MXET 375
Applied Dynamic Systems

Multidisciplinary
Engineering Technology
COLLEGE OF ENGINEERING

LABORATORY # 7

Electromechanical System

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Introduction

The purpose of lab 7 is to examine the modeling and simulation of a DC motor-based electromechanical system using Simulink, guided by experimental data obtained from a physical demonstration. The primary objective is to replicate and analyze the behavior of the motor by creating a dynamic model and comparing simulated output with real-world measurements. This lab emphasizes practical applications of electromechanical system simulation, data processing, and model configuration within Simulink. Task 1 involves observing a demonstration of the DC motor system to collect data on rotational speed and current draw under various input voltages. The collected experimental data will be used to produce plots of motor response in Excel, with a focus on identifying and interpreting trends in angular velocity and current over time. Task 2 focuses on applying motor-specific dynamic equations to model the DC motor mathematically. By analyzing key parameters, such as resistance, inductance, and damping, this task underscores the impact of these variables on system behavior and prepares the data needed for subsequent simulation. Task 3 extends the modeling approach by constructing a Simscape representation of the motor, incorporating mechanical and electrical characteristics specific to the system. Simulations will be conducted at three different input voltages to evaluate variations in system response, providing a comprehensive analysis of the motor's behavior across operating conditions. Completion of Lab 7 will provide a robust understanding of electromechanical system modeling, including techniques for dynamic system setup, motor response analysis, and the comparison of simulated outputs with physical data, using Simulink, Simscape, Simscape Multibody, and MATLAB.

Procedure & Lab Results

This lab has three tasks total. Each task includes a detailed description of the setup, procedure, results, relevant figures, and discussion focusing on developing a better understanding and interpretation of what the results mean and how they were derived. All tasks focus on an electromechanical system which can be seen in Figure 1.

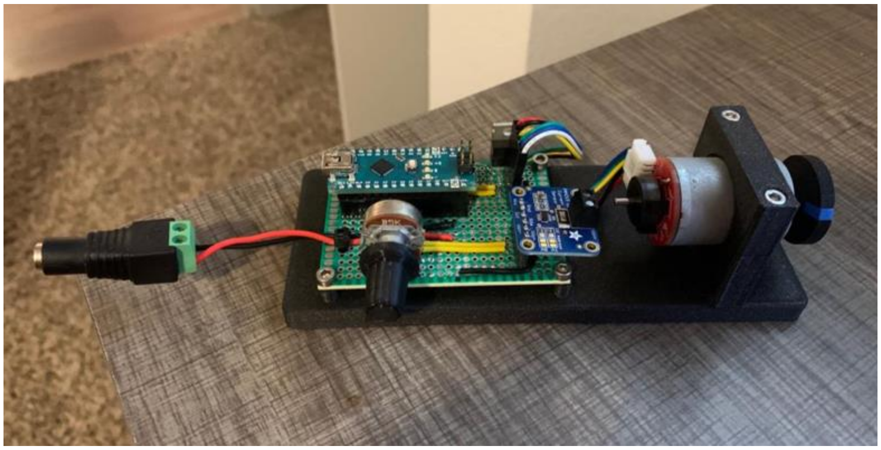

Figure 1: Physical DC Motor System [1]

This system is an Arduino Nano controlled DC motor. The model also records positional feedback of the motor shaft as it rotates, as well as the current draw of the motor. The rotary dial on the side can be used to vary the input voltage to the DC motor and thus can vary the rotational speed. A DC barrel jack is used to power the circuit board and subsequently the DC motor. [1]

Task 1

Following the live demonstration of the electromechanical system, and obtaining the data collected from that demonstration, task 1 can begin. This system consisted of a circuit board and a motor, such that when current was applied to the circuit, the motor would begin to rotate. Throughout the duration of the demonstration, the amperage of the circuit and the angular velocity of the motor were recorded as a function of time. This experiment was performed for an input voltage of 6 V, 9 V, and 12 V.

Task 1 involves examining the angular velocity and current data collected from the physical demonstration of the electromechanical system. This data, stored in an Excel file titled " dcMotor_Data.xlsx," consists of time values, source voltage values, amperage data, and angular velocity data for each of the source voltage configurations (6V, 9V, and 12V). The first step is to open the file and observe the dataset, which includes columns with all the relevant values being measured. One more column must be added with the conversion of all the angular velocity values from RPM to rad/s. The task then requires the creation of a visual plot, using a "Scatter with Smooth Lines" chart, of the entire data set from 0 to 3 seconds, which provides a graphical representation of the values being examined. The plot will then be properly formatted with a title, labeled axes, an additional axis, and a legend to clearly show the changes in the values over the duration of the experiment. The final formatted plot can be seen in Figure 2.

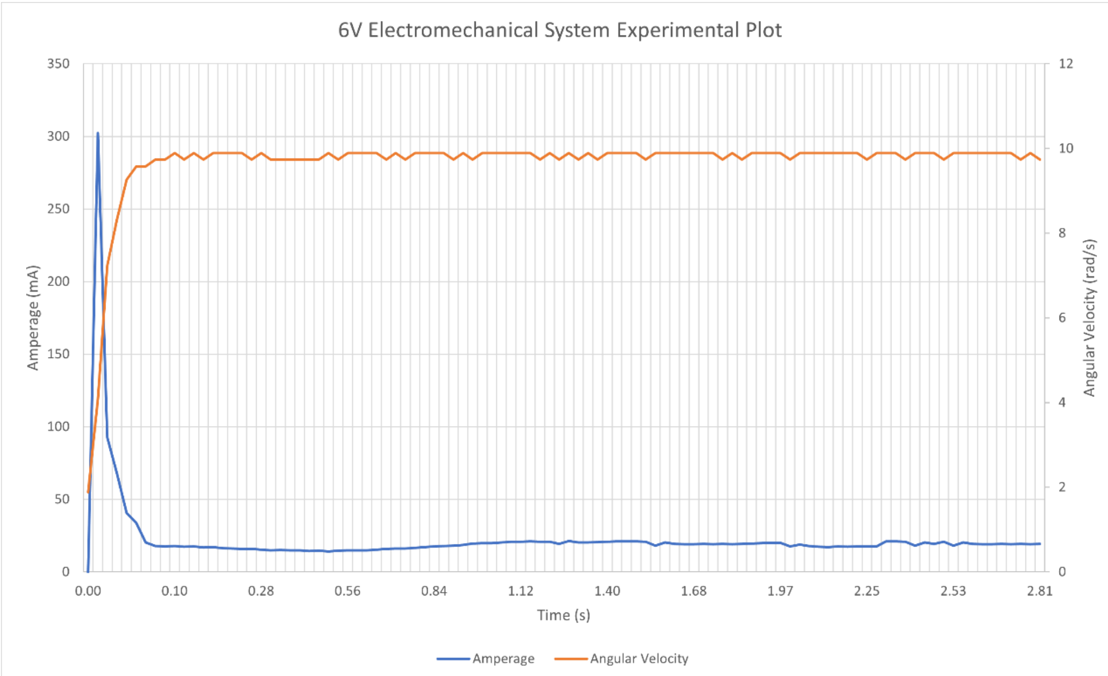

Figure 2: Task One 3 Second 6V Input Electromechanical System Experimental Amperage and Angular Velocity Vs. Time Plot

After collecting this plot, the same procedure is followed to create the next plot with the only change being that the data being examined is now only for the first 0.25 seconds. This will result in the creation of the plot seen in Figure 3.

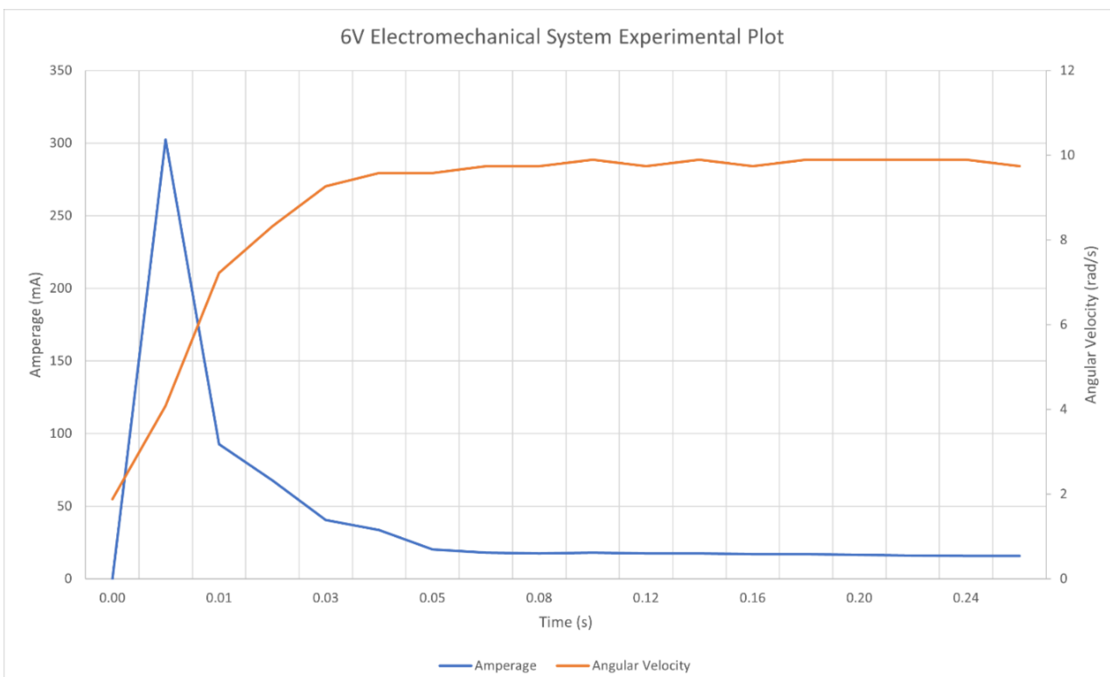

Figure 3: Task One 0.25 Second 6V Input Electromechanical System Experimental Amperage and Angular Velocity Vs. Time Plot

After collecting this plot, the same procedure is followed to create the next plot with the only change being that the data being examined is now for the 9 Volt supply voltage instead of the 6 Volt supply voltage. This will result in the creation of the plot seen in Figure 4.

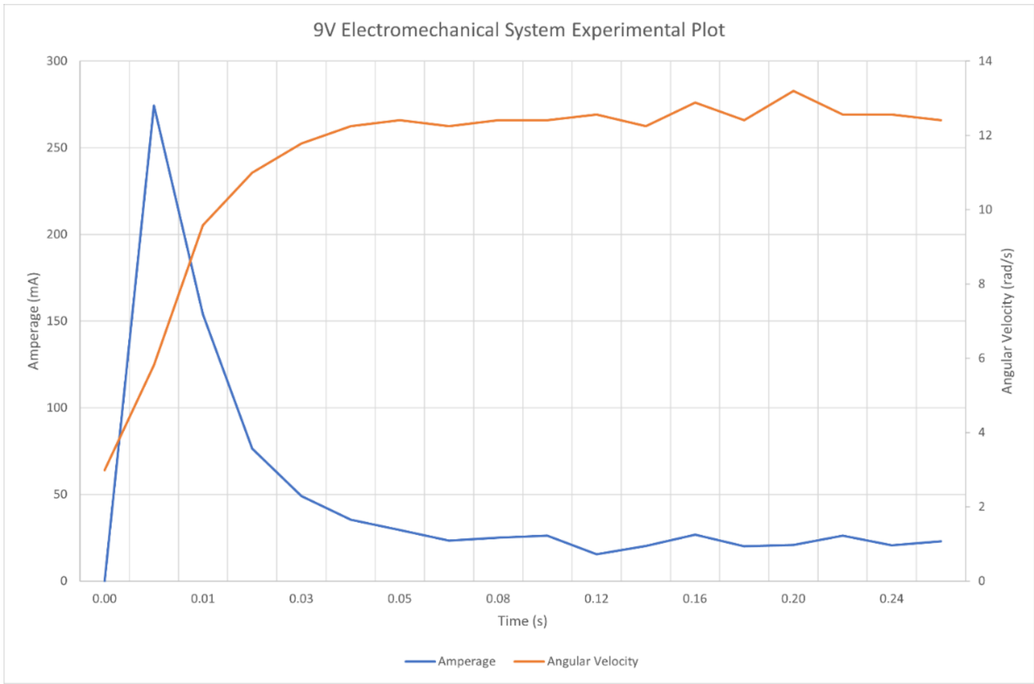

Figure 4: Task One 0.25 Second 9V Input Electromechanical System Experimental Amperage and Angular Velocity Vs. Time Plot

After collecting this plot, the same procedure is followed to create the next plot with the only change being that the data being examined is now for the 12 Volt supply voltage instead of the 9 Volt supply voltage. This will result in the creation of the plot seen in Figure 5.

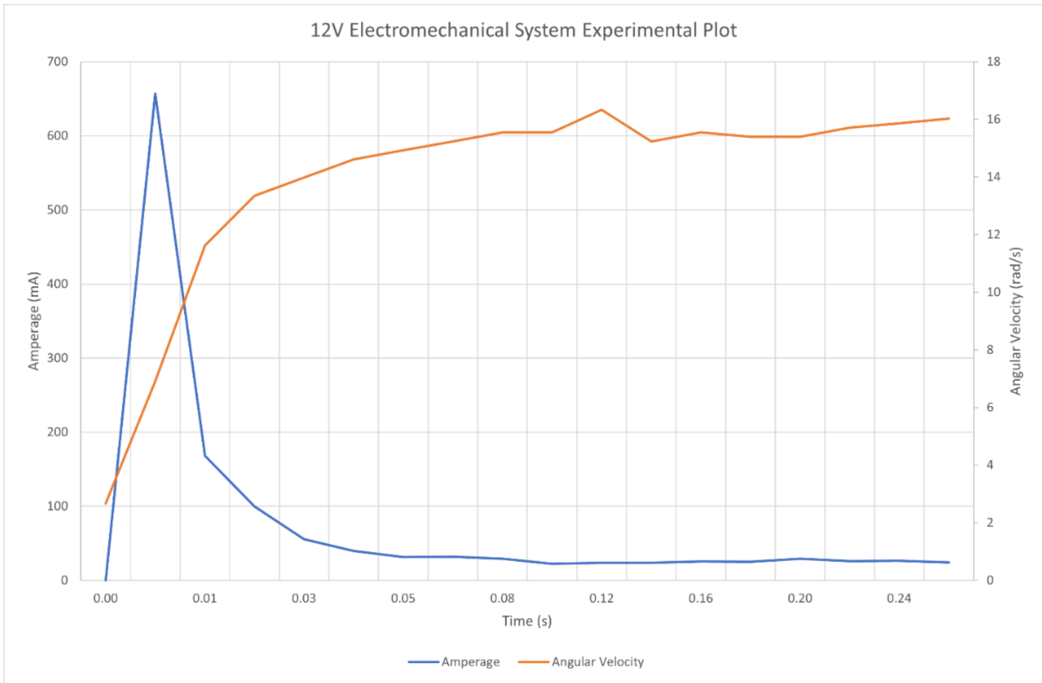

Figure 5: Task One 0.25 Second 12V Input Electromechanical System Experimental Amperage and Angular Velocity Vs. Time Plot

One similarity between the system responses at the three different voltage levels is that they all have a sudden spike of current that eventually stabilizes. The common variable between the system responses is the source voltage changing from 6V to 9V to 12V. Changing it results in a directly proportional effect on the system's current and angular velocity.

These resulting plots all display a common relationship as they all generally follow the same behavior. The current amperage curve is the same throughout all the plots beginning with a drastic increase, reaching a peak, and then a drastic decrease until stabilizing. The angular velocity curve is the same throughout all the plots as well beginning with a drastic increase until stabilizing. The only change between the plots is in the values associated with each curve. As the source voltage increases so does the peak of the amperage and the steady state of the angular velocity. Each plot exhibits a sudden spike in current which then rapidly drops to a value close to zero. This spike of current occurs in order to charge the inductor in the motor. Since a large amount of current is supplied to the motor inductor, the motor will begin to rotate. This can be seen by the sudden increase in the rotational velocity that is accompanied by the spike in current. Once the inductor is charged from the initial spike in current, a large magnetic field will be generated. This magnetic field generates a back EMF. In this experiment, the back EMF works to oppose the flow of current. This is why the current drops quickly after its initial spike. The back EMF will eventually bring the current to a steady state, which can be seen by the approximately constant current from 0.05 seconds onwards. Thus, the motor will receive a constant current, resulting in a constant rotational velocity. This is why the rotational velocity remains approximately constant from 0.05 seconds onwards.

Task 2

Task 2 focuses on finding and understanding the ordinary differential equations (ODEs) that can be used to model a DC motor using common methods of mechanical and electrical dynamic analysis. This generic DC motor setup being modeled can be seen in Figure 6.

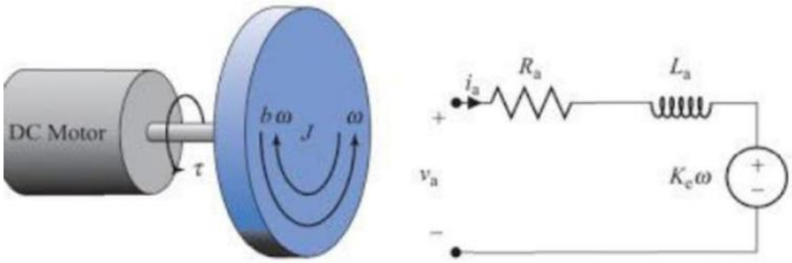

Figure 6: Task Two DC Electric Motor Model with Labeled Components and Defined Variables [1]

To begin this task first involves identifying the ordinary differential equations which can be seen in Equation 1 and Equation 2 where the main terms being solved for are the motor torque (τ) and supply voltage (v).

$$J\dot{\omega} + b\omega = \tau = ki \qquad \textbf{Equation 1}$$

Where ‘J’ is the shaft inertia, ‘$\dot{\omega}$’ is the rotational acceleration, ‘b’ is the rotational damping coefficient, ‘ω’ is the rotational velocity, ‘τ’ is the motor torque, ‘k’ is the motor constant, and ‘i’ is the current.

$$v = Ri + L\frac{di}{dt} + k\omega \qquad \textbf{Equation 2}$$

Where ‘v’ is the supply voltage, ‘R’ is the resistance, ‘i’ is the current, ‘L’ is the inductance, ‘k’ is the motor constant, and ‘ω’ is the rotational velocity. Other variables that relate to these equations may include ‘θ’ which is the rotational position and ‘θ^*’ which is the rotational velocity and can also be written as ‘ω’. The name of the electro-magnetic property that generates ‘$k\omega$’ in this equation is back EMF.

These equations are used to model the electromechanical system in this experiment. Equation 1 is essentially Newton’s 2nd law in rotational terms. The motor torque (τ) minus the force due to damping (bω) is equal to the product of the inertia and the angular acceleration (Jώ). In this equation and subsequent equations, the term ‘ώ’ (omega dot) is equal to the derivative of the rotational velocity, which is equivalent to the angular acceleration. The term ‘θ^*’ (theta dot) is equal to the derivative of the angular position, which is equivalent to the rotational velocity. The second part of Equation 1 identifies the relationship between the electrical system and the mechanical system. Essentially, the output of the mechanical system (τ) is equal to the input of the mechanical system (i) multiplied by a constant (k).

Finally, Equation 2 is found using Kirchhoff's Voltage Law. The sum of the forces across a loop must equal zero, so the source voltage is equal to the summation of all of the voltage drops across the loop. 'Ri' is equal to the voltage drop across the resistor and 'L di/dt' is equal to the voltage drop across the inductor. However, there is an additional term ($k\omega$) which has not been encountered before. This term refers to the back EMF. The back EMF is a quantity that is generated from the behavior of the circuit and works to oppose the supply voltage. In a dc motor, the back EMF is proportional to the rotational velocity, which is why its term is $k\omega$. The 'k' term is referred to as the constant of proportionality, which can be altered within Simulink to adjust the back EMF. When the motor is first turned on, the back EMF is 0 V since there is no rotational velocity. However, as the rotational velocity of the motor increases, the back EMF increases. This reduces the voltage across the coil, and thus reduces current. Because of the back EMF, the circuit will eventually reach a steady state where the current and the rotational velocity of the motor remain approximately constant over time.

Task 3

The focus of Task 3 shifts to modeling the physical system in a Simulink simulation using Simscape. The purpose of this task is the same as task 1, which is to expand the understanding and precision in modeling electromechanical systems. This task provided the assignment of creating an electromechanical system using common control system elements and the Simscape Library. This system is made up of one resistor block, one inductor block, one current sensor block, one DC voltage block, two mechanical rotational reference blocks, one inertia block, one ideal rotational motion sensor block, two PS-simulink converter blocks, one solver configuration block, one rotational damper block, one rotational electromechanical converter, one bus creator, and one scope block. The provided lab manual for this lab walks through the exact setup, configuration, and procedure for creating this block diagram. The procedure for this began with importing all the required blocks and setting them up in the correct setup configuration. The setup configuration of the required block diagram to produce the correct plots, with all block names, can be seen in Figure 7.

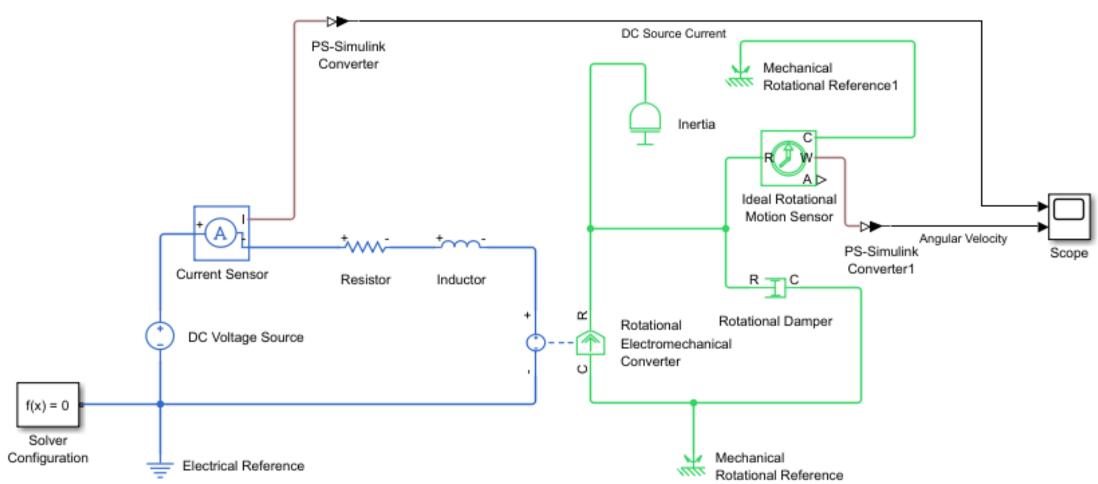

Figure 7: Task Three Electromechanical System Complete Block Diagram

With the setup complete the next step was to configure each block with the appropriate values. In the case of this problem that is done by setting the DC voltage to 6V, resistor to 1 Ohm, Inductor to 100 nH, constant of proportionality to K = 0.75, damping coefficient to 0.01 Nm/ (rad/s), and inertia to 0.01 kg*m^2. Lastly, in the configuration parameters window of Simulink the stop time must be set to 3 seconds to match the experimental data, the max step size must be set to 0.2 seconds, and the solver must be changed to “ode23t (mod.stiff/Trapesoidal)”. Once that is complete the final step is to run the system and format the result to the specified requirements. This result can be seen in Figure 8.

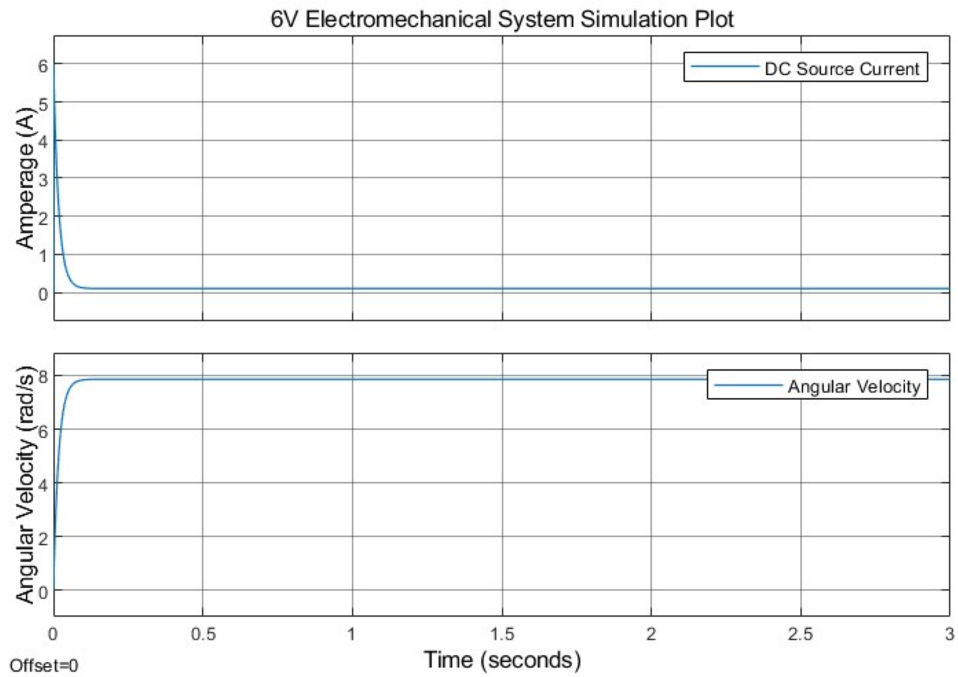

Figure 8: Task Three 3 Second 6V Input Electromechanical System Simulation Amperage and Angular Velocity Vs. Time Plot

After collecting this plot, the stop time should be set to 0.25 seconds and the simulation should be run again. This will result in the creation of the plot seen in Figure 9.

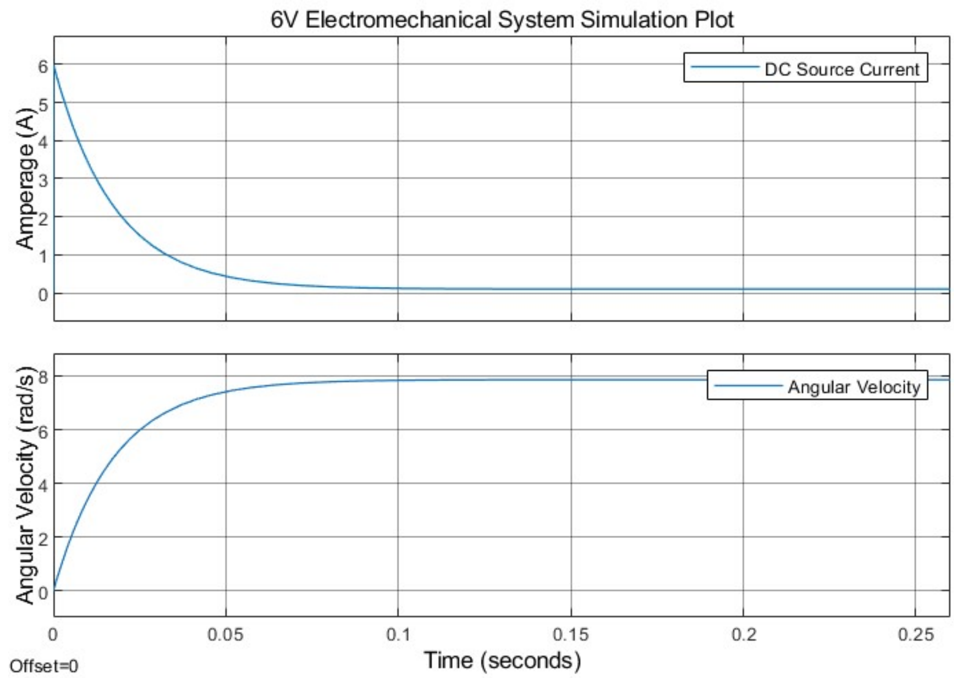

Figure 9: Task Three 0.25 Second 6V Input Electromechanical System Simulation Amperage and Angular Velocity Vs. Time Plot

After collecting this plot, the DC voltage should be set to 9 Volts and the simulation should be run again. This will result in the creation of the plot seen in Figure 10.

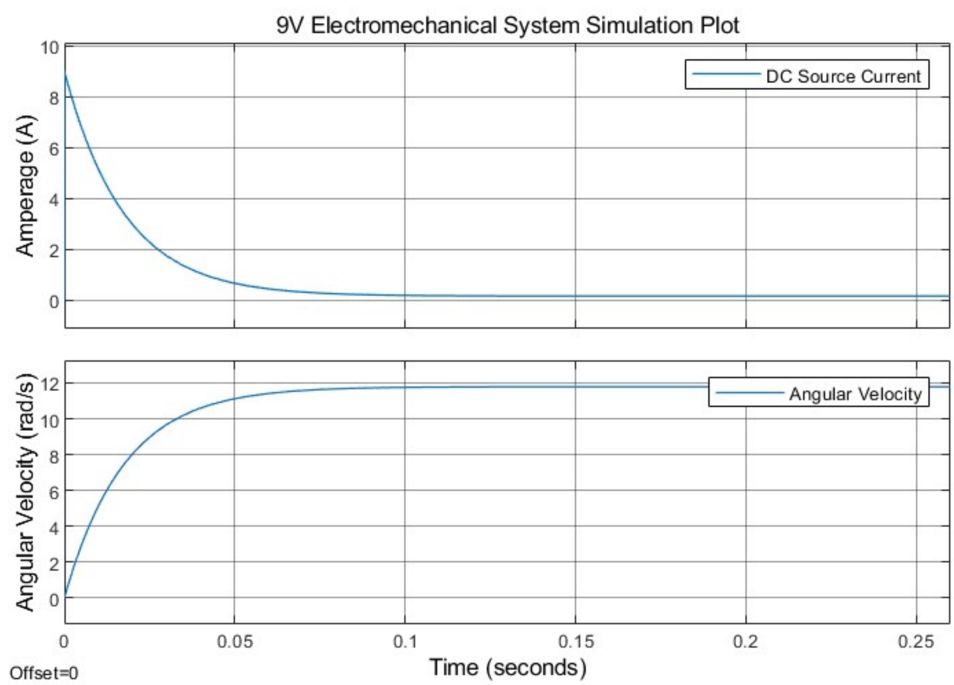

Figure 10: Task Three 0.25 Second 9V Input Electromechanical System Simulation Amperage and Angular Velocity Vs. Time Plot

Lastly, after collecting this plot, the DC voltage should be set to 12 Volts and the simulation should be run again. This will result in the creation of the plot seen in Figure 11.

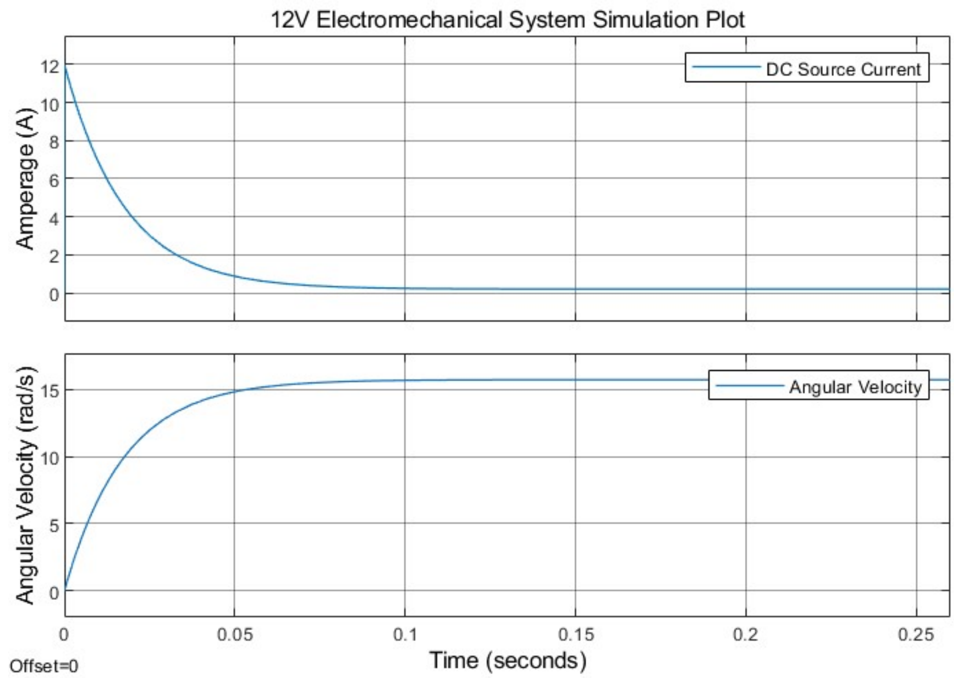

Figure 11: Task Three 0.25 Second 12V Input Electromechanical System Simulation Amperage and Angular Velocity Vs. Time Plot

For both the physical and simulated models of a dc motor, the current suddenly increases for a short period before drastically reducing down to a steady state because it is initially charging the inductor in the motor but because of back EMF it reduces to steady state. Back EMF of a DC motor is what opposes the supply voltage, it works to prevent the motor from continually speeding up. The parameter responsible for adjusting this in Simulink is the constant of proportionality (K).

The comparison between the physical model and the simulated plots generated in Simulink reveals several insights into the dynamic behavior and accuracy of the DC motor model. Both the physical and simulated plots display an initial spike in current, consistent with the inductor charging behavior in the motor, followed by a decrease that stabilizes due to the influence of back electromotive force (EMF). This steady-state current behavior indicates that both models effectively capture the inductor's initial charging phase and the regulating effect of back EMF on motor speed over time. Angular velocity trends in both the physical and simulated plots demonstrate a sharp initial increase that gradually approaches a steady state, reflecting the motor's acceleration dynamics accurately. As the input voltage rises from 6V to 12V, a proportional increase in steady-state angular velocity is observed, which aligns with theoretical expectations: higher input voltages yield higher rotational speeds due to increased current flow before back EMF establishes the steady-state condition. After comparing the plots generated from the data that was obtained from the physical model to the simulated plots from the Simulink model there are many comparisons and conclusions that can be made. Some of these comparisons and conclusions are good while others aren't necessarily the best. Slight differences in the magnitude of peak values for current and angular velocity are present between the physical and simulated data. These discrepancies can likely be attributed to certain assumptions in the Simulink model that do not perfectly account for real-world parameters, such as frictional losses and minor variances in motor resistance and inductance. Potential sources of error in this analysis include model simplification, measurement tolerances, and environmental factors. The Simulink model's reliance on ideal component values may omit factors such as frictional damping variations or temperature effects that could subtly influence motor performance in physical tests. Additionally, minor discrepancies may arise from the precision of physical sensors used to measure current and angular velocity, as well as environmental factors, like ambient temperature, that might alter resistance or mechanical damping in ways unrepresented by the idealized model. The comparison between the physical and simulated plots confirms the model's efficacy in representing the DC motor's response to varying input voltages. Although minor variances in peak magnitudes exist, these differences are largely attributable to idealizations within the model and slight tolerances in measurement. Overall, the Simulink model provides a robust approximation of the motor's behavior, supporting its application for further analysis and predictive modeling in electromechanical systems.

Conclusion

Lab 7 provided an in-depth examination of electromechanical system modeling, specifically focusing on the behavior of a DC motor under various input voltages. Through tasks involving data collection, dynamic equation application, and Simulink simulation, the lab illustrated how theoretical modeling can be effectively aligned with real-world data. Observing the motor's response across different voltages revealed that as the input increased, there was a proportional rise in both the peak current and angular velocity until reaching steady-state conditions. This steady state, influenced by the back electromotive force (EMF), demonstrated the motor's self-regulating behavior to prevent continuous acceleration, underscoring the significant role of EMF in DC motor dynamics. In comparing physical measurements with the simulated model, the analysis uncovered minor variations in peak current and velocity, likely due to factors such as frictional losses, unmodeled resistances, and idealized component values within Simulink. These discrepancies highlighted the challenges in achieving exact balance between simulation and real-world performance, as environmental influences like temperature and measurement tolerances affect physical systems in ways not captured by idealized models. Overall, this lab reinforced essential skills in MATLAB and Simulink, including the application of dynamic equations, system modeling, and comparative analysis. It demonstrated the effectiveness of using simulation to predict and analyze electromechanical behaviors, offering valuable insights into how model-based design can support system development. This exercise not only strengthened practical skills in modeling and simulation but also emphasized the importance of accounting for real-world variances to enhance model accuracy and reliability in predictive engineering applications.

References

[1] Author not listed, *Texas A&M University MXET375 - Lab 07 - Electromechanical System*. College Station, TX, USA: Date not listed.
[2] Rex K., *MXET375 - Kyle Rex - Lab Report 6*. College Station, TX, USA: 10/23/2024.