LQR and LQT System Optimization Models to Improve the Output Response Performance of Brushless DC Motors (BLDC) in the Context of Maritime Community Empowerment

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Abstract: *Brushless DC Motors (BLDC) are essential components commonly found in industrial settings and daily applications. To ensure optimal performance, control systems are required to enhance the operational efficiency of these motors. Modeling plays a critical role in determining whether the inherent response of a BLDC motor, even before applying a load, meets the desired performance criteria. Common plant models include SISO, SIMO, MISO, and MIMO systems, each requiring a mathematical representation to illustrate system responses through graphical outputs generated using software tools. This research focuses on the mathematical modeling of first-order and second-order BLDC motors, specifically the 42BLFX02 type, and examines their responses under different configurations, both with and without noise. In real-world scenarios, it is unrealistic for a plant to operate without disturbances, with internal noise being a common issue that impacts system performance. The study aims to compare the responses of first-order and second-order BLDC motors modeled in SISO, SIMO, MISO, and MIMO configurations, highlighting the effects of noise disturbances. Results indicate that the SISO model without noise exhibits the most optimal response, characterized by linear behavior and the absence of ripples. Additionally, second-order mathematical models produce responses closer to the setpoint values compared to first-order models. In MISO and MIMO configurations, the system's output responses tend to align with the shape of one of the input signals. Furthermore, noise inclusion causes the motor's output response to mimic the shape of the introduced noise signals. This study contributes to the development of control systems by providing insights into motor response behavior under various modeling configurations. The findings have significant implications for empowering maritime communities, particularly by optimizing energy-efficient BLDC motor applications in vessels to improve operational reliability and reduce energy consumption.*

Keyword: *Brushless DC Motor, Control Systems, Overshooting, Community Empowerment.*

Introduction

Brushless DC Motors (BLDC) are electronic components widely found in everyday life and industrial applications. These motors function as electromagnetic devices that convert electrical energy into mechanical motion (Imroatul Hudati, 2021). The principle of BLDC motor operation is based on ensuring the rotor's magnetic field direction opposes the stator's magnetic field direction, creating a repulsive force. A current-carrying coil generates a magnetic field around the armature coil in a specific direction (Alfian Ma'arif, 2021). In general, BLDC motors tend to decelerate under load conditions and do not maintain a constant speed. The motor speed can be adjusted by varying the input voltage. For instance, when the load increases and the motor slows down, its speed can be restored by increasing the input voltage (Widagdo Purbowaskito, 2017). Therefore, a control system is necessary to stabilize the motor speed during load variations. The primary function of a controller is to compare the plant's actual output with the reference input, calculate the error, and produce a control signal to minimize the error to near zero (Salman Jasim Hammoodi, 2020).

One of the methods employed for controlling BLDC motors to enhance their output is the Linear Quadratic Regulator (LQR) and the Linear Quadratic Tracker (LQT). The LQR method aims to make the motor's response closer to the desired setpoint while minimizing overshoot and undershoot within the system. The LQR control method has features such as robustness, reliability, and static gain generation, among others. By utilizing this optimal control method in multi-input systems, efficient control of several outputs can be achieved reliably and economically. The LQR technique designs an optimal controller that minimizes the specified cost function, also known as the performance index.

Meanwhile, LQT is a linear control system that ensures the system output follows a desired trajectory or reference (Akbar et al., 2016). The LQT is a model-based tracking control mechanism that employs affine state feedback to provide optimal control efforts. The LQT consists of a conventional state feedback component for linear dynamic systems and an additional feedforward control term, which depends on the reference signal vector (Saleem et al., 2018). LQT is often used in optimization problems involving tracking systems.

In this context, an experiment was conducted within the Optimization System course at the Department of Automation Engineering, Surabaya State Shipping Polytechnic, to observe the effects of LQR and LQT methods on the output response of a BLDC motor. The study further investigated the impact of noise disturbances on the system. Specifically, it evaluated whether the addition of LQR and LQT methods could mitigate the effects of noise or whether the motor response remained affected. The experiment also compared the performance differences between LQR and LQT optimization methods applied to the same BLDC motor type.

Methodology

1. Identification Phase of Brushless DC Motor Specifications

In this phase, the specifications of the Brushless DC Motor (BLDC) used in the research are identified. The motor selected for this study is a Brushless DC Motor with the type designation 86BLF03. Below is the datasheet for the motor:

Brushless DC Motor

86BLF Series

General Specifications

Winding Type: Star
Hall Effect Angle: 120°C Electrical Angle
Insulation Class: B
Ambient Temperature Range: -20°C ~ +50°C
Insulation Resistance: 100 MΩ Min. 500 VDC
Dielectric Strength: 750 VAC 1 minute

Customized solutions on request.

Hetai Motor

Electrical Specifications

Model		86BLF01	86BLF02	86BLF03	86BLF04	86BLF06	86BLF07
Number of Poles		8	8	8	8	8	8
Number of Phases		3	3	3	3	3	3
Rated Voltage	*VDC*	48	48	48	48	48	48
Rated speed	*RPM*	3000	3000	3000	3000	3000	3000
Rated Torque	*Nm*	1.4	1.05	0.7	0.35	1.8	2.1
Rated Current	*A*	14	9.6	6.6	3.9	18	22
Output Power	*W*	440	330	220	110	550	660
Peak Torque	*Nm*	4.2	3.2	2.1	1.05	5.4	6.3
Peak Current	*A*	38.0	29.0	19.8	10.8	46	55
Torque constant	*Nm/A*	0.115	0.115	0.112	0.11	0.115	0.116
Back EMF	*V/KRPM*	12.0	12.0	11.8	11.5	12.0	12.2
Rotor inertia	*gcm^2*	1250	950	650	350	1550	1850
Body Length	*mm*	94	81	67	57	109	124
Mass	*kg*	2.75	2.2	1.75	1.1	2.75	2.75

Caution: Peak Torque is provided for the purpose of performance calculations only. Operating near, or at this condition can result in motor damage.

Figure 1. Datasheet of Brushless DC Motor 86BLF03

From the datasheet, mathematical modeling of the motor is developed by deriving variable values critical for control optimization. These values serve as a foundation for integrating Linear Quadratic

Regulator (LQR) and Linear Quadratic Tracker (LQT) control systems aimed at improving energy efficiency and operational stability, particularly within maritime applications for community empowerment.

2. First-Order Mathematical Model

Mathematical modeling is conducted to determine the system response characteristics of the BLDC motor. The first-order system can be expressed as follows (Rahmatillah, 2020):

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

Where:

- C(s): System output
- R(s): System input
- *K: Overall gain*
- *τs+1: Time constant representing 63.2% response*

From the datasheet, torque (τ) and current (i) values are obtained, and the gain (K) is calculated as:

$$K = \frac{T}{i} = \frac{0.2}{2.1} = 0.095 \tag{2}$$

Substituting this into equation (1), the motor's transfer function becomes:

$$G(s) = \frac{K}{Ts+1} = \frac{0.095}{0.687\,s+1} \tag{3}$$

This model serves as the baseline for further optimization through the LQR and LQT methodologies.

3. Linear Quadratic Regulator (LQR) Control

LQR is a modern control theory method that optimizes multi-input, multi-output systems by minimizing a performance index J expressed as (Hammoodi, 2020):

$$J = \int_0^{\infty} \left(X^T Q x + u^T R_a \right) dt \tag{4}$$

The LQR seeks the optimal control signal u*, derived from:

$$u^{¿} = -Kx \tag{5}$$

Where K is the feedback gain matrix, calculated using the Algebraic Riccati Equation (ARE). The LQR control approach is particularly beneficial in maritime applications for improving BLDC motor response under varying loads, contributing to fuel efficiency and stability in community fishing vessels.

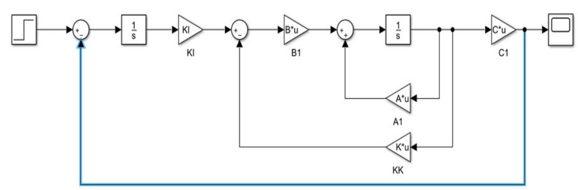

Figure 2. LQR Block Diagram

4. MATLAB Implementation of LQR on BLDC Motor 86BLF03

Below is the MATLAB code implementing the LQR optimization system:

```
% OPTIMIZATION OF LQR SYSTEM ON BLDC MOTOR

Clear; CLC;

% Motor Model Parameters

J=0.00000242; b=0.1; K=0.0167; R=0.343; L=0.00018;
```

```
% State-Space Representation
A = [-b/J K/J; -K/L -R/L];
B = [0; 1/L];
C = [1 0];
D = [0];

% LQR Parameters
Q = [1 0 0; 0 1 0; 0 0 1000];
R = [1];

% LQR Gain
K_lqr = lqr(A, B, Q, R);
disp(K_lqr);
```

5. Linear Quadratic Tracker (LQT) Control

LQT builds upon LQR by introducing feedforward terms to optimize trajectory tracking for reference signals *r(t)* (Saleem et al., 2018):

$$d(t) = -Kx(t) + K_{ff}\, r(t) \tag{6}$$

Where K_{ff} is the feedforward gain, critical for tracking maritime vessel performance under dynamic conditions. The Riccati Equation for LQT is extended to account for reference trajectories, enhancing stability during variable load scenarios.

6. System Block Diagrams

The first-order block diagram evaluates the motor's natural response, serving as a baseline for LQR and LQT enhancements.

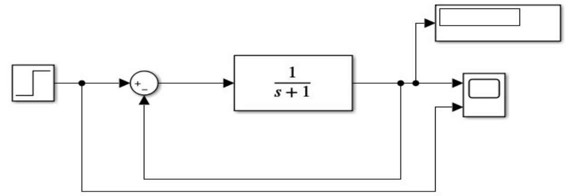

Figure 3. First-Order BLDC Motor Block Diagram

This block diagram integrates LQR to assess its impact on response improvements.

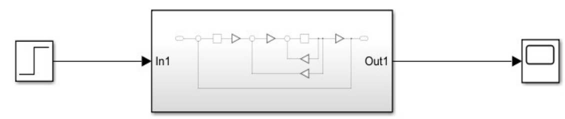

Figure 4. LQR Block Diagram for BLDC Motor

Noise is introduced to simulate real-world maritime conditions, analyzing LQR robustness.

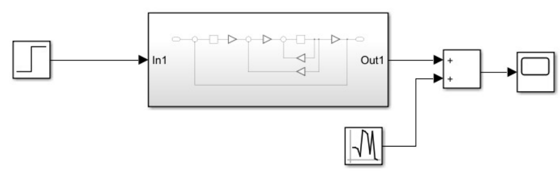

Figure 5. LQR with Noise on BLDC Motor Block Diagram

Results and Discussions

This section discusses the performance analysis of the DC motor response under first-order mathematical modeling, as well as the application of the LQR method with and without noise. The outcomes were obtained through simulation using MATLAB Simulink software.

1. First-Order Response of Brushless DC Motor 866BLF03

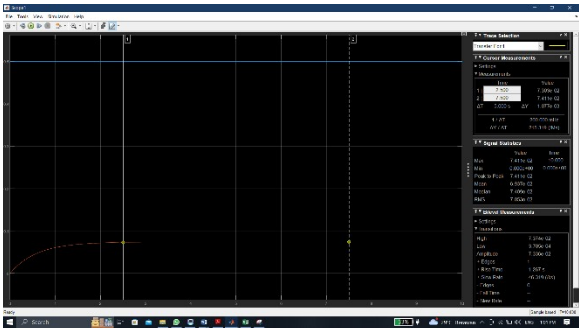

Figure 6. First-Order Response of Brushless DC Motor 866BLF03

The first-order response output, as depicted in Figure 6, demonstrates that the motor's output is significantly distant from the desired setpoint. The orange waveform represents the motor's response, while the blue line signifies the desired setpoint. The target setpoint is 0.5, whereas the motor response only reaches 0.07. The observed DC motor exhibits linear characteristics, as indicated by the absence of ripples in the signal. The motor reaches a steady-state condition at approximately 2 seconds after being activated. This response can be categorized as slow and suboptimal for maritime community applications that require rapid adjustments in energy systems.

2. Response of Brushless DC Motor 866BLF03 Using LQR Method

Figure 7. Response of Brushless DC Motor 866BLF03 with LQR Method

As shown in Figure 7, the LQR-optimized response of the Brushless DC Motor 866BLF03 successfully aligns with the desired setpoint of 0.5. The motor achieves this setpoint within approximately 1.2 seconds without exhibiting any overshoot or undershoot. The use of the LQR method significantly enhances the motor's performance, ensuring a stable and accurate response. This improvement makes the system more suitable for energy optimization in maritime communities, where precise motor control is essential for tasks such as propulsion or power generation.

3. Comparison of Responses with and Without LQR Method

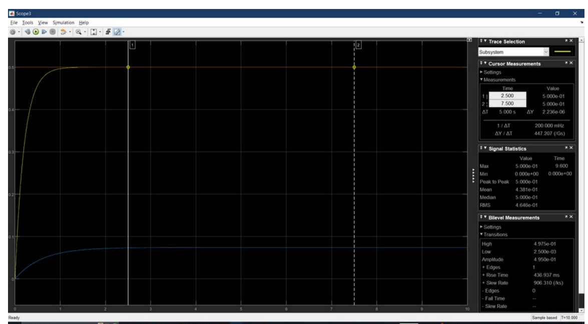

Figure 8. Comparison of Responses for Brushless DC Motor 866BLF03 with and Without LQR Method

Figure 8 highlights the comparative performance of the Brushless DC Motor 866BLF03 when optimized using the LQR method versus no optimization. The orange line represents the desired setpoint, the blue line shows the motor response without LQR, and the yellow line depicts the motor response with LQR. The results reveal that the LQR-optimized motor response is significantly closer to the setpoint, achieving faster stabilization and eliminating overshoot or undershoot. The enhanced stability and precision underscore the potential of LQR-based systems in maritime community empowerment projects, where reliability and efficiency are critical.

4. Response of Brushless DC Motor 866BLF03 Using LQR Method with Noise

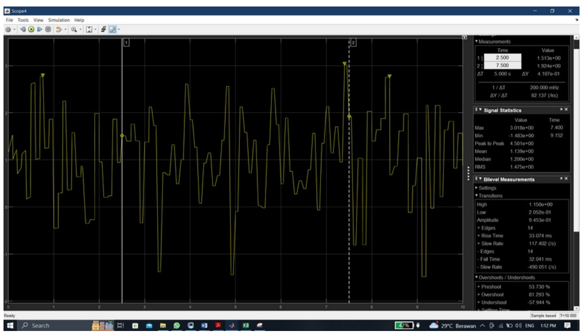

Figure 9. Response of Brushless DC Motor 866BLF03 with LQR Method under Noise Conditions

Figure 9 illustrates the motor response when subjected to noise while using the LQR method. The yellow signal, representing the motor response, displays significant ripple effects and closely mimics the noise input. The signal deviates from its linear form and fails to maintain steady-state conditions at the desired setpoint. This finding highlights the limitations of the LQR method in mitigating noise interference, suggesting a need for further optimization, such as incorporating robust control techniques. Addressing this issue is vital for maritime community applications, where noise from environmental factors like waves and engine vibrations can significantly impact performance.

Conclusion

The experimental results demonstrate that the application of the LQR method improves the performance of the Brushless DC Motor 866BLF03. The optimized motor response successfully reaches the desired setpoint with a faster settling time compared to the non-optimized response. The results validate the theory that LQR optimization enhances DC motor performance by ensuring a stable and accurate response. However, when noise is introduced into the system, the LQR method struggles to maintain its optimized response, resulting in outputs that mimic the noise signal. This limitation highlights the need for further research and the integration of noise-resistant methods to ensure optimal motor performance under real-world maritime conditions.

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