TEXAS A&M UNIVERSITY

MEEN 364 ***Spring 2018***

Assignment: Lab 4 & 6	
Instructor: Dr. Prabhakar Pagilla	
Section: 501	
Submission Date: 19 March 2018	

All authors have contributed to the preparation of the report and have read the final version of the report.

On my honor, as an Aggie, I have neither given nor received unauthorized aid on this academic work.

Name of Authors	Signature
Andres Contreras	
Jacob Hartzer	
Perry Inhofe	
Colin Michels	

I. Abstract

In this lab, a DC motor and inertial mass system was analyzed to better understand the modeling and implementation of open and closed loop controllers using MatLab and Simulink software. Open and closed loop controller simulations were created using calibration data and compared to experimental data. In the first section of the lab, the calibration data showed that both the potentiometer voltage and the motor response behaved linearly with the potentiometer K_x value as 17.589 [deg/V]. The second section of the lab showed that error is naturally induced in open loop controllers due to parameter uncertainty and that there are lower limitations on the motor speed. The data collected showed that both in simulations and implementations, the closed loop controller outperformed the open loop controller in regards to steady state error, confirming predictions. In the closed loop controller, the data showed that increasing the K_p value reduced the time constant of the system, but increased the steady state error. Finally, the comparisons between the modeled and experimental data confirmed the validity of the simulations used as models for the real world system.

II. Introduction

In lab 4, a system comprised of a DC motor and inertia was modelled using simulink to calibrate sensors and measure the states of the system. In lab 6, this calibration data was utilized to implement both open loop and closed loop controllers on the same system. The difference between an open and closed loop control is that in an open-loop control, the output has no effect on the input, while in a closed-loop control, the system tracks the input using the output. The objectives of this series of experiments were to understand different types of controllers including closed-loop and open-loop, analyze the effect of parameter uncertainty on speed control of the system, and to contrast implementation on a real system and simulations of a simplified model. The conclusions drawn from these labs have great importance in the real life applications of DC motor systems ranging from toys to rocket ships, choosing the best controls for different parameters of these systems, and understanding the validity of simulations vs real systems.

III. Theory

The system to be simulated and experimentally analyzed in these labs is shown below in Figure 1:

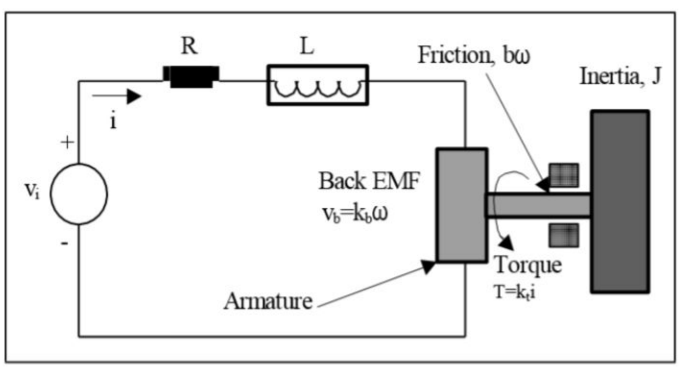

Figure 1. DC Motor Model (from lab manual)

It consists of a disk with mass moment of inertia J for inertial load, power amplifier to increase current, a motor with an attached tachometer for measuring speed, and a potentiometer to measure angular position. By analyzing the constant flux, the current flowing through the current diagram, and ignoring inductance in the system, we are able to model the response of the system to input voltage v_i with the equation 1 below:

$$\frac{J}{B+\frac{K_bK_t}{R}}\frac{d\omega}{dt} + \omega = \frac{K_t}{R(B+\frac{K_bK_t}{R})}v_i \tag{1}$$

This follows the form of equation 2:

$$\tau\frac{d\omega}{dt} + \omega = K_s v_i \tag{2}$$

Where K_s is calculated below using the steady state value of ω from the response in equation 3:

$$\omega_{ss} = K_s v_i \tag{3}$$

To calibrate the tachometer, voltages were run across the DC motor and the steady state angular velocities were recorded to calculate K_V using equation 4:

$$\omega = K_V V_o \tag{4}$$

To calibrate the potentiometer, voltages were recorded at different angles in 45° increments and K_x was calculated using equation 5:

$$\theta = K_x V_{o2} \tag{5}$$

In the second part of the experiment, the motor is used with an open loop controller as well as a closed loop controller. The open loop controller shown in Figure 2 has no feedback in it while the closed loop controller shown in Figure 3 does have feedback. The closed loop controller differs from the open loop controller because the output of the system is used to influence the input of the controller in order to more quickly approach the desired output of the system.

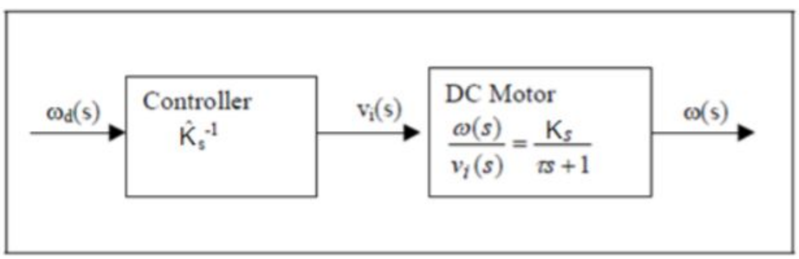

Figure 2. DC Motor Open Loop Controller Block Diagram (from lab manual)

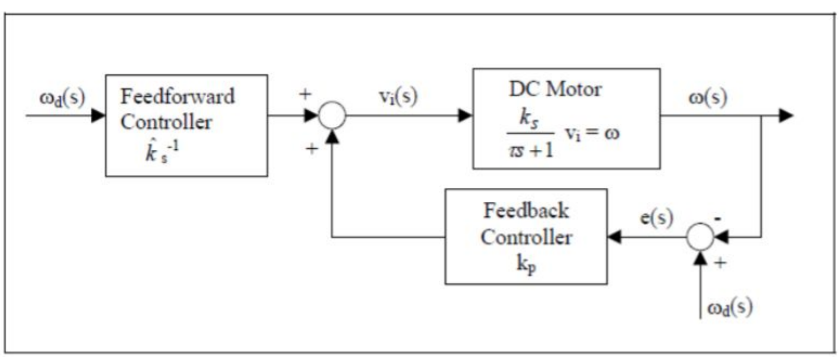

Figure 3. DC Motor Closed Loop Feedforward-Feedback Control Diagram (from lab manual)

The motor and the controller are simulated for both the open and closed loop control for comparison to the experimental data. K_s is decreased by roughly 10% from the value of $\widehat{K_s}$ in order to make the simulation more realistic by adding inherent error from calibration of the system. This error will cause the steady state values to differ from the desired outputs of the simulation. In the experimental results, the inherent error and fluctuations of the motor will cause the steady state value to be less than the desired outputs of the controller. The simulation and experimental results can then be compared to determine the benefit of each controller.

IV. Procedure

In the first part of this experiment, simulink was used to create a model which would send an input voltage to the motor while recording the output from the tachometer. The internal tachometer was calibrated with its output voltage and the handheld tachometer. After taking data from the tachometer, the motor constants were estimated ($\widehat{K_s}$, $\Delta\widehat{K_s}$, K_v, *and* τ). The internal potentiometer could then be calibrated by comparing the output voltage to the angle rotated. This data was then used to estimate K_x.

For the second part of the experiment, we had to switch motors due to a malfunction in our experiment setup making recorded data inaccurate. All constants were recalculated for the new motor. The motor constants were applied to the open loop controller simulation in simulink and the system was run for several desired outputs. The steady state operating speed and the error could then be calculated and experimentally measured. This simulation data was then compared to implementation data using the same controller on the DC motor system. For the closed loop controller, two different speeds and three different K_p values were inputted. The steady state angular velocity was measured by the internal tachometer and confirmed by the handheld tachometer and the response curves were taken by Simulink. The error could then be calculated and experimentally measured. The closed loop controller experimental results were then compared with the simulations.

V. Results and Discussion

Calculated from the experiments run in Lab 4 at multiple input voltages, the values for various constants are given in the table below.

Constant	Value
$\widehat{K}_s$	120.879 [rpm/V]
$\Delta\widehat{K}_s$	5.6286 [rpm/V]
K_v	121.597 [rpm/V]
τ	0.1415 [s]

Table 1. Constants Calculated in Lab 4

Additionally, the potentiometer calibration produced the linear relationship shown in *Figure 4*. As shown by the linear trend, the value for K_x that relates θ and V_{o2} is 17.589 [deg/V].

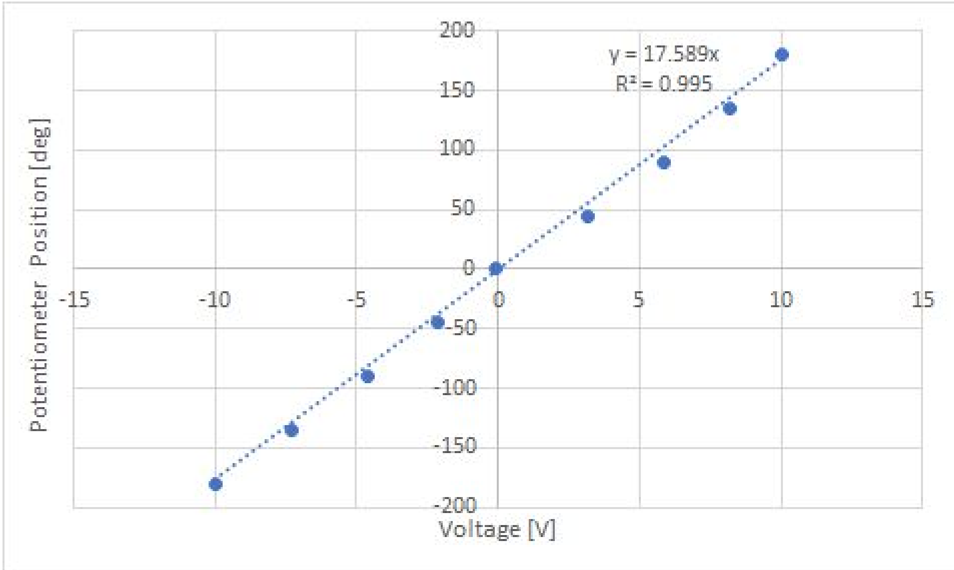

Figure 4. Calibration Curve for the Potentiometer

The last noteworthy result of lab 4 is the linearity of the system. As shown in *Figure 5*, the system responds linearly to input voltage as was predicted by the model.

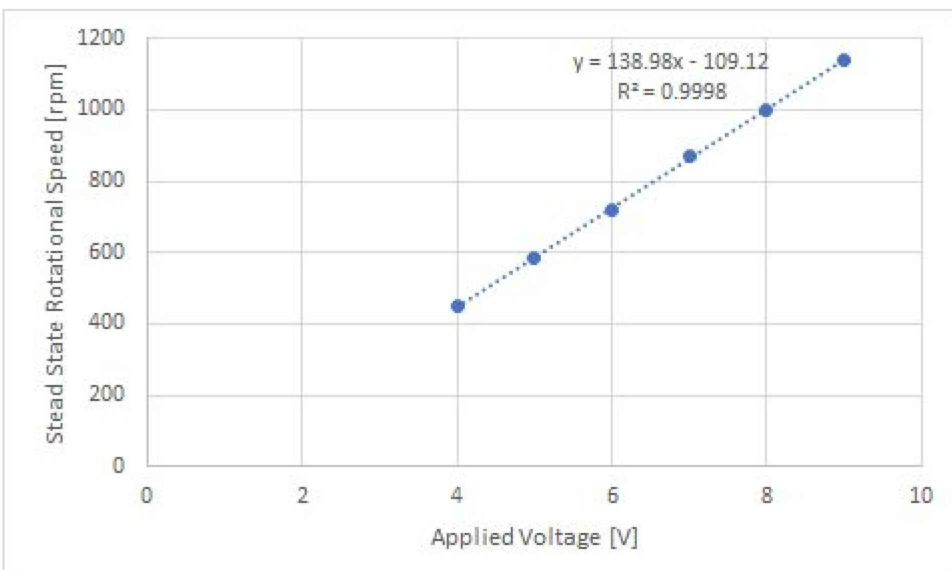

Figure 5. Relationship between Applied Voltage and ω_{ss}

In lab 6 , the open loop simulation showed that the error between desired and steady state motor speed increased with increasing desired speeds as summarized in *Table 5*. This is expected with an open loop controller and linear controller. However, the implementation showed decreasing error with increasing desired motor speed as shown in *Table 6*. This can be explained by the voltage barrier for the motor so the linear approximation by the model becomes increasing accurate at higher desired speeds. However, due to the nature of the open loop speed controller, there cannot be zero steady state error as this can only occur at a speed of zero. Due to variations in the motor system, K_s cannot be exactly known, inducing error in the system. Additionally, the model suggests that the range of operating speeds for the motor are determined solely by the input voltage which is limited by the hardware of the system such as the motor or connecting wires. However, it was observed that there is a minimum voltage below which the motor will not turn. This voltage can be found to be somewhere below an input voltage of 4 V as seen in *Table 2* from lab 4.

As predicted, the closed loop controller implementation and simulations showed significantly lower error in the motor speed. This is due to the feedback the controller receives about the current state that allows the controller to reduce the error further. Increasing the value of K_p increases the error at steady state because small errors due to noise are overcorrected, generating more error than what existed prior.. Without this noise, the simulation had much lower error than the implementation. Additionally, increasing the value of K_p also reduced the time constant for the system. This is clearly seen in the simulations. Other than the errors at steady state, the models matched quite closely to the experimental data, verifying the validity of using such a simulink simulation to predict how this system will respond to stimuli.

VI. Conclusions

In conclusion, these labs covered the calibration of a DC motor and inertial mass system and closed and open loop controllers of that system. The data collected showed the similarities between the simulations and implementations of open and closed loop controllers. However, due to the uncertainty in system parameters, it was not possible to eliminate all errors in the implementation of the open loop controller. The closed loop controller, however, the data showed significantly less error, confirmed the predictions of the model. The experiment also showed that increasing values of K_p reduced the time constant of the system, but at the expense of an increased steady state error. Overall, these labs validated the use of Simulink to simulate the DC motor system, while revealing the issues with having a simplified model.

VII. References

Alladi, Vijay et. al. (2006) *MEEN 364 Lab Manual: Lab 4 -DC Servomoter Modeling.* Texas A&M University. Web.

Alladi, Vijay et. al. (2006) *MEEN 364 Lab Manual: Lab 6 - Implementation of DC Motor Speed Control.* Texas A&M University. Web.

S.S. Rao, *Mechanical Vibrations*, 4th edition, 2004.

VIII. Appendices

Appendix A. MatLab Code.

CalcTimeConstant.m

```
tach_data = ScopeData.signals(1).values;
pot_data = ScopeData.signals(2).values;

avg = mean(tach_data(end-1000:end));
minimum = min(tach_data);

i = 1;
while true
   if tach_data(i) > (avg - minimum) * (1 - exp(-1)) + minimum
      break
   end
   i = i + 1;
end

fprintf('Vout: %f \nTime Constant: %f\n\n', avg, i/1000);
```

Appendix B. Simulink Code.

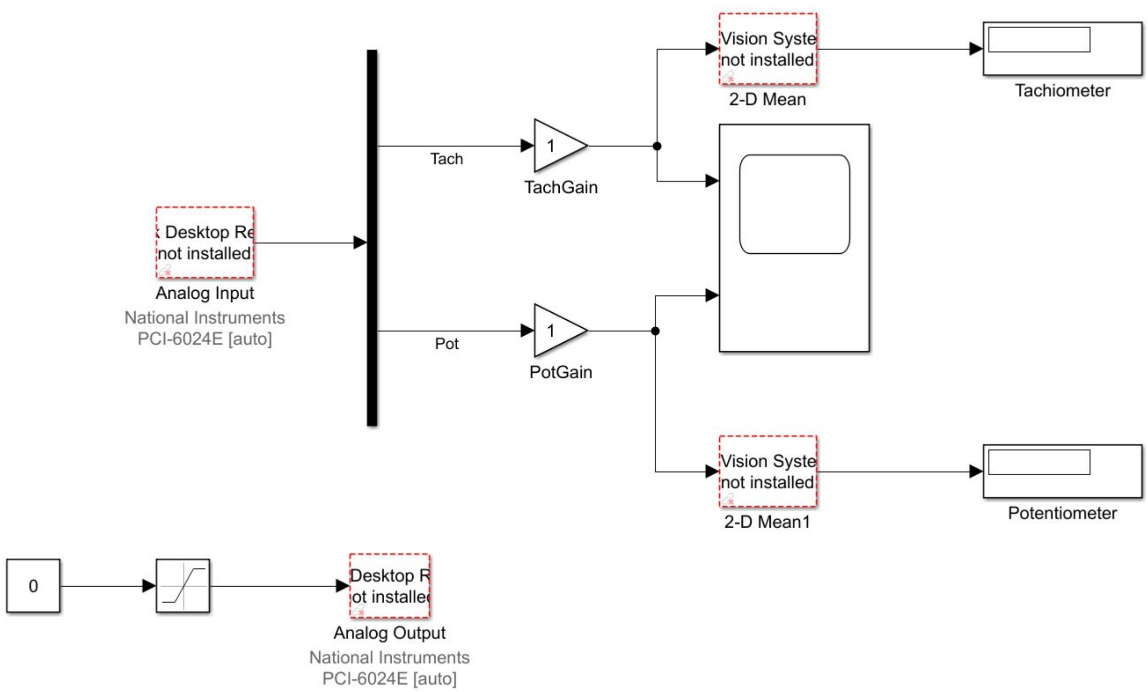

Figure 6. Lab 4 Simulink Code

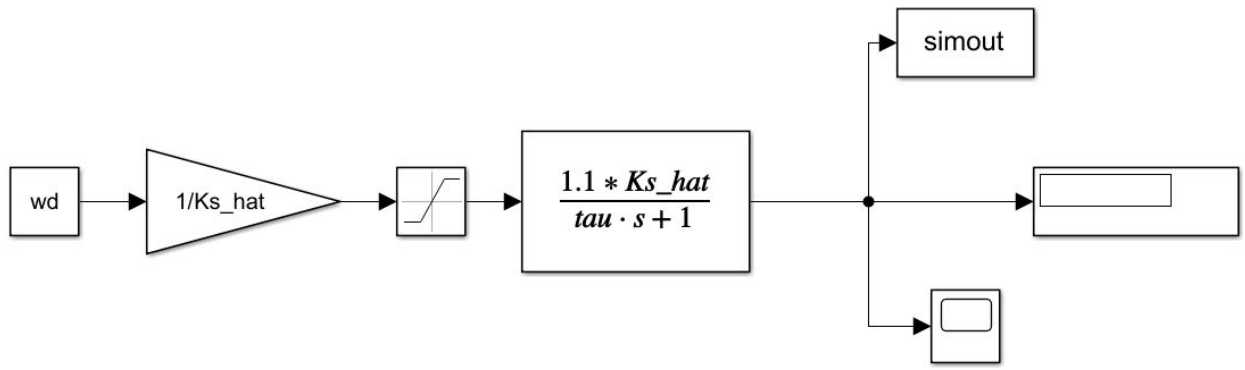

Figure 7. Open Loop Controller Simulation Simulink Code

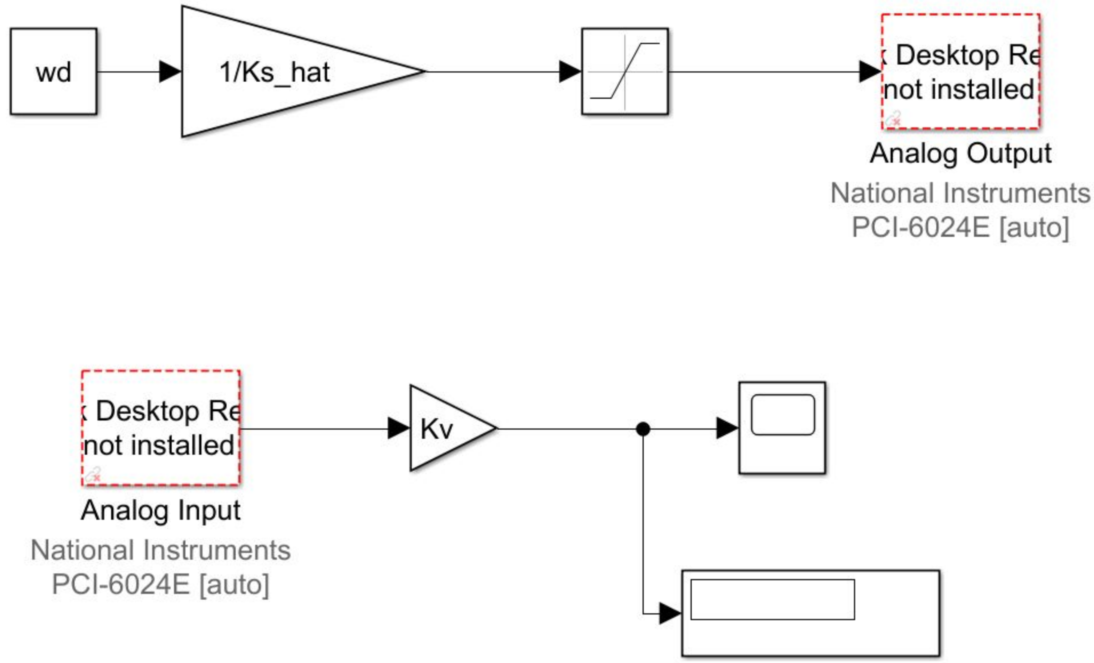

Figure 8. Open Loop Controller Implementation Simulink Code

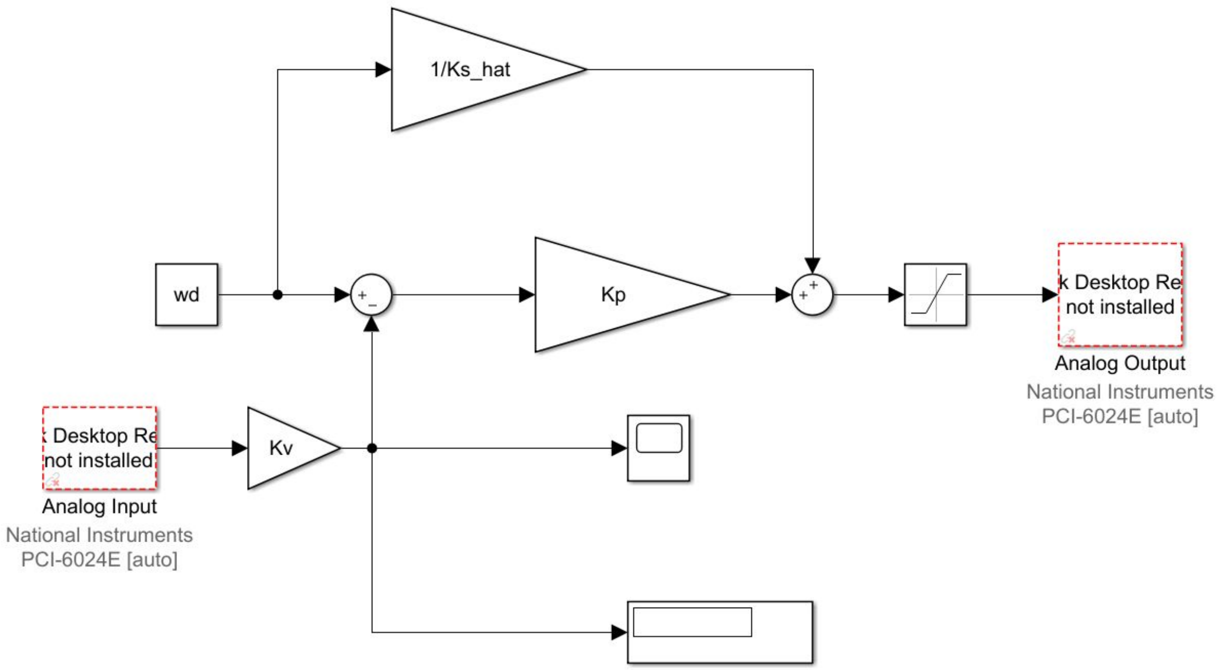

Figure 9. Closed Loop Controller Implementation Simulink Code

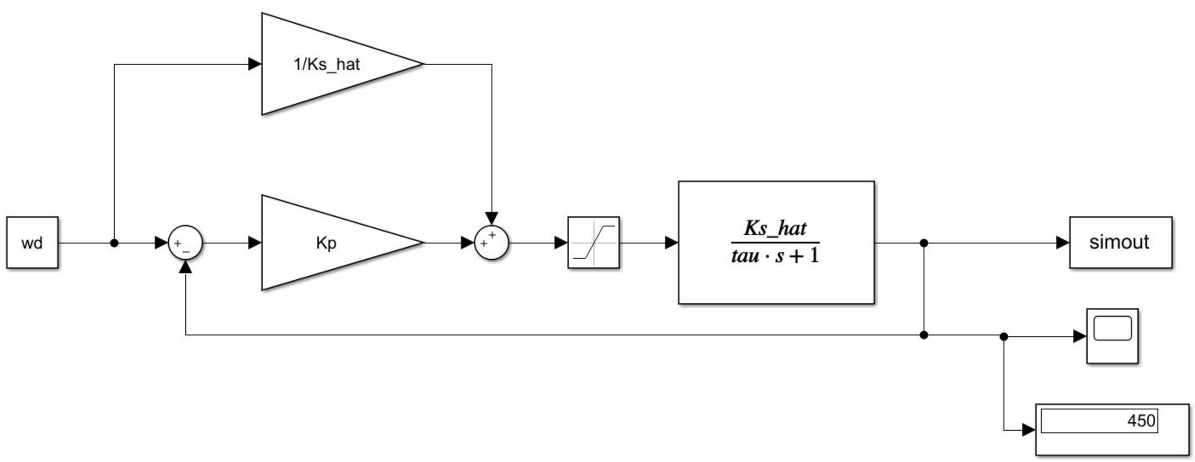

Figure 10. Closed Loop Controller Simulation Simulink Code

Appendix C. Raw Data and Figures.

Run	*vi* [V]	*Vo* [V]	*ωss* [rpm]	*Kv* = *ωss*/*Vo* [rpm/V]	*Ks*_hat = *ωss*/*vi* [rpm/V]	*τ* [sec]
1	4	3.716	447.8	120.5059203	111.95	0.052
2	5	4.89	586.7	119.9795501	117.34	0.105
3	6	5.96	718.8	120.6040268	119.8	0.143
4	7	7.01	869.2	123.9942939	124.1714286	0.156
5	8	8.242	1001	121.4511041	125.125	0.179
6	9	9.281	1142	123.0470854	126.8888889	0.214
Mean				121.5969968	120.8792196	0.1415

Table 2. Lab 4 Estimation of Tau

Rotation [degrees]	Potentiometer Voltage [V]
-180	-10
-135	-7.305
-90	-4.575
-45	-2.134
0	-0.055
45	3.174
90	5.889
135	8.195
180	10

Table 4. Lab 4 Calibration of the Potentiometer

run	wd (rpm)	wss (rpm)	wd-wss (rpm)	(delt_ks_hat / ks) * wd (rpm)
1	100	90	10	5.116868377
2	250	225	25	12.79217094
3	400	360	40	20.46747351
4	550	495	55	28.14277608
5	700	630	70	35.81807864
6	900	810	90	46.0518154

Table 5. Open Loop Controller Simulation Data

run	wd (rpm)	wss onboard tach (rpm)	wss' handheld Tach (rpm)	wd - wss (rpm)
1	100	-	-	-
2	250	172	161.7	78
3	400	342	343.6	58
4	550	498	511.5	52
5	700	674	679.1	26
6	900	883	857.8	17

Table 6. Open Loop Controller Implementation Data

run	wd (rpm)	Kp (V/rpm)	wss Onboard tach (rpm)	wss' handhelp tach (rpm)	wd-wss (rpm)
1	600	0.01	600	594	0
2	600	0.2	599.9	593	0.1
3	600	0.6	600	594	0
4	450	0.01	450	445	0
5	450	0.2	449.9	445	0.1
6	450	0.6	449.9	445	0.1

Table 7. Closed Loop Controller Implementation Data

Run	wd (rpm)	Kp (V/rpm)	wss (rpm)	wd-wss (rpm)	(dKs/Ks)/(1+KsKp) * wd
1	600	0.01	600	0	0
2	600	0.2	600	0	0
3	600	0.6	600	0	0
4	450	0.01	450	0	0
5	450	0.2	450	0	0
6	450	0.6	449	1	1

Table 8. Closed Loop Controller Simulation Data

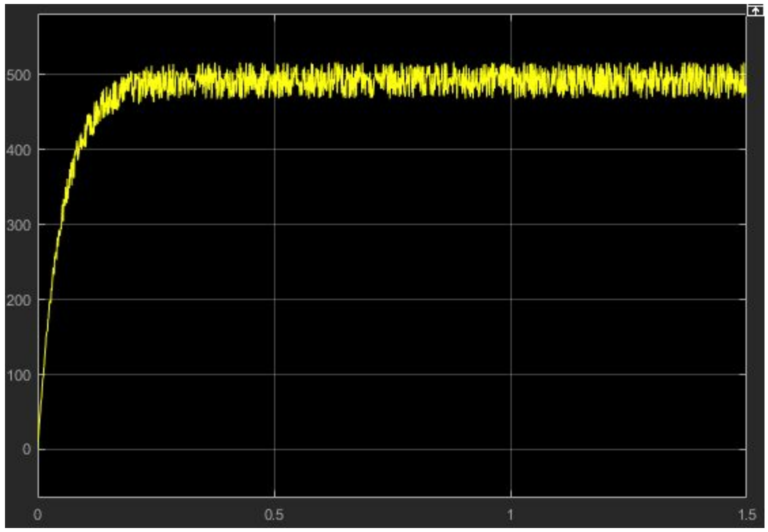

Figure 11. Time Constant Calculation Run 1

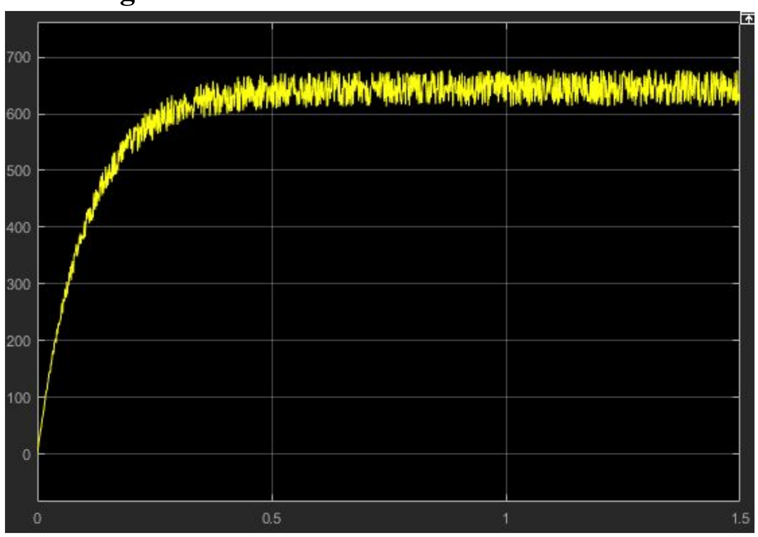

Figure 12. Time Constant Calculation Run 2

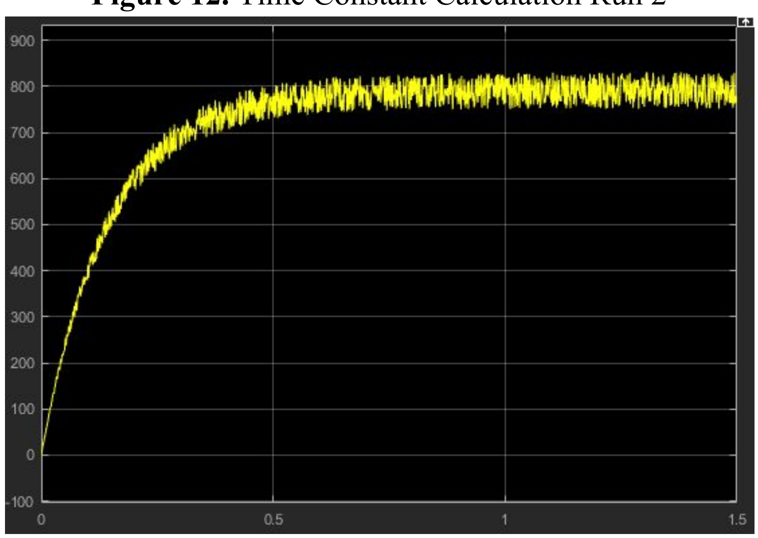

Figure 14. Time Constant Calculation Run 3

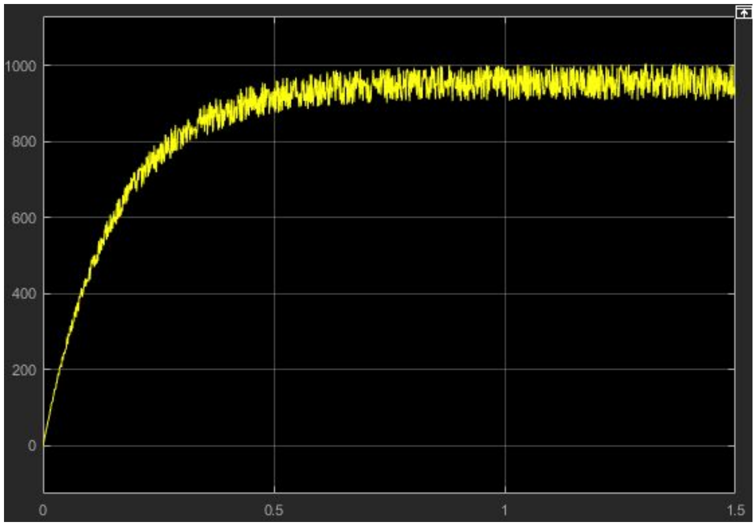

Figure 15. Time Constant Calculation Run 4

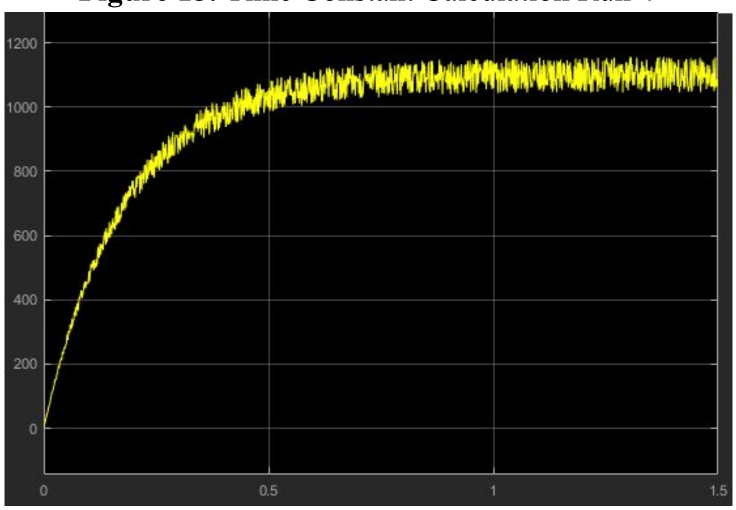

Figure 16. Time Constant Calculation Run 5

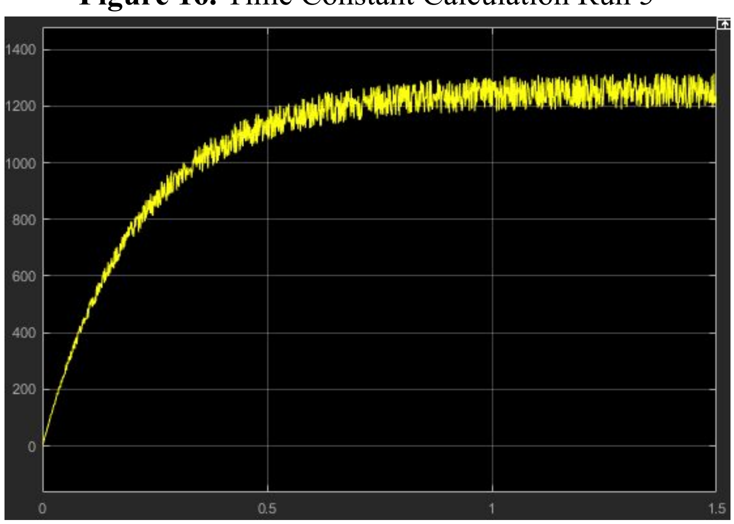

Figure 17. Time Constant Calculation Run 6

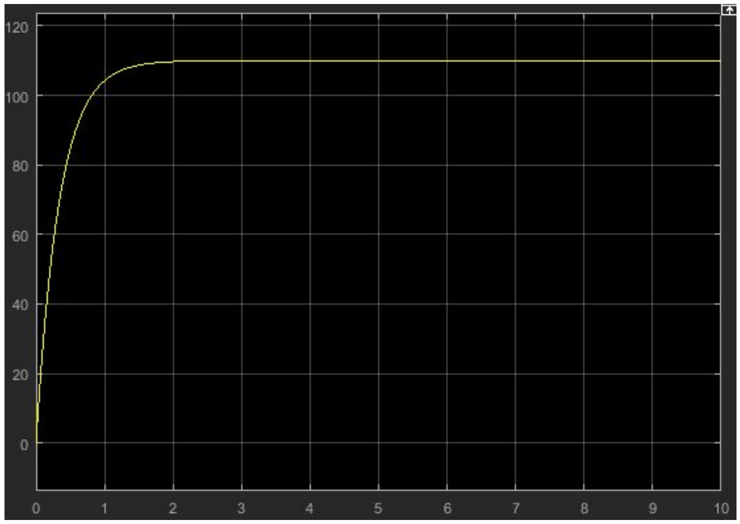

Figure 18. Open Loop Controller Simulation $\omega_d = 100$

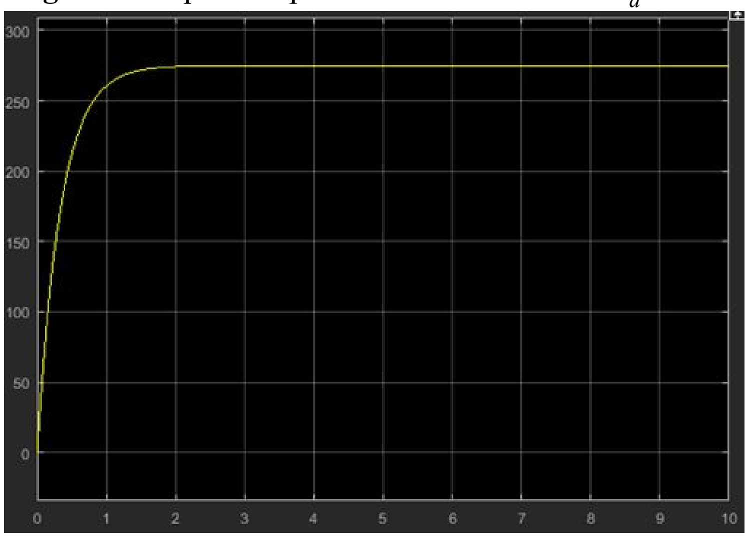

Figure 19. Open Loop Controller Simulation $\omega_d = 250$

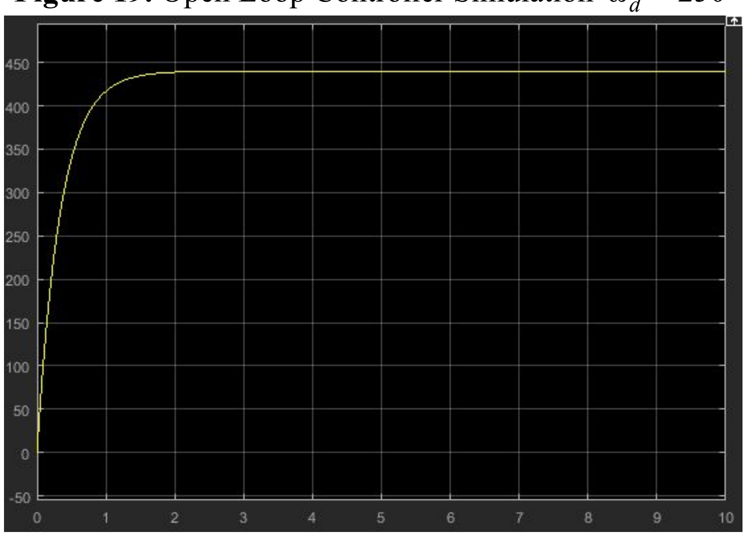

Figure 20. Open Loop Controller Simulation $\omega_d = 400$

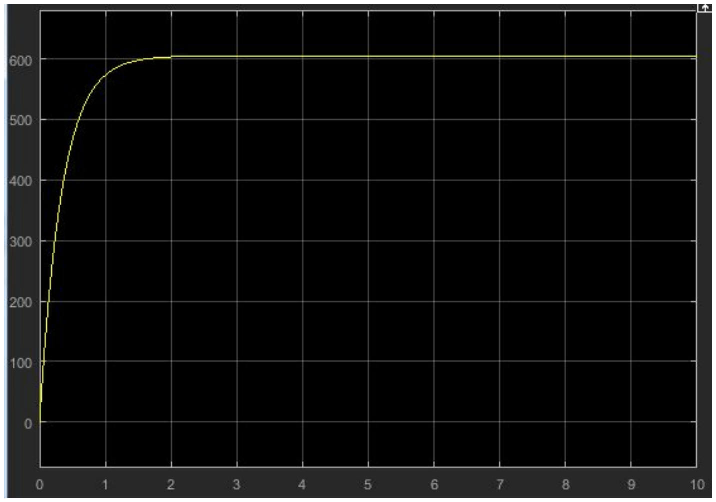

Figure 21. Open Loop Controller Simulation $\omega_d = 550$

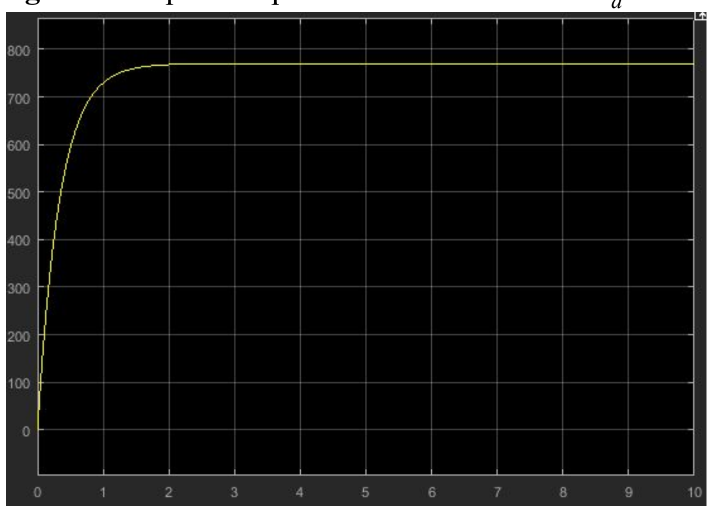

Figure 22. Open Loop Controller Simulation $\omega_d = 700$

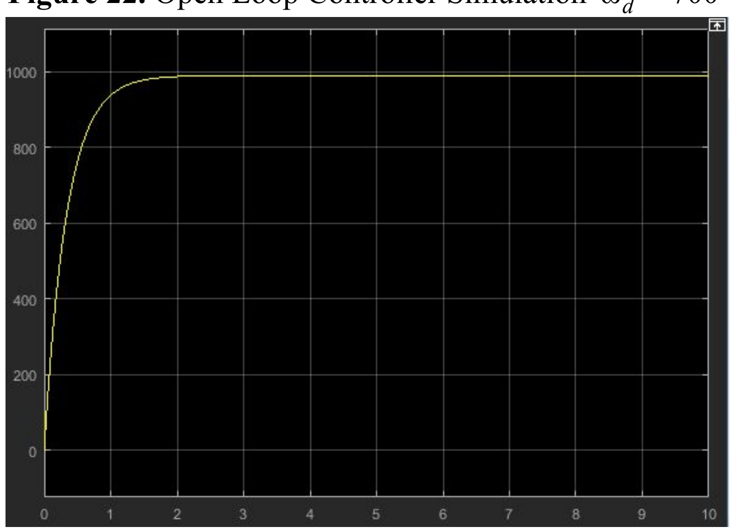

Figure 23. Open Loop Controller Simulation $\omega_d = 900$

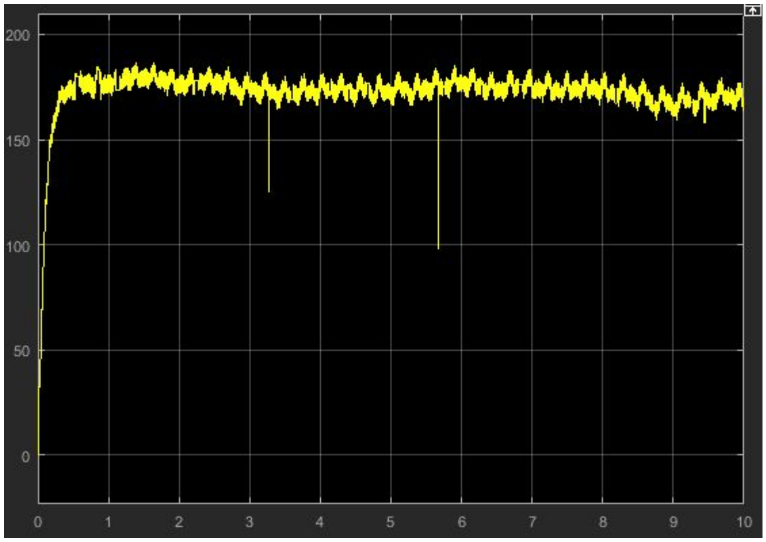

Figure 24. Open Loop Controller Implementation $\omega_d = 250$

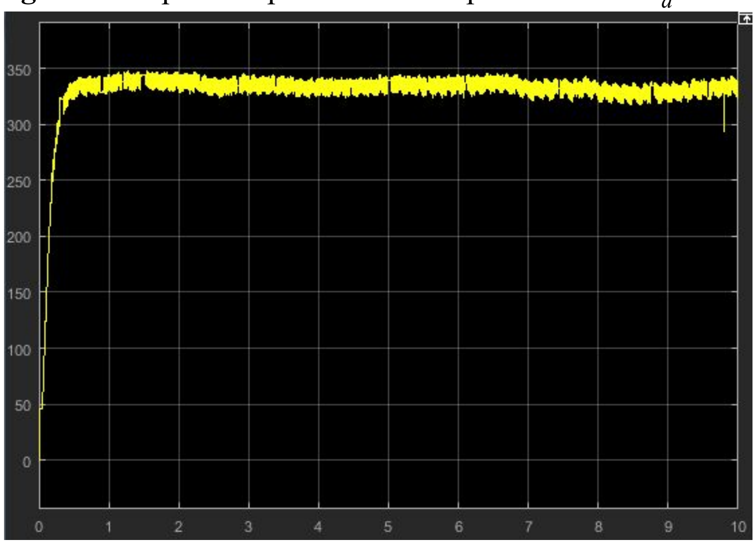

Figure 25. Open Loop Controller Implementation $\omega_d = 400$

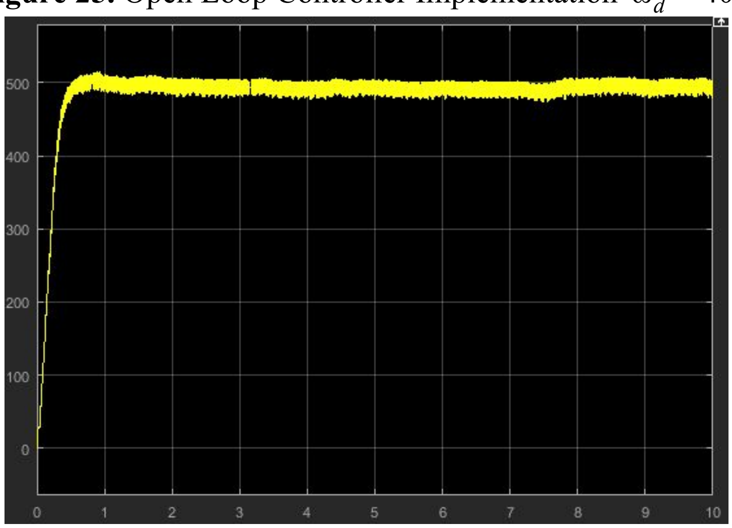

Figure 26. Open Loop Controller Implementation $\omega_d = 550$

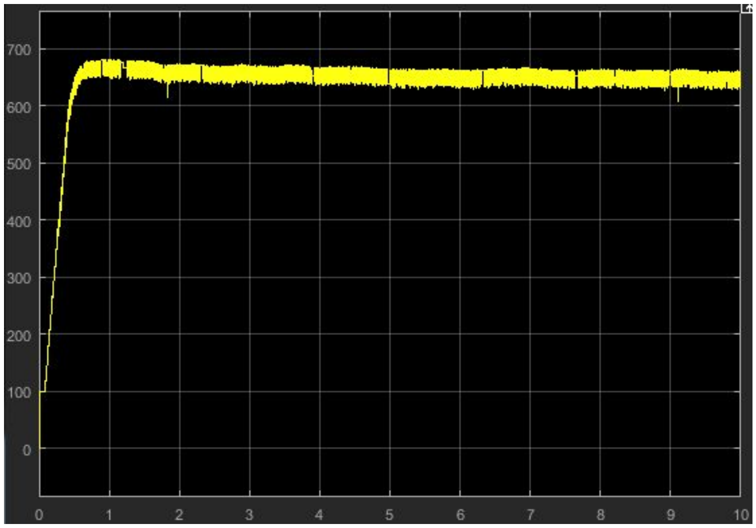

Figure 27. Open Loop Controller Implementation $\omega_d = 700$

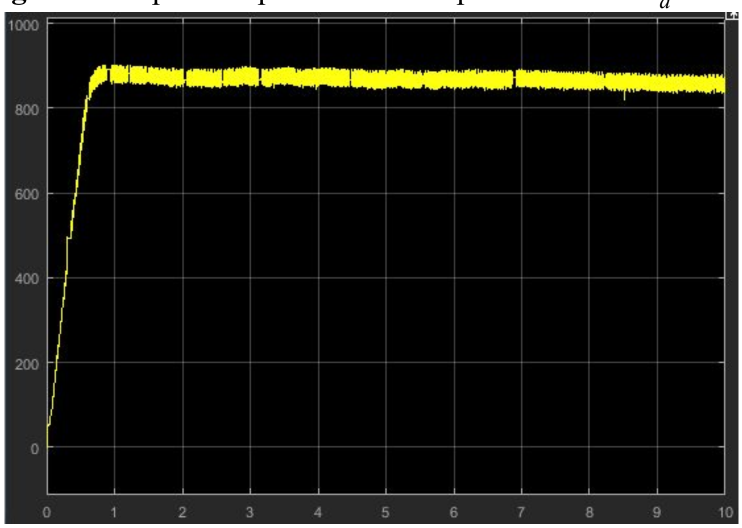

Figure 28. Open Loop Controller Implementation $\omega_d = 900$

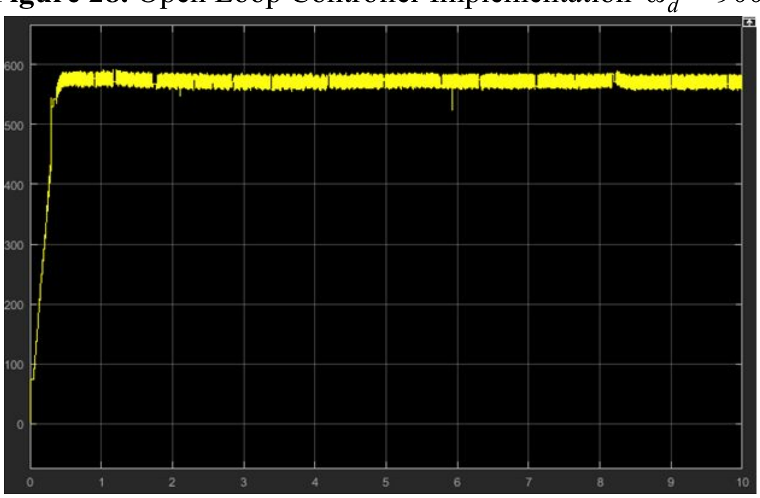

Figure 29. Closed Loop Controller Implementation $\omega_d = 600$; $K_p = 0.01$

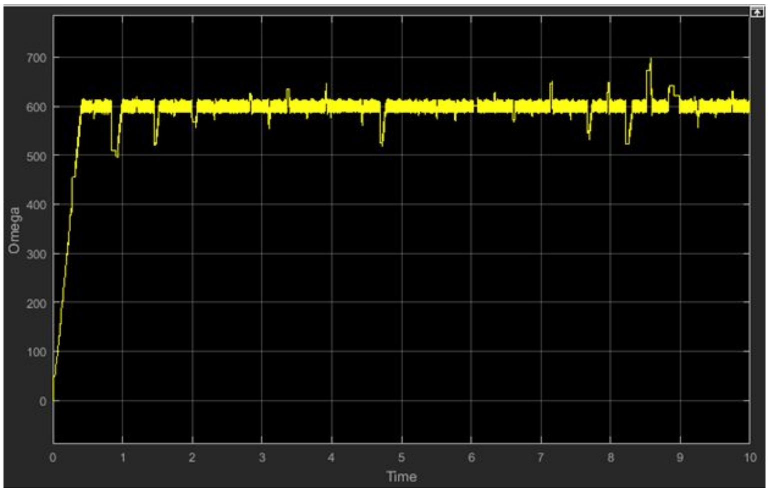

Figure 30. Closed Loop Controller Implementation ω_d = 600; K_p = 0.2

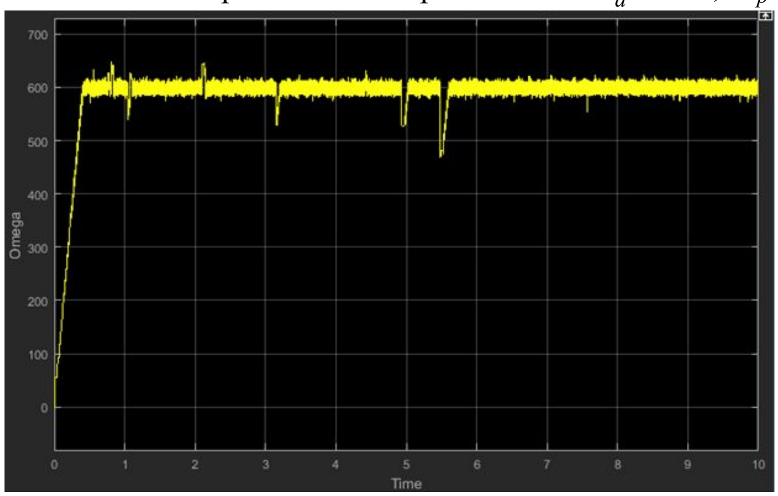

Figure 31. Closed Loop Controller Implementation ω_d = 600; K_p = 0.6

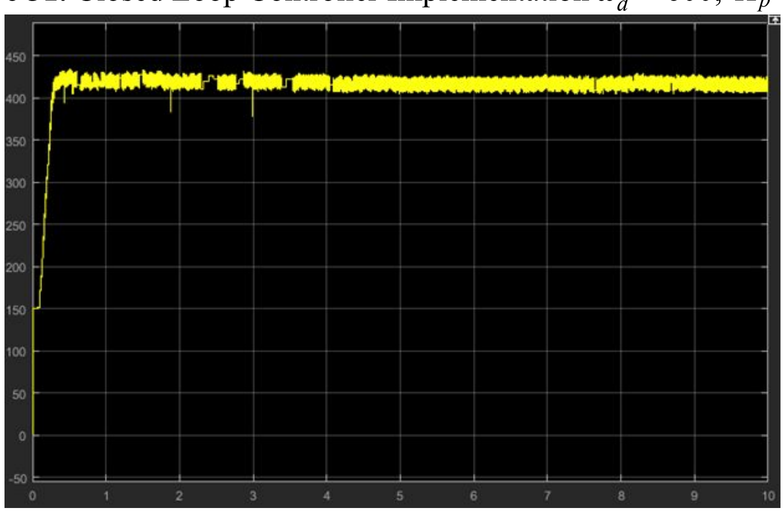

Figure 32. Closed Loop Controller Implementation ω_d = 450; K_p = 0.01

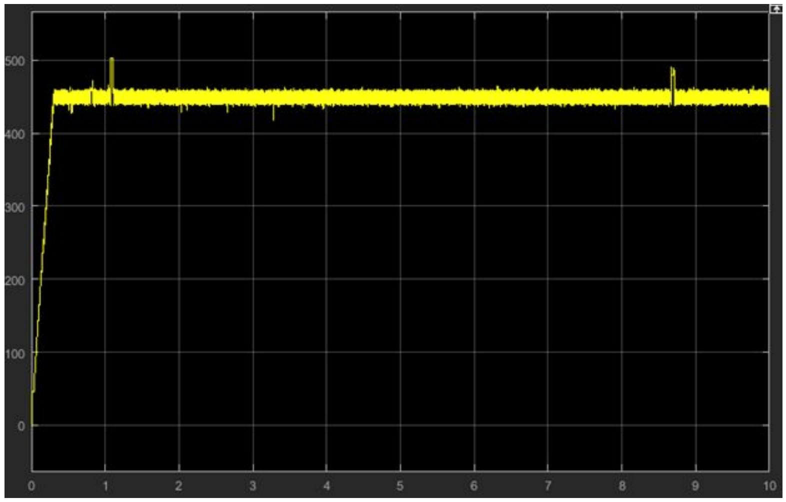

Figure 33. Closed Loop Controller Implementation $\omega_d = 450;\ K_p = 0.2$

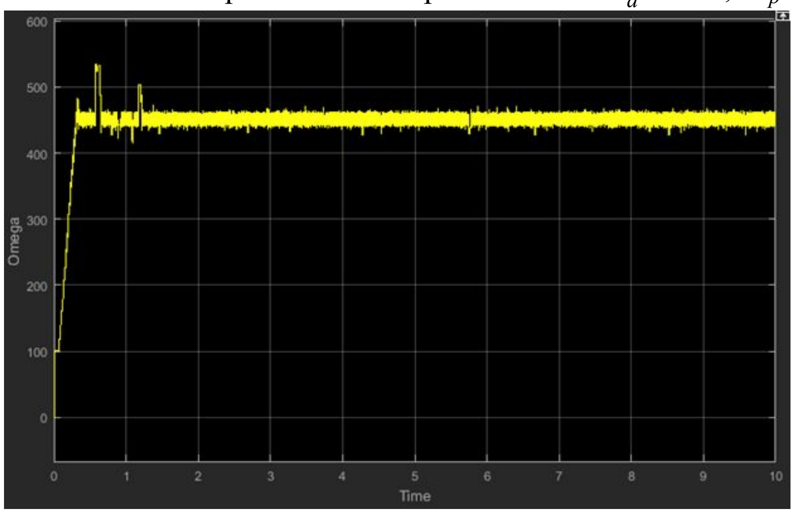

Figure 34. Closed Loop Controller Implementation $\omega_d = 450;\ K_p = 0.6$

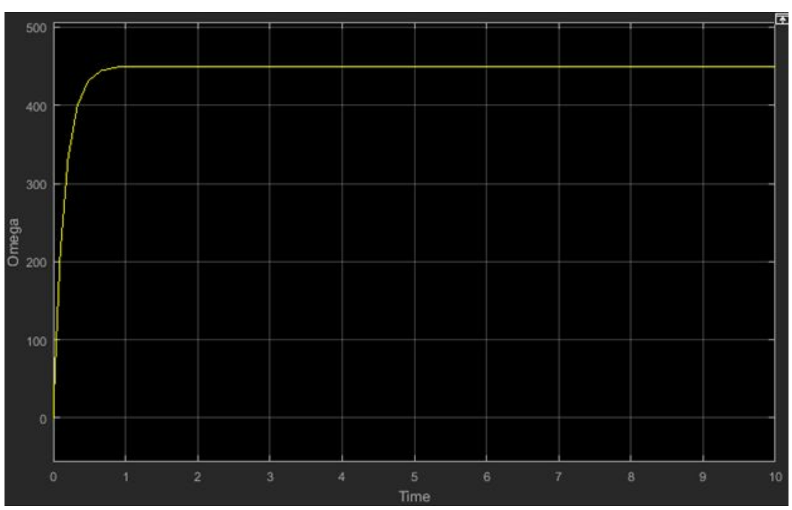

Figure 35. Closed Loop Controller Simulation $\omega_d = 450;\ K_p = 0.01$

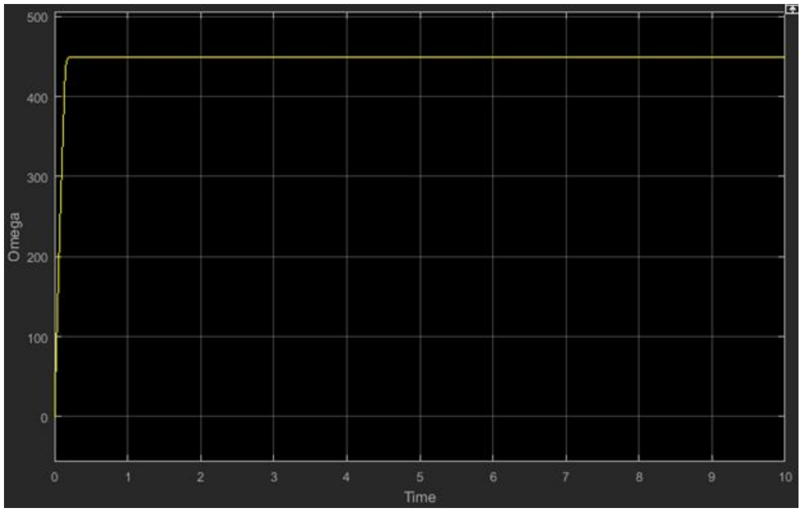

Figure 36. Closed Loop Controller Simulation $\omega_d = 450$; $K_p = 0.2$

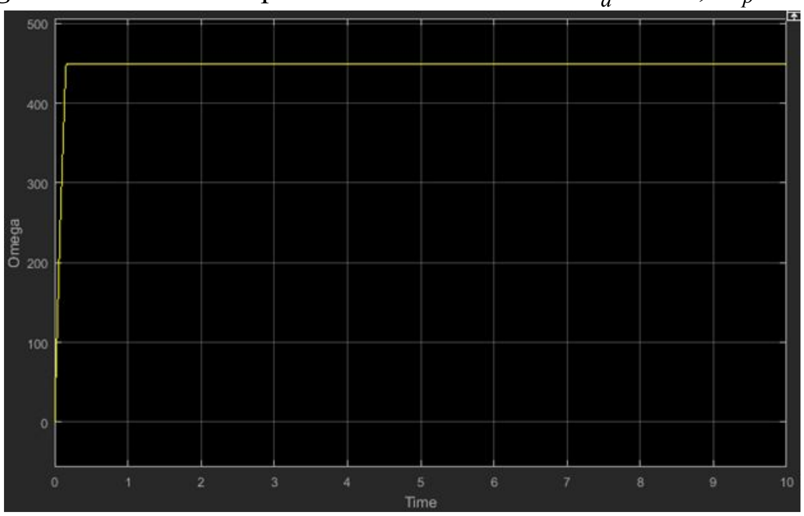

Figure 37. Closed Loop Controller Simulation $\omega_d = 450$; $K_p = 0.6$

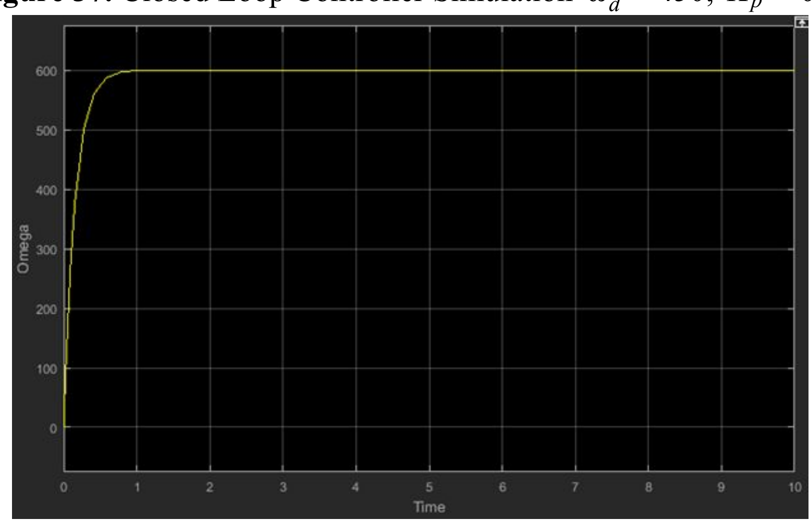

Figure 38. Closed Loop Controller Simulation $\omega_d = 600$; $K_p = 0.01$

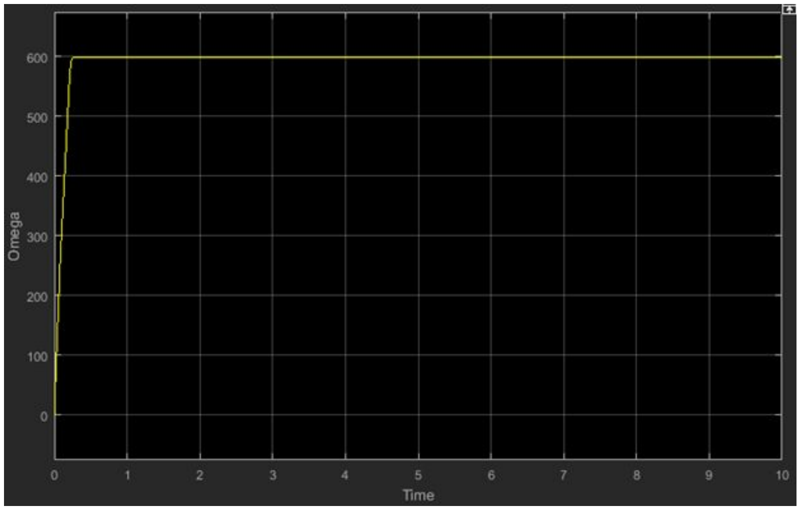

Figure 39. Closed Loop Controller Simulation $\omega_d = 600$; $K_p = 0.2$

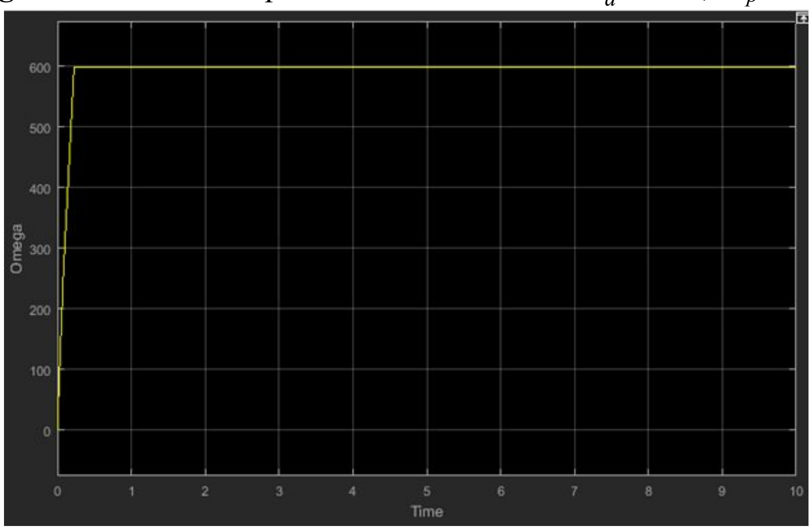

Figure 40. Closed Loop Controller Simulation $\omega_d = 600$; $K_p = 0.6$