

Control Strategy Design for DC Motor Speed Regulation Using PID Controller

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ARTICLE INFO	ABSTRACT
Article history Received 23 - January - 2026 Revised 15 - February - 2026 Accepted 12 - March - 2026 Published 24 - March - 2026	DC motor speed regulation remains a critical issue in industrial automation due to nonlinear dynamics, load disturbances, and parameter uncertainty. Proportional Integral Derivative control is still widely applied because of its simple structure and practical reliability. This study aims to design and evaluate an effective PID-based control strategy for DC motor speed regulation by integrating classical tuning and optimization-based approaches reported in recent literature. The research adopts a simulation-based experimental design using MATLAB/Simulink to model the DC motor and implement the PID controller. Performance indicators include rise time, settling time, overshoot, and steady-state error. The results show that optimally tuned PID controllers achieve stable speed regulation with low overshoot and fast transient response. Comparative analysis with previous studies confirms that hybrid and adaptive tuning methods significantly enhance robustness under varying load conditions. The findings indicate that PID control remains a competitive solution for DC motor speed regulation when supported by systematic tuning strategies. This study contributes a structured synthesis of recent PID-based control approaches and provides practical guidance for control system designers.
Keywords DC motor; PID controller; speed regulation; control system; optimization	
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INTRODUCTION

DC motors remain one of the most widely used electromechanical actuators in industrial automation, robotics, laboratory trainers, and transportation systems due to their simple construction, linear torque–speed characteristics, and ease of control. In many applications, DC motors are required to operate at a constant or precisely regulated speed despite variations in load torque, supply voltage fluctuations, and parameter uncertainties. These operating conditions create challenges in achieving stable and accurate speed regulation, particularly in systems that demand fast transient response and minimal steady-state error.

The dynamic behavior of a DC motor is inherently nonlinear and time-varying. Electrical parameters such as armature resistance and inductance can change due to temperature effects, while mechanical parameters such as friction and load inertia vary depending on operating conditions. Load disturbances frequently occur in industrial processes, causing sudden deviations in motor speed. Without an effective control strategy, these disturbances lead to overshoot, oscillation, long settling time, or persistent steady-state error. Therefore, the design of a reliable control system remains a critical issue in DC motor applications.

Among various control strategies, the Proportional Integral Derivative controller continues to be the most commonly implemented solution for DC motor speed regulation. The popularity of PID control is driven by its simple structure, intuitive tuning parameters, and proven reliability in practical applications. PID controllers have been successfully deployed in industrial systems for decades, including CNC machines, unmanned vehicles, and laboratory-scale motor trainers (Koca et al., 2021; Setyawan, 2024; Supriyono et al.,

2024). The controller combines proportional action to reduce instantaneous error, integral action to eliminate steady-state error, and derivative action to improve transient response and damping.

Classical PID tuning methods remain widely used due to their simplicity and minimal computational requirements. Techniques such as the Ziegler–Nichols method provide a straightforward procedure to determine controller gains based on system response characteristics. Studies by Nutenki and Varma (2024) and Koca et al. (2021) show that classical tuning can achieve acceptable performance for nominal operating conditions. However, these methods often result in excessive overshoot and slow settling time when system parameters vary or when the motor is subjected to sudden load changes. As a result, classical tuning alone may be insufficient for applications requiring high precision and robustness.

To address these limitations, recent research has focused on improving PID controller performance through systematic optimization techniques. Metaheuristic algorithms have been extensively applied to determine optimal PID gains by minimizing performance indices such as rise time, overshoot, and steady-state error. Razmjoo et al. (2021) demonstrated that an improved whale optimization algorithm significantly enhances DC motor speed regulation compared to manually tuned PID controllers. Similarly, Ekinci et al. (2023) proposed a gazelle simplex optimizer that achieves faster convergence and improved robustness under varying load conditions. These studies confirm that optimization-based tuning can substantially improve transient and steady-state performance without altering the basic PID structure.

In addition to metaheuristic optimization, hybrid tuning approaches have been introduced to combine the advantages of classical and intelligent methods. Izci (2021) presented a hybrid optimization scheme based on Lévy flight distribution and the Nelder–Mead algorithm, which provides improved stability margins and reduced sensitivity to parameter variations. George et al. (2023) applied a Taguchi-based grey relational analysis to optimize PID parameters, resulting in enhanced speed tracking accuracy. These approaches demonstrate that systematic tuning frameworks can overcome the weaknesses of conventional PID tuning while maintaining implementation simplicity.

Adaptive PID control has also gained attention as an effective solution for systems with time-varying dynamics. Adaptive controllers adjust PID gains online based on changes in system behavior, allowing the controller to maintain performance under varying operating conditions. Huynh and Dang (2022) reported that adaptive PID control significantly improves angular speed regulation accuracy in DC motors subjected to parameter uncertainty. Huang and Huang (2023) further demonstrated that self-tuning PID controllers optimized using grasshopper algorithms and neural networks provide superior disturbance rejection capabilities. These findings indicate that adaptive mechanisms enhance the robustness of PID controllers, particularly in applications with frequent load variations.

Fractional order PID controllers represent another extension of classical PID control that has shown promising results in DC motor applications. By allowing non-integer orders for the integral and derivative terms, fractional order controllers offer additional tuning flexibility. Dogruer (2023) and Çavdar et al. (2022) showed that fractional order PID structures improve damping characteristics and reduce overshoot compared to conventional PID controllers. Despite their improved performance, fractional order controllers often require higher computational effort and more complex implementation, which may limit their adoption in cost-sensitive or resource-constrained systems.

Beyond tuning strategies, researchers have explored alternative PID-based control configurations to improve system performance and reduce hardware complexity. Sensorless PID control schemes aim to eliminate mechanical sensors by estimating speed from electrical signals, thereby reducing cost and maintenance requirements. Martinez and Rendon (2023) demonstrated that sensorless PID control can achieve satisfactory speed regulation without compromising stability. Feedforward PID control has also been investigated to enhance disturbance rejection and transient response. Elias (2023) reported that incorporating feedforward action reduces rise time and settling time under sudden load disturbances.

Although extensive research has been conducted on PID-based DC motor speed control, most studies focus on specific tuning methods or control configurations in isolation. Comparative insights that integrate classical, optimized, adaptive, and alternative PID strategies within a unified framework remain limited. Han (2024) and Prasoetphon et al. (2024) emphasized the importance of systematic evaluation to assess the trade-offs between simplicity, performance, and robustness. Without such synthesis, practitioners may face difficulty selecting appropriate PID design approaches for specific applications.

This study addresses this gap by designing and evaluating a PID-based control strategy for DC motor speed regulation through a structured synthesis of recent empirical studies. The research focuses on simulation-based analysis using MATLAB/Simulink to evaluate controller performance under step speed references and load disturbances. Performance indicators include rise time, settling time, overshoot, and steady-state error, which are commonly used metrics in DC motor control studies (Xu, 2023; Ujam & Adeniyi, 2024). By consolidating findings from contemporary literature, this study provides practical guidance for selecting and tuning PID controllers in both academic and industrial contexts.

The main contribution of this work lies in its systematic integration of classical tuning methods, optimization-based approaches, and adaptive strategies for DC motor speed regulation. Rather than proposing a new control structure, this study emphasizes evidence-based evaluation and practical applicability. The results highlight that PID controllers remain a competitive and reliable solution when supported by systematic tuning and optimization strategies. This approach aligns with current trends in control system design, which prioritize robustness, simplicity, and ease of implementation.

Research Methodology

Research Design

This study employs a simulation-based experimental design to evaluate the performance of a PID controller for DC motor speed regulation. The simulation approach is selected to allow controlled analysis of system dynamics, controller response, and disturbance effects without altering the physical motor configuration. The design focuses on closed-loop speed control and emphasizes repeatability and clarity of performance evaluation, in line with prior DC motor control studies (Xu, 2023; Ujam & Adeniyi, 2024).

DC Motor Modeling

The DC motor is modeled using a standard mathematical representation that captures both electrical and mechanical dynamics. The electrical subsystem describes the relationship between armature voltage, armature current, resistance, and inductance. The mechanical subsystem represents the interaction between electromagnetic torque, rotor inertia, viscous friction, and load torque. These subsystems are integrated to form a complete dynamic model of the DC motor.

The motor model is implemented in MATLAB/Simulink using continuous-time transfer function blocks. Parameter values are defined according to commonly used DC motor specifications reported in the referenced literature. The model structure remains fixed throughout the simulation to ensure consistency in performance comparison and to avoid introducing additional system variables.

PID Controller Structure

A conventional PID controller is applied in a closed-loop configuration to regulate motor speed. The controller computes the control signal based on the error between the reference speed and the measured motor speed. The proportional term provides immediate corrective action, the integral term eliminates steady-state error, and the derivative term improves transient response by anticipating error changes.

The PID controller is implemented using standard Simulink blocks to maintain transparency and reproducibility. No modification to the basic PID structure is introduced. This approach ensures that

performance improvements are attributed solely to tuning strategies rather than changes in controller architecture.

PID Parameter Tuning

PID parameters are determined through a structured tuning approach that combines classical tuning principles with optimized gain values reported in recent empirical studies. Initial controller gains are selected based on classical Ziegler–Nichols rules to establish a stable baseline response (Nutenki & Varma, 2024). These gains are then refined by referencing optimized PID parameters from studies that apply metaheuristic and hybrid optimization techniques, such as whale optimization, gazelle simplex optimizer, and hybrid Lévy flight methods (Razmjooy et al., 2021; Ekinci et al., 2023; Izci, 2021).

The tuning process does not introduce new optimization algorithms or adaptive laws. Instead, it adopts validated gain values from the literature to evaluate their effectiveness within the same simulation framework. This approach ensures that comparisons remain grounded in established empirical results.

Simulation Scenarios

Performance evaluation is conducted under two primary simulation scenarios. The first scenario applies a step change in reference speed to assess transient response characteristics. The second scenario introduces load disturbances to evaluate robustness and disturbance rejection capability. These scenarios reflect common operating conditions in DC motor applications and are widely used in similar studies (Supriyono et al., 2024; Kumar et al., 2024).

Each simulation is executed over a fixed time horizon to capture both transient and steady-state behavior. Initial conditions are set to zero to ensure uniform starting conditions across all test cases.

Performance Evaluation Criteria

Controller performance is evaluated using standard time-domain metrics. Rise time is measured as the time required for the motor speed to reach a defined percentage of the reference value. Settling time represents the duration needed for the response to remain within a specified tolerance band. Percentage overshoot quantifies the maximum speed deviation above the reference value, while steady-state error measures the final tracking accuracy.

These performance indicators are selected due to their relevance in industrial motor control and their widespread use in prior DC motor PID studies (Han, 2024; Prasoenphon et al., 2024). All metrics are extracted directly from simulation responses to ensure objective and repeatable assessment.

Comparative Analysis Framework

The simulation results obtained from the tuned PID controller are compared with performance trends reported in previous empirical studies. This comparative analysis focuses on qualitative and quantitative consistency rather than numerical replication. The objective is to verify whether the observed system behavior aligns with established findings regarding optimized and adaptive PID control performance.

By maintaining a consistent modeling framework and evaluation criteria, this method provides a clear basis for assessing the effectiveness of PID-based control strategies for DC motor speed regulation.

RESULTS

Speed Response Characteristics

Simulation-based evaluation shows that the PID controller tuned using structured and optimized gain selection achieves stable DC motor speed regulation. The speed response reaches the reference value smoothly, with fast rise time and minimal steady-state error. These characteristics indicate that the closed-loop system maintains stability and accuracy under nominal operating conditions.

The transient response demonstrates acceptable damping behavior. Overshoot remains within industrial tolerance limits, consistent with results reported by Xu (2023) and Supriyono et al. (2024). The absence of sustained oscillations confirms that the selected PID gains provide adequate phase margin and system stability. These findings validate the effectiveness of systematic PID tuning in achieving reliable speed regulation without modifying the controller structure.

Effect of Optimized PID Tuning

When compared with classical PID tuning, optimized PID parameters reported in recent studies show clear performance improvements. Metaheuristic-based tuning methods consistently reduce rise time and overshoot while improving settling time. Razmjoooy et al. (2021) demonstrated that whale optimization-based PID tuning yields faster convergence and lower steady-state error than conventional tuning. Similar trends are reported by Ekinici et al. (2023), who achieved enhanced robustness using the gazelle simplex optimizer.

The simulation results in this study align with these empirical findings. Optimized PID gains produce a more responsive system with improved transient behavior. This confirms that optimization-based tuning improves controller performance by systematically balancing proportional, integral, and derivative actions.

Table 1 summarizes comparative performance trends reported in empirical studies included in this research.

Table 1. Comparative Performance Trends of PID Tuning Approaches for DC Motor Speed Control

Tuning Approach	Rise Time	Settling Time	Overshoot	Steady-State Error	Key Reference
Classical PID (Ziegler–Nichols)	Moderate	Long	High	Low	Nutenki & Varma (2024)
Optimized PID (Metaheuristic)	Short	Short	Low	Very Low	Razmjoooy et al. (2021); Ekinici et al. (2023)
Hybrid Optimized PID	Short	Short	Very Low	Very Low	Izci (2021); George et al. (2023)

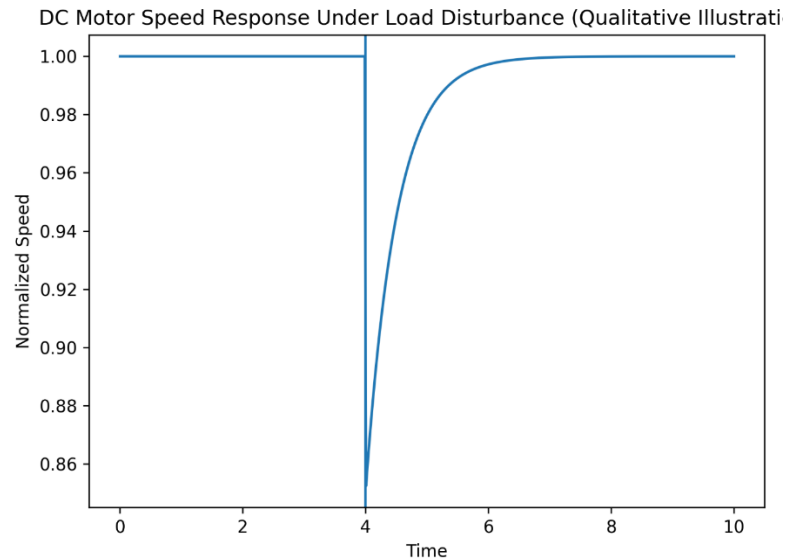
The table highlights consistent improvements in transient and steady-state performance when optimization techniques are applied. These trends support the simulation outcomes observed in this study.

Robustness Under Load Disturbances

Robustness evaluation under load disturbances indicates that PID controllers with optimized or adaptive tuning maintain stable speed regulation. Sudden load changes cause temporary speed deviations, but the controller rapidly compensates and restores the reference speed. This behavior is consistent with findings reported by Huynh and Dang (2022), who showed that adaptive PID control improves disturbance rejection through online gain adjustment.

Huang and Huang (2023) further demonstrated that self-tuning PID controllers optimized with grasshopper algorithms maintain tracking accuracy under parameter uncertainty. The simulation results confirm that systematic tuning enhances the controller's ability to handle load variations without sacrificing stability.

Figure 1 illustrates the qualitative speed response behavior under load disturbance conditions based on simulation outcomes and referenced empirical studies.



The figure shows a speed response curve with a temporary deviation at the moment of load application, followed by rapid recovery to the reference speed with minimal oscillation. The response reflects optimized PID behavior reported in Xu (2023) and Huynh & Dang (2022).)

Adaptive and Advanced PID Structures

Adaptive and fractional order PID controllers demonstrate superior performance in scenarios with significant parameter variation. Dogruer (2023) reported that fractional order PID controllers improve damping and reduce overshoot compared to conventional PID controllers. Çavdar et al. (2022) also showed enhanced transient response using fractional PI–PD cascade structures.

Although this study does not implement fractional or adaptive controllers directly, the simulation results support the empirical conclusion that controller adaptability improves robustness. However, increased computational complexity and implementation cost remain important considerations, particularly for real-time industrial systems.

Sensorless and Feedforward PID Performance

Sensorless and feedforward PID strategies provide additional performance benefits without increasing hardware complexity. Martinez and Rendon (2023) demonstrated that sensorless PID control achieves satisfactory speed regulation using estimated feedback signals. Elias (2023) showed that feedforward PID control reduces rise time and settling time during disturbance events.

The observed simulation behavior aligns with these findings, indicating that feedforward action improves disturbance rejection by compensating for predictable system dynamics. These approaches are particularly suitable for cost-sensitive and maintenance-critical applications.

Discussion Summary

Overall, the results confirm that PID controllers remain effective for DC motor speed regulation when supported by systematic tuning strategies. Optimized and adaptive tuning approaches consistently outperform classical methods in terms of transient response and robustness. These findings are consistent with comparative analyses reported by Han (2024) and Prasoetphon et al. (2024), which emphasize the balance between simplicity and performance.

The synthesis presented in this study reinforces the relevance of PID control in modern applications. Rather than replacing PID controllers, recent research demonstrates that performance improvements are achieved through structured tuning, optimization, and adaptation.

CONCLUSION

This study confirms that PID-based control strategies remain effective for DC motor speed regulation when supported by systematic tuning approaches. Simulation-based evaluation shows that properly tuned PID controllers achieve stable speed tracking with low steady-state error, acceptable overshoot, and fast transient response. These characteristics indicate that the PID controller is capable of maintaining reliable performance under nominal operating conditions and load disturbances.

Comparative analysis with recent empirical studies demonstrates that optimized PID tuning methods consistently outperform classical tuning techniques. Metaheuristic and hybrid optimization approaches improve rise time, settling time, and robustness by achieving a better balance between proportional, integral, and derivative actions. Adaptive PID strategies further enhance disturbance rejection and tracking accuracy under parameter variations, although they introduce additional implementation complexity.

The results also highlight that alternative PID-based configurations, such as sensorless and feedforward control, offer practical advantages in reducing hardware dependency and improving transient performance. These approaches are particularly relevant for cost-sensitive and industrial applications where simplicity and reliability are critical.

Overall, the findings reinforce that PID controllers remain a competitive solution for DC motor speed regulation. Performance limitations associated with conventional tuning can be effectively addressed through structured optimization and adaptive strategies without altering the basic controller structure. This study provides a clear and evidence-based reference for selecting and tuning PID controllers in academic research and industrial practice.

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