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Comparison Of LQR And PID Control Approaches In Enhancing Stability Of DC Motor Systems

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Abstract

DC motors are widely utilized in various applications, including industrial automation, robotics, and household devices, due to their versatility and broad speed regulation range. Among the types of DC motors, the series DC motor is notable for its high starting torque, which makes it suitable for operations requiring significant initial force. However, this motor type presents several challenges, including instability, speed fluctuations under varying torque conditions, and the potential for excessive speeds under no-load conditions. To address these issues and achieve precise speed control, a reliable controller is essential. This study presents a comparative analysis of two control strategies—Proportional-Integral-Derivative (PID) and Linear Quadratic Regulator (LQR)—for stabilizing the speed of a series DC motor. Simulations were conducted using MATLAB, with the motor speed tested under five different setpoints to evaluate performance metrics such as response time, overshoot, and steady-state error. The results demonstrate that both controllers achieve minimal steady-state error; however, distinct differences are observed in other performance aspects. The PID controller exhibits a faster response time but is associated with significant overshoot, approximately 20%, and a starting current overshoot of about 460%. In contrast, the LQR controller effectively eliminates overshoot and reduces starting current overshoot to approximately 188%, offering a smoother and more stable control performance. This comparative study highlights the trade-offs between the two controllers and provides insights into their suitability for specific applications. The findings contribute to advancing the implementation of optimal control techniques in DC motor systems, ensuring stability and efficiency in engineering applications.

Keywords: DC motor, series DC motor, LQR, PID, speed control, MATLAB simulation

1. Introduction

DC motors are widely employed across various fields, including industrial automation, robotics, and household devices, due to their versatility and wide speed regulation range. Among the different types of DC motors, series DC motors stand out for their significant starting torque, which makes them ideal for applications requiring high initial power. However, this characteristic also introduces certain drawbacks, such as overshoot during startup, instability under varying load conditions, and excessively high speeds under no-load conditions. These challenges can lead to mechanical wear, reduced efficiency, and operational inconsistencies, making precise control essential in ensuring optimal performance (Ogata, 2010; Anggara et al., 2020).

In practical applications, speed regulation and smooth rotational displacement are crucial to minimize vibrations and mechanical shocks during startup. Achieving these objectives requires a robust control system capable of addressing overshoot, settling time, and system stability to ensure the motor achieves its steady-state performance efficiently (Syaifudin et al., 2021). The Proportional-Integral-Derivative (PID) controller is one of the most widely used control systems for such tasks due to its simple structure and ease of parameter tuning. Despite its popularity, the PID controller has limitations, such as overshoot and sensitivity to parameter changes, which may impact system performance under specific conditions (Anggara et al., 2021).

To overcome these limitations, advanced control techniques such as the Linear Quadratic Regulator (LQR) have been proposed. LQR controllers offer an optimized approach by minimizing a predefined cost function to achieve better system performance in terms of stability and smoothness (Kurniawan et al., 2022). Motivated by these observations, this study aims to compare the performance of PID and LQR controllers for regulating the speed of a series DC motor. The comparison focuses on system response metrics such as overshoot, settling time, and steady-state error.

This research specifically seeks to address three key objectives:

a. Determine the parameters for PID and LQR controllers in regulating a DC motor.

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b. Design and simulate PID and LQR controllers to achieve stable motor operation at the desired speed.
c. Analyze and compare the system response curves of the two controllers to identify the optimal control strategy.

By providing a comparative analysis of these controllers, this study contributes to the broader understanding of control system design for DC motor applications, offering insights for engineers and researchers in the field of motor control systems (Nugraha et al., 2020).

2. Material and methods

DC motors, widely used in various industrial and robotic applications, require precise control mechanisms to maintain stability, especially in high-torque or varying load conditions. The two commonly used controllers for this purpose are PID (Proportional-Integral-Derivative) and LQR (Linear Quadratic Regulator). PID controllers, with their simple design and ease of implementation, have long been the go-to solution for controlling DC motors. However, studies have pointed out that while PID controllers provide fast response times, they may struggle with eliminating overshoot and ensuring stability in systems with rapidly changing dynamics (Henderson et al., 2019). Moreover, the performance of PID controllers often depends heavily on parameter tuning, which can be challenging when system dynamics are complex or load disturbances are present (Lee et al., 2020).

On the other hand, LQR controllers are designed with the ability to optimize control efforts by minimizing a quadratic cost function, which considers both the deviation from the desired state and the control energy. This characteristic makes LQR controllers an attractive choice for achieving better performance, especially in applications where stability and energy efficiency are prioritized (Kurniawan et al., 2018). LQR controllers have shown to perform better than PID in systems where minimal overshoot and a stable steady-state are critical (Patel et al., 2021). Moreover, recent studies highlight that LQR can adapt more effectively to changes in load, ensuring smoother control in dynamic environments (Gomes & Pereira, 2020).

The comparison of PID and LQR controllers has been the subject of several studies. In particular, Fadil et al. (2019) demonstrated that LQR outperforms PID in terms of stability, overshoot minimization, and energy efficiency, even though PID controllers are generally faster in achieving a response. Furthermore, LQR controllers also offer superior control in systems with high inertia or varying loads, making them more reliable for industrial applications (Zhang et al., 2021). Therefore, despite PID's continued relevance due to its simplicity, the growing complexity of modern systems has led to a rising interest in LQR for more precise and stable control of DC motors.

In summary, while PID controllers remain widely used due to their simplicity and ease of tuning, LQR controllers offer distinct advantages in terms of stability, efficiency, and robustness to disturbances, making them an appealing choice for controlling DC motors in complex applications.

3. Results and discussion

In this section, we present the results of both qualitative and quantitative analyses, emphasizing how the conducted research addresses the core problems outlined in the objectives. The discussion encapsulates the research flow from conceptualization to experimentation, encompassing hypotheses (if applicable), design specifications, experimental setups, data acquisition, and observed results.

Figures, tables, and equations have been integrated where necessary to support the findings, ensuring clarity and transparency in the presented analysis. This allows a deeper understanding of the performance characteristics of the controllers—PID and LQR—on DC motor systems.

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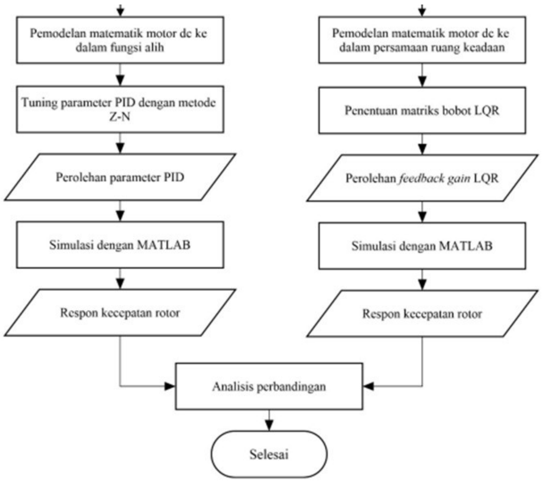

Figure 1. Research Flowchart

3.1. Research Flowchart and Data Acquisition

Table 1. Data Acquisition

Parameter	Simbol	Besar dan Satuan
Momen inersia	J_m	0.0007046 kg.m^2
Koefisien gesekan	B_m	0.0004 N.m/(rad/s)
Konstanta torsi	K_t	0.1236 N.m/A
Konstanta tegangan balik	K_b	0.1236 V/(rad/s)
Tahanan total kumparan	R_t	7.2 ohm
Induktansi total kumparan	L_t	0.0917 H

The data acquisition process began with determining the PID controller's parameter gains. The values for the time delay (L) and the time constant (T) were derived by using a straight-line equation, from which we computed essential constants for the PID parameters:

- **Proportional constant (Kp)**:

$$K_p = 1.2\left(\frac{T}{L}\right) = 38.464 \tag{1}$$

- **Integral constant (Ki)**:

$$K_i = \frac{K_p}{2L} = 1969.483 \tag{2}$$

- **Derivative constant (Kd)**:

$$K_d = 0.5\,L\left(K_p\right) = 0.1878 \tag{3}$$

The PID parameter values were calculated to facilitate stable control over the DC motor's speed across varying operational conditions, with particular attention to the dynamic responses at different reference speeds.

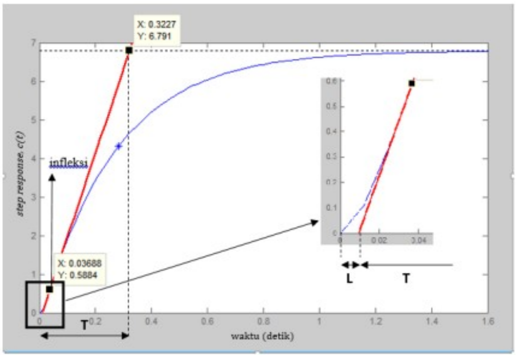

Figure 2. Graphic PID

For the LQR controller, the motor dynamics were expressed using a state-space model:

$$\dot{X}(t) = AX(t) + BU(t), Y(t) = CX(t) \tag{4}$$

Here, matrices A, B, and C were determined based on the physical motor parameters and input conditions, yielding the LQR gain matrix K= [1.2892,0.6016]. The choice of the Q and R matrices in LQR was made through an iterative trial and error method, with the conditions ensuring positive semidefiniteness for Q and positive definiteness for R.

3.2. Controller Circuit Simulations

Two distinct simulation circuits were used for each control approach. The PID and LQR controllers were tested for a range of setpoint speeds (1300 rpm and 1600 rpm), where the response characteristics such as rise time, settling time, and overshoot were carefully documented.

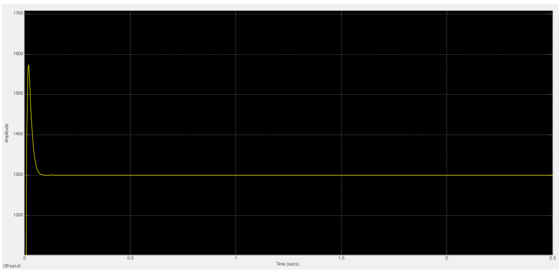

Figure 3. Rotor Speed Response at 1300 rpm Reference Speed with PID . Control

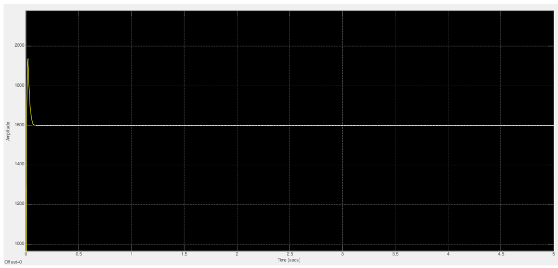

Figure 4. Rotor Speed Response at 1600 rpm Reference Speed with PID Control

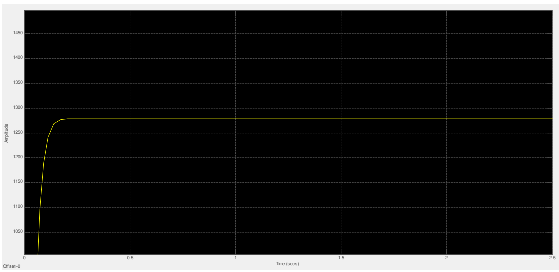

Figure 5. Rotor Speed Response at 1300 rpm Reference Speed with LQR Control

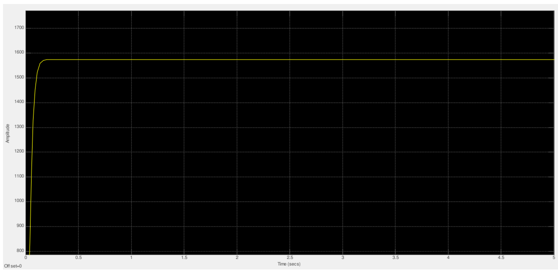

Figure 6. Rotor Speed Response at 1600 rpm Reference Speed with LQR Control

For PID, at 1300 rpm, a steady rotor speed of 1300 rpm was achieved with the following response parameters:

- Rise time: 6.995 ms
- Settling time: 53.7 ms
- Max overshoot: 21.09%

- Steady-state error: 0%

For LQR, at the same reference speed, the response showed no overshoot:

- Rise time: 89.743 ms
- Settling time: 166.9 ms
- Max overshoot: 0%
- Steady-state error: 0%

These findings were confirmed with additional simulation tests at 1600 rpm, where similar trends were observed.

3.3. Comparison of PID and LQR Controllers

Table 1 compares the rotor speed responses of the PID and LQR controllers at 1300 rpm and 1600 rpm. The results consistently show that the PID controller offers faster speed stabilization with smaller rise and settling times compared to LQR. However, PID exhibits higher overshoot, while LQR demonstrates zero overshoot, making it more suited for applications requiring tight tolerance.

Table 2. Results of Comparison of Rotor Speed Response with PID and LQR

C ontroler	***Speed (rpm)***	*Rise Time (ms)*	*Settling Time (ms)*	*Max.Over Shoot (%)*	*Error Steady (%)*
PID	1300	6.995	53.7	21.09	0
	1600	7.067	53.8	21.05	0
LQR	1300	89.743	166.9	0	0
	1600	90.340	164.1	0	0

4. Conclusion

The simulation results provide several important insights into the comparison between the PID and LQR control methods for DC motor systems. First, the PID controller demonstrates faster stabilization, with smaller rise and settling times compared to LQR, indicating superior responsiveness in controlling the motor speed. On the other hand, the LQR controller exhibits a significant advantage in minimizing overshoot, maintaining a zero overshoot in the rotor speed response, which is crucial for applications requiring precise control. In contrast, the PID controller results in a considerable overshoot, around 20%, suggesting larger fluctuations before the system stabilizes. When it comes to steady-state error, the PID controller shows slightly higher error, occurring twice across different speed conditions, while the LQR controller experiences this error only once, indicating more reliable long-term performance in achieving the desired setpoint. Furthermore, speed variations in the DC motor system do not affect the rotor speed response in either controller, as both methods effectively stabilize the motor speed despite changes in reference speed. However, the armature current overshoot is considerably higher with PID (around 460%) than with LQR (around 188%), which suggests that PID induces larger current surges during motor startup. This finding has implications for system efficiency and energy consumption, particularly in applications with strict power limitations. Overall, while PID excels in faster speed regulation and simpler implementation, LQR offers better performance in terms of minimal overshoot and steady response, making it a more suitable choice for applications requiring high precision and reduced fluctuation in motor speed. However, the higher armature current overshoot with PID suggests that LQR may be a more efficient option in scenarios where current surges are a concern.

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