Improving Electric Vehicle Performance Through Analyzing and Applying PI Control for Torque Regulation

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Abstract. Efficient control of torque in Electric vehicles (EVs) is crucial for achieving optimal performance, enhancing energy efficiency, and ensuring a smooth driving experience. The development of effective control strategies for electric vehicle torque control has become an active area of research and development in the field of electric mobility. This paper explores the theory and application of PI control in the context of electric vehicle torque control. The design and simulation of a control system using Falstad software are presented, along with the corresponding circuit diagrams and output waveforms. The study investigates the impact of different proportional (K_P) and integral (K_I) control parameters on the performance of the control system. The results demonstrate the trade-off between control accuracy, overshoot, and steady-state error elimination. Furthermore, the paper discusses the limitations of proportional-integral (PI) control in electric vehicle applications and provides an outlook on potential alternatives such as proportional-integral-derivative (PID) control, neural networks, and fuzzy control. The findings of this study contribute to advancing the understanding of torque control in electric vehicles.

Keywords: PI control; Electric vehicles; torque control.

1. Introduction

Electric vehicles (EVs) have gained significant popularity due to their environmental benefits and potential to reduce dependence on fossil fuels [1]. The efficient operation of an EV relies on effective torque control, with proportional-integral (PI) control being a widely used approach in control systems [2].

This paper investigates the theory and simulation of PI control for electric vehicle torque control, analyzing the impact of different control parameters on system performance. Section 2 delves into the theory behind electric vehicle operation, with a focus on the crucial aspect of torque control. Understanding the principles and mechanisms of torque control is essential for effective electric vehicle performance and control system design. The simulation experiment conducted using Falstad software is presented in section 3. It includes an introduction to Falstad, the system design scheme, circuit diagrams with varying proportional and integral parameters, and the simulation output waveforms. The analysis explores the impact of different control parameters on the speed regulation of a DC motor. Section 4 discusses the limitations of PI control in electric vehicle applications and presents prospects for future research. It highlights the need for adaptive control strategies to handle varying operating conditions and disturbances. Furthermore, it explores the potential of proportional-integral-derivative (PID) control, neural networks, and fuzzy control as alternatives to further enhance the control performance of electric vehicles.

2. Theoretical Background

2.1. Electric Vehicle Operation Principles

The operation of electric vehicles relies on precise control of various parameters, with torque control being a critical aspect. Electric vehicles typically use electric motors as their propulsion systems, and the control of these motors plays a crucial role in determining the vehicle's performance and efficiency. The torque produced by the motor directly affects the acceleration, speed, and overall

dynamics of the vehicle [3]. Therefore, understanding the principles of electric vehicle torque control is essential for designing effective control systems.

The torque control of electric vehicles involves regulating the output torque of the electric motor based on the desired performance requirements [4]. The control system needs to ensure that the torque generated by the motor matches the driver's input and the vehicle's operating conditions. By accurately controlling the torque, various driving characteristics, such as acceleration, deceleration, and regenerative braking, can be precisely managed.

2.2. Principles of PI control

PI control, which stands for proportional-integral control, is a widely adopted control strategy in various engineering applications, including electric vehicle torque control [5]. PI control combines proportional control and integral control to achieve effective control performance.

Proportional control involves adjusting the control output based on the proportional relationship between the error signal and the control action. In the context of torque control, the error signal represents the difference between the desired torque (set value) and the actual torque output by the motor. The proportional controller multiplies this error signal by a proportional gain (K_P) to determine the control action. A higher K_P value results in a more significant adjustment in the control output, aiming to reduce the error more rapidly.

Integral control, on the other hand, focuses on the accumulated error over time. It continuously integrates the error signal and multiplies it by an integral gain (K_I) to determine the control action. The integral control component helps to eliminate steady-state errors by continuously adjusting the control output based on the cumulative error. Increasing the K_I value increases the integral action, enabling faster elimination of steady-state errors but also potentially leading to overshoot and instability if not properly tuned.

$$P(s) = \frac{\omega}{v}. \tag{1}$$

$$C(s) = K_P + \frac{K_I}{S} = \frac{K_P(S+\frac{K_I}{K_P})}{S} = \frac{K_I((\frac{K_P}{K_I}S)+1)}{S}. \tag{2}$$

$$syscl = \frac{PC}{1+PC}. \tag{3}$$

By combining proportional and integral control, PI control provides a balanced approach that can effectively respond to both instantaneous and accumulated errors. Proportional control provides a fast response to reduce the error rapidly, while integral control helps eliminate steady-state errors and improve the system's overall accuracy and stability.

Overall, PI control is widely used in electric vehicle torque control due to its simplicity, effectiveness, and ease of implementation. However, to achieve optimal performance, it is essential to carefully tune the proportional and integral gains based on the specific characteristics of the motor and the desired control objectives. An image used to briefly explain PI control is shown in figure 1.

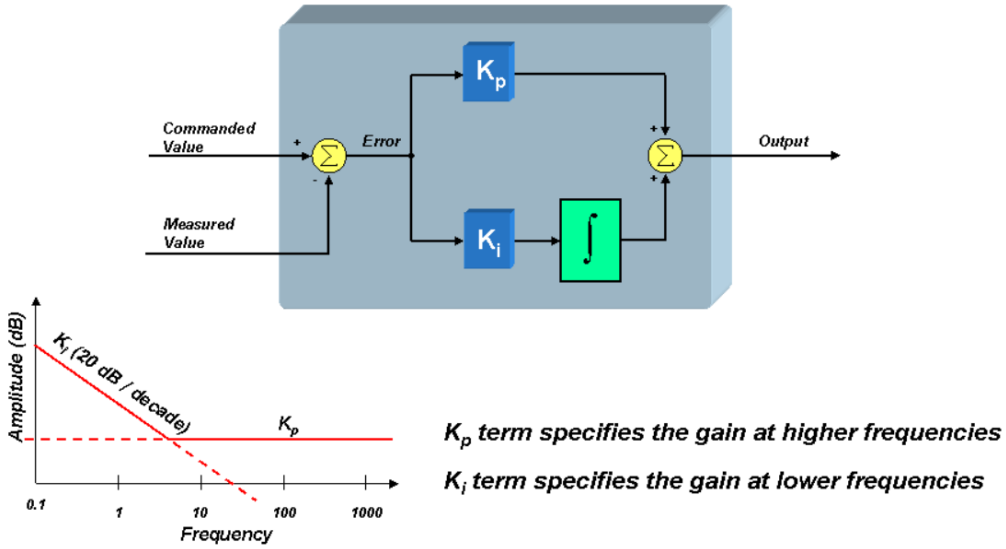


Fig. 1 PI control explanation (Photo/Picture credit: Original)

3. PI control Simulation using Falstad

3.1. Introduction to Falstad

Falstad is a simulation software used for circuit design and analysis. In this study, Falstad is employed to simulate the PI control system for electric vehicle torque control. This section provides a brief introduction to Falstad and its application in the study.

3.2. System Design Scheme

Figure 2 is the control system loop of this simulation experiment. The control system is composed of a proportional control link, an integral control link, two adders, and a mathematical model of a DC motor. The error e(t) between the input set value and the actual value passes through the proportional controller and the integral controller respectively, and the sum of their output quantities is added as the final control quantity to control the speed of the motor, and finally the actual speed value output by the motor is fed back to the input terminal, and compared with the set value, a new error value e(t) is obtained until e(t) is equal to 0, so that the actual output is equal to the set value.

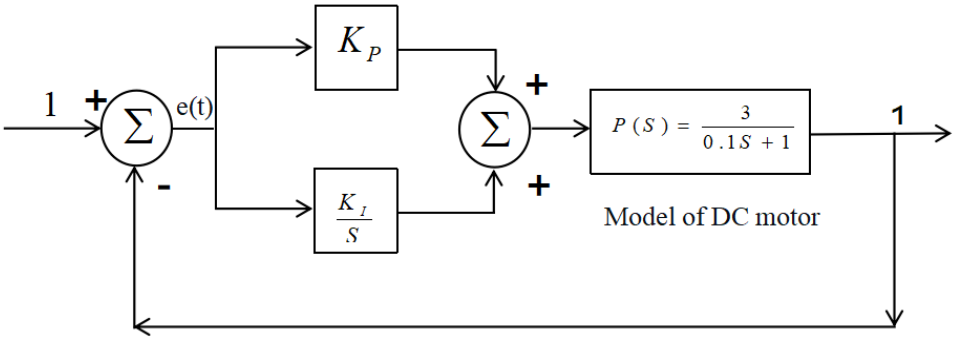


Fig. 2 The control system loop (Photo/Picture credit: Original)

3.3. System Parameters Setting

Table 1 sets three different sets of proportional and integral parameters for the simulation experiment. The K_P values are set to 0.15, 1.5, and 15 respectively, and the corresponding K_I values are respectively 3, 30, and 300. According to that $S = -\frac{K_I}{K_P}$ at zero point, set their zero points at S = -20.

Table 1. Three different sets of proportional and integral parameters

Group	Group 1	Group 2	Group 3
K_P	0.15	1.5	15
K_I	3	30	300
S	-20	-20	-20

3.4. Simulation Circuit Design

Three groups of circuit diagrams are given respectively, and the PI control loop composed of different K_P values and different K_I values is applied to the simulation of DC motor speed regulation, which is shown in figure 3, 4 and 5. The first stage of the circuit is an adder, the second stage is composed of a proportional controller and an integral controller, and the third stage is an adder and a DC motor mathematical model transfer function. The same part of the three groups of circuits contains five operational amplifiers and six 1K resistors, a 10K resistor, two 20K resistors, a 60K resistor, a square wave signal generator, the output voltage amplitude of the square wave signal generator is set to 500mV, the DC offset is 500mV, and the final output voltage peak value is 1V. Different parts of the three groups of circuits are resistors and capacitors with different K_P and K_I values.

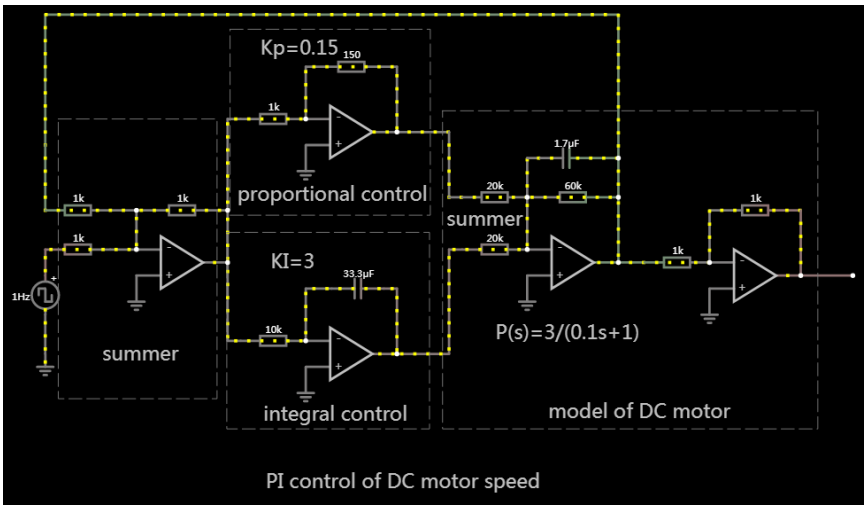


Fig. 3 Simulation circuit diagram when K_P = 0.15, K_I = 3, R = 150KΩ, C = 33.3μF (Photo/Picture credit: Original)

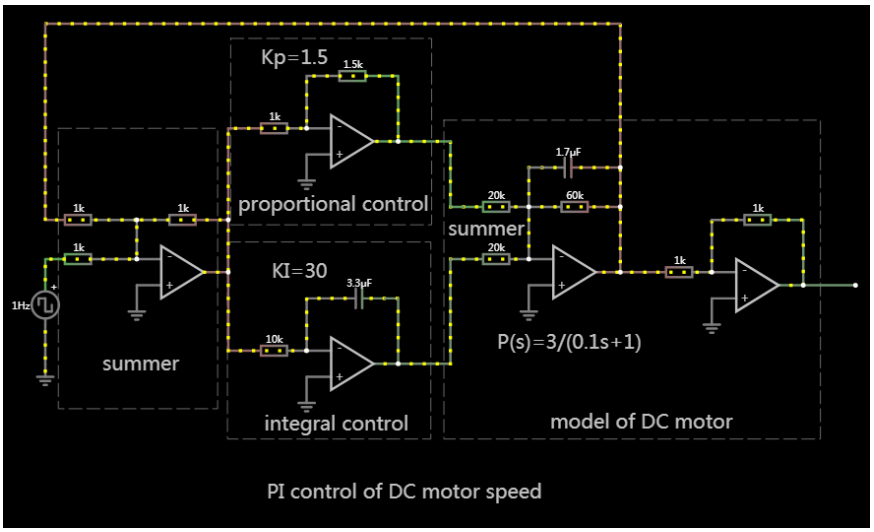


Fig. 4 Simulation circuit diagram when K_P = 1.5, K_I = 30, R = 1.5KΩ, C = 3.3μF (Photo/Picture credit: Original)

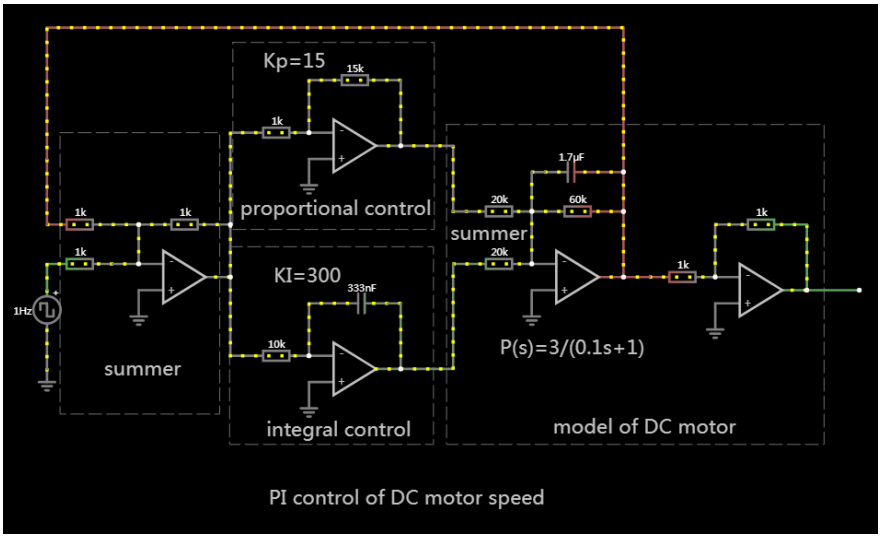


Fig. 5 Simulation circuit diagram when K_P = 15, K_I = 300, R = 15KΩ, C = 0.333μF (Photo/Picture credit: Original)

3.5. Circuit Simulation Output Waveform

Figure 6 shows the simulation results. In the output waveform, the PI control parameters corresponding to the purple curve are K_P = 0.15, K_I = 3, the PI control parameters corresponding to the red curve are K_P = 1.5, K_I = 30, and the PI control parameters corresponding to the orange curve are K_P = 15, K_I = 300, where green is the input setting value represented by the square wave signal source with 1Hz and amplitude of 1V.

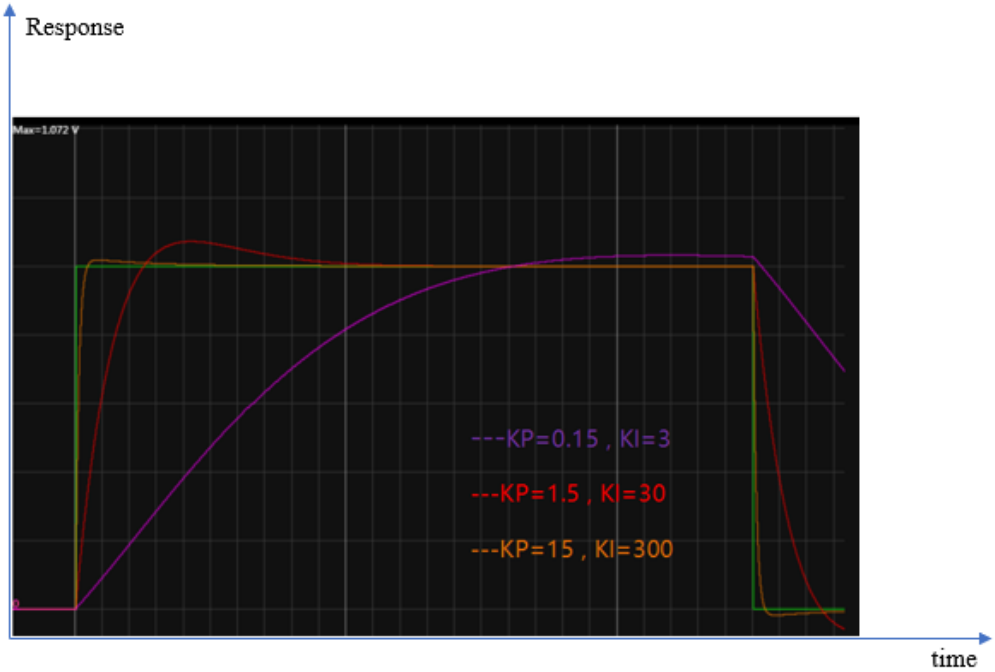


Fig. 6 The simulation results (Photo/Picture credit: Original)

3.6. Simulation Experiment Conclusion

Observing the output waveforms under the three groups of control parameters, it is found that different K_P and K_I control parameters have different rising rates, overshoots and steady-state error elimination time when the speed setting values are the same. As shown in Table 2.

Table 2. Different observation results

Group	K_P	K_I	Observation Results
1	0.15	3	The curve changes slowly, the output overshoot is in the middle, the steady-state error can be eliminated for the longest time, and the system stability is the worst.
2	1.5	30	The curve change speed is in the middle, the output overshoot is the largest, the steady-state error elimination time is in the middle, and the system stability is in the middle.
3	15	300	The fastest curve change speed, the smallest output overshoot, the shortest steady-state error elimination time, and the best system stability.

For proportional control, the output of the controller is proportional to the input error signal. When there is an error in the system output, the proportional adjustment immediately produces a certain ratio of adjustment to reduce the deviation. The larger the ratio K_P, the faster the adjustment speed, and the error will be reduced rapidly. Excessive K_P value will cause a large overshoot of the system, and even cause oscillation. When there is only proportional control, there will be steady-state errors that cannot be eliminated in the system output.

For integral control, its output is proportional to the integral of the input error signal. The amount of error increases with time, so that even if the error is small, the steady-state error will further decrease until it is equal to zero. The larger the K_I, the faster the integral speed, the greater the integral output, and the faster the steady-state error can be eliminated. However, too strong integral action will aggravate the overshoot and even cause oscillation.

For PI control, only by selecting the appropriate K_P and K_I control parameters, can the overshoot be reduced, the output be stabilized quickly, and the steady-state error be eliminated quickly, thereby improving the control accuracy.

4. Limitations and Prospects

4.1. Limitations of Electric Vehicle PI Control

While PI control has proven to be an effective strategy for electric vehicle torque control, it does have certain limitations that should be acknowledged and addressed. Understanding these limitations can guide future research and development efforts to further enhance the control performance of electric vehicles.

One limitation of PI control is its inability to adapt to varying operating conditions and disturbances. The control gains, K_P and K_I, are typically set based on steady-state conditions or nominal operating points. However, the performance of an electric vehicle can be affected by factors such as changes in road conditions, variations in battery voltage, and thermal effects on motor performance [6]. These factors can introduce uncertainties and disturbances that may challenge the effectiveness of the fixed PI control gains. To overcome this limitation, advanced control techniques that incorporate adaptive or robust control algorithms could be explored. These techniques can dynamically adjust the control gains based on real-time system conditions, ensuring optimal control performance under varying operating conditions [7].

Another limitation of PI control is its potential for overshoot and oscillations, especially when the system is subject to sudden changes or disturbances. The integral action, designed to eliminate steady-state errors, can lead to an excessive response, and cause the system to overshoot its desired set value. Additionally, if the control gains are not properly tuned, the integral action can introduce oscillations and instability [8]. To mitigate these issues, more advanced control strategies such as PID control could be considered. PID control incorporates derivative action, in addition to proportional and integral actions, to improve control response and damping characteristics. By carefully tuning the derivative gain, the system's transient response can be improved, reducing overshoot and oscillations.

4.2. Exploring Advanced Control Strategies for Electric Vehicle Torque Control

To overcome the limitations of PI control and further enhance the control performance of electric vehicles, researchers have explored alternative control strategies that offer increased robustness, adaptability, and improved control accuracy. Two potential avenues for future research are PID control and the application of advanced control techniques such as neural networks and fuzzy control.

PID control extends the capabilities of PI control by introducing derivative control. The derivative action improves the system's response to changes in the error signal, enabling faster error reduction and better damping characteristics. The derivative gain (KD) can be adjusted to fine-tune the control system's response to transient conditions. The incorporation of derivative control can help mitigate overshoot, improve settling time, and enhance the overall stability and performance of the electric vehicle control system. However, it is important to note that PID control may introduce additional complexity in terms of tuning the control gains, and careful consideration should be given to avoid overcompensation or instability.

Beyond PID control, emerging technologies such as neural networks and fuzzy logic offer promising opportunities for electric vehicle control [9]. Neural networks have the capability to learn and adapt to complex nonlinear relationships within the control system. By training a neural network with appropriate data, it can effectively model the dynamic behavior of the electric vehicle and provide accurate control actions. Fuzzy logic, on the other hand, allows for rule-based control that can handle uncertainties and imprecise information. Fuzzy control systems can accommodate linguistic variables and expert knowledge to make control decisions, thereby improving the system's robustness and adaptability.

These advanced control techniques hold potential for enhancing the control performance of electric vehicles by addressing the limitations of traditional PI control. By combining the strengths of different control strategies and leveraging advanced algorithms, electric vehicle control systems can achieve higher levels of accuracy, robustness, and adaptability [10].

5. Conclusion

This paper provides an in-depth analysis and simulation of PI control for electric vehicle torque control. The study presents the theory and principles of PI control, implements a simulation experiment using Falstad software, and evaluates the impact of different control parameters on system performance. The findings demonstrate the trade-off between control accuracy, overshoot, and steady-state error elimination. The paper also discusses that while PI control is a widely used approach for electric vehicle torque control, it does have limitations that need to be considered. The exploration of alternative control strategies such as PID control, neural networks, and fuzzy control opens new possibilities for improving the performance of electric vehicle control systems. Overall, this work contributes to the understanding and advancement of torque control in electric vehicles.

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