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Simulation Analysis of LQR & LQT (Linear Quadratic Regulator & Linear Quadratic Tracking) with M644E DC Motor Plant

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ABSTRACT

In today's modern era, the development of renewable technology is increasingly rapid, which of course was created by humans. One method used by humans to develop technology is to optimize the system. System optimization is a way to achieve the best desired results. This is comparable to a control system, which is designed to replace the role of humans in controlling a system. Some system optimization circuits include the LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracking) circuits. LQR and LQT have different purposes. LQT is used to find optimal solutions in control problems that aim to keep the system with variables/outputs within small limits, while LQR is used to find optimal solutions in tracking problems that aim to force the system output to follow the desired path. In this paper, the LQR and LQT optimal control systems will be discussed using the M644E DC motor plant.

Keywords *: : DC Motor, Linear Quadratic Regulator (LQR), Linear Quadratic Tracking (LQT), Simulink, Matlab.*

I.INTRODUCTION

Optimization technique is an approach used to achieve the best desired results. Optimization is a discipline in mathematics that focuses on finding the minimum or maximum value mathematically of a function, opportunity, or other value search in various contexts[1][2]. Thus, it can be concluded that system optimization is a method or system used by humans to design a control system that aims to achieve optimal results according to the desired goals[3].

In this "System Optimization" lesson, the author discusses the use of the LQR method on a DC motor system by attaching a data sheet. The data from the specification sheet will be entered into a MATLAB script and then simulated using MATLAB SiM644E software which has values for moment of inertia, driving constant, damping ratio, resistance, and inductance[4][5].

Please open the link to see the step response. The DC motor used is the M644E type which has moment inertia, motor constant, damping ratio, resistance, and inductance[6].

Through this paper, it will also be explained the differences between the signal graphic images created through the oscilloscope of the LQR and LQT circuits, both with and without noise[7][8]. In this paper, it will be discussed in depth about the efficiency of using LQR and LQT in its application to a system, with the aim of optimizing the system according to the desired needs.

II.METHODOLOGY

2.1 Research Stages

In the System Optimization practicum, the author uses Matlab software to design a circuit with the help of Simulink[9]. Before designing the circuit, the initial step is to create a code in the Matlab script, which requires a Datasheet[10]. The results of this process will be used to build the circuit in Simulink Matlab.

2.1.1. Problem Identification

When doing a practicum, sometimes inaccuracy in identifying DC motors occurs because there are some incomplete DC motors and inadequate explanations in the datasheet[11][12]. In this situation, we have to look for alternative formulas in journals to get the necessary information. Another challenge faced is the lack of articles or journals about circuits, so we need to look for relevant international publications and understand the principles of circuits well to avoid mistakes[13][14].

2.1.2. Problem Determination

At this stage, it can be concluded that challenges arise when designing code and operating the software. Finding a comprehensive datasheet will make the calculation process easier[15].

2.1.3. Literature Study

In carrying out the problem solving process, we can find various literature that can be used as support through books, references, and research journals.

2.2 Problem Solving Methods

Table 2.1 below presents the methods for solving this problem, which are explained in detail and include the steps of the solution that will help in the process of creating the article.

No.	Steps - Steps	Explanation
1	Looking for a DC Motor that suits your article creation needs	The author uses the M66E DC Motor type
2	Create LQR & LQT coding by paying attention to the data sheet	LQR and LQT coding can be found in articles or on YouTube.
3	Creating normal LQR & LQT circuits in Simulink	The circuit must be made carefully
4	Creating LQR & LQT Simulink circuits under noise conditions	The circuit must be made carefully
5	Write a conclusion when all simulations have been carried out	The conclusion is obtained after carrying out all simulations, comparing simulations under normal conditions and noise conditions.

The steps explained above must be followed when compiling an article, because if there is no prior planning, there is a high probability that errors will occur in calculating, designing, or writing the article.

2.3 LQR (Linear Quadratic Regulator)

LQR is one of the best control techniques in a system that uses a state space approach. The LQR controller has two factors, namely the Q and R weight matrices, which must be selected to produce the best control action according to needs [16]. One application of the LQR method is in regulating the speed of an induction motor, controlling the frequency of a generator power plant, and even in controlling a quadcopter drone. By applying the LQR method, the system will maintain the state at zero from the predetermined set point, so that it remains stable even though there is interference or noise [17].

2.4 LQT (Linear Quadratic Regulator)

Linear Quadratic Regulator (LQR) is one of the optimal control methods used in state space-based systems[18]. The LQR controller is characterized by two parameters, namely the weight matrices Q and R, which must be selected to produce the desired optimal control action. Unlike the Proportional-Integral-Derivative (PID) controller, which has systematic tuning methods such as Ziegler-Nichols and Cohen-Coon, the LQR controller does not have a specific systematic tuning method to determine the weight matrices Q and R[19].

2.5 DC Motor

A DC motor is a type of electric motor that converts a direct current voltage supply to the field coil into mechanical motion energy. A DC motor consists of a stator (the stationary part) containing the field coil and a rotor (the rotating part) containing the armature coil[20]. The structure of a DC motor can be seen in Figure 2.5.

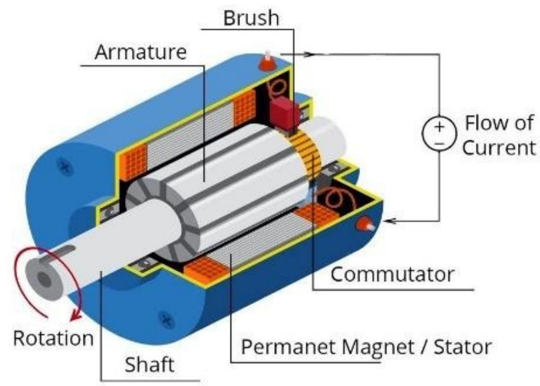


Figure 2.1 DC Motor Construction

2.6 MATLAB Software

The MATLAB programming language is a software system that utilizes a matrix base for data processing activities, algorithm creation, and model and application creation. There is a figure 2. 6 that displays the MATLAB software interface.

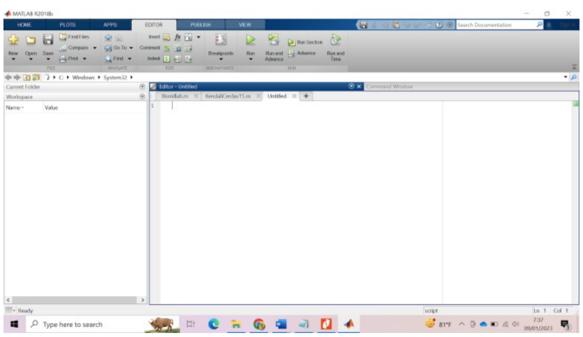


Figure 2.6 MATLAB display

To observe the response generated by the DC motor, the author utilizes the Simulink capability in MATLAB. Simulink is a part of the MATLAB tool that functions as a graphical programming tool.

Simulink is primarily used to create simulations of dynamic systems. Simulations are performed using functional diagrams consisting of interconnected blocks with their respective functions equally. Simulink allows modeling, simulating, and analyzing dynamic systems using a graphical user interface. Simulink is a software consisting of several groups of toolboxes that can be used to perform system analysis, both linear and non-linear.

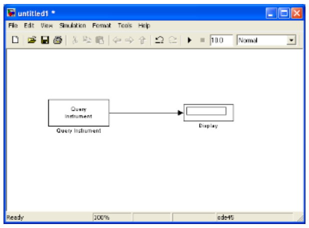


Figure 2.6.1 MATLAB Simulink View

2.7 M644E DC Motor Modeling

Specification: dc servo motor M600 series

		Servo motors		Motor-tacho	
Specification	Units	M642E 0860	M644E 1340	M642TE 0860	M644TE 1340
Maximum Voltage	Vdc	60	60	60	60
Typical Voltage	Vdc	24	50	24	50
Maximum Continuous Output Power	Watts	150	440	150	440
Maximum No-load speed	rpm	4000	4000	4000	4000
Typical speed @ rated torque	rpm	2250	3000	2250	3000
Rated Torque	Nm	0.66	1.4	0.66	1.4
Maximum Peak Torque	Nm	3.3	6.36	3.3	6.36
Typical No load current	Amps	0.5	0.30	0.5	0.30
Rotor Inertia	Kgcm²	1.2	2.4	1.3	2.6
Mechanical time constant	milli secs	8.1	6.5	8.1	6.8
Torque Constant	Nm / A	0.0816	0.130	0.0816	0.130
Voltage Constant	V / 1000 rpm	8.6	13.4	8.6	13.4
Terminal Resistance	Ohms	0.6	0.46	0.6	0.46
Rotor inductance	mH	0.42	0.64	0.42	0.64
Commutation	copper graphite				
Bearings	pre-loaded ball				
Maximum radial load	45 N				
Maximum axial load	130N				
Tacho Specification					
Voltage constant	V/1000 rpm			14 ± 10%	
Average ripple	peak / peak			0.7 @ 1000 rpm	
Ripple frequency	Per rev.			21	
Rotor resistance	Ohms			600-800	
Max. continuous speed	rpm			4,000	

Figure 1. Datasheet for DC Motor type M644E

- Moment of inertia (J) : 2.4 kg.m2/s2
- Mechanical system damping (B) : 0.01 Nms
- Motor Constant (K) : 0.130 Nm/A
- Resistance (R) : 0.46 ohms
- Inductance (L) : 0.00064 H

From the datasheet, we can also determine the mathematical model of the first-order system of the M644E DC motor. A first-order system is a type of system where only one change occurs. The following are details about the modeling of a first-order system.

Based on the DC motor datasheet, the first order equation is obtained:

Where $\tau = K.i$, *sehingga*

$$K = \frac{\tau}{i} = \frac{1,47}{8} = 0,184$$

Information :

Gs= Gain

i = Current

T = Torque

K = Constant

1st order equation:

$$G(S) = \frac{K}{\tau s + 1}$$

$$G(s) = \frac{0,184}{1,47\,s + 1}$$

2.8 Design of LQR DC Motor FAPG36-BL3650 in Simulink

2.8.1 Components list

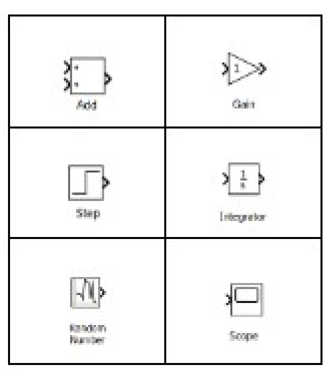


Figure 2.8.2 Simulink components

2.8.2 M644E DC Motor Series 1st & 2nd Order

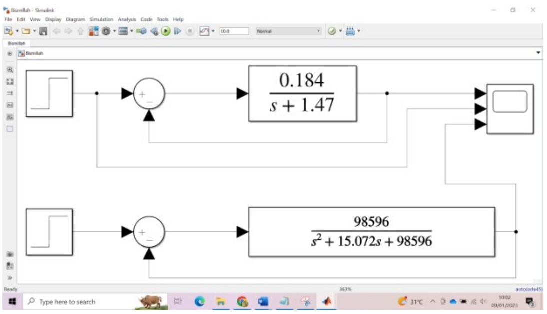


Figure 2.8.2 M644E 1st & 2nd order circuit

2.8.3 LQR circuit

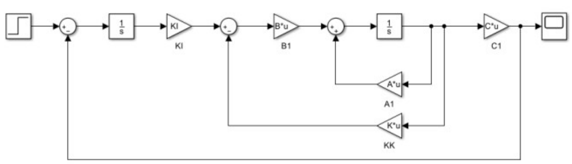


Figure 2.8.3 LQR circuit

2.8.4 LQR Subsystem Circuit without Noise

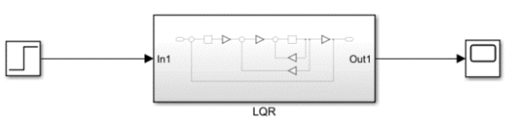


Figure 2.8.4 LQR circuit without noise

2.8.5 LQR Subsystem Circuit with Noise

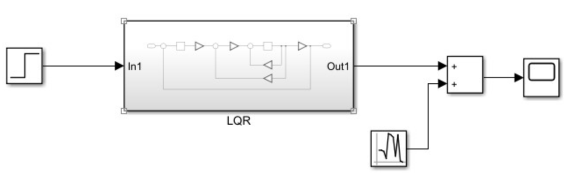


Figure 2.8.5 LQR circuit without noise

2.8.6 LQT series

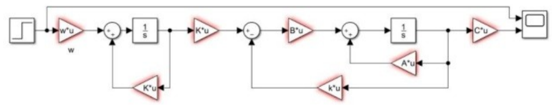
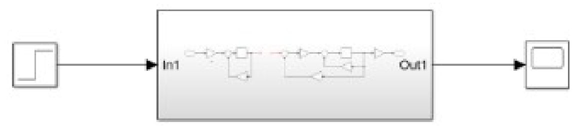


Figure 2.8.6 LQT circuit

2.8.7 Noise-free LQT Subsystem Circuit



Gambar 2.8.7 Rangkaian LQT tanpa noise

2.8.8 LQT Subsystem Circuit with Noise

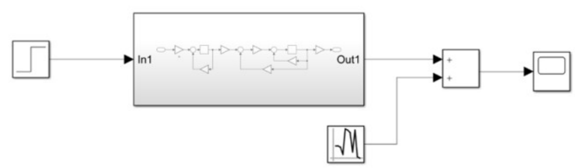


Figure 2.8.8 LQT circuit with noise

III.RESULTS & DISCUSSION

3.1 MATLAB LQR Program

% LQR SYSTEM OPTIMIZATION ON DC MOTOR

clear;

clc;

% DC Motor Models

J = 2.4 ; b= 0.01 ; K= 0.013 ; R= 0.46 ; L = 0.00064 ;

```
% J = Momentum, b = Damping ratio, K = constant, R = resistance, L = Inductance

A = [-b/JK/J; -K/L -R/L];

B = [0;1/L];

C = [1 0]

AA = [ A zeros(2,1); -C 0];

BB = [B;0];

% Pole Placement

J = [-3 -4 -5];

K = acker(AA,BB,J);

KI = -K(3);

KK = [K(1) K(2)];

% LQR Matrix

Q = [1 0 0;

     0 1 0;

     0 0 1000];

R = [1] ;

K_lqr = lqr(AA,BB,Q,R)
KI2 = -K_lqr(3);
KK2 = [K_lqr(1) K_lqr(2)];
```

3.2 MATLAB LQT Program

```
% LQT SYSTEM OPTIMIZATION ON DC MOTOR

clear;

clc;

% DC Motor Models

J = 2.4 ; b= 0.01 ; K= 0.013 ; R= 0.46 ; L = 0.00064 ;

% J = Momentum, b = Damping ratio, K = constant, R = resistance, L = Inductance

A = [-b/JK/J; -K/L -R/L];

B = [0;1/L];

C = [1 0]

Q = 10; R=0.0000000001; %0.00000000000001

W=C'*Q; %

[S,o,m,n]=care(A,B,C'*Q*C,R) %m=v(t) %S=P

K=inv(R)*B'*S %feedback Gain

ACL=(AB*K)'
L=inv(R)*B' %model following gain
```

3.3 Simulation Results of 1st & 2nd Order M644E DC Motor

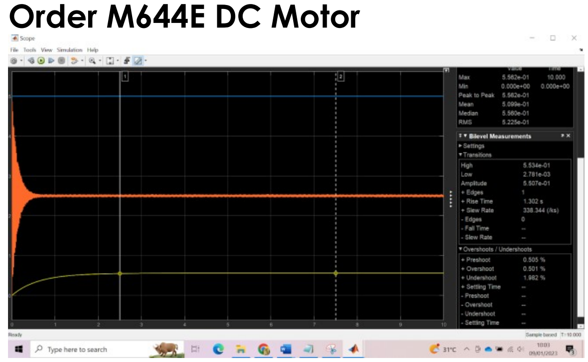


Figure 3.3 Simulation of 1st & 2nd order M644E DC Motor

In Figure 3.3, we can see the step response of the M644E DC motor in SISO system with 1st & 2nd order without any noise. This step response graph shows a stable response with an amplitude of 0.507 (which does not reach the set point), a rise time of 1.302

seconds, an overshoot of about 0.501%, and an undershoot of about 1.982%.

3.4 LQR Simulation Results without Noise

Figure 3.4 LQR Step Response Display without Noise

Figure 3.4 shows the step response of the M644E DC motor with LQR control without noise. It can be seen that the output step response of the M644E DC motor controlled by LQR reaches an amplitude of about 0.99, which can be considered as 1, thus reaching the setpoint. This response has a maximum rise time of about 1.109 seconds and has relatively small overshoot and undershoot, each about 0.505%.

3.5 LQR Simulation Results with Noise

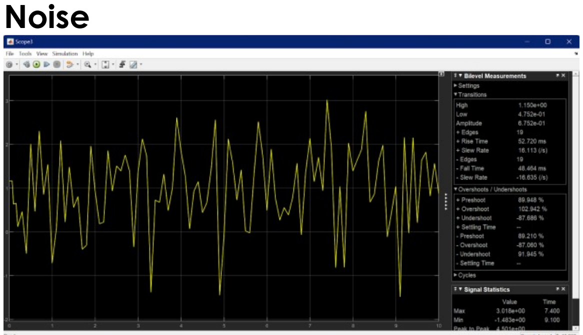


Figure 3.5 LQR Step Response Display with Noise

Figure 3.5 shows the step response of the M644E DC motor controlled by LQR under noise conditions. It can be seen that the output step response of the M644E DC motor controlled by LQR experiences graphic fluctuations due to the existing noise. The system reaches an amplitude of about 0.67, so the system has not reached the setpoint. This response has a maximum rise time of about 52,720 milliseconds and experiences an overshoot of 102,942%, and an undershoot of about -87,686%.

3.6 LQT Simulation Results without Noise

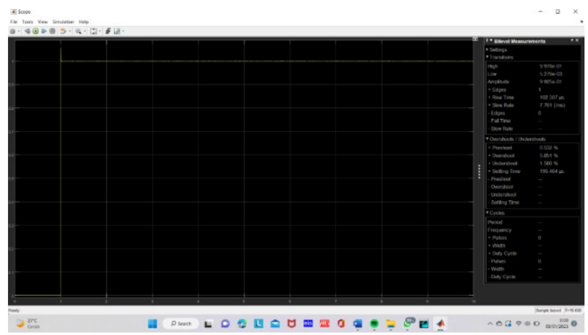


Figure 3.6 LQT Step Response Display without Noise

Figure 3.6 shows the output response graph produced by the LQT circuit without any disturbance from the BN28 DC motor plant. The output graph shows an amplitude of around 9.925, and an overshoot of 5.58%. This graph shows that the LQT circuit experiences a fairly large overshoot. This is different from the LQR output graph which has a smaller overshoot and reaches the setpoint slowly and gradually.

3.7 LQT Simulation Results with Noise

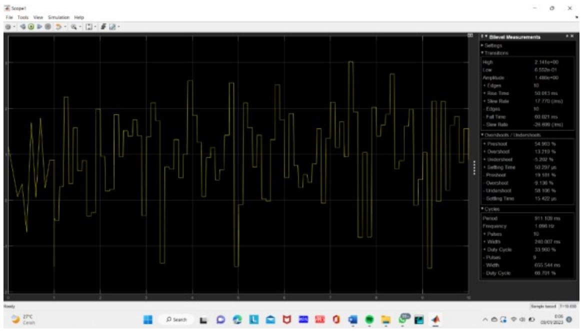


Figure 3.7 LQT Step Response Display with Noise

Figure 3.7 shows the output response graph produced by the LQT circuit on the BN28 DC motor plant with disturbance (noise). In the LQT graph with the disturbance, there is an undershoot of about -9.136% and an overshoot of about 13.219%. This graph only reflects the fluctuations due to the noise given, or the noise components installed (in the form of random numbers). This circuit does not reach the setpoint and has a maximum rise time of about 50.013 milliseconds.

IV.CONCLUSION

1. To obtain the mathematical model of the 1st order DC motor and the variables required in LQR control, a DC motor datasheet is required containing information such as moment of inertia, motor constant, damping ratio, resistance, and inductance. Using this data, 1st order mathematical calculations can be performed, and through the execution of the Matlab script for LQR control, we can obtain the values of variables such as A, B, C, K_lqr, and so on that will appear in the workspace.
2. The step response of the M644E DC motor with order 1 produces a stable response graph with an amplitude of around 0.507 (which does not reach the set point), a rise time of around 1.302 seconds, and an overshoot of around 0.501% and an undershoot of around 1.982%.
3. Through the comparison and analysis of the step response results of the two systems, it can be concluded that the M644E DC motor system using LQR shows more optimal results compared to the M644E DC motor with order 1. This is due to the fact that by using LQR, the step response of the M644E DC motor can reach the set point, show a stable graph, have a faster rise time, and experience overshoot and undershoot with lower values.
4. The output response graph produced by the LQT circuit on the M644E DC motor system with noise shows that there is an undershoot of about -9.136% and an overshoot of about 13.219%. In the graph of this circuit, fluctuations are seen caused by the disturbance given, or by random components installed. This circuit does not reach the setpoint, and has a rise time that reaches a maximum value of about 50.013 milliseconds.

V.CLOSING

1.Awards

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