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Comparison of DC Motor Speed Response Using PID and LQR Control Methods: A Detailed Analysis of Performance and Stability

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Abstract

DC motors are widely used in various applications, such as industry, robotics, and home appliances, due to their ease of use and broad speed control range. Among different types of DC motors, series DC motors are known for their high starting torque, which often leads to significant overshoot during startup. Additionally, series DC motors tend to be less stable, with speed variations influenced by torque fluctuations; they slow down under high torque and speed up during idle conditions. To achieve stable speed control and minimize overshoot, the use of an appropriate controller is essential. This paper presents a detailed comparative analysis of two control strategies—PID (Proportional-Integral-Derivative) and LQR (Linear-Quadratic Regulator)—for controlling the speed of a series DC motor. A simulation was conducted using MATLAB, with the motor speed controlled across four different speed setpoints. The results demonstrate that both controllers lead to minimal speed errors, with the PID controller offering faster rotor speed response times compared to LQR. However, while the PID controller exhibits some overshoot, the LQR controller effectively eliminates this issue. Additionally, the PID controller results in higher starting current compared to the LQR controller.

Keywords: Series DC Motor, LQR, PID, speed control, MATLAB

1. Introduction

DC motors are versatile devices widely employed in various domains such as industrial automation, robotics, and household appliances due to their ease of use and broad speed control range (Nugraha and Eviningsih, 2022). Among the different types of DC motors, series DC motors stand out for their high starting torque (Sheila et al., 2024). However, this characteristic often leads to significant overshoot during initial operation (Paluga et al., 2024). Additionally, series DC motors exhibit inherent instability, where high torque slows the motor down, and low torque accelerates it. These motors also tend to reach excessive speeds when operating under no-load conditions.

In many engineering applications, variable speed control is essential to meet operational demands (Almunawar et al., 2024). Moreover, precise adjustments to rotational transitions are crucial to minimizing vibrations and mechanical stresses, particularly during startup phases. To address these challenges, implementing a reliable and effective control system becomes imperative (Saputra et al., 2024).

Control systems are designed to address critical performance parameters such as overshoot, settling time, and system stability, ensuring that the motor transitions seamlessly to a steady-state operation (Fauzi et al., 2024). Among the most commonly used control methods is the Proportional-Integral-Derivative (PID) controller. Renowned for its simplicity and straightforward parameter tuning, the PID controller has been a cornerstone in motor speed control (Rahman et al., 2024). Nevertheless, alternative advanced control strategies, such as the Linear Quadratic Regulator (LQR), have demonstrated significant potential for optimizing stability and performance in more complex scenarios.

2. Material and methods

2.1. Motor DC

A machine that converts DC electrical energy into mechanical energy is commonly referred to as a DC motor. Its operation is based on the principle that a conductor carrying current experiences a mechanical force when placed in a magnetic field (Mu'in et al., 2023). DC motors are a critical component in various engineering applications, ranging from industrial automation to robotics, owing to their versatility and reliability.

a. Construction of a DC Motor

The basic structure of a DC motor can be broadly divided into two main components: the stationary part, known as the stator, and the rotating part, referred to as the rotor (Amrullah et al., 2023) . The stator provides the magnetic field necessary for motor operation, while the rotor interacts with this magnetic field to produce mechanical motion (Nugraha et al., 2024).

Figure 1 illustrates the detailed structure of the stator in a DC motor, and depicts the rotor's structural components. These structural diagrams are crucial for understanding the fundamental

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working principles and design considerations essential for developing advanced control systems in motor applications.

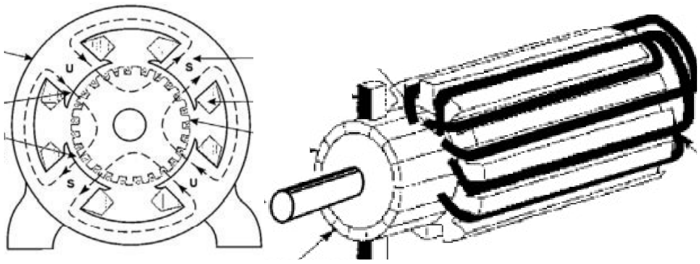

Figure 1. Motor DC

b. Working Principle of a DC Motor

The operation of a DC motor is rooted in electromagnetic principles. Every current-carrying conductor generates a surrounding magnetic field, whose direction can be determined using the right-hand rule. The strength of this magnetic field is directly proportional to the magnitude of the current passing through the conductor [3].

When a current flows from a DC voltage source through the armature windings, the armature behaves as an electromagnet. The interaction between the magnetic field of the stator and the magnetic field generated by the armature produces torque, causing the rotor to rotate. Figure 3 demonstrates the functional principle of a permanent magnet DC motor. The following stages describe its operation in detail:

- Position 1: Current flows from the positive to the negative brush. This creates a torque that rotates the motor counterclockwise.
- Position 2: At this point, the brushes are aligned with the neutral sections of the commutator. The current flow through the motor is interrupted, resulting in no torque generation. However, the rotor continues to spin due to inertia, passing beyond the neutral position.
- Position 3: The armature windings are now reversed compared to Position 1. The commutator switches the direction of the electron flow through the armature coils. Consequently, the direction of current in the armature windings matches that in Position 1, generating torque and continuing the counterclockwise rotation of the rotor.
- Neutral Point: At the neutral point, the inertia of the armature shaft ensures continuous rotation, allowing the motor to maintain its operation.

This cycle repeats continuously, ensuring a smooth and sustained rotational motion of the DC motor.

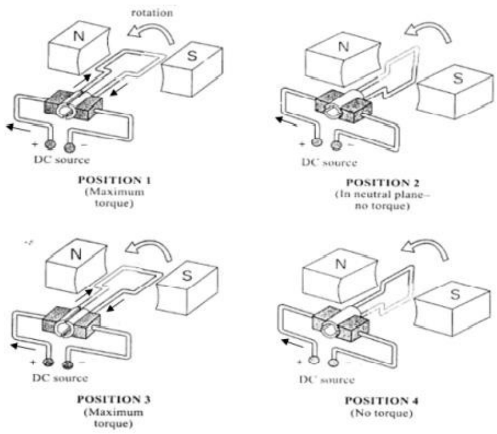

Figure 2. Motor DC Work principle

2.2. Linier Quadratic Regulator

The most effective control system is one that delivers the highest performance for a given set of reference conditions (Xiang and Wei, 2021). Achieving optimal control performance requires the application of well-defined optimization criteria that guide the system's response toward an ideal behavior, particularly when deviations occur during operation (Aremu et al., 2024). These criteria are quantified through the establishment of a performance index, which serves as a cost function representing how closely the system's actual performance aligns with its desired performance objectives (Maghfiroh et al., 2022). A lower value of the performance index indicates a more optimal control system. Thus, the performance index acts as a benchmark for evaluating and designing optimal control systems (Satrianata et al., 2023).

In many engineering processes, disturbances can cause the control variables to deviate from their desired setpoints. To address such deviations, regulators are designed to compensate for disturbances, ensuring system stability and reliability under varying operating conditions (Ivanova and Valov, 2024).
Among the various methods available for designing optimal control systems, the Linear Quadratic Regulator (LQR) is a widely recognized and effective approach. One of the primary advantages of LQR is its ability to provide a systematic framework for calculating the state feedback gain matrix (K) for systems with multiple control inputs (u). The control law implemented by LQR is expressed in a well-defined mathematical format, ensuring a structured approach to optimization and stability. The control signal format is given by:

$$U = -Kx$$

where u represents the control input vector, K is the gain matrix calculated to minimize the quadratic cost function, and x denotes the state vector. This formulation inherently balances the trade-off between energy usage and system performance, a critical consideration in engineering applications.

2.3. Kontroler Proporsional – Integral – Derivative (PID)

The integration of proportional control, integral control, and derivative control events results in what is known as the Proportional-Integral-Derivative (PID) control system (Latif et al., 2020). This combination leverages the individual strengths of each control mechanism to provide a robust response to dynamic system behavior. The mathematical representation of this combined control action is expressed as follows:

$$U(t) = K_P e(t) + K_i \int_0^t e(T)\,dT + K_d \frac{de(t)}{dt}$$

with Kp proportional gain, Ti integral time, and Td derivative time. PID control is shown in Figure 3.

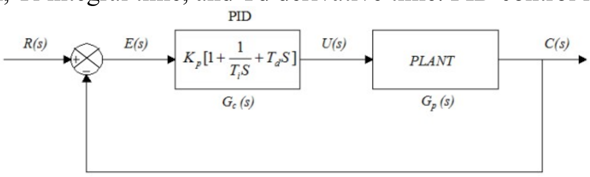

Figure 3. Block diagram PID

A very important aspect in designing a PID controller is determining the parameters of the PID controller so that the closed loop system meets the desired performance criteria (Rahayu et al., 2022). This is also known as controller tuning. Ziegler Nichols introduced two adjustment methods, the first method and the second method (Ma'arif and Setiawan, 2021).

a. First Method
The first method is to experimentally obtain the plant's reaction to unit-step input. The response is represented by two parameters (Hammoodi et al., 2020). L is the time delay and T is the time constant. This parameter is obtained by plotting the step response tangent to the inflection, and there is no intersection of the time axis and the steady value. Ziegler-Nichols control parameters are derived from the equations shown in Table 1.

Table 1. Ziegler Nichols type 1

Control	Kp	Ti	Td
P	T/L	∞	0
PI	0,9T/L	L/0,3	0
PID	1.2T/L	2L	0.5L

b. Second Method
This technique was developed to achieve results in a closed loop system with a maximum overshoot of 25% (Wati, 2020). The setup procedure for the second Ziegler-Nichols method is as follows:
1. Only use proportional feedback control.
2. Reduce the integrator and differential gains to zero.
3. Increase Kp from 0 to critical value. Continuous vibration occurs when Kp = Kc. If not, you can use another method.
4. Record the value of Kc and the corresponding period of continuous oscillation Pc.
Table 2 shows the controller gain from the Ziegler-Nichols method.

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Table 2. Ziegler Nichols type 2

Control	Kp	Ti	Td
P	0,5Kc	∞	0
PI	0,45Kc	Pc/0,3	0
PID	0,6Kc	Pc/2	Pc/8

3. Results and discussion

3.1. PID

To obtain the PID parameters, the second Ziegler-Nichols method is used. The DC motor is modeled in an open loop transfer function as follows:

$$G(s)=\frac{1}{¿¿}$$

- Calculate the gain margin

$$\frac{C_{(S)}}{G_{(S)}}=\frac{K\,G_{(S)}}{1+KG_{(S)}.H_{(S)}}$$

$$1+KG_{(S)}.H_{(S)}=0$$

$$1+\frac{K}{S^2+3S+3S+1}=0$$

$$S^2+3S+3S+(1+K)=0$$

S 3	1	3
S 2	3	1+K
S 1	b1	b2
S 0	c1	c2

$$-1<K<8$$

- Calculate frequency margin

S3	1	3
S2	3	9
ROW3	0	0
ROW4		

$$3s^2+9=0$$

$$S_{1,2}=\frac{-b\ \pm\sqrt{b^2-4ac}}{2a}.j$$

$$S=\frac{-0\ \pm\sqrt{0-4(3)(9)}}{2(3)}.j$$

$$s=\frac{5,2}{3}.j\,;Wc=1,733\,rad/sec$$

$$pc=\frac{2\pi}{Wc}=\frac{2\pi}{1,733}=3,62$$

- Value Kp,Ti,Td

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Table 3. Value Kp,Ti,Td

Control	Kp	Ti	Td
P	4	∞	0
PI	3,6	3	0
PID	4,8	1,8	0,45

3.2. Model motor in State space

The motor is modeled in state space, namely:

Xt=Ax(t)+Bu(t)
Y(t) =Cx(t)

Where matrix A,B,C is:

$$A=\begin{bmatrix} \frac{-7,2}{0,0917} & \frac{-0,1236}{0,0917} \\ \frac{0,1236}{0,0007046} & \frac{-0,004}{0,0007046} \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{0.09170} \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & 1 \end{bmatrix}$$

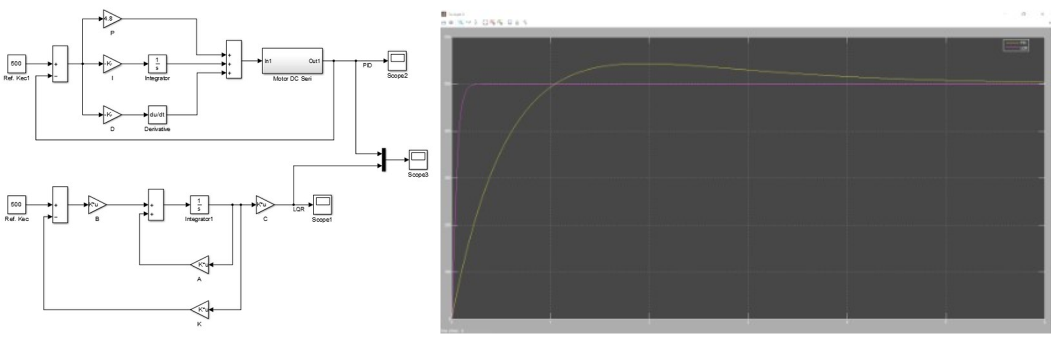
To obtain the matrices Q and R, a MATLAB program script is used with the trial and error method which can be seen in Appendix II, where the terms for the Q matrix are real positive semidefinite matrices ($Q \geq 0$) and the R matrices are real positive definite matrices ($R > 0$),

We set the initial value: $Q=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \wedge R=[1,15]$

3.3. Simulation PID and LQR

In this simulation, the motor will be set at varying speeds, namely 500 rpm, 1000 rpm, 1500 rpm and 2000 rpm.

1. Simulation with speed of 500 rpm



(a) (b)

Figure 4. (a) Simulation cicuit 500 rpm; (b) Respond waveform 500rpm

2. Simulation with speed of 1000 rpm

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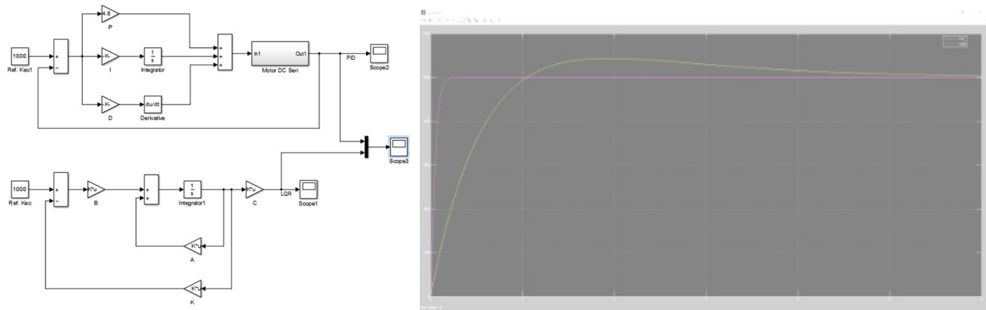
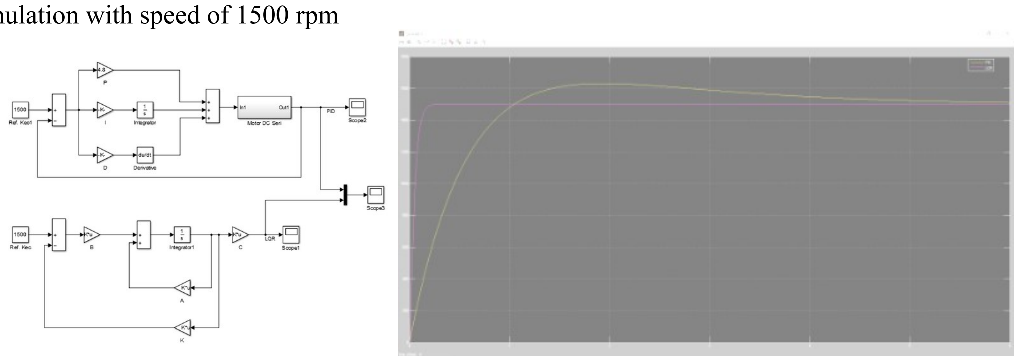


(a) (b)

Figure 5. (a) Simulation cicuit 1000 rpm; (b) Respond waveform 1000rpm

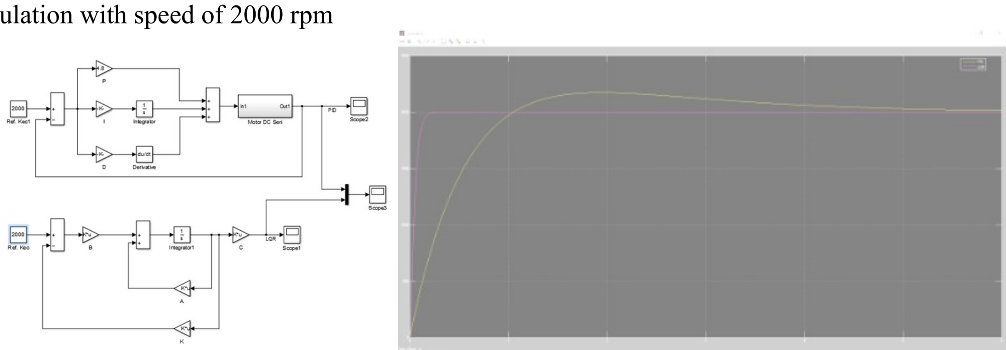
3. Simulation with speed of 1500 rpm



(a) (b)

Figure 6. (a) Simulation cicuit 1500 rpm; (b) Respond waveform 1500rpm

4. Simulation with speed of 2000 rpm



(a) (b)

Figure 6. (a) Simulation cicuit 2000 rpm; (b) Respond waveform 2000rpm

4. Conclusion

Based on the simulation results, several conclusions can be drawn as follows:

- Faster Achievement of Steady-State Speed:The Linear Quadratic Regulator (LQR) demonstrates a significantly faster response in achieving steady-state speed compared to the Proportional-Integral-Derivative (PID) controller. Both the rise time and settling time obtained with the LQR method are markedly shorter than those achieved using PID control.
- Overshoot-Free Rotor Speed Response: The rotor speed response characteristics obtained using the LQR controller exhibit no overshoot whatsoever, ensuring smooth system behavior. In contrast, the PID controller produces a substantial overshoot, which could lead to potential mechanical stress and system inefficiencies during transient conditions..

Credit authorship contribution statement

Author Name: Conceptualization, Writing – review & editing. **Author Name**: Supervision, Writing – review & editing. **Author Name**: Conceptualization, Supervision, Writing – review & editing.

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