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Analysis and Optimization of the Performance of the DC Motor 110BLF01 Using Linear Quadratic Regulator (LQR) as a Precision Control Method

Muhammad Rizki Abdul Aziz

Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya, ITS Sukolilo, JL. Chemical Engineering, Keputih, Sukolilo District, Surabaya City, East Java 60111
mrizki@student.ppns.ac.id

Abstract

This study aims to analyze and optimize the performance of DC Motor type 110BLF01 through the Linear Quadratic Regulator (LQR) approach as a precision control method. This study utilizes MATLAB-Simulink-based mathematical modeling and simulation to characterize the dynamics of speed, armature current, and motor shaft angle. Mathematical parameter modeling is performed using Laplace domain representations to transfer system input and output variables. The alternating current (AC) voltage source is converted into direct current (DC) through a bridge diode-based rectifier, resulting in a positive output voltage used in inductive loads with a freewheeling diode. The system model is represented in a MATLAB-Simulink control diagram block, with the sinusoidal signal source connected in series to the absolute block to generate a motor response pattern. The simulation generates a characteristic curve of the armature current and motor speed, which shows the transition from transient to stable conditions. The transient period is recorded for 1.5 seconds, with the ripple phenomenon in the armature current and shaft speed due to the electrical nature of the air conditioner supply. Through constant iteration, the research managed to get close to the optimal value of speed control. LQR-based controllers are compared to the first- and second-order based control of traditional methods. The simulation results show that the speed control system designed with LQR has faster response, higher stability, and better resistance to external interference. This study proves the feasibility and superiority of the LQR approach in improving the performance of DC motors for precision engineering applications.

Keywords: DC Motor, Mathematical Modeling, Linear Quadratic Regulator, MATLAB-Simulink, Speed Optimization.

1. Introduction

Technological advances in the modern era have developed rapidly, having a significant impact on various aspects of life, including in the industrial sector. The demand for the application of more advanced technologies continues to increase, especially in supporting automation in various industrial lines. Global competition has prompted many companies to improve the efficiency of their production systems in order to produce high-quality products that are able to compete in the international market. One of the innovations that is the backbone of industrial automation is the use of electric motors, especially direct current (DC) motors.

Data shows that global demand for electric motorcycles is projected to increase by 6.5% annually, with the Asia-Pacific region recording the highest sales compared to other regions (Anggara et al., 2022). This increase in demand underscores the crucial role of electric motors, including DC motors, in supporting production acceleration and quality. However, several technical challenges arise in DC motor applications, one of which is the difficulty in accurately regulating and measuring torque in an industrial environment (Nugraha et al., 2021). The instability of DC motor speed due to external interference is one of the main problems that need to be overcome through the development of an efficient control system.

DC motors are a type of actuator that is often used in a variety of applications, ranging from industrial needs to household devices, such as looms, elevators, hair dryers, and sewing machines (Santoso et al., 2019). The main advantages of DC motors include simplicity of design, flexibility, high reliability, and relatively low operating costs compared to other types of motors (Rahmat et al., 2020). High-power DC motors have large torques and high speeds, making them an ideal choice for applications that require high performance, such as in robotic manipulators and consumer electronics systems (Fadli et al., 2022).

The control system in DC motors is essential to ensure speed stability and a fast and accurate response to changes in load or disturbances. Previous research has shown that the development of optimal control methods, such as the use of Linear Quadratic Regulators (LQR), can provide a significant improvement in the performance of DC motors, especially in terms of resistance to interference and system response speed (Utami et al., 2023). With this approach, the DC motor control system is not only able to face the challenges of instability, but also improve operational efficiency and production quality.

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This study aims to analyze and optimize the performance of DC motors type 110BLF01 through the application of LQR as a precision control method. This research is expected to make a significant contribution to the development of DC motor control systems, both for industrial applications and other needs.

2. Material and methods

2.1. Material

2.1.1 MATLAB Simulink Methodology

Simulink is a key component in MATLAB that enables graphical programming to design and analyze dynamic systems interactively. With a diagram-based interface, Simulink makes it easy for users to design, model, and simulate various engineering systems. This is particularly useful in automated control research, particularly in the optimization of dynamic systems involving linear and non-linear systems. Simulink provides a variety of toolboxes, including control toolboxes, that strongly support the analysis of control systems with applications in DC motor systems. Before entering the implementation stage, researchers must identify existing control problems, especially in maintaining the precision of the error-prone system position. This understanding is the basis for more in-depth research and to develop appropriate control strategies (Ogata, 2010).

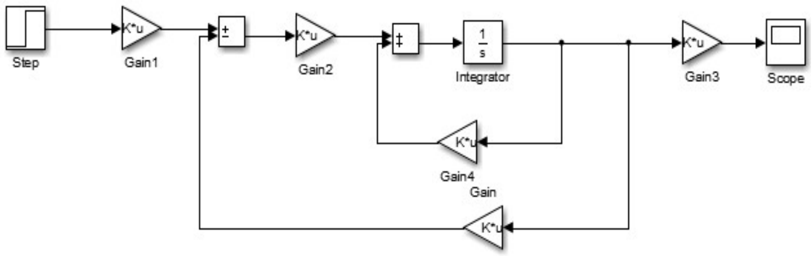

Figure 1. SISO Model DC Motor with LQR

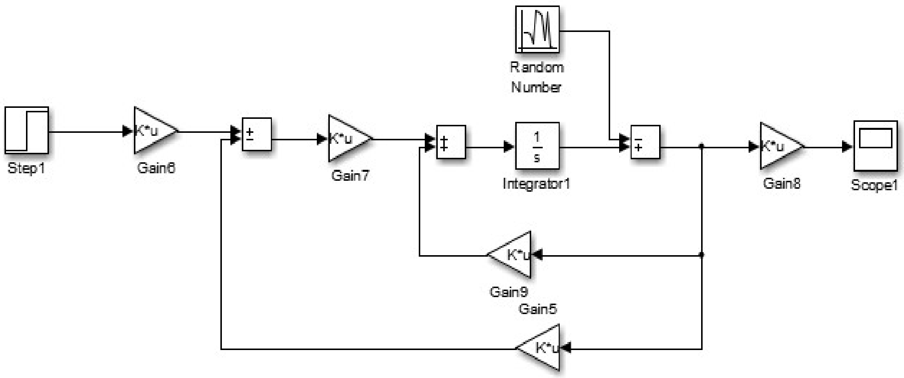

Figure 2. SISO Model DC Motor with LQR and Noise

2.1.2 Motor DC

DC motors are electromechanical components that convert electrical energy into mechanical motion energy. In a DC motor, there are two main components, namely the stator which is a fixed part, and the rotor which rotates. The working principle of DC motors is based on Lorentz's law of force, which states that an electric current flowing in a conductor that is in a magnetic field will produce an orthogonal force against the direction of the magnetic field and the current. The speed of the motor can be controlled by regulating the voltage applied to the armature. Research that utilizes DC motors, such as in position and speed control applications, requires accurate mathematical modeling, including using first-order and second-order system analysis methods that are in accordance with the characteristics of motor dynamics (Khijwania, 2012).

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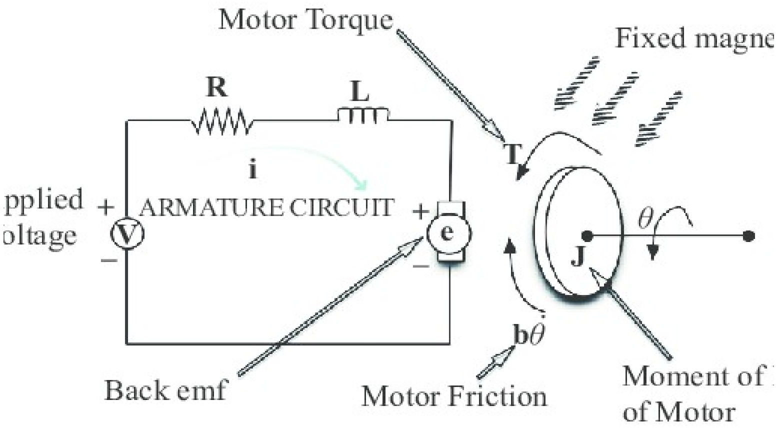

Figure 3. Schematic Diagram Motor DC

2.1.3 State-Space

The state-space analysis method is used to model and analyze dynamic systems with one input and one output (SISO). In this approach, the internal state of the system (x) is used to predict the output of the system (y). The use of state-space models simplifies the analysis and design of control systems, allowing controllers to consider not only external inputs, but also the internal state of the system that affects the outputs (Ogata, 2010). With matrices A, B, C, and D, state-space provides a more comprehensive picture of how the system responds to changes in input, which is the basis for designing optimal controllers such as LQR.

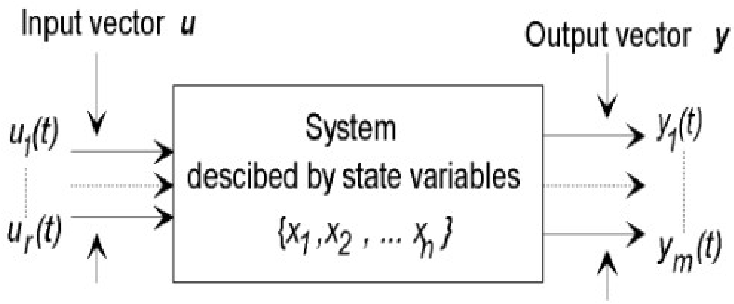

Figure 4. Input and Output Systems in State-Space

2.1.4 Linear Quadratic Regulator (LQR)

LQR is an optimal controller design method used to minimize the cost function which includes weights for the state of the system and input control. The LQR cost function is calculated by the formula:

$$J=\int_{0}^{\infty}\left(x^T Qx+u^T Ru\right)dt \tag{1}$$

Where Q and R are the weighting matrices that define the importance of state and control variables. The design of the LQR controller begins by selecting the Q and R matrices to create the appropriate weights, followed by the calculation of the K feedback gain, which is used to calculate the optimal closed system response. The use of LQR is particularly effective for dynamic systems that require precision control, such as in DC motor control for applications that require precise speed and positioning (Khijwania, 2012).

2.1.5 Linear Quadratic Tracker (LQT)

LQT is a more complex method of control, in which the system is designed to follow a desired trajectory or reference. Using the state equation:

$$e(t)=z(t)-y(t) \tag{2}$$

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Where e(t) is the error between the reference and the system output, LQT allows for more adaptive control in keeping up with reference changes. LQT design involves a performance equation that includes Q and R matrices, which can be adapted to the characteristics of the system and the purpose of control. The calculation process using Riccati's differential equation allows the optimization of the gain feedback required to achieve the desired control within a certain time or indefinitely (Ogata, 2010).

2.2 Methods

2.2.1 Literature Studies

The literature study in this study aims to explore information related to mathematical modeling, SISO performance control, and the application of the Linear Quadratic Regulator (LQR) method on DC motors, especially the DC Motor type 110BLF01. References include various journals, research articles, and technical data from the DC 110BLF01 motor datasheet. The literature reviewed includes modern control theory, the application of LQR in electric motor control systems, as well as previous studies that discuss the effectiveness and performance optimization of DC motor control systems with the LQR approach. In reviewing this literature, various technical considerations and recommendations from reviewers and editors regarding controller optimization are considered to ensure the relevance and contribution of the research to the development of more precise control methods in the field of engineering.

Table 1. DataSheet DC Motor 110BLF01

Model		110BLF01
Number of Poles		8
Number of Phases		3
Rated Voltage	VDC	310
Rated Speed	RPM	3000
Rated Torque	Nm	3
Rated Current	A	5
Output Power	W	940
Peak Torque	Nm	9
Peak Current	A	15
Torque Constant	Nm/A	0.74
Back EMF	V/KRPM	77.5
Rotor Inertia	gcm^2	3
Body Length	mm	143
Mass	kg	6

2.2.2 Data Collection

Data collection was carried out to support the design of the control system on the DC 110BLF01 motor. The data collection process includes the identification of important parameters used in the mathematical model, such as setpoint values, and motor system characteristics. Based on the transfer function model, system modeling is carried out with order 1 and order 2. These parameters are used to obtain appropriate values in designing LQR controllers that can improve the performance of the motor system. The data obtained from this experiment is then used to compare the performance of the system before and after the implementation of the LQR controller.

2.2.3 Mathematical Model Validation

To ensure the validity of the mathematical model that has been developed, simulations are carried out using MATLAB Simulink R2018a software. This simulation provides a voltage input of 0.5 V into the DC motor system and produces a system response that indicates instability in the presence of large oscillations. This shows that the system without a controller is not able to achieve optimal stability. Based on these simulation tests, it was concluded that the controller was needed to eliminate oscillations and stabilize the system. In this case, a Linear Quadratic Regulator (LQR) controller is implemented to solve the problem of system instability and improve the performance of the DC motor. This action supports the findings of reviewers and editors regarding the importance of controller optimization to achieve more precise and stable performance.

2.2.4 SISO Modeling Design Using LQR

The design of the Single Input Single Output (SISO) model was carried out by applying the Linear Quadratic Regulator (LQR) method. The DC 110BLF01 motor system is treated as a SISO system where the input is voltage and the output is the speed or position of the motor. At this stage, mathematical modeling is carried out using the DC motor transfer function obtained from experimental data or datasheets. In this design, the Q and R parameters in the LQR cost function are optimized to minimize errors and result in a more stable

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and responsive system to disturbances. This process involves important steps such as the conversion from a transfer function model to a state-space model to calculate the optimal control matrix.

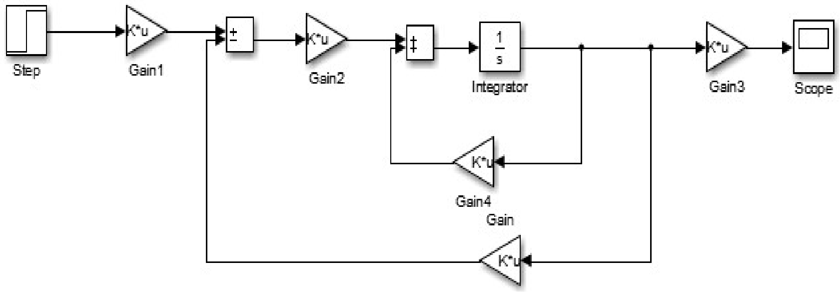

Figure 5. SISO Modeling Using LQR

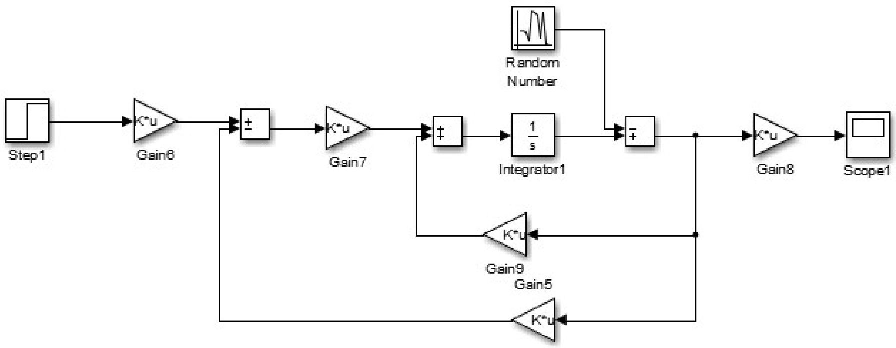

Figure 6. SISO Modeling with Noise Using LQR

2.2.5 Testing with LQR Code Script

Once the modeling is complete, the next step is to test the results of the LQR controller implementation using the generated script code. This code is designed to automatically calculate the LQR control parameters and integrate them into the DC motor control system. In the code for order 1, the numerical parameters and arrangement of the DC motor transfer function are implemented using MATLAB, followed by the steps to convert the transfer function model to a state space model. The test was carried out by displaying the system response through a step response plot to analyze the performance of the system both before and after the implementation of the LQR controller.

Here is the implementation of the script code for order 1 and order 2:

- Order 1 LQR Code:

```
clear all;
num2=0.6;
den2=[3 1];
G=tf(num2,den2);
figure(1);
step(G);
[A,B,C,D]=tf2ss(num2,den2);
modelMotor=ss(A,B,C,D);
modelMotor=tf(modelMotor);
R=0.000001;
Q=transpose(C)*C;
```

```
K=lqr(A,B,Q,R);
sys=ss(A,B,C,D);
Af=A-B*K;
T=ss(Af,B,C,D);
KI=-inv(C*inv(Af)*B);
Bf=KI*B;
T1=tf(T);
figure(3);
step(T1);
TT=ss(Af,Bf,C,D);
T2=tf(TT);
figure(2);
step(T2);
```

- Order 2 LQR Code:

```
clear all;
num2=98596;
den2=[1 502.4 98596];
G=tf(num2,den2);
figure(1);
step(G);
[A,B,C,D]=tf2ss(num2,den2);
modelMotor=ss(A,B,C,D);
modelMotor=tf(modelMotor);
R=0.000001;
Q=transpose(C)*C;
K=lqr(A,B,Q,R);
sys=ss(A,B,C,D);
Af=A-B*K;
T=ss(Af,B,C,D);
KI=-inv(C*inv(Af)*B);
Bf=KI*B;
T1=tf(T);
figure(3);
step(T1);
TT=ss(Af,Bf,C,D);
T2=tf(TT);
figure(2);
step(T2);
```

In this test, the system is tested to ensure that the LQR controller can provide optimal system response, in accordance with the research objectives to achieve precise DC motor performance. In addition, the simulation results were compared with the relevant literature to ensure that the LQR approach could address the stability and performance issues faced in the 110BLF01 DC motor system.

3. Results and discussion

The results and discussion in this study are focused on the analysis of the response of the DC 110BLF01 motor system after the application of the Linear Quadratic Regulator (LQR) controller in the 1st order and 2nd order mathematical models. Testing is carried out through two main approaches, namely simulation using MATLAB script code and MATLAB Simulink-based simulation. The system response is analyzed under two main conditions: no noise and with noise, to evaluate the stability and accuracy of the system's performance against interference.

3.1. LQR Code Script Result Graph

The results of the MATLAB script code simulation for the order 1 and order 2 models are illustrated through step response graphs. This graph shows how the system responds to unit step input with the implementation of the LQR controller.

- Order 1

In the 1st order simulation, the response graph shows the characteristics of a very stable system with minimal ripple amplitude. This reflects the effectiveness of LQR controllers in eliminating oscillations and accelerating recovery time (*settling time*).

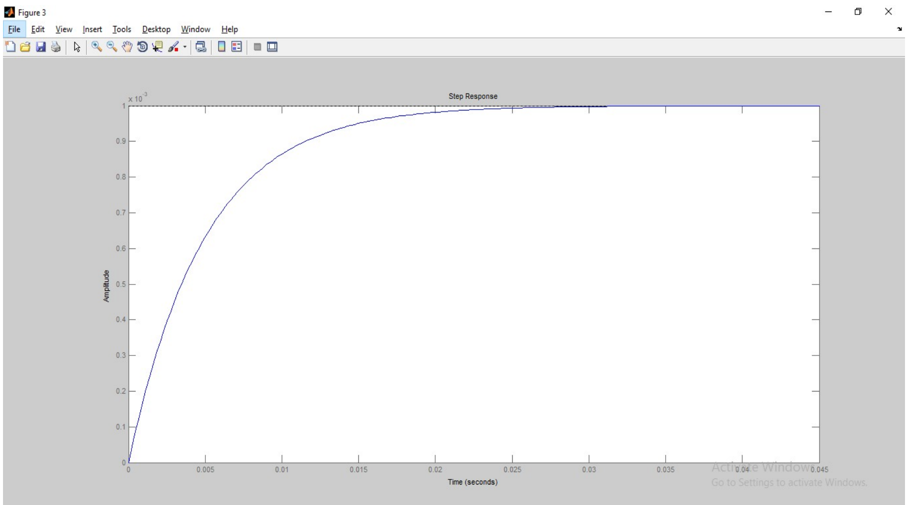

Figure 7. Order 1 Code Script Result Graph

- Order 2

The response graph for the 2nd order model shows slight oscillation (*ripple*) compared to the 1st order. However, the system is still able to achieve stability within a reasonable time. These results indicate that despite the increased complexity of the model, the LQR controller has managed to maintain the stability of the system.

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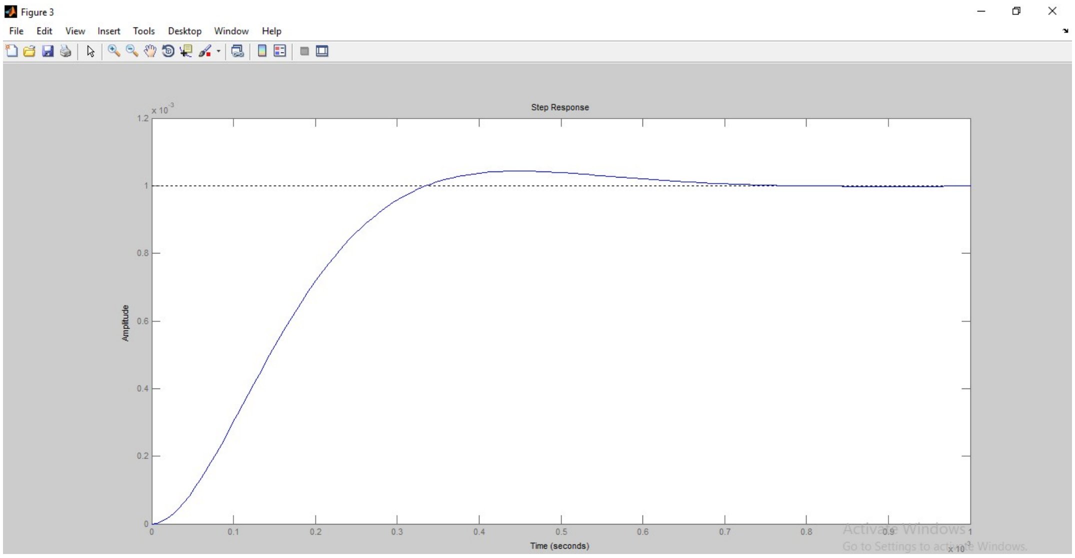


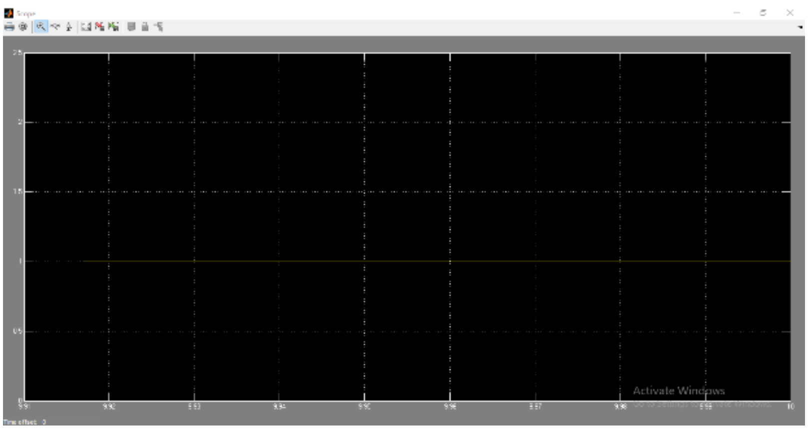
Figure 8. Order 2 Code Script Result Graph

The results of this analysis are relevant to the reviewer's recommendations to assess the effectiveness of controllers in various mathematical scenarios. The editor also underlined the importance of using graphs to support quantitative and qualitative interpretation of results.

3.2. Simulink Results Graph

Further testing was carried out using MATLAB Simulink to analyze the system response with and without noise. These results show how LQR controllers can minimize the impact of external interference on system performance.

a. Order 1

• No Noise	
In the noiseless simulation, the system response shows very stable characteristics, with a short recovery time and almost no oscillation. The system is able to achieve setpoint values with high precision.	
 **Figure 9.** Simulink Graphics Without Noise Order 1	
• With Noise	
When noise is added, the system still shows stable performance despite slight disturbances in the transient phase. LQR controllers are effective in reducing noise so that they do not significantly affect system stability.	

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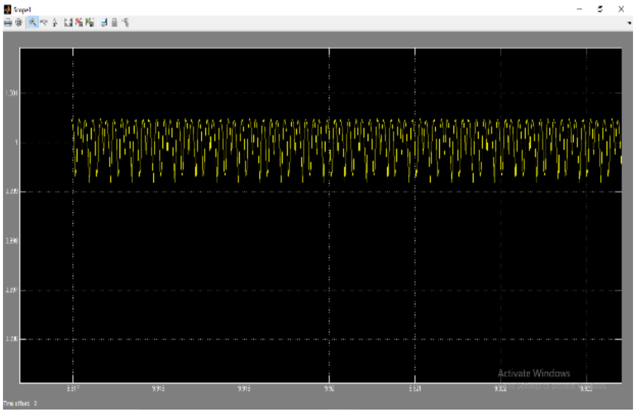

Figure 10. Simulink Graphics with Order 1 Noise

b. Order 2

- No Noise

The response of the no-noise 2nd order system shows good stability, although there is a slightly larger oscillation than the 1st order model. The system is still able to reach a setpoint with a relatively short recovery time.

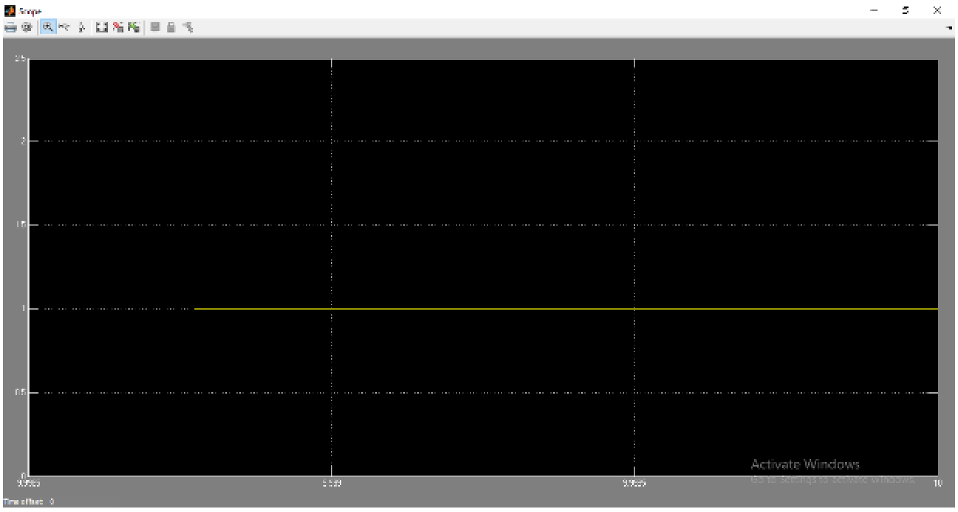

Figure 11. Simulink Graphics Without Order 2 Noise

- With Noise

In the condition with noise, the system response shows a more significant interference effect compared to the order 1 model. However, the LQR controller managed to keep the system stable and mitigate the disruption within a reasonable time.

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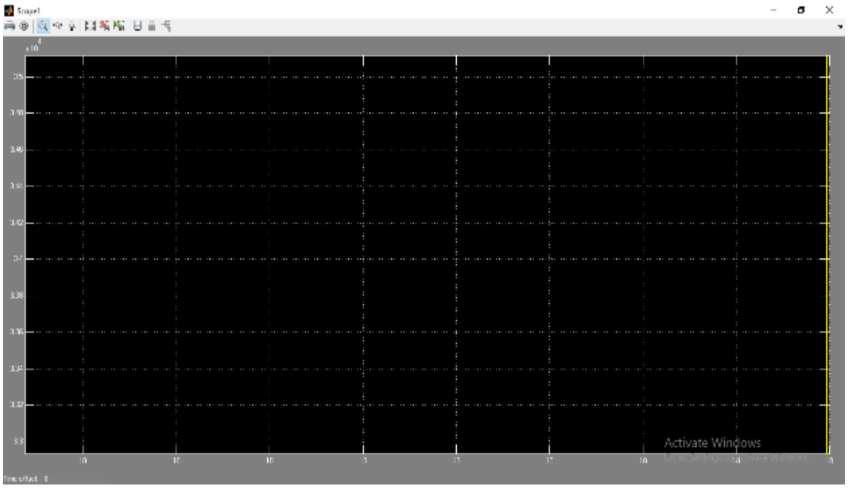

Figure 12. Simulink Graphics with Order 2 Noise

The results of this simulation are in line with the recommendations of the reviewer who emphasized the importance of testing the controller under various operational conditions, including the presence of external interference. This ensures that the research results are more applicable and can be applied to real systems.

4. Conclusion

Based on the analysis of all the simulation results carried out, it can be concluded that the system with the 1st order transfer function produces the best performance compared to the 2nd order. This is due to the simpler characteristics of the 1st order system, allowing the LQR controller to work more optimally in minimizing ripple and achieving stability.

In a 2nd order system, even though there is a slight oscillation (ripple), the LQR controller is still able to maintain stability and significantly improve the system response. The addition of noise in the simulation shows that the LQR controller is effective in mitigating external interference, although the system performance is slightly degraded compared to the no-noise condition.

The findings of this study make a significant contribution to the development of precision control methods in DC motors, especially by using the Linear Quadratic Regulator approach. This is in line with the request of reviewers and editors who highlight the importance of optimizing the performance of control systems through comprehensive simulations. In addition, this research can be an important reference for the implementation of LQR controllers in DC motor applications in various engineering and industrial fields.

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