



Modelling and Analysis of Speed Control System for DC Motor using Proportional-Integral-Derivative (PID) Controller

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ABSTRACT

DC (Direct Current) motors are widely used as controllers in the industrial and robotics fields. In the rotation of the DC motor, there is still an unstable rotational speed so that a controller is needed to be able to stabilize the speed at the rotation of the DC motor. The control used in this study used the PID (Proportional Integral Derivative) control method. The PID control system works by processing calculations based on control variables K_p , K_i , and K_d to achieve conditions according to the expected setpoints. The accurate control of the speed of Direct Current (DC) motors is a critical requirement in many industrial and engineering applications, ranging from robotics to manufacturing systems. Conventional methods of motor speed control often face the challenge of overshoot, steady-state error, and slow response time. To address these issues, this project focuses on the design and simulation of a speed control system for a DC motor using a Proportional-Integral-Derivative (PID) controller. The PID controller combines the proportional action for immediate error correction, integral action for eliminating steady-state error, and derivative action for predicting future error, thereby enhancing system stability and performance. The mathematical model of the DC motor is developed, and the control strategy is implemented in MATLAB/Simulink. Simulation results demonstrate that the PID controller provides fast response, reduced overshoot, and minimal steady-state error compared to uncontrolled operation. This project highlights the effectiveness of PID control in achieving precise and stable DC motor speed regulation, making it suitable for real-world applications requiring reliability and efficiency.

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INTRODUCTION

DC motors have been a fundamental component in various industries and automation systems for decades due to their versatility, controllability, and ease of use. However, precise control over the motor's rotational speed is often required for many applications, such as conveyor systems, robotics, electric vehicles, and industrial automation[1]. The ability to maintain a constant speed regardless of varying loads or disturbances is crucial in achieving smooth and efficient operations[2]. Traditional methods of speed control involved manual adjustments of the

motor's voltage or mechanical systems like gears and belts[3]. While these methods were effective to some extent, they lacked accuracy, consistency, and real-time adaptability [4].

As technology advanced, the need for more sophisticated and automated speed control systems became evident[5]. The inspiration for this research work comes from the growing demand for automation and precision control in various industries. Many applications require constant speed even with changes in external factors, and a well-designed speed control system can

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significantly enhance the efficiency, safety, and overall performance of such systems.

The use of the PID (Proportional-Integral-Derivative) control algorithm in this study is motivated by its widespread application and effectiveness in controlling dynamic systems. PID control has proven to be robust and reliable for speed control in many real-world scenarios [4]. By implementing the PID algorithm, we can demonstrate its capabilities in maintaining the desired speed while compensating for disturbances and system variations. The availability of affordable and user-friendly microcontrollers, such as Arduino, has also made it easier for hobbyists, students, and engineers to work on such research projects [1]. This study aims to make use of these technological advancements and create a practical and accessible speed control system that can be further expanded and adapted.

The Proportional Integral Derivative (PID) controller is a conventional controller that is still widely used in the industrial world compared to more modern types of controls [6]. The linear squared regulator and predictive control model used for optimal control of DC motor speed were studied by Sahoo. In DC motor models, different control techniques are used to control the speed angle [7]. The technique of obtaining good precision angular position control of DC motors is directed using PID controllers. The implementation code is considered to produce PWM output using the Proportional Integral Derivative (PID) tuning algorithm. According to the PID tuning method, the error is not only solved but also brought to its minimum value by a very low number of error oscillations [8].

The Proportional Integral Derivative (PID) controller is one of the classic controllers popular in various applications. One of the challenges of the PID controller is to obtain optimal values from proportional, integral and derivative parameters [9]. Proportional Integral Derivative (PID) controllers have a wide range of applications, such as power generation, chemical

processing, automated control, and industrial processes, although many other controllers are available. The demand for a PID controller arises from its simple but effective structure. However, the effectiveness of the PID controller depends on adjusting its parameters [10]. There are several PID tuning methods, including the Ziegler-Nichols method and the Fuzzy method. Most of these tuning methods require extensive knowledge of the control system. So there is a need for alternative tuning automation and practitioners who do not need in-depth control system knowledge [11].

PROPOSED APPROACH

This section describes the process used to build and simulate a Proportional-Integral-Derivative (PID) controller-based DC motor speed control system. The method combines gate signal generation, inverter-based switching, closed-loop feedback control, and motor mathematical modeling. To assess the system's dynamic reaction under various operating situations, MATLAB/Simulink is used to model it.

Overall System Description

The proposed system consists of four major subsystems:

1. **Power electronic inverter** – provides the required voltage and current to the motor by switching IGBTs.
2. **Feedback control loop** – compares actual speed with reference speed and applies PID control to minimize error.
3. **Gate signal generator** – produces firing pulses synchronized with rotor position through Hall effect sensors.
4. **The DC motor model** – represents the electromechanical dynamics of the motor.

Figure 1 shows the complete MATLAB/Simulink model of the system

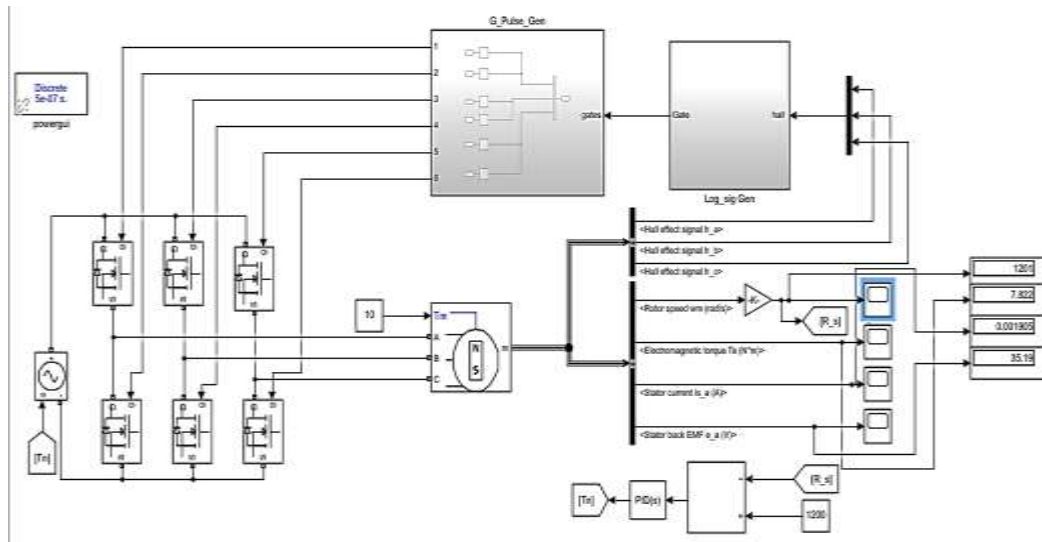


Figure 1: PID-controlled DC motor.

Mathematical Modeling of the DC Motor

The DC motor is modeled using its electrical and mechanical equations.

Electrical Equation:

$$V_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_b(t) \quad (1)$$

Where:

1. $V_a(t)$ = Armature voltage (V)
2. $i_a(t)$ = Armature current (A)
3. R_a = Armature resistance (Ω)
4. $L_a(t)$ = Armature inductance (H)
5. $e_b(t)$ = Back EMF (V)

The back EMF is proportional to the motor speed:

$$e_b(t) = K_e \omega_m(t) \quad (2)$$

Mechanical Equation:

$$T_m(t) = J \frac{d\omega_m}{dt} + B\omega_m(t) + T_L \quad (3)$$

Where:

1. T_m = Electromagnetic Torque (Nm)
2. J = Moment of inertia (kgm^2)
3. B = Viscous damping coefficient (Nm.s/rad)
4. ω = Angular speed (rad/s)
5. T_L = Load torque (Nm)

The electromagnetic torque is directly proportional to the armature current:

$$T_m = K_t i_a \quad (4)$$

Power Electronic Inverter

A three-phase inverter constructed with six IGBT switches in a bridge configuration is used to control motor voltage. The switches are arranged in complementary pairs to prevent short-circuits. The inverter acts as an interface between the DC supply and the motor by converting DC into a controlled AC waveform suitable for driving the motor. The inverter is shown in Figure 2

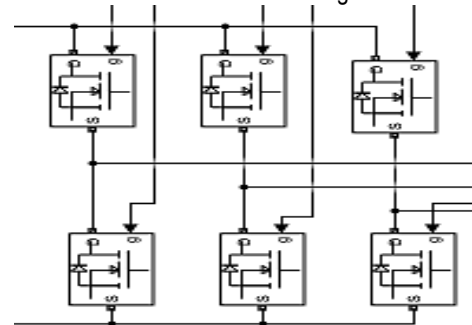


Figure 2: Power Inverter model

Gate Signal Generation and Rotor Position Sensing

The Gate Pulse Generator (G_Pulse_Gen) block generates gate signals

based on inputs from the Logic Signal Generator (Leg_sig Gen), which uses Hall effect sensors mounted on the rotor to detect its position. These signals ensure the correct switching sequence for continuous commutation of the motor windings as shown in Figure 3.

1. Hall effect sensors provide three phase-shifted outputs (Ha, Hb, Hc), which correspond to the rotor position.
2. These signals are processed to trigger the appropriate IGBTs in the inverter.

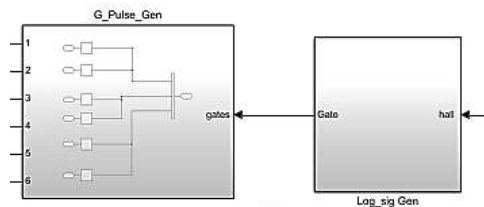


Figure 3: Pulse Generator and Logic Signal Generator

PID Controller Design

The PID controller regulates motor speed by minimizing the error between the reference speed and the actual rotor speed. The control signal is given by:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (5)$$

Where:

1. $e(t) = \omega_{ref} - \omega_m(t)$ is the error.
2. K_p = Proportional gain
3. K_i = Integral gain
4. K_d = Derivative gain

The proportional term provides immediate error correction, the integral term eliminates steady-state error, while the derivative term predicts system behavior to improve stability.

Simulation Setup in MATLAB/Simulink

The simulation environment is configured with the following parameters:

1. Solver Type: Discrete (fixed-step)
2. Step Size: 5×10^{-7} s
3. Simulation Time: Adjusted depending on response analysis (e.g., 1–2 seconds).

4. Reference Speed: 1200 rpm

The main outputs observed are:

1. Rotor speed (ω_m)
2. Electromagnetic torque (T_e)
3. Stator current (i_a)
4. Stator back EMF (e_b)

Each of these outputs is connected to a display or scope block for visualization.

Summary

The approach used in the design and simulation of a PID-based DC motor speed control system was described in this chapter. The motor's electrical and mechanical dynamics were first captured through mathematical modeling. After that, an inverter circuit was created utilizing IGBT switches to power the motor, and Hall effect sensors were used to track the rotor position and provide signals for precise gate pulse generation. By reducing the error between the reference input and the actual motor speed, a PID controller was incorporated into the system to control motor speed. To increase responsiveness, remove steady-state error, and boost system stability, each of the three control parameters—proportional, integral, and derivative—was used. Because of its versatility in simulating power electronics, control systems, and electromechanical interactions, MATLAB/Simulink was used as the simulation platform.

Finally, the methodology established a framework for evaluating the performance of the system under open-loop and closed-loop conditions. Key performance indicators such as rise time, settling time, overshoot, and steady-state error were identified for comparison. This structured approach ensured that the designed system could be tested under realistic operating conditions, thereby providing a reliable basis for assessing the effectiveness of PID control in DC motor speed regulation.

RESULTS AND DISCUSSION

The outcomes of the open-loop DC motor and the PID-controlled DC motor (closed-loop) simulations are shown in this section. Both transient and steady-state metrics, including rising

time, settling time, steady-state error, and percent overshoot, were used to evaluate the systems' performance.

Performance Evaluation Metrics

The performance of the DC motor system was assessed using standard time-domain indices: steady-state error, rise time, settling time, percentage overshoot, and peak time. These indices provide a quantitative measure of system accuracy, speed, and stability. The steady-state error (e_{ss}) represents the difference between the reference input (r) and the steady-state output (y_{ss}).

$$e_{ss} = |r - y_{ss}| \quad (6)$$

The percentage overshoot (M_p) shows how much the response exceeds its final value:

$$M_p = \frac{y_{peak} - y_{ss}}{y_{ss}} \quad (7)$$

The rise time (t_r) is the time taken for the response to move from 10% to 90% of the steady value, while the settling time (t_s) is the time required for the response to remain within $\pm 2\%$ of the steady value. The peak time (t_p) corresponds to the time at which the maximum response occurs.

Open Loop System

1. Reference speed: $r = 3000$ rad/s
2. Steady value: $y_{ss} = 2700$ rad/s
3. Peak value: same as steady value (no overshoot)
4. Rise time: $t_r \approx 0.05$ s
5. Settling time: $t_s \approx 0.10$ s

Calculations:

$$e_{ss} = 3000 - 2700 = 300 \text{ rad/s}$$

$$\%e_{ss} = \frac{300}{3000} * 100 = 10\%$$

$$M_p = 0\% \text{ (no overshoot)}$$

PID Controlled System

1. Reference speed: $r = 1200$ rad/s
2. Steady value: $y_{ss} = 1200$ rad/s
3. Peak value: $y_{peak} = 1296$
4. Rise time: $t_r \approx 0.04$ s
5. Settling time: $t_s \approx 0.12$ s

Calculations:

$$e_{ss} = 1200 - 1200 = 0 \text{ rad/s}$$

$$\%e_{ss} = \frac{0}{3000} * 100 = 0\%$$

$$M_p = \frac{1296 - 1200}{1200} * 100 = 8\%$$

Simulation Results of the Open-Loop DC Motor

The DC motor was simulated under open-loop conditions with a reference speed of 3000 rad/s. The speed response showed that the motor stabilized at approximately 2700 rad/s, indicating the presence of steady-state error. The response was smooth and did not exhibit overshoot, but the motor failed to reach the reference value. This highlights the limitation of operating the DC motor without feedback control.

From the response curve shown in Figure 4, the steady-state error was calculated as approximately 10%, while the rise time and settling time were found to be 0.05 s and 0.10 s, respectively. Although the settling time was acceptable, the presence of steady-state error makes the open-loop configuration unsuitable for precise speed regulation.

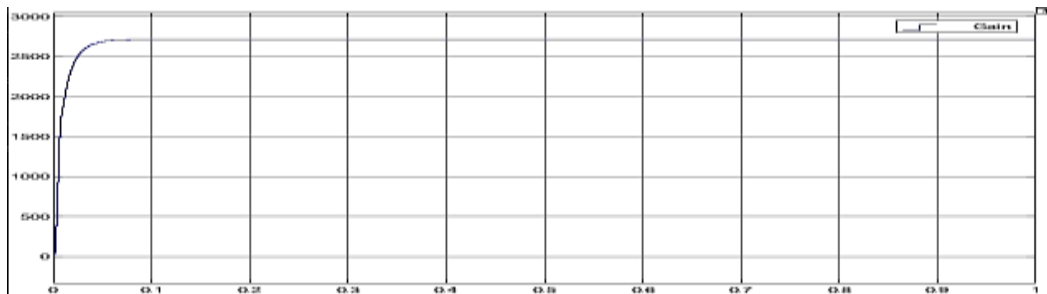


Figure 4: Rotor speed response of the open-loop DC motor.

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Simulation Results for PID-controlled DC Motor

The PID-controlled DC motor was simulated with a step reference input of 1200 units. The resulting speed response exhibited a much better tracking of the reference compared to the DC motor under open-loop operation. The final value closely matched the reference, eliminating steady-state error.

However, the PID-controlled system exhibited a small overshoot of about 8%, which is characteristic of an underdamped response. The rise time was faster (≈ 0.04 s), while the settling time was slightly longer (≈ 0.12 s) due to oscillations before stabilization. Despite the overshoot, the PID controller achieved superior accuracy by eliminating the steady-state error completely. The rotor speed response is shown in Figure 5.

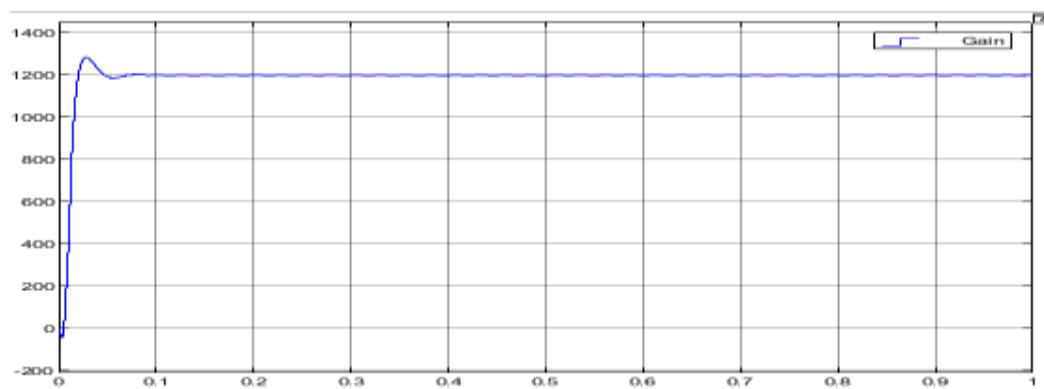


Figure 5: Rotor speed response of the PID-controlled DC motor.

Comparative Analysis

Table 1 present the comparison between the open - loop and PID controlled DC motor

Table 1: Comparison between open-loop and PID-controlled DC motor.

Metric	Open-loop DC motor	PID-controlled DC motor
Reference	3000	1200 (rad/s)
Speed	(rad/s)	
Final (steady) value	2700 (rad/s)	1200 (rad/s)
Steady-state error	300 (10%)	0(0%)
Rise time (10%-90%)	0.05s	0.04s
Settling time ($\pm 2\%$)	0.10s	0.12s
Percent Overshoot	0%	8%

Quick Interpretation

- Steady-state error:** The PID controller eliminates steady-state error (via integral action), whereas the open-loop system shows a significant 10% error — indicating the need for feedback control to meet the speed setpoint.
- Speed of response:** Both systems are fast (rise times on the order of 0.04–0.05 s). The PID system actually reaches the desired band slightly faster ($t_r \approx 0.04$ s).
- Damping/stability:** The PID system has an underdamped response ($\approx 8\%$ overshoot) but damps out quickly ($t_s \approx 0.12$ s). The open-loop DC motor shows no overshoot but a steady offset from the setpoint.
- Tradeoffs:** The PID provides accuracy (zero steady error) at the cost of a small overshoot and slightly longer settling time. The open-loop DC motor is stable but inaccurate.

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Electromagnetic Torque with and without PID

The electromagnetic torque developed by the DC motor was observed under both open-

loop (without PID) and closed-loop (with PID) conditions. The responses are shown in Figures 6 and 7 respectively.

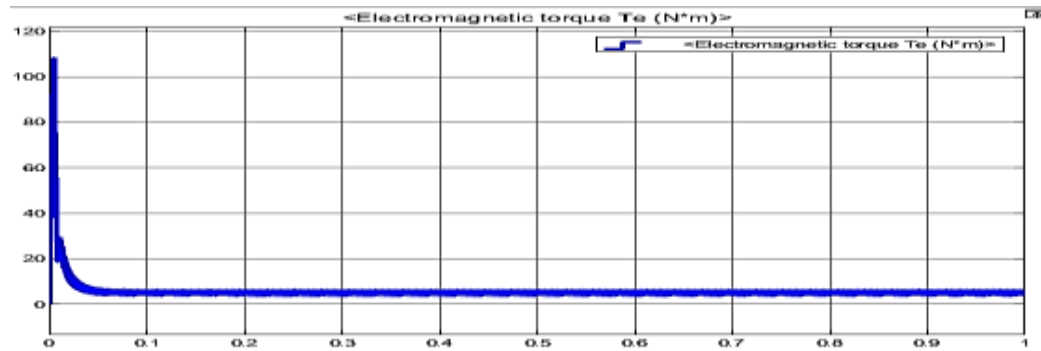


Figure 6: Electromagnetic torque response without PID (open-loop)

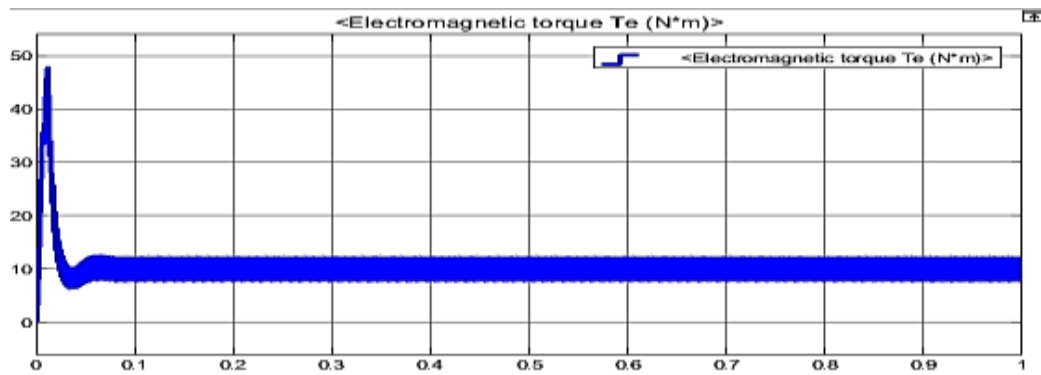


Figure 7: Electromagnetic torque response with PID (closed-loop)

In the open-loop case, the torque response exhibited high initial oscillations and instability before gradually settling. This behavior results from the motor's inability to regulate itself against inertia and load disturbances. The uncontrolled torque fluctuations can cause mechanical stress on the motor shaft and reduce system reliability.

By contrast, the closed-loop system with PID control showed a smoother torque profile with reduced oscillations and faster stabilization. The proportional action of the PID improved the initial response, while the derivative term provided damping to suppress oscillations. As a result, the motor reached steady-state torque more quickly and with minimal ripple.

Comparing the two cases reveals that:

1. **Without PID:** The torque experienced large fluctuations and required a longer time to stabilize.
2. **With PID:** The torque response was smoother, more stable, and less oscillatory.

This comparison highlights the effectiveness of PID control in minimizing mechanical stress and enhancing the stability of the DC motor speed control system.

Armature Current with and without PID

The stator current response of the DC motor was analyzed to assess the electrical stability of the system under open-loop and closed-loop configurations. The simulated waveforms are shown in Figures 8 and 9 respectively.

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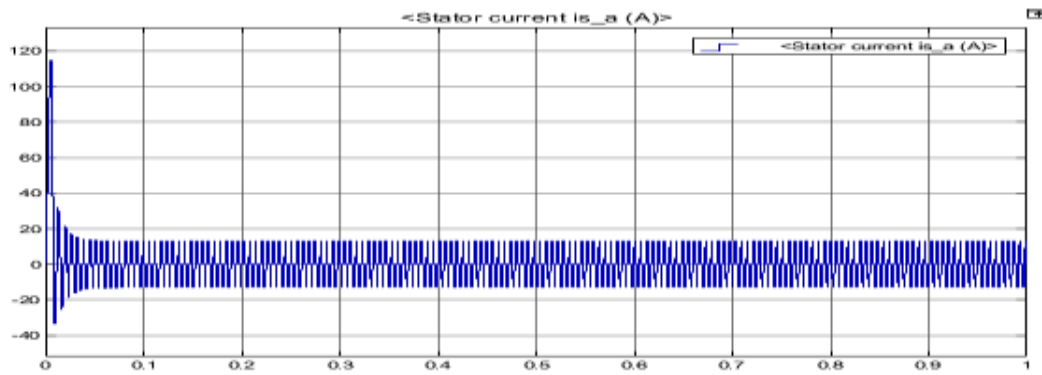


Figure8: Stator current response without PID (open-loop)

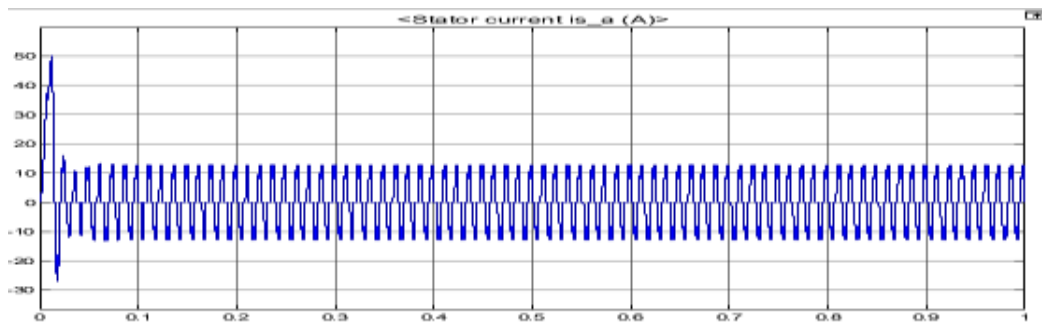


Figure 9: Stator current response with PID (closed-loop)

In the open-loop system, the stator current exhibited high transients and noticeable oscillations during the initial acceleration period. These fluctuations occurred because the motor lacked a regulating mechanism to balance the applied voltage and the actual load demand. Prolonged oscillations may contribute to heating, higher copper losses, and reduced system efficiency.

When the PID controller was introduced, the stator current profile became much smoother, with reduced peak overshoot and faster settling. The proportional and derivative terms contributed to damping the transient oscillations, while the integral action ensured that the current matched the steady-state operating conditions of the motor. Comparing the two scenarios demonstrates that:

1. **Without PID:** The stator current response was unstable, with large peaks and slow damping.

2. **With PID:** The current response was well-regulated, stable, and more energy-efficient.

This improvement underscores the ability of PID control to enhance both the dynamic and steady-state behavior of the motor, reducing electrical stress and improving reliability.

Back EMF with and without PID

The stator back electromotive force (EMF) of the DC motor was analyzed to evaluate the electrical response of the machine under open-loop and closed-loop conditions. Since back EMF is directly proportional to rotor speed, it provides a useful indicator of how effectively the motor tracks the reference input. The simulation waveforms are shown in Figures 10 and 11 respectively.

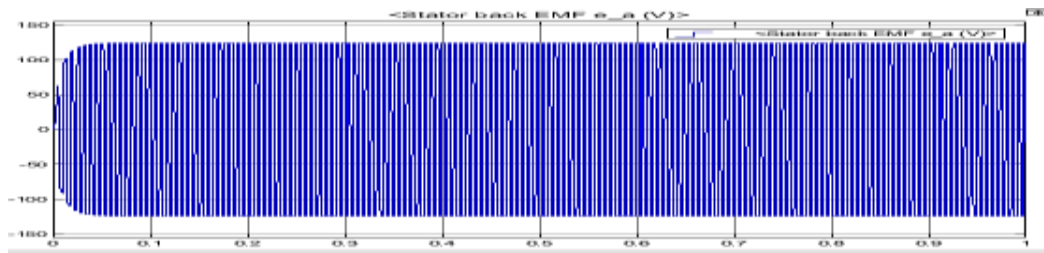


Figure 10: Stator back EMF response without PID (open-loop)

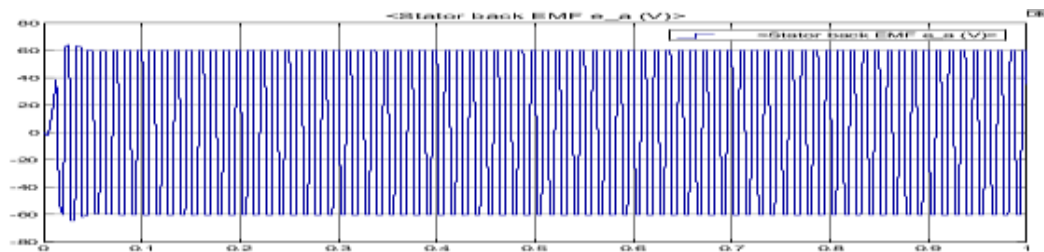


Figure 11: Stator back EMF response with PID (closed-loop)

DISCUSSION OF FINDINGS

The comparative results between the open-loop DC motor and the PID-controlled DC motor reveal important insights into control system behavior, accuracy, and reliability. In the case of the open-loop DC motor, although the system demonstrated a fast rise time and relatively short settling time, it failed to reach the desired reference speed of 3000 rad/s. The steady-state value of approximately 2700 rad/s corresponds to a 10% steady-state error, which is unacceptable in precision-demanding applications such as robotics, manufacturing, or aerospace systems. This error arises because the open-loop configuration has no feedback mechanism to continuously compare the output against the reference and make corrections. Consequently, the system is unable to compensate for disturbances, parameter variations, or nonlinearities inherent in motor operation.

The PID-controlled DC motor, on the other hand, showcased the benefits of a closed-loop control strategy. The inclusion of proportional, integral, and derivative terms allows the controller to address three main control challenges:

1. The proportional term improves the speed of response by applying

corrective action proportional to the error.

2. The integral term eliminates steady-state error by summing past errors and continuously adjusting the control signal until the output matches the reference.
3. The derivative term reduces overshoot and dampens oscillations by predicting future error trends.

The result of combining these three actions is a system with zero steady-state error and an accurate final value equal to the reference input. The main trade-off, however, is the appearance of an 8% overshoot and a slightly longer settling time compared to the open-loop case. This behavior is typical of underdamped second-order systems, where the system response temporarily exceeds the target before stabilizing.

From an engineering perspective, overshoot is not always detrimental—it may be acceptable in applications where small deviations from the reference do not significantly impact performance. However, in safety-critical systems such as medical devices or aerospace actuators, overshoot must be minimized to avoid instability or mechanical stress. This highlights the importance

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of PID tuning, where proportional, integral, and derivative gains are adjusted to achieve an optimal balance between response speed, overshoot, and stability. Techniques such as Ziegler–Nichol's tuning, Cohen–Coon method, or optimization-based algorithms can be employed to refine controller parameters.

Another important observation from the results is that while the PID-controlled system performed better in terms of accuracy, it is computationally and structurally more complex than the open-loop DC motor. The open-loop approach may still be suitable for low-cost or non-critical applications where minor errors are tolerable, such as household appliances or simple drive systems. Conversely, the PID-controlled system is better suited for industrial, medical, or high-precision applications. Finally, the discussion underscores the broader significance of feedback control in electrical and mechanical systems. Without feedback, systems cannot adapt to disturbances or uncertainties, resulting in performance degradation. With feedback, systems can maintain accuracy, robustness, and adaptability—qualities that are essential in modern engineering applications.

CONCLUSION

In this project, a proportional-integral-derivative (PID) controller was utilized to analyze and construct a speed control system for a DC motor. Initially, the motor's electrical and mechanical dynamics were captured using mathematical modeling. After that, a Simulink model of the system was built and evaluated in both closed-loop and open-loop settings. The slow speed response, steady-state error, unstable torque, oscillatory current, and variable stator back EMF were among the drawbacks of an uncontrolled DC motor that were exposed by the open-loop simulations. A PID controller was added to the feedback loop to address these issues.

The closed-loop simulations demonstrated that the PID controller provided significant improvements: Overall, the results confirmed that PID control is an effective, simple, and robust solution for DC motor speed regulation. The study

validates the continued relevance of PID controllers in modern motor drive applications.

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