Journal for Maritime in Community Service and Empowerment ISSN:
Vol. xx, No xx, Month-year

Comparison of LQR Optimization Methods in Enhancing the Output Response of Maxon EC-i 40 DC Motors for Community

* Nur Zafira Arya Ar Rahmah
Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya, Indonesia
*Correspondence author: nurzafira@student.ppns.ac.id

Abstract: *DC motors are widely used in both industrial and everyday applications due to their versatility and reliability. To optimize the performance of DC motors, implementing an effective controller is essential to ensure efficient operation under varying conditions. Modeling plays a critical role in evaluating whether the intrinsic response of a DC motor, even before being subjected to load, meets performance expectations. Common modeling techniques include SISO (Single Input Single Output), SIMO (Single Input Multiple Output), MISO (Multiple Input Single Output), and MIMO (Multiple Input Multiple Output). Accurate plant modeling requires the mathematical representation of the system to visualize its response graphically, often aided by specialized software. This study focuses on first-order and second-order mathematical models of DC motors, analyzing their behavior under different configurations and disturbances. Real-world systems are inevitably affected by disturbances, including internal noise, which can significantly influence system performance. The primary objective of this research is to compare the response characteristics of a 42BLFX02 DC motor under first-order and second-order mathematical models when configured as SISO, SIMO, MISO, or MIMO systems, with and without noise interference. The findings reveal that the SISO configuration without noise interference delivers the most stable and linear response, free of ripples. Second-order mathematical models produce responses closer to the setpoint compared to first-order models. In MISO and MIMO configurations, the system's output response tends to mirror one of the input signals. The introduction of noise significantly alters the output response, causing it to emulate the noise pattern.*

Keyword: *Modeling, SISO, SIMO, MIMO, MISO*

Introduction

DC motors are electronic components widely used in everyday life, owing to their versatility and efficiency in converting electrical energy into mechanical motion [5]. The working principle of DC motors involves the interaction between the rotor's magnetic field and the stator's magnetic field, where opposing forces result in rotational movement. This interaction is facilitated by current flowing through the armature windings, creating a directional magnetic field around the rotor [2][3].

In practical applications, DC motors tend to slow down under load, resulting in non-uniform speeds. The speed can be regulated by adjusting the input voltage [12]. For instance, when a load increases and the motor slows down, increasing the input voltage can restore the desired speed. This highlights the necessity for controllers to stabilize motor speed amidst varying load conditions. The primary function of a controller is to compare the actual output value of a system (plant) with the reference input (desired value), determine the error, and generate a control signal to minimize the error as closely as possible to zero [10].

Among the methods used to enhance the output performance of DC motors are the Linear Quadratic Regulator (LQR)[6]. LQR aims to optimize motor response, bringing it closer to the desired setpoint while reducing overshoot and undershoot in the system. The LQR control method exhibits robust characteristics, including reliability, static gain generation, and efficient control over systems with multiple inputs and outputs[7]. This method is particularly effective in large systems with multiple inputs, enabling reliable and economical control of multiple outputs by minimizing a predefined cost function or performance index.

On the other hand, LQT is designed for trajectory tracking, where the system output follows a desired reference trajectory [1]. LQT is a model-based tracking control mechanism that employs affine state-feedback to provide optimal control effort. It consists of regular state feedback for linear dynamic systems, combined with an additional feedforward control term that depends on the reference signal vector [9]. Typically, LQT is applied in optimization problems that involve system tracking requirements[8].

In the Optimization System course at the Shipbuilding Polytechnic of Surabaya, experiments were conducted to investigate the impact of LQR optimization methods on the output response of DC motors. The experiments also examined the system's behavior under noise conditions, evaluating whether the addition of LQR methods could mitigate noise effects or if the motor's response would still be influenced. Furthermore, the study aimed to compare the performance differences between LQR optimization methods for a specific type of DC motor.

This research has practical significance, particularly in community engagement initiatives, such as improving automation systems for small-scale industries or renewable energy applications in rural areas. By enhancing the reliability and efficiency of DC motor operations, these optimization methods contribute to sustainable development efforts and community empowerment.

Methodology

1. DC Motor Identification

At this stage, identification is carried out regarding the specifications of the DC Motor that will be researched. The form of the DC Motor that is researched is in the form of a motor Brushless with the name and type Maxon EC-I 40 70 Watt. The following is data sheet from Maxon EC-I 40 70 Watt DC Motor.

		with Hall sensors	449469
Motor Data			
	Values at nominal voltage		
1	Nominal voltage	V	18
2	No load speed	rpm	10100
3	No load current	mA	354
4	Nominal speed	rpm	8230
5	Nominal torque (max. continuous torque)	mNm	68.7
6	Nominal current (max. continuous current)	A	3.93
7	Stall torque[1]	mNm	876
8	Stall current	A	52.5
9	Max. efficiency	%	84
	Characteristics		
10	Terminal resistance phase to phase	Ω	0.343
11	Terminal inductance phase to phase	mH	0.18
12	Torque constant	mNm/A	16.7
13	Speed constant	rpm/V	572
14	Speed/torque gradient	rpm/mNm	11.7
15	Mechanical time constant	ms	2.98
16	Rotor inertia	gcm^2	24.2

Figure 1. Maxon EC-I 40 70 Watt DC Motor Datasheet

From Figure 1, data can be taken regarding the specifications of the Maxon EC-I 40 70 Watt DC Motor.

2. First Order Mathematical Modelling

Mathematical modeling is carried out in order to obtain the response results of the DC motor[11]. The mathematical model of the first-order system can be written as follows [4]:

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

Where:
C(s) = System output.
R(s) = Input system.
K = Overall Profit.
τs+1 = Time required to reach 63.2% (seconds) on order one.

Where τ= $K.i$ so that:

$$K = \frac{\tau}{i}$$

Where:
τ = Torque
i = current

So the calculation for the Maxon EC-I 40 70 Watt DC motor type is based on the specifications of data sheet what is obtained is:

$$K = \frac{\tau}{i} = \frac{0.2}{2.1} = 0{,}095$$

Substitute the results of equation 3 into equation 1 to obtain the mathematical model of the 42BLFX02 type DC motor:

$$G(s) = \frac{K}{\tau s + 1} = \frac{0{,}174}{0.687s + 1}$$

3. Optimal Control Linear Quadratic Regulator (LQR)

The Linear Quadratic Regulator (LQR) is an advanced control method that employs a state-space representation approach. It involves determining two key parameters, the weight matrices Q and R, to achieve the desired control behavior[13]. Adjusting the weights of these matrices enables the control response to meet specific design requirements. The control system under consideration is defined by the equations:

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

The optimization process in the LQR method involves finding the input signal that transitions the state of a linear system from an initial condition x(t0) to a final condition x(t), while minimizing a quadratic performance index. This performance index serves as a cost function, reflecting the degree to which the system's actual performance aligns with the desired outcome[14]. The cost function is expressed as the integral over time of a quadratic form of the state vectors x and u, as represented in the following equation:

$$J = \int (X^T Q_x + u^T R_a) dt$$

Here, Q is a positive definite or positive semidefinite real symmetric matrix, and R is a positive definite real symmetric matrix. These matrices Q and R define the trade-off between system performance errors and energy consumption

The LQR approach aims to derive optimal control signals using state feedback.

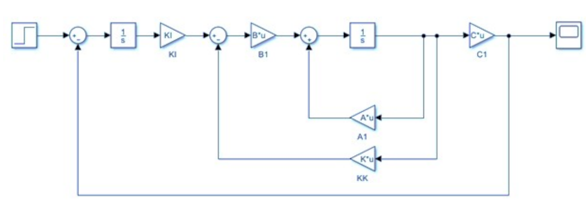

Figure 2. LQR Circuit

4. Optimal Control Linear Quadratic Tracker (LQT)

Linear Quadratic Tracking (LQT) is an optimal control method developed for linear plants to overcome tracking problems with a control system whose output is regulated so that it follows (tracking) a predetermined path through input [19][15].

The general form of the state equation of a linear system is shown by the following equation:

$$\dot{x}=Ax+Bu\,y=Cx$$

Apart from having a state equation, a system also has an error vector like the following equation:

$$e(t)=z(t)-y(t)$$

LQT aims to ensure that the system output follows the reference model output as closely as possible and minimizes the given performance index. Where the performance index is defined in the following equation:

$$J=\frac{1}{2}e'(t_f)F(t_f)e¿$$

Assuming that $F(t_f)$ and Q(t) are symmetric positive semidefinite matrices with dimensions (m x m)[16]. R(t) is a positive definite matrix which is also symmetric (R×R). Matrix Q and R are weighting matrices that determine the performance of the system to be controlled[18].

After obtaining a mathematical model of the system in statespace form and matrices A(t) and B(t), the Riccati differential equation solution matrix can be obtained with the following equation for the finitetime case:

$$\dot{P}(t)=-P(t)A(t)-A'(t)P(t)+P(t)B(t)R^{-1}(t)$$

and The following equation is for the infinite-time case

$$0=-P(t)A(t)-A'(t)P(t)+P(t)B(t)R^{-1}(t)B'(t)P(t)+C$$

The Q and R matrices can be assumed to be in accordance with the desired performance of the system. After obtaining the Riccati equation, the non-homogeneous vector differential equation can be searched using Eq:

$$\dot{g}(t)=-[A(t)-B(t)R^{-1}(t)B'(t)P(t)]'+C'(t)Q(t)$$

After getting the matrix P(t) which is a symmetric positive definite matrix and g(t), the feedback gain values K(t) and u*(t) can be found using the Riccati equation:

$$K(t)=R^{-1}(t)B'(t)P(t)$$
$$u*(t)=-K(t)x*(t)+R^{-1}(t)B'(t)g(t)$$

From the equation above, we get a constant K matrix value that does not change as a function of time [20].

5. Diagram block

- First order block diagram
  In the first order motor block diagram, the aim is to find out the original response
  results of the DC motor if the Maxon EC-I 40 70 Watt DC motor is not added to the method carried out in simulink software.

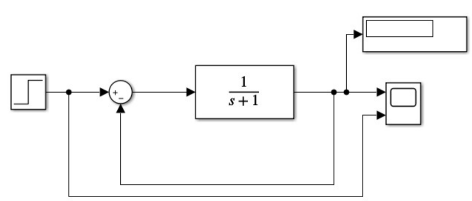

Figure 3. First Order Block Diagram of DC Motor

Figure 3 shows a first-order block diagram of a DC motor consisting of an input and a output. Input which is used in various types step response. Transfer Function The diagram can contain the modelling of a first-order DC motor. The
response results will be displayed on scope And display to find out the maximum response value generated.

- Without noise
  In the LQR block diagram of the Maxon EC-I 40 70 Watt DC Motor, the aim is to find out the response results of the DC motor if the DC motor is given the addition of the LQR optimization method which is carried out on simulink software.

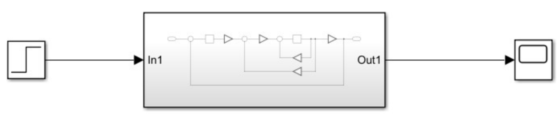

Figure 4. Block Diagram of Maxon EC-I 40 70 Watt DC Motor LQR

- With noise
  In the LQR block diagram of the Maxon EC-I 40 70 Watt DC Motor with noise aims to find out the response results of the DC motor if the DC motor is given the addition of the LQR optimization method and the addition of noise on the system carried out on simulink software.

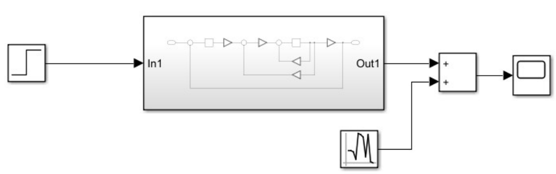

Figure 5. Block Diagram of LQR DC Motor Maxon EC-I 40 70 Watt with noise

Results and Discussions

In this section, the results of the response of the Maxon EC-I 40 70 Watt DC motor are discussed in the first-order mathematical model and when given the LQR method with and without noise. The response results were obtained using simulations on software Matlab Simulink.

1. First Order Response Results of Maxon EC-I 40 70 Watt DC Motor

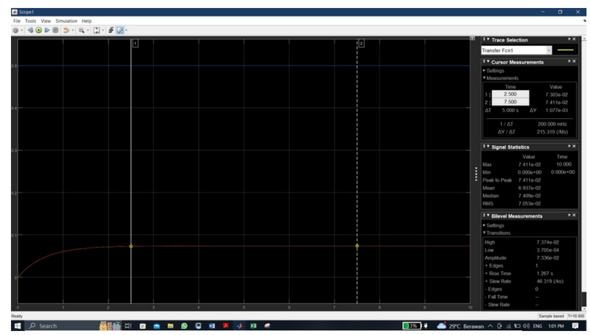

Figure 3.1 Results of the Maxon EC-I 40 70 Watt DC Motor Response in First Order Mathematical Modeling

On output The first order modal response seen in Figure 3, shows that the motor response graph in the first order has an output that is very far from the desired set point. The orange wave is the result of the motor response while the blue wave is the desired set point. The desired set point is 0.5 while the motor response is only at a value of 0.07. The observed Maxon EC-I 40 70 Watt DC motor has linear characteristics as indicated by the signal shape that has no ripples. The motor response is in a condition steady stateat ±2 seconds, after the motor is turned on. The response is quite slow.

2. Response Results of Maxon EC-I 40 70 Watt DC Motor Using LQR Method

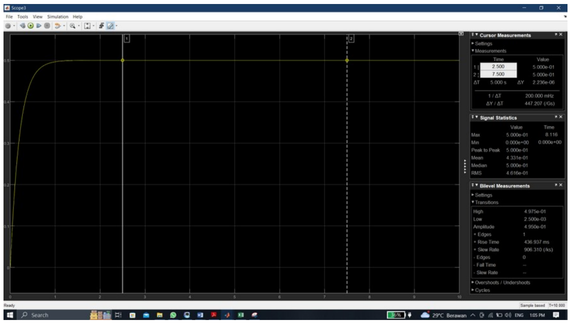

Figure 7. Results of the Maxon EC-I 40 70 Watt DC Motor Response with the LQR Method

On output capital response figure 7, it can be seen that the response graph of the Maxon EC-I 40 70 Watt DC motor using LQR has the same output as the desired set point value. The desired set point is 0.5, the motor response successfully reaches the set point value at ±1.2 seconds without any value overshoot And undershoot. The response of the Maxon EC-I 40 70 Watt DC motor using the LQR method is better that without using the LQR method.

3. Comparison Results of Maxon EC-I 40 70 Watt DC Motor Response Using LQR Method and Without LQR Method

Figure 8. Comparison Results of Maxon EC-I 40 70 Watt DC Motor Response with LQR Method and no

Onoutputcapital comparison response figure 8, shows the response graph of the Maxon EC-I 40 70 Watt DC motor using LQR and not using the method has a different response output. The orange wave is the desired set point, the blue wave is the motor response without using the LQR method, and the yellow wave is the motor response using the LQR method. it is clearly seen that the response of the Maxon EC-I 40 70 Watt DC motor with the LQR method has a better response compared to without the LQR method. In addition to the response that has a value according to the desired set point without any overshoot And undershoot, The motor response also becomes faster to reach the value steady state.

4. Response Results of Maxon EC-I 40 70 Watt DC Motor Using LQR Method with Noise

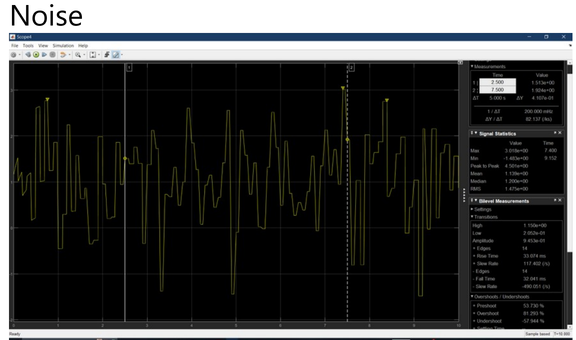

Figure 9. Results of the Maxon EC-I 40 70Watt DC Motor Response with the LQR Method When Given Noise

From the results of Figure 4.4, it can be seen that the yellow signal which is the result of the response of the Maxon EC-I 40 70 Watt DC motor with the LQR method has changed shape from before the noise was given. The signal shape experiences a lot of ripples and imitates the shape of the noise signal given. The resulting signal is no longer linear and far from stable conditions or steady state at the given set point.

Conclusion

The experimental results on the Maxon EC-I 40 70W DC motor demonstrated that the application of the Linear Quadratic Regulator (LQR) optimization method significantly improves the motor's output response. This improvement is evident as the Maxon EC-I 40 70W motor consistently achieved the desired setpoint within a shorter time frame compared to its performance without the LQR method. Without LQR optimization, the motor's response deviates substantially from the desired setpoint and requires a longer time to stabilize. These findings validate the theoretical premise that the LQR optimization method enhances the dynamic response of DC motors, ensuring faster and more precise performance.

However, the study also revealed a limitation of the LQR method: its inability to maintain robust response results in the presence of noise. When noise was introduced into the system, the motor's output response using LQR closely followed the noise signal, resulting in a non-linear and unstable output. This behavior underscores the need for further optimization or complementary methods to enhance noise resistance.

The implications of these findings extend beyond technical performance, particularly in community engagement applications. By adopting optimized control methods like LQR, communities and small-scale industries relying on DC motors for automation or renewable energy systems can benefit from enhanced efficiency and reliability. Addressing the noise sensitivity of the LQR method could further contribute to its utility in real-world applications where environmental or operational disturbances are common.

Future research could explore the integration of Linear Quadratic Tracker (LQT) or hybrid optimization techniques to address the limitations observed, especially in noise-prone environments. This progression aligns with the broader goal of empowering communities with resilient and efficient motor systems, ultimately supporting sustainable development initiatives and technological advancement.

References

[1] Akbar, F. C., A.K, R. E., & Iskandar, E. (2016). Tuning Parameter Linear Quadratic Tracking Menggunakan Algoritma Genetika Untuk Pengendalian Gerak Lateral Quadcopter. Jurnal Teknik ITS, 5(1). https://doi.org/10.12962/j23373539.v5i1.14364

[2] Alfian Ma'arif, R. I. (2021). Kontrol Proporsional Integral Derivatif (PID). ELKOMIKA: : Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika, 9(2), 375.

[3] Fauzi Yuda Pratama, E. (2018). RANCANG BANGUN PENGENDALIAN KECEPATAN BRUSHLESS DC MOTOR TIPE

A2212/10T 1400 KV MENGGUNAKAN KONTROLER PID BERBASIS LABVIEW. Teknik Elektro, 7(3), 157-166.

[4] Gany Rahmatillah, B. S. (2020). SISTEM PENGENDALIAN KECEPATAN MOTOR DC PADA PROTOTIPE LIFT MENGGUNAKAN KONTROLER PI BERBASIS ARDUINO. Jurnal Teknik Elektro, 9(2), 269-275.

[5] Imroatul Hudati, A. P. (2021). KENDALI POSISI MOTOR DC DENGAN MENGGUNAKAN KENDALI PID. Jurnal Listrik, Instrumentasi dan Elektronika Terapan, 25.

[6] Kumara, I. N. S., 2007. MODELING PENGATURAN KECEPATAN MOTOR DC DENGAN SIMULINK. Teknologi Elektro, 6(1), p. 25.

[7] Ljung, L., 1999. Model validation and model error modeling. Linköping University Electronic Press.

[8] Saisudha V., S. G. R. V. P. G. M. R. R. B., 2016. Analysis of speed control of DCmotor using LQR method. IJCTA, 9(15), pp. 7377-7385.

[9] Saleem, O., Rizwan, M., & Ahmad, M. (2018). Augmented linear quadratic tracker for enhanced output-voltage control of DC-DC buck converter. Control Engineering and Applied Informatics, 20(4), 40–49.

[10] Salman Jasim Hammoodi, K. S. (2020). Design and implementation speed control system of DC Motor. International Journal of Power Electronics and Drive System (IJPEDS), 127-134.

[11] Shah, C. R. (2017). Performance and Comparative Analysis of SISO, SIMO, MISO, MIMO. International Journal of Wireless Communication and Simulation, 1-14.

[12] Widagdo Purbowaskito, C.-H. H. (2017). Sistem Kendali PID untuk Pengendalian Kecepatan Motor Penggerak Unmanned Ground Vehicle untuk Aplikasi Industri Pertanian. INFOTEL, 9(4), 376-381.

[13] Nugraha, Anggara Trisna, et al. "IOT-Based Smart Home Control Design Using Blink Application and Esp8266 Wi-Fi Module." Mein: Journal of Mechanical, Electrical & Industrial Technology 1.1 (2024): 7-11.

[14] Nugraha, Anggara Trisna, et al. "PEMODELAN DAN SIMULASI OPEN LOOP SERTA CLOSE LOOP MOTOR DC TYPE 18105 ORDE 2." Prosiding Seminar Nasional Terapan Riset Inovatif (SENTRINOV). Vol. 10. No. 1. 2024.

[15] Achmad, Irgi, and Anggara Trisna Nugraha. "Implementasi Buck-Boost Converter pada Hybrid Turbin Angin Savonius dan Panel Surya." Journal of Computer, Electronic, and Telecommunication (COMPLETE) 3.2 (2022).

[16] Febrianti, Chusnia, and Anggara Trisna Nugraha. "Implementasi Sensor Flowmeter pada Auxiliary Engine Kapal Berbasis Outseal PLC."

Journal of Computer, Electronic, and Telecommunication (COMPLETE) 3.2 (2022).

[17] Ivannuri, Fahmi, Anggara Trisna Nugraha, and Lilik Subiyanto. "Prototype Turbin Ventilator Sebagai Pembangkit Listrik Tenaga Angin." Journal of Computer, Electronic, and Telecommunication (COMPLETE) 3.2 (2022).

[18] Jamil, M. H., et al. "The existence of rice fields in Makassar City." IOP Conference Series: Earth and Environmental Science. Vol. 681. No. 1. IOP Publishing, 2021.

[19] Syahdana, O. P., Syai'in, M., & Nugraha, A.T (2022). RANCANG BANGUN AUTOFEEDER DENGAN SISTEM NAVIGASI WAYPOINT DAN KENDALI KESTABILAN POSISI MENGGUNAKAN METODE FUZZY LOGIC. Jurnal Conference on Automation Engineering and Its Application, 2. 261-269

[20] Agna, Diego Ilham Yoga, Salsabila Ika Yuniza, and Anggara Trisna Nugraha. "The Single-Phase Controlled Half Wave Rectifier with Single-Phase Generator Circuit Model to Establish Stable DC Voltage Converter Result." International Journal of Advanced Electrical and Computer Engineering 3.3 (2022).