ISSN: 2583-5637 (Online)

International journal of Inventive Research in Science and Technology

Volume 4 Issue 8 August 2025

Review Paper 1

Intelligent Speed Control of BLDC Motor Using Fuzzy-Tuned Proportional-Integral (PI) Controller

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Abstract

This paper reviews the intelligent speed control of Brushless DC (BLDC) motors using Fuzzy-Tuned Proportional-Integral (PI) controllers. It addresses the limitations of conventional PI controllers in handling the inherent non-linearity and disturbances characteristic of BLDC motors. The review elucidates the working principles of BLDC motors, the theoretical foundations of PI and fuzzy logic control, and the methodology of integrating fuzzy logic for adaptive PI gain tuning. Key advantages, recent challenges, and future research directions are discussed, highlighting the superior performance of fuzzy-tuned PI controllers in achieving robust and precise speed regulation.

Keywords

Brushless DC (BLDC) Motor, Speed Control, Proportional-Integral (PI) Controller, Fuzzy Logic, Fuzzy-Tuned PI, Intelligent Control.

ISSN: 2583-5637 (Online)
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I. Introduction

Brushless DC (BLDC) motors are synchronous motors driven by direct current (DC) electricity, distinguished by their electronic commutation system that replaces mechanical brushes. This design offers significant advantages, including high efficiency, high power density, extended lifespan, reduced maintenance, and precise speed control. Their widespread applications range from computer hard drives and electric vehicles to medical equipment and aerospace systems. Achieving precise speed control for BLDC motors is paramount to ensure stable and efficient operation, especially under varying load conditions and external disturbances.

Proportional-Integral (PI) controllers are extensively employed in industrial control systems due to their straightforward structure and inherent robustness. They combine a proportional action, which responds to the current error, with an integral action, which addresses accumulated error over time to eliminate steady-state errors. However, conventional PI controllers often exhibit suboptimal performance when applied to inherently non-linear systems like BLDC motors. This is particularly evident under fluctuating operating conditions or significant load disturbances, leading to issues such as undesirable overshoot, prolonged settling times, and oscillations. Optimal tuning of fixed-gain PI controllers for such dynamic systems remains a persistent challenge. The derivative component (in PID controllers) can amplify noise, making PI controllers a more common choice in industrial settings for enhanced stability.

The intrinsic non-linearity and parameter variations characteristic of BLDC motors present considerable challenges for conventional PI controllers with fixed gains. This inadequacy of standard PI for BLDC's non-linearity creates a clear need for an "intelligent" solution. Fuzzy logic is a form of many-valued logic designed to handle imprecise and non-numerical information, effectively mimicking human-like decision-making based on "partial truth". It offers an intelligent, adaptive control paradigm that does not necessitate a precise mathematical model of the controlled system, making it a natural fit where precise mathematical models are difficult to obtain. The integration of fuzzy logic with PI control enables dynamic, online tuning of the PI controller's proportional (Kp) and integral (Ki) gains based on real-time error and change in error. This adaptive mechanism significantly enhances the controller's adaptability and overall performance in complex, non-linear operational environments. This approach represents a logical evolution, directly addressing the limitations of conventional PI for BLDC motor control. [1]-[3]

II. Literature Review

Historically, BLDC motor control relied on conventional feedback methods, primarily Proportional-Integral-Derivative (PID) and its simplified variant, PI controllers. While these controllers are known for their simplicity and reliability, they frequently deliver suboptimal performance under varying operating conditions and in non-linear modes. The challenge of effectively tuning fixed PID/PI gains for non-linear systems is a well-documented issue in control engineering, often resulting in undesirable characteristics such as excessive overshoot, prolonged settling times, and system oscillations.

To mitigate these performance limitations, research progressively shifted towards intelligent control techniques. Fuzzy Logic Controllers (FLC) emerged as a promising alternative, demonstrating capabilities such as reducing starting current, eliminating overshoot in torque and speed responses, and simplifying the design process by obviating the need for complex mathematical models. However, standalone FLCs can present their own challenges, including difficulties in automatic tuning and potentially high computational demands in terms of time and memory for real-time applications. This led to the development of hybrid control approaches, specifically Fuzzy-Tuned PI/PID controllers. This progression highlights a clear trend from simple, fixed-gain controllers struggling with BLDC non-linearity to the necessity of adaptive, intelligent approaches. These hybrid systems combine the inherent robustness and simplicity of conventional PI/PID controllers with the adaptive and knowledge-based capabilities of fuzzy logic. The primary objective of these hybrid controllers is to dynamically adjust the PI/PID gains in real-time based on the system's error and change in error, thereby achieving superior control performance. Numerous studies, predominantly simulation-based, have consistently demonstrated that fuzzy-tuned PI/PID controllers offer enhanced control execution, improved transient response characteristics (e.g., reduced overshoot, faster settling time), and greater robustness when compared to their conventional PI/PID counterparts. This "hybrid" nature

ISSN: 2583-5637 (Online)

International journal of Inventive Research in Science and Technology

Volume 4 Issue 8 August 2025

represents a pragmatic solution, leveraging the strengths of both traditional and intelligent control. [4]-[6]

III. Methods

BLDC Motor Fundamentals

BLDC motors are composed of a stationary stator containing windings and a rotating rotor embedded with permanent magnets. Unlike traditional brushed motors, the commutation process—which involves switching currents to the windings to generate continuous torque—is performed electronically by a dedicated controller. Rotor position is typically detected using Hall effect sensors or optical encoders, enabling the electronic controller to precisely time and sequence the current switching in the motor windings, thereby ensuring smooth and efficient operation. While sensorless commutation, which infers rotor position from back-EMF, is also feasible, it presents specific challenges during initial motion.

PI Controller Theory

A Proportional-Integral (PI) controller integrates both proportional (P) and integral (I) control actions. The proportional term generates a control output directly proportional to the current error, aiming to reduce it. The integral term, conversely, accumulates past errors over time, ensuring the elimination of any steady-state error. The combined control signal is thus proportional to both the instantaneous error signal and the integral of the error signal. Mathematically, its transfer function is often expressed as $K_p(1+1/(T_i s))$, where K_p is the proportional gain and T_i is the integral time constant (related to K_i, the integral gain, by $T_i=K_p/K_i$). PI controllers are frequently favored over full PID controllers in many industrial applications to mitigate the amplification of high-frequency noise that can be introduced by the derivative part.

Fuzzy Logic System Fundamentals

Fuzzy logic processes information based on "partial truth," where truth values can range continuously between 0 (completely false) and 1 (completely true). Its primary function is to map an input space to an output space using a set of "if-then" rules. The operational process of a fuzzy logic system typically involves three core steps:

1. **Fuzzification:** Crisp (numerical) input values, such as the system error and change in error, are converted into fuzzy linguistic variables (e.g., "Negative Large," "Zero," "Positive Small") using predefined membership functions, which are often triangular or trapezoidal in shape.
2. **Rule-Based Inference:** A collection of "if-then" rules (e.g., "IF Error is Negative Large AND Change in Error is Negative Large THEN Output is Positive Very Large") are evaluated in parallel. These rules typically encapsulate expert knowledge or behavioral insights of the system.
3. **Defuzzification:** The fuzzy output functions derived from the inference process are converted back into a single, crisp (numerical) output value, which serves as the control signal for the system.

Fuzzy-Tuned PI Controller Design

The fundamental concept behind a fuzzy-tuned PI controller is to employ a fuzzy logic controller to adaptively and continuously tune the proportional (Kp) and integral (Ki) gains of the conventional PI controller online. In this configuration, the fuzzy logic controller typically receives the system's error (e) and the change in error (ec) as its primary inputs. Its outputs are the dynamic adjustments ΔKp, ΔKi) that are then applied to the existing PI gains, or in some designs, the fuzzy logic directly outputs the new Kp and Ki values. This adaptive gain adjustment allows the PI controller parameters to change dynamically in response to the system's real-time performance, significantly enhancing its responsiveness and robustness against disturbances and non-linearities inherent in BLDC motor operation. This self-tuning capability directly addresses the well-known difficulty of optimally tuning fixed-gain PI controllers for complex, non-linear systems. This highlights how fuzzy logic directly addresses the primary weakness of conventional PI control for BLDC motors: fixed gains in a dynamic, non-linear system.

IV. Advantages

Fuzzy-tuned PI controllers offer significant performance improvements over conventional PI methods for BLDC motor speed control. These advantages collectively point to a paradigm shift from static to dynamic control, where the intelligence of fuzzy logic translates directly into practical performance gains.

- **Enhanced Speed Regulation and Disturbance Rejection:** Fuzzy-tuned PI controllers consistently demonstrate a superior ability to maintain the desired motor speed, even when subjected to sudden load changes or external disturbances. Simulation results explicitly highlight their improved robustness compared to conventional PI controllers.
- **Improved Dynamic Response:** These controllers achieve significantly faster response times (reduced rise time), quicker settling times, and substantially reduced or entirely eliminated overshoot and undershoot in speed responses. This translates into smoother, more stable, and more precise motor operation.
- **Robustness to Non-linearity and Parameter Variations:** The adaptive nature inherent in fuzzy tuning enables the controller to effectively manage the intrinsic non-linearity of BLDC motors and accommodate variations in motor parameters (e.g., changes in resistance). This represents a significant advancement over conventional PI controllers, which typically struggle with such complexities.
- **Automatic and Online Tuning:** Fuzzy logic provides a powerful mechanism for automatic, online adjustment of PI gains, thereby overcoming the challenges and inherent unreliability associated with manual tuning methods (such as Ziegler-Nichols), particularly for real-time process control. This capability renders the system more adaptive and less sensitive to parameter changes over time.
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International journal of Inventive Research in Science and Technology
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The following table summarizes the comparative performance metrics:

Parameter	Conventional PI	Fuzzy-Tuned PI
Rise Time	Longer	Shorter/Faster
Settling Time	Longer	Shorter/Reduced
Overshoot	Present/Significant	Reduced/Eliminated
Steady-State Error	Present/Non-zero	Eliminated/Zero
Robustness to Load Disturbances	Poor	Good/High
Robustness to Parameter Variations	Poor	Good/High

V. Recent Challenges

Despite their advantages, fuzzy-tuned PI controllers face practical implementation hurdles. The intelligence comes at a cost of design complexity and computational overhead, which can limit their widespread adoption, especially in cost-sensitive or resource-constrained applications.

- **Complexity in Fuzzy Logic Design:** Designing and optimally tuning fuzzy membership functions and the associated rule base can be a complex and subjective process. This often necessitates a deep understanding of the system dynamics and frequently relies on expert human knowledge and extensive trial-and-error. While some research attempts to simplify the rule base (e.g., reducing from 49 to 25 rules) , the challenge of defining truly optimal and comprehensive rules for all system behaviors remains significant.
- **Computational Demands and Hardware Implementation:** Intelligent control techniques, including fuzzy logic, can sometimes impose considerable computational demands, requiring more processing power and data storage capacity than simpler controllers. This can present a barrier to their deployment on cost-sensitive or resource-constrained hardware platforms. Real-time implementation of complex fuzzy systems may also consume significant time and memory resources.

ISSN: 2583-5637 (Online)
International journal of Inventive Research in Science and Technology
Volume 4 Issue 8 August 2025

- **Reliance on Sensors:** Many existing fuzzy-tuned PI control implementations for BLDC motors continue to rely on physical position sensors, such as Hall effect sensors or optical encoders, for accurate rotor position determination. This sensing is critical for precise commutation. This reliance adds to the overall system complexity, cost, and introduces potential points of failure, somewhat counteracting the desire for simpler, more robust systems.
- **Validation Gaps (Simulation vs. Real-world):** While numerous studies demonstrate highly promising results through simulation environments like MATLAB/SIMULINK , transitioning from simulation to robust physical hardware implementation often introduces additional, unforeseen challenges and necessitates further fine-tuning and calibration to ensure real-world applicability. The prevalence of simulation studies implies a gap in widespread real-world validation, suggesting a practical challenge for broader adoption.

VI. Future Directions

Future directions are geared towards making fuzzy-tuned PI controllers more autonomous, cost-effective, and robust for widespread industrial adoption. The trend is towards greater intelligence and practical feasibility.

- **Advanced Optimization and Self-Learning:** Future research can focus on developing and applying advanced optimization algorithms, such as genetic algorithms or Particle Swarm Optimization (PSO), to automatically optimize fuzzy membership functions and rule bases. This would significantly reduce the reliance on tedious manual tuning and expert knowledge, leading to improved performance and design efficiency. Furthermore, the development of truly adaptive fuzzy controllers capable of learning and adjusting their rules in real-time based on changing operating conditions is a crucial area of exploration.
- **Integration with Sensor less Control:** A promising direction involves the seamless integration of fuzzy-tuned PI control with sensor less commutation techniques (e.g., those based on back-EMF estimation). This approach aims to reduce hardware complexity,

lower system cost, and enhance overall reliability by eliminating the need for physical position sensors.

- **Hybridization with Other Intelligent Control Methods:** Exploring further hybridization with other cutting-edge intelligent control techniques, such as neural networks (e.g., fuzzy neural-network PI), deep learning algorithms, or cerebellar model articulation controllers (CMAC), holds the potential for creating even more robust, adaptive, and high-performance control systems. This avenue seeks to leverage the complementary strengths of different AI paradigms for superior performance and adaptability in complex, dynamic environments.
- **Hardware Implementation and Industrial Applications:** A critical future direction involves transitioning research beyond theoretical simulations to robust hardware implementation and extensive experimental validation of fuzzy-tuned PI controllers in real-world industrial applications. This includes rigorous investigation of their performance under a wide range of load disturbances and parameter variations in practical operational scenarios.

VII. Conclusion

Fuzzy-tuned Proportional-Integral (PI) controllers represent a significant advancement in the intelligent speed control of Brushless DC (BLDC) motors. By leveraging the adaptive capabilities of fuzzy logic to dynamically tune PI gains, these controllers effectively overcome the inherent limitations of conventional PI methods in handling BLDC motor non-linearity and disturbances. Research consistently demonstrates their superiority in achieving enhanced speed regulation, improved dynamic response, and increased robustness. While challenges related to design complexity and computational demands persist, ongoing research into advanced optimization, sensor less integration, and hybridization promises to further refine and expand the applicability of fuzzy-tuned PI controllers, paving the way for their broader adoption in high-performance motor drive systems.

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