Drive and Control of DC Motor and its simulation

Haoheng Li
School of Automation
Beijing Instite of technology
Beijing, China
li_hheng@163.com 1120203107

***Abstract*—This paper investigates DC motor drive systems, focusing on single-loop and dual-loop speed control systems, and simulates their behavior using Matlab Simulink. Our aim is to analyze and compare the performance of these two types of DC motor drive systems.**

***Index Terms*—DC Motors, Matlab Simulink, Single-Loop Control System, Dual-Loop Control System, Performance Analysis.**

I. Introduction

DC motors are widely used in various industrial applications due to their simple structure, high efficiency, and easy controllability. The performance of DC motors depends on various factors such as the load, speed, and voltage applied to the motor. The control of DC motors is critical for their optimal performance, and it requires an accurate understanding of the motor's behavior under different conditions.

DC motor speed control systems can be categorized into two primary types: single-loop and dual-loop. Single-loop systems use a single feedback loop consisting of a speed sensor and a controller to adjust the motor's power supply based on the comparison of measured and desired speed. Although simpler and less expensive, single-loop systems may not provide the same level of accuracy and precision in speed control as dual-loop systems, which use two feedback loops (inner loop for current and outer loop for speed) that work together to provide superior performance in terms of speed control and accuracy. However, dual-loop systems are more complex and expensive than single-loop systems.

In this paper, we will analyze the performance of two control systems above by simulating them in Simulink.

II. Motor parameters and design requirement

The PWM-based dual close loop speed regulation system with the following parameters:

- DC motor:$U_N = 220V$, $I_N = 136A$, $n_N = 1460rpm$, $R_a = 0.2\Omega$, $\lambda = 1.5$;
- PWM-based source: $T_s = 0.0167s$, $K_s = 40$;
- Resistance in armature circuit: $R = 0.5\Omega$;
- Inductance in armature circuit: $L = 15mH$;
- $GD^2 = 22.5N \cdot m^2$;
- Current feedback coefficient:$\beta = 0.05$V/A;
- Speed feedback coefficient:$\alpha = 0.007V/rpm$;
- Time constants of filters:$T_{oi} = 0.002s$, $Y_{on} = 0.01s$.

Control system design requirement:

1) design a single loop speed regulation system with no steady error.
2) design a dual loop speed regulation system with:
   a) No steady error;
   b) overshoot in current $\sigma_i \leq 5\%$;
   c) overshoot in speed $\sigma_n \leq 10\%$;
3) 2-level PWM source is used and all the modulation methods can be taken except carrier phase-shifted.

III. Theorertical analysis

A. Mathematical Model of a DC Motor

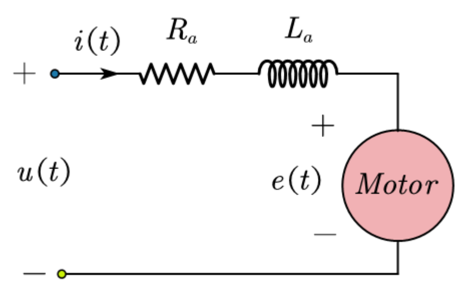

Fig. 1. Simplified Model of a DC Motor

For analytical purposes, we simplify the complex structure of the DC motor into the model depicted in Fig. 1 [1]. The simplified model allows us to capture the essential features of the DC motor. Based on the fundamental characteristics of DC motors, we derive the following transfer function:

$$G(s) = \frac{1/C_e}{T_m T_l s^2 + T_m s + 1} \tag{1}$$

In (1), $G(s)$ represents the transfer function that characterizes the behavior of the DC motor; C_e is the electromotive force (EMF) constant; T_m stands for the electromechanical time constant; and T_l is the time constant of the armature circuit.

Based on Fig. 1, it can be observed that, neglecting viscous friction and elastic torque, the equations governing the balance of armature circuit voltage and the dynamic behavior can be derived as follows:

$$\begin{cases} u = r_a i + L_a \frac{\mathrm{d}i}{\mathrm{d}t} + e \\ T - T_L = \frac{GD^2}{375}\frac{dn}{dt} \end{cases} \tag{2}$$

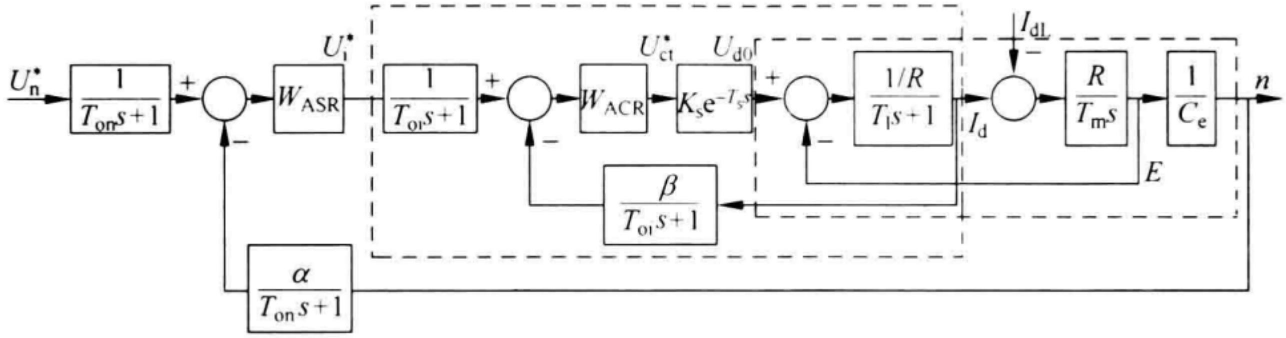

Fig. 2. Dual-loop speed control block diagram

B. Design of ACR

Fig. 2 shows the block diagram of dua-loop speed control system.

Reference [2] shows the design process of current regulator(ACR) and speed regulator(ASR).

The design requires no static error in the current loop, so we need integral part in the ACR. There's no integral part in current loop, thus, we have to calibrate the current loop to a typical $Type\ II$ system. We choose PI regulator to realise our ACR disign, whose transfer function is:

$$W_{ACR}(s) = \frac{K_i(\tau_i s + 1)}{\tau_i s} \tag{3}$$

The current open loop transfer function is:

$$W_{opi}(s) = \frac{K_i(\tau_i s + 1)}{\tau_i s} \frac{\beta K_s / R}{(T_l S + 1)(T_{\Sigma_i} s + 1)} \tag{4}$$

In the process of calibrating to a $type\ I$ system, one can apply the principle of pole-zero cancellation. This principle allows for the cancellation of the terms in the numerator $\tau_i s{+}1$ with the high-inertia terms in the denominator $T_l s + 1$. As a result, the response speed of the system can be improved. Therefor, $\tau_i = T_l = \frac{L}{R} = 0.03s$ [3]. To satisfy the requirement $\sigma_i \leq 5\%$, we should design $K_{op,i} T_{\Sigma_i} = 0.5$. Therefore,

$$T_{\Sigma_i} = T_s + T_{o_i} = 0.0036s$$
$$K_{\text{op.i}} = \frac{1}{2T_{\Sigma_i}} = \frac{1}{2 \times 0.00367} = 136.2\text{s}^{-1}$$

After this, we can obtain the proportional gain of PI controller is

$$K_i = \frac{K_{op.i} \tau_i R}{\beta K_s} = 1.022$$

Finally, in the process of correcting the current loop into a Type-I system, the effects of the changes in back electromotive force on the current loop and the non-linear factors of the PWM converter have been overlooked. Additionally, the current loop has been treated as a small inertia link. Therefore, it is necessary to conduct an approximate verification for each individually. Only when the conditions for approximate treatment are satisfied will the above analysis hold true. For detailed calculations and conditions for the approximation, please refer to [3]. Upon calculation, this design uniformly satisfies the aforementioned approximate processing conditions. Upon calculation, this design uniformly satisfies the aforementioned approximate processing conditions.

C. Design of ASR

Given the requirements for zero steady-state error in the design, it is necessary for the speed regulator to include an integral link. Taking into account the dynamic requirements, the speed regulator should adopt a Proportional-Integral (PI) controller, designed according to a typical Type II system for speed control loop:

$$W_n(s) = \frac{K_n \alpha R (\tau_n s + 1)}{\tau_n \beta C_n T_m s^2 (T_{\Sigma_n} s + 1)} = \frac{K_{op,n}(\tau_n s + 1)}{s^2 (T_{\Sigma_n} s + 1)} \tag{5}$$

The transfer function of the speed regulator is represented by the following equation:

$$W_{\text{ASR}}(s) = \frac{K_n(\tau_n s + 1)}{\tau_n s} \tag{6}$$

Considering both dynamic disturbance rejection performance and startup dynamic performance comprehensively, the mid-frequency bandwidth h=5 is comparatively better. According to the γ_{max} criterion, the lead time constant of ASR is:

$$\tau_n = h T_{\Sigma_n} = 5 \times 0.01734 = 0.0867s$$

The open loop gain for speed loop is:

$$K_{\text{op.n}} = \frac{1}{h\sqrt{h} T_{\Sigma n}^2} = \frac{1}{5 \times \sqrt{5} \times 0.01734^2} = 297.5s^{-2}$$

The proportional constant for ASR is :

$$K_n = \frac{\beta C_e T_m}{\sqrt{h} \alpha R T_{\Sigma_n}} = 8.75$$

After completing all parameter calculations, it is necessary to verify whether the conditions for simplifying the current loop transfer function and the small time constant approximation of the speed loop are met. If these conditions are not satisfied, the aforementioned design method would not be applicable.

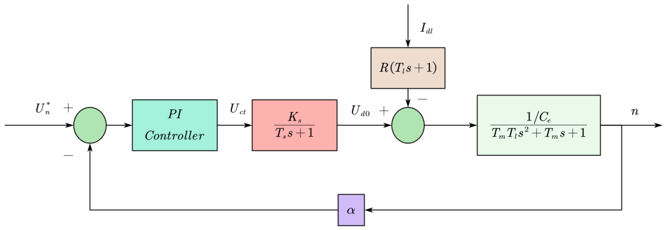

Fig. 3. Single-loop speed control block diagram

IV. Single close loop speed regulation system simulation

A. Simulation modeling

Based on the block diagram shown in Fig. 3, we model the single-loop speed control system in Simulink, as displayed in Fig. 4. The complete model comprises three primary parts: the controller and PWM gate signal generator based on control signal (located at the bottom left), the power source driven by a full bridge converter (located at the top left), and the DC motor to be controlled (on the right). Our design is implemented

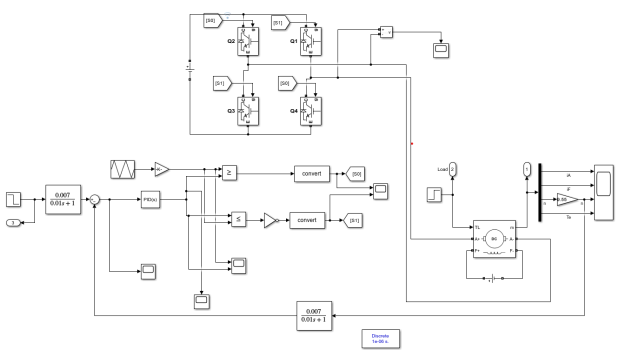

Fig. 4. Single-loop speed control Simulink model

based on ode3 simulation algorithm, and we conduct our study with a sampling period of 1 microsecond (1e-6s). The simulation spans from t = 0s to t = 6s. A rated constant torque load, simulated with a step signal, is introduced at t = 4s. The reference speed undergoes a step change from 1460rpm to 500rpm at t = 3s, allowing us to examine the system's adaptability to sudden load and speed changes.

B. Analysis of Results

Upon executing the simulation, we gathered data and produced graphical representations of the speed, torque, and armature current responses of the single-loop speed control system.

Fig. 5 showcases the speed response of the single-loop speed control system. The system's speed response overshoot is 5.1% which meets the requirement $\sigma \leq 10\%$. The rise time is 0.13s. The settling time is 0.48s.

The torque response of the single-loop speed control system is depicted in Fig. 6. This representation allows us to assess how the torque varies over time.

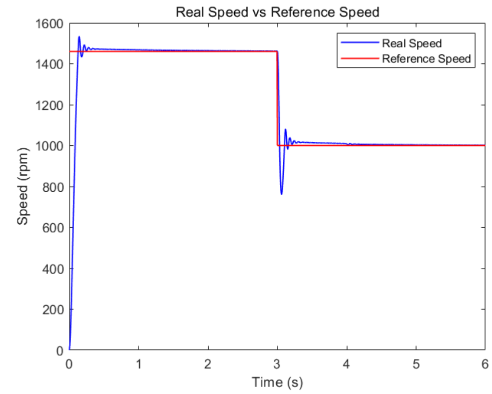

Fig. 5. Speed response of the single-loop speed control system

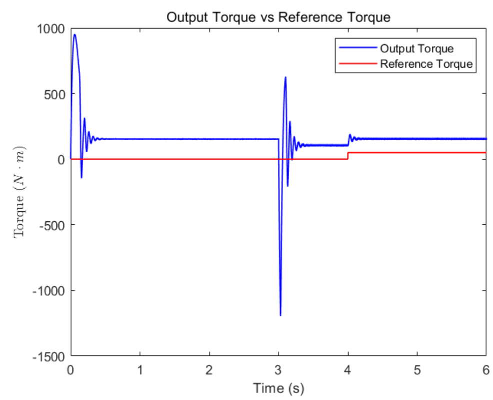

Fig. 6. Torque response of the single-loop speed control system

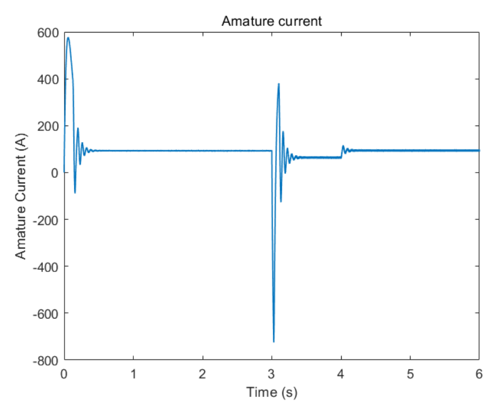

Fig. 7. Armature current response of the single-loop speed control system

Lastly, Fig. 7 illustrates the armature current response of the single-loop speed control system.

In single-loop speed control systems, excessive current overshoot during startup can potentially harm the DC motor. To mitigate this, current-limiting strategies can be applied, such as incorporating current cutoff negative feedback. Alternatively, a dual-loop DC speed control system can be adopted, which will be discussed in the following section.

V. Dual close loop speed regulation system simulation

In order to exert speed and current negative feedback receptivity in the system, they will not mutually restrain and affect the property of the system, and set up two regulators in the system, and adjust speed and current respectively, implement cascade connections between the two. That is to say, we regard the output of speed regulator as the input of current regulator and then the output of current regulator control the initiating device of silicon controlled rectifier. From the outer structure of the closed- loop feedback, the current adjustment loop in the inside loop, known as the inner loop; speed adjustment loop on the outside, known as the outer loop. This formed a double-closed-loop speed system of DC motor. In order to obtain good static and dynamic performance, the two regulators of double closed-loop speed systems of DC motor adopt generally PI regulator [4].

A. Establishment of the current loop

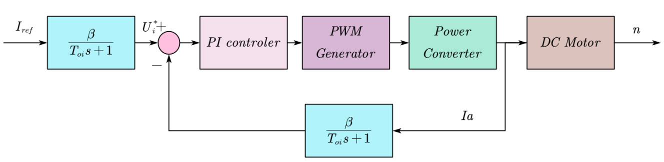

Fig. 8. Block diagram of current loop

1) Simulation modeling: The design goal within the current loop is to notably reduce or entirely eliminate armature current overshoot during dynamic operations while ensuring robust disturbance rejection. This requires precision in designing and tuning the current control system. Fig.8 displays the block diagram of the current loop. Guided by this diagram, we first construct the current loop, known as the inner loop, depicted in Fig.9 [5].

We employed the VariableStepAuto algorithm for our design implementation. The simulation timeline ranges from t = 0s to t = 6s, with a reference current change from 136A to 50A introduced at t=3s.

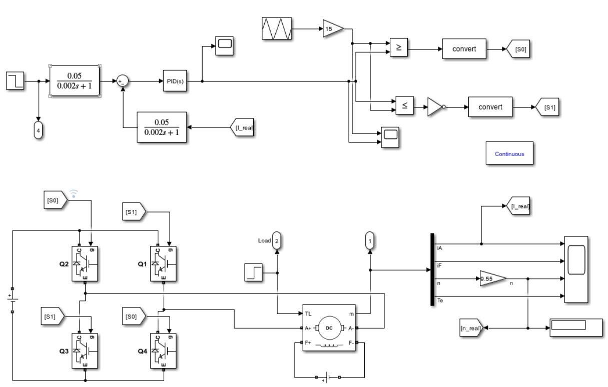

Fig. 9. Simulink model of current loop

2) Analysis of Results: The simulation execution allowed us to gather data and produce a visual representation of the system's current response. The step response to the rated current (136A) is presented in Fig. 10, demonstrating an overshoot of 4.91% and a settling time of 2.1s.

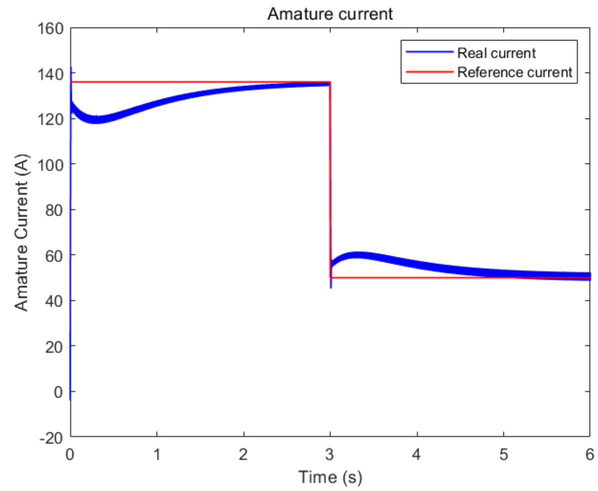

Fig. 10. Step response of current loop

B. Establishment of the speed loop

1) Simulation modeling: To construct the speed loop, we derive our model from Fig. 2, and results a Simulink model shown in Fig. 11.

Our design is implemented based on ode3 simulation algorithm, and we conduct our study with a sampling period of 1 microsecond (1e-6s). The simulation spans from t = 0s to t = 6s. The reference speed undergoes a step change from 1460rpm to 500rpm at t = 3s, allowing us to examine the system's adaptability to sudden load and speed changes.

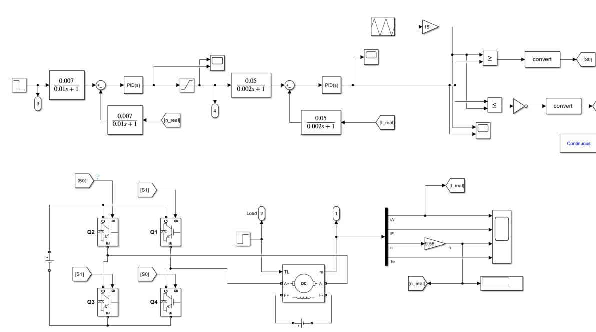

Fig. 11. Simulink model of dual-loop system

2) Analysis of Results: Upon executing the simulation, we gathered data and produced graphical representations of the speed, torque, and armature current responses of the dual-loop speed control system.

Fig. 12 showcases the speed response of the dual-loop speed control system. The system's speed response overshoot is 5.5%

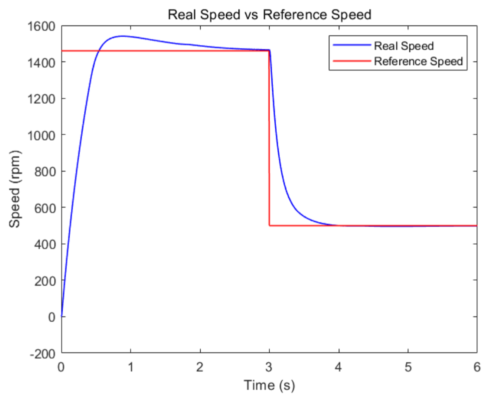

Fig. 12. Speed response of the dual-loop speed control system

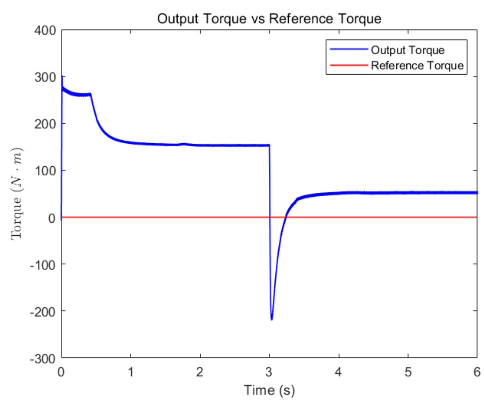

Fig. 13. Torque response of the dual-loop speed control system

which meets the requirement $\sigma \leq 10\%$. The rise time is 0.54s. The settling time is 2.18s.

The torque response of the dual-loop speed control system is depicted in Fig. 13. This representation allows us to assess how the torque varies over time.

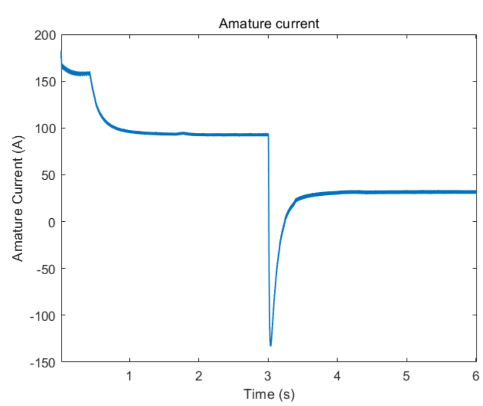

Fig. 14. Armature current response of the dual-loop speed control system

Lastly, Fig. 14 illustrates the armature current response of the single-loop speed control system. It's noticeable that the armature current in the range of maximum current: $\lambda \times I_a = 204A$.

VI. Difference in Performance of Single and Dual Loop Systems

A single-loop control system for a DC motor focuses solely on speed regulation. Here, the speed of the motor is constantly measured and fed back to the controller. The controller then compares the actual speed with the reference speed to generate an error signal, which is used to adjust the control action, voltage in our design, sent to the motor.

A dual-loop control system, on the other hand, incorporates a second loop for current control. This system is also known as a cascade control system. Here, the speed controller outputs a reference current instead of voltage. This reference current is then compared with the actual motor current in the current controller to generate a control action.

The dual-loop system provides better control of the motor because it can manage both speed and current independently. The outer loop controls the speed, and the inner loop controls the current, ensuring the current doesn't exceed a safe value during start-up or high load conditions. Fig. 15 shows the difference of step response between single-loop and dual-loop speed control system. The corresponding current is shown in figure 16.

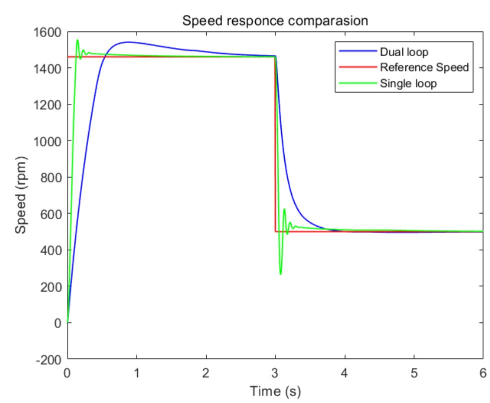

Fig. 15. Speed response comparison

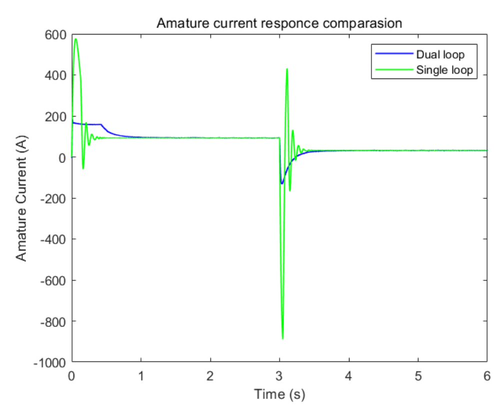

Fig. 16. Current response comparison

The Single-Loop Speed Control System for a DC motor, focusing solely on speed regulation, is simpler to design and implement, making it sufficient for applications requiring primarily speed control and experiencing minimal load variations. However, it struggles with sudden load changes and may allow excessive current draw during startup or high load conditions, potentially damaging the motor. On the other hand, the Dual-Loop Speed Control System, which independently controls both speed and current, offers better adaptability to sudden load changes and motor protection by limiting armature current. However, this system is more complex, harder to design, and potentially costlier due to the requirement of two different control strategies and controllers.

VII. Conclusion

This study has presented a comprehensive comparison between the Single-Loop and Dual-Loop Speed Control Systems for DC motors. Through in-depth simulation modeling and results analysis, we have demonstrated the distinctive attributes of each system and how they influence system performance under varying conditions.

The Single-Loop Speed Control System, with its emphasis on speed regulation, has proven to be relatively straightforward to design and implement. It has displayed sufficient performance for applications where speed control is a dominant requirement, and load variations are minimal. However, its performance can falter when encountering sudden load changes, leading to potential issues like excessive current draw during motor startup or under high load conditions, which can contribute to motor damage.

In contrast, the Dual-Loop Speed Control System, which controls both speed and current independently, has shown superior adaptability to sudden load changes. It provides improved motor protection by effectively limiting armature current, thus mitigating the risks associated with the Single-Loop system. Nevertheless, this system is more complex to design and potentially more expensive to implement due to the necessity of two separate control strategies and controllers.

In conclusion, the choice between Single-Loop and Dual-Loop Speed Control Systems hinges on the specific application requirements and constraints, such as the importance of speed control, the predictability of load changes, the budget, and the need for motor protection. While the Single-Loop system might be adequate in simpler applications, the Dual-Loop system offers robust performance and motor protection in more complex or demanding applications. Future studies could focus on optimizing the design and cost-effectiveness of Dual-Loop systems, and exploring advanced control strategies that might combine the advantages of both systems.

References

[1] L. Y. S. R. F. X. . G. L. Cheng Zhijiang, Xie Yongliu, "Simulation of current-tracking pwm dc motor dual closed-loop speed control system," *Hydropower*, vol. 41, no. 56-59+90, 2015.

[2] J. C. amp; Lei Wang, "Dynamic simulation of double closed-loop speed control system of dc motor," *Digital Technology and Applications*, vol. 40, no. 29-31, 2022.

[3] G. Yang and Y. Luo, *Electrcal Machinery adn Motion Control System*. No. 147-149, Tsinghua University Press, 2014.

[4] X.-k. Wang, Z.-l. Sun, L. Wang, and S.-p. Huang, "Simulation and optimization of parameters on dc motor double closed-loop control system based on simulink," in *2009 International Conference on Intelligent Human-Machine Systems and Cybernetics*, vol. 1, pp. 153–155, 2009.

[5] R. S. RAMAKRISHNAN, "Closed loop control of dc motor." https://ww2.mathworks.cn/matlabcentral/fileexchange/87774-closed-loop-control-of-dc-motor, 2023. [Online; accessed June 17, 2023].