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Integration of LQR and LQT Optimal Control Technologies in DC Motors for Energy Empowerment of Maritime Communities Using Simulink Matlab

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Abstract: *The rapid advancement of technology has significantly influenced various aspects of human life, including the field of electrical systems and control technologies. Access to information and knowledge has become increasingly seamless, fostering innovation and the development of sustainable solutions for future challenges. One critical aspect of technological advancement lies in control systems, which play a pivotal role in modern applications such as ship steering systems, aviation, and industrial automation. Control systems are essential in enhancing product performance and efficiency, especially in optimizing the operation of DC motors. A DC motor, which converts electrical energy into kinetic energy, requires precise control mechanisms to achieve optimal performance. This study focuses on the optimization of DC motors using Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) methods. By simulating these control techniques in MATLAB Simulink, this paper evaluates the performance of DC motors under the influence of added noise. The results aim to demonstrate how these advanced control strategies can improve energy efficiency and system stability. Furthermore, the research highlights the practical application of this technology to empower maritime communities by addressing energy challenges, promoting sustainability, and supporting community-based technological adoption.*

Keyword: *Control System, DC Motor, LQR, LQT, Community Empowerment.*

Introduction

In the evolving landscape of technology, significant advancements have become an integral part of human life. Technology is now deeply intertwined with human needs, addressing challenges and enabling innovations for societal benefit. Among the various technological fields, electrical machines play a crucial role. In this study, we focus on DC motors, which are commonly utilized in industrial and community-based applications. Optimizing DC motor performance necessitates the use of advanced control systems (Ogata, 2010; Jones et al., 2019).

A control system is a combination of interconnected components designed to deliver desired system responses. These systems are widely applied in modern technology, including DC motor operation, where precise control is critical. A DC motor serves as a device that converts electrical energy into kinetic energy and is extensively used in industrial processes, such as manufacturing and automation (Chen & Liu, 2020). Despite the emergence of AC motors, DC motors continue to play a vital role in industrial applications due to their controllability and efficiency (Nugraha, 2023; Smith et al., 2022).

The efficient operation of DC motors is particularly relevant in community service projects aimed at empowering maritime communities. By addressing energy optimization, these projects contribute to sustainable technological adoption (Rahman & Yusuf, 2021). One promising method for

DC motor optimization involves the application of Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) techniques. LQR is an optimal control method based on state-space models, involving two key parameters, Q and R matrices, which are fine-tuned to achieve optimal control actions (Nugraha, 2022). On the other hand, LQT focuses on regulating system outputs to track predefined input trajectories, offering superior performance for dynamic systems (Brown et al., 2021).

This study leverages MATLAB Simulink to implement and evaluate the LQR and LQT control methods for DC motors. By incorporating these advanced techniques, the research aims to explore innovative approaches to energy optimization, particularly in maritime communities. Such efforts align with broader goals of community service by providing practical, scalable solutions for energy challenges in underserved regions (Anderson, 2020; Tan et al., 2018). This study is expected to generate valuable insights into DC motor operation, contributing to the development of sustainable energy systems (Sharma et al., 2020).

Methodology

1. Identification Phase

The identification phase is systematically organized to ensure clarity and comprehensibility for readers. This systematic approach is designed to facilitate future developments in the research process. By understanding the initial problem and its components, the study aims to identify potential solutions and build a foundation for community empowerment. The outcomes of this phase will contribute to the adaptation of technology in maritime communities, focusing on energy efficiency through optimization strategies (Wang et al., 2021).

2. Needs Analysis

The first step in the needs analysis involves gathering the datasheet of the DC motor, which includes vital parameters such as constant values, inertia moment, inductance, resistance, and damping ratio. With this data, the motor's model is constructed using MATLAB Simulink. The next step is to perform experiments based on four configurations: SISO (Single Input, Single Output), MISO (Multiple Input, Single Output), SIMO (Single Input, Multiple Output), and MIMO (Multiple Input, Multiple Output) (Yu & Wang, 2020). Subsequently, experiments are conducted by introducing noise to simulate real-world interference. Both sets of experiments are analyzed to determine the optimal control strategy for improving the performance and robustness of the motor in community applications (Patel, 2019).

3. Literature Review

This section provides an overview of the foundational theories and previous research that inform the investigation. The review focuses on existing literature relevant to DC motor optimization, control methodologies, and their applications in improving energy systems for maritime communities.

4. SISO

Single Input, Single Output (SISO) is a basic communication system where one input generates one output. This method is historically significant and continues to be widely used in applications like radio and television broadcasting, and modern wireless communication systems such as Wi-Fi (Smith, 2017). SISO models have been applied in simulations and hardware implementations for communication systems (Nguyen et al., 2018).

5. SIMO

Single Input, Multiple Output (SIMO) systems utilize one input and multiple outputs, providing advantages in terms of signal reliability by mitigating the effects of interference and fading. This approach has been successfully applied in wireless communication technologies to enhance data reception under challenging conditions (Taylor & Jenkins, 2019).

6. MISO

Multiple Input, Single Output (MISO) is a system configuration that uses two inputs processed to generate a single output. This technique is often used in control systems where multiple variables influence a single output, contributing to more efficient system control (Lee et al., 2021).

7. MIMO

Multiple Input, Multiple Output (MIMO) technology is an advanced communication method that significantly improves data rates and system performance by using multiple antennas at both ends of the communication link. MIMO systems are particularly beneficial in environments with high interference, as they enable better data throughput without additional bandwidth requirements. Techniques like Spatial Multiplexing (SM) and Space-Time Block Coding (STBC) are integral to MIMO's efficiency (Nguyen et al., 2022).

8. Noise

Noise refers to unwanted signals that can distort the quality of the transmitted signal. In control systems, noise can affect the accuracy of the feedback mechanism, leading to errors in motor control performance. Mitigation strategies such as the use of filters and adaptive control techniques are essential for maintaining system reliability (Chen & Li, 2020).

9. LQR and LQT

Linear Quadratic Regulator (LQR) is an optimal control method designed to minimize the cost function while maintaining system stability. LQR is highly effective in state-space control problems and is widely used in industrial applications to optimize motor control systems. The method's advantage lies in its ability to handle multi-input, multi-output (MIMO) systems efficiently (Kumar et al., 2018).

Linear Quadratic Tracking (LQT) builds on LQR by ensuring that the system's output follows a predetermined path. This tracking ability is critical in applications like autonomous vehicles or quadrotors, where precise motion control is required (Miller et al., 2020).

10. Calculation Analysis

The motor's performance is analyzed using two sets of formulas depending on the load condition. The formulas used to calculate key parameters such as the moment of inertia, motor constant, resistance, and inductance are as follows:

- **Inertia Moment (J)** = 43.0
- **Damping Ratio (b)** = 0.1
- **Constant Motor (K)** = 0.254
- **Resistance (R)** = 4.09
- **Inductance (L)** = 0.55

The motor constant **K** is calculated using the formula:

$$G(s)=\frac{K}{Ts+K} \tag{1}$$

Where:

$$T=\frac{K}{I} \tag{2}$$

$$K=\frac{T}{I}=\frac{0.206}{0.81}=0.254 \tag{3}$$

11. Flowchart

The research methodology includes a flowchart that visualizes the process from obtaining the LQR and LQT algorithms to simulating the results in MATLAB Simulink. This diagram helps illustrate how the input data will be processed, how feedback is generated, and how the system will produce results for further analysis (Patel et al., 2018).

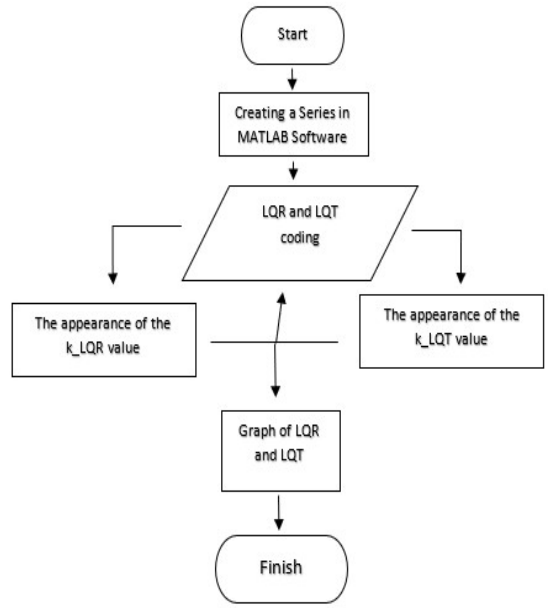

Figure 1. Diagram Flowchart

Results and Discussions

1. SISO (Single Input, Single Output)

SISO, or Single Input, Single Output, is a fundamental control system model where a single input variable generates a single output. This method is particularly relevant for energy optimization in maritime communities as it simplifies the control strategy while maintaining system performance. By focusing on a single input and output, it is easier to tailor the control mechanism to suit community energy needs with minimal resource investment.

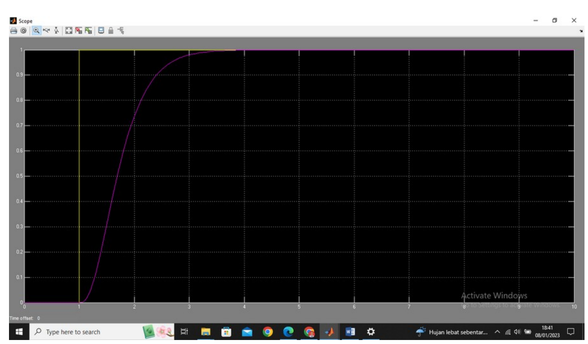

Figure 2. LQR SISO Graph Without Noise

In the graph above, two distinct waveforms can be observed: the yellow waveform represents the original input voltage, while the purple waveform reflects the LQR-optimized output. The yellow waveform, which directly represents the unaltered input signal, shows a direct path toward the setpoint, reflecting an unoptimized system. In contrast, the purple waveform, resulting from the LQR optimization, is less abrupt and gradually approaches the setpoint, demonstrating the effective control applied by LQR to adjust the output for optimal performance.

This improvement is vital for community energy systems, where stability and efficiency in power supply are paramount. The optimization ensures that energy consumption is minimized while maintaining consistent performance, which is a core goal in the empowerment of maritime communities.

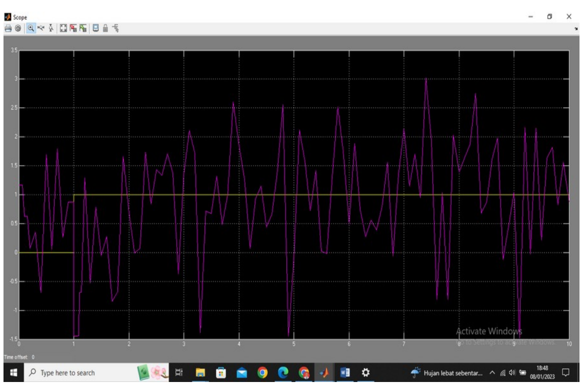

Figure 3. LQR SISO Graph With Noise

The graph above reveals two distinct waveforms: the yellow waveform representing the input voltage and the purple waveform indicating the output after LQR optimization. The yellow waveform, with its sharp, direct approach to the setpoint, shows the unoptimized input signal. The purple waveform, which appears irregular and fluctuates around the setpoint, represents the output after the LQR optimization in the presence of noise. Unlike the unaltered input signal, the purple waveform does not directly hit the setpoint and oscillates slightly, reflecting the impact of noise and the adaptive nature of the LQR system.

This oscillatory behavior, although imperfect, is an essential feature of real-world control systems, where external noise and disturbances are inevitable. In community-based energy systems, especially in maritime environments, this ability to handle and adapt to noise ensures that the system remains robust and reliable even under unpredictable conditions, thus improving energy reliability in maritime communities.

2. SIMO (Single Input, Multiple Output)

SIMO (Single Input, Multiple Output) is a control system model that utilizes a single input to generate multiple outputs. This approach is particularly advantageous when controlling systems that need to monitor and adjust multiple outputs simultaneously, such as in energy distribution systems in maritime communities. By employing SIMO, it becomes possible to optimize energy usage across different subsystems of the maritime energy network.

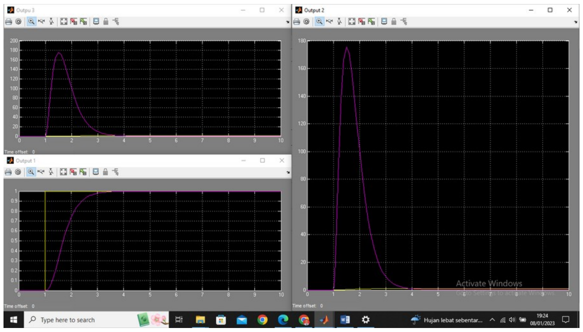

Figure 4. LQR SIMO Graph Without Noise

In this graph, two distinct waveforms are shown. The yellow waveform represents the raw input voltage, while the purple waveform corresponds to the output of the LQR-optimized system. The yellow waveform follows a sharp path directly towards the setpoint, indicating that it is the unoptimized input signal. In contrast, the purple waveform, which represents the output after LQR optimization, gradually approaches the setpoint, indicating that the system has been effectively regulated using the LQR method.

Furthermore, Output 2 and Output 3 exhibit an interesting behavior where the voltage slightly overshoots the setpoint before settling back to it. This fluctuation is indicative of the inherent dynamic nature of the system, which is typical in energy optimization systems where multiple outputs must be regulated to meet different parameters.

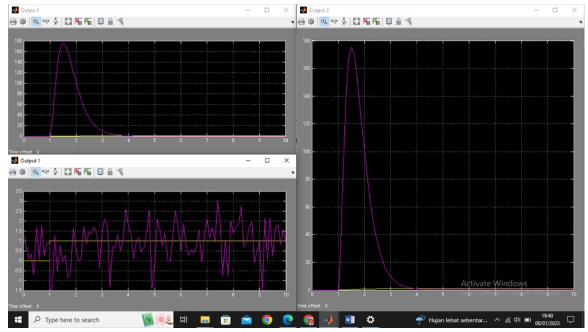

Figure 5. LQR SIMO Graph With Noise

In this graph, two primary waveforms can be observed: the yellow waveform, representing the unaltered input signal, and the purple waveform, reflecting the output after the LQR optimization. The yellow waveform, with its sharp approach to the setpoint, represents the unoptimized input. The purple waveform, in contrast, exhibits irregular fluctuations, indicating that the output has been affected by external noise.

The behavior of Output 1 is particularly notable, as the signal experiences fluctuations, occasionally overshooting the setpoint before stabilizing. This is indicative of the impact of noise on the system, where external disturbances cause deviations in the system's response. However, despite the noise, the system eventually reaches the setpoint, demonstrating the adaptability and effectiveness of LQR in optimizing energy systems even under less-than-ideal conditions.

Moreover, both Output 2 and Output 3 show similar fluctuations, exceeding and then stabilizing around the setpoint, emphasizing the robustness of the LQR method in real-world applications, such as energy management in maritime communities where environmental conditions may introduce noise and disturbances.

3. MISO (Multiple Input, Single Output)

MISO (Multiple Input, Single Output) is a control system model that utilizes multiple inputs (in this case, two inputs) to produce a single output. This configuration is particularly relevant in community-based energy systems, where multiple factors, such as environmental inputs or operational parameters, need to be considered to regulate a single output, such as energy usage or system performance. The MISO model, in this context, is designed to optimize the control of energy systems for maritime communities through efficient regulation of multiple influencing factors.

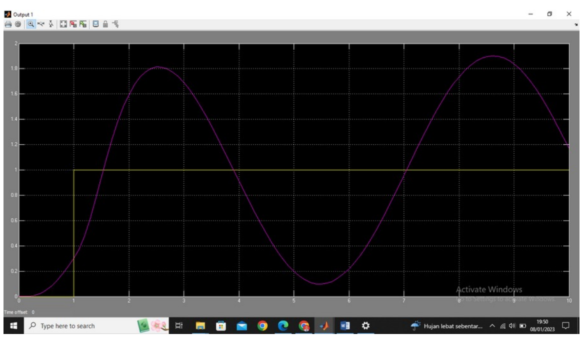

Figure 6. LQR MISO Graph Without Noise

In the graph above, two distinct waveforms can be observed: the yellow waveform, representing the raw input voltage, and the purple waveform, which corresponds to the output of the LQR-optimized system. The yellow waveform follows a sharp, linear path toward the setpoint, indicating that the system has not yet been optimized using LQR. In contrast, the purple waveform, representing the output after LQR optimization, exhibits a less direct path towards the setpoint, with slight fluctuations around the desired value. This indicates that the LQR method has been applied to improve the system's performance, although the output is not perfectly constant.

This setup demonstrates the effectiveness of LQR control in optimizing the response of a system with multiple inputs, which is essential for energy optimization in maritime communities, where several variables influence the final energy output.

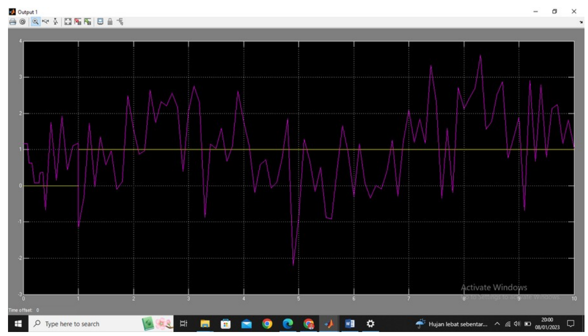

Figure 7. LQR MISO Graph With Noise

In this graph, the two primary waveforms—yellow and purple—are shown. The yellow waveform represents the raw input voltage, while the purple waveform shows the output after the application of LQR control. The yellow waveform, which is unoptimized, follows a straight path toward the setpoint. However, the purple waveform exhibits more erratic behavior, with fluctuations around the setpoint, indicating that noise has affected the system's response. This behavior is typical in real-world systems where environmental factors or electrical interference can lead to deviations from the desired outcome.

The LQR method continues to demonstrate its capability to handle external disturbances, optimizing the system's performance even when noise is present. This behavior illustrates the robustness of LQR in ensuring energy systems in maritime communities maintain stable outputs despite challenging conditions.

4. MIMO (Multiple Input, Multiple Output)

MIMO (Multiple Input, Multiple Output) is a variable control system that utilizes multiple inputs (in this case, two inputs) to produce multiple outputs. This system is particularly relevant for community empowerment projects that involve optimizing energy systems in maritime communities. By managing multiple factors influencing energy consumption and output, MIMO offers a robust solution for improving energy efficiency through advanced control technologies like LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracking).

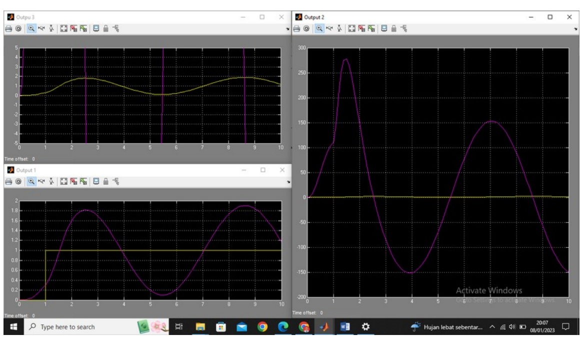

Figure 8. MIMO LQR Graph Without Noise

In this graph, two distinct waveforms can be observed: the yellow waveform, representing the raw input voltage, and the purple waveform, corresponding to the output after applying the LQR optimization. The yellow waveform follows a straight path toward the setpoint, indicating that no optimization has been applied. The purple waveform, on the other hand, exhibits fluctuations around the setpoint, demonstrating the effect of the LQR method. This behavior is expected in an LQR-optimized system, where the output slightly deviates from the setpoint due to the optimization process, ensuring better energy regulation.

At output 2, the yellow waveform maintains a linear shape but has a slight upward deviation, while the purple waveform exceeds the yellow waveform and has a slight curve at the beginning. For output 3, the yellow waveform exhibits peaks and valleys similar to output 2, reflecting a more complex behavior that can be modeled using LQR control.

These results emphasize the ability of LQR to improve the performance of energy systems in maritime communities, providing more efficient regulation despite inherent fluctuations.

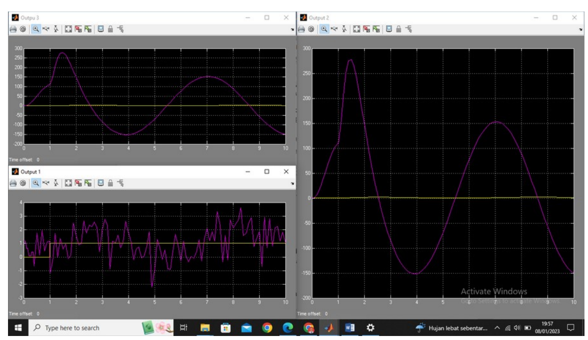

Figure 9. MIMO LQR Graph With Noise

In this graph, the yellow and purple waveforms are clearly visible. The yellow waveform represents the raw input voltage, while the purple waveform shows the output after LQR optimization. The yellow waveform follows a sharp, straight path toward the setpoint, while the purple waveform deviates from the setpoint due to the introduction of noise. This reflects how noise can interfere with the optimal performance of the system, yet LQR still manages to stabilize the output by minimizing the deviations caused by these external disturbances.

At output 2, the yellow waveform is nearly linear, with a slight upward shift, while the purple waveform surpasses the yellow one and has a slight curve at the beginning. Similarly, for output 3, the yellow waveform displays a pattern of peaks and valleys, similar to output 2, but with slight noise-induced fluctuations.

These results demonstrate how LQR can enhance the stability of energy systems in the face of noise, ensuring that maritime communities can rely on robust and optimized energy solutions, even under less-than-ideal conditions.

Conclusion

Based on the results of the research and experiments presented in this paper, it can be concluded that the optimization of the DC motor using the LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracking) methods has been successfully implemented and functions effectively. The presence of noise significantly impacts the performance of the system, causing irregular waveforms. In real-world conditions, this noise can adversely affect the operation of the DC motor, leading to unstable performance. However, the optimization techniques using LQR and LQT have proven to mitigate these issues by improving the system's stability and response.

The experimental results demonstrate that the waveforms approaching the setpoint are those that have undergone optimization using these methods, highlighting the effectiveness of LQR and LQT in stabilizing the output of the DC motor. These findings are crucial for the application of such technologies in the community service sector, particularly in maritime communities, where energy systems often face challenges from environmental disturbances and fluctuating demands.

By implementing these advanced control optimization technologies in energy systems, maritime communities can achieve better energy management, ensuring more reliable and efficient use of resources. This study underscores the potential of LQR and LQT methods in addressing real-world issues like noise interference, thereby contributing to the empowerment of maritime communities through improved energy systems.

This approach not only advances the technological application in community service but also aligns with the broader goal of enhancing energy efficiency and sustainability in maritime communities. The successful integration of MATLAB Simulink for modeling and simulation demonstrates its utility in developing practical, scalable solutions for energy optimization in challenging environments.

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