Simulation Of Startup Speed of DC Motor Using PI And PID Control

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Abstract. Proportional-Integral (PI) control and Proportional-Integral-Derivative (PID) control have found widespread application across various disciplines. This article focuses on the impact of PI and PID control on the startup speed of the Direct-Current (DC) motor. By setting up a simulation circuit and simulation module, the gain parameters of the control module are adjusted to obtain different output results. The simulation circuit will involve the DC motor, the control module, and the desired speed input. By adjusting the gain parameters of the control module, the behavior of the motor's startup speed can be simulated and observed. For PI control, increasing both the proportional gain and the integral gain proportionally can lead to shorter settling time and smaller overshoot in the output response. For PID control, increasing the derivative gain can significantly reduce the settling time without causing a significant change in the overshoot. When comparing PI and PID controllers, the addition of the derivative term can improve the output performance. By simulating different control modules and adjusting the gains, it is possible to qualitatively identify controllers with better control performance and more suitable gain parameters. This provides insights for the future design and application of DC motor control modules.

Keywords: PI; PID; DC motor; Simulation; Automatic control.

1. Introduction

Automation technology has a captivating history. Prior to the emergence of control theory, various types of controllers were independently designed based on the principle of "design on demand" due to the absence of unified guidance from control theory [1]. Automation control has been propelled forward by numerous new inventions. However, the development of a complete theoretical framework within the field of automatic control is essential to enhance control accuracy. While in the field of automatic control, PID control is an important feedback control method to improve the accuracy of control.

This paper explores the effects of PI control and PID control on the startup speed of a DC motor, aiming to provide a comprehensive understanding of their respective impacts in the field of control systems engineering. In the System Description section, this research paper provides a comprehensive exposition of the constituent elements of a DC motor. Additionally, it presents a detailed introduction to the structural configuration of first-order PI and PID controllers. In the Simulation Design section, the main focus of this part is on utilizing the Fasltad tool to build circuit simulation models for DC motor PI and PID controllers. In order to analyze the results obtained under various gain settings, it also entails the building of PID control simulation module using Simulink in MATLAB. In the Simulation Results Analysis part, a detailed analysis of the Simulink simulation results was conducted. The comparison was made among the PI control with different gains, the PID control with different gains, and the PI and PID control with the same gain. For the Drawbacks and Improvements section, the analysis focuses on the advantages of current PID control compared to traditional control methods, as well as the shortcomings that still persist. Additionally, it proposes improvement methods for traditional PID control and provides an outlook on the future development of PID control.

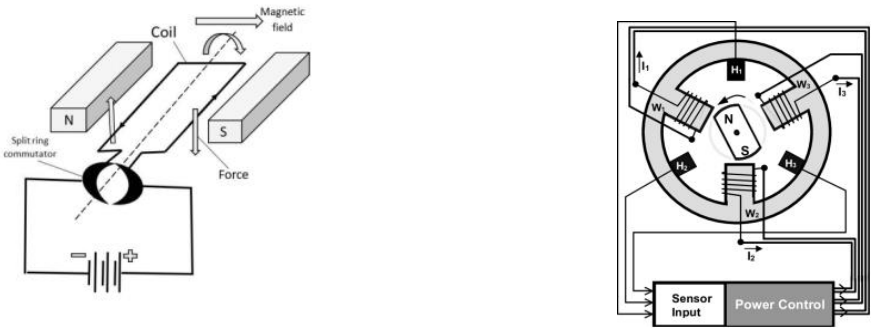
PID control has a wide range of applications in various fields. Due to its straightforward structure and straightforward implementation, the PID controller has grown to be the most extensively used controller across a variety of application domains. The usage of PID control has been made significantly simpler by the newly developed features of automatic tuning [2]. In the future, PID-

based control techniques for numerical control system applications, such as optimum fractional order PID, fractional fuzzy PID, and self-tuning of PID, may be expanded.

2. System Description

2.1. Basics of DC motor

A DC motor is a kind of electric motors that employs the transformation principle to convert the mechanical energy into electrical energy. Using Faraday's law, this motor can date back to the second Industrial Revolution and indeed has a long history of application. Electric motor functioning is caused by the interaction of the motor's electric field and current windings. Such interaction generates force in the rotation form [3]. The majority of motors tend to be the DC type [3]. It obtains the electricity directly from the distribution generators. Using the supplied voltage to the windings, a typical motor can change. According to the presence or absence of brush, DC motors can be divided into Brushed DC and Brushless DC [4]. The category of DC motor and its structure are shown in Figure1, where Figure 1(a) shows the brushed DC motor and Figure 1(b) shows the brushless DC motor.



(a) Brushed DC motor (b) Brushless DC motor

Fig. 1 Types of DC motor [4]

The analysis of a DC motor model can be viewed from two perspectives: the mechanical world and the electrical world. In the electrical world, the DC motor model is similar to a first-order resistor-capacitor (RC) circuit, and its differential equation can be derived by applying Kirchhoff's voltage law (KVL). On the DC motor's electrical side, a current flow i_a through the armature, the amplifier's drive voltage is v_a, the motor's inductance is L_a and resistance is R_a, the back electromotive force (emf) voltage is V_{emf}. The back emf opposes the driving voltage and is inversely proportional to the motor's speed, so it can be described as $V_{emf} = K_e \cdot \Omega$, where Ω represents the angular speed of DC motor and K_e is a constant. By implementing KVL, the operation equation (1) can be obtained.

$$v_a - V_{emf} = L_a \cdot \frac{di_a}{dt} + R_a \cdot i_a \tag{1}$$

The Figure 2 shows the equivalent circuit of the DC motor.

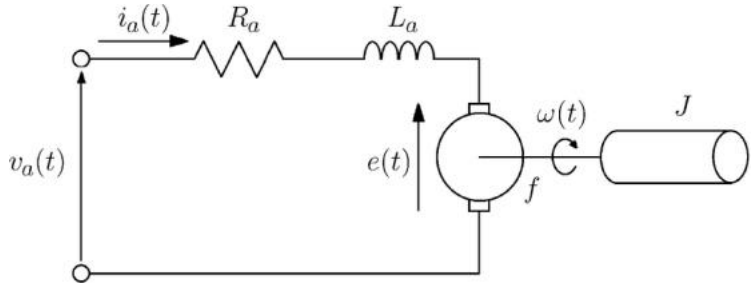


Fig. 2 The equivalent circuit of the DC motor (Photo/Picture credit: Original)

In the mechanical world, the motor applies a mechanical torque to the shaft through the electrical armature current. K_t represents torque constant. The equation (2) shows the relationship between the current and torque. The applied torque generates an angular velocity ω according to the moment of inertia J and friction B of the motor and load just as the equation (3) shows.

$$\tau = K_t \cdot I \tag{2}$$

Where τ means torque of the DC motor.

$$\tau = J \cdot \frac{d\omega}{dt} + B \cdot \omega \tag{3}$$

In order to simplify the analysis, friction is usually ignored. By combing equation (2) and equation (3), then equation (4) is gained.

$$K_t \cdot I = J \cdot \frac{d\omega}{dt} = J \cdot \dot{\Omega} \tag{4}$$

Where I is the flowing current，$\dot{\Omega}$ refers to angular acceleration.

Since the current is the same in the same circuit and $\frac{di_a}{dt}$ is small which can also be ignored not precisely, it can be obtained simultaneously with the equation (5).

$$v_a = \frac{J\dot{\Omega}R_a}{K_t} + K_e\Omega \tag{5}$$

The equations listed above connect the electrical world and mechanical world of a DC motor and will be employed in the study of speed control of DC motor by derivation of transfer function later in this paper.

2.2. PI controller structure

PI and PID controllers have been cited as the second-most significant control decision and communication tool of the 20th century [5]. In the field of engineering, automatic control is essential. Along with other applications, it has become crucial for robotic systems and contemporary manufacturing process. Examples of these activities include these activities include pressure control, temperature regulation and humidity management and so on. For a closed loop, the transfer function should be like $\frac{Y(s)}{R(s)} = \frac{P(s)C(s)}{1+P(s)C(s)}$ [6]. A typical block diagram of a closed loop control system in the Laplace domain is shown in Figure 3.

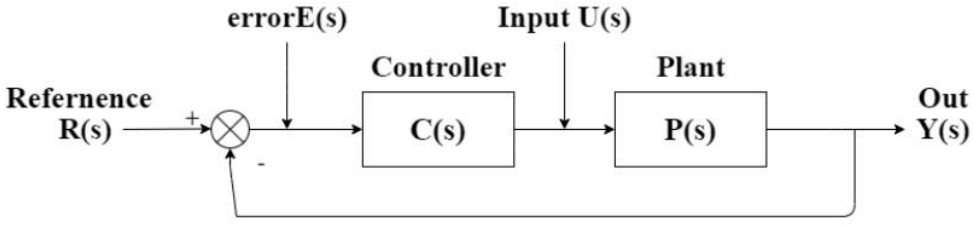


Fig. 3 Closed loop control system diagram [6]

In order to obtain diverse output outcomes, adjustments can be made to the control module C(s) to achieve the desired results. One common control method utilized is the Proportional-Integral (PI) control. PI control is a closed loop control. The proportional (P) control component operates on the feedback of the signal to offer an output proportionate to the error between the intended setpoint and the real procedure varying. The integral (I) control element provides a corrective action to get rid of any steady-state error and integrates the error across time. It diminishes offset and enhances the system's capacity to follow the setpoint precisely by continually adjusting the control signal depending on the accumulated error. The block diagram of PI control is shown in Figure4.

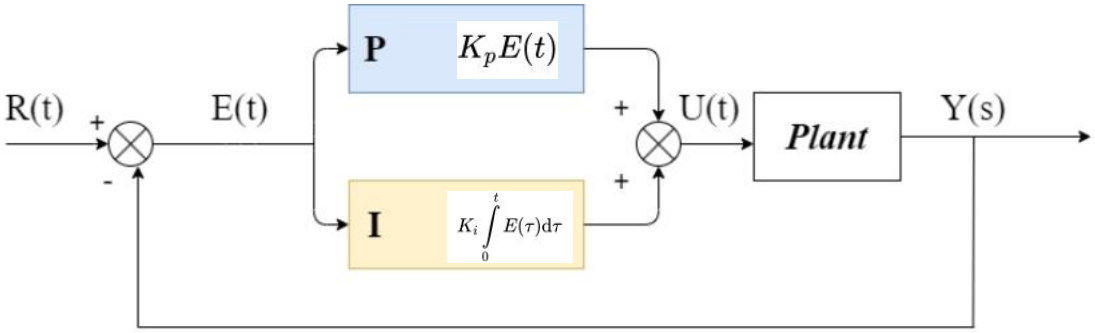


Fig. 4 PI control block diagram (Photo/Picture credit: Original)

With P component and I component working synergistically to provide both quick response and precise steady-state control, the output result can behave in better steady condition and has better working performance. The proportional term addresses the immediate error, while the integral term eliminates any persistent errors. This combination allows PI control to effectively regulate various processes and maintain system stability.

2.3. PID controller structure

PID control is also a closed loop control. The only difference between PID control and PI control is that PID control includes an additional term, the Derivative term, compared to PI control. The rate of change of the error is determined by the derivative (D) control element which also enables the controller to predict future trends and modify the control signal appropriately. The derivative action provides damping to the control system, helping to speed up reaction time and lessen overshoot and oscillations. The block diagram of PID control is shown is Figure 5.

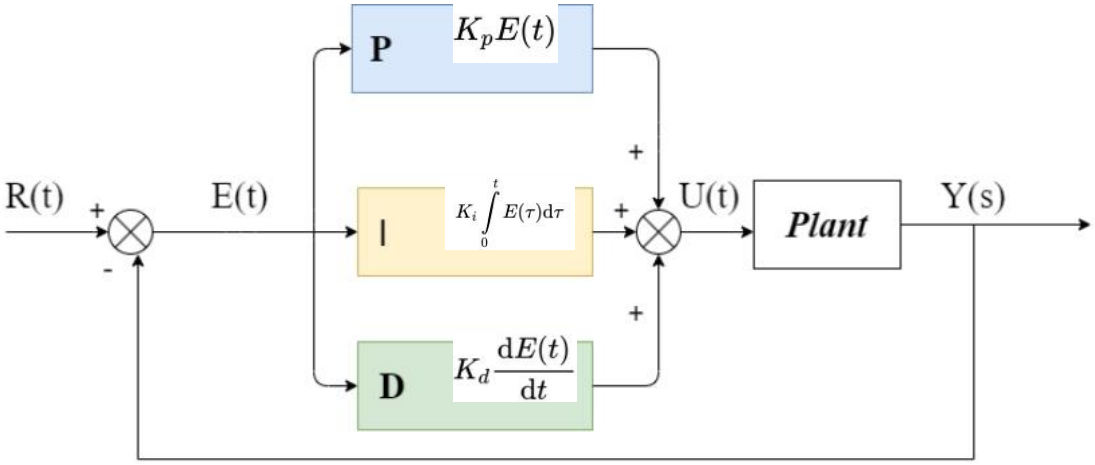


Fig. 5 PID control block diagram [7]

While PI control concentrates on the proportional and integral actions for achieving stability and precise control, PID control contains the derivative component to improve reaction time and system damping. The PID controller's stability to respond to unpredictable shifts in the procedure variable and further enhance overall control performance are both made possible by the inclusion of the derivative term [7]. As a result, though PID controller is more complex than PI controller, it indeed can get better output result.

3. Simulation Design

3.1. Simulation tool introduction

For the simulation part, circuit simulation tool Falstad and analyze tool MATLAB will be used. Falstad, also called the circuit simulator applet, is a free JavaScript-based programmed created by

Paul Falstad which enables users to quickly and easily simulate a variety of electrical circuits on web browsers. The programmed is sophisticated enough to provide an exact examination of the constructed circuit while also offering a degree of visual feedback that is appropriate for electronic beginners. The effects of resistor selection, chip type selection, or clock frequency selection may be quickly seen using the simulator's tools and modules. The biggest advantage of Falstad is that it is simple to operate. Its page is concise, the circuit can be set up quickly and the simulation results can be clearly obtained. In this paper, Falstad is used for building simulation circuit. A high-level programming language and environment designed specifically for numerical computation, data analysis, and visualization is called MATLAB (Matrix Laboratory). The MathWorks-created software package MATLAB offers a robust set of tools and functions for addressing a variety of scientific and engineering issues. MATLAB will mainly be used for drawing plots and making comparisons between PI control and PID control as well as the same kind of control with different gains in the analysis part.

3.2. Simulation circuit construction

In Falstad, ideal operational amplifiers, few resistors as well as capacitors were used to simulate the PI control of the speed of DC motor. As for PI control, $C(s) = K_p + \frac{K_I}{s} = \frac{K_I(\frac{K_p}{K_I}s+1)}{s}$. It can be known that the zero is $s = -\frac{K_I}{K_p}$. In the whole analysis process, one could consider $s = -20$. In this case, it means that if $K_p = 5$, then $K_I = 100$. By adjusting the values of these two parameters, different waveforms of output speed of the DC motor can be observed and compared. Assuming all initial conditions are set to zero. Set $C(s) = 5 + \frac{100}{s}$, as for the $C(s)$ part, here is the derivation of its circuit. Figure 6 shows the circuit of the control module of PI control.

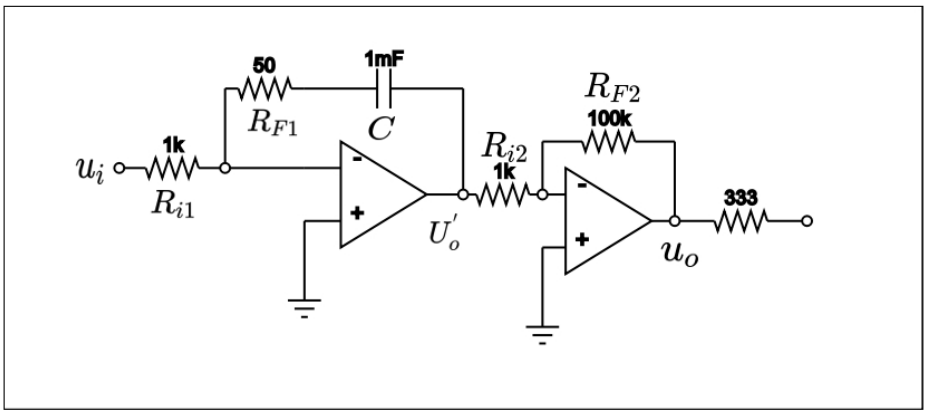


Fig. 6 Circuit of C(s) of PI control (Photo/Picture credit: Original)

The control module $C(s)$ is shown as follows.

$$C(s) = 5 + \frac{100}{s} \tag{6}$$

Let the amplification factor of the inverting amplifier be 100 times, which should be.

$$\frac{u_o}{U_o'} = 100 \tag{7}$$

So, the ratio of the middle output voltage to the input voltage should be.

$$\frac{U_o'}{u_i} = \frac{1}{s} + 0.05 \tag{8}$$

According to the virtual short and virtual open properties of an operational amplifier, it can be included that.

$$\frac{U_o'}{u_i} = -\frac{\frac{1}{j\omega C}+R_{i1}}{R_{i1}} = -(\frac{1}{j\omega CR_{i1}} + \frac{R_{F1}}{R_{i1}} = -(\frac{1}{sCR_{i1}} + \frac{R_{F1}}{R1}) \quad (9)$$

By assigning values to the resistors and capacitors (as shown in Figure 7), the desired transfer function $C(s)$ part can be obtained.

As for the DC model part, to simplify the calculating process, DC motor model can roughly be represented by first order circuit, which is a First-order active low-pass filter in fact because both of their transfer function has the same form. Figure6 shows the circuit model of the DC motor.

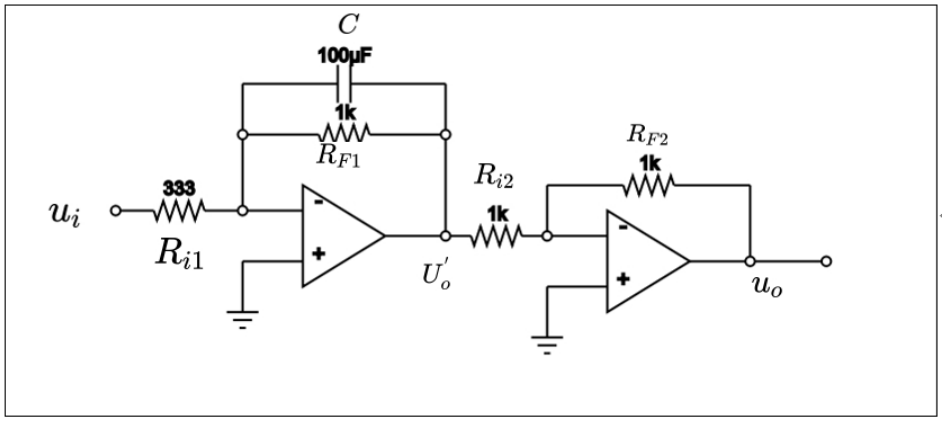


Fig. 7 Circuit of model of DC motor (Photo/Picture credit: Original)

Similarly, it can also be obtained that.

$$\frac{U_o'}{u_i} = -\frac{R_{F1}}{R_{i1}}\frac{1}{1+j\omega CR_{F1}} = -\frac{R_{F1}}{R_{i1}}\frac{1}{1+sCR_{F1}} \quad (10)$$

Through equation (5), it can be known that the transfer function of DC motor is $\frac{\Omega}{v_a} = \frac{K_m}{\tau s+1}$, where $K_m = \frac{1}{K_e}$. Also, by adjusting values of resistors and capacitors, transfer function can be set as $\frac{\Omega}{v_a} = \frac{3}{0.1s+1}$.

With the core $C(s)$ and the DC motor circuit section, introduce the DC motor's output angular velocity as negative feedback into the closed-loop circuit and construct the circuit for PI control by using a summer. The whole PI control circuit is shown in Figure8.

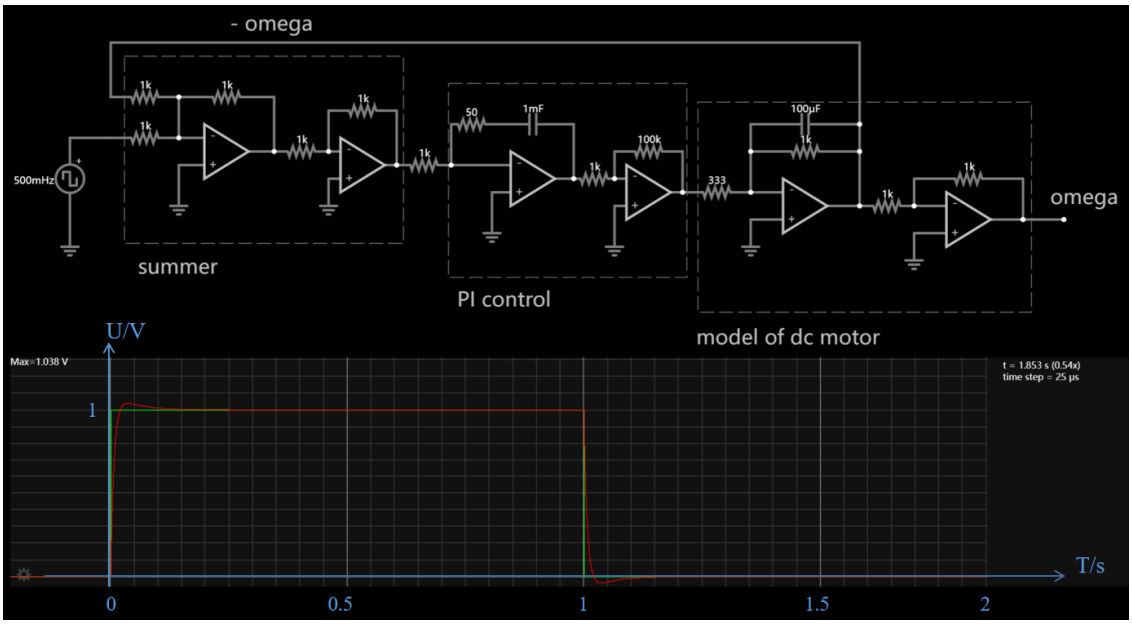


Fig. 8 Circuit of PI control; C(s)=5+100/s (Photo/Picture credit: Original)

From the waveform samples, it can be observed that by applying PI control, comparing the output with the reference square wave, the output waveform exhibits minimal overshoot and reaches a steady state after a certain period of time.

By adjusting the gains K_p and K_I, different outputs can be obtained. A rough comparison allows for a preliminary judgment: as the gains increase, the time required for the output waveform to reach a steady state decrease, and the overshoot decreases as well. These results will be shown in detail with MATLAB later.

As for PID controller, the only thing needs to be done on the PI circuit is to change the $C(s)$ part. By adding a resistor in parallel with the capacitor, the K_d term is introduced. Also, the circuit of control module of PID controller is shown in Figure 9.

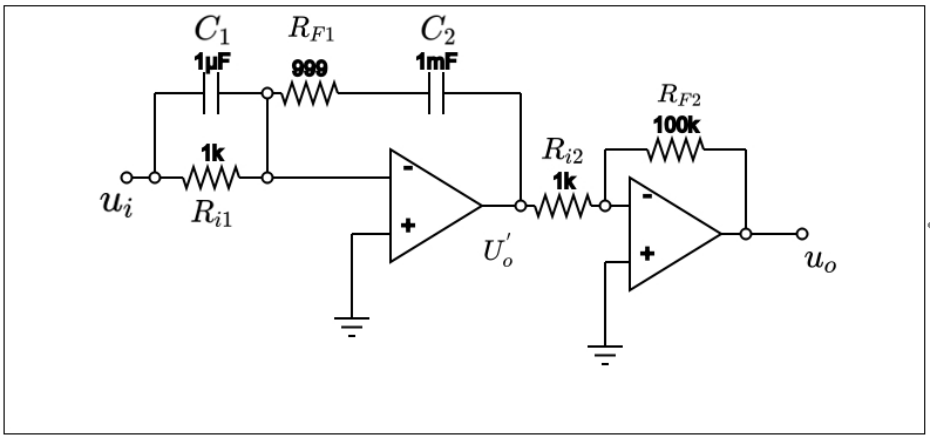


Fig. 9 Circuit of C(s) of PID control (Photo/Picture credit: Original)

Due to the virtual short and virtual open properties of an operational amplifier,

$$\frac{u_i}{R_{i1}} + u_i j\omega C_1 = -\frac{U_o'}{R_{F1}+\frac{1}{j\omega C_2}} \tag{11}$$

So, it can be obtained that.

$$\frac{U_o'}{u_i} = -\frac{R_{F1}+\frac{1}{j\omega C_2}}{\frac{1}{R_{i1}}+j\omega C_1} \tag{12}$$

By adjusting the parameter values of the components, set $C(s) = \frac{100}{s} + 5 + 0.1s$.Similarly, the complete circuit diagram for the PID control is shown in Figure 10. It can be observed that after adding the derivative term, the output waveform differs from the PI control, which can be seen that the time it reaches the steady state is shorter than PI control.

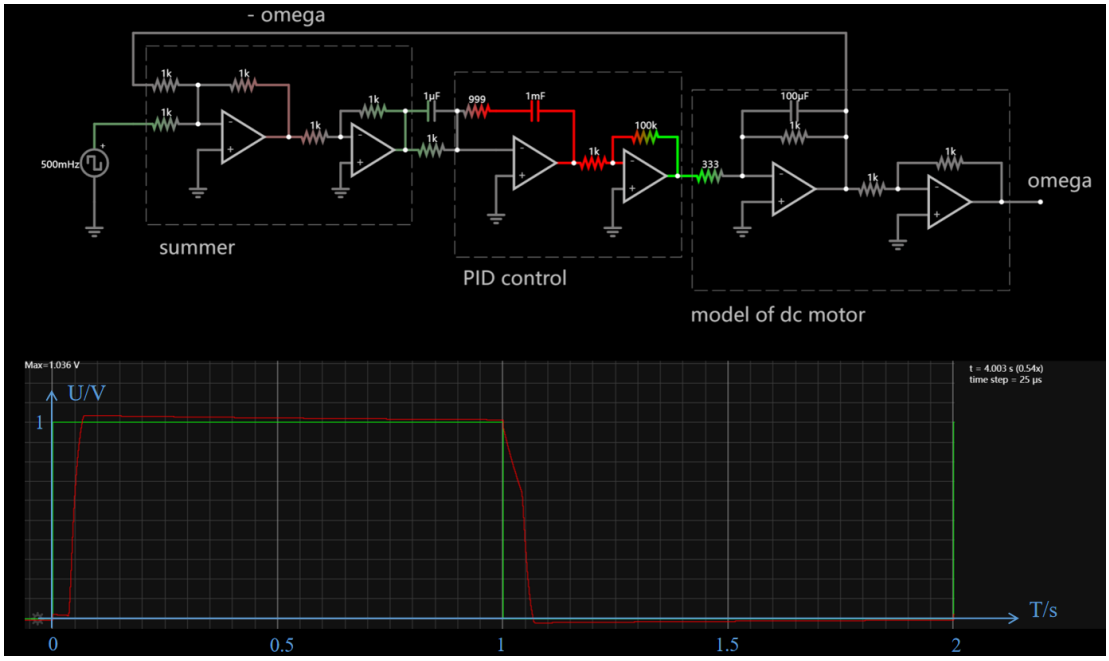


Fig. 10 Circuit of PID control; C(s)=100/s+5+0.1s (Photo/Picture credit: Original)

3.3. Matlab simulation

A control block diagram can be constructed using MATLAB's Simulink tool, depicted in Figure 11. The transfer function of the DC motor serves as the input while a constant value of 1 is set as the reference. A closed-loop control system is formed by introducing the error into the negative feedback loop [8]. The comparison of the input error and control module for three different gains can be achieved through the adjustment of gain parameters, and this can be visually displayed using an oscilloscope-like visualization.

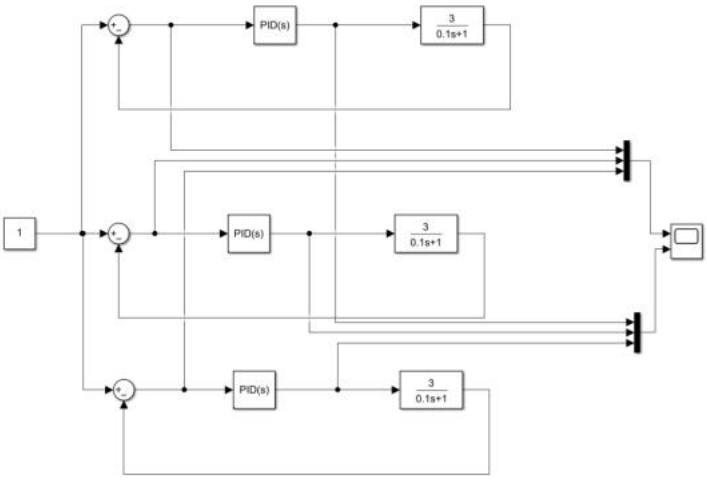


Fig. 11 Simulink block of comparison between different gains (Photo/Picture credit: Original)

Similarly, a block diagram can be constructed to compare the PI control and PID control, evaluating the performance under different control strategies, which is shown in Figure 12.

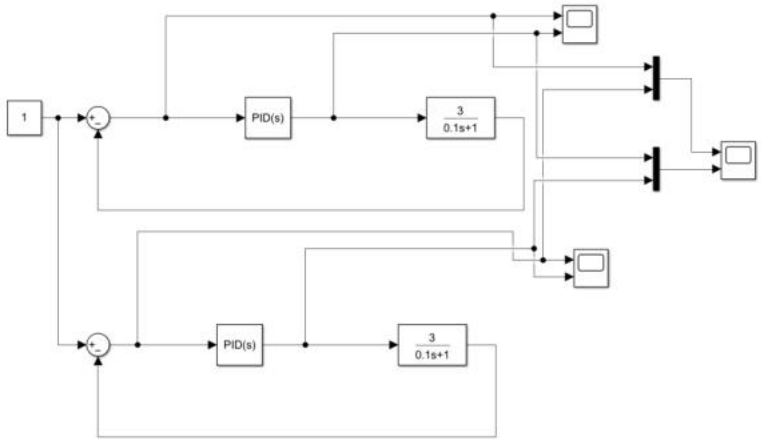


Fig. 12 Simulink block of comparison between PI control and PID control (Photo/Picture credit: Original)

4. Simulation Results Analysis

Maintaining a ratio of 20 between K_I and K_p, the waveform comparison below shows the response of the system under PI control with three different gains: $K_{p1}K_{I1}$; $K_{p2}K_{I2}$; $K_{p3}K_{I3}$. The curves above correspond to the initial state of the errors, while the curves below represent the final state after adjustments by the control module. The results of different gains in PI control is shown in Figure 13.

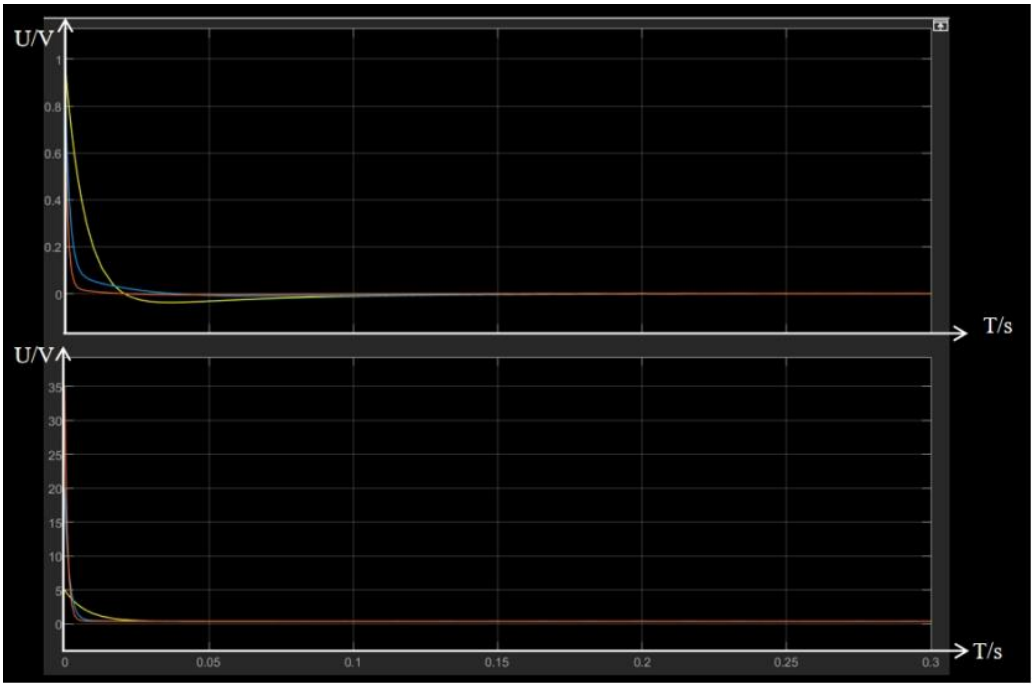


Fig. 13 Waveforms of PI control with different gains (Photo/Picture credit: Original)

The yellow waveform represents the output response under PI control with $C(s) = \frac{100}{s} + 5$. It exhibits a certain response time and settles to a steady state with a moderate level of overshoot. The blue waveform represents the output response with $C(s) = \frac{200}{s} + 10$. It shows a faster response compared to the first gain, reaching the steady state more quickly with a reduced overshoot. The red

waveform represents the output response with $C(s) = \frac{500}{s} + 25$. It exhibits the fastest response among the three gains, reaching the steady state almost immediately with minimal overshoot. By comparing these waveforms, it is evident that increasing the gain (K_p and K_I) leads to a faster response and reduced overshoot, while lower gains result in a slower response but potentially more stability. The optimal gain value depends on the specific system requirements and desired performance.

For PID control, maintaining K_p and K_I constant, adjusting the gain K_d. Figure 14 shows the waveforms of PID control with different gains. The yellow waveform represents the output response under PI control with PID control of $C(s) = \frac{100}{s} + 5 + 0.1s$, the blue one shows $C(s) = \frac{100}{s} + 5 + s$ and the red one shows $C(s) = \frac{100}{s} + 5 + 10s$. As the K_d gain gradually increases, the overshoot may not show significant changes, but the time to reach steady state decreases obviously.

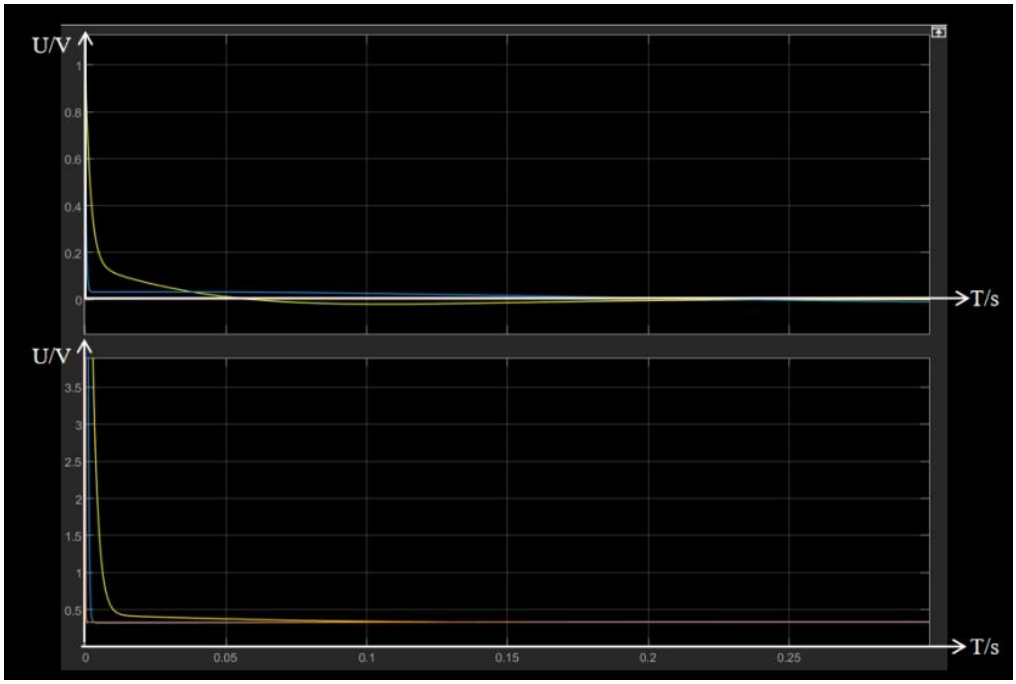


Fig. 14 Waveforms of PID control with different gains (Photo/Picture credit: Original)

Meanwhile, Figure 15 shows the result of comparison between PI and PID control. Comparing PI control and PID control, the yellow waveform represents the output response under PI control with $C(s) = \frac{100}{s} + 5$.The blue waveform represents the output response under PI control with $C(s) = \frac{100}{s} + 5 + 0.1s$. It can be observed that introducing PID control results in a shorter time to reach steady state and reduced overshoot, which verified the derivative (D) term to provide damping and help the system respond faster as well as reduce overshoot. It indicates that using the same set of parameters, PID control generally provides better control performance for the system than PI control.

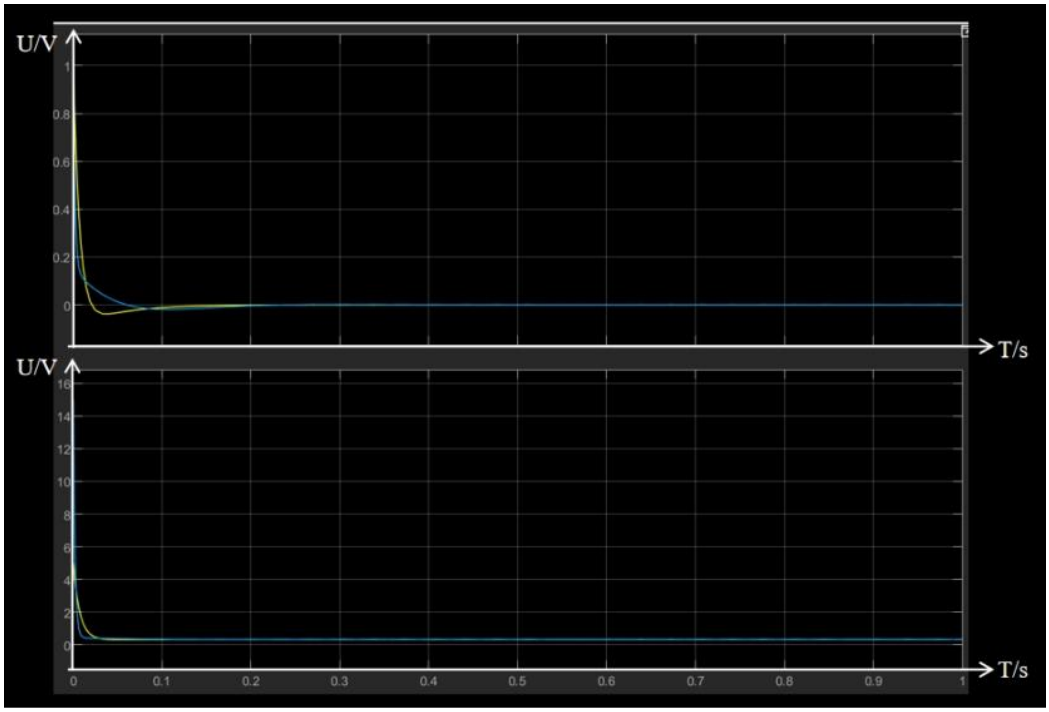


Fig. 15 Waveforms between PI control and PID control (Photo/Picture credit: Original)

5. Drawbacks and Improvements

PID controllers are widely used in industry to manage flow, temperature, pressure, level, and many other process variables in automation processes and control applications [9]. As a result, numerous specialists in control engineering continue to express a strong interest in the issues related to effective and innovative rules (soft computing-fuzzy and neural, resilient, adaptive PID control) and improved PID control system design approaches. Despite a number of benefits, PID controllers can have the following disadvantages when used for feedback control.

First of all, PID controller doesn't take action until the process senses a disturbance. Since the controlled variable cannot vary from the set point when the load or setpoint changes, complete control cannot be achieved. Secondly, instability could result from tweaking the PID control framework. Thirdly, for specific domains like robotics, due to the nonlinearity of the robot manipulator caused by the unexpected environment, conventional PID controllers are insufficient to provide the appropriate tracking control performance. Although fuzzy PID controllers can be used, the mathematical model of the system is difficult or too complex to derive [10].

There are several ways to take use of more information about process dynamics and enhance the feedback PID controller design, including the following: To be first, using explicit modelling for calculating control parameters or using the combination MPC-PID. Besides, measuring extra process outputs (like cascade and feed-forward).

In this article, the classical PID control is used to control the speed of the DC motor. Based on the understanding of the drawbacks and improvements, PID control can be categorized into the classical group and advanced group. Therefore, future experiments could be conducted to enhance the realism and credibility of the experimental model using the improvements discussed in this article.

6. Conclusion

This paper concludes by arguing the influence of PI control and PID control on the startup speed of the DC motor. The research findings indicate that for PI control, increasing the proportional gain (K_p) and integral gain (K_I) can reduce the time required for the DC motor to reach a steady state during startup while also reducing overshoot. Moreover, it enhances the stability of the system output.

As for PID control, increasing the derivative gain (K_d) does not result in a significant change in overshoot. However, it noticeably decreases the time required for the DC motor to reach a steady state during startup. By maintaining constant values for the gains K_I and K_p as well as comparing PI control with PID control, it was observed that the introduction of an increased K_d gain leads to a notable decrease in the time needed for the system to achieve a stable state. Additionally, the system exhibits enhanced stability characteristics with the incorporation of the K_d gain.

However, it is important to acknowledge that the findings presented in this research article are derived from idealized simulation models. As a result, there might be discrepancies between these simulated results and the actual outcomes in real-world scenarios. In practical applications, the selection of gains is typically based on considering two aspects: the impact on the dynamic performance and the steady-state performance of the system. To ensure appropriate gain selection, tuning of the gain parameters can be performed using methods akin to those employed in analog controllers. In future research on PID control, it would be beneficial to incorporate real-world considerations based on the foundation established in this study. This could involve setting more appropriate gains by considering practical constraints and system characteristics. Additionally, increasing the complexity of the system model would allow for a more comprehensive analysis of PID control performance under diverse operating conditions.

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