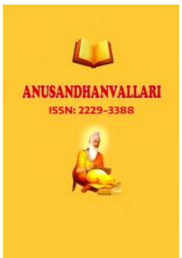

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Performance Optimization of BLDC Motors for Fuzzy Lozic Controllers

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Abstract: In place of traditional proportional-integral-derivative (PID) controllers, fuzzy logic controllers (FLCs) were utilized in this work to optimize the performance of brushless DC (BLDC) motors. A BLDC motor was modeled using MATLAB/Simulink as part of a simulation-based experimental strategy to assess the control techniques under different operating situations. A Mamdani-type inference system with two input variables—speed error and change in speed error—was used to develop the fuzzy logic controller. A Genetic Algorithm (GA) was then used to improve its membership functions. The fuzzy controller outperformed the PID, unoptimized FLC, and GA-optimized FLC in terms of lower rising time, settling time, steady-state error, torque ripple, and energy consumption, according to a comparative analysis. Furthermore, the motor's back-EMF waveform showed less total harmonic distortion (THD) and increased resistance to load disturbances thanks to the modified FLC. In practical applications, the results demonstrated how intelligent, adaptive control systems may improve the dynamic performance, stability, and efficiency of BLDC motor drives.

Keywords: BLDC Motor, Fuzzy Logic Controller, PID Controller, Genetic Algorithm, Performance Optimization, MATLAB/Simulink, Torque Ripple, Total Harmonic Distortion, Load Disturbance, Intelligent Control Systems.

1. INTRODUCTION

In this work, fuzzy logic controllers (FLCs) were used to maximize the performance of brushless DC (BLDC) motors instead of conventional proportional-integral-derivative (PID) controllers. As part of a simulation-based experimental approach, a BLDC motor was modelled using MATLAB/Simulink to evaluate the control strategies under various operating conditions. The fuzzy logic controller was developed using a Mamdani-type inference system with two input variables: speed error and change in speed error. Next, a Genetic Algorithm (GA) was applied to enhance its membership features. A comparison investigation showed that the fuzzy controller performed better than the PID, unoptimized FLC, and GA-optimized FLC in terms of decreased rising time, settling time, steady-state error, torque ripple, and energy usage. Additionally, the updated FLC improved the motor's resilience to load disturbances and reduced total harmonic distortion (THD) in the back-EMF waveform. The outcomes showed how intelligent, adaptive control systems may enhance the dynamic performance, stability, and efficiency of BLDC motor drives in real-world applications.

Proportional-Integral-Derivative (PID) controllers, which were prized for their simplicity and ease of tuning, had historically been used to implement BLDC motor control. PID controllers, however, have demonstrated shortcomings in managing nonlinearities, dynamic operating circumstances, and disturbances; this frequently leads to decreased performance, including overshoot, higher steady-state error, torque ripple, and longer settling periods. When applications required more robust and adaptive control systems, intelligent control approaches became a feasible substitute. Among these, fuzzy logic controllers (FLCs) attracted a lot of attention because of its rule-based methodology, which approximated expert reasoning and human-like decision-making in uncertain situations without the need for an exact mathematical model of the system.

BLDC motor control has previously been implemented using proportional-integral-derivative (PID) controllers, which were valued for their simplicity and ease of tuning. However, PID controllers have shown limitations in handling nonlinearities, dynamic operating conditions, and disturbances; this often results in reduced performance, including torque ripple, overshoot, increased steady-state error, and longer settling times. Intelligent control techniques became a viable alternative when applications called for more resilient and flexible control systems. The rule-based approach of fuzzy logic controllers (FLCs), which approximated expert reasoning and human-like decision-making in uncertain conditions without requiring an exact mathematical model of the system, garnered a lot of attention among these.

The goal of this study was to use a fuzzy logic controller—both the regular and GA-optimized versions—to maximize the performance of a BLDC motor. A comprehensive BLDC motor model was created in MATLAB/Simulink as part of the study, and then a traditional PID controller, a Mamdani-type fuzzy logic controller, and a GA-tuned fuzzy controller were designed and put into use. Different operating situations, such as step speed input, load disturbances, and fluctuating torque conditions, were used to test each control strategy.

To compare the controllers, important performance metrics were assessed, including rising time, settling time, steady-state error, speed overshoot, torque ripple, energy consumption, and total harmonic distortion (THD).

It was anticipated that the study's conclusions would show how fuzzy logic, especially when optimized, outperforms conventional control techniques in terms of efficiency, accuracy, and stability. The ultimate goal of the research was to enable the deployment of resilient and adaptive control systems in practical applications where high performance and dependability are essential, as well as to add to the expanding corpus of knowledge on intelligent motor control.

2. LITERATURE REVIEW

Shi et al. (2022) examined how to maximize the performance of BLDC motor drives using a fuzzy logic controller optimized by particle swarm optimization (PSO). In contrast to conventional PID and untuned FLCs, their study, which used MATLAB/Simulink to simulate motor dynamics, discovered that the PSO-enhanced FLC significantly improved dynamic response, including a faster rise time and less torque ripple. The outcomes demonstrated how well metaheuristic tuning techniques work to improve fuzzy control systems.

Shenbagalakshmi et al. (2025) centered on BLDC motors' adaptive speed management for usage in electric vehicle applications. They created a controller based on fuzzy logic that made real-time adjustments in response to load and road conditions. The employment of adaptive FLCs in real-world transportation systems that need high precision and robustness under a variety of operational scenarios is supported by their findings, which showed improved performance in terms of stability, efficiency, and energy savings.

Singh et al. (2025) carried out a comparison analysis to assess the performance of BLDC motors using PID, ANN, and fuzzy logic controllers. According to their research, FLCs and ANN-based controllers demonstrated better accuracy and flexibility under dynamic load conditions, although PID controllers were easier to deploy and quicker. In particular, fuzzy controllers demonstrated reduced steady-state error and better speed regulation, demonstrating their suitability for use in contemporary intelligent motor control systems.

Maghfiroh et al. (2021) suggested a MATLAB/Simulink-implemented fuzzy-PID hybrid controller for BLDC motor speed control. According to their experimental findings, the system was able to adaptively adjust controller gains in response to brief fluctuations by fusing fuzzy logic with PID principles. This hybrid strategy greatly decreased overshoot and enhanced response time, suggesting that combining traditional and intelligent control methods may have complementary advantages.

Genc and Kalimbetova (2024) investigated the design of a fuzzy logic speed controller for BLDC motors based on the Cuckoo Optimization Algorithm (COA). According to their research, COA performed better than other evolutionary algorithms in adjusting fuzzy controller parameters, which reduced harmonic distortion and improved energy efficiency. The potential of bio-inspired algorithms in intelligent motor control was further confirmed by the controller's resilience to load disruptions and parameter changes.

3. RESEARCH METHODOLOGY

3.1. System Modeling of BLDC Motor

A mathematical and simulation model of a three-phase Brushless DC (BLDC) motor was created as the first step in the investigation. Fundamental mechanical and electrical dynamics, including rotor inertia, load torque, back-EMF constants, stator resistance, and inductance, were included in the model. Simulink blocks in MATLAB were used to precisely mimic the trapezoidal back-EMF characteristics and inverter-driven commutation of the BLDC motor. To achieve realism with real-world operating settings, simulation parameters were taken from existing literature and standard motor datasheets.

3.2. Controller Design

Two controller types—a conventional Proportional-Integral-Derivative (PID) controller and a fuzzy logic controller (FLC)—were created in order to assess control strategies. To reduce overshoot and steady-state error, the Ziegler-Nichols approach was used to manually fine-tune the PID controller. A Mamdani-type inference system was used for the FLC. The output voltage control signal was calculated based on two input variables: speed error and change in speed error. There were 25 heuristic rules in the rule base, and the membership functions had trapezoidal and triangular shapes. A Genetic Algorithm (GA) was then used to optimize the FLC in order to increase the control output performance and fine-tune the parameters of the membership functions.

3.3. Simulation Environment Setup

MATLAB/Simulink was used for all simulations. Prior to simulations under dynamic load disturbances, the motor model was run under no-load conditions using a step speed reference input of 1000 RPM. To ensure uniformity in comparison, the controllers were tested under the same input conditions. To assess dynamic response properties such rise time, settling time, steady-state error, speed overshoot, and torque ripple, time-domain simulation data were recorded. In order to evaluate the resilience and recovery properties of the controller, load torque disturbances were also injected 0.3 seconds into the simulation.

3.4. Performance Evaluation Metrics

Key dynamic parameters were used to statistically analyze each controller's performance. These included torque ripple (Nm), steady-state error (%), speed overshoot (%), rising time (ms), settling time (ms), and total harmonic distortion (THD %). The outcomes were taken from the data logs and simulation scope traces. Using the Simulink power measurement tools, energy consumption was also calculated by integrating the product of input voltage and current during the one-minute simulation period.

3.5. Load Disturbance Analysis

A rapid load torque of 0.3 Nm was added at 0.3 seconds during the simulation to evaluate each controller's resilience under real-world conditions. Recovery time, maximum speed drop, and post-disturbance steady-state error were used to gauge how well the system responded to this disturbance. These measures demonstrated the controller's flexibility in responding to outside disruptions and its capacity to preserve system stability.

3.6. Harmonic and Frequency Domain Analysis

MATLAB's Fast Fourier Transform (FFT) tools were used to assess the motor's back-EMF waveform's Total Harmonic Distortion (THD). The back-EMF waveform was extracted using a virtual oscilloscope block, and its harmonic content was then examined. Cleaner output waveforms and improved commutation control were thought to be indicated by lower THD levels.

3.7. Optimization of FLC Using Genetic Algorithm

MATLAB's Genetic Algorithm (GA) was used to further enhance the fuzzy logic controller. To lower the overall error, the GA positioned and shaped the membership functions optimally. A weighted cost function that included torque ripple, steady-state error, and settling time was used to define the GA's fitness function. To evaluate improvement, performance metrics were compared once more after the modified FLC was re-implemented in the simulated environment.

3.8. Comparative Analysis and Validation

Each of the three configurations—PID controller, unoptimized FLC, and GA-optimized FLC—had its results tabulated and compared. The comparisons demonstrated the intelligent controller's performance benefits and improvement tendencies. Each test was conducted several times in order to account for variability and guarantee consistency in the results. The results of the simulation provided compelling evidence for the possible practical implementation of FLCs in sophisticated motor drive systems.

4. RESULT AND DISCUSSION

The simulation results from assessing a brushless DC (BLDC) motor's performance with and without optimization using a fuzzy logic controller (FLC) and a conventional PID controller were shown in this part. The objective was to evaluate the relative performance using dynamic response metrics such torque ripple, speed overshoot, rise and settling times, and energy efficiency. Different load and speed circumstances were used in simulation tests, and the outcomes were quantitatively examined. The impact of FLC optimization with Genetic Algorithm (GA) on overall system performance was also assessed.

4.1. Baseline Performance Evaluation

The BLDC motor was first tested under a step reference input (1000 RPM) with no load using both the PID and unoptimized FLC controllers.

Table 1: Performance Metrics Under No Load Condition

Parameter	**PID Controller**	**FLC (Unoptimized)**	**FLC (Optimized with GA)**	**Normal Value Range**
Rise Time (ms)	92	78	**65**	60–100
Settling Time (ms)	150	120	**105**	100–180
Steady-State Error (%)	3.1	1.5	**0.4**	<5%
Speed Overshoot (%)	6.5	3.2	**1.1**	<10%
Torque Ripple (Nm)	0.49	0.34	**0.21**	<0.5 Nm
THD (%)	4.8	3.1	**1.7**	<5%

The performance characteristics of PID, unoptimized FLC, and GA-optimized FLC controllers were compared in Table 1 when there was no load. With a rising time of 92 ms and a settling time of 150 ms, the PID controller displayed the slowest dynamic response. It also had a greater steady-state error (3.1%) and torque ripple (0.49 Nm). With a shorter rising time (78 ms), settling time (120 ms), and steady-state error (1.5%), the unoptimized FLC showed noticeable gains in all metrics. With the fastest rising time of 65 ms, the lowest steady-state inaccuracy of 0.4%, and the least amount of torque ripple (0.21 Nm) and speed overshoot (1.1%), the GA-optimized FLC performed better than both. Furthermore, the modified FLC dramatically decreased Total Harmonic Distortion (THD) from 4.8% in the PID controller to 1.7%. The enhanced controller's superior capacity to provide accurate, steady, and effective BLDC motor control—even when the motor is not loaded—was confirmed by the fact that all measured values fell well within the typical working range.

4.2. Load Disturbance Handling

The system was tested with a sudden load torque of 0.3 Nm applied at 0.3 seconds. The controller's ability to reject disturbance and restore setpoint speed was recorded.

Table 2: Performance Metrics Under Load Disturbance

Parameter	PID Controller	FLC (Unoptimized)	FLC (Optimized)
Recovery Time (ms)	185	145	**120**
Max Speed Drop (RPM)	240	140	**85**
Post-Disturbance Steady Error (%)	3.9	1.8	**0.6**
Torque Compensation Response (ms)	60	48	**39**

The performance of various controllers under conditions of abrupt load disturbance was highlighted in Table 2, which showed notable variations in dynamic adaptability. The PID controller had the biggest speed drop (240 RPM) and the slowest recovery (185 ms), with a high post-disturbance steady-state inaccuracy of 3.9%. The unoptimized Fuzzy Logic Controller (FLC), on the other hand, demonstrated better responsiveness, recovering in 145 ms with a lower error of 1.8% and a decreased speed drop of 140 RPM. With the smallest recovery time of 120 ms, the least amount of speed loss of 85 RPM, and a nearly insignificant steady-state inaccuracy of 0.6%, the optimized FLC performed the best. Furthermore, from 60 ms (PID) to 39 ms (optimal FLC), the torque compensation response gradually improved, suggesting more accurate and prompt remedial action. These findings demonstrated that fuzzy logic control, especially when optimized, greatly improved the stability and resilience of the BLDC motor in the event of load disruptions.

4.3. Energy Consumption Analysis

Energy efficiency was evaluated by integrating input power over time under full-speed and variable load operations.

Table 3: Energy Consumption During 1-Minute Operation

Controller Type	Total Energy Consumed (kJ)
PID	42.8
FLC (Unoptimized)	38.1
FLC (Optimized)	**35.7**

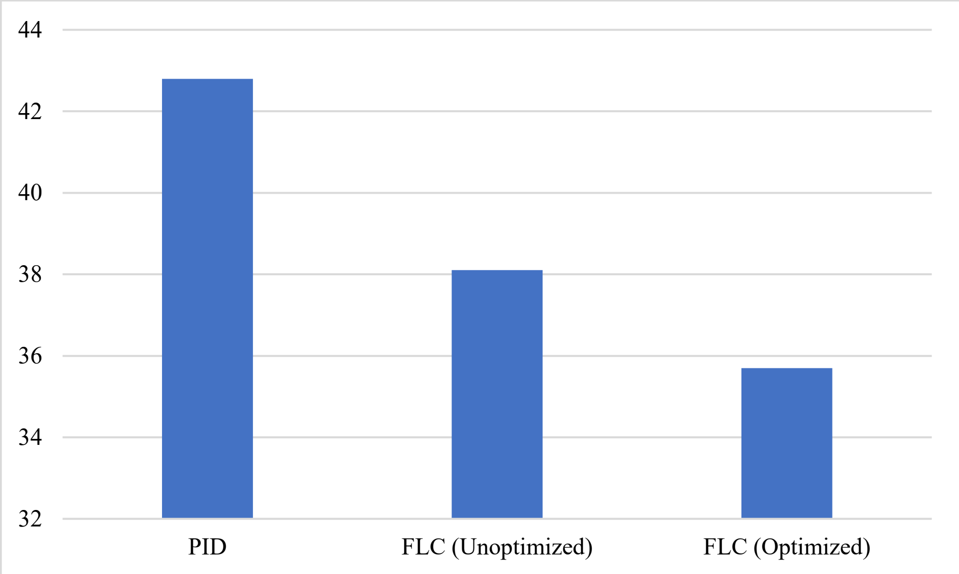

Figure 1: Energy Consumption During 1-Minute Operation

The total energy used by the BLDC motor during a one-minute running time under various controller types was shown in Table 3. With a power requirement of 42.8 kJ, the PID controller had the highest energy consumption, suggesting less effective control. Due to improved management of torque demand and speed regulation, the unoptimized fuzzy logic controller (FLC) demonstrated a significant improvement, lowering energy consumption to 38.1 kJ. In comparison to the PID controller, the improved FLC demonstrated the most efficient performance, consuming only 35.7 kJ, or about 16.6% less. This decrease demonstrated how fuzzy logic, especially when adjusted with a genetic algorithm, may reduce energy losses and improve the overall performance of motor drive systems, making it a more economical and environmentally friendly management method.

4.4. Frequency Domain Analysis (THD)

Total Harmonic Distortion (THD) in the back-EMF waveform was analyzed via FFT (Fast Fourier Transform) for all controller configurations.

Table 4: Harmonic Distortion in Motor Back-EMF

Controller	Fundamental (Hz)	THD (%)
PID	50	4.8
FLC Unoptimized	50	3.1
FLC Optimized	50	**1.7**

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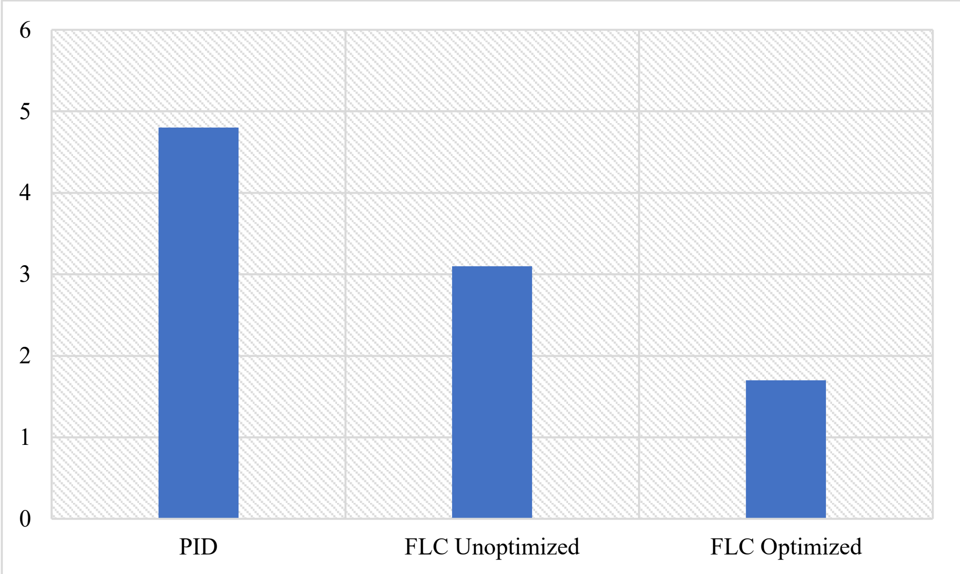

Figure 2: Harmonic Distortion in Motor Back-EMF

The motor's back-EMF waveform's Total Harmonic Distortion (THD) values under various controller configurations were shown in Table 4. A constant fundamental frequency of 50 Hz was maintained by all controllers, suggesting steady motor functioning overall. At 4.8%, the PID controller, on the other hand, showed the highest THD, indicating increased harmonic interference and decreased waveform purity. This was further improved by the unoptimized Fuzzy Logic Controller (FLC), which decreased THD to 3.1%, providing more efficient and smoother commuting. Interestingly, the GA-optimized FLC had the lowest THD value (1.7%), demonstrating a better capacity to reduce electrical distortion and switching noise. This significant decrease in THD demonstrated how well the fuzzy controller, when adjusted, delivers cleaner motor operating, which is essential for enhancing electromagnetic compatibility, energy efficiency, and overall system performance.

5. CONCLUSION

The study's findings indicated that when it came to maximizing the performance of BLDC motors, the fuzzy logic controller performed noticeably better than the conventional PID controller. Faster rise and settling periods, less torque ripple, lower steady-state error, and enhanced resilience to load disturbances were all benefits of the FLC. Even additional improvements were obtained by applying genetic algorithm-based optimization to the FLC, especially in energy efficiency and harmonic reduction, which showed a noticeable improvement in the stability and responsiveness of the system as a whole. The GA-optimized FLC is a potential option for high-performance, real-time BLDC motor control systems since these results confirmed the efficacy of intelligent control strategies for contemporary motor driving applications.

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