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Simulation and Optimization of a PID Speed Control System for a DC Motor Based on Falstad Simulation and GNU Octave

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Abstract. DC motors are widely used in electromechanical drive systems. However, traditional open-loop speed control systems suffer from slow response, large steady-state errors, and poor stability. This paper studies a separately excited DC motor speed control system. This study builds a PID speed control system on the Falstad Simulation platform and establishes a DC motor mathematical model in GNU Octave for transfer function derivation, simulation analysis, and PID parameter tuning. A single closed-loop PID control system is constructed, and the controller parameters are tuned and optimized to improve both the dynamic and steady-state performance of the system. Simulation results show that, compared with open-loop control and conventional PID control, the optimized PID controller significantly reduces the overshoot, shortens the settling time, and nearly eliminates the steady-state error. Specifically, the overshoot is reduced from 18.7% to 3.2%, the settling time is shortened from 1.25 s to 0.38 s, and the steady-state error is approximately zero. Moreover, the system can rapidly recover to a stable operating state after external disturbances, demonstrating excellent dynamic performance and strong disturbance rejection capability. The results verify the effectiveness of the PID control strategy and parameter optimization method for DC motor speed control systems, providing a reliable simulation basis and theoretical reference for electromechanical control system design.

Keywords: DC motor, Speed control, PID control, Falstad Simulation, System simulation

1. Introduction

DC motors are essential components in modern electromechanical systems and have broad applications in industrial drive devices and automated equipment [1]. High-precision speed control is essential for ensuring the stable operation of electromechanical equipment. Although traditional open-loop speed control systems are simple to implement, they suffer from inherent limitations such as slow dynamic response, large steady-state errors, and poor disturbance rejection capability, making them unsuitable for high-performance applications [2].

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PID control is a classic and mature control method commonly applied in motor speed regulation research [3, 4]. Numerous studies have demonstrated its practical effectiveness; however, improper parameter tuning often results in excessive overshoot and long settling time [5, 6]. Although extensive research has been conducted on PID-based DC motor speed control systems, several research gaps still exist [7, 8]. First, many studies mainly rely on empirical methods for parameter tuning, lacking systematic optimization approaches. Second, comparative studies between conventional PID controllers and optimized PID controllers remain insufficient. Therefore, this study establishes a DC motor speed control model and conducts comparative simulation experiments to address these research gaps.

This paper takes a separately excited DC motor speed control system as the research subject. A mathematical model of the motor is established using the Falstad Simulation platform, and a single closed-loop PID control system is developed. The trial-and-error method is adopted to tune and optimize the PID parameters in order to improve system performance. To verify the effectiveness of the proposed PID optimization strategy, comparative simulation experiments are carried out using three control schemes: open-loop control, conventional PID control, and optimized PID control. The optimization performance of the PID controller is comprehensively evaluated by comparing overshoot, settling time, steady-state error, and disturbance rejection capability. The main contributions of this study are summarized as follows: (1) A mathematical model of a separately excited DC motor speed control system is established, providing a theoretical foundation for system simulation and controller design [9]. (2) Based on the Falstad Simulation platform and GNU Octave, this work designs and optimizes a PID speed control system, and analyzes how PID parameters affect the system's dynamic response performance [3, 5, 10]. (3) Comparative simulation experiments involving open-loop control, conventional PID control, and optimized PID control are conducted to verify the effectiveness of the proposed optimization strategy, providing practical guidance for the design and optimization of industrial motor control systems.

2. System design and research methodology

2.1. Overall system architecture

The DC motor speed control system designed in this study adopts a single closed-loop feedback control structure based on PID control theory. System modeling and simulation analysis are performed using the Falstad platform and GNU Octave. The entire system mainly consists of a reference input module, a PID controller, a DC motor model, a feedback unit, and a performance evaluation module.

During system operation, the reference input module generates the target speed signal, which is compared with the actual motor speed to obtain the error signal. The PID controller processes the error signal through proportional, integral and derivative calculations and outputs control signals to adjust the motor operating state. The output speed is fed back to the controller input through the feedback module, forming a closed-loop control system that improves system stability and control accuracy. Finally, the overall system performance is evaluated using overshoot, settling time, steady-state error, and disturbance rejection capability.

2.2. Simulation platform and system modeling

This study builds and debugs the DC motor speed control model on Falstad Simulation, and conducts mathematical modeling, parameter tuning and data analysis via GNU Octave. Since this

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study focuses on simulation rather than hardware implementation, emphasis is placed on the construction of the simulation model and its functional modules.

The DC motor model is established according to the mathematical model and transfer function of a separately excited DC motor to describe its dynamic response characteristics (see Fig. 1).

The PID controller regulates the system output by adjusting the proportional, integral, and derivative gains. The Step module provides unit step input signals, and an additional disturbance module is added to simulate external load changes, so as to test the system's dynamic response and anti-interference performance.

A modular design approach is adopted, in which all functional simulation modules are interconnected through signal links to form a complete negative-feedback control system, realizing the functions of reference input, error calculation, PID control, motor response, and feedback regulation.

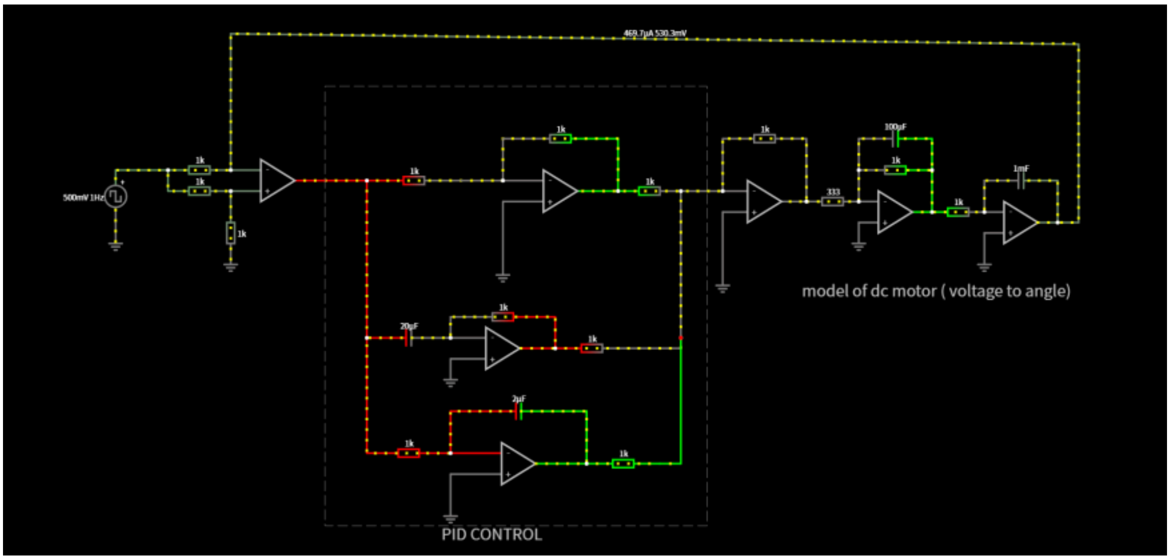

Figure 1. Simulation model of the DC motor PID speed control system based on falstad simulation

2.3. Simulation parameter setting and PID optimization

To verify the effectiveness of the PID control strategy, we used the Falstad platform to build a separately excited DC motor PID speed control system with a single closed-loop feedback structure [11-13]. Three control schemes, namely open-loop control, conventional PID control, and optimized PID control, were developed and analyzed under identical simulation conditions.

A fixed-step solver was adopted for numerical computation. The simulation time was set to 5 s, and a unit step signal was used as the input to simulate the motor starting and speed regulation processes. The PID parameters were tuned using the trial-and-error method. Through repeated simulation experiments, an optimal parameter combination was obtained to improve the system response speed, reduce overshoot, and minimize the steady-state error.

2.4. Performance evaluation criteria

To comprehensively evaluate performance, we used four key performance indices: overshoot, settling time, steady-state error, and disturbance rejection capability.

(1) Overshoot

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Overshoot refers to the maximum percentage by which the system output exceeds the desired value during the transient response. It is used to evaluate the stability of the system. A smaller overshoot indicates weaker oscillation and better control performance.

(2) Settling Time

Settling time denotes the time required for system output to stabilize within the allowable error range. It reflects the speed at which the system reaches a stable state. A shorter settling time indicates a faster system response.

(3) Steady-state Error

Steady-state error is the difference between the desired output and the actual output after the system reaches a stable operating condition. It is used to evaluate the steady-state accuracy of the control system. A smaller steady-state error indicates higher tracking accuracy.

(4) Disturbance Rejection Capability

Disturbance rejection capability refers to the ability of the system to recover from external disturbances and return to a stable operating state. In this study, an external disturbance signal was applied after the system reached steady-state operation. The output response and recovery time were observed to evaluate the disturbance rejection performance of different control strategies. Faster recovery and smaller fluctuations indicate stronger disturbance rejection capability.

In summary, these four performance indices were adopted as the primary evaluation criteria for comparing different control strategies. Based on the simulation results, we compared the open-loop, conventional PID, and optimized PID control schemes.

3. Simulation results and analysis

To explore the dynamic performance of DC motor speed regulation under different control methods, this paper establishes three simulation models: open-loop control, traditional PID control, and optimized PID control, and compares their step response characteristics.

3.1. Analysis of open-loop control simulation results

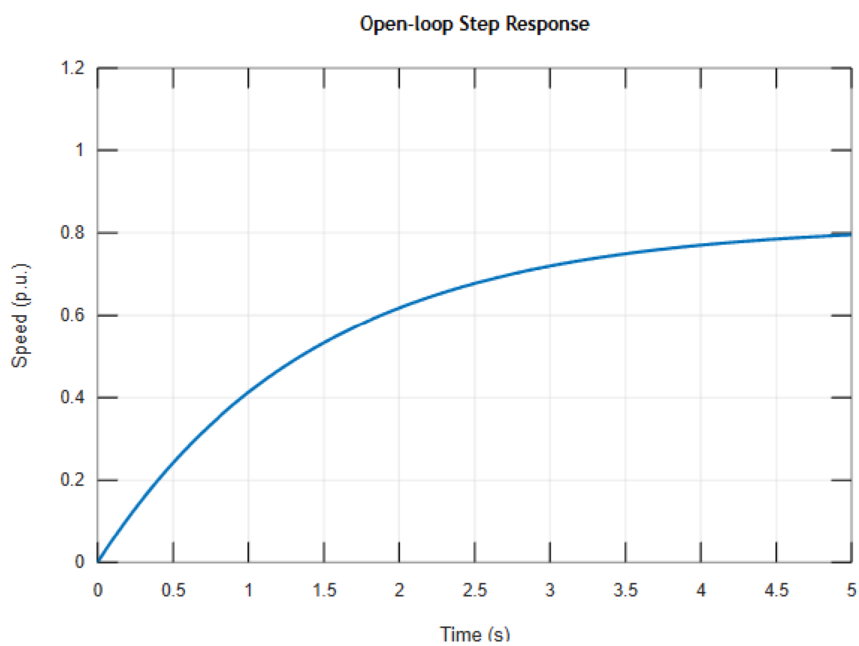

Figure 2. Step response of the open-loop control system

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Figure 2 shows the step response of the open-loop control system. Simulation results show that the open-loop system can realize basic speed output but features slow response speed and obvious steady-state errors. Moreover, the system presents weak anti-interference ability under external disturbance and cannot meet high-precision speed control requirements. Therefore, the open-loop control strategy alone is insufficient to achieve high-precision and high-stability motor speed regulation.

(2) Analysis of Conventional PID Control Simulation Results

Figure 3 shows the step response of the conventional PID control system. Compared with open-loop regulation, traditional PID control greatly improves the system's dynamic performance. The response speed is increased, and the steady-state error is substantially reduced. However, since the PID parameters have not yet been optimized, the system still exhibits a certain degree of overshoot and a relatively long settling time. Therefore, there is still considerable room for further improvement in the overall control performance.

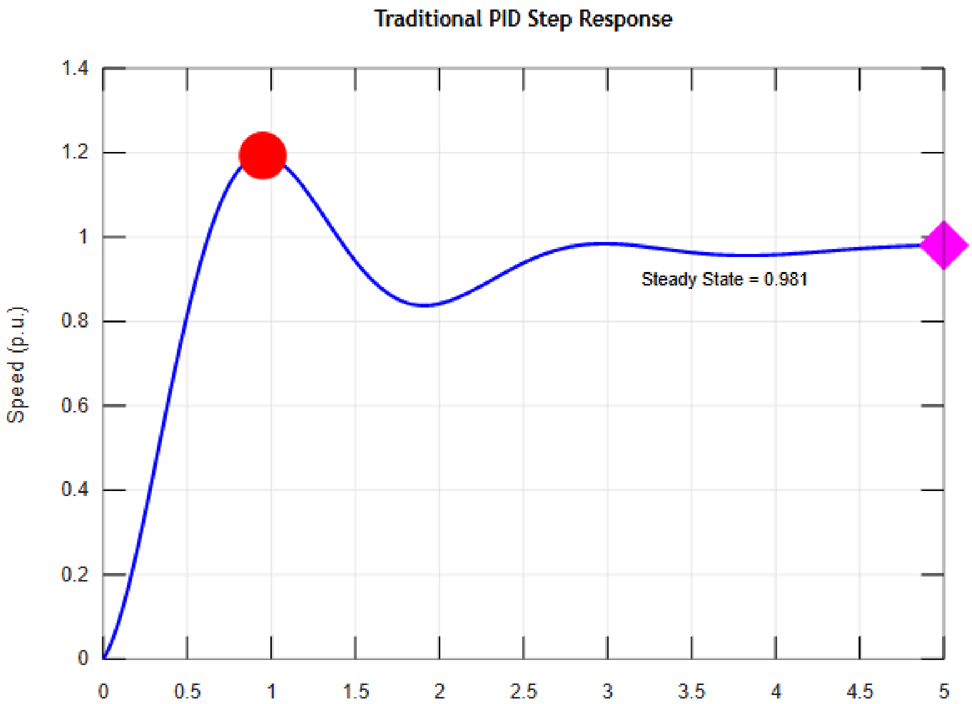

Figure 3. Step response of the conventional PID control system

(3) Analysis of Optimized PID Control Simulation Results

Figure 4 shows the step response of the optimized PID control system. After the PID parameters were optimized, the system exhibited a significant reduction in overshoot, a further decrease in settling time, and an almost negligible steady-state error. In addition, after an external disturbance was introduced, the system rapidly returned to a stable operating state, demonstrating strong disturbance rejection capability. The simulation results verify that the optimized PID controller significantly enhances the dynamic response and overall stability of the DC motor speed control system.

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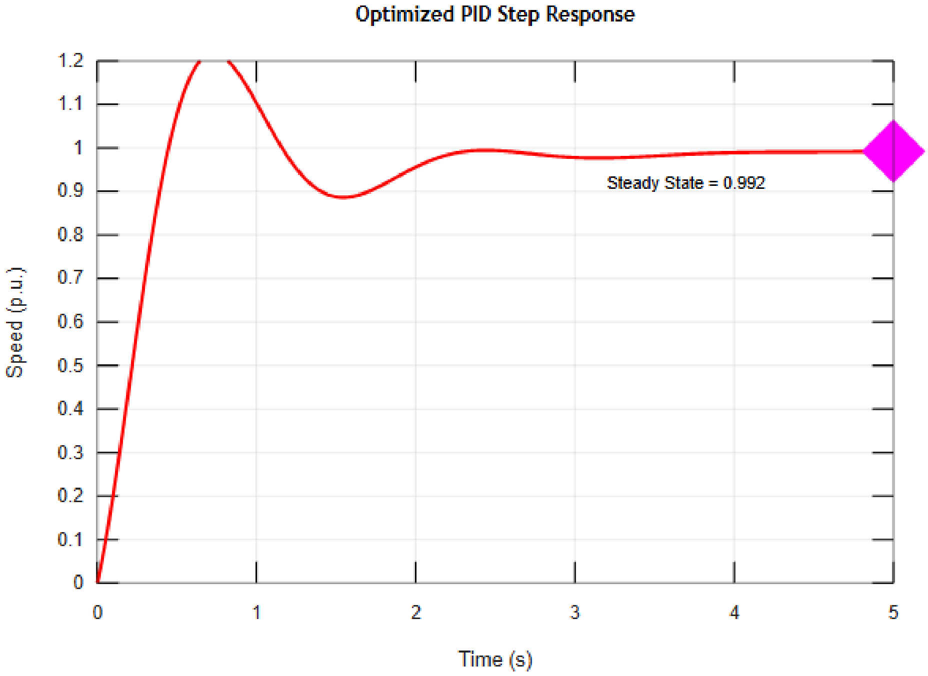

Figure 4. Step response of the optimized PID control system

Table 1. Comparison of control performance under different strategies

Control Strategy	Overshoot (%)	Settling Time (s)	Steady-state Error	Disturbance Recovery
Open-loop	0.0	4.10	18.0%	Poor
Conventional PID	18.7	1.25	0.35%	Moderate
Optimized PID	3.2	0.38	≈0	Excellent

To further verify the effectiveness of the proposed PID parameter optimization strategy, this paper conducts comparative simulation tests on three control schemes: open-loop control, traditional PID control, and optimized PID control.

First, the step response characteristics of the three control schemes were compared. The simulation results indicate that the open-loop control system suffers from slow response and relatively large steady-state error. Traditional PID control greatly optimizes system dynamic performance but still causes obvious system overshoot. After PID parameter optimization, the control system demonstrates superior performance in terms of response speed, control accuracy, and system stability.

Second, to evaluate the disturbance rejection capability of the system, an external disturbance signal was introduced after the system reached steady-state operation, and the output response was observed. The results prove that the optimized PID system can quickly restore stable operation, with outstanding anti-interference ability and robustness.

Comparative results show that compared with open-loop and traditional PID control, the optimized PID controller effectively reduces overshoot, shortens settling time, almost eliminates steady-state errors, and greatly improves system anti-interference performance. These findings indicate that PID parameter optimization can substantially improve the dynamic performance and

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control accuracy of the DC motor speed control system, thereby verifying the effectiveness and feasibility of the proposed control strategy.

4. Discussion

4.1. Analysis of experimental and simulation results

The simulation results show that different control strategies significantly affect both the dynamic and steady-state performance of the system.

First, because the open-loop control system lacks a feedback regulation mechanism, the system output depends entirely on the input signal and cannot be dynamically corrected according to the actual operating conditions. Accordingly, parameter fluctuations and external interference easily cause obvious steady-state errors and weak anti-interference performance. In addition, the dynamic response of the open-loop control system is relatively slow, making it difficult to satisfy the requirements of high-precision speed regulation.

In contrast, the conventional PID control system introduces a negative-feedback mechanism to continuously compare the system output with the reference value and dynamically adjust the control signal. The proportional link accelerates system response, the integral link eliminates steady-state errors, and the derivative link predicts error variation trends, jointly optimizing the system's dynamic performance.

Compared with the open-loop control system, the conventional PID controller significantly improves the response speed, stability, and control accuracy. After optimizing the PID parameters, the overall system performance is further enhanced. The optimized proportional gain improves response speed, the integral gain eliminates steady-state error, and the derivative gain suppresses overshoot and oscillations. Consequently, the optimized PID control system not only achieves a shorter settling time and lower overshoot but also exhibits stronger disturbance rejection capability and robustness.

Overall, appropriate PID parameter optimization can improve the dynamic response and control accuracy of the DC motor speed control system. The simulation results verify the effectiveness of the proposed optimization method and provide both a theoretical basis and practical reference for the design and optimization of DC motor speed control systems.

4.2. Comparison with existing studies

In recent years, extensive research has been conducted on PID-based DC motor speed control systems both domestically and internationally [6-8]. Owing to its simple structure, good stability, and ease of engineering implementation, conventional PID control has been widely applied in industrial control systems. However, most existing studies rely on empirical methods for parameter tuning and lack systematic analysis of the PID parameter optimization process. In addition, few studies carry out quantitative comparison among multiple control schemes.

Different from previous works, this paper builds a complete DC motor mathematical model and constructs a full PID speed regulation system based on the Falstad Simulation platform. Through comparative simulations of open-loop control, conventional PID control, and optimized PID control, the effects of PID parameters on the dynamic and steady-state performance of the system are systematically analyzed. Simulation results prove that optimized PID parameters can reduce system overshoot, shorten settling time, and greatly improve the system's anti-interference ability.

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Furthermore, quantitative performance analysis based on comparative experiments makes the research findings more intuitive and reliable. Although a classical PID control strategy is adopted, the results further confirm the engineering value of PID control in DC motor speed control systems through appropriate parameter optimization and comprehensive performance evaluation.

4.3. Research limitations

Although this study establishes, simulates, and optimizes a DC motor PID speed control system based on GNU Octave and achieves acceptable performance, there are some limitations. First, the research is conducted entirely through simulation without hardware implementation or experimental validation. Therefore, differences may exist between the simulation results and practical engineering applications. Second, the trial-and-error method is adopted for PID parameter tuning. Although this method is simple to implement, it relies largely on engineering experience and cannot guarantee optimality. In addition, this study focuses only on a single closed-loop PID control system, while more complex operating conditions, multivariable control, and intelligent optimization algorithms have not been investigated in depth. Future work may integrate intelligent optimization techniques, such as genetic algorithms and particle swarm optimization, to achieve automatic PID parameter tuning and further improve control performance.

4.4. Engineering significance and practical applications

DC motor speed control systems are widely used in industrial automation, electric drives, robotic control, and intelligent manufacturing. Therefore, improving the control accuracy and dynamic performance of speed control systems is of great engineering significance.

In this study, a DC motor PID speed control model is established using GNU Octave, and the dynamic and steady-state performance of the system is improved through PID parameter optimization. The results demonstrate that appropriate PID parameter tuning can effectively reduce overshoot, shorten the settling time, and enhance the disturbance rejection capability of the system, thereby providing a reference for the optimal design of industrial motor control systems.

Moreover, the combination of simulation and comparative analysis adopted in this study provides a useful research approach for the design, debugging, and optimization of similar electromechanical control systems. The research findings improve the operating performance of DC motor speed control systems and have value for promoting the development of industrial automation and control technology.

5. Conclusion

This study investigated the modeling, simulation, and optimization of a PID control strategy for a separately excited DC motor speed control system. A mathematical model of the DC motor and a single closed-loop PID speed control model were established using GNU Octave. This paper analyzes and optimizes the system's dynamic and steady-state performance, and verifies the effectiveness of PID parameter optimization through comparative simulation tests.

Based on the mathematical model and transfer function of the separately excited DC motor, a single closed-loop PID speed control system was developed in GNU Octave to perform system simulation and performance analysis. To address the defects of open-loop control, such as slow response speed, large steady-state errors and poor anti-interference performance, this paper designs a PID-based closed-loop speed control system. The PID parameters were tuned and optimized using the trial-and-error method. Adjusting the proportional, integral, and derivative gains improved the system's dynamic response, and enhanced control accuracy and stability. Comparative simulations were conducted for three control strategies: open-loop control, conventional PID control, and optimized PID control. The results indicate that, compared with the open-loop control system, PID control significantly improves the dynamic performance and reduces the steady-state error. Furthermore, the optimized PID controller further reduces overshoot, shortens the settling time, and enhances the disturbance rejection capability and robustness of the system. The simulation results verify the effectiveness and feasibility of the proposed PID parameter optimization method for DC motor speed control systems.

Although we achieved acceptable results, there are still some limitations. First, this study is based primarily on simulations using the Falstad Simulation platform and GNU Octave. Therefore, differences may exist between the simulation results and practical engineering applications. Second, this work focuses only on a single closed-loop PID control system, while complex operating conditions, multivariable control, and nonlinear control problems have not been investigated in depth.

Corresponding improvement directions are proposed for future research. First, an experimental hardware platform can be established to validate the simulation results and improve the engineering applicability of the proposed method. Second, intelligent optimization algorithms, such as genetic algorithms, particle swarm optimization, and fuzzy control, can be incorporated to achieve automatic PID parameter optimization and online tuning. Third, future research can explore advanced intelligent control strategies adapted to complex working conditions, to further enhance the control precision, robustness and environmental adaptability of DC motor speed systems.

In conclusion, this study completed the modeling, simulation, and optimization of a DC motor PID speed control system based on the Falstad Simulation platform and GNU Octave. This paper fully verifies the effectiveness of the PID control strategy and parameter optimization method, providing reliable theoretical support and practical guidance for the design and performance optimization of industrial DC motor control systems.

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