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Speed control of BLDC motor using PID controller

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ABSTRACT

The current state of science, technology, and industrial revolutions did not occur overnight. Many years of empirical study attempts by human intelligence have led to the world's current status. As a result, new technologies and innovations would constantly propel human civilization forward. Another outstanding invention of the present day is the brushless DC (BLDC) motor. This paper outlines the design of a BLDC motor control system utilizing MATLAB/Simulink software. The main aim of this project is to control the speed and to obtain time domain specifications of PID controller. The application of speed control of motor is vast and also required to maintain the work efficient without any disturbance, the power consumption, and any other fuel to run. On the basis of this the brushless DC motor as application is selected because of reduction in losses and also the power. The PID control system is built to control the speed of the motor and gives the precise output. The universal bridge is used to amplify the current in the output of the application. PID controller reduces the error and increases the stability of the system.

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1. INTRODUCTION

Brushless direct current (BLDC) motors have emerged as key components in numerous industrial, automotive, and consumer applications because of their high efficiency, compact size, and precise controllability [1]. BLDC motors have a number of benefits over conventional brushed DC motors, such as higher power-to-weight ratios, better dependability, and lower maintenance needs [2], [3]. The motor speed regulation is one of the most important components of BLDC motor control since it has a direct impact on system efficiency and performance. Numerous control algorithms and methods have been developed to accomplish precise speed control; nevertheless, the proportional integral derivative (PID) controller continues to be one of the most popular because of its ease of use and practicality [4], [5].

By modifying the control signal in response to system feedback, the PID controller functions. The PID controller can efficiently regulate the speed of BLDC motors by continually modifying the applied voltage or current thanks to this control method, which includes the proportional component (P), the integral of the error over time (I), and the derivative of the error (D) [6], [7]. Enhancing PID-controlled BLDC motor systems' performance has been the subject of recent research [8], [9]. Optimizing PID controller parameters to minimize steady-state error, shorten settling time, and enhance overall system stability has been the subject of numerous studies [10], [11]. Furthermore, in order to adaptively modify controller parameters in real-time depending on system dynamics, sophisticated PID tuning strategies have been presented, including adaptive control methods and auto-tuning algorithms [12], [13]. BLDC motor systems can now precisely manage speed and track position thanks to the integration of PID control with sophisticated sensor technologies such as encoders and Hall effect sensors [14]-[17]. Additionally, the responsiveness and transient performance of PID-controlled BLDC motor systems have been improved by the addition of feedforward control techniques and predictive algorithms, allowing for quick and precise speed adjustments in dynamic working conditions [18]-[20]. Even with these developments, BLDC motor systems still face difficulties in reaching ideal speed control performance, especially in applications where accuracy, responsiveness, and energy efficiency are crucial [21], [22]. Strong control strategies and adaptive tuning techniques are required for PID-controlled BLDC motor systems because of factors such as mechanical load changes, system nonlinearities, and disturbances that can impact performance [23]-[25].

2. METHOD

2.1. Mathematical model of BLDC

A permanent magnet on the rotor causes some variations, but otherwise, the development of a BLDC motor model is comparable to that of a synchronous machine. The material of the magnet affects the flux linkage from the rotor, leading to common occurrences of magnetic flux linkage saturation in these motors. Unlike traditional three-phase motors, a BLDC motor can be powered by a voltage source that does not have to be sinusoidal. As long as the peak voltage remains below the motor's maximum voltage limit, alternative waveforms such as square waves can be used. The armature winding model of the BLDC motor is described by (1), (2), and (3).

$$V_r = Ri_r + L\frac{di_r}{dt} + e_r \tag{1}$$

$$V_y = Ri_y + L\frac{di_y}{dt} + e_y \tag{2}$$

$$V_b = Ri_b + L\frac{di_b}{dt} + e_b \tag{3}$$

Where L is armature self-inductance [H], R is resistance [Ω] in armature, V_r, V_y, V_b are phase voltage [V] at terminal, i_r, i_y, i_b are input current [A] of motor, and e_r, e_y, e_b are motor back- EMF [V].

2.2. PID controller

There are three subblocks in the CONTROLLER_MOD block as shown in Figure 1. These building blocks are all finite state machines. The duty of keep the necessary current flowing through each machine. The CONTROLLER_MOD block assumes control and opens the necessary voltage source inverter (VSI) gates to establish and maintain the desired current once the estimate block has produced the reference. The inverter's construction with BLDC motor is displayed for reference as shown in Figure 2. Each machine employs straightforward logic. For example, the machine managing the U phase checks whether the actual current in phase R (IR) exceeds the desired current (IRSTAR). If it does, transistor Q4 is turned on. Otherwise, transistor Q1 is activated.

2.3. BLDC motor

The five variables derived from (1), (2), and (3) are central to the state-space model calculations. After further processing, these variables produce a total of 25 observable outputs. The block also receives voltage values applied to the windings, along with load torque data. Instead of using the Sim Power Systems block set, which requires substantial computational power and memory, input values are sourced from general Simulink blocks. Since solving differential equations is necessary for output calculations, only numerical values are used. Figure 3 displays the Simulink diagram for the BLDC motor.

2.4. Simulink model of the BLDC motor

This brushless DC motor model has a conventional setup. Motor speed is controlled by an outside feedback loop, while current is regulated by an interior feedback loop. The motor and driver subsystem's servomotor block balances mechanical and electrical power and models the inner current feedback loop. Modeling the current switching regulated by the motor driver is typically not required for system design, but it is vital to make sure the torque-speed characteristics and current pulled from the DC supply are correct. In actuality, the maximum driving current determines the vector of maximum torque values. It is assumed that the system that uses the motor and driver will take care of making sure the motor doesn't overheat by running at high torque and speed combinations for extended periods of time. To match the datasheet values, three motor and driver mask settings must be adjusted. These are the time constant for the inner-loop current controller and the proportional and integral gains for the speed feedback controller. The datasheet states that the no-load time constant in this case is 5 ms. An inner control loop should, as a general rule, be at least ten times quicker than the outer loop. This indicates that the present controller's time constant is 0.5 ms. Once this value has been established, the proportional term is raised until the speed time constant is roughly 5 ms. When executing a speed step under load, the integral gain should then be established and increased until the steady-state error is eliminated, which should take about 5 ms. The 5 ms increase time under no load must then be recovered with some fine-tuning of the two gains. Figure 4 illustrates the Simulink model of the BLDC motor, which was developed in the rotor reference frame. The BLDC motor control system comprises several components, including the BLDC motor itself, an inverter, and a controller.

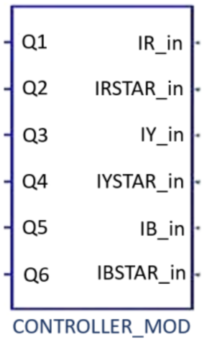

Figure 1. Controller block

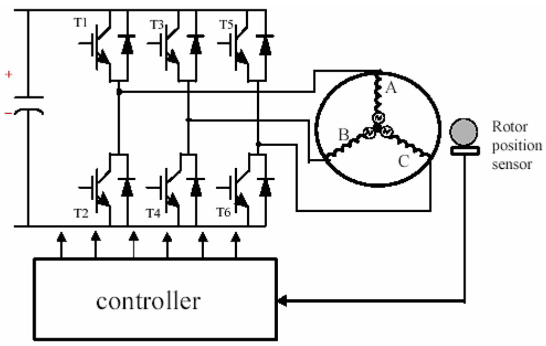

Figure 2. BLDC motor as well as VSI configuration

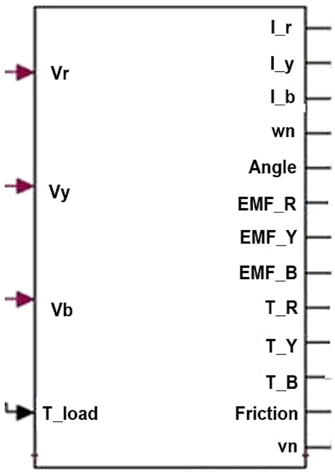

Figure 3. Simulink diagram for BLDC motor

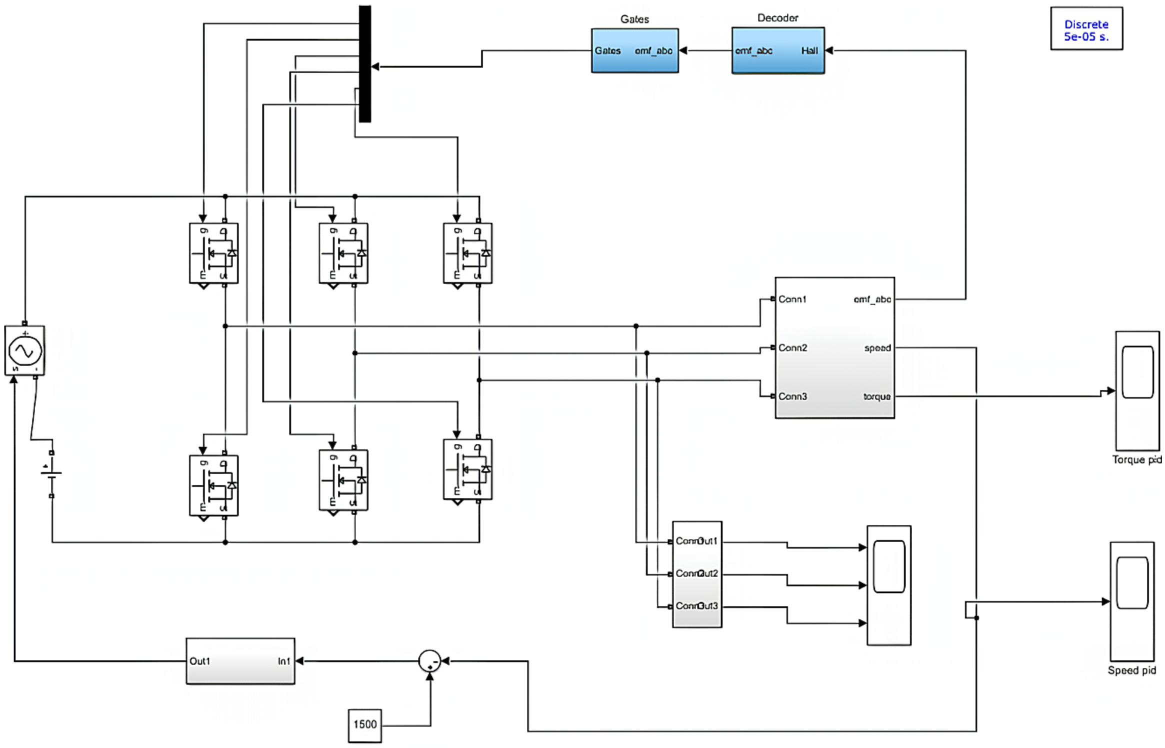

Figure 4. MATLAB simulation

3. RESULTS AND DISCUSSION

As shown in Figures 5 and 6, torque and speed characteristics are smoother and more stable. PID control helps in maintaining precise control over both speed and torque, reducing oscillations and improving responsiveness. The motor can efficiently adjust to changes in load conditions, ensuring more reliable performance. As shown in Figures 7 and 8, torque and speed characteristics can be unstable and exhibit significant oscillations. Without PID control, the motor may struggle to maintain consistent speed and torque, especially under varying loads. There might be a noticeable lag in response to changes in speed or torque commands.

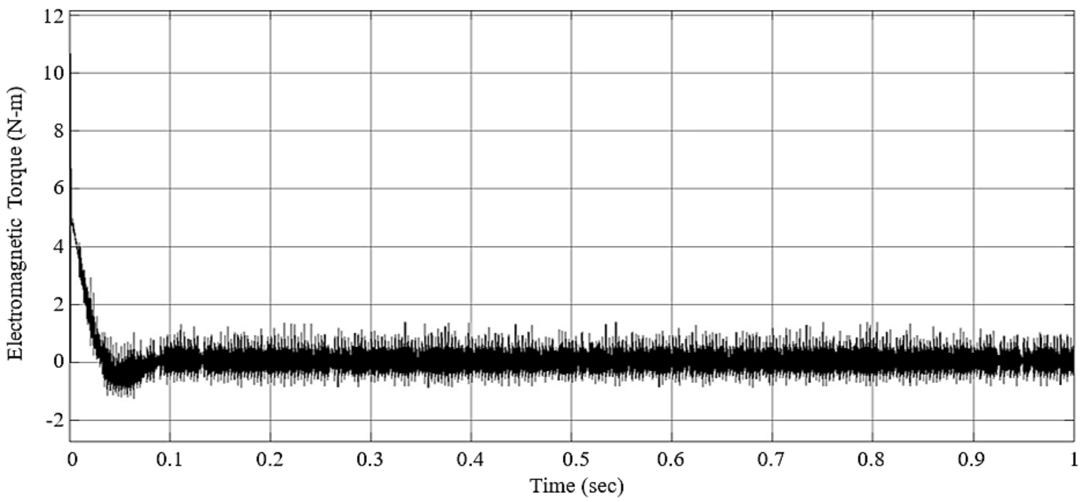

Figure 5. Electromagnetic torque vs time characteristics with PID controller

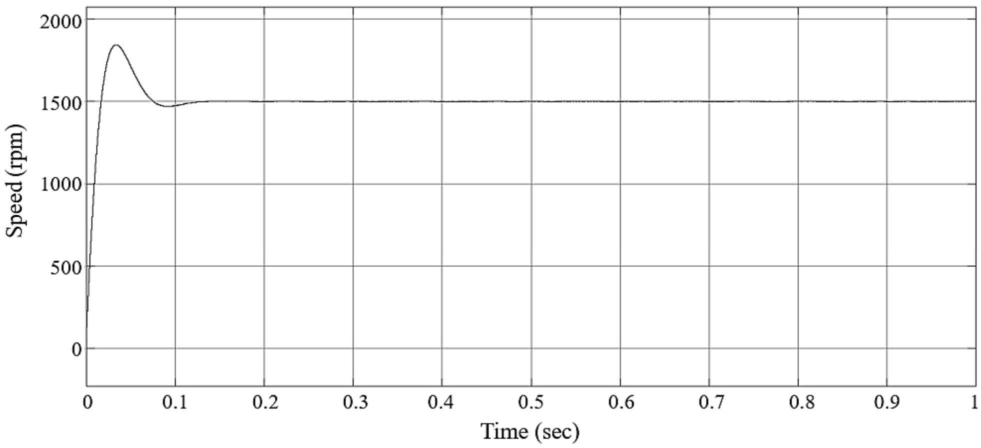

Figure 6. Speed vs time characteristics with PID controller

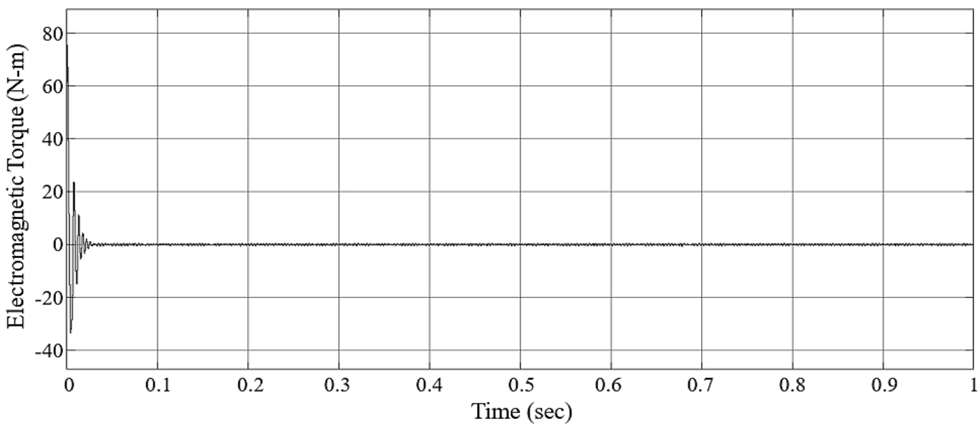

Figure 7. Torque vs time characteristics without PID controller

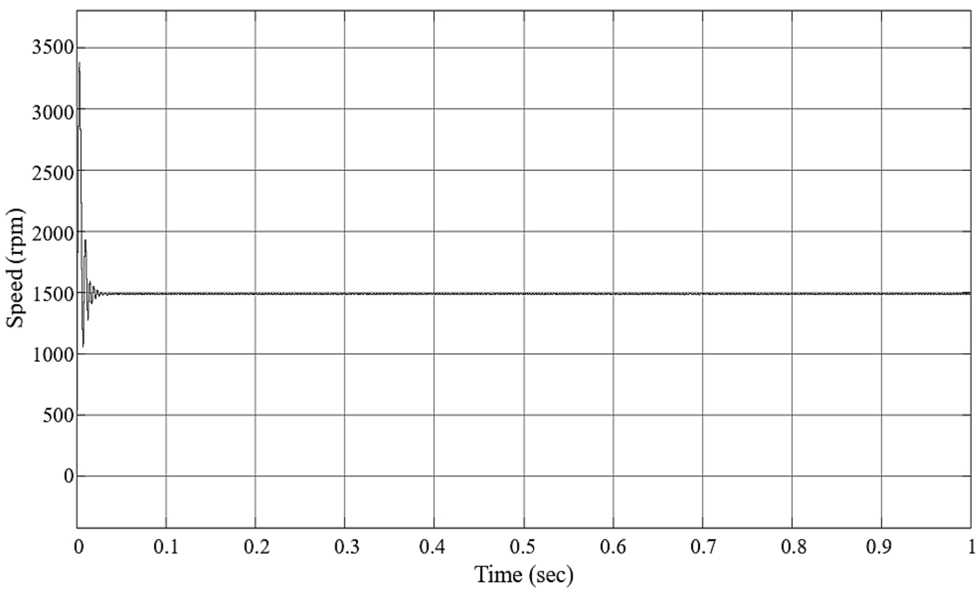

Figure 8. Speed vs time characteristics without PID controller

As shown in Figures 9 and 10, torque and speed characteristics are generally smoother and more stable compared to a P controller. The addition of the integral term in the PI controller helps to eliminate steady-state errors by continuously integrating the error over time. The PI controller provides improved responsiveness and better adaptation to varying load conditions, resulting in more precise control over speed and torque. As shown in Figures 11 and 12, speed vs torque characteristics may exhibit some degree of stability, but there could be overshoot or undershoot in response to sudden changes in load or speed commands. The P controller provides proportional control, meaning the torque output is directly proportional to the speed error. However, it lacks integral and derivative actions, which could result in steady-state errors and slower response to disturbances.

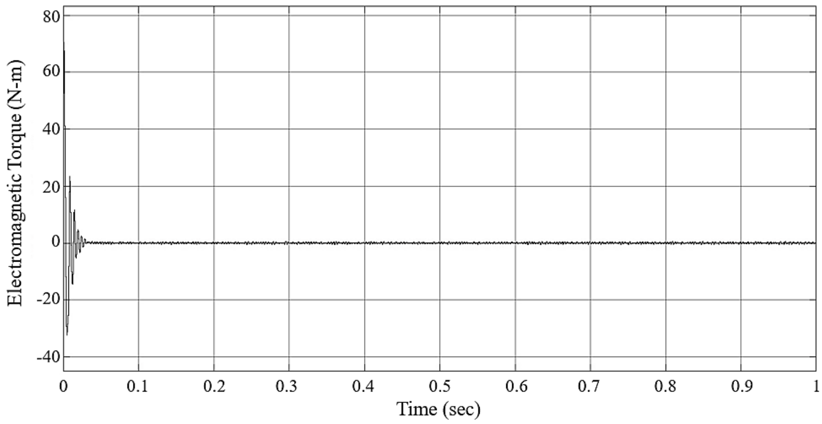

Figure 9. Torque vs time characteristics with PI controller

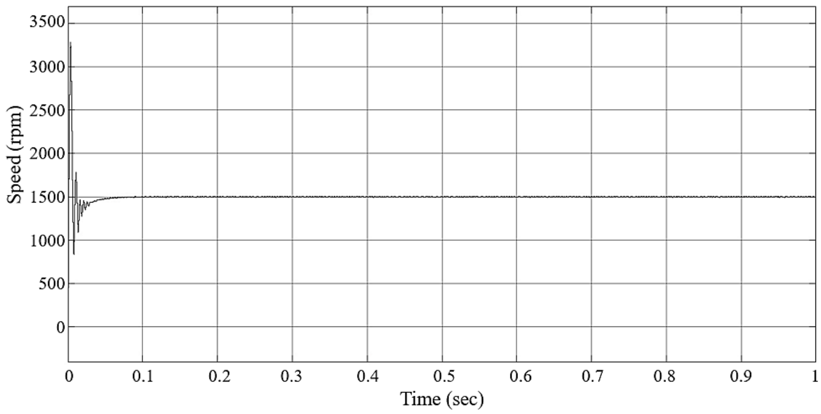

Figure 10. Speed vs time characteristics with PI controller

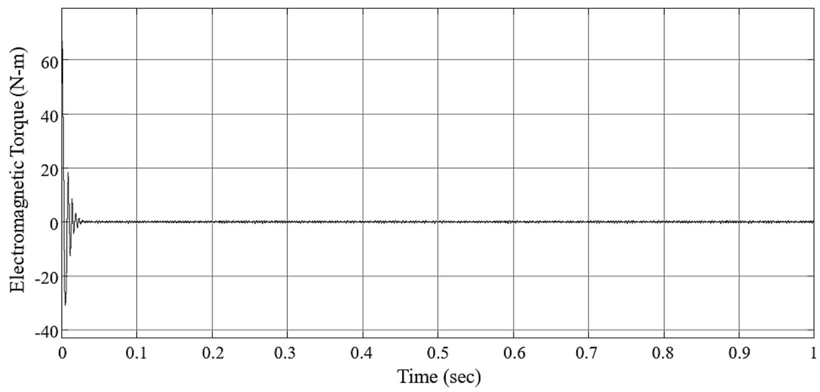

Figure 11. Torque vs time characteristics with P controller

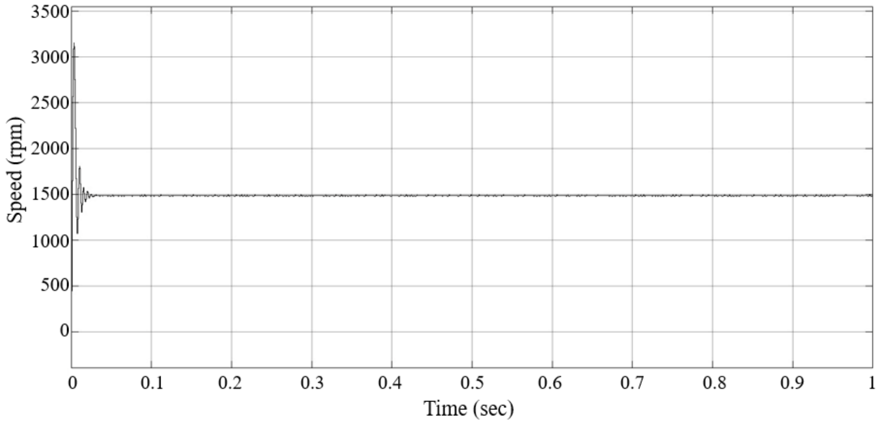

Figure 12. Speed vs time characteristics with P controller

3.1. Mathematical analysis

The time domain specifications are rise time, peak time, delay time, settling time, overshoot, and steady-state error. The time it takes for a signal to cross a predetermined lower voltage threshold and then a predetermined upper voltage threshold is known as the rise time. In both analog and digital systems, this is a crucial parameter. It characterizes the amount of time a signal spends in the transitional stage between two valid logic levels in digital systems. Peak time is the amount of time needed by the reaction to reach its initial peak, which is the peak of the first oscillation cycle or first overshoot. The amount of time it takes for a response to reach half of its ultimate value during its initial oscillation cycle is known as the delay time. The amount of time it takes for the output of a control system to attain and remain within a given error range following an input stimulus is known as the settling time. It's a crucial sign of the stability and performance of a control system. By deducting the steady-state value from the peak response value and dividing the result by the steady-state value gives the overshoot and is often reported as a percentage. It is possible to program controllers to prevent overshoot, but doing so typically entails reducing control effort as the setpoint gets closer. Reaching the target value may take longer as a result. The discrepancy between a control system's intended and actual output after it has achieved a steady-state is known as steady-state error.

a. Without PID controller
- Rise time: usually longer because of sluggish response when the controller is not adjusted. Longer settling time as a result of steady-state error and overshoot being uncontrollable.
- Peak time: a longer time to achieve the peak overshoot and a higher overshoot may occur.
- Overshoot: a higher overshoot could result from a lack of control. Depending on the dynamics of the system and changes in load, there may be a considerable steady-state inaccuracy.

b. P controller
- Rise time: Much the same as or marginally better than systems without PID control. Although it may be marginally better than systems without PID control, steady-state error is still a possibility.
- Peak time: Comparable to systems that don't use PID.
- Overshoot: The amount of overshoot may vary based on the controller gain.
- Steady-state error: Improved compared to systems without PID control, but steady-state error may still exist.

c. PI controller
- Rise time: Generally improved compared to P controller and systems without PID control.
- Settling time: Typically reduced due to the elimination of steady-state error by the integral action.
- Peak time: Similar to P controller or slightly improved.
- Overshoot: Reduced compared to P controller and systems without PID control.
- Steady-state error: Eliminated or significantly reduced due to the integral action.

d. PID controller
- Rise time: Improved compared to PI controller and systems without PID control, thanks to the derivative action.
- Settling time: Typically further reduced compared to PI controller due to enhanced control over overshoot.
- Peak time: Generally similar to PI controller or slightly improved.
- Overshoot: Reduced compared to PI controller and systems without PID control due to the damping effect of the derivative action.

- Steady-state error: Virtually eliminated due to the combined actions of proportional, integral, and derivative terms.

The time domain specification with formula is given in Figure 13. The simulation result values of rise time, peak time, transient time, and settling time for P, PI, PID, and without PID controllers are shown in Table 1. The positive peak, negative peak, and steady-state difference values for different controllers are shown in Table 2.

Time domain specification	Formula
Delay time	$t_d = \frac{1+0.7\delta}{\omega_n}$
Rise time	$t_r = \frac{\pi-\theta}{\omega_d}$
Peak time	$t_p = \frac{\pi}{\omega_d}$
% Peak overshoot	$\%M_p = \left(e^{-\left(\frac{\delta\pi}{\sqrt{1-\delta^2}}\right)}\right) \times 100\%$

Figure 13. Formula for time domain specification

Table 1. Simulation results

Controller	Rise time	Peak time	Transient time	Settling time
PID	0.016	0.033	0.087	1.000
PI	9.888×10^(-4)	3.626×10^(-3)	0.028	1.000
P	1.648×10^(-3)	3.626×10^(-3)	0.027	1.000
Without PID	5.603×10^(-3)	8.899×10^(-3)	0.020	1.000

Table 2. Steady-state difference of simulation

Controller	Positive peak	Negative peak	Steady-state difference
PID	1503.555	1498.526	5.029
PI	1504.388	1484.573	19.815
P	1491.406	1480.837	10.569
Without PID	1356.739	1329.031	27.708

4. CONCLUSION

To sum up, adding a PID controller to a BLDC motor improves both its control accuracy and operational stability. Speed vs. torque characteristics could show oscillations and instability without PID control, resulting in uneven performance. But with a PID controller, the motor can maintain more stable and smoother speed vs. torque characteristics, which guarantees better responsiveness, more accurate control, and greater flexibility under different load circumstances. As a result, BLDC motor systems' efficiency and dependability are greatly increased by the use of a PID controller. To sum up, adding a PID controller to a BLDC motor improves both its control accuracy and operational stability. Speed vs. torque characteristics could show oscillations and instability without PID control, resulting in uneven performance. But with a PID controller, the motor can maintain more stable and smoother speed vs. torque characteristics, which guarantees better responsiveness, more accurate control, and greater flexibility under different load circumstances.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Sreevardhan Cheerla		✓				✓		✓	✓	✓	✓	✓		
Ravi Kumar Kallakunta	✓		✓	✓			✓			✓	✓		✓	✓
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Cheeli Ashok Kumar	✓				✓		✓	✓	✓	✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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