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Research On Optimizing The Pid Controller For A Dc Motor Control System

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Abstract
The Proportional-Integral-Derivative (PID) controller plays a crucial role in automatic control systems by improving performance, enhancing stability, and optimizing operational processes. With high adaptability, PID is widely applied in industries, transportation, and medical field. This paper analyzes the operating principle of the PID controller, with a focus on optimizing its parameters using the trial-and-error method for position and speed control of a 3.7kW DC motor with a rated speed of 1750 rpm. The simulation process conducted in MATLAB/SIMULINK evaluates the effectiveness of the optimized controller. The results show that the steady-state error approaches zero, the transient response time is shorter, the overshoot is significantly reduced, and the system quickly reaches the desired value. This study not only reinforces PID control theory but also demonstrates the practical effectiveness of parameter tuning methods in meeting the technological requirements of DC motor control systems.
Keywords: *PID controller, speed control, position control, DC motor.*

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I. Introduction

The Proportional-Integral-Derivative (PID) controller is an automatic control mechanism used in closed-loop control systems. It consists of three main components: the proportional (P) component, which acts based on the current error; the integral (I) component, which accounts for the accumulated past errors; and the derivative (D) component, which responds to the rate of change of the error. By combining these three elements, the PID controller computes the control input signal to effectively minimize the error. The proportional gain (K_p), integral gain (K_i), and derivative gain (K_d) are critical parameters in optimizing the system's performance [1, 2].

With its simple design, high reliability, and good disturbance rejection capability, the PID controller allows the system to reach a stable state quickly, minimize oscillations and errors, and respond rapidly to changes in the control signal [2]. With these advantages, PID is widely applied in industrial control systems, ranging from process control and electric drive systems to temperature and pressure control [1, 3].

A common method to regulate for PID parameters is the Ziegler-Nichols method [4], which provides an automatic procedure for determining PID parameters and enables a fast initial response. However, it may result in large oscillations and is not always optimal in certain situations. The trial-and-error method allows manual fine-tuning of PID parameters based on real-time observations to optimize system response. Although it takes more time, this method tends to be more effective for nonlinear systems or those with specific requirements. Another approach is the magnitude optimum method [5]. Over time, PID has been extended into variations such as cascade PID for furnace temperature control [6] and fuzzy PID for DC motor control [7].

In this study, the trial-and-error method is selected over the Ziegler-Nichols method due to its flexibility and better optimization capabilities for DC motor systems. To verify the effectiveness of this method, simulations are conducted on a 3.7kW, 1750 rpm DC motor. In addition to analyzing the PID control theory including its structure, function, and the impact of each P, I, and D component on system performancethe focus of this study is to design a PID controller for speed and position control of a DC motor. The simulation and evaluation are performed in MATLAB/SIMULINK [8], with key performance indicators including: transient time that ensures steady-state error within ±5%, and overshoot limited to around 20% to avoid excessive system oscillations.

The results of this study not only reinforce the understanding of PID control but also provide practical evidence of the effectiveness of PID in controlling medium to large power DC motors (from 0.5 kW to several kW). These motors are widely used in both industrial and residential applications, where high performance, stability, and accurate control of speed and position are required. Therefore, the study confirms the efficiency and flexibility of the PID controller in modern industrial drive systems

II. Methodology

Theoretical Basis of the PID Controller

The PID controller is made up of three components: Proportional (P), Integral (I), and Derivative (D).

P (Proportional): Generates a control signal that is directly proportional to the current error, helping to reduce the error quickly through strong feedback when the error is large.

I (Integral): Adjusts the control signal based on the accumulated error over time, eliminating steady-state error by accumulating past errors and correcting the system to reach the desired setpoint.

D (Derivative): Modifies the control signal based on the rate of change of the error, improving system stability by predicting the error trend and reducing overshoot.

The PID controller combines these three components P, I, and D to produce a composite control signal, enabling the system to achieve optimal performance by responding rapidly and stably to changes in the process.

The expression of the PID control algorithm [2] is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

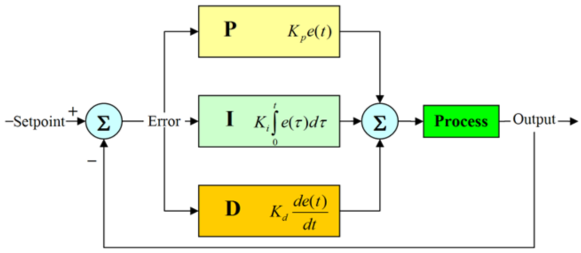

Figure 1. Block diagram of the PID controller

The structure of the controller is described as shown in Figure 1. In this, u(t) is the output signal, and e(t) is the error. Adjusting the parameters K_p, K_i, and K_d of the PID controller plays a key role in optimizing the system's performance [1]. The proportional parameter K_p directly affects the system's response speed: as K_p increases, the system responds faster but may also increase the amplitude of oscillations and errors. If the K_p value is too high, the system may become unstable, leading to saturation oscillations.

The integral parameter Ki helps eliminate steady-state error, but if K_i is too large, the system may experience stronger oscillations and a significant increase in overshoot. Adjusting Ki requires a balance between the ability to reduce error and the impact on the system’s response quality.

The derivative parameter K_d reduces overshoot and helps improve system stability during the transient phase. However, a very high K_d value can amplify noise, causing unwanted oscillations in the system. Therefore, choosing K_d should ensure stability without reducing the system's response speed.

The goal of designing the PID controller is to determine the optimal values of the three parameters Kp, Ki, and Kd to meet important criteria such as low overshoot, small steady-state error, and short settling time. This process requires careful consideration of the parameters to achieve optimal control performance for each specific application.

To determine the PID controller parameters, various tuning methods can be used, the most common of which are the Ziegler-Nichols method and the trial-and-error method. In this study, the trial-and-error method is applied to control the speed of a DC motor, where the mathematical model of the motor is defined as a first-order inertia system.

Transfer function of the controlled object

The schematic diagram of the DC motor is illustrated in Figure 2 [1].

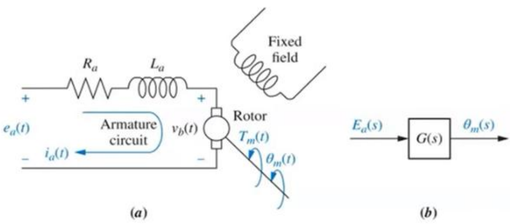

Figure 2. Schematic diagram of the electrical part of the DC motor: (a) Detailed diagram; (b) Summary diagram in the form of a transfer function.

Based on the schematic diagram, the dynamic equations describing the operation of the DC motor in the time domain are established [9].

The voltage balance equation:

$$R_a i_a(t) + L_a \frac{di_a(t)}{dt} + v_b(t) = e_a(t) \qquad (2)$$

The back electromotive force equation:

$$v_b(t) = K_b \frac{d\theta_m}{dt} \qquad (3)$$

The electromagnetic torque equation:

$$T_m = K_t i_a(t) \qquad (4)$$

The electromechanical equation:

$$J_m \frac{d^2\theta_m}{dt^2} + D_m \frac{d\theta_m}{dt} = T_m(t) \qquad (5)$$

E_a is the armature voltage (V);
R_a is the armature resistance (Ω);
L_a is the armature inductance (H);
i_a is the armature current (A);
$V_b(t)$ is the back electromotive force (V);
θ_m is the rotor angular position (rad);
T_m is the motor torque (Nm);
J_m is the rotor moment of inertia (kg·m²);
D_m is the viscous friction constant (Nm/rad);
K_t is the torque constant (Nm/rad);
K_b is the back electromotive force constant (Vs/rad).

To construct the transfer function of the system, starting from the dynamic equations of the DC motor (2), (5) in the time domain, Laplace transforms are applied to convert them to the frequency domain (6), (7) in the form of transfer functions (8), (9) [1, 2].

$$R_a I_a(s) + L_a s_a(s) + K_b s\theta_m(s) = E_a(s) \qquad (6)$$

$$J_m s^2\theta_m(s) + D_m s\theta_m(s) = K_t I_a(s) \qquad (7)$$

Transfer function of the position controller:

$$G_p(s) = \frac{\theta_m(s)}{E_a(s)} = \frac{K_t}{L_a J_m s^3 + (R_a J_m + L_a D_m)s^2 + (R_a D_m + K_b K_t)s} \qquad (8)$$

Transfer function of the speed controller:

$$\omega_p(s) = \frac{K_t}{L_a J_m s^2 + (R_a J_m + L_a D_m)s + (R_a D_m + K_b K_t)} \qquad (9)$$

III. Results And Discussion.

Using the transfer function to design the position and speed controllers for the DC motor in MATLAB/Simulink software, the input signal is the armature voltage, and the output signals are the rotor angular position and angular velocity. The parameters selected for simulation are as follows: DC motor 3.7 kW, rated speed 1750 rpm; R_a = 11.4 Ω; L_a = 0.1214 H; J_m = 0.02215 kg·m²; D_m = 0.002953 Nm/rad; K_t = 1.28 Nm/rad; K_b = 0.0045 Vs/rad.

The program for computing the transfer function of the controlled object was written in an M-file in MATLAB, as shown in Figure 3. The simulation diagram of the controller is shown in Figure 4.

The result of the computed transfer function of the position controller:

$$G_p(s) = \frac{1.28}{0.002689s^3 + 0.2529s^2 + 0.03942s} \qquad (10)$$

The result of the computed transfer function of the speed controller:

$$G_v(s) = \frac{1.28}{0.002689s^2 + 0.2529s + 0.03942} \qquad (11)$$

The position controller was designed as shown in the schematic diagram in Figure 3.

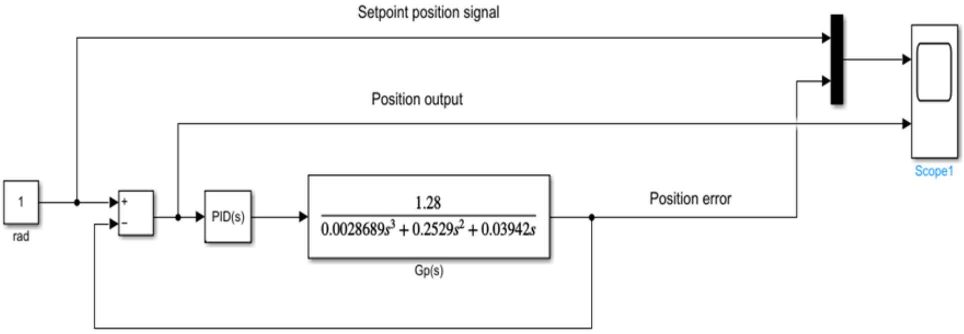

Figure 3. SIMULINK simulation diagram of the DC motor position controller

(a) (b) (c)

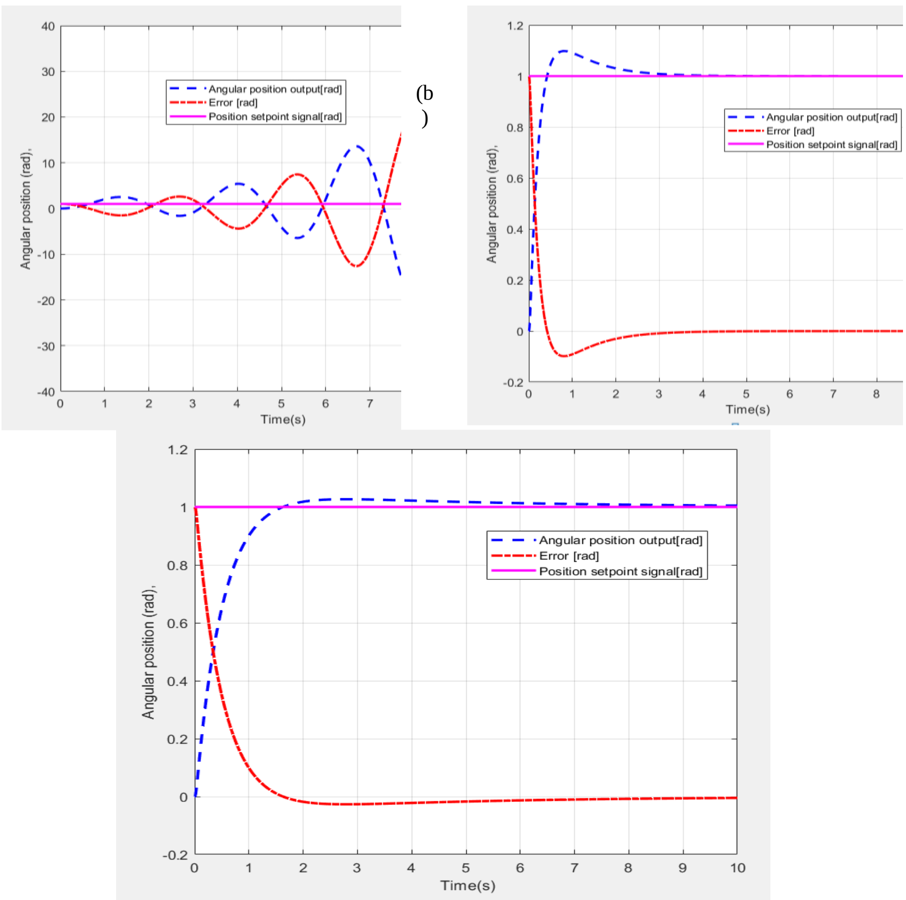

Figure 4. Simulation results of position output response and error: (a, b) Before tuning; (c) After tuning

The simulation results in Figure 4 illustrate the process of optimizing the PID controller for the DC motor. Initially, with $K_p = 1$, $K_i = 1$, $K_d = 0$ (Figure 4a), the system experiences strong oscillations and an overshoot of 37% at 9.5 seconds, leading to instability. When adjusted to $K_p = 1$, $K_i = 0$, $K_d = 1$ (Figure 4b), the error is reduced, the signal follows the setpoint more closely, and the overshoot drops to 1.3%. Further tuning yields the optimal parameters: $K_p = 0.1$, $K_i = 0$, $K_d = 0.4$ (Figure 4c), eliminating overshoot, producing an accurate output signal, and driving the error to zero. This PID controller ensures high performance and the ability to self-adjust when the input changes.

The design of the speed controller is presented in the diagram shown in Figure 5.

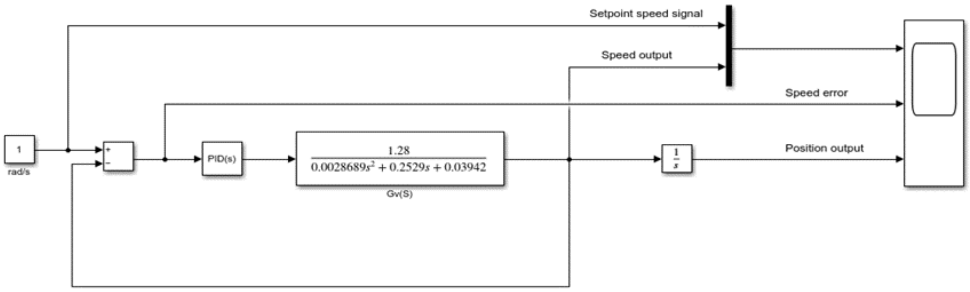

Figure 5. SIMULINK simulation diagram of the DC motor speed controller

(a) (b)

(c)

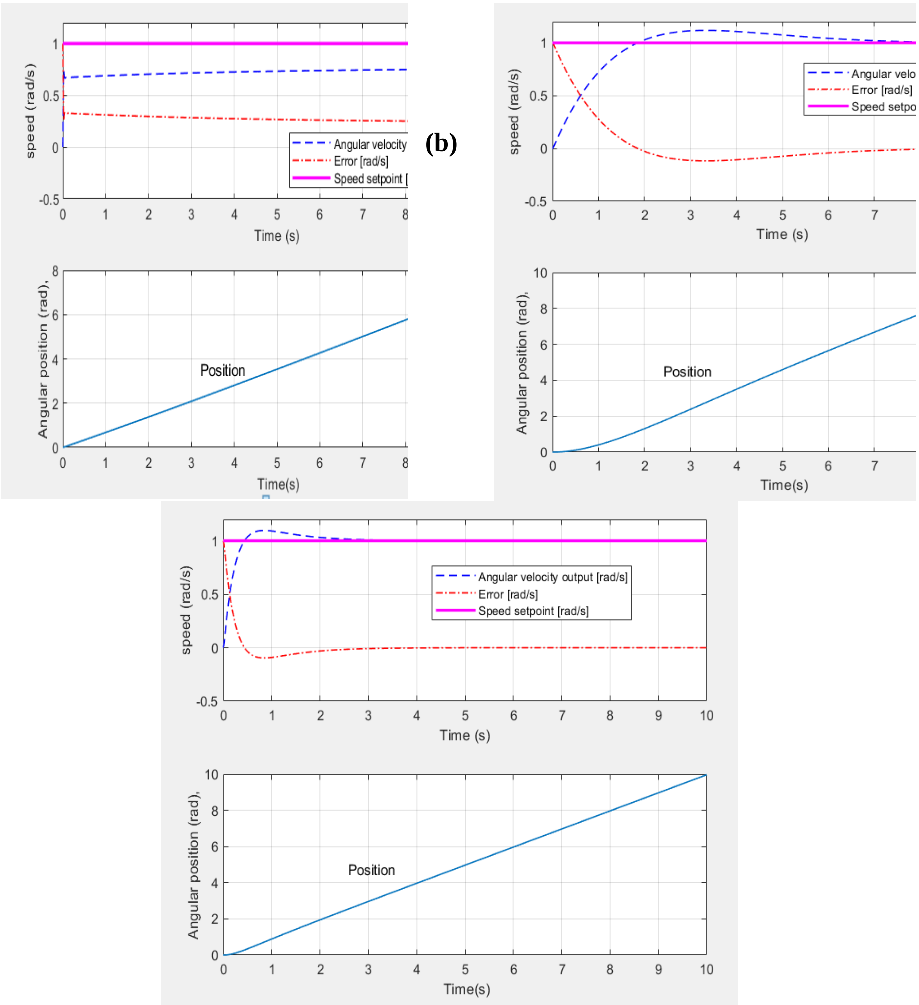

Figure 6. Simulation results of speed output response, position output, and error: (a, b) Before tuning; (c) After tuning

Figure 6 illustrates the impact of PID parameters on the system response. With $K_p = 0.1$, $K_i = 0$, $K_d = 0.4$ (Figure 6a), the steady-state error is large (67%) and the system becomes unstable. When adjusted to $K_p = 0.2$, $K_i = 0.1$, $K_d = 0$ (Figure 6b), the overshoot is small but the settling time is long (7s), indicating a slow response.

Finally, with $K_p = 1$, $K_i = 1$, $K_d = 0$ (Figure 6c), the system experiences a slight overshoot, but it remains within acceptable limits, the settling time is short (2s), and the steady-state error is reduced to zero, ensuring stability.

The results show that the optimal PID parameters for speed control differ from those for position control, highlighting the importance of proper tuning for each specific application. This study confirms the role of PID parameter optimization in enhancing the performance of DC motor control.

IV. Conclusion

This study analyzes the basic theory and structure of the PID controller, including its components, functions, trial-and-error method, and applications in position and speed control of DC motors. By adjusting the PID parameters to meet control quality criteria when the model changes, the trial-and-error method was chosen due to its simplicity, ease of implementation, and tuning. By optimizing the parameters sequentially, the system achieved quick and accurate responses, improved performance, increased stability, and reduced overshoot and settling time.

The simulation results using MATLAB/SIMULINK in both position control and speed control of the DC motor demonstrated that the PID controller, based on the trial-and-error method, effectively selected the adaptive Kp, Ki, and Kd parameters that met control requirements. This reduced overshoot, settling time, and achieved an error approaching zero, effectively meeting technological requirements. Additionally, the controller enhanced noise resistance and maintained stable performance in real-world environments. This study not only has academic value but also provides important practical applications. It contributes to improving performance, saving energy, and enhancing the reliability of control systems in various fields, thereby contributing to the development and advancement of technology.

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