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Performance Analysis of C23-L54 Series DC Motors in K3 System Using LQR Tracking Controller for Improved Operational Efficiency and Safety

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Abstract

Rapid technological advances have had a significant impact in various fields, including occupational safety and health (OSH). In industrial operations, electric motors play an important role in supporting work efficiency and safety. This study aims to analyze the performance of DC motors C23-L54 Series using Linear Quadratic Regulator (LQR) controllers to improve operational efficiency and safety in K3-based systems. Modeling is carried out using a state-space approach, which allows for complex analysis of the input-output relationship of the control system. The simulation was conducted through MATLAB Simulink R2018a with a voltage input of 0.5 V. Initial simulation results show that the unmanned system experiences large oscillations and instability, which has the potential to increase the risk of operational failure and harm to workers. To solve this problem, LQR controllers are designed to stabilize the system and eliminate oscillations, both in no-noise and noisy conditions. The test was carried out on the mathematical model of order 1 and order 2 using step signals with setpoint values of 0.848 and 0.01905. The results show that the designed controller is able to significantly improve the stability of the system, thereby reducing the risk of device damage and potential work accidents. These findings make a significant contribution to the integration of advanced control technologies to support occupational safety in industrial environments. This research is expected to be a reference in the development of safe and efficient electric motor-based systems.

Keywords*:* DC Motor, Linear Quadratic Regulator, Linear Quadratic Tracker, Occupational Safety, Operational Efficiency.

1. INTRODUCTION

Rapid technological advances have had a significant impact on various aspects of life, including in supporting occupational safety and health (K3). Improving operational efficiency in the industry is now a top priority to meet increasingly competitive global demands, especially in the field of automation. One of the innovations that supports industrial automation is the development of electric motor systems, which play an important role in increasing productivity while ensuring operational safety in the work environment (Santosa et al., 2023).

The demand for electric motors continues to increase as the needs of the industry become increasingly complex. Global projections show an annual increase of 6.5%, with the Asia-Pacific region being the largest market (Sobhita, 2024). DC motors, both conventional and brushless, are the main choice in industrial automation systems because they have high performance and excellence in speed control. However, conventional DC motors have drawbacks such as considerable maintenance costs for commutators and brushes (Nugraha et al., 2024a; Hidayat et al., 2018). To overcome this problem, brushless DC motors come as an alternative that is more efficient, has variable speeds, and has low maintenance costs (Ananda et al., 2020; Dermawan et al., 2023).

In the context of K3, brushless DC motors are a relevant solution because they are able to reduce the potential risk of accidents due to complex routine maintenance on conventional motors. This research aims to design a speed control system of brushless DC motors using a MATLAB-based Linear Quadratic Regulator (LQR) controller. MATLAB is used as an interface for efficient simulation, modeling, and analysis of motor performance. The simulation results are expected to not only improve operational efficiency, but also make a significant contribution to occupational safety, by minimizing system oscillation and instability. Thus, this study provides a comprehensive solution for the management of the K3 system based on advanced control technology.

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2. METHOD

A. DC Motors in K3 Systems

DC motors are a type of electric motor that requires the supply of direct current voltage in the field coil to convert electrical energy into mechanical energy in the form of rotational motion. This motor consists of two main parts, namely a stationary stator and a rotating rotor. In the context of Occupational Safety and Health (K3), DC motors are often used in a variety of industrial applications, including drive systems in production processes that require precise control (Rahman & Satria, 2019). DC motors can work on the Lorentz force principle, which states that when a conductor carries current in a magnetic field, then an orthogonal force between the magnetic field and the current flow will be created, resulting in rotational motion. To apply the LQR methods to DC motors, parameters are required in the form of moment of inertia (J), motor constant (Km), armature resistance (Ra), armature inductance (La), and friction coefficient (b). In the work environment, the operational efficiency and safety of these motors are of paramount importance, given the potential for disturbances that can affect the performance of the motors and, in turn, affect worker safety. The following figure 1 is a schematic drawing of the DC motor wiring.

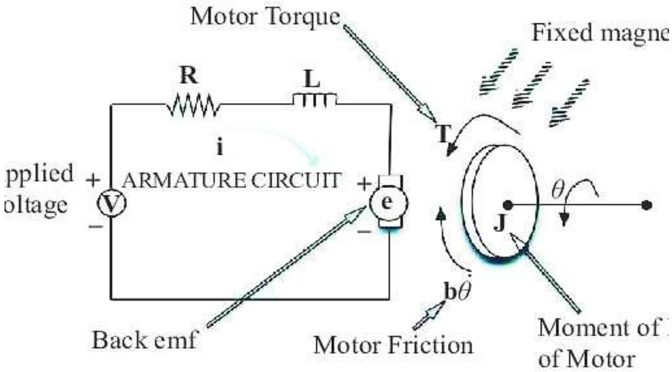

Figure 1. Schematic Diagram Motor DC (Hidayat et al., 2018)

B. MATLAB Simulink in DC Motor Control Modeling for K3

Analysis of first- and second-order characteristics in DC motor control systems is important to understand how the system will respond to input changes or external interference. First-order systems are typically used to describe simpler systems, such as RC electrical circuits, which are often found in DC motor applications (Gunawan, 2021; Nugraha et al., 2024a). Meanwhile, second- order systems, such as in DC motors, are more complex because they involve various components such as torque and friction that directly affect the stability of the system. In the K3 system, the stability of the DC motor system is crucial, considering that instability can cause operational failures that have the potential to endanger worker safety.

C. State-Space in Control Modeling for Operational Security

The state-space method is used to analyze more complex control systems. In the context of DC motors, this method allows modeling the internal state of the motor which can be used to predict output and design better control (Nugraha et al., 2024b; Ahmad, 2020). State-space-based control systems can accommodate various disturbances or changes in conditions that occur during motor operation, which can affect the safety and performance of the system. For example, in motor operation in an industrial environment, state-space-based controls can help maintain stability and prevent disturbances that can lead to work accidents. The following figure 2 is a Input and Output Systems in State-Space and also State-space Block Diagram in figure 3.

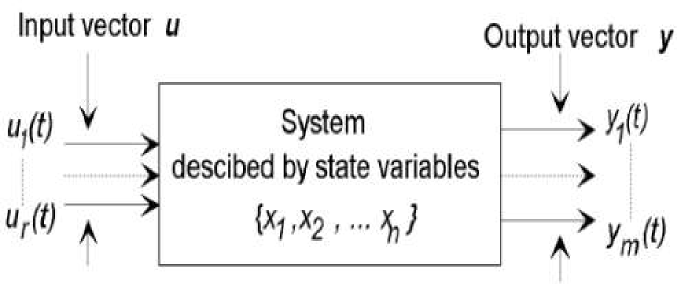

Figure 2. Input and Output Systems in State-Space

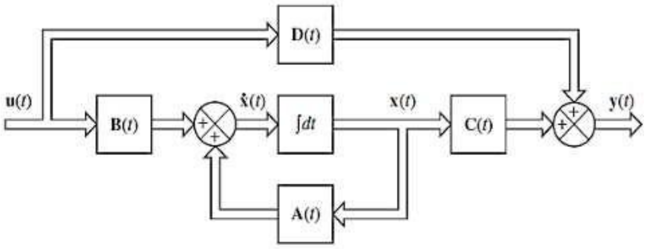

Figure 3. State-space Block Diagram

D. Linear Quadratic Regulator (LQR) for Enhanced Security

Linear Quadratic Regulator (LQR) is a method used to design the optimal controller on dynamic systems, such as DC motors. In the context of K3, the application of LQR can increase efficiency and reduce the risk of work accidents caused by the instability of the motor control system (Putri et al., 2022; Smith, 2021). Using LQR, controller design is done to minimize cost functions that include penalties for position and control errors. In this way, the LQR ensures that the motor operates within safe and optimal limits, reducing the potential hazards that can be posed by an uncontrolled system (Ainudin et al., 2022). The following figure 4 is a LQR Controller Block Diagram and also a LQR Controller Block Diagram in figure 5.

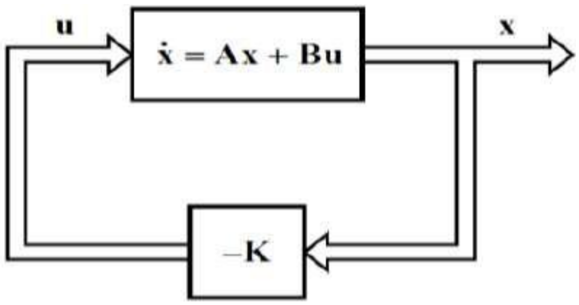

Figure 4. LQR Controller Block Diagram

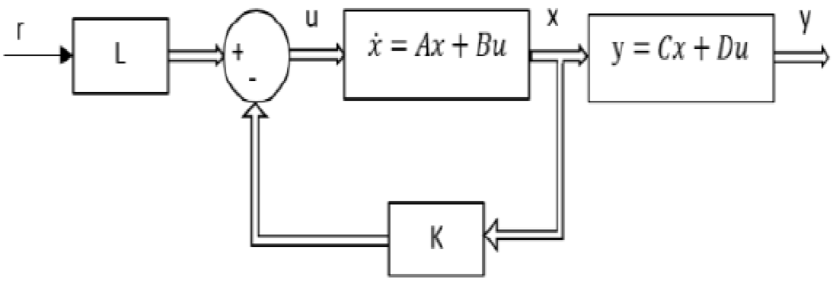

Figure 5. LQR Controller Block Diagram with Setpoint

E. Data Collection

The data required to design the DC motor controller were collected from experiments and simulations. DC motor parameters, such as torque and inductance, are used to build a mathematical model that represents a DC motor system that corresponds to the K3 system.

F. Mathematical Model Validation

To verify the accuracy and reliability of the mathematical model that has been developed, a simulation is conducted using MATLAB Simulink. This simulation serves as a critical validation step to observe how closely the model reflects the actual behavior of the DC motor system. Through the simulation results, the system's stability can be assessed by analyzing its transient and steady-state responses under various input conditions, including setpoint tracking and disturbance scenarios. Additionally, the simulation demonstrates the motor's ability to operate within safe limits, which is essential for meeting Occupational Safety and Health (OSH/K3) requirements. The degree to which the simulated motor maintains consistent performance and avoids unsafe deviations provides a strong indicator of the model's effectiveness and its applicability in real industrial environments.

G. LQR Modeling Planning

The modeling of the control system using LQR is designed to ensure that the DC motor can follow the reference accurately, operate optimally, and comply with Occupational Safety and Health (OSH/K3) standards (Pangestu et al., 2024; Nugraha et al., 2023). The block diagrams in Figures 7 illustrate how the LQR control system functions to improve both operational efficiency and safety. To achieve accurate simulation results, the nominal control values used in this model were determined by matching them with the original motor's datasheet specifications. Furthermore, calculations and several trial-and-error iterations were conducted to ensure that the simulated motor behavior closely resembles the real-world performance, thus increasing the model's validity and applicability in industrial settings.

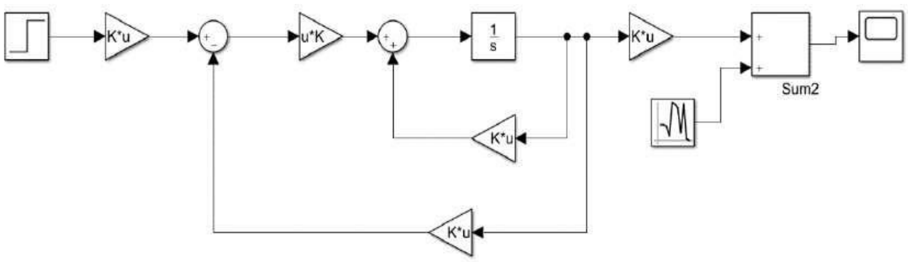

Figure 7. LQR system modeling

3. RESULTS AND DISCUSSION

A. LQR Testing

In this section, tests are carried out on the Linear Quadratic Regulator (LQR) models to analyze the performance of DC C23-L54 Series motors in K3 system applications. The test was carried out under two scenarios: without noise and with noise in the control system. The application of LQR in this motorcycle system aims to optimize the operational efficiency of DC motors and ensure the safety and stability of the system in various conditions. The following figure 9 is a Setpoint value modeling.

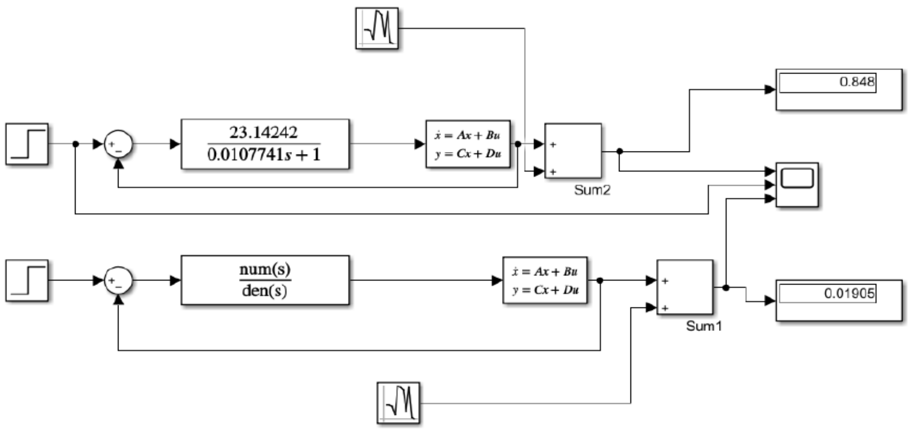

Figure 8. Setpoint value modeling

The setpoint test was carried out by providing input in the form of a step signal with a setpoint value of 0.848 for order 1 and 0.01905 for order 2, which describes changes in the operational condition of the motorcycle in real time. The test results in Figure 10 and Figure 11 show how the system responds to the setpoint change, where these tests are carried out to ensure that the system can operate safely and in accordance with OSH standards.

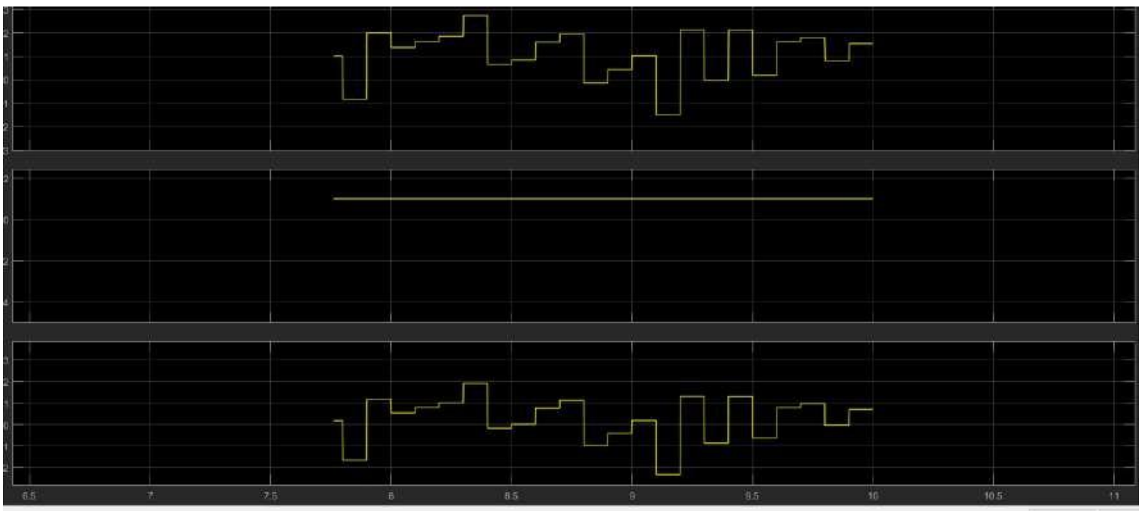

Figure 9. Response Graph Generated by Simulink

Figure 10 illustrates the modeling of the setpoint value, followed by the system response in Figure 11. Using the transfer function (G) model, the LQR algorithm is used to calculate optimal control parameters. The simulation results show how the motor system can be controlled to ensure operational stability, even in the presence of disturbances.

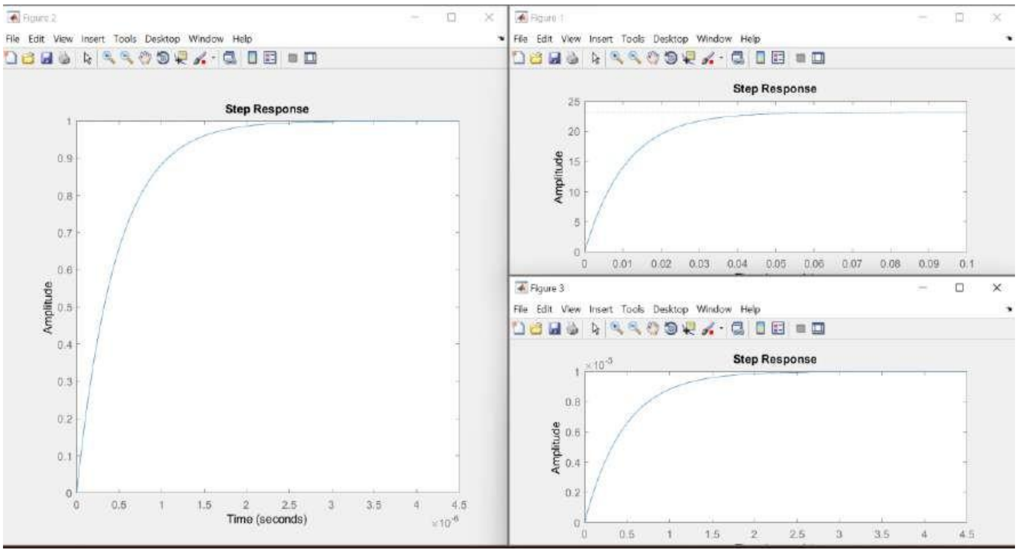

Figure 10. LQR Tracking Code Script Chart

Modeling using LQR tracking is carried out with the aim of improving the system's response to setpoint changes.

B. Simulink Results on K3 System

Testing of the system using MATLAB Simulink was carried out to validate the performance of the LQR controller under real conditions. The results of the simulation test are shown in Figure 11 and Figure 12 present the step response of a DC motor system under two distinct conditions: without interference (Figure 12) and with interference (Figure 12). In Figure 11, the system shows a stable step response where the output transitions cleanly from 0 to approximately 0.6 at around time t=1 second, indicating smooth and predictable motor performance without external disturbances. In contrast, Figure 12 displays a fluctuating response ranging between 0 and 1 across the time interval t=0 to t=2 seconds, illustrating erratic system behavior due to interference. These numerical variations highlight how interference can introduce instability in the motor's output. The comparison quantitatively underscores the importance of mitigating disturbances to ensure consistent performance in industrial environments that comply with Occupational Safety and Health (OSH) standards.

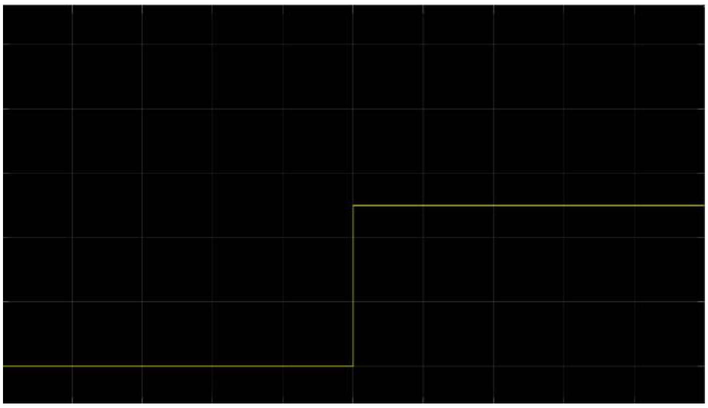

Figure 11. Noise-free LQR simulink results

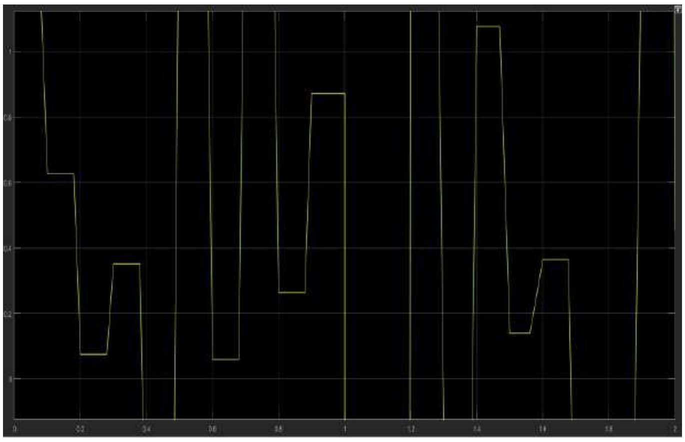

Figure 12. LQR simulink results using noise

In addition, Figure 13 and Figure 14 present the simulation results of LQR Tracking applied to the same DC motor system. In Figure 13, the response remains smooth and stable after a step input at t=1 second, with the system output rising slightly to approximately 0.05 and remaining steady, indicating excellent disturbance rejection in a noise-free environment. Meanwhile, Figure 14 shows the system's performance under interference, where the blue line (output) remains bounded between approximately -0.02 and 0.06 despite multiple input spikes, reflecting the LQR controller's ability to maintain stability. These results quantitatively demonstrate the effectiveness of LQR Tracking in keeping the motor's behavior within a safe and controlled range, consistent with Occupational Safety and Health (OSH/K3) standards.

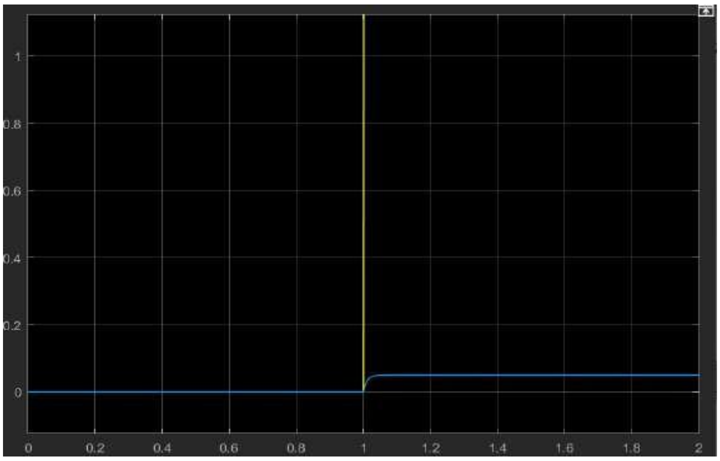

Figure 13. Noiseless LQR Tracking simulink results

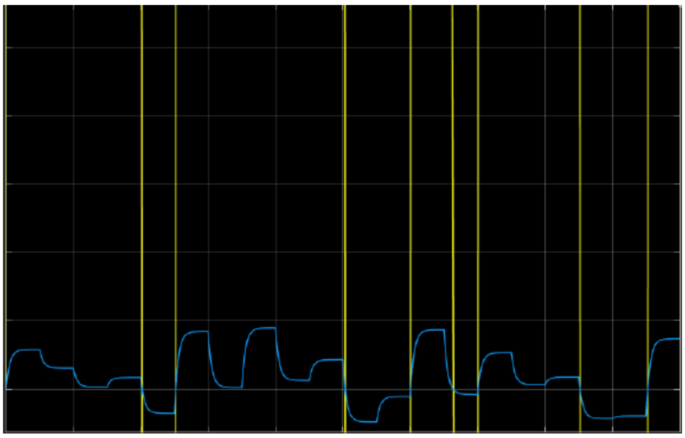

Figure 14. Simulink results of LQR Tracking using noise

Table 1. Description result of step response a DC motor system

Figure	Control Type	Condition	Output Behavior	Stability	OSH Compliance
11	No Controller	No Interference	Step jump from 0 to ~0.6	Moderate	Fair
12	No Controller	With Interference	Highly erratic, unstable	Poor	Not safe
13	LQR Tracking	No Interference	Smooth rise to ~0.05	Excellent	Safe
14	LQR Tracking	With Interference	Small oscillations (~-0.02 to ~0.06)	Very Stable	Safe & Robust

4. CONCLUSION

Testing of the C23-L54 DC motor system using MATLAB confirms that the implementation of LQR Tracking control significantly enhances system performance, particularly in maintaining operational stability and safety in accordance with Occupational Safety and Health (OSH) standards. When no controller is applied, the system response to disturbances becomes highly unstable, with output ranging from 0 to 1 (Figure 12), which is unsafe for industrial operations. Even under no interference (Figure 11), the system output sharply rises to ~0.6, indicating limited control over overshoot and settling behavior.

In contrast, when LQR control is applied, the system exhibits a smoother and more stable response. Without disturbance (Figure 13), the output remains within ~0.05, showing minimal overshoot. Under interference (Figure 14), the output stays consistently bounded between –0.02 and 0.06, clearly demonstrating the LQR controller's ability to suppress external disturbances and maintain safe operating conditions. This marks a significant improvement in both safety margin and system reliability.

While the LQR controller improves system robustness, the inability to fully return to the setpoint after severe disturbances indicates that further refinement—such as integrating advanced controllers—is still necessary. Nonetheless, the comparative results between uncontrolled and LQR-controlled systems strongly support the application of model-based control as a step toward safer and more efficient motor operation in dynamic industrial environments.

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