KTO KARATAY UNIVERSITY

FACULTY OF ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

MEM622 FEEDBACK CONTROL SYSTEMS

SHAFT STARTING WITH ELECTRIC ROTOR CONTROL

PROJECT REPORT

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PROJECT SUMMARY

This project is named Shaft Starting with Electric Rotor. The system can be defined as an electromechanical system by establishing an electrical circuit, starting a motor with armature current, and connecting a shaft to this motor. The project deals with an understandable engineering application using a mathematical modeling approach and simulation through the MATLAB program. In this project, a PID controller has been added to the system. The PID controller is used to control the speed and position of the motor. This ensures that the motor reaches the desired positions and speeds at specific times. The aim is for the motor to maintain both a constant position and reach desired positions. Using MATLAB and Simulink, the dynamic behavior of the system has been modeled and simulated. The simulations carried out show that the motor can be successfully controlled with the PID controller, maintaining its constant position and reaching desired speed and position values. This project serves as an important example in the control and simulation of electromechanical systems.

1. INTRODUCTION

This project focuses on an electromechanical system called the Electric Rotor Shaft Starting System. The system aims to initiate and control a shaft using an electrical circuit and a motor. The project encompasses mathematical modeling and simulation studies conducted using MATLAB Simulink.

The Electric Rotor Shaft Starting System is designed to control the speed and position of the motor using a PID controller. This controller is utilized to ensure that the motor reaches desired positions and speeds at specific times. Additionally, the system aims for the motor to maintain a steady position and accurately reach desired positions.

The objective of this project is to evaluate the performance of the Electric Rotor Shaft Starting System by modeling and simulating its dynamic behavior in the MATLAB Simulink environment. The simulations conducted demonstrate that the motor can be successfully controlled using the PID controller, achieving desired positions and speeds while maintaining a steady position.

This project serves as a significant example in the field of electromechanical system control and simulation. It is considered a valuable contribution to the development of control systems used in industrial automation, robotics, and related fields.

2. PROJECT

A commonly used actuator in control systems is a DC motor, which provides direct rotary motion and can provide translational motion when paired with wheels, drums, and cables. The electrical equivalent circuit of the armature and the free body diagram of the rotor are shown in Figure 1 below.

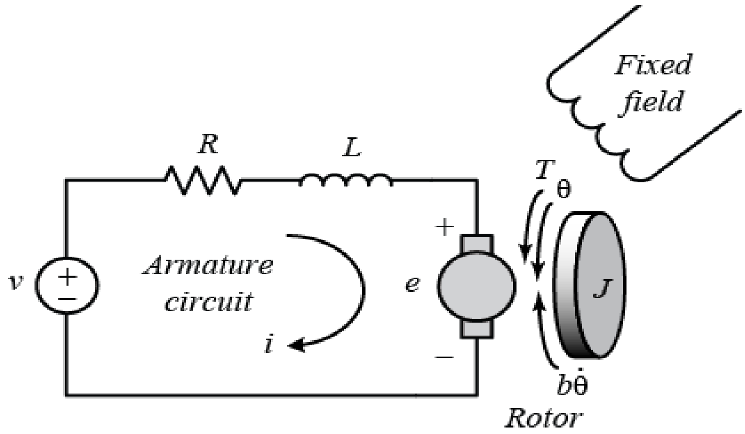

Figure 1. Armature Electrical Circuit.

In this project, we will assume that the input to the system is the armature voltage (V) applied to the motor, and the output is the shaft's rotational speed θ. The rotor and PTO shaft are assumed to be rigid. A viscous friction model is also assumed, meaning the friction torque is added proportional to the shaft angular velocity. In the electrical model, the rotor behaves like a shaft, but in the figure, the rotor is designed as a rigid rod.

The mechanical part of the project includes a shaft. This shaft is chosen as a Flexible Shaft from the MATLAB Simscape library. The reason for choosing a Flexible Shaft is the availability of the Torsional Stiffness value in the MATLAB Simscape feature. This value represents the stiffness of the spring in the mechanical drawing theoretically. Therefore, by combining our motor, rotor, and shaft in the Simscape environment, we can obtain our output speed again in rad/s and have the ability to analyze this speed by connecting the scope. Additionally, this Torsional Stiffness value was considered in MATLAB Simulink as well. The project is generally based on this logic. The project consists of two stages. The first stage is electrical, and the second stage is mechanical. The mathematical model of these two stages was prepared, and Simulink and Simscape simulations were drawn based on this model.

Within the scope of the project, a PID controller was added in MATLAB, and a saturation block was used to limit the control signal. With these changes, it was aimed to control the behavior of electrical and mechanical systems more precisely. This approach aims to improve the overall performance of the project. Simulations conducted in MATLAB Simulink and Simscape environments show that controlled systems better match the desired speeds and positions.

2.1 Electrical Model Of System

The electrical model of the project was prepared in MATLAB Simulink and Simscape environment.

2.1.1 MATLAB Simulink

Figure 2 shows the MATLAB Simulink simulation of the electrical part of the project. This model was calculated according to the theory seen in the course and the block diagram was prepared in MATLAB Simulink

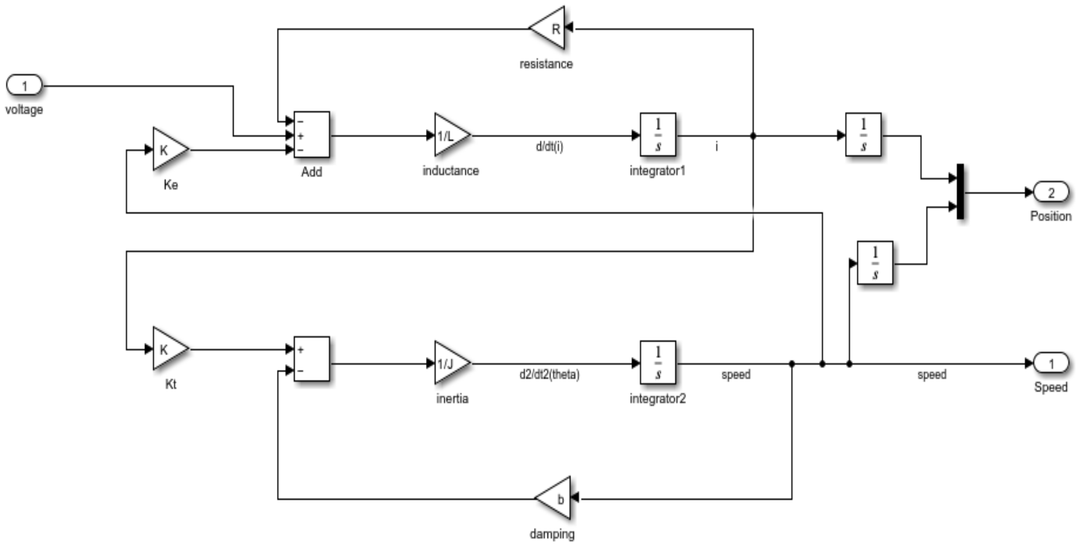

Figure 2. MATLAB Simulink Electric Model.

2.1.2 MATLAB Simscape

Figure 2 shows the MATLAB Simscape simulation of the electrical part of the project. This model was prepared by researching according to the theory of modelling electrical systems seen in the course and prepared in MATLAB Simscape environment.

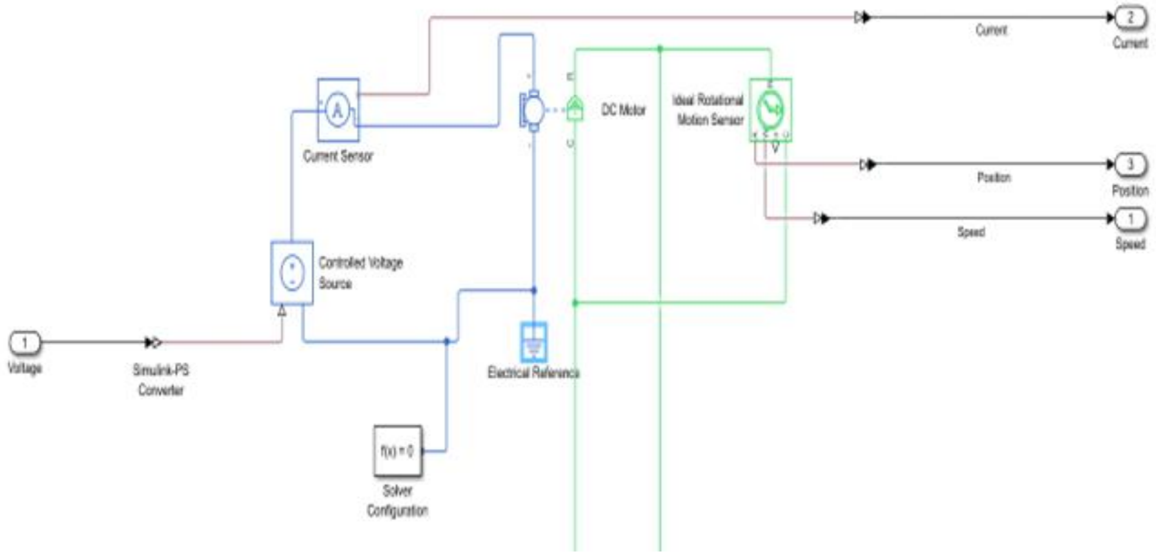

Figure 3. MATLAB Simscape Electric Model.

2.2 Mechanical Model

The mechanical model of the project was prepared in MATLAB Simulink and Simscape environment.

2.2.1 MATLAB Simulink

Figure 4 shows the MATLAB Simulink simulation of the mechanical part of the project. This model was calculated according to the theory seen in the course and the block diagram was prepared in MATLAB Simulink environment.

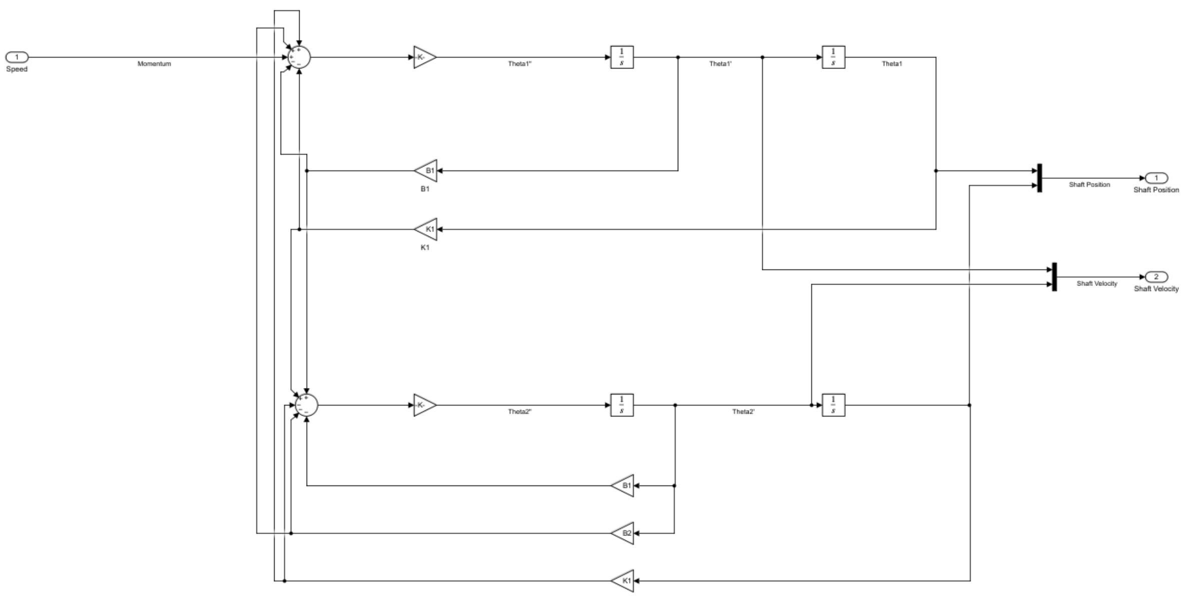

Figure 4. MATLAB Simulink Mechanical Model.

2.2.2 MATLAB Simscape

Figure 5 shows the MATLAB Simscape simulation of the mechanical part of the project. This model was prepared by researching according to the theory of modelling rotational mechanical systems seen in the course and prepared in MATLAB Simscape environment.

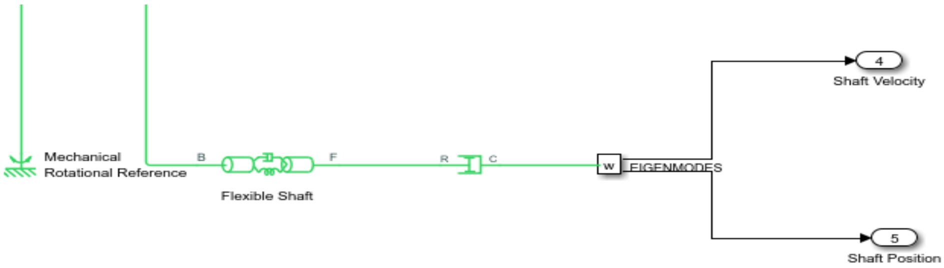

Figure 5. MATLAB Simscape Mechanical Model.

2.2.3 MATLAB Simulink With PID Controller

In the project, 5 different situations were analysed.

In the first case, a fixed input is given. At this fixed input, position control is performed and the input and output graphs of the system are analysed. By analysing these graphs, the reasonableness of the results is discussed. Simulink and graphs are given in figure 6 and figure 7.

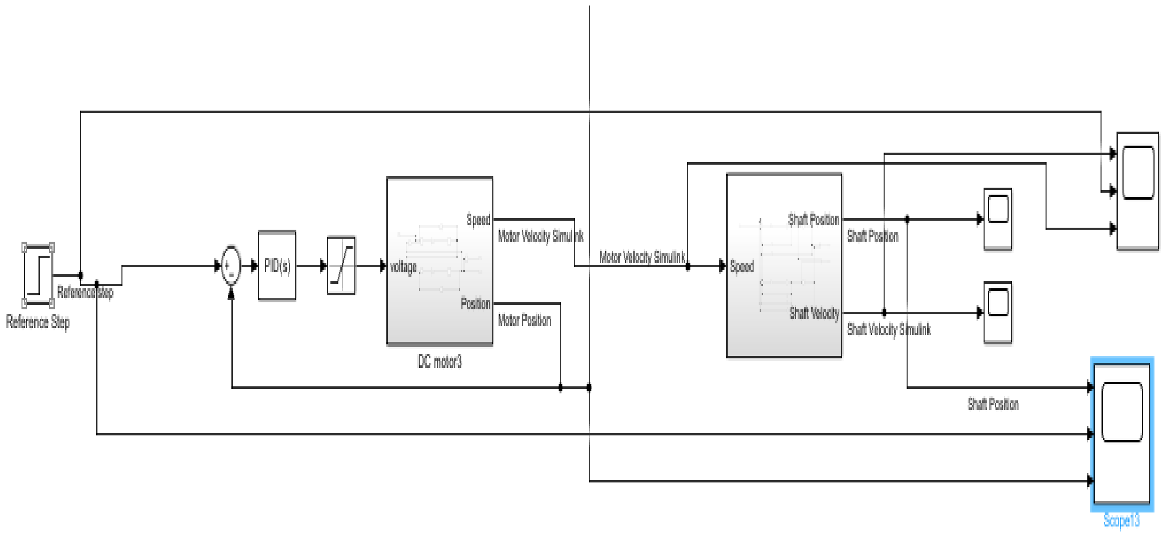

Figure 6. MATLAB Simulink With PID Position Control.

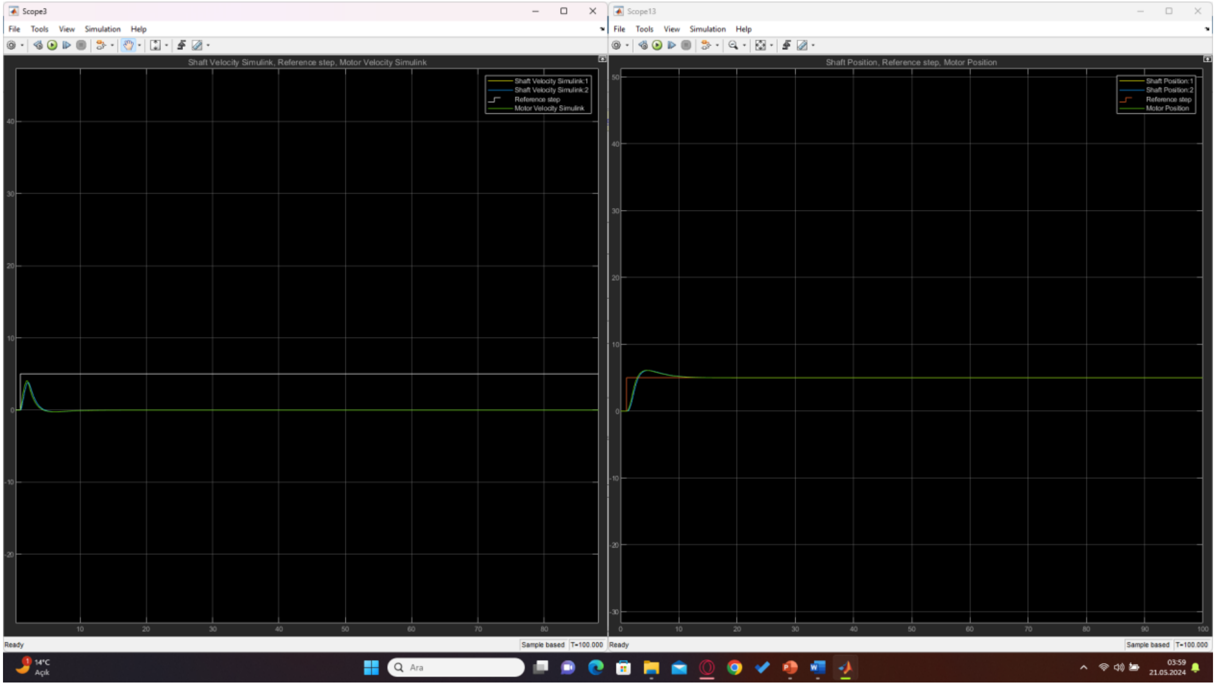

Figure 7. MATLAB Simulink With PID Controller Graph.

In the second case, a fixed input is given. The input and output graphs of the system were analysed by controlling the velocity at this fixed input. By analysing these graphs, the reasonableness of the results is discussed. Simulink and graphs are given in figüre 8 and figüre 9.

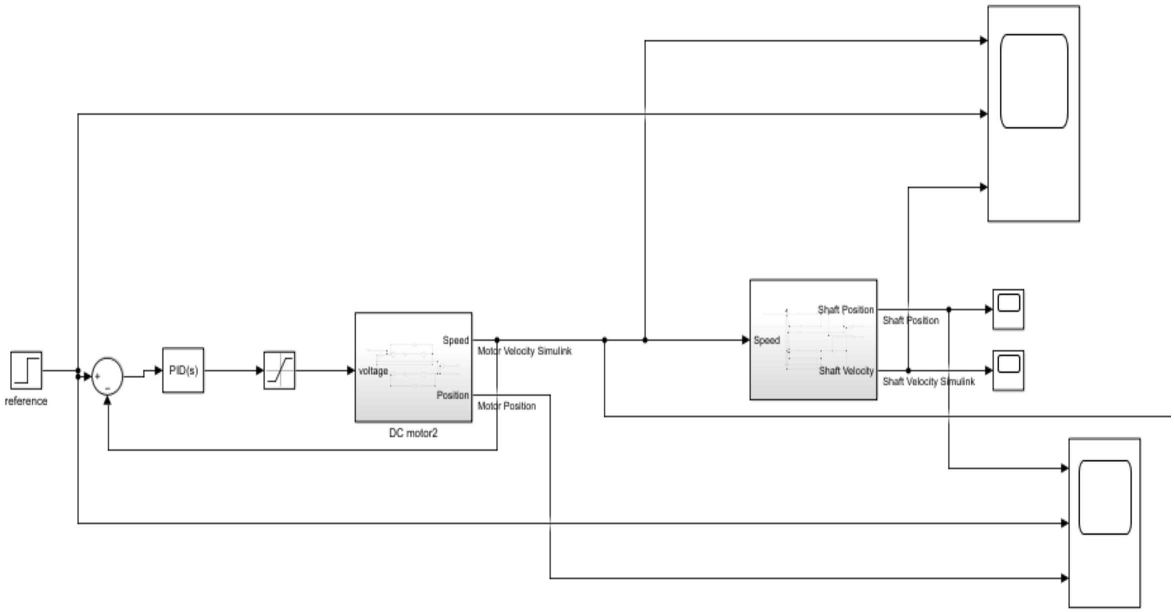

Figure 8. MATLAB Simulink With PID Velocity Control.

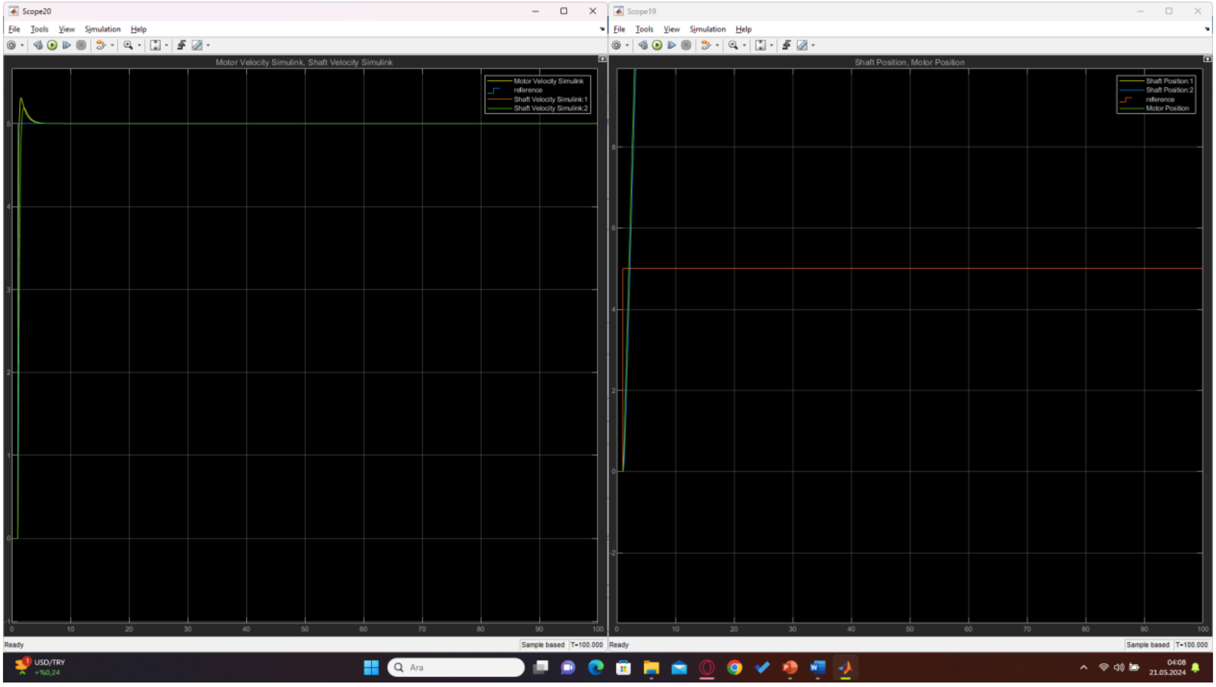

Figure 9. MATLAB Simulink With PID Velocity Control Graph.

In the third case, the desired position data is given as an input. By controlling the speed at this desired input, the input and output graphs of the system were analysed. By analysing these graphs, the reasonableness of the results is discussed. Simulink and graphs are given in figure 10 and figure 11.

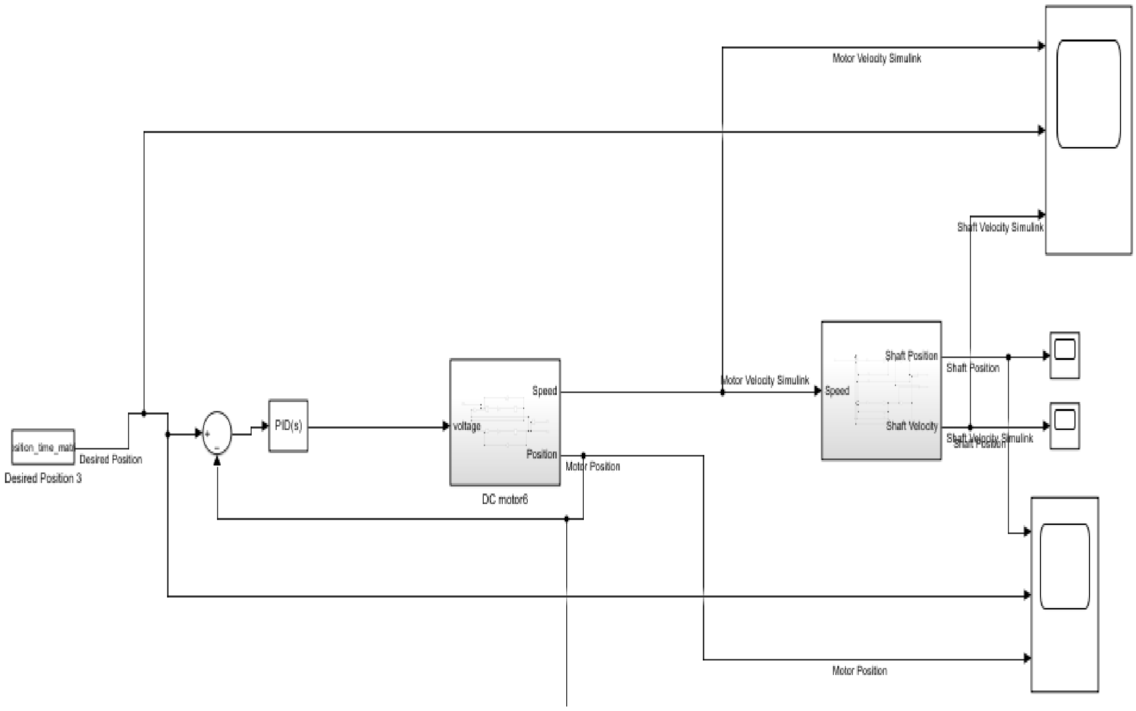

Figure 10. MATLAB Simulink With PID Position Control (Desired Position).

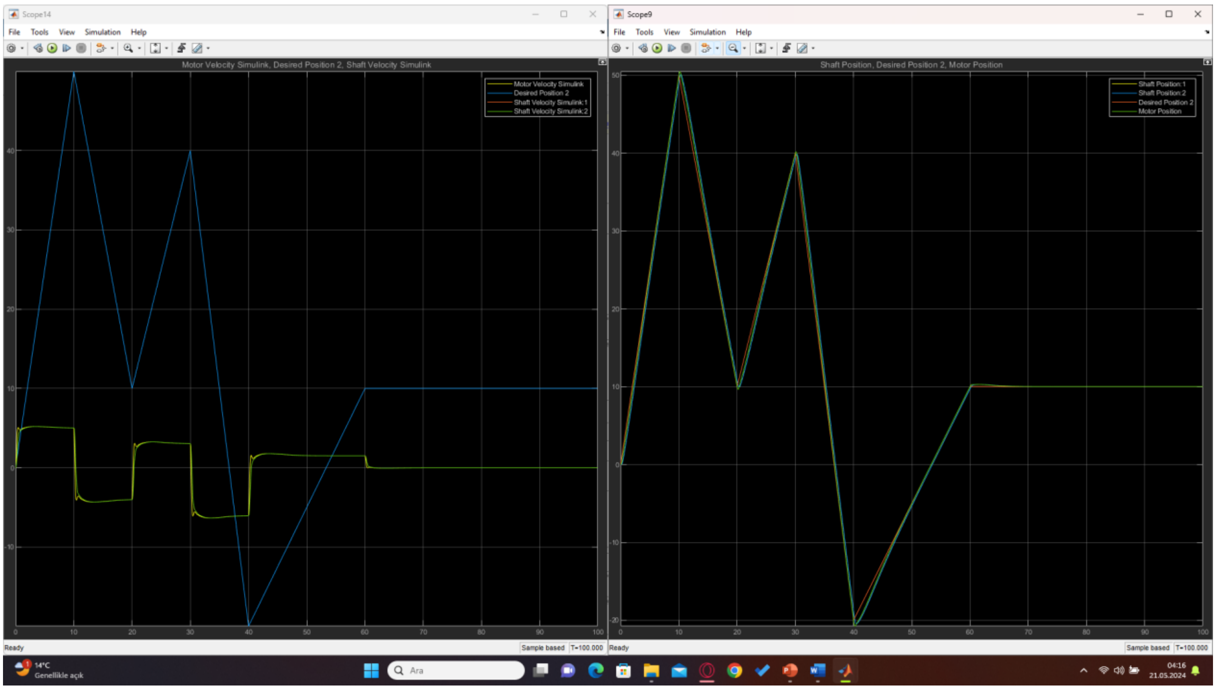

Figure 11. MATLAB Simulink With PID Position Control Graph (Desired Position).

In the fourth case, the desired velocity data is given as an input. The input and output graphs of the system were analysed by controlling the speed at this desired input. By analysing these graphs, the reasonableness of the results is discussed. Simulink and graphs are given in figure 12 and figure 13.

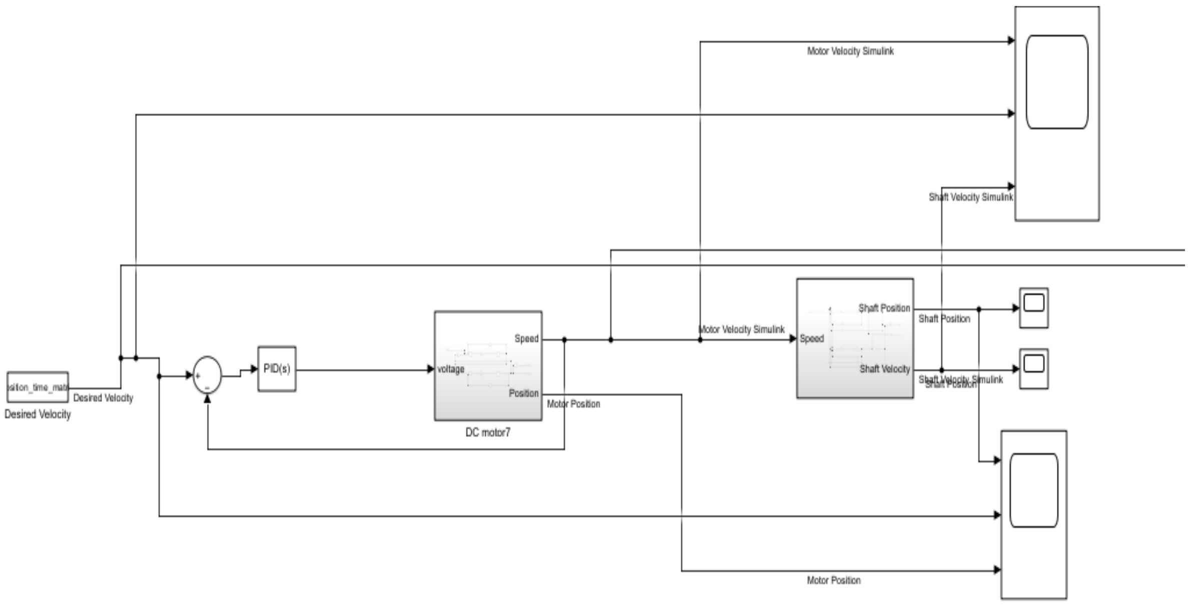

Figure 12. MATLAB Simulink With PID Velocity Control (Desired Velocity).

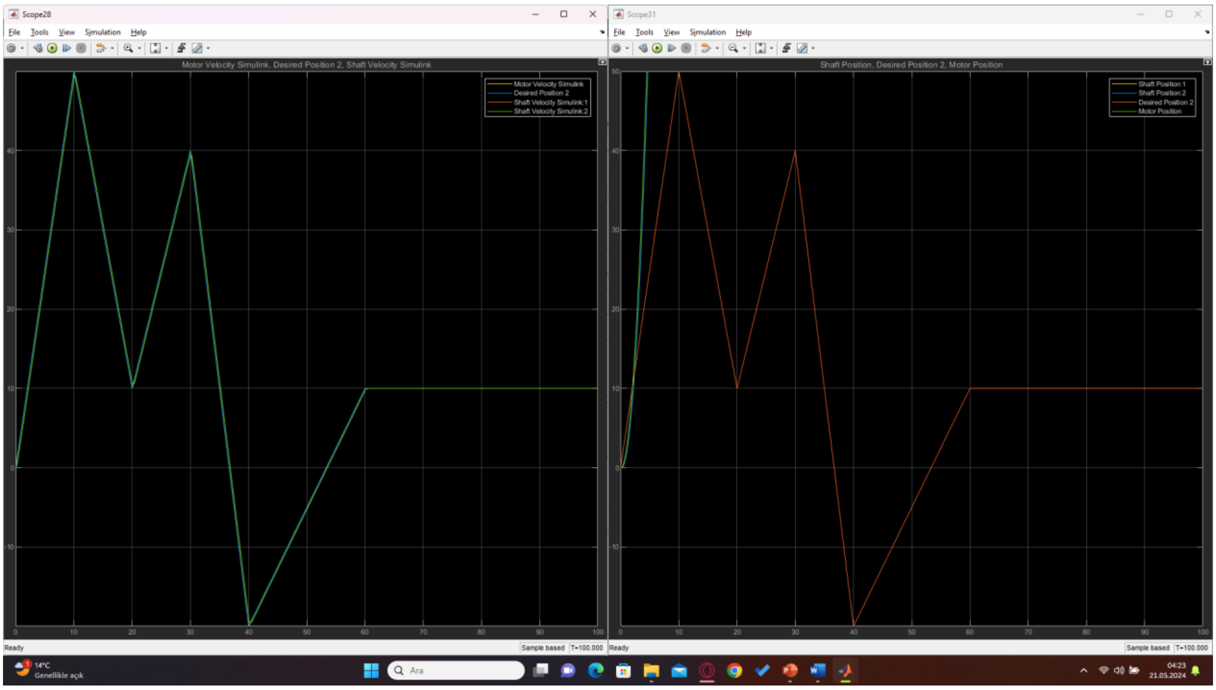

Figure 13. MATLAB Simulink With PID Velocity Control Graph (Desired Velocity).

In the last case, the desired velocity and position data is given as an input. In this desired input, velocity and position were controlled and the input and output graphs of the system were analysed. By analysing these graphs, the reasonableness of the results is discussed. Simulink and graphs are given in Figure 14 and Figure 15.

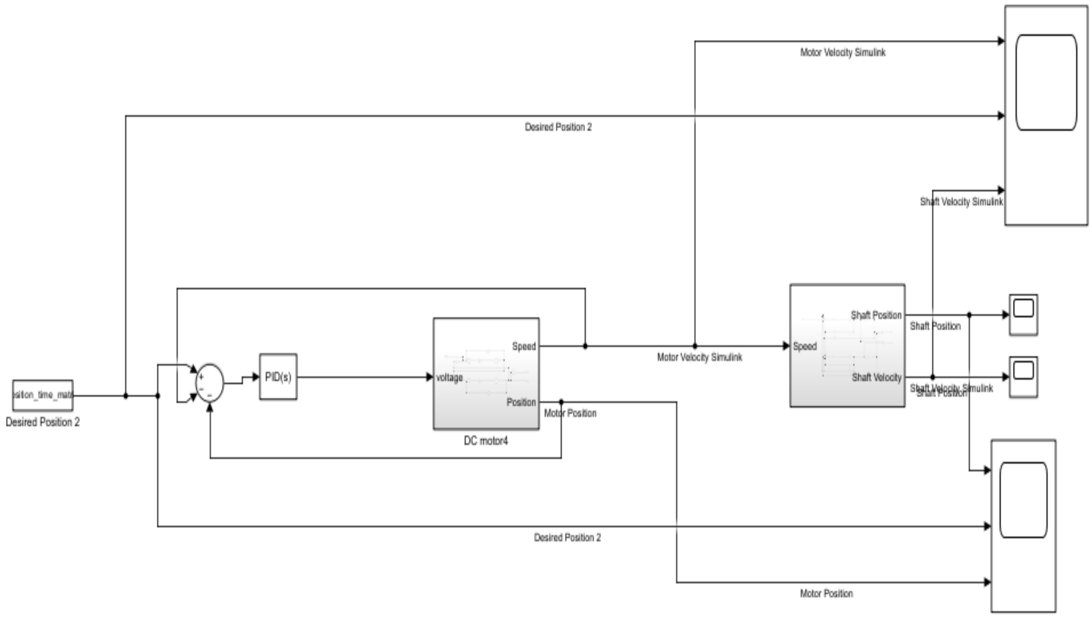

Figure 14. MATLAB Simulink With PID Velocity And Position Control (Desired).

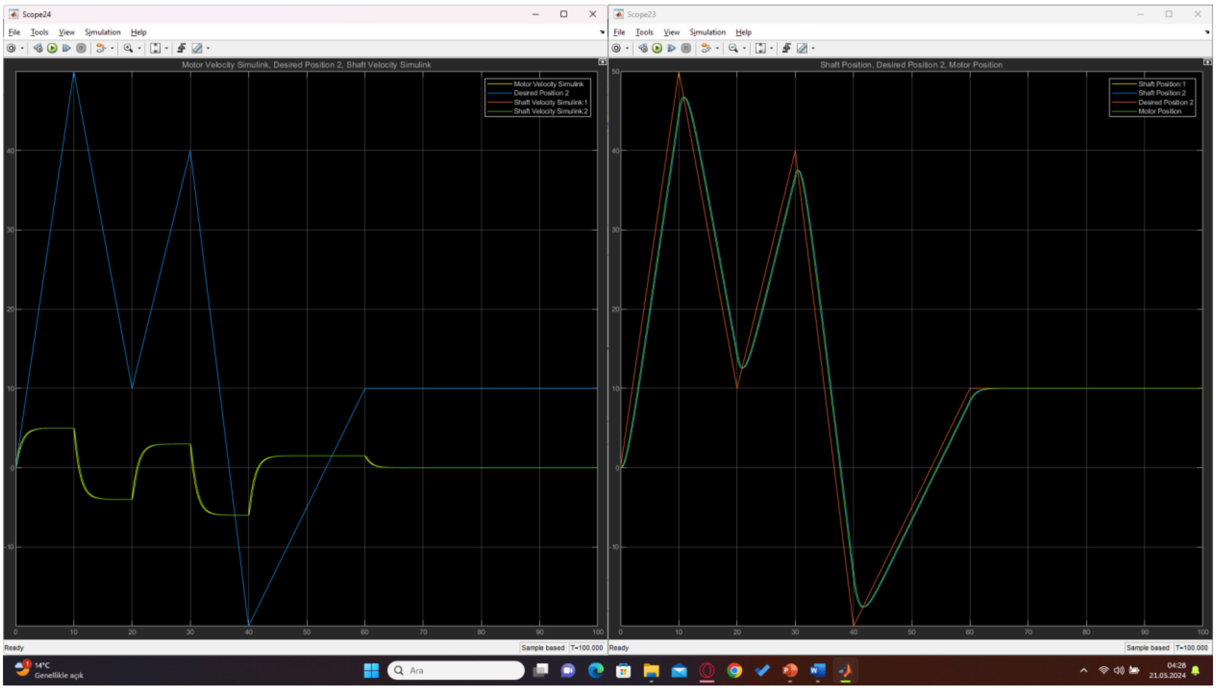

Figure 15. MATLAB Simulink With PID Velocity And Position Control Graph (Desired).

The outputs (desired-desired, fixed-fixed) of different position and speed controls at fixed and desired inputs are given in figure 16 to compare and make sure.

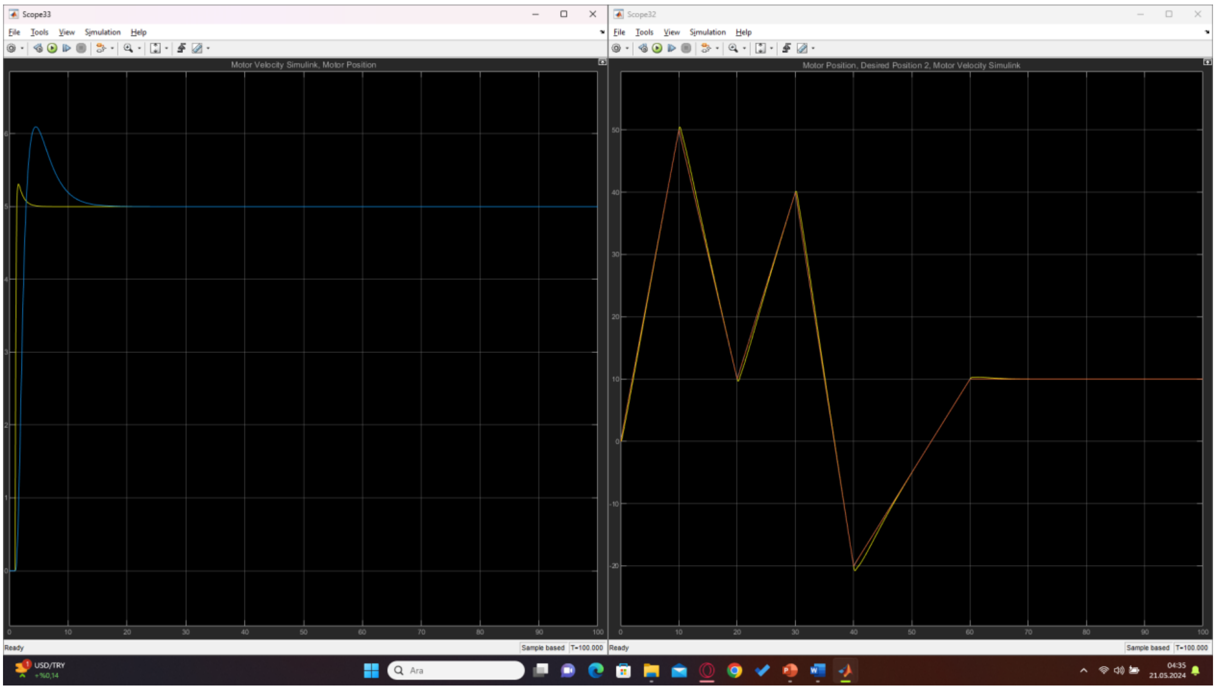

Figure 16. Comparison Graphs.

2.3 Mathematical Calculations of the Project

The first step of the mathematical model of the system is prepared for the block diagrams used in MATLAB Simulink. Since the system is an electromechanical system, the mathematical calculations of the electrical and mechanical parts are handled separately. And thanks to these mathematical calculations, the block diagrams of the system were created and placed on MATLAB Simulink and the system was analysed. The drawing given in Figure 17 is the theoretical version of the project on paper.

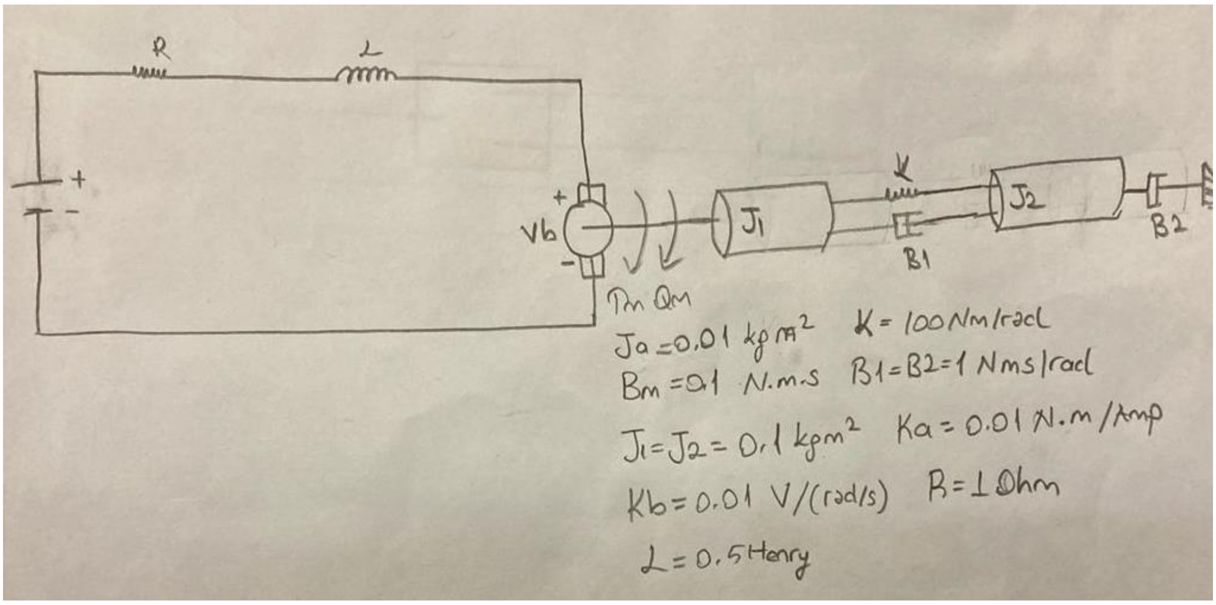

Figure 17. Theoretical Project.

2.3.1 Mathematical Calculation Of The Electrical Section

At this stage of the project, calculations were made for the electrical section. Thanks to these calculations, the MATLAB Simulink block diagram given in Figure 2 was made.

- $T_m = K_a * I_a \rightarrow I_a = T_m / K_a$
- $V_b(s) = K_b * s * \theta_{m1}(s)$

$$I_a R_a + I_a L_a + V_b = V_a \quad (1)$$

$$J_a \ddot{\theta}_{m1} + B_m \dot{\theta}_{m1} = K_a * I_a(s) \quad (2)$$

$$I_a(Ls + R) + K_b * s * Q_{m1}(s) = V_a(s) \quad (3)$$

$$Q_{m1}(s)(J_a s^2 + B_m s) = K_a * I_a(s) \quad (3.1)$$

$$Q_{m1}(s)[(J_a s^2 + B_m s)/(K_a) * (L_a * s + R) + K_b * s] = V_a(s) \quad (3.2)$$

2.3.2 Mathematical Calculation of the Mechanical Section

At this stage of the project, calculations were made for the mechanical part. Thanks to these calculations, the MATLAB Simulink block diagram given in Figure 4 was made. The action-response forces of the two masses according to the direction of rotation are given in Figure 18.

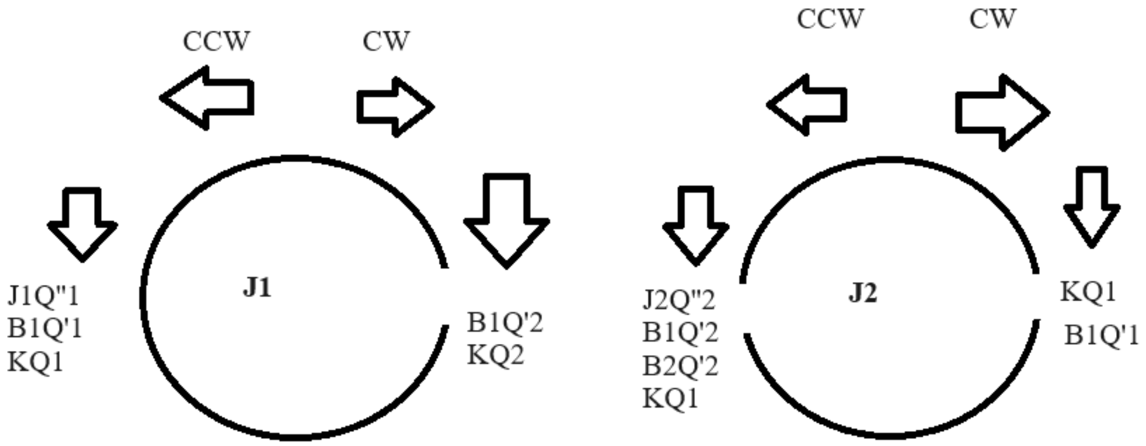

Figure 18. Impact-Response Forces of Mechanical Section.

1. $J_1\ddot{\theta}_{m1} + B_1\dot{\theta}m_1 + K\theta_{m1} - B_1\dot{\theta}m_2 - K\theta_{m2} = T_m$ (1)
2. $J_2\ddot{\theta}_{m2} + (B_1+B2)\,\dot{\theta}m_1 + K\theta_{m2} - B_1\dot{\theta}m_1 - K\theta_{m1} = 0$ (2)
3. $\ddot{\theta}_{m1}\,[\,J_1 + B_1 + K] + \ddot{\theta}_{m2}\,[-B1 - K] = T_m$ (1.1)
4. $\ddot{\theta}_{m1}\,[\,-B1 - K] + \ddot{\theta}_{m2}\,[J_2 + (B_1 + B2) + K] = 0$ (2.1)

2.3.3 Transfer Function Calculation of the Project

The transfer function of the project is composed of two parts as seen in the last two sections. Since it is an electromechanical project, the transfer function of the electrical and mechanical parts are calculated separately and finally the transfer function of the electromechanical system is found by multiplying these two transfer functions. Calculations in the last two sections were made for block diagram and Simulink. The calculations in this section are the continuation of the last two calculations. In the calculations made in this section, the values are substituted.

Transfer function calculation for electrical section:

$$\theta_{m1}(s) = [((0.005s^3 + 0.06 s^2 + 0.1001s) / 0.1) + ((0.0001s) / 0.01)] = V_a(s) \quad (3.3)$$

$$\theta_{m1}(s) = [((0.005s^3 + 0.06s^2 + 0.1001s) / 0.01)] = V_a(s) \quad (3.4)$$

$$(\theta_{m1}(s) / V_a(s)) = [(0.01) / (0.005s^3 + 0.06s^2 + 0.1001s)] \quad (3.5)$$

Transfer function calculation for mechanical part:

$$\theta_{m1}(s) [0.1s^2 + s + 100] + Q_{m2}(s) [-s - 100] = T_m \quad (1.2)$$

$$\theta_{m1}(s) [-s - 100] + Q_{m2}(s) [0.1s^2 + 2s + 100] = 0 \quad (2.2)$$

$$\begin{matrix} 0.1s^2 + s + 100 & -s - 100 \\ -s - 100 & 0.1s^2 + 2s + 100 \end{matrix} * \begin{matrix} \theta m1(s) \\ \theta m2(s) \end{matrix} = \begin{matrix} Tm \\ 0 \end{matrix}$$

$$\theta_{m1}(s) = [(T_m (0.1s^2 + 2s + 100)) / (0.01s^4 + 0.3s^3 + 19.01s^2 + 98s)] \quad (1.3)$$

$$\theta_{m2}(s) = [(T_m(s + 100)) / (0.01s^4 + 0.3 s^3 + 19.01s^2 + 98s)] \quad (2.3)$$

$$\theta_{m2}(s) / \theta_{m1}(s) = [(s + 100) / (0.1s^2 + 2s + 100)] \quad (3)$$

Finally, to find the transfer function of the electromechanical section, the two transfer functions obtained are multiplied. And the result [$\theta m_2(s) / Va(s)$] gives the transfer function.

$$[\theta_{m1}(s) / V_a(s)] * [\theta_{m2}(s) / \theta_{m1}(s)] = [\theta_{m2}(s) / V_a(s)]$$

$$[\theta_{m2}(s) / V_a(s)] = [(0.01s + 1) / (0.0005s^5 + 0.016s^4 + 0.63001s^3 + 6.2002s^2 + 10.01s)]$$

2.3.4 Conclusion Graphs And Controller Parameters

Fixed and desired positions are given to the input of the transfer function. The output graphs of these inputs are shown in figüre 19.

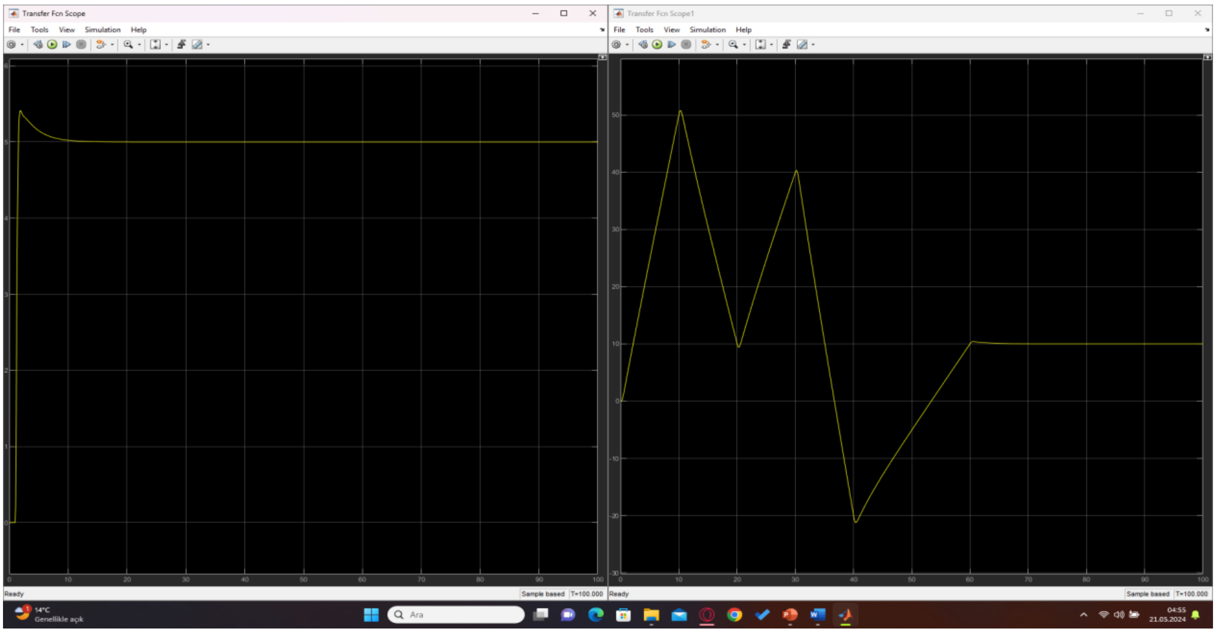

Figure 19. Fixed And Desired Position Graph Of Transfer Function.

The control parameters from the first system to the last system respectively are given below.

Controller Parameters

	Tuned	Block
P	43.842	32.3001
I	12.6969	8.7638
D	18.6252	21.3186
N	405.4947	424.6051

Performance and Robustness

	Tuned	Block
Rise time	0.362 seconds	0.406 seconds
Settling time	4.75 seconds	6.49 seconds
Overshoot	9.69 %	5.67 %
Peak	1.1	1.06
Gain margin	40.6 dB @ 62.6 rad/s	40.6 dB @ 66.8 rad/s
Phase margin	64.5 deg @ 3.55 rad/s	74.7 deg @ 3.72 rad/s
Closed-loop stability	Stable	Stable

Figure 20. First System Controller Parameters.

Controller Parameters

	Tuned	Block
P	18.2217	207.3245
I	51.3285	588.7945
D	0.95754	17.9278
N	37.2193	4054.9474

Performance and Robustness

	Tuned	Block
Rise time	0.419 seconds	0.0606 seconds
Settling time	1.55 seconds	0.377 seconds
Overshoot	7.12 %	2.26 %
Peak	1.07	1.02
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	69 deg @ 3.55 rad/s	90 deg @ 35.5 rad/s
Closed-loop stability	Stable	Stable

Figure 21. Second System Controller Parameters.

Controller Parameters

	Tuned	Block
P	18.2217	207.3245
I	51.3285	588.7945
D	0.95754	17.9278
N	37.2193	4054.9474

Performance and Robustness

	Tuned	Block
Rise time	0.419 seconds	0.0606 seconds
Settling time	1.55 seconds	0.377 seconds
Overshoot	7.12 %	2.26 %
Peak	1.07	1.02
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	69 deg @ 3.55 rad/s	90 deg @ 35.5 rad/s
Closed-loop stability	Stable	Stable

Figure 22. Third System Controller Parameters.

Controller Parameters

	Tuned	Block
P	43.842	41.2623
I	12.6969	11.2106
D	18.6252	37.7197
N	405.4947	704.6691

Performance and Robustness

	Tuned	Block
Rise time	0.362 seconds	0.236 seconds
Settling time	4.75 seconds	6.33 seconds
Overshoot	9.69 %	3.78 %
Peak	1.1	1.04
Gain margin	40.6 dB @ 62.6 rad/s	40.3 dB @ 87.7 rad/s
Phase margin	64.5 deg @ 3.55 rad/s	65.7 deg @ 6.17 rad/s
Closed-loop stability	Stable	Stable

Figure 23. Fourth System Controller Parameters.

Controller Parameters

	Tuned	Block
P	378.7006	2045.6149
I	1742.1196	4710.8934
D	18.8528	197.3629
N	225.44	45112.7327

Performance and Robustness

	Tuned	Block
Rise time	0.0322 seconds	0.00554 seconds
Settling time	0.286 seconds	0.01 seconds
Overshoot	12 %	0 %
Peak	1.12	0.998
Gain margin	-Inf dB @ 0 rad/s	-Inf dB @ 0 rad/s
Phase margin	69 deg @ 41.3 rad/s	89.6 deg @ 395 rad/s
Closed-loop stability	Stable	Stable

Figure 23. Fifth System Controller Parameters.

3. CONCLUSION OF THE PROJECT

This project, carried out in accordance with the course curriculum, has contributed significantly to our engineering skills. Thanks to the MATLAB Simulink and Simscape simulations based on the mathematical calculations covered in the course, we are now able to predict how a system should behave and have the ability to make comments based on the analysis and results. By learning a lot about MATLAB, we have developed ourselves and learned to integrate theoretical knowledge into a system from an engineering perspective and to simulate it. Within the scope of this project, the addition of the PID controller and the saturation block allowed us to control the behavior of electrical and mechanical systems more precisely. This approach has enhanced the overall performance of the project. Simulations conducted in MATLAB Simulink and Simscape environments show that controlled systems better match the desired speeds and positions.