Dean&Francis
ISSN 2959-6157

Optimal Zero Placement for PI and PD Control of DC Motors in Medical Applications

Jiangtai Wu[1, *]

1School of International,
Beijing University of Posts
and Telecommunications,
Beijing,100876
China

*Corresponding author:
wujiangtai@bupt.edu.cn

Abstract:

In medical devices, DC motors are crucial components due to their high efficiency and high starting torque, which effectively address sudden load increases. This study focuses on improving the inherent performance of the system. The proposed approach utilizes PI control for motor speed and PD control for motor angle to optimize system performance. Gain selection is central to this process, ensuring the system maintains robustness while improving response time and minimizing overshoot. The primary task of this research is to select appropriate zero points and gains to achieve optimal performance. Using the root locus method and Matlab, gains for rapid response were identified for a 100mHz DC motor under PI and PD control. Zero points of -11 and -12 were found for high stability requirements and general demands, respectively, offering reduced overshoot and shorter response times. The resulting circuit was constructed based on these values, yielding ideal waveforms and verifying the feasibility of the proposed results. On this basis, further refinement in zero-point selection and optimization of the underlying control system can be pursued.

Keywords: DC motor, PI control, PD control, Gain searching

---

1. Introduction

In the application of medical devices, DC motors are a critical component in many systems. They exhibit characteristics of high efficiency, high starting torque, and controlled deceleration, which contribute to preventing sudden load increases [1]. Among the commonly used control systems for DC motors, PI and PD controllers are widely applied. The use of PID control in the practical applications of DC motors in medical devices offers numerous advantages, including greater complexity and improved disturbance rejection, outperforming standalone PI or PD control.

To leverage the benefits of PI and PD control, this paper adopts a strategy where PI control is used for speed regulation, and PD control is employed for angle regulation, thereby controlling the overall system.

ISSN 2959-6157

Numerous studies focus on enhancing the performance of basic PI or PD systems, such as the application of hybrid algorithms to improve PD control [2]. This highlights the importance of improving the underlying PI and PD control systems, with emphasis on the selection of gains. Ensuring appropriate system robustness is a prerequisite [3], and on this basis, efforts can be made to enhance other performance metrics. In the field of medical devices, response time and overshoot are key performance indicators. To improve these indicators, the selection of zero placements acts as a bridge between the two types of gains, enabling system improvements through optimal zero placement [4]. This work provides a foundation for future optimization efforts.

2. Methodology

In the research methodology presented in this paper, PI control, and PD control were chosen to regulate the speed and angle of the DC motor system separately, rather than employing PID control to manage the overall motion of the DC motor [5]. The separate control of DC motor speed and angle offers distinct advantages. Firstly, the design is simplified, reducing overall complexity. Secondly, oscillations and overshoots are minimized. Utilizing PD and PI control independently allows for more precise parameter tuning for different tasks, thereby enhancing system robustness (disturbance resistance) [6]. Stability and precision are particularly critical in medical devices [7]. PD and PI provide more stable performance for distinct control objectives, whereas PID can sometimes be overly complex and difficult to fine-tune for accurate control. The principles of PI and PD control are shown in Fig. 1.

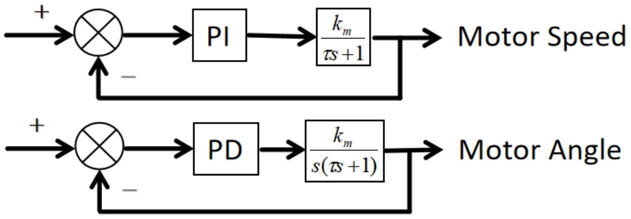

Fig. 1 The principles of PI and PD control (Photo/Picture credit: Original)

2.1 PI Control for DC Motor Speed

The PI controller is widely recognized for its effectiveness in speed regulation, particularly in DC motor applications, due to its ability to eliminate steady-state errors through the integral component [8]. This ensures not only accurate but also stable speed control. The tuning of the proportional (Kp) and integral (Ki) gains plays a crucial role in optimizing system performance. By systematically adjusting these parameters, one can achieve an optimal balance between stability and responsiveness, resulting in a performance curve with minimal overshoot and fast settling time. The absence of a derivative term also reduces sensitivity to noise, which is especially beneficial in applications requiring high reliability, such as medical devices.

In the design process, it is essential to begin by selecting and testing three representative values of the proportional gain (Kp) to observe their respective step responses. Following this, analytical tools such as the Pole-Zero map and the Root Locus method can be employed to fine-tune both Kp and Ki, allowing for the identification of the optimal parameter combination. The desired performance curve should exhibit a minimal or non-existent overshoot, a rapid response time, and no oscillatory behavior, ultimately surpassing the performance of proportional-only control models. By iterating through this process, the optimal PI controller configuration can be found, leading to enhanced control dynamics and robustness in real-world applications [9].

2.2 PD Control for DC Motor Angle

PD controllers excel in angle control by delivering both fast response and accurate positioning [10]. The proportional (Kp) term provides immediate corrective action, while the derivative (Kd) term anticipates future trends, reducing lag and overshoot. This synergy ensures smoother control dynamics and enhances overall system performance, making PD controllers ideal for applications demanding high precision and reliability, such as medical devices. These features are critical for maintaining stability and accuracy, especially in dynamic environments.

In the design of angle control systems, a systematic approach is necessary. Begin by selecting three representative proportional gain Kp values and evaluating their step response characteristics. Next, utilize analytical tools such as the Pole-Zero map and Root Locus method to fine-tune both Kp and Kd, identifying the optimal parameter combination. The objective is to achieve a control response that minimizes overshoot, eliminates oscillations, and maintains a fast response time. By comparing the PD controller's performance with that of purely proportional control models, the ideal balance between speed and stability can be found, leading to superior system performance.

3. Results and Discussions

3.1 Results of PI Control for DC Motor Speed

3.2.1 System modeling of the speed control system

A PI controller was selected for speed control, with the system utilizing feedback regulation. The feedback and instantaneous signals are processed by a summer, and the resulting signal is applied to the controller, which then acts on the plant, transmitting the signal to the DC motor to convert it into motor speed. The controller's equation and the DC motor's plant equation are:

$$\mathrm{P} = \frac{3}{0.1s+1} \tag{1}$$

$$C(s) = k_p + \frac{k_i}{s} \tag{2}$$

where Kp is the proportional gain, and Ki is the integral gain.

The key aspect of the system's response lies in the product of these two equations, which allows us to determine the system's poles and zeros. The poles are fixed at -1 and -10, while the zero is a variable. A zero point greater than -10 is selected can lead to discontinuities in the root locus, resulting in lower system robustness, where small fluctuations in gain can cause significant effects. Therefore, selecting a zero smaller than 10 offers better robustness, providing a foundation for identifying the optimal gain to achieve the best performance.

Through experimentation, different zeros and gains were selected. For the selection of zeros, integer points were chosen, progressing from -10 towards the negative half of the real axis. For the selection of gains, the gain values were chosen based on the root locus diagram, targeting the gain that yields the fastest or near-fastest response under the given zero condition. Combining these factors, the following data were tested, as shown in Table 1.

Table 1 Performance of PI Control with Different Gains

z	Ki	Kp	Overshoot	Settling Time(s)
-11	6.0	0.55	0.33%	0.20
-11	6.8	0.62	0.40%	0.18
-12	9.0	0.75	1.27%	0.13
-12	9.5	0.79	1.30%	0.12
-13	12.0	0.92	2.20%	0.19
-13	12.3	0.95	2.20%	0.19
-14	15.0	1.07	3.03%	0.19
-14	15.4	1.10	3.03%	0.19
-15	18.0	1.20	3.78%	0.19
-15	18.7	1.25	3.76%	0.18

The best performance was observed when the zero was set at -12. At this point, the overshoot was minimal, while the response speed remained very fast. Zeros smaller than -12 were found to be inferior in terms of both overshoot and response time and were therefore eliminated. When the zero was set at -11, the overshoot was exceptionally low, but the response time was relatively longer. Consequently, two different zero selections can be considered depending on specific requirements. For systems with strict overshoot constraints, selecting -11 is a better choice; for systems with higher demands on response speed, -12 is more suitable. In both cases, the overshoot remained below 1.5%, making them appropriate for applications where high stability is critical.

3.2.2 Simulation of the speed control system

The PI controller chosen employs a combination of a proportional and an integral operation. The proportional operation is:

$$V_{out} = -\frac{R_f}{R_i} V_{in} \tag{3}$$

The structure is shown in Fig. 2.

And for the integral operation :

$$V_{out} = -\frac{1}{R_i C} V_{in} \tag{4}$$

ISSN 2959-6157

The structure is shown in Fig. 3.

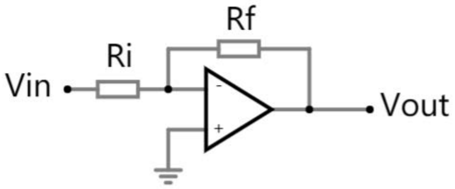

Fig. 2 Proportional operator. (Photo/Picture credit: Original)

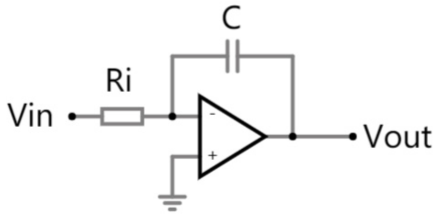

Fig. 3 Integral operator. (Photo/Picture credit: Original)

By setting the resistor Ri to 1kΩ, the values of other components can be calculated based on the proportional gain. Using the calculated component values, the system's controller was designed and implemented. The finalized PI control system is illustrated in Figs. 4 and 5, which provides a visual representation of the controller's design and configuration. To validate the design, circuit simulations were conducted, and the results closely matched the anticipated performance.

The simulation outcomes demonstrated that the PI controller effectively eliminates steady-state error, which is crucial for maintaining accurate control over the system. Additionally, the PI controller significantly enhances the response speed, ensuring that the system reacts promptly to changes in input. The waveform generated during the simulations was exceptionally smooth, indicating that the system achieved a response characterized by no overshoot. This smooth waveform is indicative of a well-tuned controller that maintains a stable speed, which is essential for applications demanding high precision and reliability.

The circuit was simulated using Falstad, and the actual performance closely aligned with the simulation results, indicating good system robustness. The outcome with the zero set at -11, as shown in Fig. 4, demonstrated strong stability. Meanwhile, the result with the zero set at -12, illustrated in Fig. 5, exhibited both a certain degree of stability and a faster response time.

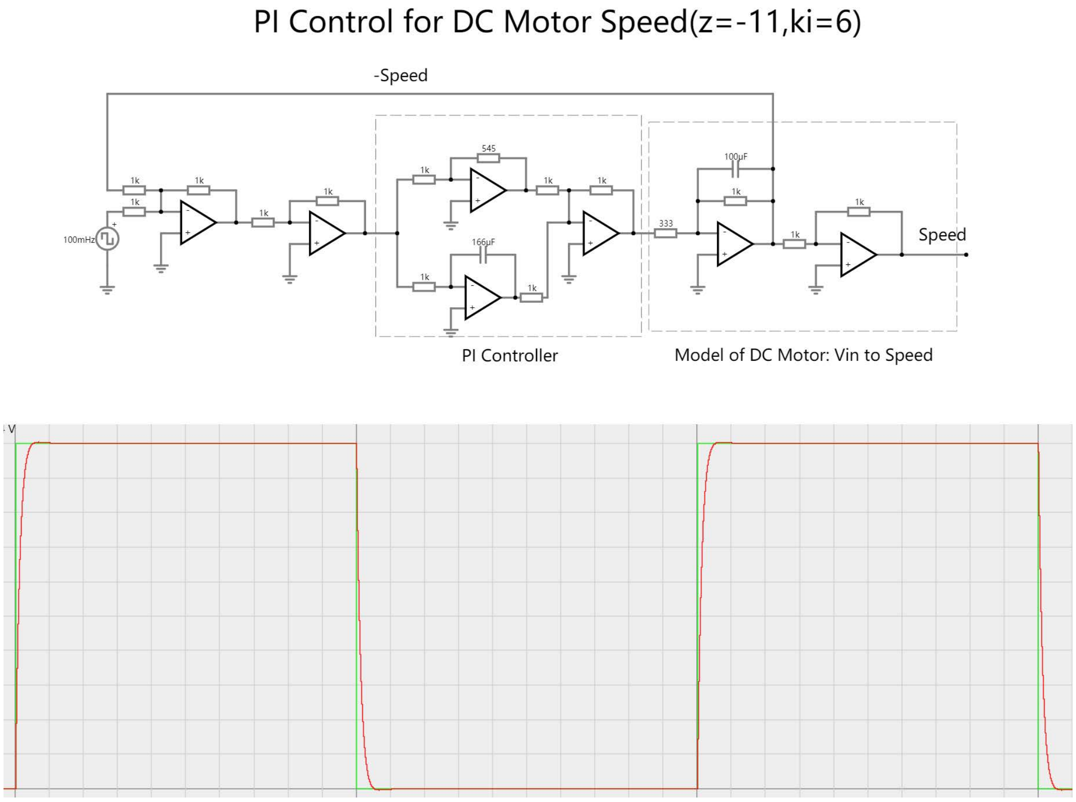

Fig. 4 PI control system with the zero at -11. (Photo/Picture credit: Original)

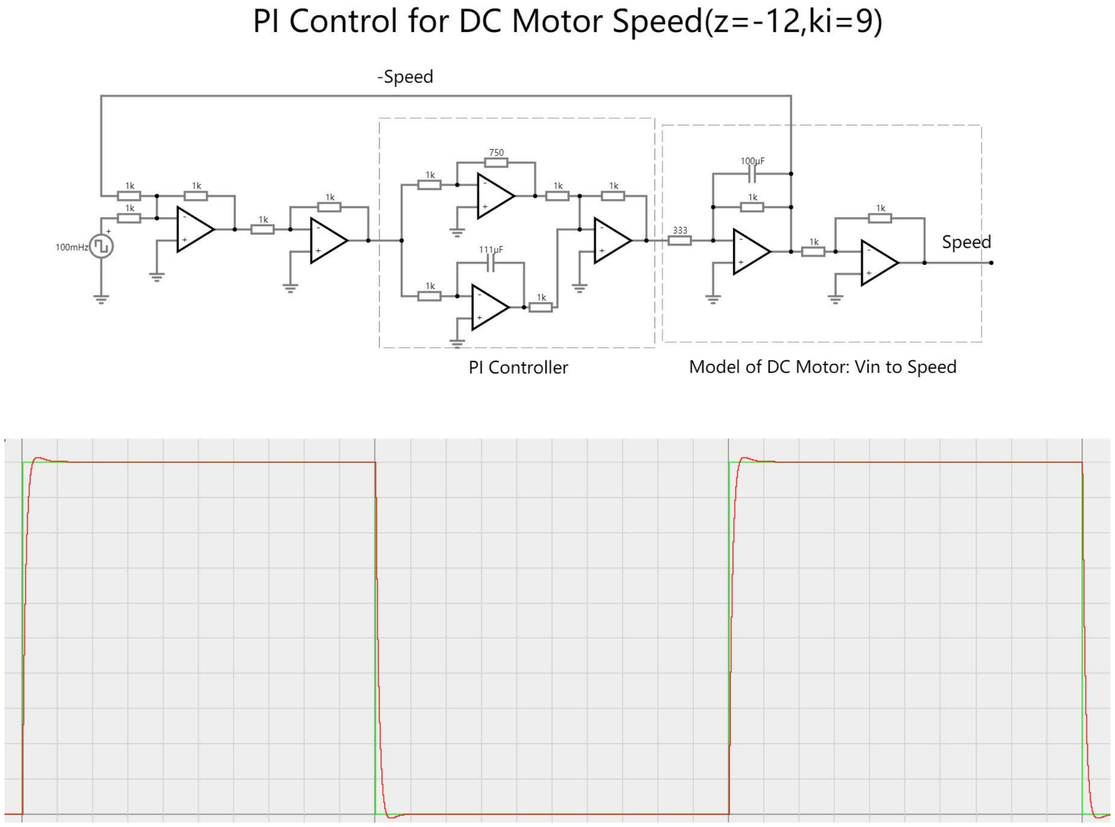

Fig. 5 PI control system with the zero at -12. (Photo/Picture credit: Original)

3.2 Results of PD Control for DC Motor Angle

3.2.1 System modeling of the angle control system

The controller's equation and the DC motor's plant equations are:

$$P = \frac{5}{0.1s^2 + s} \tag{5}$$

$$C(s) = k_p + sk_d \tag{6}$$

where Kp is the proportional gain and Kd is the derivative gain.

In designing the PD control for the DC motor angle, both the root locus and PZ map methods were employed to determine the optimal gain and zero values. A critical component of the system's dynamic behavior is determined by the interaction between these two equations, which enables the identification of the system's poles and zeros. In this context, the poles are positioned at -1 and -10, while the zero is treated as a variable parameter. Choosing a zero greater than -10 introduces discontinuities in the root locus plot, thereby reducing the system's robustness and making it highly sensitive to minor variations in gain. As a result, selecting a zero smaller than 10 provides enhanced robustness, forming a more stable basis for tuning the gain to achieve optimal system performance.

In the experimental phase, various combinations of zeros and gains were tested. For zero selection, integer values were systematically chosen, progressing from -10 along the negative real axis. Gain values were then selected using the root locus plot, focusing on identifying the gain that delivers the fastest or near-optimal response speed for each zero. Based on this methodology, the data shown in Table 2 were obtained through testing.

Table 2 Performance of PD control with different gains

z	Kp	Kd	Overshoot	Settling Time(s)
-11	4.0	0.36	0.39%	0.18
-11	4.1	0.37	0.40%	0.17
-12	5.0	0.42	1.22%	0.14

-12	5.7	0.48	1.30%	0.12
-13	7.0	0.54	2.19%	0.19
-13	7.4	0.57	2.20%	0.19
-14	9.0	0.64	3.03%	0.19
-14	9.2	0.66	3.03%	0.19
-15	11.0	0.73	3.77%	0.18
-15	11.2	0.75	3.76%	0.18

Although the specific gain selections for the PD and PI controllers differed, the choice of zero was found to be similar between the two. The results from the PD controller closely mirrored those of the PI controller, particularly in terms of system behavior concerning overshoot and response time. Optimal performance was observed when the zero was positioned at -12, where overshoot was minimal and the response speed remained rapid. Zeros less negative than -12 demonstrated inferior performance in both overshoot and speed, leading to their exclusion. When the zero was set at -11, the overshoot was exceptionally low, but the response time was somewhat slower. Therefore, the selection of zeros can be adjusted based on specific requirements: a zero at -11 is ideal for minimizing overshoot, while a zero at -12 is more suitable for systems requiring faster response times. In both cases, overshoot remained below 1.5%, ensuring stability in high-precision applications.

3.2.2 Simulation of the angle control system

The values of the resistor and inductor can be determined based on the PD controller. The equation of the PD controller is

$$V_{out} = -\frac{R_f + sL}{R_i} V_{in} \tag{7}$$

The structure is shown in Fig. 6.

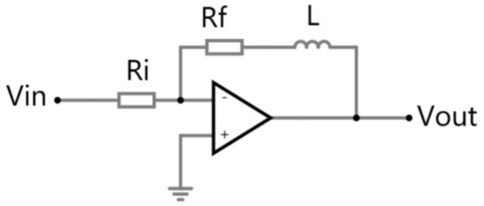

Fig. 6 Derivative operator. (Photo/Picture credit: Original)

Using these calculated values, the system's controller was subsequently designed and implemented. To verify the design's accuracy, circuit simulations were performed, with results aligning closely to the expected theoretical performance.

The circuit was simulated using the Falstad platform, and the observed performance was in close agreement with the simulation outcomes, confirming the robustness of the system. When the zero was positioned at -11, as depicted in Fig. 7, the system exhibited high levels of stability. Conversely, with the zero set at -12, as shown in Fig. 8, the results indicated a balance between stability and an enhanced response speed. This distinction underscores the varying system dynamics dependent on zero placement.

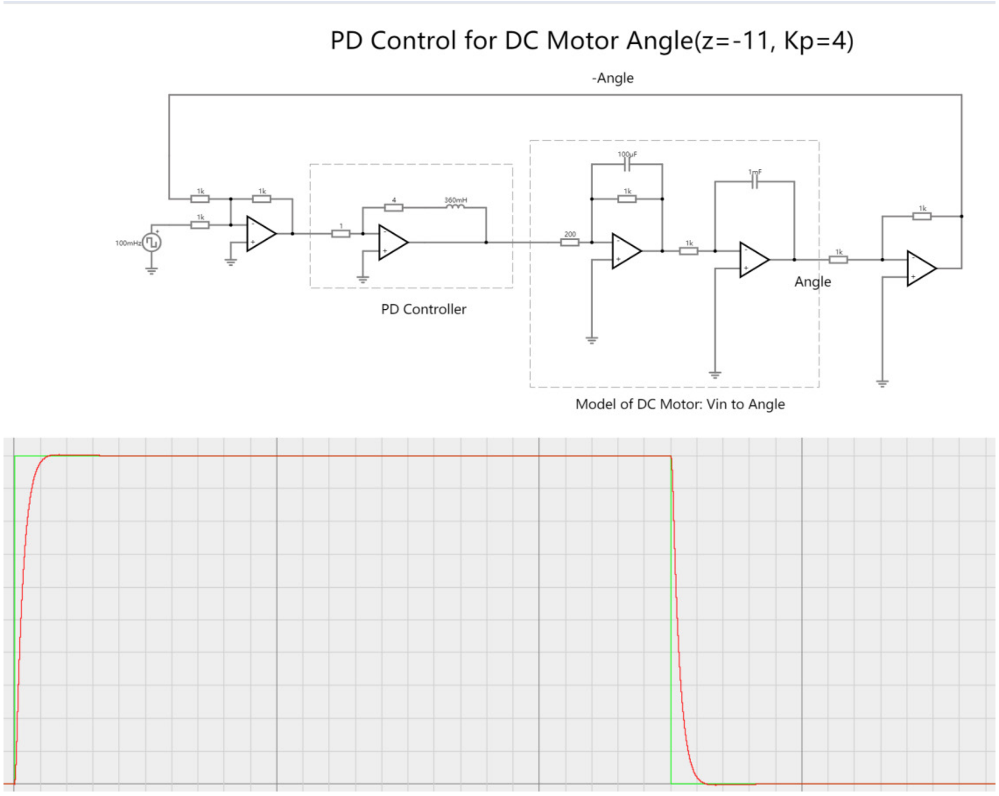

Fig. 7 PD Control System with the zero at -11. (Photo/Picture credit: Original)

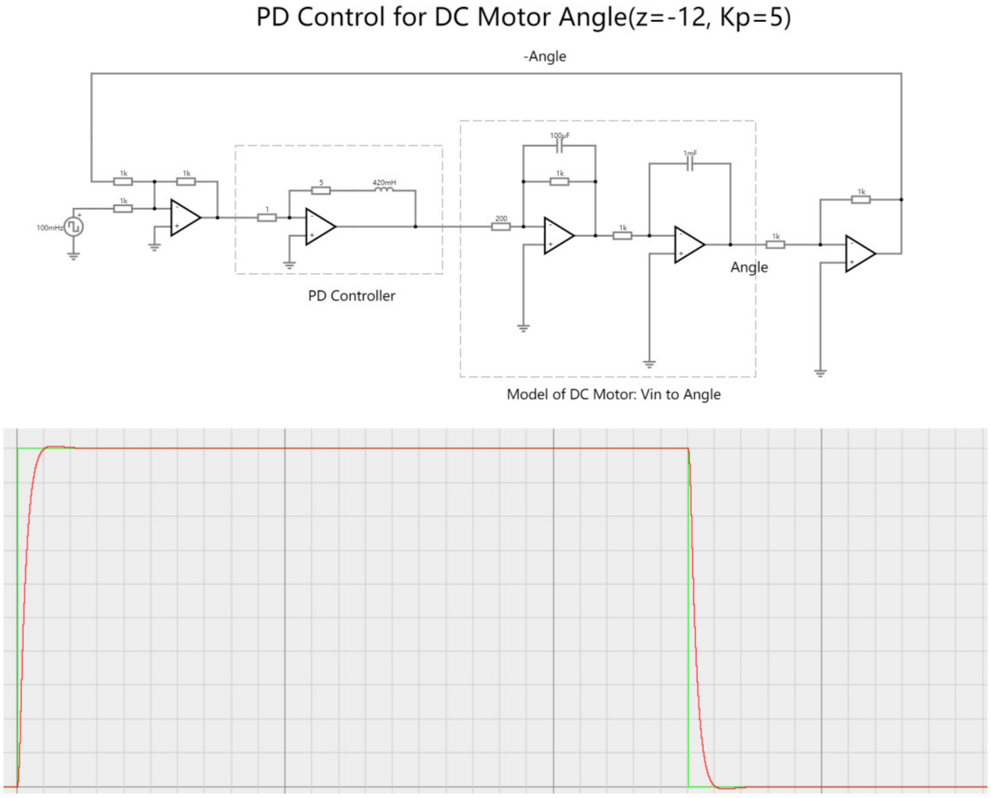

Fig. 8 PD control system with the zero at -12. (Photo/Picture credit: Original)

ISSN 2959-6157

4. Conclusion

This study evaluates the performance of controllers with different gain selections through root locus analysis, comparing simulations and verifying the actual performance. Based on the research findings, it is evident that there is an optimal range of zeros for both PI and PD control that provides superior performance. Specifically, within the range of low overshoot, there exists a corresponding range where the response speed is also relatively fast. In this study, for a common example with a 100 mHz signal, the optimal integer zero identified was -12, which can serve as a foundation for further exploration. This research deviates from the conventional approach of using a single PID controller for DC motors and instead employs PI and PD controllers separately to manage speed and angle, respectively. Future work could involve optimization techniques such as fuzzy logic to potentially achieve better performance than PID alone. The current study has a limited amount of data, and further optimization should focus on plotting function graphs for specific zeros and gain ratios to identify trends, thereby discovering more precise zeros and corresponding gains, moving beyond integer values. Additionally, testing and enhancing system robustness is also valuable. Although the root locus selection considered this aspect, there remains room for further optimization.

References

[1] Thanh D. C. and Huy D. N., Speed control of bldc motor using pi controller in MATLAB Simulink, J. Electrical Systems, 2024, 20, 9, 1125-1131.

[2] Fadaei M. H. K., Pahnehkolaei S. A. H., and Hesarlou M. J., Design of Hybrid Fuzzy-PD Controller for an Inverted Pendulum, Majlesi Journal of Mechatronic Systems, 2021, 10, 2, 21-27.

[3] Okoro I. S. and Enwerem C. O., “Robust control of a DC motor,” *Heliyon*, 2024, 10, 17, pp. 1-10,

[4] Li X., Shang D., Li H., and Li F., Resonant Suppression Method Based on PI Control for Serial Manipulator Servo Drive System, Science Progress, 2020, 103, 3, 1-39.

[5] Borase R P, Maghade D K, Sondkar S Y, et al. A review of PID control, tuning methods and applications. International Journal of Dynamics and Control, 2021, 9: 818-827.

[6] Lloyds Raja G, Ali A. New PI-PD controller design strategy for industrial unstable and integrating processes with dead time and inverse response. Journal of Control, Automation and Electrical Systems, 2021, 32: 266-280.

[7] Kumar V., Rana K. P. S., and Mishra P., Robust speed control of hybrid electric vehicle using fractional order fuzzy PD & PI controllers in Cascade Control Loop, Journal of the Franklin Institute, 2016, 353, 3-11.

[8] Mathe S E, Pamarthy A C, Kondaveeti H K, et al. A review on Raspberry Pi and its robotic applications. 2022 2nd International Conference on Artificial Intelligence and Signal Processing (AISP). IEEE, 2022: 1-6.

[9] Gao Z, Liu Y, Wang Z. On stabilization of linear switched singular systems via PD state feedback. IEEE Access, 2020, 8: 97007-97015.

[10] Soriano L A, Zamora E, Vazquez-Nicolas J M, et al. PD control compensation based on a cascade neural network applied to a robot manipulator. Frontiers in Neurorobotics, 2020, 14: 577749.