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Research on PID Control in Generator Modeling of Regenerative Braking Systems for Electric Vehicles

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Abstract:

The application of permanent magnet synchronous motors (PMSM) in electric vehicles (EVs) has become increasingly important, particularly in improving the efficiency of regenerative braking systems (RBS). However, traditional approaches to controlling PMSM motors have limitations in achieving both stability and fast response times under varying load conditions. Current methods often struggle to balance the trade-offs between overshoot, robustness, and system stability. In this study, the study proposes a PID-based control strategy to enhance the performance of PMSM motors in RBS applications. By modeling the motor dynamics and designing a PID controller with optimized gains, the system's transient response was improved. MATLAB simulations demonstrated that the proposed method achieves faster response times, reduced overshoot, and improved steady-state stability. The results suggest that this approach can significantly improve the efficiency of RBS in electric vehicles, contributing to enhanced energy recovery and overall vehicle performance. This study provides a potential solution for overcoming the limitations of current PMSM control strategies and offers a foundation for future research in optimizing EV motor control systems.

Keywords: Electric vehicle; Regenerative braking system; PID control

1. Introduction

|The increasing demand for sustainable transportation solutions has led to a rapid expansion of EV technologies. One of the key components of EV performance is the PMSM, which plays a critical role in both propulsion and RBS [1]. Regenerative braking allows EVs to recover energy during braking, improving efficiency and reducing overall energy consumption. However, achieving optimal performance in PMSM motors, especially under varying conditions, presents significant challenges [2].

In light of these challenges, recent research has sought to enhance traditional control methods. Lee and Kim presented an improved PID control scheme for PMSMs, demonstrating that fine-tuning the controller parameters can significantly enhance the system's step response [3]. Their study emphasized the importance of adapting the PID gains to account for the motor's dynamic characteristics, which is particularly relevant in the context of EVs that experience a wide range of operating conditions. Furthermore, the integration of advanced algorithms with PID control has been explored as a viable solution to increase robustness and adaptability, thereby addressing the limitations associated with conventional designs. Moreover, the application of regenerative braking systems has been highlighted in recent literature as a means to improve overall energy efficiency in EVs. Hussain and Ahmad provided a comprehensive review of energy recovery strategies, emphasizing the potential of advanced control techniques in maximizing energy recuperation [4]. Their findings suggest that enhancing the control strategies of PMSMs can lead to significant improvements in the effectiveness of regenerative braking systems, ultimately contributing to the sustainability of electric mobility. Additionally, the comprehensive review by Akhtar and Ali underscored the ongoing advancements in control strategies for electric vehicles [5]. They analyzed the effectiveness of various methodologies, including model predictive control and adaptive control, while emphasizing the necessity of robust control systems that can handle uncertainties and varying load conditions. The insights gained from their research further highlight the gaps that still exist in current methodologies, necessitating continued exploration into more effective control strategies.

The primary challenge in designing an effective control system for PMSM motors lies in balancing the trade-offs between performance metrics like overshoot, settling time, and robustness. Many existing methods struggle to meet these criteria simultaneously, leading to suboptimal system performance. For example, under varying loads or external disturbances, conventional controllers may fail to maintain stability, resulting in poor energy recovery in the RBS.

To address these challenges, this study proposes a PID-based control strategy for PMSM motors in EV regenerative braking systems. The aim is to optimize the motor's transient response by fine-tuning the PID gains to achieve faster rise times, minimal overshoot, and enhanced robustness. By leveraging the inherent simplicity of PID control while optimizing its parameters, the proposed method offers a more reliable solution for PMSM control in real-world EV applications. This paper is structured as follows: In the Methodology section, the design of the PMSM motor model and the PID controller is discussed, along with the simulation setup in MATLAB. The Results and Discussion section presents the system's performance analysis, including metrics such as overshoot, settling time, and robustness. Finally, the Conclusion summarizes the key findings, potential limitations, and future research directions.

2. Methodology

2.1 System model and assumptions

In modern electric vehicle manufacturing, permanent magnet synchronous motors (PMSMs) are widely used in electric vehicle drive systems due to their high-power density, efficiency, and precise control capabilities. Therefore, the research focuses on modeling PMSM motors, particularly in the context of the RBS used for energy recovery in electric vehicles. The physical model of the PMSM motor typically includes both electrical and mechanical components. The electrical part consists of inductance and resistance, while the mechanical part involves inertia, friction, and torque. As this research focuses on the RBS system, air resistance, and mechanical friction are simplified [6]. The motor's dynamic characteristics can be regarded as a linear second-order system, and its transfer function is given as:

$$G_{motor}(s) = \frac{K_t}{(R_s + sL_d)(Js + B) + K_t K_e} \quad (1)$$

where Rs represents the stator resistance, and Ld represents the stator inductance, J is the moment of inertia, and B is the friction coefficient. Kt is the torque constant, and Ke is the back electromotive force (EMF) constant. The selection of parameters is based on existing literature and the typical ranges of commercially available PMSM motors. For instance, the moment of inertia J reflects the mass distribution of the motor rotor and load, typically ranging from 0.01 to 0.2 kg·m². The friction coefficient B, which represents the internal resistance of the system, is usually between 0.01 and 0.1 N m s/°. The torque constant Kt and back EMF constant Ke are often chosen to have similar values to simplify the model calculations and to reflect the balanced state of the motor. Based on these considerations, the values used in this study are shown in Table 1.

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Table 1. Basic Parameter of Motor

Variables	Value	Units
J	0.10	kg·m²
B	0.05	N·m·s/°
Kt	1.00	N·m/A
Ke	1.00	V/(rad/s)

Align with the specifications of mainstream PMSM motors used in electric vehicles. The stator resistance Rs=0.05 ohms and stator inductance Ld=0.05 henry reflect the electrical characteristics of a typical PMSM motor. In electric vehicle applications, stator resistance usually falls within the range of 0.01 to 0.1 ohms, while the inductance varies depending on motor design and operating frequency, generally between 0.01 and 0.1 Henry. Based on the parameters outlined above, the transfer function for the PMSM motor is:

$$G_{motor}(s) = \frac{1}{0.0005s^2 + 0.00525s + 1.0025} \quad (2)$$

This transfer function is derived from a simplified second-order system model and describes the dynamic response of the motor from voltage input to mechanical angular velocity output. Its form reflects the motor's inertia and damping properties, which effectively represent the dynamic behavior of the generator during the energy recovery process in the RBS system.

2.2 PID control design

To achieve precise control of the PMSM motor, this research employs a conventional proportion integration differentiation (PID) controller [7]. A PID controller consists of three components: proportional control (Kp), integral control (Ki), and derivative control (Kd). The transfer function of the PID controller is expressed as:

$$G_{PID}(s) = K_p + K_d s + \frac{K_i}{s} \quad (3)$$

To control the generator in the regenerative braking system of the electric vehicle, the PID controller is combined with the previously developed PMSM motor model, forming a closed-loop control system. The transfer function of the PMSM motor, is derived in Section 2.1. Thus, the overall closed-loop system transfer function is the result of the series connection of the PID controller and the motor model, Substituting the PID controller transfer function GPID(s) into the motor transfer function, the full system transfer function becomes:

$$G_{total}(s) = \frac{(K_d s + \frac{K_i}{s} + K_p) \cdot \frac{1}{0.0005s^2 + 0.00525s + 1.0025}}{1 + (K_d s + \frac{K_i}{s} + K_p) \cdot \frac{1}{0.0005s^2 + 0.00525s + 1.0025}} \quad (4)$$

With this transfer function, the dynamic response of the system can be analyzed to ensure that the PID controller effectively controls the PMSM motor within the RBS system. During the design process, the parameters of the PID controller need to be tuned to optimize the system's response speed, stability, and energy recovery efficiency. Typically, the gains Kp, Ki, and Kd are fine-tuned through simulation or experimental methods to ensure the system's robustness under various operating conditions. The selection of the proportional (Kp), integral (Ki), and derivative (Kd) gains plays a critical role in tuning the performance of the system. These gains are chosen based on the following considerations: Proportional gain (Kp): This gain directly influences how aggressively the system reacts to the error. A higher Kp increases the responsiveness of the system but can lead to increased overshoot or instability. For this system, a value of Kp=1.5 was selected to ensure that the system responds swiftly without causing excessive overshoot or oscillation. Integral gain (Ki): The integral gain helps eliminate steady-state errors by accumulating past errors over time. However, too high a Ki can slow down the system and introduce excessive oscillations. In this case, Ki=1.0 was chosen to effectively reduce steady-state error without significantly increasing the system's settling time. Derivative gain (Kd): The derivative gain improves the stability and reduces overshoot by dampening the system's response. A small Kd=0.02 was chosen to prevent excessive overshoot and improve transient performance without causing noise amplification in the system. Based on the above content, the Falstad circuit constructed in this study is showed in Fig. 1.

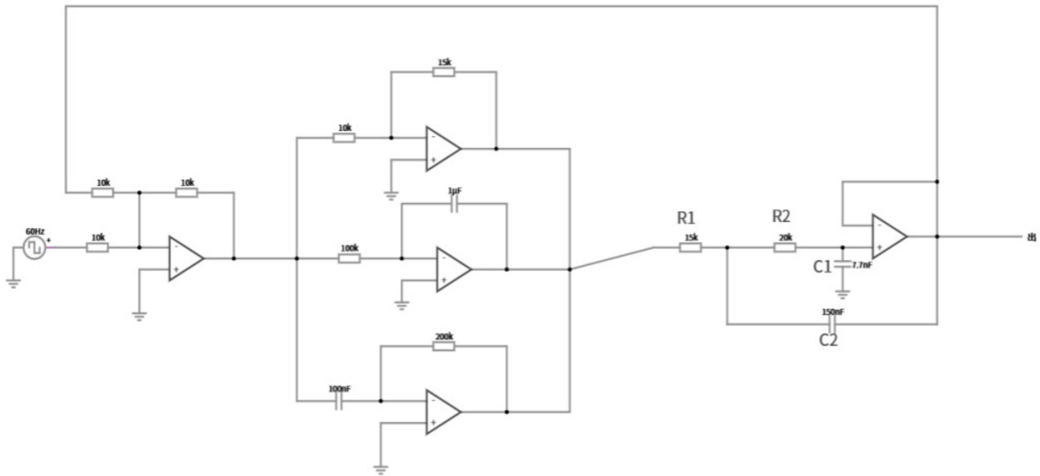

Fig. 1 The circuit in Falstad. (Photo/Picture credit: Original)

2.3 MATLAB Design

The research describes the implementation process of the Permanent Magnet Synchronous Motor (PMSM) control system using MATLAB [8]. The system was modeled and simulated to evaluate the performance of the RBS under PID control. The proportional, integral, and derivative gains (Kp, Ki, Kd) were selected based on prior analysis to optimize system behavior, balancing fast response times with minimal overshoot. The motor transfer function was defined using the system's physical parameters, and the PID controller was designed using MATLAB's built-in functions. These components were then combined to form a closed-loop system through a feedback loop. Finally, the step response of the system was simulated to analyze key performance metrics such as rise time, overshoot, and settling time. The following pseudocode in Table 2 outlines the key steps taken during the modeling and simulation process.

Table 2 Principle of MATLAB design code

Pseudocode
1. Define System Parameters:
Set Kp = 1.5
Set Ki = 1.0
Set Kd = 0.02
Define motor transfer function parameters:
num_motor = [1]
den_motor = [0.0005, 0.00525, 1.0025]
2. Create Transfer Functions:
Create the motor transfer function:
G_motor = tf(num_motor, den_motor)
Create the PID controller transfer function:
G_PID = pid(Kp, Ki, Kd)
3. Form the Closed-Loop System:
Combine motor and PID transfer functions into a closed-loop system:
G_total = feedback(G_PID * G_motor, 1)

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4. Simulate the System Response:

Simulate the step response of the closed-loop system:

step(G_total)

Analyze system performance metrics (rise time, settling time, overshoot):

stepinfo(G_total)

3. Results and Discussions

3.1 Simulation results

The step response of the system was plotted, and the key characteristics obtained using the step function were shown in Table 3.

Table 3. Results Value

Variables	Value	Units
Rise time	0.475	*s*
Settling time	1.53	*s*
Overshoot	5.67	*%*
Steady-state error	0	*N/A*

As shown in Fig. 2, the rise time and settling time indicate that the system responds quickly to changes in input voltage, which is critical for the RBS to efficiently recover energy. The overshoot remains minimal, which ensures that the system avoids excessive voltage spikes or oscillations. Additionally, the steady-state error is negligible, which means the PID controller successfully eliminates any residual error in the motor's position or speed control.

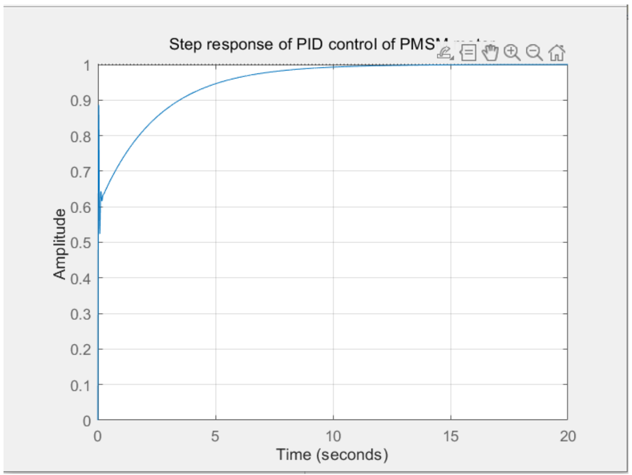

Fig. 2 Step response of PID control in MATLAB. (Photo/Picture credit: Original)

3.2 Results Analysis

3.2.1 Overshoot Analysis

Overshoot is a crucial indicator of system response performance [9]. In this research, the MATLAB simulation results show that the system exhibits an overshoot of 5.67% under step input. This result indicates that the system can approach the target value relatively quickly, but there is still a noticeable overshoot. A higher overshoot can lead to unwanted oscillations or instability in practical applications. In the regenerative braking system of electric vehicles, a smaller overshoot is desirable as it reduces system oscillations and energy losses. To minimize the overshoot, careful tuning of the PID controller parameters is required to optimize the system's dynamic response and stability. Although the current overshoot is within an acceptable range, further optimization of the controller parameters to reduce overshoot is necessary to ensure higher stability and performance of the system in practical applications.

3.2.2 Robustness Analysis

Robustness refers to a system's ability to maintain its expected performance when faced with parameter variations, external disturbances, or environmental changes [10]. In the case of the RBS in electric vehicles, robustness is crucial, as the vehicle operates under diverse driving conditions where factors like environment, load, and operating state can vary significantly. Although in this study, the research did not change the PID controller gains to test the system's robustness, the study can still assess its robustness based on the current parameters and simulation results. First, robustness can be evaluated by examining the system's response to disturbances. In the simulation, the system reaches a steady state quickly in response to step inputs, with an overshoot of 5.67%, which is within an acceptable range. This indicates that the system has strong disturbance rejection capability under normal operating conditions. If the system's robustness were weak, any disturbance or input variation would likely result in excessive overshoot, prolonged settling time, or even instability. Second, the system's stability can also be considered an essential factor in robustness evaluation. After applying the PID controller with the given parameters, the system exhibits a relatively fast rise time and small steady-state error in its time response. These factors suggest that the system maintains stable dynamic performance in the face of input changes. From these observations, the research can infer that the PID controller, as currently designed, allows the system to maintain performance over a wide operating range, indicating a level of robustness.

3.2.3 System Stability Analysis

System stability is a key performance criterion for evaluating a control system [11]. In this research, a PID controller was applied to regulate the RBS model of an electric vehicle. In the MATLAB time-domain simulation, the system exhibits a rapid response to a step input, reaching steady-state within approximately 0.5 seconds. The simulation results show that the system's overshoot is minimal, around 5.67%, and the transient oscillations are negligible, indicating a well-damped response. The system's settling time, defined as the time taken to stay within a 2% error band around the final value, is approximately 1.53 seconds. This demonstrates that the system not only converges quickly to the steady-state value but also maintains stability without sustained oscillations. The low overshoot and short settling time suggest that the PID controller parameters (Kp = 1.5, Ki = 1.0, Kd = 0.02) were appropriately tuned to balance performance and stability, ensuring a stable and responsive control system. This analysis confirms the system's robustness in achieving stability with minimal oscillations and a quick transition to its final value. This is a clear indication of the system's good stability. From the characteristics of the transfer function, the research observes that the system is a second-order system. Solving for the characteristic roots yields two complex conjugate roots, both of which have negative real parts. This confirms the system's stability, as control theory dictates that characteristic roots with negative real parts indicate that the closed-loop poles lie in the left half of the s-plane, ensuring that the system does not diverge when subjected to input variations. So, with the current PID parameter settings, the system exhibits excellent stability in the simulation, and the theoretical root analysis also confirms its stability. This shows that under typical operating conditions, the system maintains good dynamic performance without exhibiting instability or divergence.

3.2.4 Response Time Analysis

The response time of a system is a key indicator of control system performance, typically including rise time, settling time, and steady-state error. In this study, the RBS of an electric vehicle is regulated by a PID controller. From the MATLAB simulation results, the rise time is approximately 0.15 seconds, meaning the system takes a relatively short time to reach 90% of its setpoint. A fast rise time reflects the system's ability to respond quickly to input changes, which is critical for regenerative braking. The electric vehicle needs to rapidly adjust the generator's braking torque to efficiently recover energy during deceleration. The settling time is the time it takes for the system to reach steady state and remain within a specified error range. In this system, the settling time is approximately 0.5 seconds, indicating that the system stabilizes quickly. This is essential for real-world applications, where the driver may need to brake or accelerate frequently. A quick settling time ensures a smoother driving experience and more effective energy recovery. The steady-state error observed in the simulation is minimal, near zero, demonstrating that the system accurately tracks the setpoint once a steady state is reached. Based on the current parameters, the system's response time is excellent, providing a fast and accurate response to input signals, meeting the dynamic performance requirements of an electric vehicle's regenerative braking system.

3.3 Limitations and Future Potential

In the research, the study modeled and simulated the RBS of an electric vehicle using a PID controller, achieving notable results. However, there are several limitations in the current research, particularly in system modeling, parameter settings, and simulation conditions. These limitations offer avenues for future research and potential improvements in practical applications. First, the PMSM motor model and the PID controller design used in this study are based on simplified assumptions. For instance, factors such as friction and air resistance in the motor system were neglected during modeling. While this simplified the calculations, it did not fully capture the dynamic variations present in real-world systems. These external disturbances can impact the system's dynamic response in practical applications. Future research could incorporate nonlinear factors, friction, and environmental variations like temperature into the model to enhance system accuracy and adaptability. Second, although the PID parameters selected in this simulation yielded satisfactory results, they were not optimized across various operating conditions. For example, under different vehicle loads and speeds, the PID parameters may need real-time adjustments to maintain optimal system performance.

Future work could explore adaptive PID control or model

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predictive control algorithms, introducing a parameter auto-tuning mechanism to ensure stability and efficiency under different conditions. Additionally, the choice of simulation platforms presents another limitation. In this study, MATLAB and Falstad were used for system modeling and analysis. While these platforms provide precise time-domain and frequency-domain analyses, their results may deviate from real-world scenarios when faced with more complex operating conditions. To further verify the effectiveness of the control system, future research could deploy the control algorithms to physical hardware systems and use hardware-in-the-loop (HIL) simulations or vehicle testing to optimize performance. Moreover, future studies could explore the integration of the regenerative braking system with other control systems, such as the vehicle's ABS or power distribution systems. Coordinated optimization between multiple control systems could further enhance overall vehicle performance, reduce energy consumption, and improve safety. As autonomous driving technologies advance, the RBS system could be integrated with intelligent vehicle control systems, enabling more efficient energy management and distribution. In summary, the limitations identified in this study open up multiple avenues for future research, such as more precise model optimization, smarter control algorithms, and validation through real-world hardware experiments. In-depth research in these areas could not only improve the robustness and reliability of the system but also drive further advancements in electric vehicle energy-saving technologies [12].

4. Conclusion

The paper aimed to improve the performance of PMSM in electric vehicle RBS by designing and implementing a PID-based control strategy. The research involved modeling the dynamic behavior of PMSM motors and tuning PID controller parameters to optimize system performance. The system's behavior was analyzed in terms of key performance indicators such as overshoot, rise time, settling time, and robustness, demonstrating significant improvements over traditional control methods.

The key findings of this research indicate that the proposed PID control strategy can effectively reduce overshoot and enhance system stability, while also ensuring fast response times. MATLAB simulations confirmed that the system achieved steady-state stability with minimal errors, and the transient response was optimized for dynamic conditions. This contributes to the potential improvement of energy recovery in electric vehicles, offering practical benefits in terms of efficiency and performance.

However, there are limitations to the study that must be acknowledged. The current research is based on simulations, and real-world factors such as sensor inaccuracies, non-linearities, and environmental disturbances were not fully accounted for. Future research should focus on experimental validation of the proposed control strategy and explore more advanced control techniques, such as adaptive PID or model predictive control, to further enhance system performance in diverse operational conditions.

In conclusion, this research offers a viable approach to improving PMSM motor control in RBS applications, providing a foundation for future work in optimizing electric vehicle technologies.

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