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OPTIMIZATION OF DC MOTOR 054B-2 BY METHOD LQR AND LQT IN MATLAB SIMULINK

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Abstract

System identification is a method of modeling a dynamic system using input and output signals from the system to be modeled (Rohman & Izaty, 2021). Basically a mathematical model can be built through a data observation process and there are two methods that can be used to obtain a mathematical model of a dynamic system, where in this practicum the system to be controlled is a DC motor. The speed of DC motors often decreases due to the existing load, so that the speed becomes not constant so that a controller design or optimization of the system is needed. One of the software tools that can be used in learning system optimization is Matrix Laboratory (MATLAB). In the MATLAB (Matrix Laboratory) software there is a tool called Simulink. At Simulink, researchers can assemble circuits from SISO, SIMO, MISO, and MIMO after which researchers can also see the results in the form of graphs. This practicum aims to prove between calculation theory and datasheets from DC motors with simulation results from MATLAB Simulink. LQR is the optimal input which results in the form of initial state feedback, thus, it can be represented as constant feedback gain at the state of the LQR system. LQT(Linear Quadratic Tracking) is used as another method besides LQR. LQT itself is a linear control system whose output follows (tracking) the path that has been implemented through the input.

Keywords: *MATLAB, Simulink, DC motor, System, LQR, LQT*

1. Introduction

The concept of optimizing control systems provides performance index options and engineering techniques that result in an optimal control system within physical constraints. To achieve an optimal control system, it is essential to derive rules for decision-making that minimize deviations from the system's ideal behavior (Muhardian & Krismadinnata, 2020).

In the course on system optimization, the application of the LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracking) methods is discussed using a controller, actuator, and DC motor plant accompanied by its datasheet. A DC motor is a device that converts electrical energy into mechanical energy (Muhardian & Krismadinnata, 2020). It is a common component used in electrical circuit experiments and is often found in industries or locations where the main object of operation involves DC motors. One advantage of DC motors is their ability to maintain stable speeds. Additionally, they produce relatively quiet sound during operation, making them less noisy (Rohman & Izaty, 2021).

The working principle of a DC motor is to ensure that the rotor's magnetic field always opposes the stator's magnetic field. This is based on magnetic properties, where opposing magnetic poles attract, and like poles repel each other (Atika & Wati, 2016). Another advantage of DC motors is the ease of controlling their rotational speed, although regular maintenance is necessary to prevent damage to critical components *(Andria, Astrowulan, MSEE, & Iskandar, ST, M.T., 2014)*.

A mathematical model can be developed through data observation. Two methods are commonly used to derive mathematical models for dynamic systems, with the system in this practice being the DC motor (Rohman & Izaty, 2021). Mathematical modeling is essential for determining key characteristics such as power, speed, and torque. The model serves as a reference for designing control systems (Atika & Wati, 2016). With an accurate model, system design can be simulated easily and cost-effectively compared to operating a real system. Simulations are useful for understanding system behavior and evaluating design results.

In this practice, mathematical modeling employs first-order and second-order systems. First-order models involve a single variable with a constant, while second-order models use multiple variables for better differentiation and results (Atika & Wati, 2016) (Achmad & Nugraha, 2022).

The LQR (Linear Quadratic Regulator) is formulated within the scope of optimization problems to determine a sequence of inputs (controls) for linear systems to minimize a quadratic value (integral), ultimately producing a steady-state gain even as the value approaches infinity. From a theoretical perspective, the fundamental

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characteristic of LQR is its optimal input, which serves as feedback for the initial state and can be represented as a constant feedback gain (Bu, Mesbahi, Fazel, & Mesbahi, 2019).

LQT (Linear Quadratic Tracking) is another method alongside LQR. LQT is a linear control system method where the output follows a predetermined path through the input (Andria, Astrowulan, & Iskandar, 2014). In this paper, the object used for implementing these methods is the DC motor. LQT is crucial for optimizing systems, identifying optimal points, and understanding the state of the tools or objects in use.

This course (System Optimization) discusses the application of both LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracking) methods using a DC motor plant*(Pambudi et al., 2021)*. The DC motor used in this paper is the DC 054B-2 type, equipped with parameters that support the application of the LQR and LQT methods. MATLAB scripting and Simulink are utilized for the implementation process.

2. Material and methods

2.1. Material

Figurw 1. DC otor 05B-2 9 (PITMAN DC Motors 054B Series)

Before conducting further research, the first step involves selecting the DC motor to be used as the research object. For this study, the researchers chose the DC motor type 054B-2 (Khabibi, Poetro, & Nugraha, 2020).

After determining the type of DC motor to be used, the researchers examined the datasheet or specifications of the selected motor. The datasheet provides detailed technical information, which is critical for understanding the motor's characteristics and ensuring its suitability for the research objectives. Below are the specifications for the DC motor type 054B-2 (Rohman & Izaty, 2021) (As’ad & Nugraha, 2022).

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Motor Data		Units								
Rated Voltage **V1**	V_r	V	12.0	15.2	19.1	24.0	30.3	38.2	48.0	60.6
Rated Torque ●	T_r	Nm	0.072	0.071	0.070	0.070	0.070	0.070	0.070	0.070
		oz-in	10	10	9.9	9.9	9.9	9.9	9.9	9.8
Rated Speed	ω_r	rpm	3720	3740	3790	3770	3780	3750	3790	3780
Rated Current	I_r	A	3.5	2.7	2.2	1.7	1.4	1.1	0.88	0.67
Rated Power	P_r	W	28	28	28	28	28	27	28	28
No Load Speed	ω_{nl}	rpm	4010	4010	4030	4010	4010	3970	4020	4000
No Load Current	I_{nl}	A	0.49	0.39	0.31	0.25	0.20	0.16	0.13	0.098
Rated Voltage **V2**	V_r	V	15.2	19.1	24.0	30.3	38.2	48.0	60.6	76.4
Rated Torque ●	T_r	Nm	0.054	0.054	0.052	0.052	0.051	0.052	0.051	0.051
		oz-in	7.7	7.6	7.4	7.3	7.3	7.3	7.2	7.2
Rated Speed	ω_r	rpm	5130	5100	5160	5160	5160	5100	5190	5160
Rated Current	I_r	A	2.8	2.2	1.7	1.4	1.1	0.85	0.68	0.53
Rated Power	P_r	W	29	29	28	28	28	28	28	27
No Load Speed	ω_{nl}	rpm	5090	5050	5080	5070	5070	5000	5090	5050
No Load Current	I_{nl}	A	0.54	0.42	0.34	0.27	0.21	0.17	0.14	0.11
Motor Constant	K_M	Nm/√W	0.041	0.041	0.042	0.042	0.042	0.042	0.042	0.042
		oz-in/√W	5.8	5.9	5.9	5.9	5.9	6.0	6.0	6.0
Torque Constant	K_T	Nm/A	0.0275	0.0349	0.0435	0.0551	0.0695	0.0884	0.110	0.139
		oz-in/A	3.89	4.94	6.17	7.80	9.84	12.5	15.6	19.7
Voltage Constant	K_E	V/rad/s	0.0275	0.0349	0.0435	0.0551	0.0695	0.0884	0.110	0.139
		V/krpm	2.88	3.65	4.56	5.77	7.28	9.26	11.5	14.6
Terminal Resistance	R_{tt}	Ω	0.450	0.710	1.09	1.73	2.74	4.37	6.85	10.9
Inductance	L	mH	0.63	1.0	1.6	2.5	4.1	6.6	10	16
Peak Current	I_{pk}	A	27	21	18	14	11	8.7	7.0	5.6
Electrical Time Constant	τ_e	ms	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5
Mechanical Time Constant	τ_m	ms	9.7	9.5	9.3	9.3	9.2	9.1	9.2	9.1

Datasheet Motor DC 054B-2

The second stage involves performing mathematical calculations based on the specifications of the DC motor type 054B-2, which serves as the primary object of this research. In this phase, the researcher applies two methods: first-order and second-order approaches. These methods are essential to model and understand the dynamic behavior of the motor and to subsequently design an optimal control system.

The first-order method focuses on deriving the transfer function equation for the DC motor type 054B-2. The transfer function for a first-order system is generally expressed as follows:

$$G(s) = \frac{K}{\tau s + K}$$ ……………………………………………………..…Persamaan(1)

were :
K = Konstanta
τs = Torsi

$$K = \frac{\tau}{I}$$ ………………………………………………………………….Persamaan(2)

were :
K = Konstanta
τ = Torsi
I = Arus

The datasheet of the DC motor 054B-2 provides the necessary parameters for these calculations. According to the datasheet, the motor operates with a current (III) of 1.7 A and generates a torque (τ\tauτ) of 0.052 Nm (Faj'riyah, Setiyoko, & Nugraha, 2021). Using these values, the researcher substitutes them into the equation to calculate KKK, the constant gain. Once KKK is determined, it is then substituted into the transfer function equation to obtain the first-order model.

After deriving the first-order transfer function, the researcher progresses to designing control system configurations using the LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracking) methods. These designs are implemented and analyzed with the help of MATLAB Simulink, a software widely used for modeling, simulation, and control system design (Ivannuri & Nugraha, 2022).

In MATLAB Simulink, the researcher constructs the circuits for both LQR and LQT control systems based on the mathematical equations derived earlier *(Muhardian & Krismadinnata, 2020)*. Once the circuits are constructed, simulations are performed to validate the theoretical models against the practical outcomes. The purpose of this simulation phase is to evaluate whether the transfer function and system model accurately represent the motor's dynamic behavior.

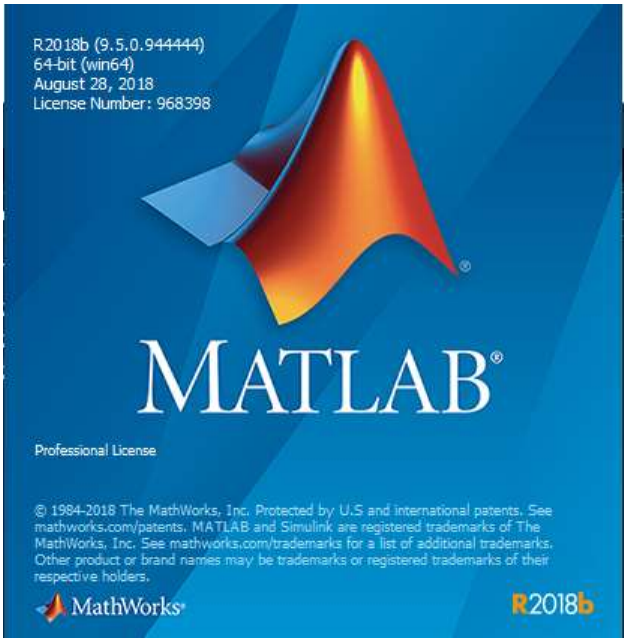

Figure 1 *Software* MATLAB
(*screenshot software* MATLAB)

Once the researcher has successfully designed the LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracking) circuits, the next crucial step is to perform simulations on these systems (Arifuddin et al., 2024). The primary objective of this simulation phase is to validate whether the mathematical equations and transfer functions derived earlier align with the actual behavior of the circuits. By comparing the simulation results with the theoretical equations, the researcher ensures that the designed control systems accurately reflect the motor's dynamic characteristics. This process helps identify any discrepancies between theory and simulation, providing a foundation for potential adjustments or improvements to the control system design.

During the simulation, both LQR and LQT circuits are tested under controlled conditions to observe their performance (Sheila et al., 2024). The researcher closely monitors how well the circuits achieve their respective control objectives whether the LQR method efficiently minimizes the quadratic cost function and the LQT method tracks the desired reference signal effectively. The data generated from these simulations, including system outputs and response curves, serve as key indicators of the control system's accuracy and reliability. By analyzing this data, the researcher can determine if the system behaves as expected and whether it meets the performance criteria established in the research objectives.

In the subsequent stage of the research, noise is deliberately introduced into the circuits during the simulation process. Noise represents external disturbances or uncertainties that a control system may encounter in real-world scenarios. The purpose of adding noise is to evaluate the robustness and effectiveness of the plant (the DC motor) under non-ideal conditions. A well-designed control system should be capable of mitigating the effects of noise, ensuring stability and maintaining optimal performance. The introduction of noise allows the researcher to assess how resilient the control system is when exposed to unexpected fluctuations.

When analyzing the simulation results with added noise, the researcher expects to observe a noticeable difference in the system's behavior. Specifically, the output graph from the noise-included simulation should demonstrate reduced fluctuations compared to a system without the plant. This reduction indicates that the plant and control system are effectively compensating for the disturbances introduced by the noise. By comparing the simulation results across different scenarios, the researcher gains valuable insights into the system's ability to maintain stability and reliability, even in challenging environments. This analysis is a critical step in determining the overall quality and robustness of the designed LQR and LQT control systems.

2.2.1. Modeling and Components Used

In system optimization, after determining the general modeling equations for first-order and second-order systems, the researcher can apply the required DC motor data into the equations. Below are the calculations for the first-order model:

Mathematical Calculation for the First-Order Model on DC Motor 054B-2

From Equation (1) and Equation (2), the researcher derives the following model:

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$$G(s) = \frac{K}{\tau s + K}$$
$$G(s) = \frac{0.03}{0.052 + 0.03}$$

$$K = \frac{\tau}{I}$$
$$K = \frac{0.052}{1.7} = 0.03$$

After completing the calculations for the first-order model, the next step is to perform further analysis and simulations using MATLAB scripting for system optimization, starting with the implementation of the LQR method.

LQR

```
% OPTIMASI SISTEM LQR PADA MOTOR DC
clear;
clc;
% Model Motor DC
J = 0.000016 %J=momen inersia
b = 0.0000963 %b=damping ratio
K = 0.03 %K=Konstanta torsi(Kt)
R = 1.09 %R=resistansi
L = 0.016 %L=induktansi

A = [-b/J K/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)];

% Matrix LQR
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)];
```

LQT

```
% OPTIMASI SISTEM LQR PADA MOTOR DC
clear;
clc;
% Model Motor DC
J = 0.000016; % J = Momeninersia
b= 0.000011; %b = Rasioredam
K= 0.03;   %K= konstanta
R= 1.03;  %R= resistansi
L = 0.0016; %L=Induktansi

A = [-b/J K/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=(A-B*K)'
    L=inv(R)*B' %model following gain
```

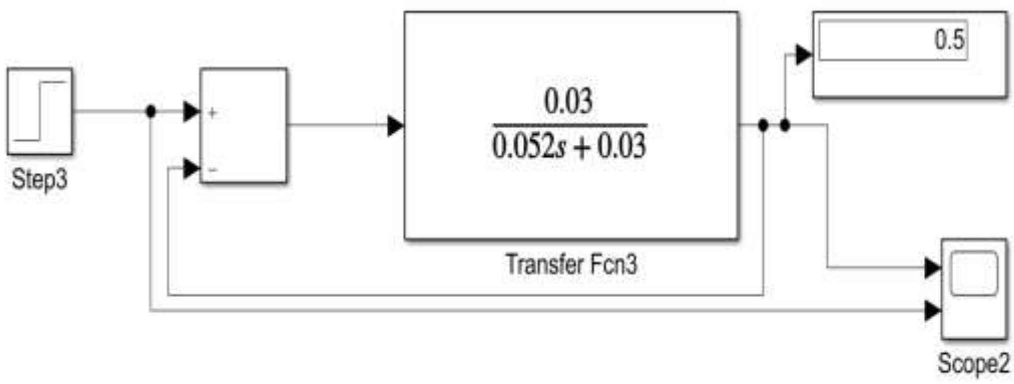
The next step involves identifying the components utilized in the LQR and LQT circuits. Below is the list of components employed in these circuits:

List Componen Simulink	
Add	Gain
Step	Integrator
Random Number	Scope
Mux	Sum
Out1	In1

Tabel 1. List component Simulink

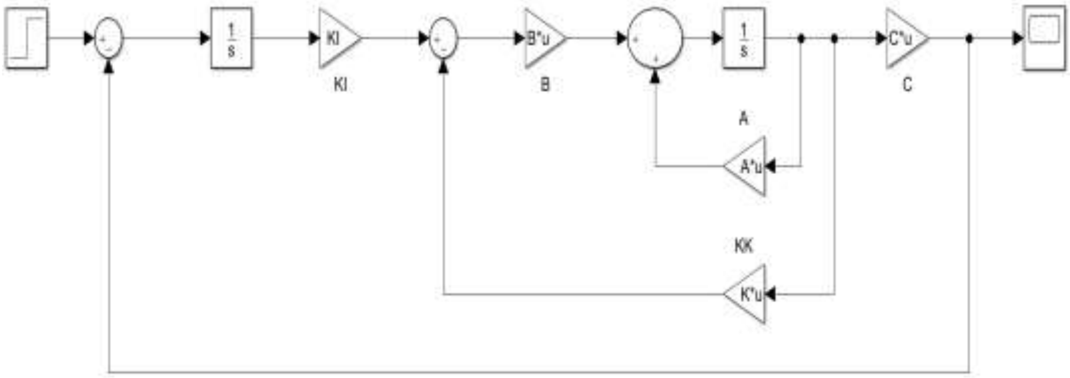
From table 2.1, researchers can use it to assemble LQR and LQT circuits in MATLAB simulink. The series can be seen below:

1. Wiring orde 1

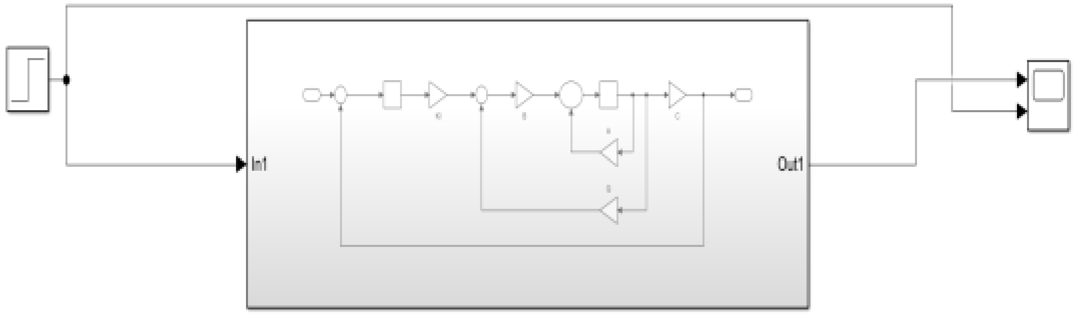


2. Wiring LQR

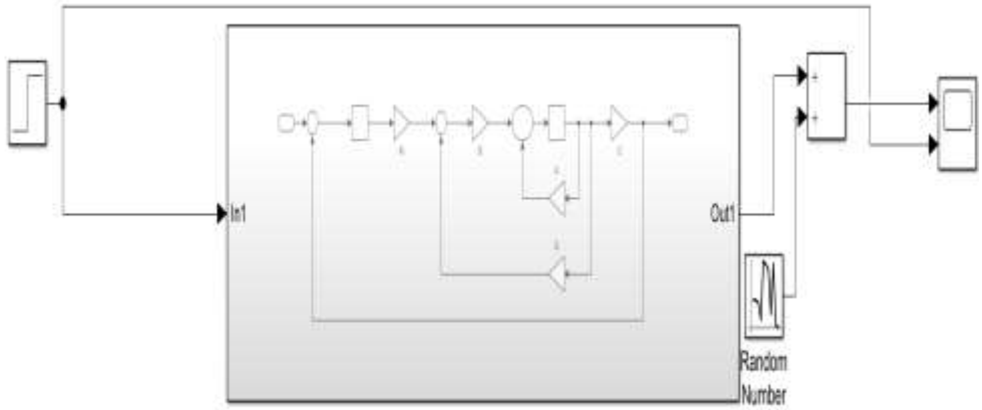
DOI xxxxxx



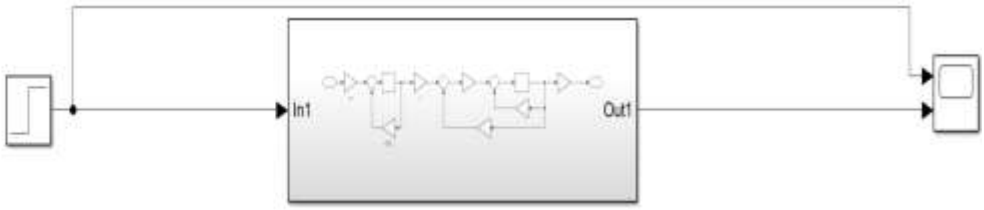
a. Wiring LQR without noise



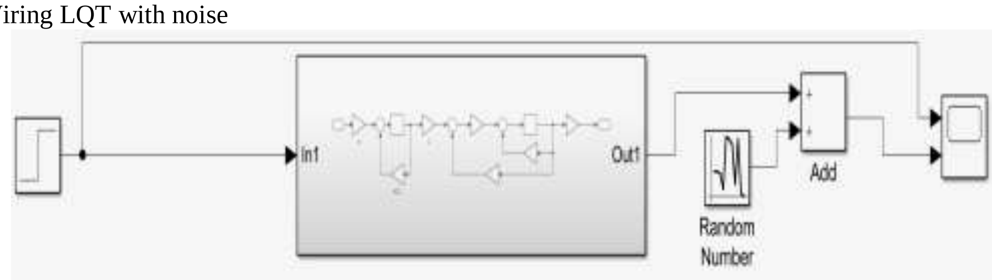
b. Wiring LQR with noise



3. Wiring LQT
   a. Wiring LQT without noise



   b. Wiring LQT with noise



DOI xxxxxx

3. Results and discussion

3.1. Orde 1

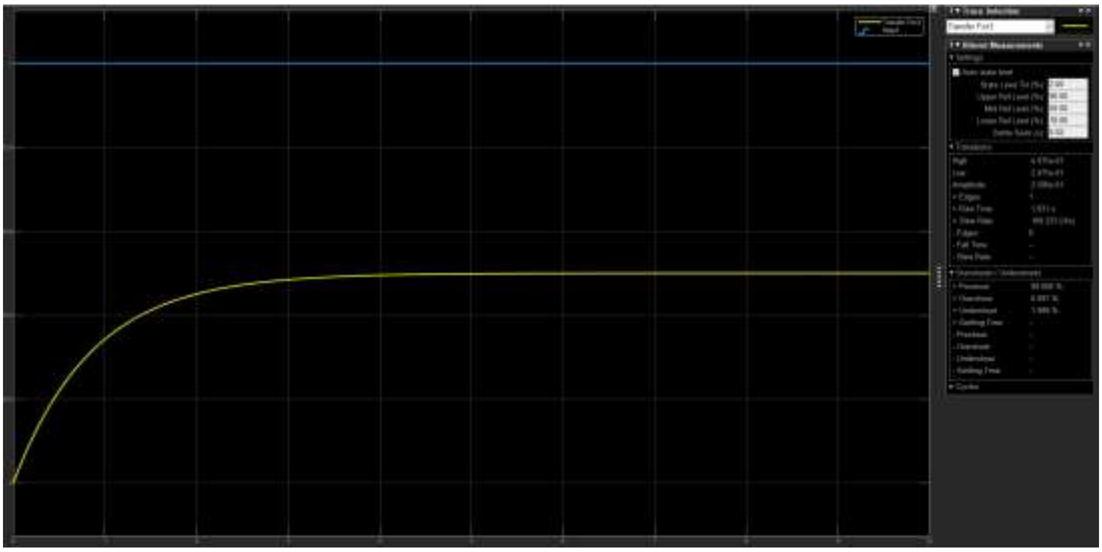
4. 

Figure Simulation orde 1

Figure 3.1 shows the step response of the 054B-2 DC motor with the SISO (Single Input Single Output) circuit. The amplitude of the results is 0.25 with a rise time of 1.831s and the graph results also produce overshoot and undershoot of 0.997% and 1.99% respectively.

3.2. LQR

- **Without noise**

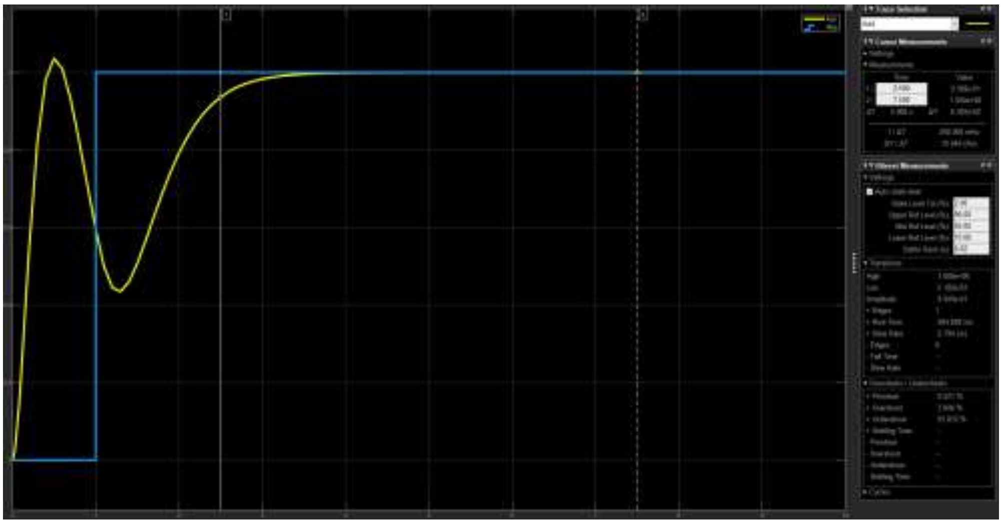


figure 3. 1 Hasil Simulasi LQR tanpa nosie

In Figure 3.2 you can see a result, namely two graphs colored blue and yellow. The blue graph is the input value or set point given to the system which has a value of one (1). Meanwhile, the yellow graph is the value or result of the modeling step response on the 054B-2 DC motor. The value of the step response for motor modeling using the LQT method reaches an amplitude of 0.994 with the time required for the value to stabilize at 4s. The overshoot that occurred in the results was 3.646% and the undershoot that occurred in the results of the LQR graph without noise was 55.821%.

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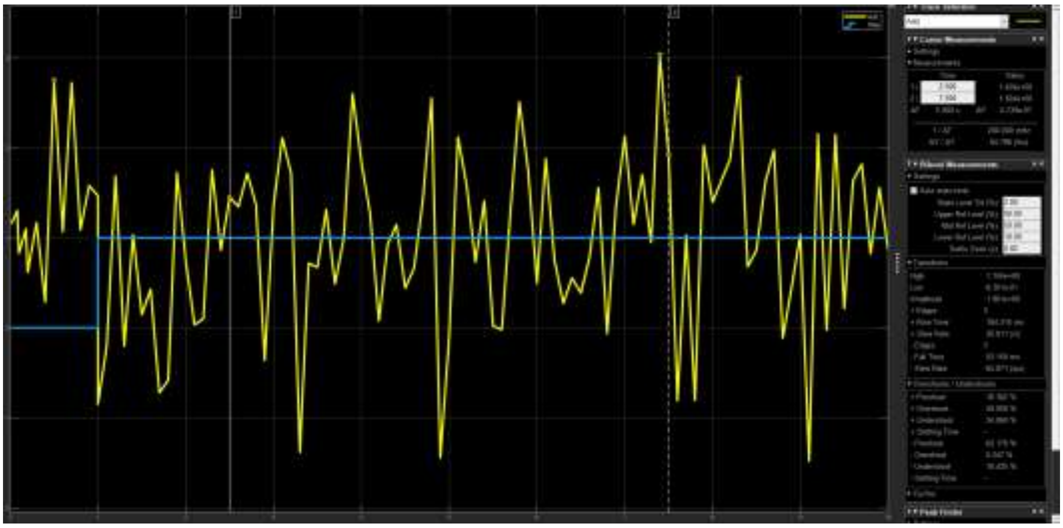
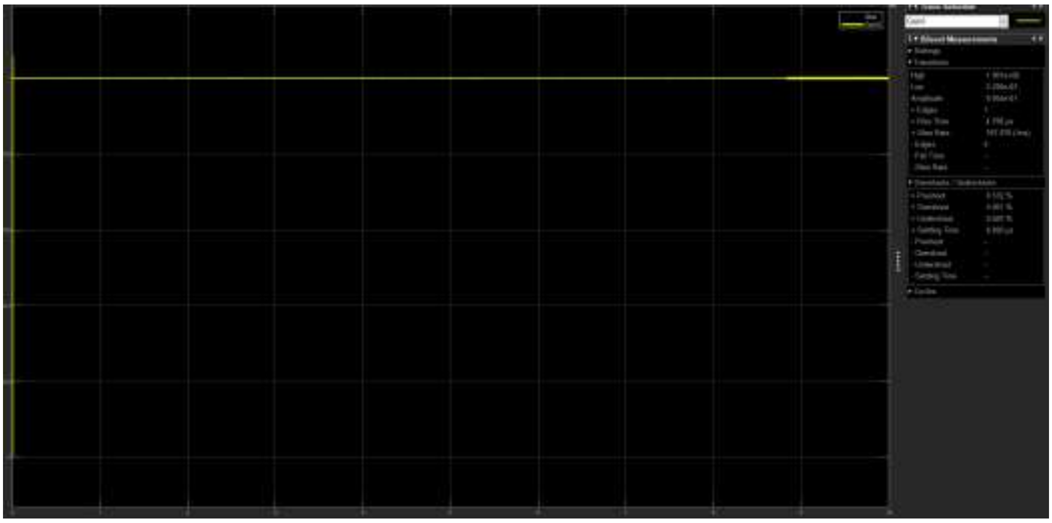
- **With noise**



In Figure 3.3 you can see a result, namely two graphs colored blue and yellow. The blue graph is the input value or set point given to the system which has a value of one (1). Meanwhile, the yellow graph is the value or result of the step response from the modeling of the 054B-2 DC motor. The value of the step response from the motor model reaches an amplitude of 1.98. The overshoot that occurred in the results was 49% and the undershoot that occurred in the LQR graph results without noise was 34%.

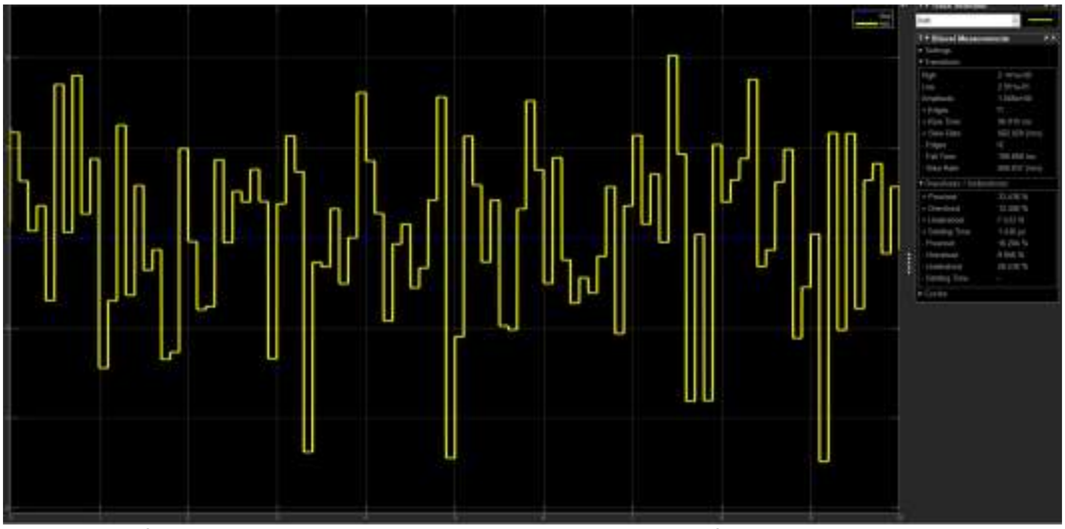
3.1.3. LQT

- **Without noise**



From the results of Figure 3.4, it can be seen that the yellow graph is the result of the LQT method. The results of the step produce an amplitude value of 0.995 with the required rise time of 4.766us. Overshoot on LQT without noise produces 5.851% while undershoot produces 0.625%. This percentage indicates that the results of the LQT method without noise are stable with minimal overshoot and undershoot.

- **With noise**



The results of Figure 3.5 show that the yellow graph is the result of the LQT method values using noise. The simulation results are different from before noise was added, namely that it produces unstable graphs. The amplitude in the LQT simulation results with this noise is 1.846 with a rise time of 90.91ms. Of course, the results of this simulation produce greater overshoot and undershoot values compared to without noise, namely 12.406% and -7.533% respectively.

COMPARISON OF NORMAL AND NOISE CONDITIONS

Table 3. 1 Comparison of Normal and Noise Conditions based on simulation results

System	**Normal**	**Noise**
LQR	Amplitude value of 0.994 with overshoot and undershoot values of 3.646% and 55.821%, respectively.	Amplitude value of 1.98 with overshoot and undershoot values of 49% and 34%, respectively.
LQT	Amplitude value of 0.995 with a rise time of 4.766 µs. Overshoot and undershoot values are 5.581% and 0.625%, respectively.	Amplitude value of 1.846 with a rise time of 90.91 ms. Overshoot and undershoot values are 12.406% and -7.533%, respectively.

5. Conclusion

The conclusion is that every method used starting from order 1, LQR, and LQT produces a step response that has overshoot and undershoot. Although the largest overshoot and undershoot values are produced when noise is added. However, at normal times or without added noise it produces overshoot and undershoot but only has relatively small or low results.

The LQR (Linear Quadratic Regulator) method produces graphs that are more stable or constant, that is, they don't go up and down. However, in the experiment LQR produced a very large undershoot compared to LQT without noise. The results of the noise method produce overshoot, undershoot and amplitude values that are greater than under normal conditions.

The LQT (Linear Quadratic Tracking) method produces graphs with a faster rise time under normal conditions compared to conditions with noise. The resulting graph is wavy but the resulting wave is stable like a straight line. The results of the LQT method without noise and by adding noise also produce overshoot and undershoot.

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