RESEARCH ARTICLE

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Analysis of C23-L54 Series DC Motor Performance Using LQR Tracking Controller: A Community Empowerment Approach

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Abstract

Technological advancements continue to influence various aspects of human life, including efforts to overcome energy challenges in underserved areas. In the context of community empowerment, integrating efficient and sustainable energy solutions has become essential. This study examines the application of the Linear Quadratic Regulator (LQR) in optimizing the performance of three-phase induction motors for community-based energy systems. Using MATLAB/Simulink R2018a, this research develops a control model designed to enhance motor efficiency and stability, particularly in environments with limited technical resources. State-space modeling is employed as the analytical framework, enabling accurate predictions of system behavior by considering internal dynamics. Initial simulations indicate that, without effective controllers, the system experiences significant oscillations and instability when subjected to an input voltage of 0.5 V. This emphasizes the importance of advanced controllers like LQR in stabilizing motor performance. Step signal tests with setpoints of 0.848 (Order 1) and 0.01905 (Order 2) demonstrate the controller's ability to achieve system stability and operational efficiency. The study highlights the potential of these technologies in empowering communities by improving the reliability of small-scale energy systems, creating economic opportunities, and promoting sustainable development. The findings serve as a framework for implementing scalable energy solutions tailored to the specific needs of rural and underserved regions.

Keywords: community empowerment, sustainable energy solutions, LQR controller, state-space modeling.

1 Introduction

Technological advancements are evolving at an unprecedented pace, influencing various aspects of human life and driving a surge in demand for innovative solutions across multiple industries[1]. Compared to previous decades, this rapid progress has intensified global competition, particularly in the field of automation and industrial optimization. Industry players continuously seek to enhance system

Submitted: 29 March 2025
Accepted: 22 May 2025
Published: 20 June 2025

Vol. 1, **No.** 1, 2025.
10.62762/ETIE.2025.268369

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Citation
Nugraha, A. T., Sobhita, R. A., & Firdaus, A. A. (2025). Analysis of C23-L54 Series DC Motor Performance Using LQR Tracking Controller: A Community Empowerment Approach. *Emerging Trends in Industrial Electronics*, 1(1), 1–8.

efficiency, improve production quality, and accelerate manufacturing processes to maintain a competitive edge. One of the key technological advancements in this regard is the widespread adoption of electric motors, which play a crucial role in modernizing industrial operations.

Market projections indicate that the global demand for electric motors will continue to grow at an annual rate of approximately 6.5%, with the Asia-Pacific region leading in sales volume. This upward trend highlights the vital role of electric motors, including DC motors, in optimizing production speed, ensuring product quality, and meeting the increasing demands of various industrial sectors [2, 3]. As industries strive to integrate more efficient and adaptable motor technologies, developments in areas such as Computerized Numerical Control (CNC) machines further demonstrate the importance of electric motors in advancing automation and precision manufacturing.

Among the various types of electric motors, conventional DC motors have been widely utilized due to their superior performance characteristics. However, they come with several drawbacks, including the requirement for regular commutator maintenance, periodic replacement of brushes, and relatively high initial investment costs. To overcome these challenges, brushless DC motors have emerged as an advanced alternative, offering higher efficiency, variable speed capabilities, and significantly reduced maintenance costs. These advantages make brushless DC motors an ideal choice for industrial applications that demand reliability, durability, and energy efficiency [4].

This study focuses on the development of a speed control system for brushless DC motors using MATLAB as the primary simulation platform. MATLAB provides a comprehensive environment for programming, graphical interfacing, and block diagram creation, enabling precise modeling and simulation of motor speed control. By implementing a Linear Quadratic Regulator (LQR) controller, this research aims to enhance the performance of brushless DC motors, ensuring optimal speed regulation and stability [5, 6]. The ultimate goal is to leverage these advancements to support energy solutions in underserved communities by providing scalable, cost-effective, and sustainable motor control systems. Through this approach, the study contributes to the broader objective of promoting efficient and accessible technological solutions for industrial and community-based applications.

2 Related Work

In the next section, previous research that is similar to the topic being discussed will be described. Below are some research summaries.

2.1 Linear Quadratic Regulator (LQR) in DC Motor Systems

A study conducted by Firdaus (2024) examines and compares two widely used control methods in DC motor systems: the Linear Quadratic Regulator (LQR) and the Proportional-Integral-Derivative (PID) Controller [1]. The primary objective of this research is to enhance the stability of DC motor systems by analyzing the performance differences between these two control approaches.

LQR in this Study: The LQR method is employed to achieve optimal control by minimizing a cost function that considers position errors, speed errors, and system input control. LQR operates by computing a feedback matrix that adjusts the control input based on the system's state, specifically the motor's position and speed. Within DC motor applications, LQR enables more precise and stable regulation, particularly in systems prone to disturbances or model uncertainties.

Findings from this study indicate that LQR outperforms PID in providing a faster and more stable response in DC motor applications, especially under varying load conditions [1]. Unlike PID, which is more susceptible to parameter variations and tuning complexities, LQR presents a more efficient solution for optimizing motor performance.

Overall, the study concludes that implementing LQR in DC motor control leads to superior stability, with a more structured approach to achieving optimal performance under complex operational conditions compared to PID.

2.2 Control Strategies for Optimizing DC Motor Systems Using MATLAB Simulink

Syaifudin (2024) explores the application of LQR and Linear Quadratic Tracking (LQT) methods in optimizing DC motor control systems [2]. This research primarily aims to enhance energy efficiency for small-scale industrial applications by leveraging MATLAB Simulink as a simulation tool.

LQR and MATLAB Simulation in the Study: MATLAB Simulink is used as a simulation environment to evaluate and compare the performance of LQR and LQT controllers in DC motor systems. The study models DC motor dynamics within MATLAB Simulink, incorporating relevant parameters to test the effectiveness of both control strategies [7].

The research demonstrates how LQR is implemented in MATLAB Simulink to optimize energy consumption while ensuring system stability and performance. Simulation results highlight the advantages of LQR, particularly in minimizing the cost function associated with energy usage, motor speed, and position regulation. The flexibility of MATLAB's simulation environment enables precise adjustments to control parameters, allowing for improved performance in home industry applications.

Additionally, the study simulates the LQT method in MATLAB Simulink to compare its effectiveness in achieving control objectives. The results indicate that both LQR and LQT significantly enhance energy efficiency and overall system performance. However, LQR exhibits superior stability and faster response times, particularly under fluctuating load conditions.

Overall, this research underscores the importance of utilizing MATLAB Simulink in the simulation and optimization of DC motor control systems. It emphasizes the potential of these control methods to enhance energy efficiency in practical applications, particularly for small-scale industrial settings [2, 3].

3 Methodology

This section outlines the research methods employed in this study. The following sub-sections will detail each stage of the research process.

3.1 DC Motor

A DC motor is an electric motor that operates using a direct current (DC) voltage supply applied to its field coil, which is then converted into mechanical motion energy [5, 6]. This conversion process is fundamental to many industrial and commercial applications, as DC motors efficiently transform electrical energy into rotational movement. The motor consists of two primary components: the stationary part, known as the stator, and the rotating section, called the rotor. The rotor contains the armature coil, which interacts with the stator's magnetic field to produce motion. As their name suggests, DC motors rely on a continuous, unidirectional current to function, distinguishing them from alternating current (AC) motors that require periodic changes in current direction.

Within a DC motor, the armature consists of one or more independent coils, each connected to a segmented ring structure known as the commutator [8]. The commutator, which is insulated between segments, serves as a crucial component in directing current flow through the armature coils. Functioning as a double-pole, double-throw switch, it ensures that the current reverses at the appropriate time to maintain consistent rotational motion. The operational principle of DC motors is rooted in the Lorentz force, which states that a conductor carrying an electric current within a magnetic field will experience a force perpendicular to both the direction of the current and the magnetic field [9]. This force is the driving mechanism behind the motor's rotational movement, making DC motors highly effective in applications that require precise and adjustable motion control.

By leveraging this fundamental principle, DC motors are widely used in various fields, including robotics, industrial machinery, and electric vehicle propulsion systems. Their ability to provide stable speed control, high torque, and adaptability to different power sources makes them indispensable in modern engineering and automation applications. Figure 1 below will show the DC motor diagram.

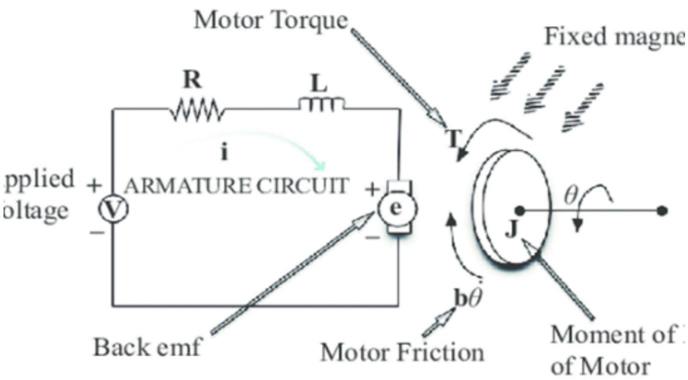

Figure 1. Diagram DC motor.

Search for and study references related to the themes discussed in this final research project, namely regarding mathematical modeling, SISO performance controllers, both from journals, research articles and the C23-L45 DC Motor DataSheet. Figure 4 is represent the block diagram of the dc motor.

3.2 Matlab Simulink

SIMULINK is a graphical programming tool integrated within MATLAB, specifically designed for simulating, modeling, and analyzing dynamic systems [10]. It provides a visual approach to system simulation, allowing users to construct models using functional diagrams. Within SIMULINK, interconnected blocks represent various system components and their respective functions, enabling an intuitive and structured representation of complex control and signal processing systems. This graphical user interface simplifies the simulation process, making it accessible for engineers and researchers working on dynamic system analysis. Figure 2 below will display the specifications parameters.

Part Number*		
Winding Code**		10
L = Length	inches	
	millimeters	
Peak Torque	oz-in	310.0
	Nm	2.189
Continuous Stall Torque	oz-in	34.0
	Nm	0.240
Rated Terminal Voltage	volts DC	12 -24
Terminal Voltage	volts DC	12
Rated Speed	RPM	1950
	rad/sec	204
Rated Torque	oz-in	25.3
	Nm	0.18
Rated Current	Amps	5.8
Rated Power	Watts	36.5
	Horsepower	0.05
Torque Senstivity	oz-in/amp	6.06
	Nm/amp	0.0428
Back EMF	volts/KRPM	4.5
	volts/rad/sec	0.0430
Terminal Resistance	ohms	0.54
Terminal Inductance	mH	0.72
Motor Constant	oz-in/watt^1/2	8.2
	Nm/watt	0.058
Rotor Inertia	oz-in-sec²	0.0052
	g-cm²	367.2
Friction Torque	oz-in	5
	Nm	0.04
Thermal Resistance	°C/watt	4.7
Damping Factor	oz-in/KRPM	0.2
	Nm/KRPM	0.001
Weight	oz	46
	g	1304
Electrical Time Constant	millisecond	1.3309
Mech. Time Constant	millisecond	10.80095
Speed/Torque Gradient	rpm/oz-in	-19.83865

Figure 2. Specification of DC motor.

One of SIMULINK's key advantages is its extensive library of toolboxes, which support both linear and nonlinear system simulations [11]. These toolboxes provide essential functionalities for various applications, including control system design, signal processing, and real-time simulations. In control system applications, some of the most commonly used libraries include mathematical operations, sinks, sources, and control blocks. These libraries enable users to design and fine-tune controllers for a wide range of dynamic systems, ensuring efficient and accurate performance.

Before conducting this research, the author first identified challenges related to position control in different system configurations, including Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO), and Multiple Input Multiple Output (MIMO) systems. These configurations vary in complexity and application, with SISO being the simplest and MIMO representing more advanced multi-variable control systems. A common issue in these systems is their susceptibility to external disturbances, which can impact their ability to maintain a desired position. By leveraging SIMULINK's powerful simulation capabilities, researchers can analyze system behavior under various conditions, develop optimized control strategies, and enhance overall system stability and performance.

3.3 Analytic order

From the mathematical model of a system, the order of the system is determined by the highest power of the variable s in its Laplace transform representation. The system order reflects the complexity of its dynamic behavior, influencing its response characteristics such as stability, transient behavior, and steady-state performance. A system is classified as first-order if its transfer function contains s raised to the first power as the highest exponent. These systems exhibit a relatively simple dynamic response, typically characterized by an exponential rise or decay over time.

Physically, first-order systems can be found in various engineering applications, including RC electrical circuits, where the relationship between voltage and current follows a first-order differential equation. Similarly, thermal systems that model heat transfer through conduction or convection often behave as first-order systems due to the proportionality between temperature change and heat input. Other examples include fluid-level systems in tanks and mechanical systems with simple damping effects, all of which display first-order dynamics [12, 13]. Understanding the behavior of first-order systems is crucial in control engineering, as they serve as foundational models for more complex higher-order systems.

The mathematical representations of first-order and second-order system models can be expressed using the following equations:

- Ordo 1

$$\frac{C(s)}{R(s)} = \frac{K}{\tau s + K} \tag{1}$$

- Ordo 2

$$\frac{C_{(s)}}{R_{(s)}} = \frac{Kt.Ke}{(Js + B)(R + Ls) + Kt.Ke} \tag{2}$$

3.4 State Space

The state-space method is a powerful analytical approach used to model and analyze complex control systems. Unlike classical transfer function-based methods, which primarily describe input-output relationships, the state-space representation provides a comprehensive view of a system's internal dynamics. This approach is particularly effective for evaluating systems with a single input and a single output, commonly referred to as SISO (Single Input, Single Output) systems. By utilizing state variables, the method enables a more detailed understanding of how the system evolves over time, making it an essential tool in modern control engineering.

In this model, the internal state variable (x) is used to predict the system's output (y) over time (t), incorporating both the immediate effect of the input and the influence of past states. This means that the system's response is determined not only by external inputs but also by its internal dynamics, which define how energy or information propagates through the system. The state-space model is particularly useful for representing multi-variable systems and time-domain analysis, allowing for the design and optimization of controllers that ensure stability and performance [14, 19].

The representation of input and output relationships in the state-space model is visually depicted in Figure 3. This graphical representation provides insight into how system states interact with inputs and outputs, facilitating the analysis of dynamic behaviors. By applying state-space techniques, engineers can effectively design controllers, analyze stability, and optimize system performance in a wide range of applications, from electrical circuits and robotics to aerospace and industrial automation.

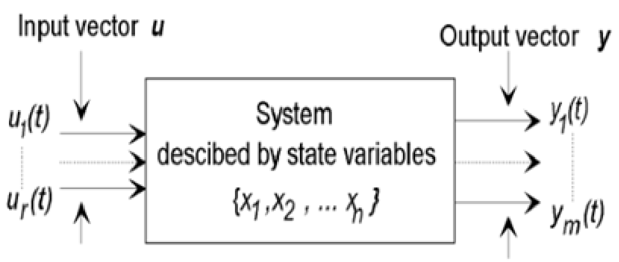

Figure 3. Input and output system inside state space.

Below is the block diagram representation of the state-space model, which visually illustrates the relationships between the system's input, state variables, and output. This diagram provides a structured overview of how the system transitions from one state to another over time based on the governing equations. The state-space formulation consists of two main equations: the state equation, which describes the evolution of the internal states based on system dynamics and input influences, and the output equation, which determines how the states contribute to the final system output.

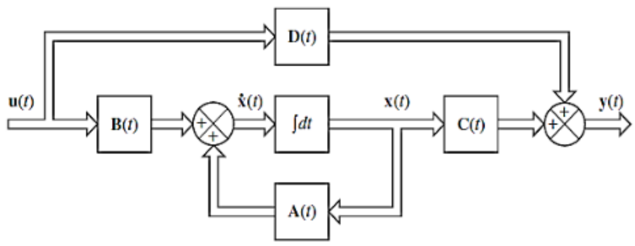

Figure 4. Block diagram state-space.

3.5 Linear Quadratic Regulator (LQR)

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

In designing an LQR controller, the first and most crucial step is the selection of the weight matrices Q and R, which directly influence the system's performance and stability. The weight matrix R is typically assigned a higher value relative to the state matrix, ensuring that excessive control effort is penalized to prevent unnecessary energy consumption. Meanwhile, the weight matrix Q is chosen to be larger than the input matrix, prioritizing the minimization of state deviations and enhancing system stability [15, 16].

Once these matrices are carefully defined, the next step involves computing the optimal feedback gain K. This gain is derived by solving the Algebraic Riccati Equation (ARE), which determines the control law that minimizes the quadratic cost function. The resulting feedback gain K is then applied to the system to regulate its state variables effectively.

After obtaining K, the closed-loop system response is analyzed through simulation, typically using MATLAB and Simulink. This simulation phase allows for the evaluation of key performance metrics such as settling time, overshoot, and steady-state error. By fine-tuning the Q and R matrices based on simulation results, the controller can be optimized to achieve the desired balance between control effort and system performance [18].

The LQR controller follows this formula:

$$U = -Kx \tag{4}$$

Challenges in the field of control systems go beyond simply achieving system stability; they also encompass

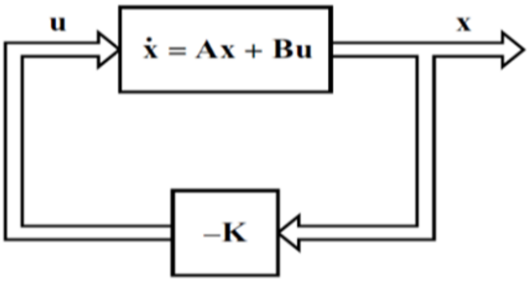

Figure 5. Block diagram of LQR.

ensuring that the system output precisely follows variations in setpoints or predefined reference values. This aspect, known as setpoint tracking, is crucial in applications where accuracy and responsiveness to changing inputs are required. A well-designed control system must be capable of dynamically adjusting its output to match the desired reference input while minimizing tracking errors and external disturbances. As can be seen in Figures 5 and 6, which depicts the LQR block diagram.

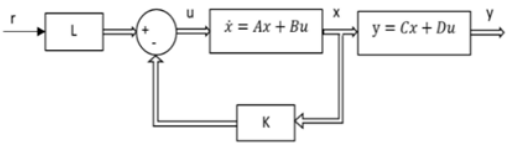

Figure 6. Block diagram control of LQR.

To achieve effective setpoint tracking, the control strategy must incorporate mechanisms that continuously compare the plant output (x) with the reference input. Any deviations should be corrected through appropriate control actions, ensuring that the system responds smoothly and efficiently. Advanced control techniques, such as feedforward control, state feedback, and adaptive control, are often employed to enhance tracking performance and robustness against uncertainties [17, 20].

To verify the accuracy of the collected data, a simulation is conducted using MATLAB SIMULINK R2018a. In this simulation, the system is supplied with a voltage input of 0.5 V. The response indicates that the system is unstable, exhibiting significant oscillations. Based on these simulation results without a controller, it is evident that the DC motor plant requires a control mechanism to mitigate oscillations and stabilize the system. To achieve this, an LQR controller is implemented.

4 Experiments

4.1 Model Circuit

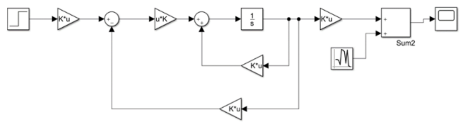

Figure 7. Simulink Circuit.

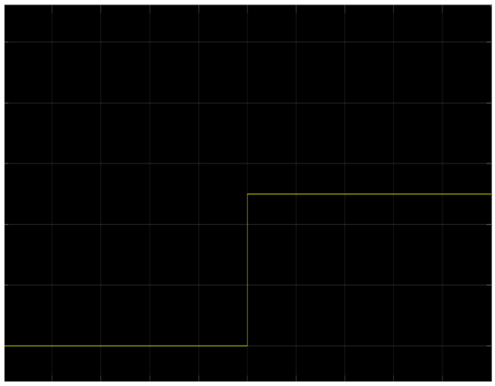

Figure 8. Simulink result LQR without noise.

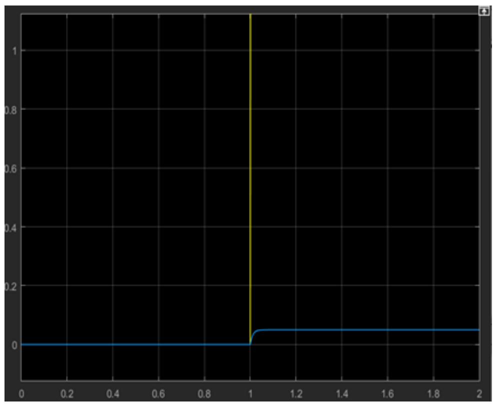

Figure 9. Simulink result LQR Tracking without noise.

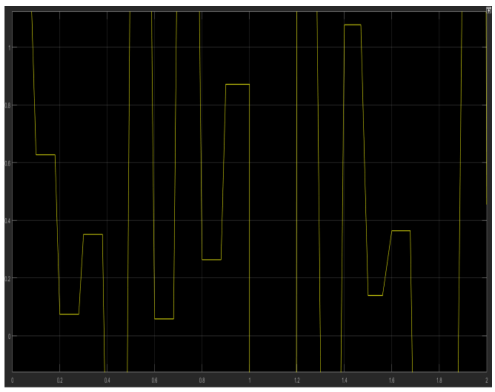

Figure 10. Simulink result LQR with noise.

The following is a waveform from the simulation process carried out in Simulink such as Figure 7. Figures 8 and 9 illustrate the system response to the

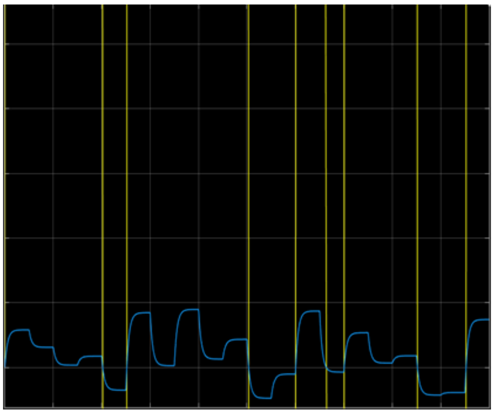

Figure 11. Simulink result LQR tracking with noise.

given input, including parameters such as amplitude, rise time, overshoot, and system stability.

As shown in Figures 10 and 11, it can be observed how the system reacts to disturbances or changes in setpoints, as well as how the control method used affects the overall performance. Comparisons between different control methods, such as LQR and LQT, can be done by analyzing this waveform.

By evaluating the waveform results from this simulation, further optimization can be done to improve system performance, reduce steady-state errors, and ensure faster and more stable responses to changes in operational conditions.

5 Conclusion

The research findings confirm that MATLAB software effectively processes real-time system response data. Various tests were conducted to assess controller performance, including setpoint variations, disturbance inputs, and sinusoidal reference signals.

The results demonstrate that the LQT controller outperforms the LQIT-GA controller in transient response and achieves a lower Integral of Absolute Error (IAE) during setpoint variation tests. The system's performance remained stable under setpoint changes, highlighting the LQT controller's superior adaptability compared to LQIT-GA.

However, in disturbance response testing, neither the LQT nor the LQIT-GA controller was able to return to the predefined setpoint after responding to disturbances, revealing a limitation in their ability to handle unexpected disruptions.

In sinusoidal reference signal testing, the LQT controller again showed better performance than the LQIT-GA controller, as indicated by a lower IAE value. This finding suggests that the LQT controller is more effective in managing dynamic reference signals.

Overall, the study underscores the potential of LQT controllers in enhancing energy solutions for community-based applications, particularly in systems requiring precise and efficient motor control. To expand its applicability in sustainable energy initiatives, further improvements are recommended to enhance disturbance-handling capabilities, ensuring reliable and efficient technology for underserved communities.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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