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Comparison of Performance of PID and LQR Methods in Improving the Stability of DC Motor Control Systems

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Abstract

DC motors are one type of motor that is widely used in various engineering and industrial applications due to their ease of use and wide speed regulation capabilities. Series DC motors, as one type of DC motor, have large initial torque characteristics, but often overshoot when starting. In addition, this motorcycle also shows low stability, where the speed can decrease at high torque and increase drastically without load. Therefore, in order to achieve more accurate and stable speed control, an effective control system is required. This study examines the comparison between two control methods, namely PID (Proportional-Integral-Derivative) and LQR (Linear Quadratic Regulator), in regulating the speed of DC series motors. In an experiment conducted using MATLAB software, the speed of the motor was tested on five different variations of speed setpoints. The simulation results show that both controllers produce very small speed errors, but with different performance characteristics. The PID controller provides a faster response time than LQR, although it still shows a considerable overshoot of about 20%. On the other hand, the LQR controller is capable of eliminating overshoot overall. In addition, the analysis of the starting current also showed significant differences, with the PID controller producing a current overshoot of about 460%, while the LQR was only about 188%. This study provides insight into the advantages and disadvantages of each control method in improving the stability and efficiency of DC motor control, which is very important in applications that require high speed and stability. Both of these methods show strong potential to be applied in a variety of motor control systems in engineering and industry, with LQR being the more stable option when it comes to overshoot avoidance.

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

1. Introduction

DC motors are one type of motor that is widely used in various industrial, robotics, and household appliance applications. DC motors have the main advantage in terms of ease of speed regulation and precise control. This type of motor, especially series DC motors, has large initial torque characteristics, but it often faces problems such as overshoot at initial starting and instability in its speed settings. The speed of the motor will tend to decrease as the torque increases, while in no-load conditions, the motor can produce very high speeds.

This stability issue is especially important in applications that require fine-tuning, high-precision speed regulation, such as in robotics and other automated drive systems. Therefore, a control system is needed that can mitigate these problems, such as the Proportional-Integral-Derivative (PID) controller which has been widely applied in various motorcycle control systems (Ogata, 2010). PIDs are known for their simple structure and ease of parameter tuning, although there are still some drawbacks related to high overshoot and longer settling times in some applications (Zhang & Zhang, 2021).

One interesting alternative to overcome such problems is to use a Linear Quadratic Regulator (LQR), which offers better stability in regulating dynamic systems such as DC motors, especially in reducing overshoot and speeding up response times (Li & Wang, 2018). LQR has the advantage of providing optimal control by taking into account penalties for errors and the control given to the system.

This study aims to compare the performance of two control methods, namely PID and LQR, in improving the stability of the DC motor control system. By using MATLAB simulations, it is hoped that a clearer picture of the performance of the two controllers in various speed variations, as well as their impact on important parameters such as overshoot, response time, and starting current.

In this study, this comparison is particularly relevant to determine which controller is more optimal in facing the stability and efficiency challenges of DC motors used in industrial applications, especially in the field of automated drives and robotic systems that require precise and responsive speed control (Dorf & Bishop, 2016).

2. Material and methods

2.1. Material

2.1.1 Motor DC

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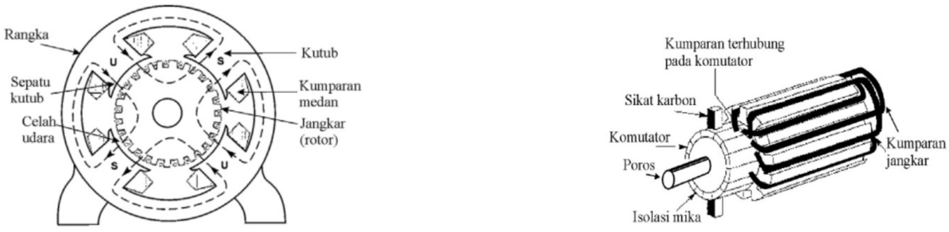
A DC motor is a device that converts direct current electrical energy into mechanical energy. The working principle of DC motors is based on a physical phenomenon, in which conductors carrying current placed in a magnetic field will experience mechanical forces that cause movement (Ogata, 2010). DC motors are widely used in various industrial applications and electric vehicles due to their ability to regulate speed efficiently (Nise, 2011).

2.1.2 DC Motor Construction

DC motors generally have two main components: a stator and a rotor. The stator is a fixed part and generates a magnetic field, while the rotor is a rotating part and serves as a conductor that produces mechanical motion (Hughes, 2013). The construction of DC motors involves critical components such as the frame, field poles, brushes, field coils, anchor coils, commutators, and air gaps, each of which plays a key role in the energy conversion process. The design and selection of materials for each of these components affect the performance and efficiency of DC motors in various applications (Lee, 2015).



a. DC Motor Stator Parts **b. DC Motor Rotor Parts**

Figure 1. DC Motor Construction

2.1.3 Types of DC Motors

DC motors can be divided into several types based on their magnetic amplifier current source. There are separately excited DC motors and self-excited DC motors, which can be distinguished into shunt, series, and compound motors (Bose, 2002). Each type of motor has different control characteristics, which can affect the implementation of the control system used, such as PID or LQR. For example, DC series motors are often used in applications that require high torque at low speeds, while shunt motors are more commonly used in applications that require constant speeds (Bose, 2002).

2.1.4 Control System

A control system is a circuit that regulates the value of a system variable to match the desired value. In the context of DC motor control, this system functions to regulate the speed or position of the rotor to remain stable even if there is an external interference (Ogata, 2010). Control systems can use a variety of approaches, including linear and non-linear controls, with the primary goal of improving system stability and performance (Nise, 2011). The selection of the right control method depends on the characteristics of the system being controlled and the possible interference.

2.1.5 System Response

The response of the control system includes several key aspects that determine the performance of the system, including stability, delay time, rise time, fall time, maximum surge, peak time, and steady-state faults. Each of these aspects plays an important role in the performance evaluation of the DC motor control system, both in speed and position control (Ogata, 2010). These parameters need to be taken into account in the design of PID and LQR controllers to achieve optimal performance (Nise, 2011).

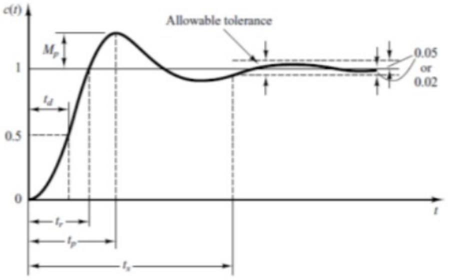


Figure 2. System Response with UnitStep Input (Step Response)

2.1.6 Closed Loop Control System

A closed-loop control system is a control configuration in which the output of the system is used to influence the input, so that errors can be minimized. In this system, proper feedback can improve the stability and accuracy of speed or position control (Ogata, 2010). PID controllers are often used in closed-loop systems due to their ability to dynamically adjust system parameters, which can overcome errors that occur (Bose, 2002). In addition, Linear Quadratic Regulator (LQR) controllers can provide advantages in optimizing overall state feedback in more complex systems (Kailath, 1980).

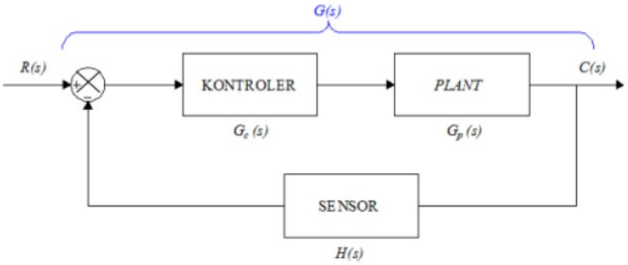


Figure 3. Closed Loop System Block Diagram

2.1.7 Proportional-Integral-Derivative (PID) Controllers

PID is the most commonly used control method in a variety of engineering applications. The PID function combines three control components, namely proportional, integral, and derivative, to generate control signals that correspond to system faults (Ogata, 2010). The equation with these three combinations is given by:

$$u(t) = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(t)\,dt + K_p T_d \frac{de(t)}{dt} \tag{1}$$

The switch function can be seen in the equation below:

$$\frac{U(s)}{E(s)} = K_p[1 + \frac{1}{T_i S} + T_d S] \tag{2}$$

with proportional reinforcement Kp, integral time, and derivative time Pd.

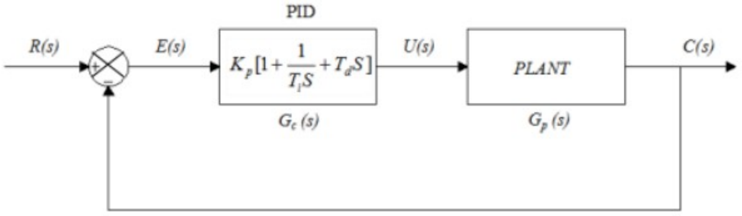


Figure 4. PID Control Block Diagram

The determination of Kp, Ki, and Kd parameters is very important in achieving optimal system stability and response. Proper PID tuning, such as that done using the Ziegler-Nichols method, can provide good results in achieving efficient control (Nise, 2011). However, it is important to note that improper PID tuning can cause oscillation or poor stability, especially in more complex systems such as DC motors.

2.1.8 Linear Quadratic Regulator (LQR) Controller

LQR is one of the methods in designing an optimal control system that aims to minimize the cost function that measures the deviation of the system from its ideal condition (Kailath, 1980). LQR uses two main matrices, namely the error cost matrix (Q) and the control cost matrix (R), to generate optimal reinforcement that minimizes the total cost in the system.

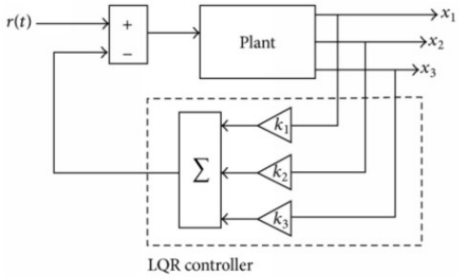


Figure 5. LQR control system

The advantage of LQR is its ability to handle disruptions and uncertainties in the system in a more systematic and optimal way compared to PID. The application of LQR in DC motors can provide more stable and responsive control in more dynamic and complex situations (Bose, 2002).

2.2. Methods

This study compares the performance of PID and LQR methods in improving the stability of DC motors. The simulation was carried out on the same DC motor model with a PID controller that had been tuned using the Ziegler-Nichols method. Meanwhile, LQR controllers are designed based on quadratic cost functions with Q and R parameters adjusted through iterative simulations to achieve optimal performance (Nugraha & Syamsul, 2019; Roy & Deb, 2017).

3.2.1 Linear Quadratic Regulator (LQR) Design

LQR is an optimal control method designed to minimize quadratic cost functions, which combine deviation from the desired position or speed with the control effort used. In LQR designs, the Q and R weight matrices are used to determine the trade-off between system performance and control energy consumption.

The main principle of LQR is to design a controller with a mathematical approach to ensure system stability while providing optimal performance against interference. The quadratic cost function can be formulated as follows:

$$J = \int_0^\infty \left(x^T Q x + u^T R u \right) dt \tag{3}$$

where J is the cost function, x is the state vector, Q is the state weight matrix, u is the control signal, and R is the control weight matrix. The Q and R parameters are adjusted through an iterative process until the system achieves the desired performance.

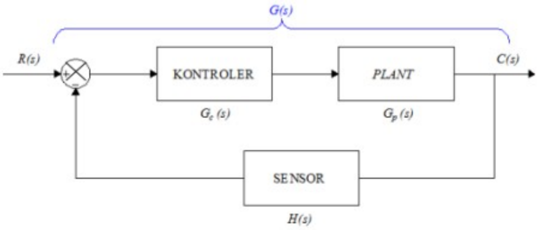


Figure 6. Closed Loop System Block Diagram

In implementation, a closed-loop system with LQR is designed to ensure that the DC motor remains in a stable condition despite external interference. Compensation for the deviation is controlled by optimizing the control signal value, as seen in Figure 7 which shows the structure of the LQR controller.

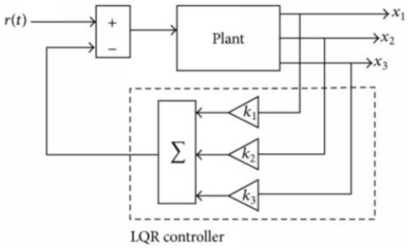


Figure 7. LQR control system

3.2.2 Proportional-Integral-Derivative (PID) Design

PID is a classic control method used to set controlled variables to reach a setpoint by relying on three main parameters: proportional gain (Kp), integral (Ki), and derivative (Kd). The PID design process involves tuning parameters to ensure the closed-loop system meets performance criteria, such as minimize overshoot, stabilization time, and steady-state errors. Some of the tuning methods that can be used include the Ziegler-Nichols method, Cohen-Coon, and algorithm-based optimization, such as the Genetic Algorithm.

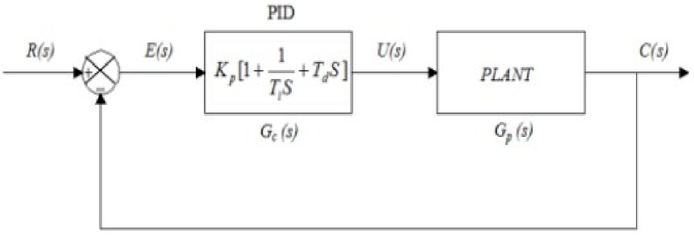


Figure 8. PID Control Block Diagram

The PID controller is designed with a closed-loop block diagram as shown in Figure 8, where the control signal is calculated based on an error which is the difference between the setpoint and the actual output. This approach provides flexibility in adjusting the parameters for the DC motor system to achieve optimal stability.

3. Results and discussion

3.1. Data Acquisition

In this study, the parameter data of the DC series motor is used to support the system control simulation. The data was obtained from recognized literature, such as IEEE journal publications, to ensure the validity and accuracy of the simulation model. The parameters of the DC motor used are presented in Table 1.

Table 1. Parameters of DC Series Motor

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

3.2. Series DC Motor Control Simulation with PID

The design of DC motor control simulation using the PID method was carried out by utilizing MATLAB Simulink software. The simulation series is shown in Figure 9 and Figure 10. The PID parameters used include Proportional (Kp), Integral (Ki), and Derivative (Kd) constants.

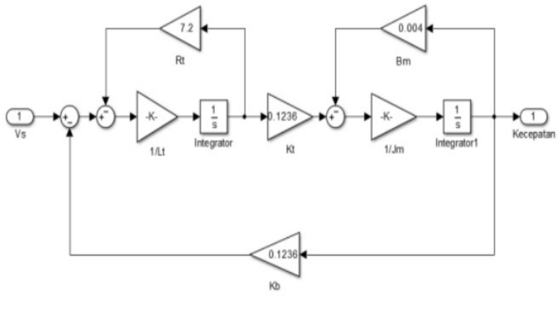


Figure 9. Series DC Motor Simulink Series with PID

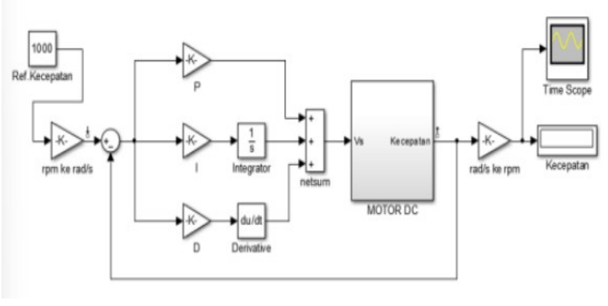


Figure 10. PID Simulation Series

3.2.1 PID Parameters

The PID parameter values are obtained through a manual approach based on system characteristics as well as tuning methods such as Ziegler-Nichols:

- Proportional Constant (Kp):

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

$$K_p = 1.2\left(\frac{0.3130}{0.009765}\right)$$

$$K_p = 38.464$$

- Integral Constant (Ki):

$$T_i = 2L,\ K_i = \frac{K_p}{T_i},\ \text{maka:}$$

$$K_i = \frac{K_p}{2L} = \frac{38.464}{2(0.009765)} = 1969.483$$

- Derivative Constant (Kd):

$$T_d = 0.5L,\ K_d = T_d K_p,\ \text{maka:}$$

$$K_d = 0.5L(K_p) = 0.5(0.009765)(38.464) = 0.1878$$

3.2.2 PID Simulation at 700 rpm Reference Speed

Simulations at a reference speed of 700 rpm result in the simulation circuit shown in Figure 11. The rotor speed response is represented in Figure 12, with the following performance parameters:

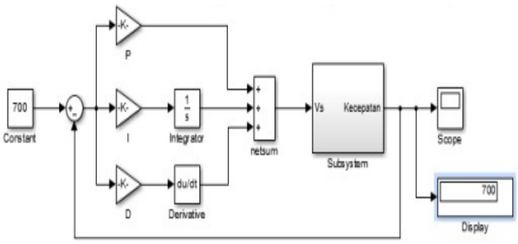


Figure 11. PID Simulation Circuit at 700 rpm

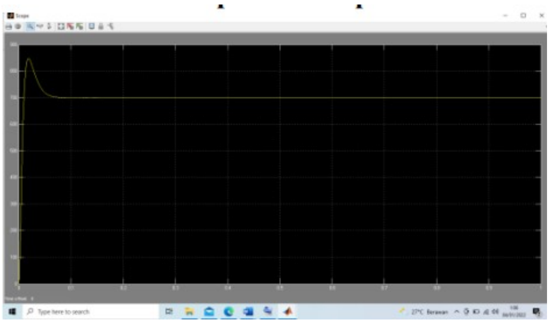


Figure 12. Rotor Speed Response at 700 rpm with PID Control

Rotor speed response parameters obtained:

- Rise time: 7.025 ms
- Settling time: 53.7 ms
- Max. Overshoot: 21.04%
- Error steady state: 0.00014%

3.2.3 PID Simulation at 1000 rpm Reference Speed

In the 1000 rpm reference speed simulation (Figure 13), the parameters are obtained with the response graph image in Figure 14:

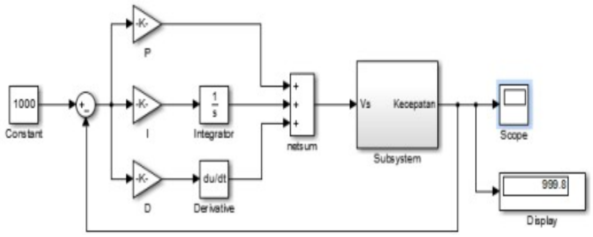


Figure 13. PID Simulation Circuit at 1000 rpm

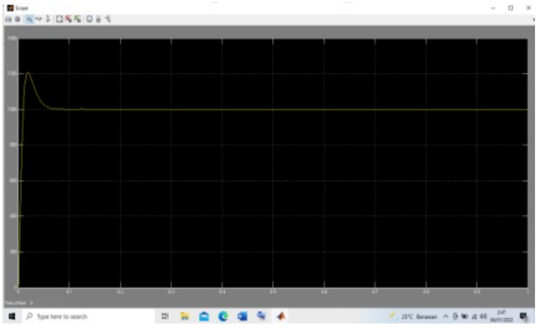


Figure 14. Rotor Speed Response at 1000 rpm with PID Control

Anchor current response parameters obtained:

- Rise time: 1.071 ms
- Settling time: 328.9 ms
- Max. Overshoot: 461.45%

3.2.4 PID Simulation at 1300 rpm Reference Speed

A 1300 rpm reference speed simulation produces a graph in Figure 15, with the parameter results shown in Figure 16:

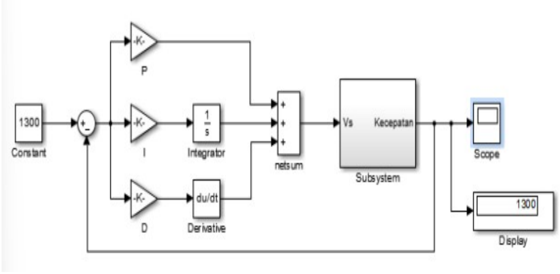


Figure 15. PID Simulation Circuit at 1300 rpm

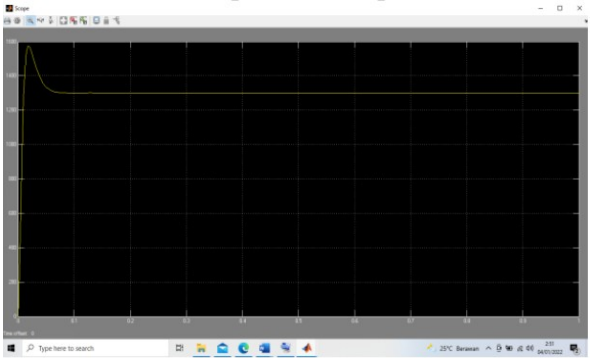


Figure 16. Rotor Speed Response at 1300 rpm with PID Control

Rotor speed response parameters obtained:

- Rise time: 3.019 ms
- Settling time: 432.7 ms
- Max. Overshoot: 455.88%

3.3. Series DC Motor Control Simulation with LQR

The LQR control simulation uses a state space approach. The mathematical model of the DC motor system is formulated in a state-space equation, with matrices A, B, C, and D shown in the following equation:

$$A = \begin{bmatrix} -\frac{R}{L} & -\frac{Kb}{L} \\ \frac{Kt}{Jm} & -\frac{Bm}{Jm} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}, \quad D = 0$$

The design of the LQR controller is carried out by defining the Q and R matrices to optimize the quadratic cost function. The gain feedback value (K) is obtained by using the lqr function in MATLAB, as shown in the following script:

```
Q = [1 0; 0 1];
R = [1.15];
[K, S, e] = lqr(A, B, Q, R);
```

The step response graph of the LQR simulation is shown in Figure 18 and Figure 17 is the diagram of the simulation series.

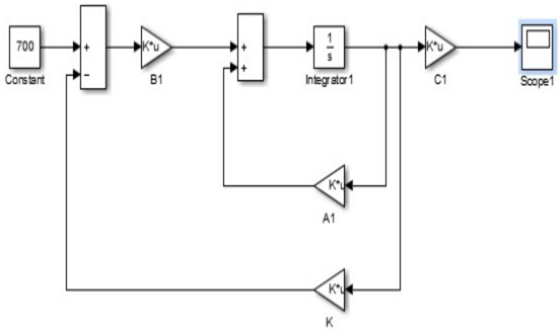


Figure 17. LQR Simulation Series

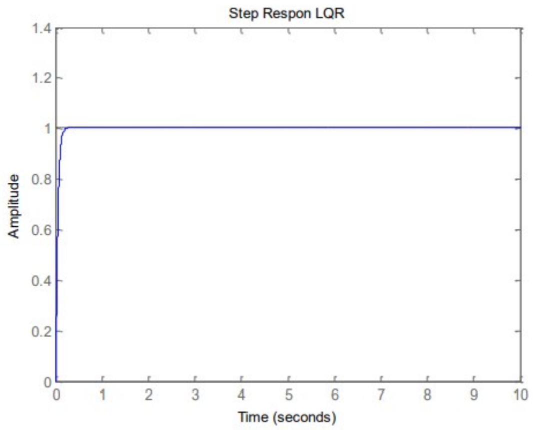


Figure 18. Graph results in LQR matlab script

3.4. LQR Simulation at 700 rpm Reference Speed

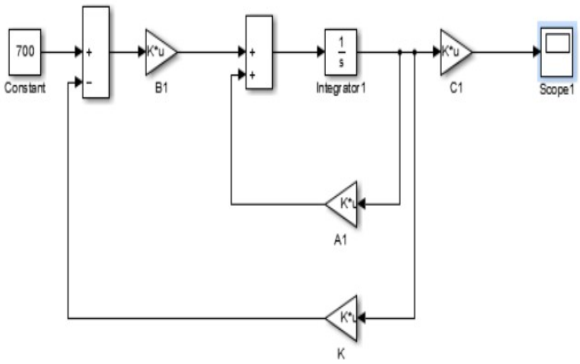


Figure 19. LQR Simulation Circuit at 700 rpm

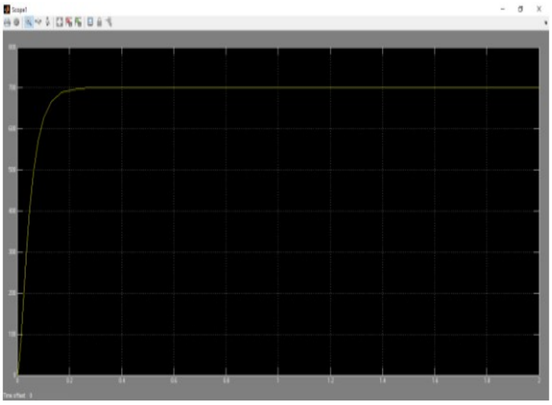


Figure 20. Rotor Speed Response at 700 rpm with LQR Control

At a reference speed of 700 rpm, the results of the LQR control performance parameters are:

- Rise time: 91.406 ms
- Settling time: 171.2 ms
- Max. Overshoot: 0%
- Error steady state: 0.00014%

3.5. LQR Simulation at 1000 rpm Reference Speed

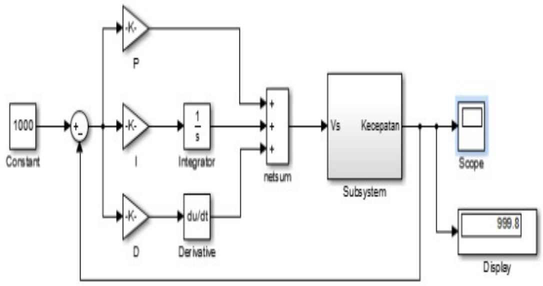


Figure 21. LQR Simulation Circuit at 1000 rpm

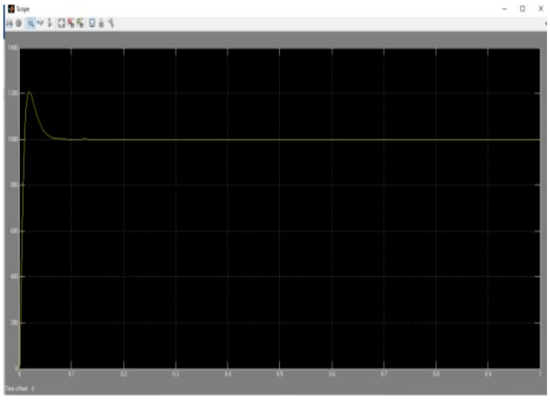


Figure 22. Rotor Speed Response at 1000 rpm with LQR Control

The simulation results show the following parameters:

- Rise time: 90.877 ms
- Settling time: 169.8 ms
- Max. Overshoot: 0%
- Error steady state: 0%

3.6. LQR Simulation at 1300 rpm Reference Speed

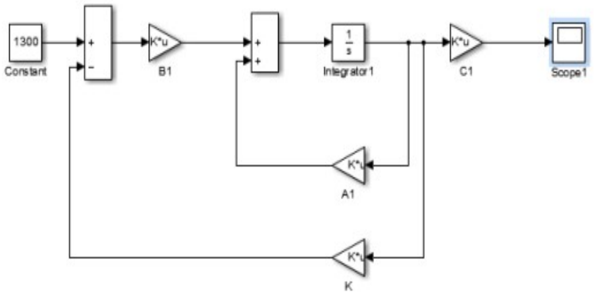


Figure 23. LQR Simulation Circuit at 1300 rpm

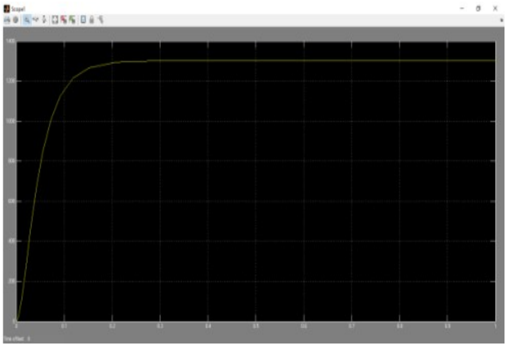


Figure 24. Rotor Speed Response at 1300 rpm with LQR Control

In this simulation, the performance parameters are:

- Rise time: 89.743 ms
- Settling time: 166.9 ms
- Max. Overshoot: 0%
- Error steady state: 0%

3.7. Comparison Results of PID and LQR Simulation

A comparison of the performance of the two methods was done for reference speeds of 700, 1000, and 1300 rpm. The simulation curve is shown in Figure 25, Figure 26, and Figure 27.

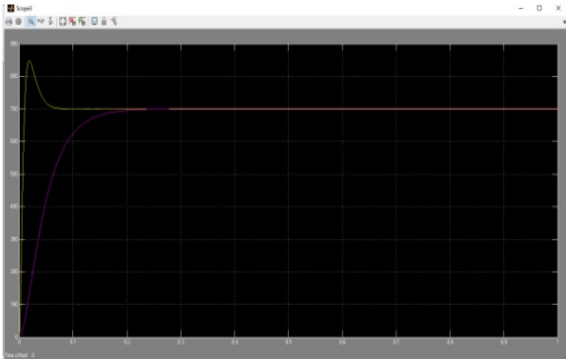


Figure 25. Rotor Speed Response at 700 rpm with LQR and PID Control

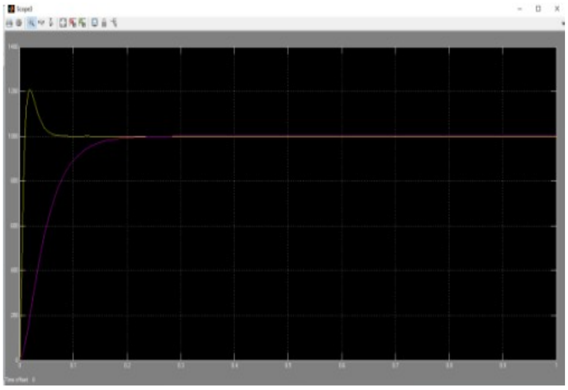


Figure 26. Rotor Speed Response at 1000 rpm with LQR and PID Control

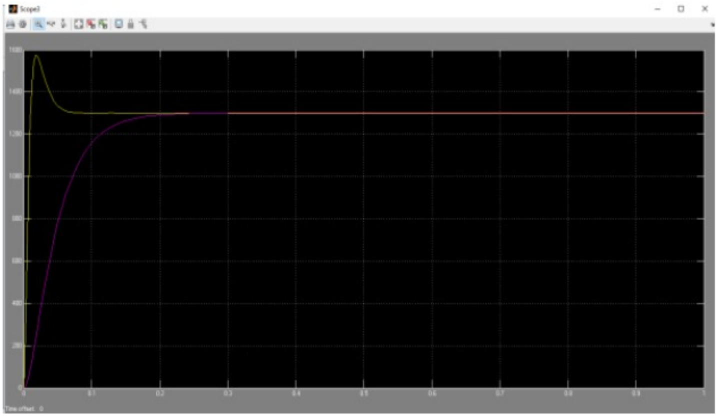


Figure 27. Rotor Speed Response at 1300 rpm with LQR and PID Control

The results showed that the PID control provided faster rise time and settling time than LQR, but with significant overshoot, reaching more than 20% in some cases. In contrast, LQR control produces an overshoot-free response with better steady-state stability. This indicates that LQR is more optimal for systems that require high stability, while PID is suitable for applications that prioritize response speed.

4. Conclusion

Based on the results of the simulation, several important points can be concluded as follows:

1. The simulation results show that Proportional-Integral-Derivative (PID) has a faster rise time and settling time compared to the Linear Quadratic Regulator (LQR) method. This indicates that PID is superior in responding to speed changes quickly and efficiently, which is one of the important criteria in DC motor control systems. Shorter response times in PIDs are also a major concern in engineering applications that prioritize stability in a minimum amount of time.
2. Although PID is faster in achieving steady-state conditions, simulation results reveal that this method produces a significant overshoot, which is about 20%. In contrast, the LQR controller does not generate overshoot at all. This shows that LQR is superior in maintaining system stability without excessive initial fluctuations. In real applications, such as motor control systems in robotics or transportation, stability without overshoot is essential to prevent hardware damage.
3. The speed variation applied to the DC series motors, both using PID and LQR controls, does not have a significant effect on the speed response performance of the rotor in achieving steady-state conditions. This indicates that both methods have good performance consistency against changes in reference speed. This aspect is important in applications that require stable performance under a wide range of operating conditions.

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