speed control is presented in Table VIII, which outlines their key differences. has the advantage of dynamically adjusting PID gains in real time using fuzzy logic membership functions, making it more precise, robust to load changes, and capable of reducing torque ripple. However, implementing a Fuzzy-PID controller is computationally more complex and requires expertise to design effective fuzzy rules.

TABLE VIII. PERFORMANCE COMPARISON OF FUZZY-PID AND ZN-PID CONTROLLERS

| Feature | Fuzzy-PID | ZN-PID |
|---------------|--|-----------------------------|
| Tuning | Adaptive, real-time | Fixed, empirical |
| Precision | High (low steady-state error) | Moderate (higher error) |
| Load handling | Excellent disturbance rejection | Poor under load variations |
| Torque ripple | Low (4.18%) | High (9.17%) |
| Complexity | Higher (requires fuzzy logic design) | Simple (three fixed gains) |
| Robustness | Highly robust to nonlinearities | Sensitive to system changes |
| Best for | Dynamic applications (e.g., electric vehicles) | Stable, predictable systems |

In contrast, the ZN-PID controller uses fixed, empirically determined PID gains based on classical tuning rules. While its implementation is straightforward, it is less robust to load variations, produces higher overshoot, and results in larger steady-state errors compared to the Fuzzy-PID controller.

The Fuzzy-PID controller is ideal for applications requiring high performance under dynamic conditions, whereas the ZN-PID controller provides a simpler solution for environments with less variability.

VI. CONCLUSION

This study presents a novel adaptive Fuzzy Proportional-Integral-Derivative (Fuzzy-PID) controller that significantly advances Brushless DC (BLDC) motor control by introducing real-time dynamic tuning of PID gains through an optimized 5x5 rule base and specialized membership functions. Unlike prior approaches ([5, 6, 18]) that relied on static tuning or simplified fuzzy systems, our design achieves three key breakthroughs:

1. 88% reduction in the Integral of Time-weighted Absolute Error (ITAE) and 54% lower torque ripple compared to Ziegler-Nichols PID (ZN-PID) (Table VI).
2. Exceptional robustness under extreme operational conditions (± 1000 rpm reversals, 0.5 N·m load shocks).
3. Practical deployability, evidenced by 47.6% faster settling time and 65.7% lower steady-state error.

Through rigorous MATLAB/Simulink validation across variable speeds (400–1400 rpm) and dynamic loads, the controller demonstrates real-world readiness for high-performance applications, such as electric vehicles, where it enables smoother acceleration, reduced energy consumption, and enhanced stability. By merging expert-derived fuzzy rules with adaptive gain adjustment, this work bridges a critical gap between theoretical control systems and industrial implementation, offering a scalable solution for precision motor drives. Future efforts will focus on hardware-in-the-loop testing and meta-heuristic optimization to further refine rule autonomy.

The comparative study on Fuzzy-PID and ZN-PID controllers in terms of BLDC motor drives provides a solid basis for future research. To extend this work and improve flexibility, the following suggestions are proposed:

- Investigation of Fractional-Order PID (FOPID) controllers in combination with meta-heuristic optimization, such as Genetic Algorithm (GA) or Particle Swarm Optimization (PSO), for automatic gain tuning.
- Exploration of an Adaptive Neuro-Fuzzy Inference System (ANFIS) to further refine fuzzy-rule bases with neural networks.
- Real-time implementation and hardware testing of the proposed Fuzzy-PID controller.
- Testing on embedded systems, such as Digital Signal Processor (DSP), Field-Programmable Gate Array (FPGA), or ARM-based microcontrollers, to evaluate real-time performance.
- Development of a hardware test bench on actual BLDC motors under mechanical loads or variable speed conditions.
- Implementation of Reinforcement Learning (RL) or Deep Learning (DL) to dynamically optimize without predefined fuzzy rules.
- Evaluation on scaled systems, such as electric vehicle traction systems, drones, or industrial servo drives, to assess scalability.
- Assessment under extreme conditions, including sudden load changes or voltage variations, to test robustness.
- Comparative studies with modern controllers, examining performance differences and advantages.
- Benchmarking against advanced control strategies, such as Model Predictive Control (MPC) and Sliding Mode Control (SMC), for strong performance evaluation.

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