LAB 4: Modeling a Robot-Arm Link in Simscape

Course Number	**MENG 3020**
Course Title	**System Modeling & Simulation**
Semester/Year	**Fall 2024**

Lab/Tutorial Report No.	**Lab 4**
Report Title	**Modeling a Robot-Arm Link in Simscape**
Section No.	N/A
Group No.	N/A
Submission Date	October 20th 2024
Due Date	

Student Name	Signature*	Total Mark
Michael McCorkell	MichaelM	46 **/ 50**

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LAB 4 Grading Sheet

Student First Name: Michael	**Student Last Name:** McCorkell
Part A: Modeling an Armature Controlled DC Motor	4 **/5**
Part B: Simscape Model of DC Motor and Geared System	9 **/10**
Part C: Simscape Model of Dynamics of a Robot Arm Joint	10 **/10**
Part D: Position Control of the Robot Arm	3.5 **/5**
Post Lab Assignment	14.5 **/15**
General Formatting: Clarity, Writing style, Grammar, Spelling, Layout of the report	5 **/5**
Total Mark	46 **/50**

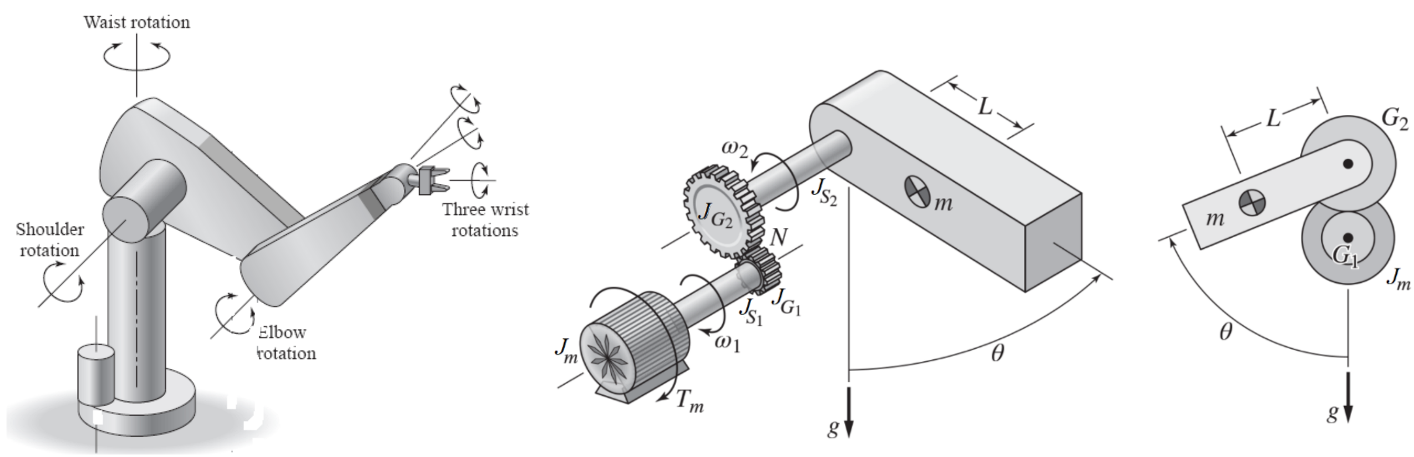
LAB 4: Modeling a Robot-Arm Link in Simscape

OBJECTIVES

- To learn how to simulate multi-physical systems in Simscape
- To acquire the results and validate them based on the system characteristics
- To understand concept of control system and negative feedback

INTRODUCTION

Simscape extends the capabilities of **Simulink** by providing tools for modeling and simulation of multi-domain physical systems, such as those with mechanical, hydraulic, and electrical components. In this lab project, you will understand how to utilize **Simscape** to construct models of electrical and mechanical systems. Shown below is a *robot arm* that has *six joints*. You will develop a model of one of those joints. A single link of a robot arm is shown in Figure 1b.



(a) Robot arm (b) A robot-arm link

Figure 1: Robot arm and a link

The goal is to develop a model and a controller to ensure that the angle θ of the robot arm joint shown below tracks a prescribed profile. The joint is actuated by a **DC motor** that drives an **arm** of mass m through a **gear** pair.

The arm mass center is located a distance L from the rotational axis of the joint. The weight mg exerts a torque $mgL\sin\theta$ that acts in the negative θ direction. The values of m and L depend on the payload being carried in the hand and thus can be different for each application.

Since a **DC motor** consists of electrical and mechanical subsystems, we will start with analysis of DC motor and its characteristics (**Part A**).

We will then build a model of the *dynamics of a rotational mechanical system* containing **gears**, such as the robot arm joint (**Part B**).

Then we will add the *gravity torque* $mgL\sin\theta$ to complete the model of the arm's dynamics (**Part C**).

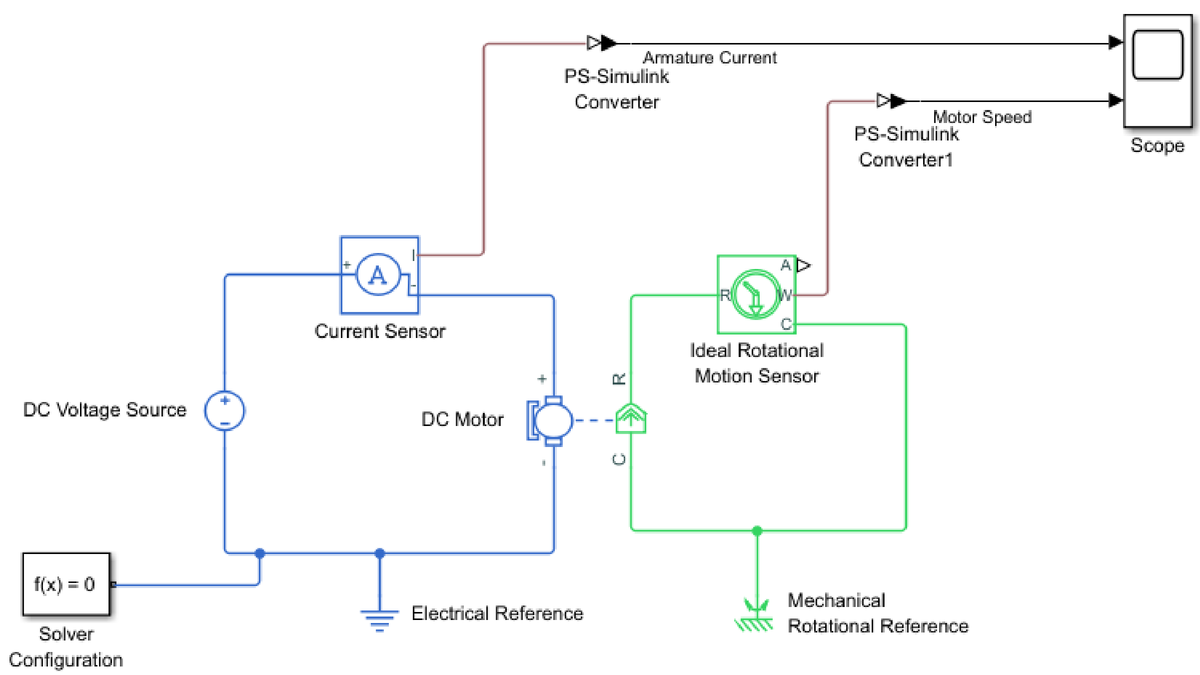
Finally, we will *design a position controller* for the system (**Part D**).

Part A: Modeling an Armature Controlled DC Motor

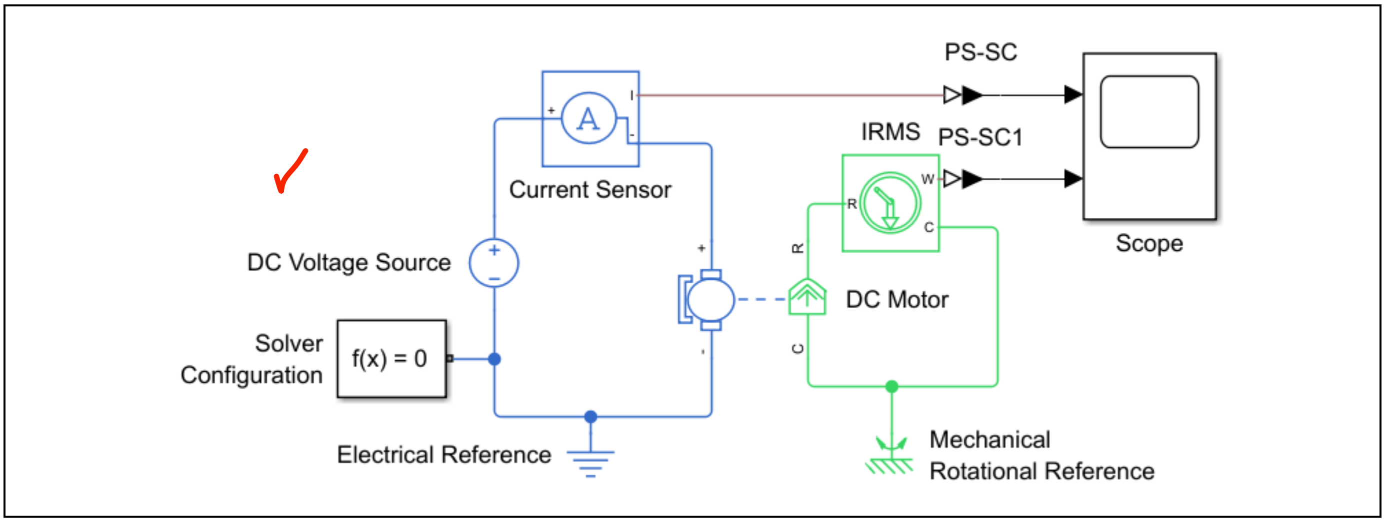
We start with the Simscape model of a **DC Motor**.

1. Open a new **Simulink** model page. Find and place the following elements and components from the **Simulink Library Browser**.
   - **Simscape > Foundation Library > Electrical > Electrical Sources > DC Voltage Source**
   - **Simscape > Electrical > Electromechanical > Brushed Motors > DC Motor**
   - **Simscape > Foundation Library > Electrical > Electrical Elements > Electrical Reference**
   - **Simscape > Foundation Library > Electrical > Electrical Sensors > Current Sensor**
   - **Simscape > Foundation Library > Mechanical > Mechanical Sensors > Ideal Rotational Motion Sensor**
   - **Simscape > Foundation Library > Mechanical > Rotational Elements > Mechanical Rotational Reference**
   - **Simscape > Utilities > PS-Simulink Converter**
   - **Simscape > Utilities > Solver Configuration**
   - **Simulink > Sinks > Scope**

2. Arrange and connect the blocks as shown:



3. Provide your final **Simscape** model diagram for **Part A** below:



4. Enter the following parameter values for **DC Voltage Source**, **DC Motor** and **PS-Simulink Converter1** blocks:

   a) DC Voltage Source:
   Constant Voltage = 12 V

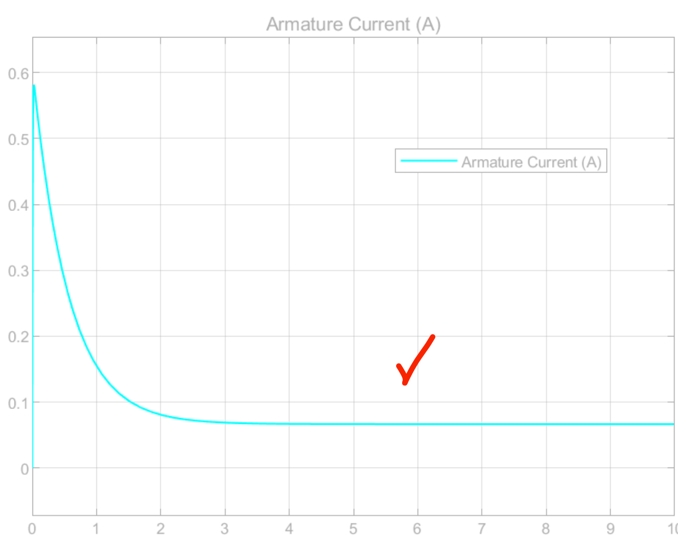
   b) DC Motor:
   Armature resistance = 20 Ohm, Armature inductance = 100 mH, Torque constant = 0.4 N.m/A
   Rotor inertia = 0.005 kg.m^2, Rotor damping = 0.001 Nm/(rad/s), Initial rotor speed = 0 rpm

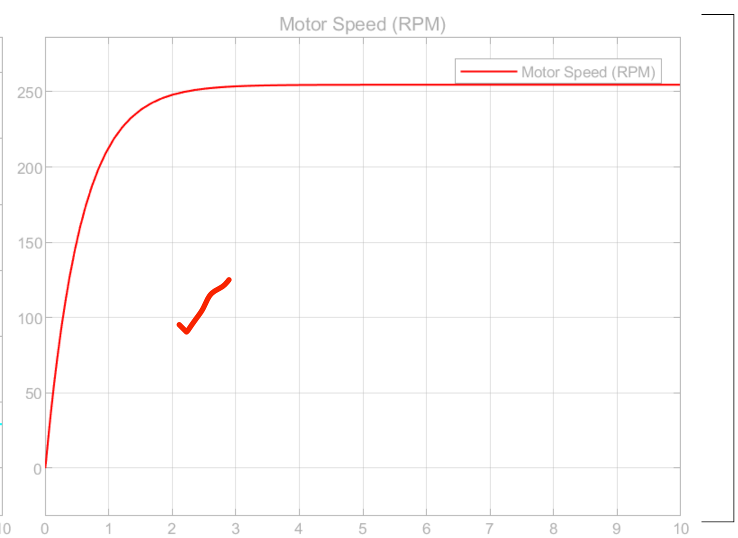
   c) PS-Simulink Converter1:
   Output Signal Unit = rpm

5. Click on the **Model Settings** icon in the **MODELING** tab to open the **Configuration Parameters** window. Click on the **Solver** drop down menu and select the **ode23t** solver. Then click **OK**.

6. **Save** the model file as **Lab4_PartA.slx**. Set the simulation **Stop Time** to **10sec** and **Run** the simulation. Open the **Scope** block. You will see the **armature current** in **ampere** and the **motor speed** in **rpm**. Provide the graphs below:

Armature Current (A) **Motor Speed (rpm)**





7. Activate the **Cursor Measurements** of **Scope** and measure the steady-state current and speed values from the plot and enter the values in **Table 1**.

   Since there is no load connected to the motor, the measured values are called **no-load current** and **no-load speed**. *The no-load current is required to provide a torque to cancel the motor damping torque.*

Table 1

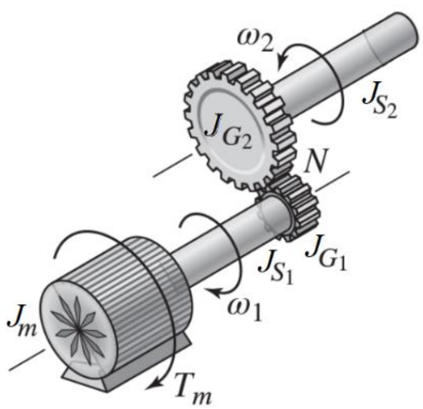
Armature Current (A)	Motor Speed (rpm)
66.67 mA — 0.06667 A ✓	255 rpm ✓

Part B: Simscape Model of DC Motor and Geared System

8. The figure below shows a representation of a rotational system containing a **DC motor** and a **gear** pair. The **inertias** $\boldsymbol{J_1}$ and $\boldsymbol{J_2}$ represent the elements on the driving side and the driven side, respectively.

$$J_1 = J_{S1} + J_{G1} \qquad and \qquad J_2 = J_{S2} + J_{G2}$$

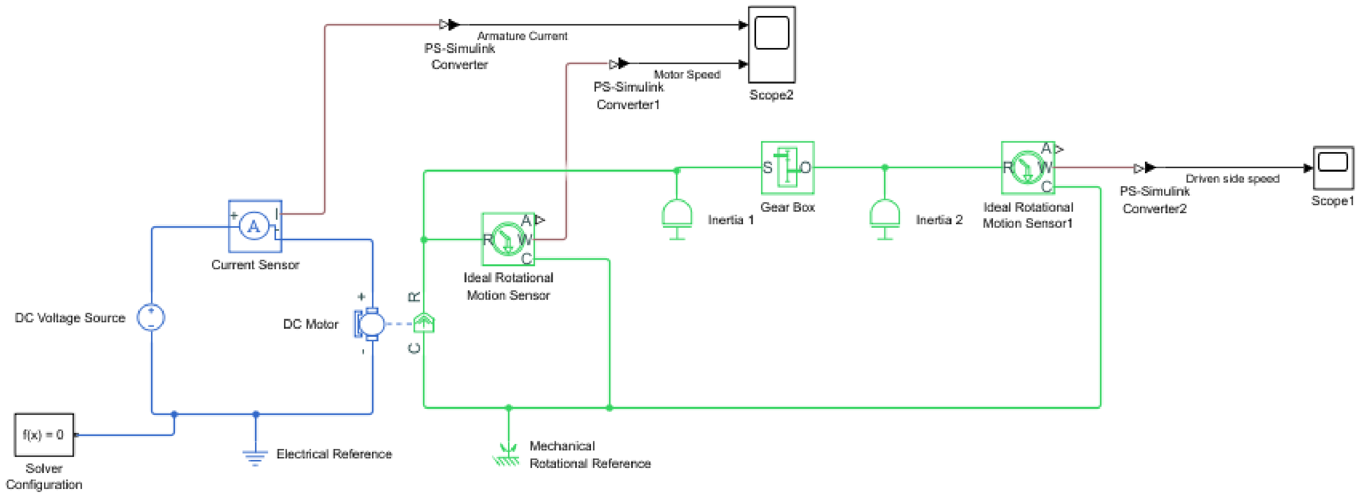
   The **gear ratio** is $N = N_2/N_1$.



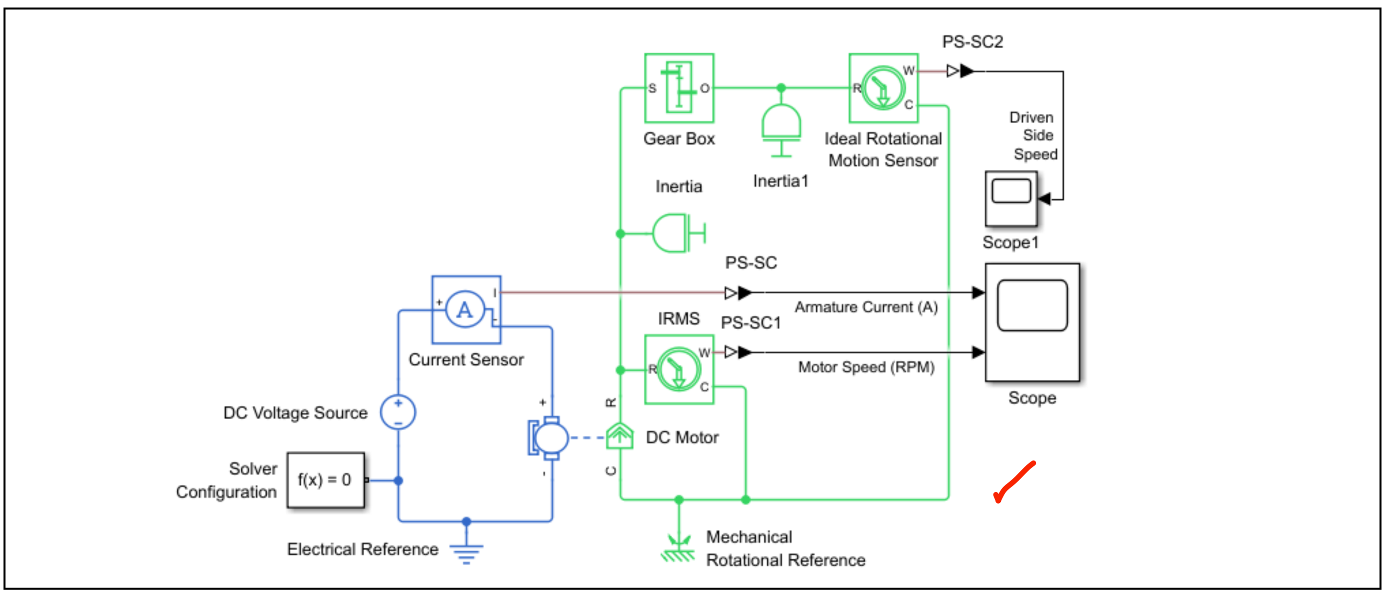
9. Modify the model from **Part A** to construct the **Simscape** model of the gear pair and the shafts. Find and place the following elements and components from **Simulink Browser Library**:

   - **Simscape > Foundation Library > Mechanical > Mechanisms > Gear Box**
   - **Simscape > Foundation Library > Mechanical > Rotational Elements > Inertia**
   - **Simscape > Foundation Library > Mechanical > Mechanical Sensors > Ideal Rotational Motion Sensor**
   - **Simscape > Utilities > PS-Simulink Converter**
   - **Simulink > Sinks > Scope**

10. Arrange and connect the blocks as shown:



Provide your final **Simscape** model diagram for **Part B** below:



11. The **Gear Box** block contains only one parameter, the ***gear ratio***. Thus, it represents a kinematic constraint only. In particular, the block does not model *gear friction* or the *gear inertias*. The former may be captured by a **Rotational Friction** element, while the latter must be included in the **inertias** $\boldsymbol{J_1}$ and $\boldsymbol{J_2}$ connected to the **gear box**.
12. Set the following values for the **Inertias** and **Gear Box**:

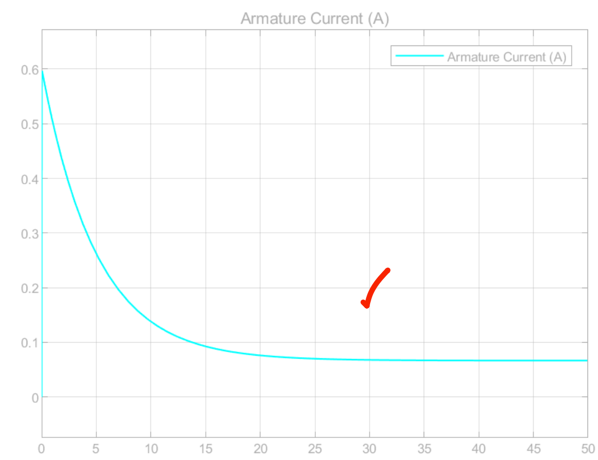
    Drive Side: Inertia 1 $\rightarrow$ $J_1 = J_{S1} + J_{G1} = 0.025 + 0.01 = 0.035\ \mathrm{kg{\cdot}\,m^2}$,

    Driven Side: Inertia 2 $\rightarrow$ $J_2 = J_{S2} + J_{G2} = 0.02 + 0.1 = 0.12\ \mathrm{kg{\cdot}\,m^2}$,

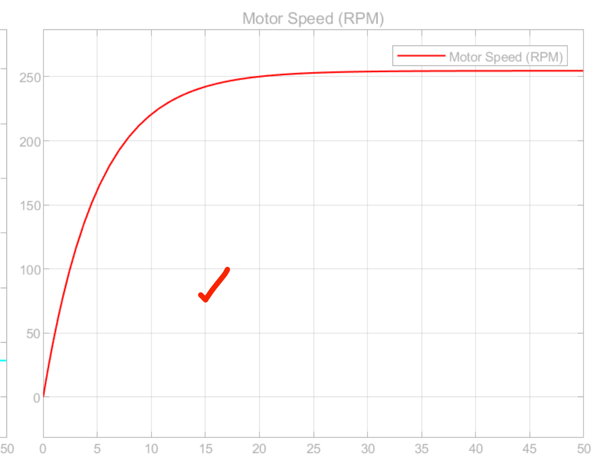
    Gear Ratio = 5
13. Set the **PS-Simulink Converter2** block **Output Signal Unit** as **rpm**.

14. **Save** the model file as **Lab4_PartB.slx** and **Run** the simulation for **50 sec**.
15. Open the two **Scope** blocks and provide the graphs below:

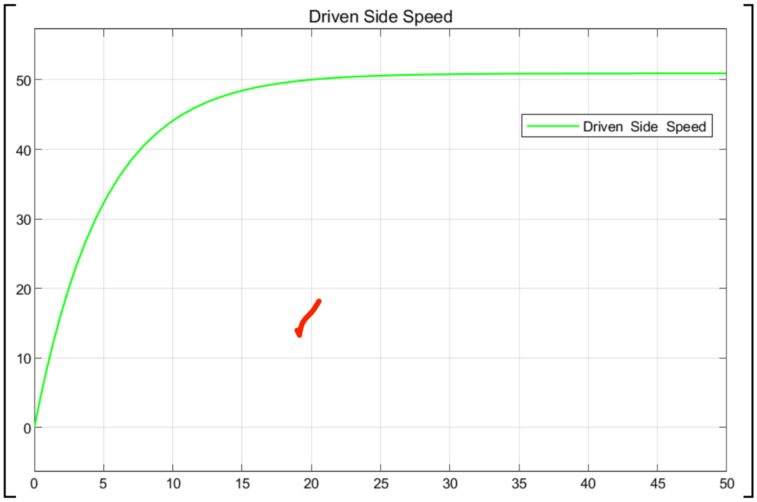
Armature Current (A)



Motor Speed (Drive side) (rpm)



Driven Side Speed (rpm)



16. Measure the steady-state current and the steady-state speed values for the drive side and the driven side from the plot and enter the values in **Table 2**.

Table 2

Armature Current (A)	Drive side Speed (rpm)	Driven side Speed (rpm)
66.705 mA	255 rpm	50.9 rpm

17. Calculate the ratio of the drive side speed to the driven side speed. Is it consistent with the **gear ratio**?

N=$\frac{255}{50.9}$ = 5.01 ✓

Yes, it is consistent with the **Gear Ratio**

18. Compare the motor speed in **Step 15** with the obtained graph in **Step 6**. Explain how additional inertia on the motor shaft affects the speed trajectory. Discuss the time constant of the speed graphs.

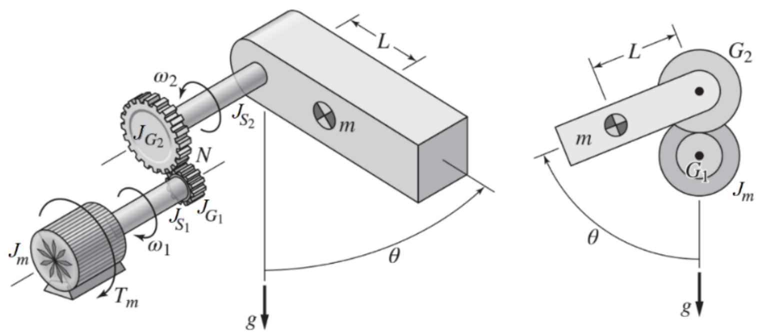
Additional Inertia on the motor shaft doesn't affect speed trajectory but having a different time constant looks like it does affect the change in Y from 2.71 rpm to 20.5 rpm

How? [-1]

Adding inertia increases the time constant, which means it takes more time for the motor to speed up and reach to the final speed.

Part C: Simscape Model of Dynamics of a Robot Arm Joint

Now we are ready to model the dynamics of the **robot arm joint** shown below.



To control the motion of the arm we need to have its equation of motion. To obtain the equation of motion in terms of the angle θ, the approach is to model the system as a single inertia rotating about the motor shaft with a speed ω_1.

The equivalent inertia referenced to the motor shaft is: $J_e = J_m + J_{S1} + J_{G1} + \left(\frac{N_1}{N_2}\right)^2 (J_{S2} + J_{G2} + mL^2)$

The reflected angle of rotation to the motor shaft is: $\left(\frac{N_2}{N_1}\right)\theta$

The reflected gravitational torque to the motor shaft is: $\left(\frac{N_1}{N_2}\right) mgL\sin\theta$

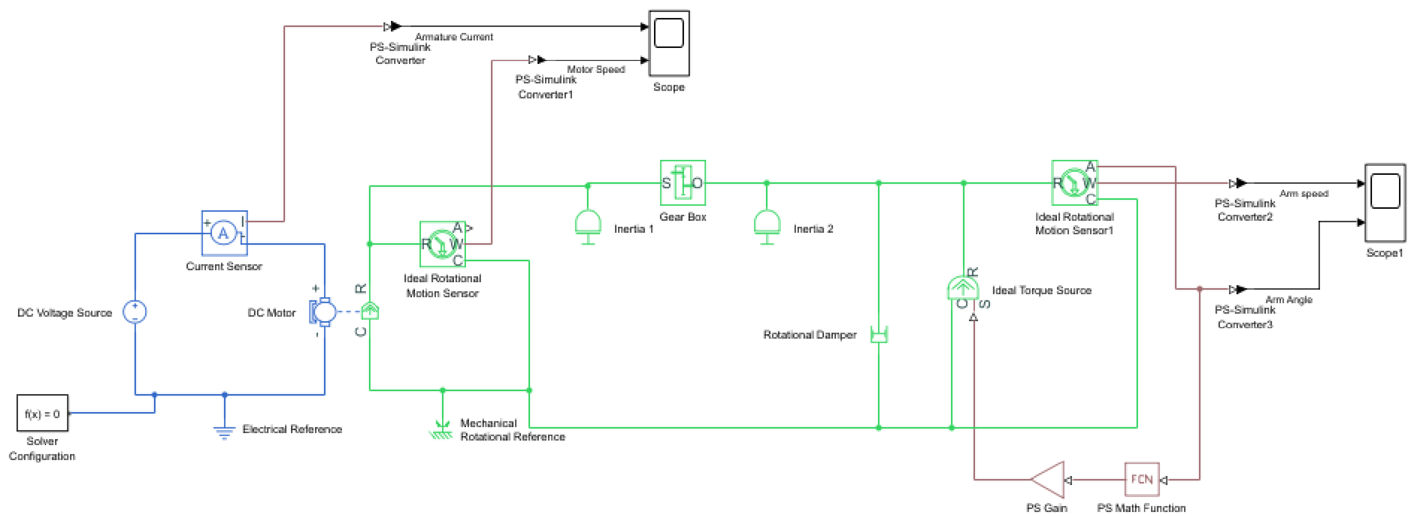
The reflected damping torque to the motor shaft is: $\left(\frac{N_1}{N_2}\right) B\dot{\theta}$

The *equation of motion* for this equivalent system on the motor shaft is:

$$J_e\dot{\omega}_1 = T_m - T_B - T_g \qquad \rightarrow \qquad J_e\left(\frac{N_2}{N_1}\right)\ddot{\theta} = T_m - \frac{N_1}{N_2}B\dot{\theta} - \frac{N_1}{N_2}mgL\sin\theta$$

The **gear ratio** is $N = N_2/N_1$

19. Insert the following blocks from the library and connect them as shown below:
    - **Simscape > Foundation Library > Physical Signals > Functions > PS Gain**
    - **Simscape > Foundation Library > Physical Signals > Functions > PS Math Function**
    - **Simscape > Foundation Library > Mechanical > Mechanical Sources > Ideal Torque Source**
    - **Simscape > Foundation Library > Mechanical > Rotational Elements > Rotational Damper**
    - **Simscape > Utilities > PS-Simulink Converter**

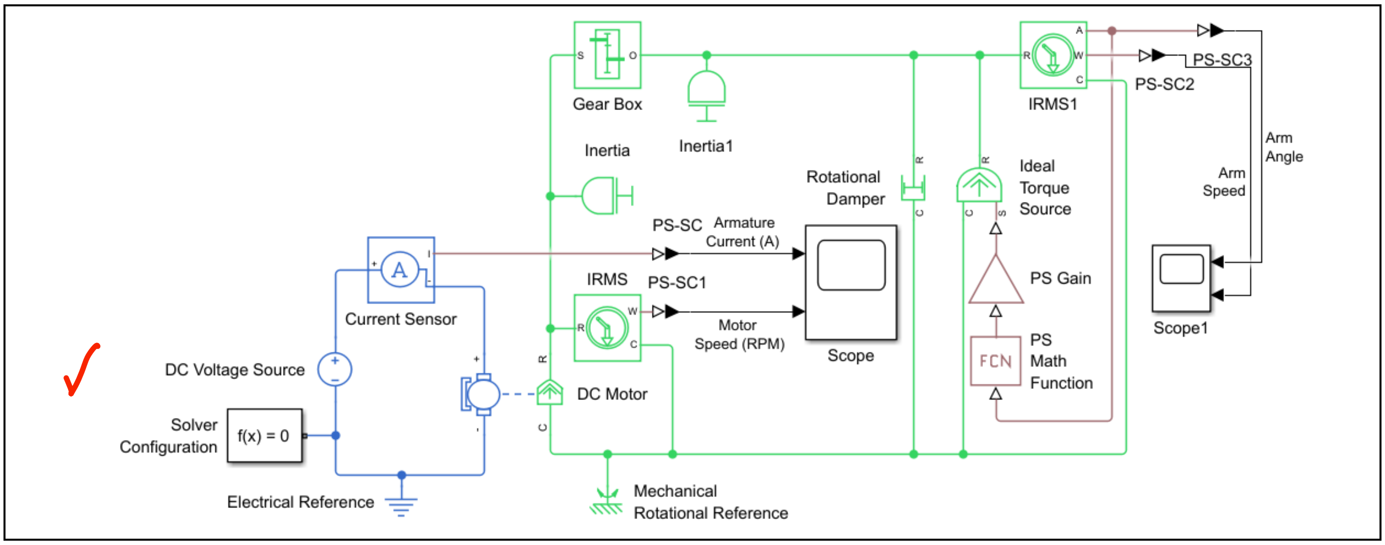


20. Let's examine the new blocks introduced to model the **gravitational torque** $-\boldsymbol{mgL}\sin\boldsymbol{\theta}$.
21. The **PS Gain** block multiplies the input physical signal by a constant called the **Gain**. Enter $-\boldsymbol{m} * \boldsymbol{g} * \boldsymbol{L}$ in the **Block Parameters** dialog box. Then assign the values of m, g, and L in the **MATLAB Command Window**. Use the following values:

$$m = 4\,kg,\ L = 0.25\,m,\ g = 9.81\ m/s^2.$$

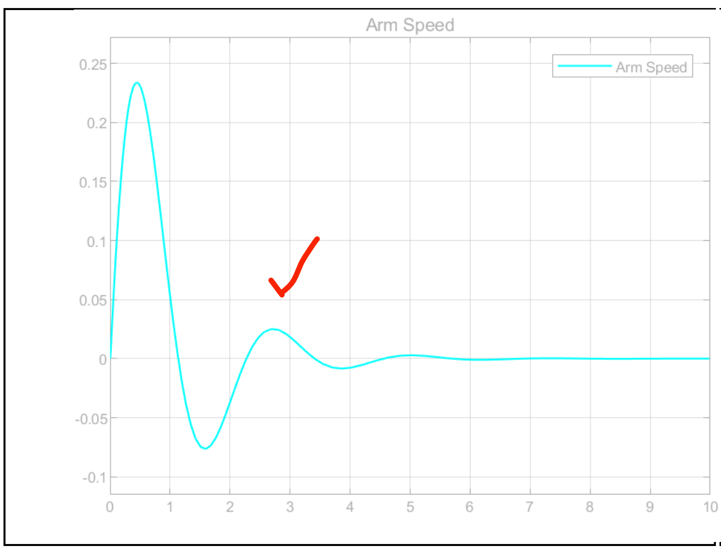
22. The **PS Math Function** block applies a mathematical function to the input u. Enter $\mathbf{sin}(\boldsymbol{u})$ in its **Block Parameter** dialog box.
23. The **Ideal Torque Source** block has no parameters. It represents a source capable of providing the torque specified at its physical-signal input port regardless of the angular velocity across its terminals. Since power is the product of torque and angular velocity ($P = T\omega$), the **Torque Source** is ideal in the sense that it is sufficiently powerful to deliver the specified torque at any speed.
24. The **Rotational Damper** block represents the damping friction effect of the joint arm and the shaft. Set the Damping Coefficient as 2 $N.m.s/rad$.
25. Set the **PS-Simulink Converter3** block **Output Signal Unit** as **deg**.

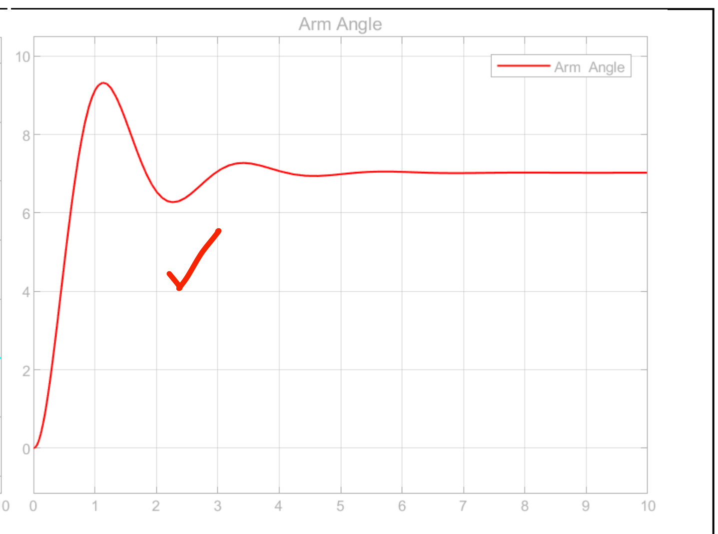
Provide your final **Simscape** model diagram for **Part C** below:



26. **Save** the model file as **Lab4_PartC.slx** and **Run** the model using a **Stop Time** of **10 sec**. Provide the <u>arm speed</u> and <u>arm angle</u> graphs below.

Arm speed (rpm) **Arm Angle (degrees)**





27. Measure the <u>steady-state speed</u> and the <u>steady-state angle</u> of the arm from the graph and enter the values in **Table3**. What is the maximum deviation of the angle from the steady-state value?

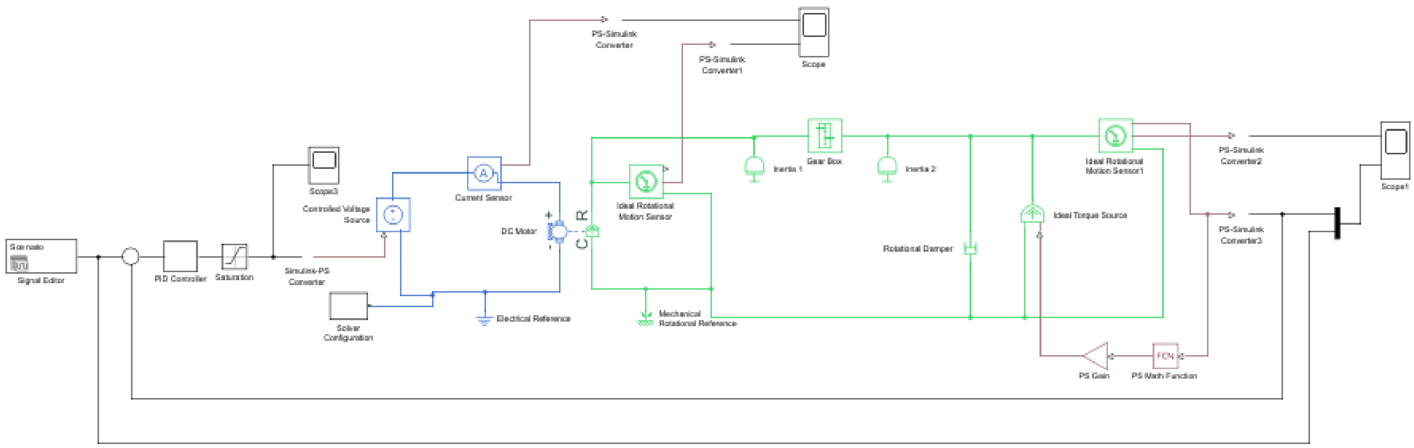
Table 3

Arm Speed (rpm)	Arm Angle (deg)	Maximum Deviation of Angle (deg)
0.000356 rpm	7.03 deg	3.04 deg deviation

Part D: Position Control of the Robot Arm

28. Insert the following blocks from library and connect them as shown below:

- **Simscape > Foundation Library > Electrical > Electrical Sources**
- **Simscape > Utilities > Simulink-PS Converter**
- **Simulink > Continuous > PID Controller**
- **Simulink > Math Operations > Sum**
- **Simulink > Discontinuities > Saturation**
- **Simulink > Sources > Signal Editor**
- **Simulink > Commonly Used Blocks > Mux**



29. Enter the following parameter values for **Saturation** and **PID Controller** blocks:

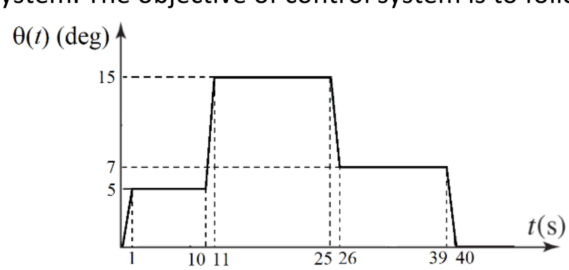
   a) Staurtaion:
   Upper limit = 36, Lower limit = -36

   b) PID Controller:
   Proportional = 4, Integral = 8, Derivative = 1.6

30. The **Saturation** block <u>limits</u> the applied controlled voltage to the DC motor between the $\pm 36V$. In this range of the voltage the armature current may not exceed $2A$.

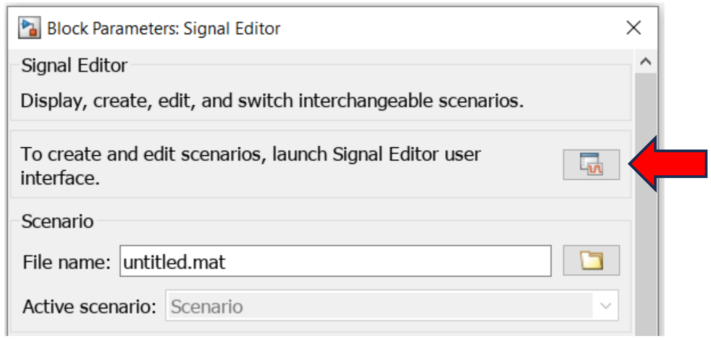
> *We have not discussed the selection of the **PID controller** gains. That is the subject of Control Systems course. There are many ways of doing this, including the MATLAB **pidtool** and **sisotool** design tools, and **Simulink Control Design**.*

31. The **Signal Editor** block generates the desired values of the robot arm angle in degrees. We use that signal as the reference input of the control system. The objective of control system is to follow the desired angle values.

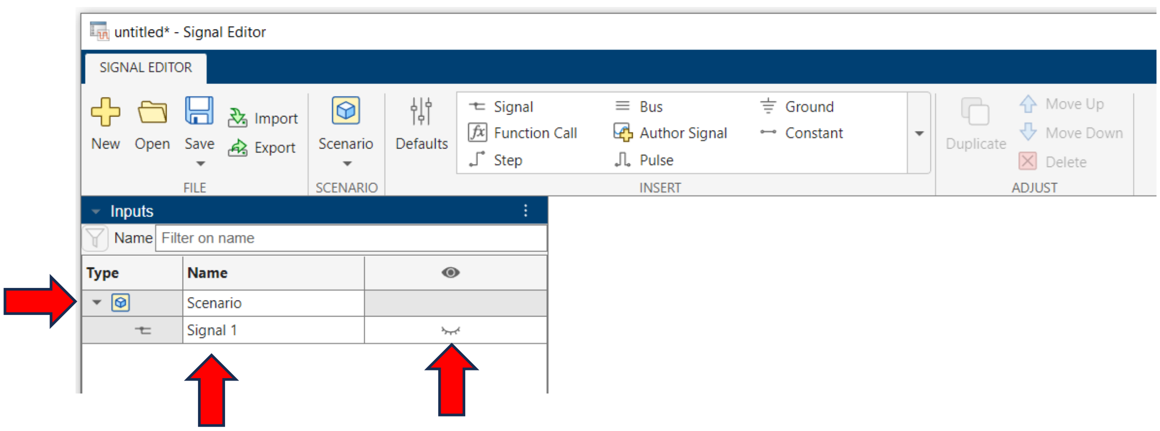


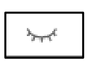
The following steps show how to set up the **Signal Editor** block.

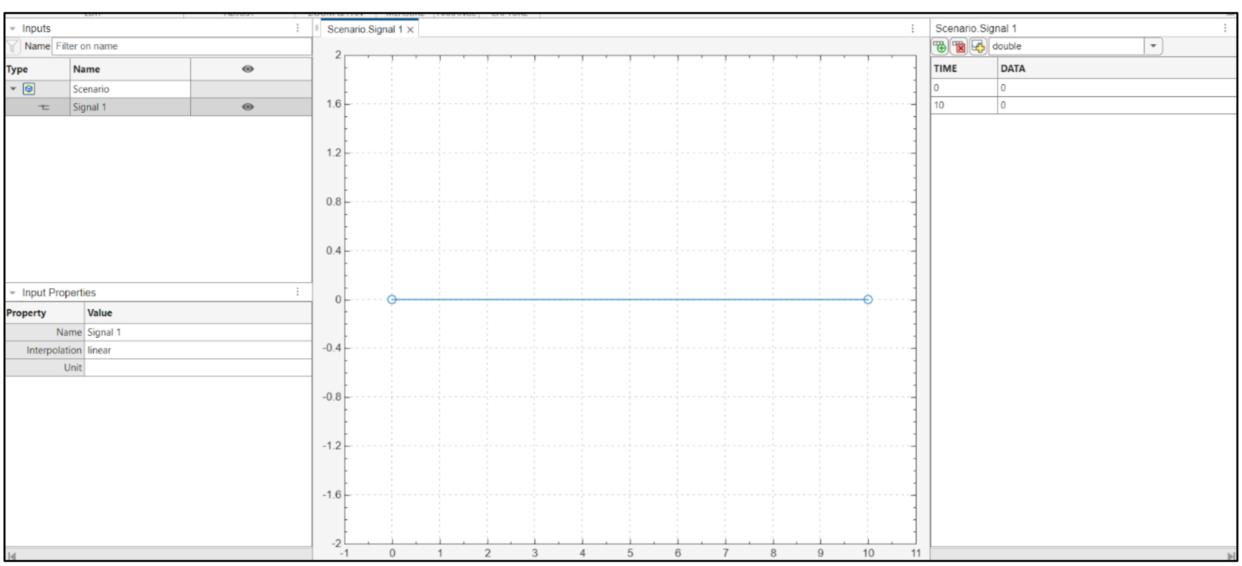
- Open the **Signal Editor** block to define the input function profile based on the Figure 6 as below:
- Click on  icon to open the **Signal Editor** window.



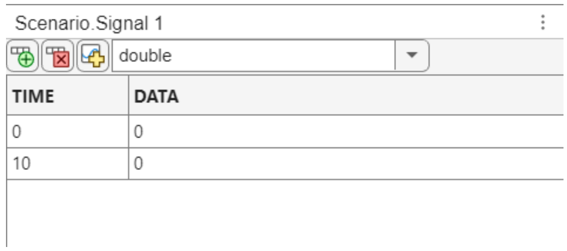
- Click on the small drop-down icon beside the **Scenario** to see the signal present in it, which is named **Signal 1** by default.



- Double-click on the  icon in the right side of the **Signal 1** to reveal what is in this signal.



- The signal is blank at the first time. You can add the data for your signal profile by editing the data table in the right side.

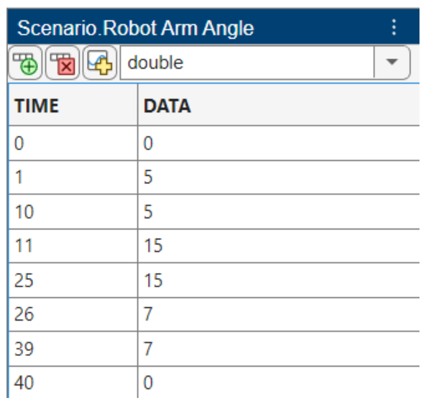


Scenario.Signal 1

double

TIME	DATA
0	0
10	0

- Click on  icon to add more rows to the data table.
- Enter the **Time** values as `[0 1 10 11 25 26 39 40]` and **Data** values as `[0 5 5 15 15 7 7 0]` based on the desired trajectory.

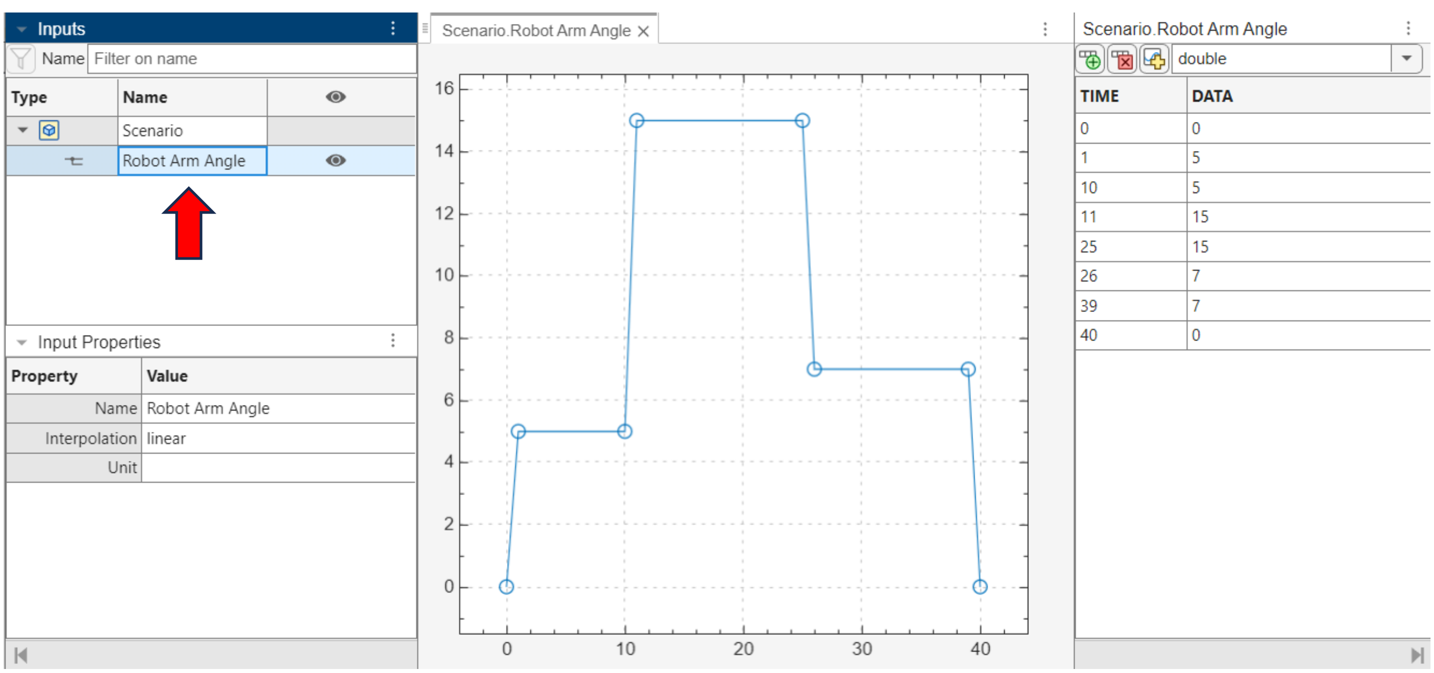


Scenario.Robot Arm Angle

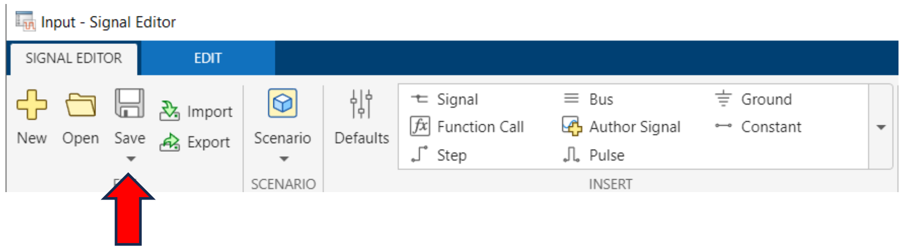
double

TIME	DATA
0	0
1	5
10	5
11	15
25	15
26	7
39	7
40	0

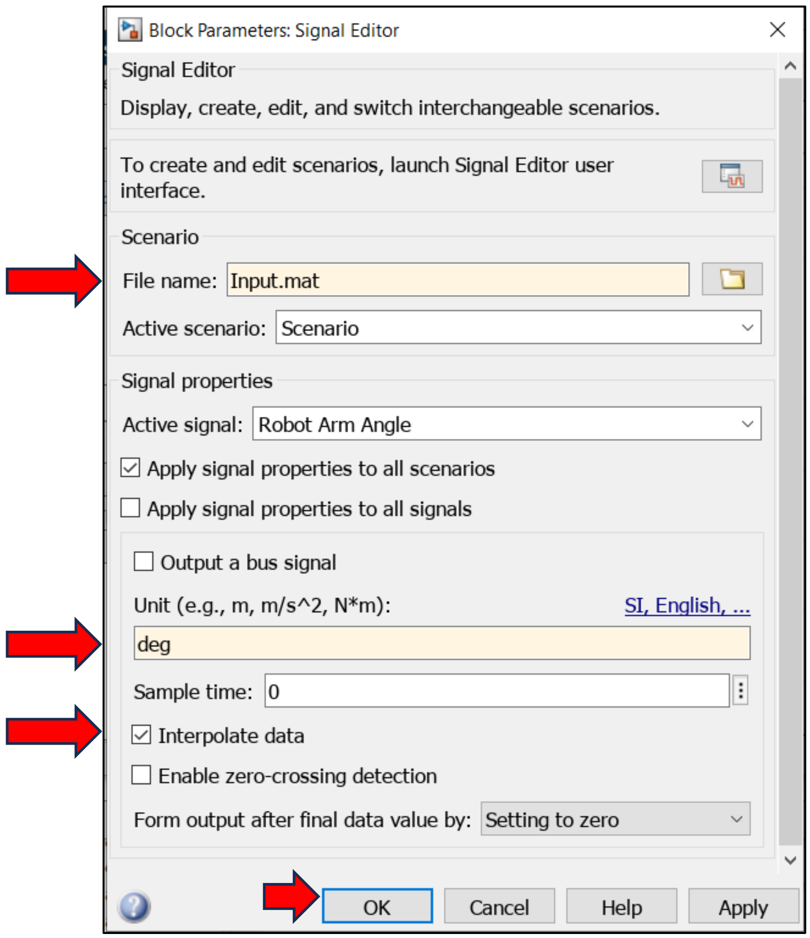
- The robot arm angle values will be created. Click on the signal name and rename the signal as **Robot Arm Angle.**



- **Save** the signal file as **Input.mat** in the same folder you will save the Simulink file.



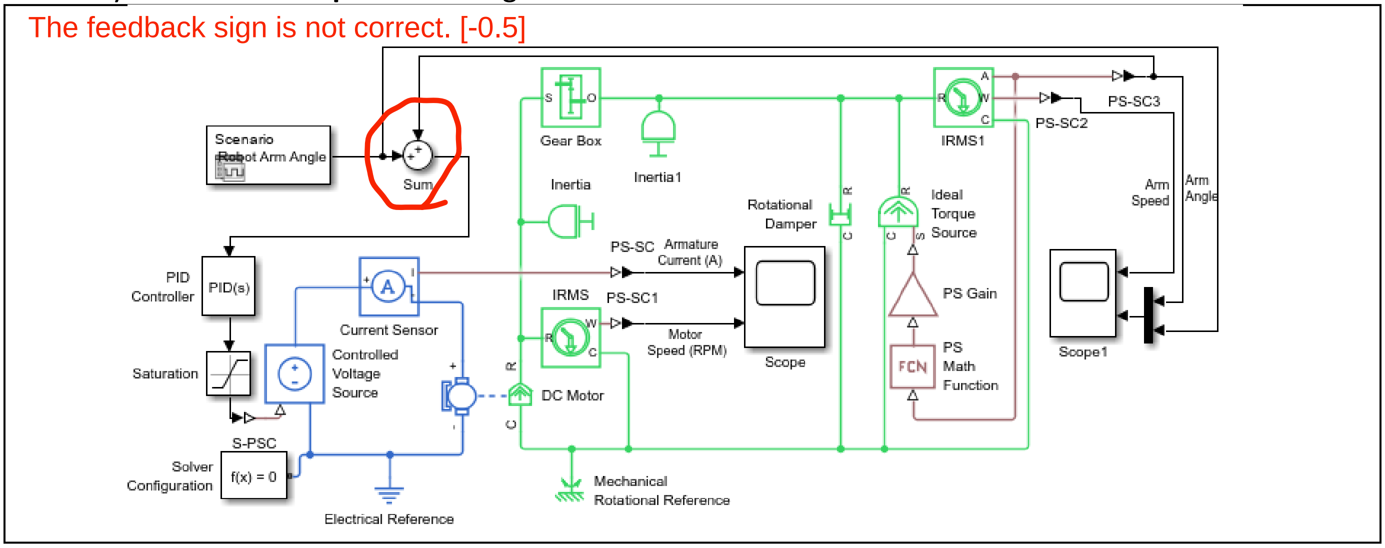
- The signal file name will be appeared in the **Block Parameters Dialogue** window.



- Set the signal data unit as **deg** (degrees) in the **Unit** box.
- Check marks the **Interpolate data** box.
- Click **OK** to close the dialogue window.

Provide your final **Simscape** model diagram for **Part D** below:

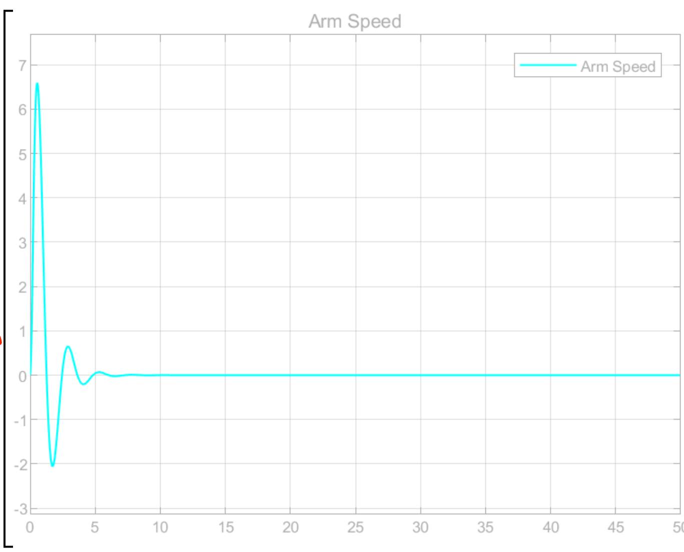
The feedback sign is not correct. [-0.5]



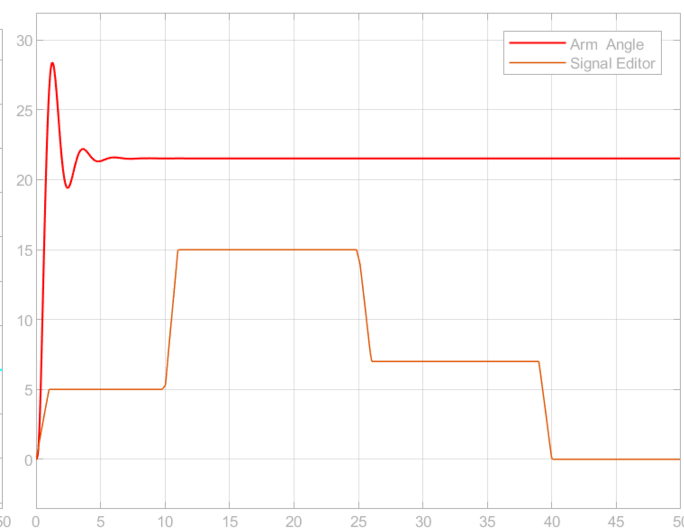
32. **Save** the model file as **Lab4_PartD.slx** Run the model with a **Stop Time** of **50 sec**. Provide the arm speed and arm angle graphs below.

The graphs are not correct. [-1]

Arm speed (rpm)



Arm Angle (deg)



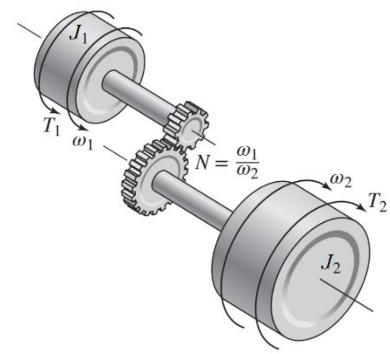
33. Observe the applied voltage and the armature current of DC motor. Insert the maximum applied voltage and the maximum armature current values in **Table 4**?

Table 4

Maximum Voltage (V)	Maximum Current (A)
1.112e+01 V	1.794e+00 A

Post Lab Assignment

1) Consider the spur gears shown in figure below, where $J_1 = 0.5\ kg.m^2$ and $J_2 = 0.5\ kg.m^2$. Shaft 1 rotates four times faster than shaft 2. The torques are given as $T_1 = 0.5\ N.m$ and $T_2 = -0.3\ N.m$. Assume that the gears' and shafts' inertias are negligible.



a. Model of the system in Simscape.

b. Connect <u>two motion sensors</u> to measure the <u>angular acceleration</u> in each side.

c. Select an appropriate simulation time and run the simulation.

d. Plot the angular accelerations as <u>two separate graphs</u> in a <u>single</u> Scope with white background.

e. Provide the <u>model diagram</u>, the <u>angular acceleration graphs</u> and the <u>Simscape file</u>.

f. Compare the angular acceleration of side 1 and side 2. Explain the effect of gear ratio on the acceleration.

Hint: You may need the following blocks:

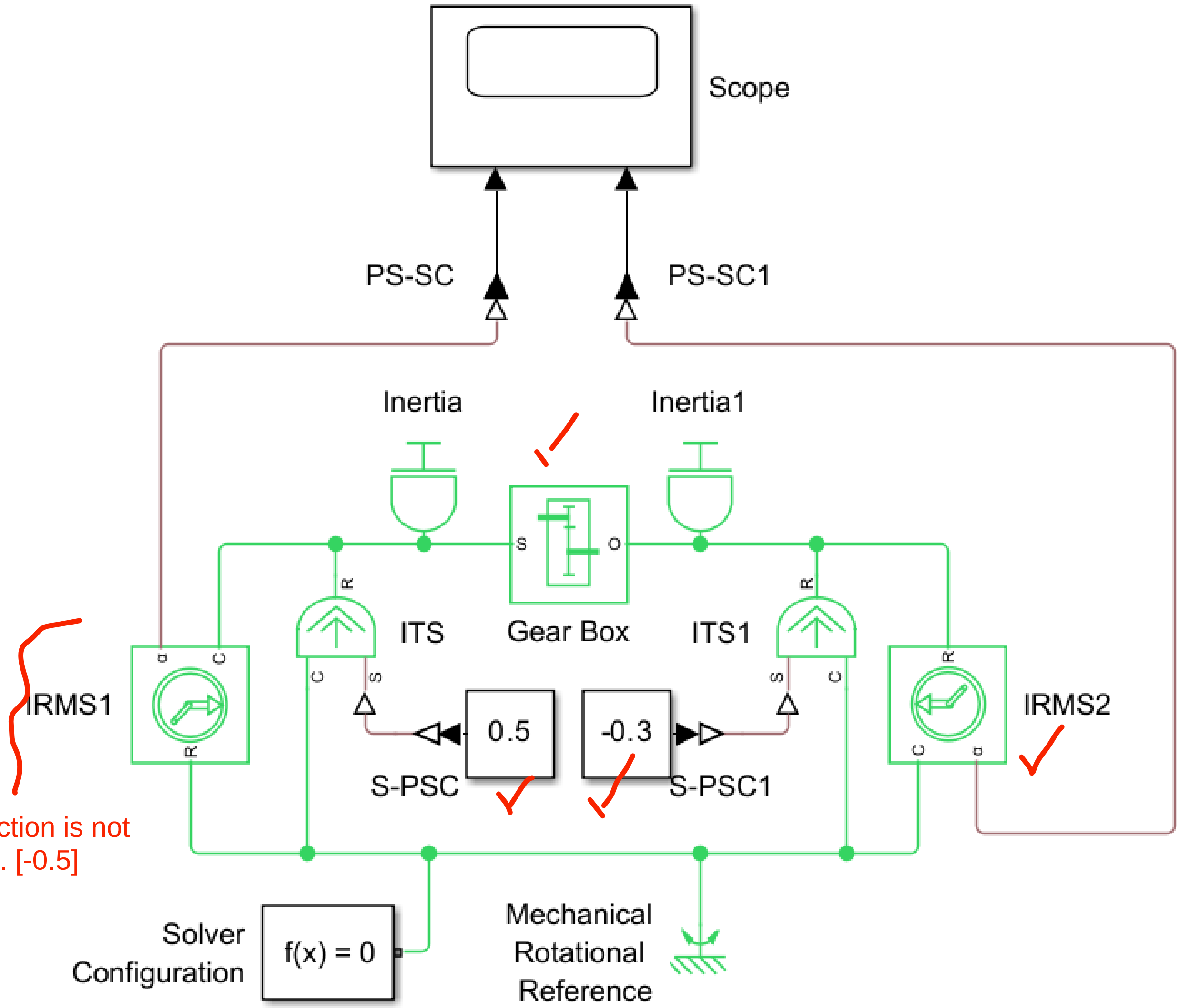
<u>From Simscape Library</u>:

- Inertia
- Gear Box
- Ideal Torque Source
- Solver Configuration
- Mechanical Rotational Reference
- Simulink-PS Converter
- PS-Simulink Converter
- Ideal Rotational Motion Sensor

<u>From Simulink Library:</u>

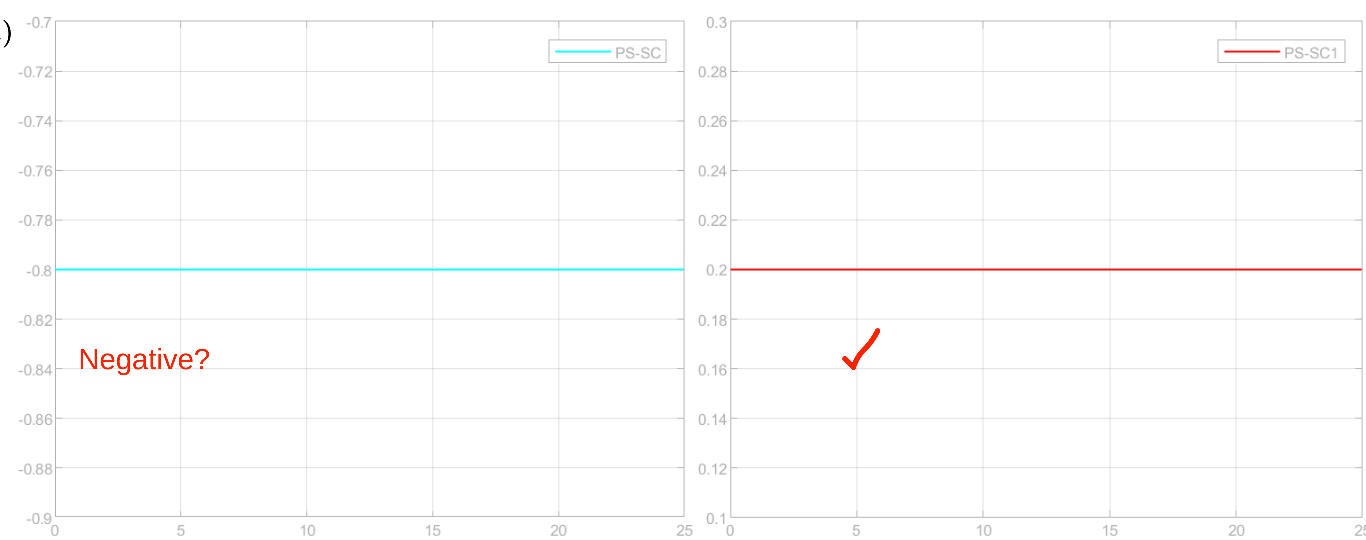
- Scope
- Constant

E-1)



Connection is not correct. [-0.5]

E-2)



F) The acceleration values make sense given the 4:1 ratio, with shaft 1 showing 4x the angular acceleration of shaft 2. The negative sign on j1 suggests that shaft 1 rotates in the opposite direction to shaft 2, which is a common characteristic of meshed gears.