

232026 DAVID LUKE BOWEN

SGEE5002

by Luke Bowen

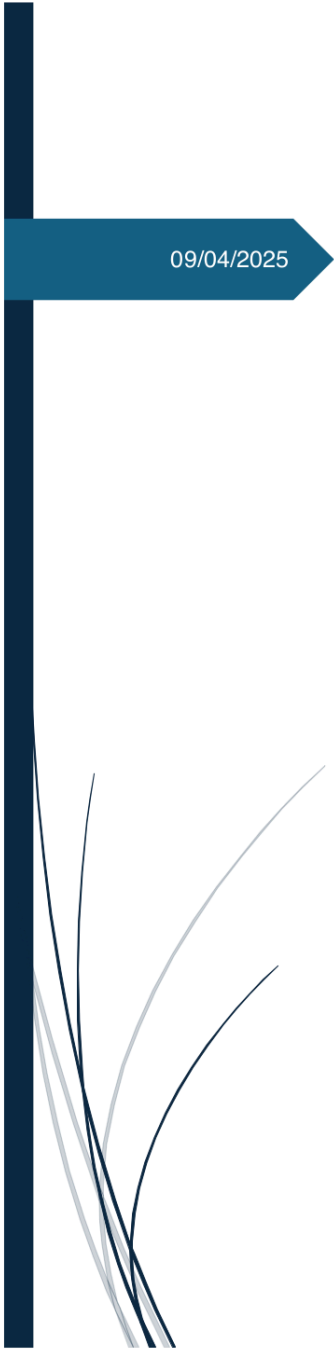
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*HNC Electrical / Electronic
Engineering Electrical and
Electronic Principles*

SGEE5002

*Analysis, Simulation and
Evaluation of Circuits and
Systems*

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Introduction

When using reactive electrical circuits, transient and frequency response analysis, first order circuits can be seen as the following differential equation when the initial conditions are zero:

$$V(t) = R \times I(t) + L \frac{dI(t)}{dt}$$

Equation 1 - Differential Equation of a First Order Reactive Electrical Circuit

This equation models an RL circuit, where the voltage across the resistor and inductor depends on the current and its rate of change. A similar approach can be used for RC circuits, where the capacitor replaces the inductor, and the differential equation involves voltage and current in a different form. This equation illustrates how the current responds dynamically to a change in applied voltage.

The transfer function is derived from the Laplace transformed differential equation.

$$H(s) = \frac{\text{Output}}{\text{Input}} = \frac{Y(s)}{U(s)}$$

Equation 2 - Transfer function



The transfer function is a fundamental concept in control theory that describes how the output of a system responds to a given input in the Laplace domain which will be investigated in this assignment.

The final part of the assignment includes the evaluation and comparison of P, PI, and PID controllers in controlling a DC motor model.

The PID controller consists of three terms:  rtional (P), which acts on current error; integral (I), which accumulates past errors; and derivative (D), which anticipates future trends based on the rate of error change. (Kuo, 2017).

Task 1 - Transient Analysis of a First Order RL Electrical Circuit

This RL circuit was built and coded to analyse the transient response. Unique component values:

Resistor 115Ω

Inductor 0.15H

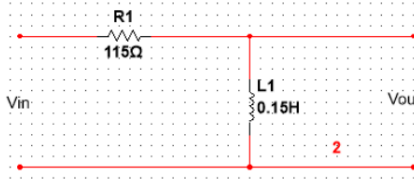


Figure 2 - RL Circuit

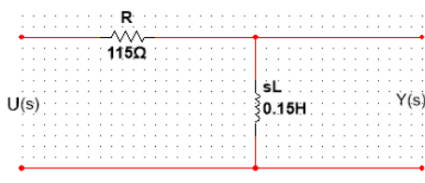


Figure 1 - Laplace Model RL Circuit

$$\text{Time Constant}(\tau) = \frac{L}{R} = \frac{0.15}{115} = 0.0013 \text{ Seconds}$$

Equation 3 - Calculation of Tau (RL Circuit)

$$Y(s) = \frac{sL}{sL + R} \times U(s)$$

Equation 4 - Potential divider rule RL circuit

Let the unit step output $U(s) = \frac{1}{s}$ and simplify where $a = \frac{R}{L}$

$$Y(s) = \frac{sL}{sL + R} \times \frac{1}{s} = \frac{L}{s(sL + R)} = \frac{1}{s + \frac{R}{L}} = \frac{1}{s + a}$$

Equation 5 - Output in Terms of s

From the table of inverse transforms

$$\mathcal{L}^{-1}\left\{\frac{1}{s + a}\right\} = e^{-at}$$

Equation 6 - Inverse Laplace transform

The output response, where $a = \frac{R}{L} (= \tau)$

$$y(t) = \left(e^{-\frac{t}{\tau}}\right) = e^{-\frac{0.0013}{0.0013}} = e^{-1} = 0.368$$

Equation 7 - Time Domain Response Rise

$$H(s) = \frac{\tau s}{\tau s + 1} = \frac{0.0013s}{0.0013s + 1}$$

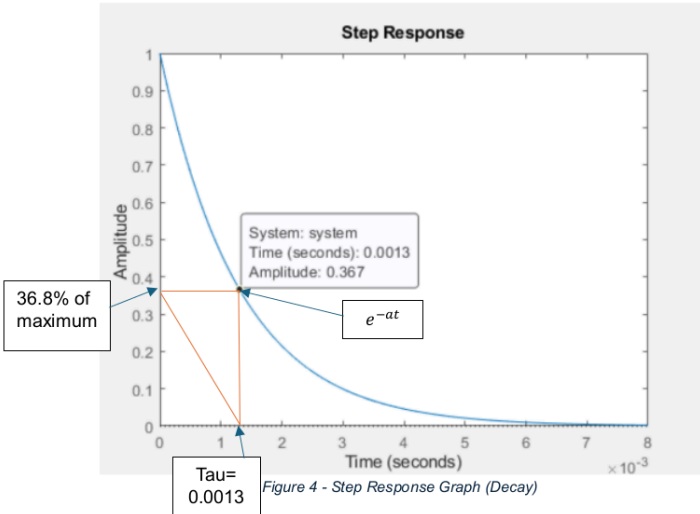
Equation 8 - Transfer Function in Terms of the Time Constant



Transfer function applied to Multisim to create figure 4.

```
1 s=tf('s');
2 system = (1.3*10^-3)*s/((1.3*10^-3)*s +1);
3 step(system)
```

Figure 3 - MATLAB transfer function step plot decay



Results recorded in table 1.

Parameter	Expected Result	Actual Result	Pass/Fail
Time Constant	1.3ms	1.3ms	Pass
RL Discharging Voltage (1T)	36.8%	36.8%	Pass
Steady State Time Constant	6.5ms	6.5ms	Pass
RL Discharging Voltage (5T)	0.7%	0.7%	Pass

Table 1 - RL circuit output decay



The Laplace model for the RL circuit shows input $U(s)$, output $Y(s)$ and the impedance $(sL+R)$, shown in Laplace domain which converts the differential equation into an algebraic equation in the s domain. The potential divider rule was used with a unit step input of 1 to determine the output in terms of s .

The transfer function $H(s)$ can also be expressed in terms of the time constant. The inverse Laplace transform can be applied in terms of t . This shows how the system responds to the changes of the time constant can control the rate at which the circuit responds to changes to the input.

The First order RL electrical circuit responded to changes in input with an exponential decay shown by the time constant (L/R) in figure 4. The time domain response is derived from the transfer functions as $e^{-1} = 0.368$ which is expected for exponential decay as it represents 36.8% of the initial value at 1T shown in the table.



Task 2 - Transient Analysis of a First Order RC Electrical Circuit

This RC circuit was built and coded to analyse the response. Unique component values:

Resistor 500Ω

Inductor 25mF

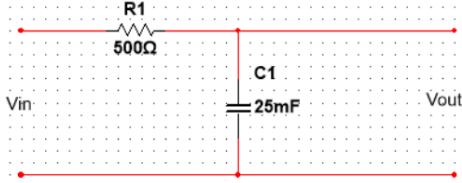


Figure 5 - RC Circuit

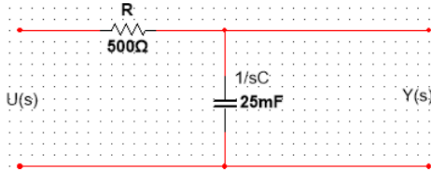


Figure 6 - Laplace Model RC Circuit

$$\text{Time Constant}(\tau) = R \times C = 500 \times 0.025 = 12.5 \text{ Seconds}$$

Equation 9 - Calculation of Tau (RC circuit)

$$Y(s) = \frac{sC}{R + 1/sC} \times U(s)$$

Equation 10 - Potential divider rule RC circuit

Multiply top and bottom by sC and let the unit step output $U(s) = \frac{1}{s}$

$$Y(s) = \frac{1}{RCs + 1} \times \frac{1}{s} = \frac{1}{s(RCs + 1)} = \frac{1}{s(s + a)}$$

Figure 7 - RC Circuit

Equation 11 - Output in terms of s

From the table of inverse transforms

$$\mathcal{L}^{-1}\left\{\frac{1}{s(s + a)}\right\} = 1 - e^{-at}$$

Equation 12 - Inverse Laplace transform

where $a = \frac{1}{RC}$

$$y(t) = 1 - e^{\left(\frac{-t}{\tau}\right)} = 1 - e^{\left(\frac{-12.5}{12.5}\right)} = 0.632$$

Equation 13 - Output response in time domain

$$H(s) = \frac{1}{RCs + 1} = \frac{1}{\tau s + 1} = \frac{1}{12.5s + 1}$$

Equation 14 - Transfer function in terms of the time constant



Transfer function applied to Multisim to create figure 8

```
1 s=tf('s');
2 system = 1/((12.5*s)+1);
3 step(system)
```

Figure 8 – MATLAB transfer function step plot decay

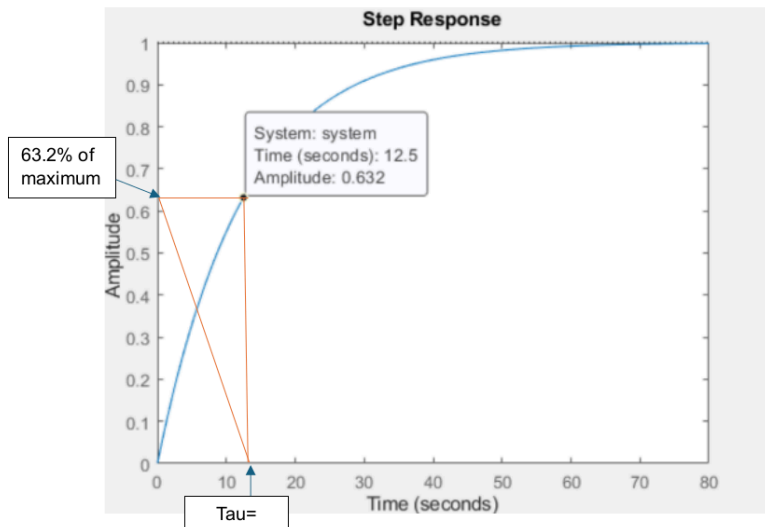


Figure 9 - Step Response Graph (Growth)

The results were recorded in table 2.

Parameter	Expected Result	Actual Result	Pass/Fail
Time Constant	12.5s	12.5s	Pass
RC Charging Voltage (1T)	63.2%	63.2%	Pass
Steady State Time Constant	62.5s	62.5s	Pass
RC Charging Voltage (5T)	99.3%	99.3%	Pass



Table 2 - RC circuit output rise

By using the Laplace model the output response in terms of the time constant was once again successfully achieved by converting the transfer function from the s domain using inverse Laplace.

In this RC charging circuit, the output voltage follows a first-order response. The time constant (RC) determines the speed of the response, the larger the time constant the slower the response. This time constant agrees well with the MATLAB simulation, as seen from the step response plot. The capacitor voltage rises with each time constant period, reaching approximately 63% ($1 - e^{-at}$) of the final value at 1T and 99.3% at 5T shown in table 2.

TASK 3 - Frequency Performance Analysis of a First Order RL Electrical Circuit

Using the same component values, they are now used to analyse the circuit in terms of the frequency domain.

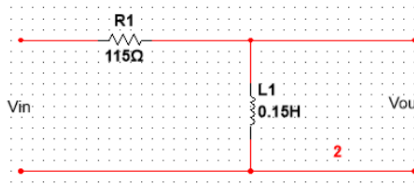


Figure 10 - RL Circuit (2)

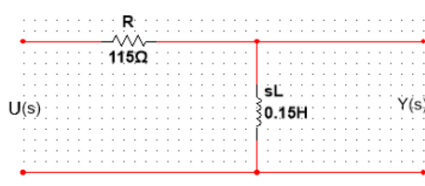


Figure 11 - Laplace Model RL Circuit (2)

Using these circuits the following can be calculated:

$$\omega C = \frac{R}{L} = \frac{115}{0.15} = 766.67 \text{ Rads/Sec}$$

Equation 15 - Cutoff frequency RL circuit

At the cutoff frequency ($\omega = \omega C$)

$$\theta = \tan^{-1} \left(\frac{\text{Imaginary Part}}{\text{Real Part}} \right) = \tan^{-1} \left(-\frac{\omega C \omega}{\omega^2 C} \right)$$

Equation 16 - Phase angle Formula

$$\theta = \tan^{-1}(-1) = -45^\circ$$

Equation 17 - Phase angle RL circuit high pass

$$Y(s) = \frac{R}{R + sL} \times U(s)$$

Equation 18 - Potential divider rule

$$H(s) = \frac{Y(s)}{U(s)} = \frac{\frac{R}{L}}{s + \frac{R}{L}}$$

Equation 19 - General transfer function RL

Where $\omega C = \frac{R}{L}$

$$H(s) = \frac{\omega C}{s + \omega C} = \frac{766.67}{s + 766.67}$$

Equation 20 - Transfer function for an RL circuit in terms of cutoff frequency high pass

Transfer function applied to Multisim to created graph (figure).

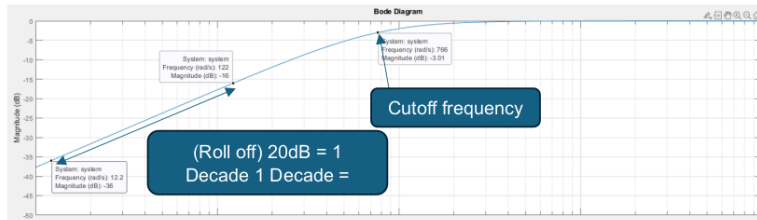


Figure 12 - Magnitude plot HPF

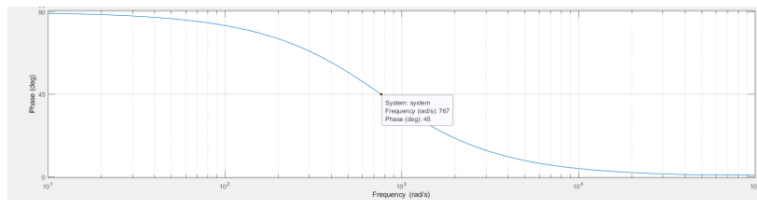


Figure 13 - Phase plot HPF

The results were recorded in table 3.

Parameter	Expected Result	Actual Result	Pass/Fail
ωC	766.67Rad/Sec	766.67Rad/Sec	Pass
Phase Shift	-45°	-45°	Pass
Roll off (1 decade)	20dB	20dB	Pass
Cut off frequency	-3dB	-3dB	Pass

Table 3 - High pass filter results

In this RL circuit was used to block high frequency signals (high impedance) and allow low frequency signals to pass (low impedance). Using Laplace transform the transfer function was derived from the s domain into terms of the cut-off frequency to simulate the magnitude and phase functions of frequency.

The Bode plot in figure 11 showed the expected -3 dB drop at the cut-off frequency (R/L) where high frequencies can pass and lower frequencies are attenuated. The attenuation follows the -20dB/decade rule where the frequency moves at a factor of 10 for every 20dB (magnitude).

Figure 12 shows the phase plot and shift of -45°, the negative phase shift is because the inductor dominates introducing a phase lag, so the output voltage is lagging behind the input voltage which is the expected for an RL high pass filter shown in equation 16. As the frequency increased, the phase continued to shift toward 0°, here the resistor dominates, and the output voltage is becoming more in phase with the input.

TASK 4 - Frequency Performance Analysis of a First Order RC Electrical Circuit

Once again using the same component values to analyse the circuit in terms of the frequency domain.

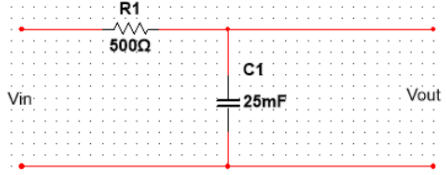


Figure 14 - RC Circuit (2)

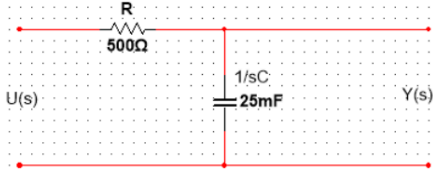


Figure 15 - Laplace Circuit (2)

Using these circuits the following can be calculated:

$$\omega C = \frac{1}{RC} = \frac{1}{500 \times 0.025} = 12.5 \text{ Rads/Sec}$$

Equation 21 - Cutoff frequency RC circuit

$$\theta = \tan^{-1}(1) = 45^\circ$$

Equation 22 - Phase Angle at the cutoff frequency RC low pass

$$Y(s) = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} \times U(s)$$

Equation 23 - RC low pass filter s domain

Simplify and multiply by sC

$$H(s) = \frac{Y(s)}{U(s)} = \frac{1}{RCs + 1}$$

Equation 24 - General transfer function RC low pass filter

$$H(s) = \frac{1}{\frac{s}{\omega C} + 1} = \frac{\omega C}{s + \omega C} = \frac{12.5}{s + 12.5}$$

Equation 25 - Transfer function in terms of the cutoff frequency low pass

Transfer function applied to Multisim to created graph (figure).

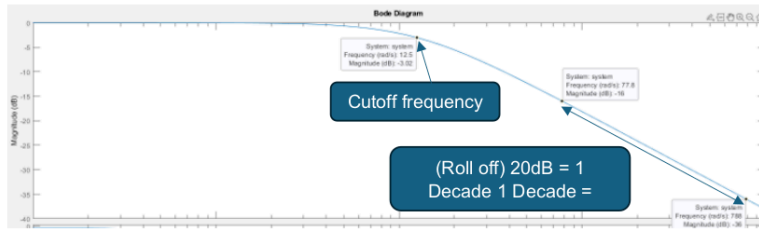


Figure 16 - Magnitude plot LPF

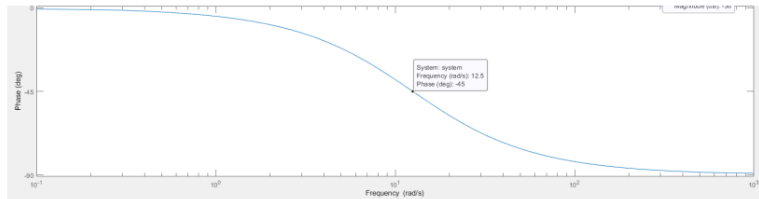


Figure 17 - Phase plot LPF

The results were recorded in table 4.

Parameter	Expected Result	Actual Result	Pass/Fail
ωC	12.5 Rad/Sec	12.5 Rad/Sec	Pass
Phase Shift	45°	45°	Pass
Roll off (1 decade)	20dB	20dB	Pass
Cut off frequency	-3dB	-3dB	Pass

Table 4 - Low pass filter results

Using the Laplace transform the transfer function was derived in terms cutoff frequency to analyse how the system responded to the different input frequencies. The cut off frequency for an RC filter is $\omega C = \frac{1}{RC}$ which was confirmed in the expected and actual results from the bode plot.

The bode plot confirms the -3dB as the standard cutoff point at 12.5rad/s and then a negative shift from here where the signals will be able to pass. The -20dB decade rule was followed beyond the cutoff point where the roll off was -20dB for every increase of the frequency by a factor of 10.

In the phase plot the shift moves from low frequency (0°) to high frequency (-90°) with a cutoff frequency of -45° which in in line with the expected values. The RC circuit functions as a low pass filter as it attenuates high frequency signals and allows low frequencies to pass, capacitor reactance is high at low frequencies blocking any current flow.

TASK 5 - Transient Performance Analysis of a Second Order Series Electrical Circuit

An RLC circuit to analyse the types of damping factor. Damping factor controls the oscillations into the system and is also used to measure the stability of a system.

Unique component values:

Inductor 0.15H

Capacitor 70Uf

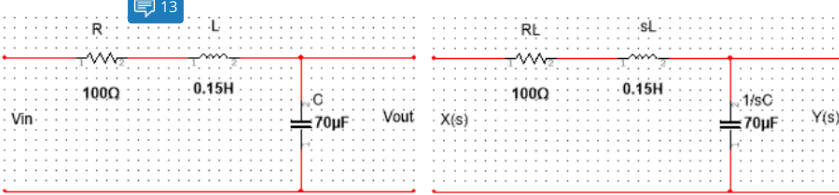


Figure 18 – RLC series circuit

Figure 19 - RLC series Laplace circuit

From these circuits the following information can be achieved:

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}}$$

Equation 26 - Damping factor

$$\omega_n = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.15 \times 70 \times 10^{-6}}} = 308.6 \text{ Rad/S}$$

Equation 27 - Natural frequency

$$H(s) = \frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

Equation 28 - Transfer function in the Laplace domain of RLC circuit

Gain (K) = 1

$$\frac{K\omega_n^2}{s^2 + \zeta\omega_n s + \omega_n^2}$$

Equation 29 - Standard form of second order system transfer function

Resistor = 195Ω

Overdamped circuit – $\zeta > 1$

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{195}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 2.1$$

Equation 30 - Damping factor (overdamped)

$$H(s) = K \frac{Wn^2}{s^2 + 2\zeta Wn s + Wn^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 2.1 \times 308.6)s) + 308.6^2}$$

Equation 31 - Overdamped transfer function

Transfer function applied to Multisim to create the graph in figure 20.

```
1 s=tf('s');  
2 system=308.6/(s^2 +195*s +308.6);  
3 step(system);  
4 grid on
```

Figure 20 - Overdamped MATLAB transfer function

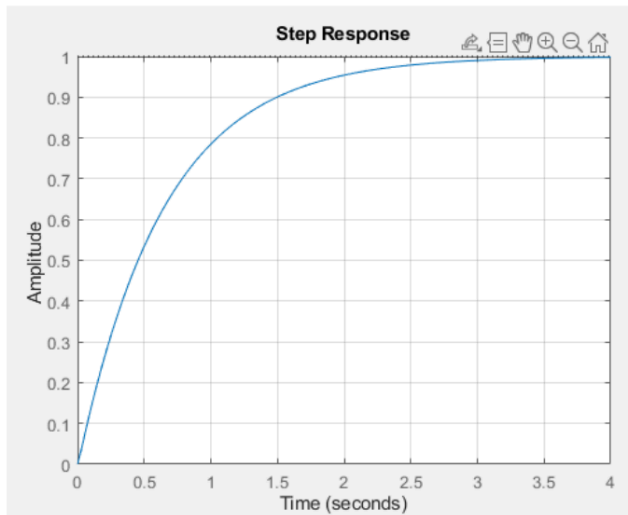


Figure 21 - Overdamped graph

Resistor = 73Ω

Underdamped circuit - ζ between 0-1

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{73}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 0.78$$

Equation 32 - Damping factor underdamped circuit

$$H(s) = K \frac{Wn^2}{s^2 + 2\zeta Wn s + Wn^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 0.78 \times 308.6)s) + 308.6^2}$$

Equation 33 - Transfer function underdamped circuit

Transfer function applied to Multisim to create the graph in figure 22.

```
1 s=tf('s');  
2 system=308.6/(s^2 +73*s +308.6);  
3 step(system);  
4 grid on
```

Figure 22 - Underdamped MATLAB transfer function code

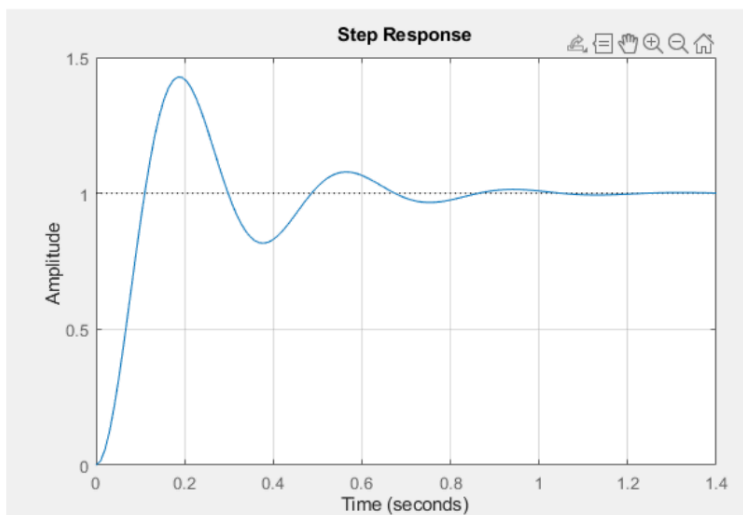


Figure 23 - Underdamped graph

Resistor = 0.0001Ω

No damping - $\zeta = 0$

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{0.0001}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 0.000001$$

Equation 34 - Damping factor=no damping

$$H(s) = K \frac{Wn^2}{s^2 + 2\zeta Wn s + Wn^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 0.000001 \times 308.6)s) + 308.6^2}$$

Equation 35 - No damping transfer function

Transfer function applied to Multisim to create the graph in figure 24.

```
1 s=tf('s');  
2 system=308.6/(s^2 +0.0001*s +308.6);  
3 step(system);  
4 grid on
```

Figure 24 - No damping MATLAB code

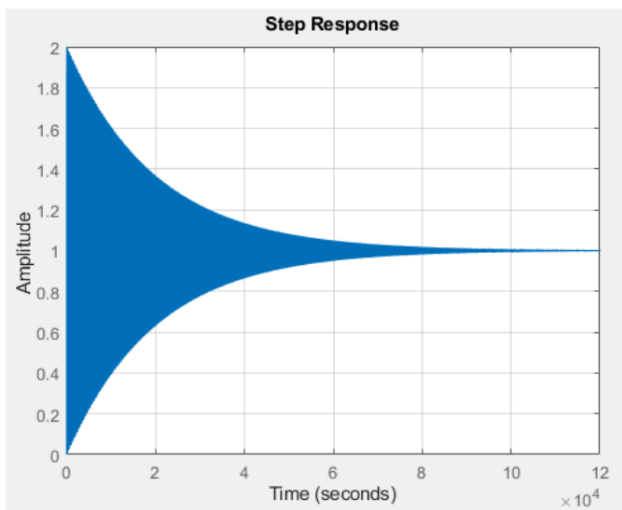


Figure 25 - No damping circuit graph

Resistor = 92.582Ω
Critical Damping $\zeta=1$

$$R = \frac{2\zeta}{\sqrt{\frac{C}{L}}} = \frac{2 \times 1}{\sqrt{\frac{70 \times 10^{-6}}{0.15}}} = 92.582$$

Equation 36 - Rearranged to achieve damping factor of 1

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{92.582}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 1$$

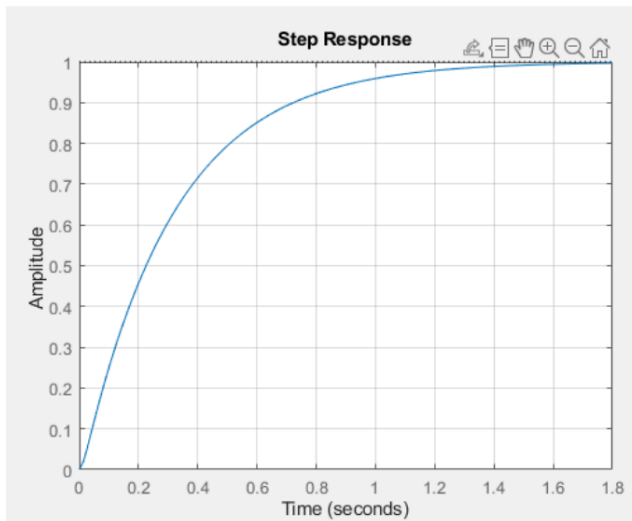
Equation 37 - Damping factor Critical damped circuit

$$H(s) = K \frac{K W_n^2}{s^2 + 2\zeta W_n s + W_n^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 92.582 \times 308.6)s) + 308.6^2}$$

Equation 38 - Critically damped circuit transfer function

```
1 s=tf('s');
2 system=308.6/(s^2 +92.582*s +308.6);
3 step(system);
4 grid on
```

Equation 39 - Critically damped circuit MATLAB Transfer function



Equation 40 -Critically damped circuit graph

Damping type	Resistor value Ω	Damping factor ζ	Expected Result	Actual Result	Pass/Fail
Over Damping	195	2.1	Over Damped	Over Damped	Pass
Under Damping	73	0.78	Under damped	Under damped	Pass
Critical Damping	92.582	1	Critically damped	Critically damped	Pass
No Damping	0.0001	0.000001	Undamped	Undamped	Pass

Table 5 - Damping factor table

The natural frequency of the system was found and used to measure the damping factor by using the Laplace domain of RLC circuit.

The value for the resistor for the circuit to be critically damped was calculated to be 92.582Ω . When the circuit is critically damped the damping factor is equal to 1, this circuit provides the fastest non oscillatory response.

The value of the resistor was more than doubled resulted the damping factor increasing with a slow and non-oscillatory response, meaning the circuit is overdamped. When the value of the resistor was decreased the damping factor dropped below 1 which is underdamped, figure 22 shows the under damped graphs decaying response. Finally the resistor value was taken as low as possible to simulate the undamped graph in figure 24 which shows pure oscillations. The reoccurring trend shows that the damping factor will increase by increasing the resistor value.



Task 6 - Frequency Performance Analysis of a Second Order Series Electrical Circuit

Still using the same component values from figure 17 and 18 to calculate the damping factor with additional underdamped values also included:

Resistor = 92.582Ω

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{92.582}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 1$$

Equation 41 - Damping factor critically damped

$$H(s) = K \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 92.582 \times 308.6)s) + 308.6^2}$$

Equation 42 - Critically damped circuit transfer function

Resistor = 195Ω

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{195}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 2.1$$

Equation 43 - Damping factor Overdamped

$$H(s) = K \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 2.1 \times 308.6)s) + 308.6^2}$$

Equation 44 - Critically damped circuit transfer function

Resistor = 73Ω

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{73}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 0.78$$

Equation 45 - Damping factor Under damped circuit 1

$$H(s) = K \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 0.78 \times 308.6)s) + 308.6^2}$$

Equation 46 - Underdamped circuit 1 MATLAB transfer function

Resistor = 40Ω

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{40}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 0.43$$

Equation 47 - Damping factor Under damped circuit 2

$$H(s) = K \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 0.78 \times 308.6)s) + 308.6^2}$$

Equation 48 - Underdamped circuit 2 MATLAB transfer function

Resistor = 15Ω

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{15}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 0.16$$

Equation 49 - Damping factor Under damped circuit 3

$$H(s) = K \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 0.78 \times 308.6)s) + 308.6^2}$$

Equation 50 - Underdamped circuit 3 MATLAB transfer function

Resistor = 5Ω

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{5}{2} \sqrt{\frac{70 \times 10^{-6}}{0.15}} = 0.05$$

Equation 51 - Damping factor Under damped circuit 4

$$H(s) = K \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 308.6^2}{s^2 + ((2 \times 0.78 \times 308.6)s) + 308.6^2}$$

Equation 52 - Underdamped circuit 4 MATLAB transfer function

The transfer function applied to Multisim to created graph (figure) with all results together to be verified and compared.

```

1      s=tf('s');
2      system1 = 95238/(s^2 +195*s +95238);
3      bode(system1);
4      grid on
5      hold on
6
7      s=tf('s');
8      system2 = 95238/(s^2 +92.582*s +95238);
9      bode(system2);
10     s=tf('s');
11     system3 = 95238/(s^2 +73*s +95238);
12     bode(system3);
13     s=tf('s');
14     system4 = 95238/(s^2 +40*s +95238);
15     bode(system4);
16     s=tf('s');
17     system5 = 95238/(s^2 +15*s ++95238);
18     bode(system5);
19     s=tf('s');
20     system6 = +95238/(s^2 +5*s ++95238);
21     bode(system6);
22
23     grid on
24

```

Figure 26 – Multiple code circuits MATLAB Transfer functions

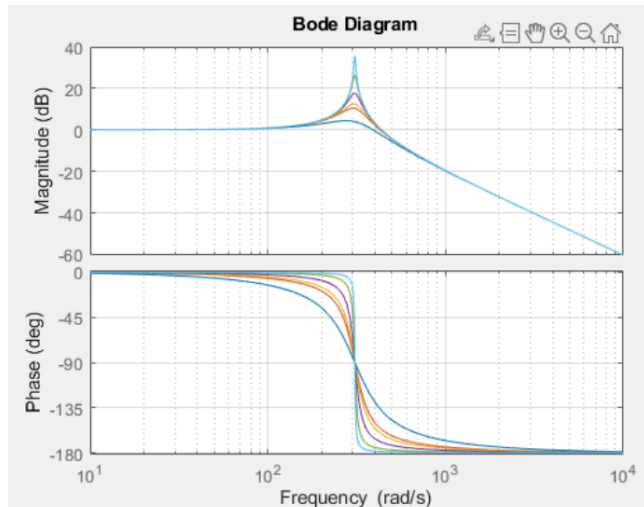


Figure 27 - Multiple circuits MATLAB graph bode plot

The transfer function constant (95238) was derived from the natural frequency calculation in equation 26 (task 5) by squaring both sides to remove the square root, resulting in $\omega_n^2 = \frac{1}{LC} = 95238$.

The bode diagram shows that the circuits with smaller resistor values will have lower damping factors and a sharper peak in the magnitude plot. The phase plots drop from 0 degrees to -180 degrees aligning at the ω_n , and the phase [15](#) also sharper as the resistor value decreases.

Task 7 - Frequency Performance Analysis of a First Order Electronic System

An electronic system was created to analyse the frequency performance. Unique component values for low pass filter:

Resistor 1 – 1k ohm

Resistor 2 - 20k ohm

Capacitor LPF - 240nf

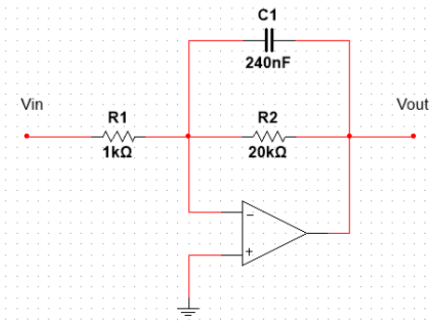


Figure 29 - Low pass filter circuit

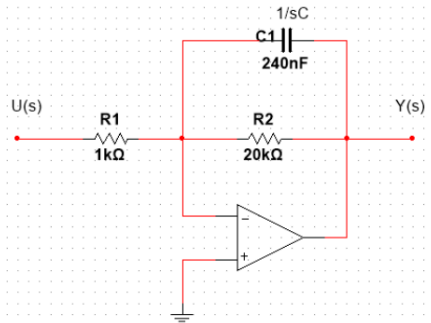


Figure 28 - Low pass filter Laplace circuit

The following was calculated to find the TF:

$$\omega C = \frac{1}{CR2} = \frac{1}{(240 \times 10^{-9}) \times 20000} = 208.33 \text{ Rads/Sec}$$

Equation 53 - Cutoff frequency

$$K = \frac{R2}{R1} = \frac{20000}{1000} = 20$$

Equation 54 - Gain

$$H(s) = -k \frac{\omega C}{s + \omega C} = -20 \frac{208.33}{s + 208.33}$$

Equation 55 - Transfer function

Transfer function applied to Multisim to created graph (figure).

```
>> s=tf('s');
>> system=-20*(208.33/(s+208.33));
>> bode(system);
grid on
```

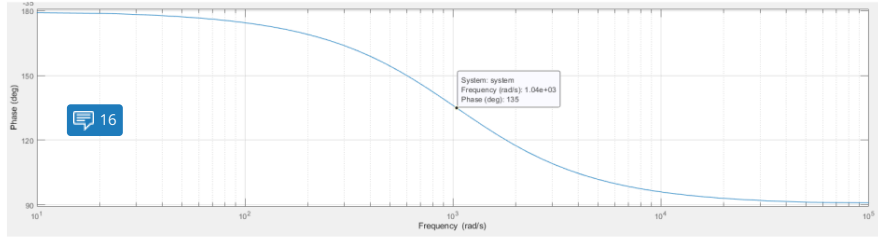


Figure 30 - Magnitude plot

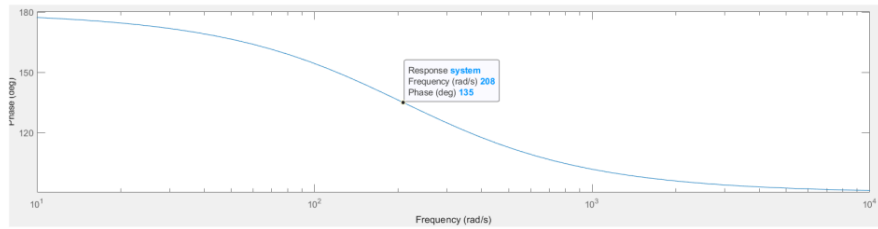


Figure 31 - Phase plot

The cutoff gain was calculated by using the equation $20_{\log_{10}}(20) - 3\text{dB}$ which equals 23dB.

The phase plot was calculated by $180\text{deg} - 45\text{deg}$ which equals 135 degrees as the circuit is a low pass filter.

The results were recorded in the table below.

Parameters	Calculated value	Simulated value
Magnitude at 208.33 rad/s	23dB	23dB
Phase angle at 208.33 rad/s	135deg	135deg

Table 6 - Low pass filter bode results

In table 6 the calculated values are aligned with the simulated values, confirming the circuit a first order inverted low pass filter.

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Task 8 - HPF Frequency Performance Analysis of a First Order Electronic System

An electronic system was created to analyse the frequency performance. Unique component values for high pass filter:

Resistor 1 – 1000 ohm

Resistor 2 - 2000 ohm

Capacitor HPF - 24nf

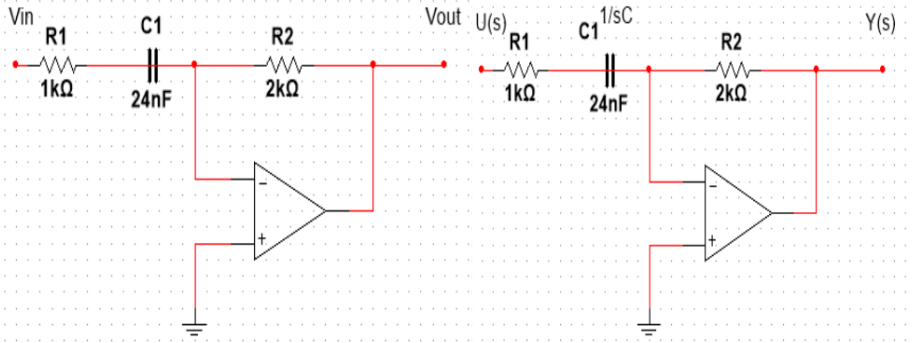


Figure 32 - High pass filter circuit

Figure 33 - High pass filter Laplace circuit

The following was calculated to find the TF:

$$\omega C = \frac{1}{CR1} = \frac{1}{(24 \times 10^{-9}) \times 1000} = 41666.67 \text{ rad/s}$$

Equation 56 - Cutoff frequency

$$K = \frac{R2}{R1} = \frac{2000}{1000} = 2$$

Equation 57 - Gain

$$H(s) = -k \frac{s}{s + \omega C} = -2 \frac{s}{s + 41666.67}$$

Equation 58 - Transfer function

Transfer function applied to Multisim to created graph (figure).

```
>> s=tf('s');
>> system=-2*(s/(s+41666.67));
>> bode(system);
grid on;
```

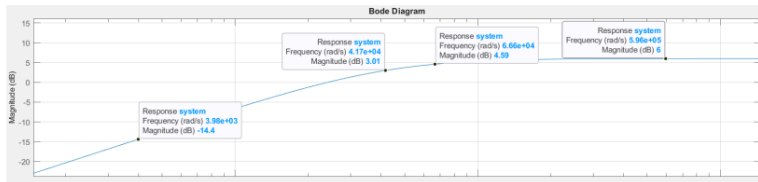


Figure 34 - Magnitude plot

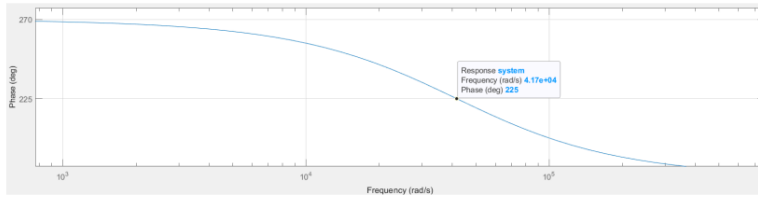


Figure 35 - Phase plot

The cutoff gain was calculated by using the equation $20\log_{10}(2)-3\text{dB}$ which equals 3dB.

The phase plot was calculated by $180\text{deg}+45\text{deg}$ which equals 225 degrees as the circuit is a high pass filter.

The results were recorded in the table below.

Parameters	Calculated value	Simulated value
Magnitude at 41666.67 rad/s	3dB	3dB
Phase angle at 41666.67 rad/s	225deg	225deg

Table 7 - High pass filter bode results

In table 7 the calculated values are aligned with the simulated values, confirming the circuit a first order inverted high pass filter.

Task 9 - First Order Control System Analysis

An open loop model is shown in figure 36.

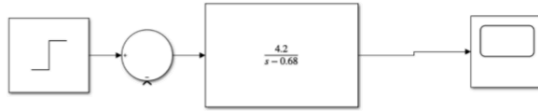


Figure 36 - Open loop circuit

$$H(s) = \frac{4.2}{s - 0.68}$$

Equation 59 - Open loop TF

The numerator determines the pole and output response to the step input.

20

The step response shows the unstable systems exponential rise in output.

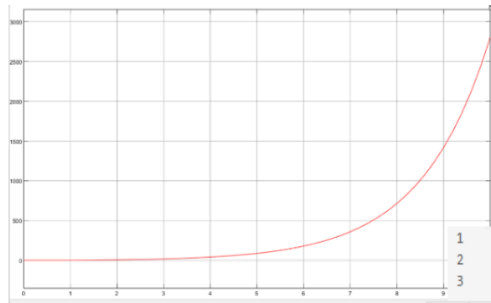


Figure 37 - Open loop unstable step response

```
1 sys = tf([4.2],[1 -0.68]);
2 step(sys)
3 grid on
```

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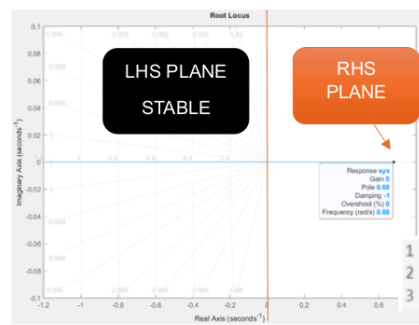


Figure 38 - Open loop unstable root locus

```
1 sys = tf([4.2],[1 -0.68]);
2 rlocus(sys)
3 grid on
```

For this open loop system the pole is plotted on the real axis meaning the system is unstable ($s > 0$). To stabilise the system the pole must be in the left half plane (negative) which can be done by adding feedback control (K).

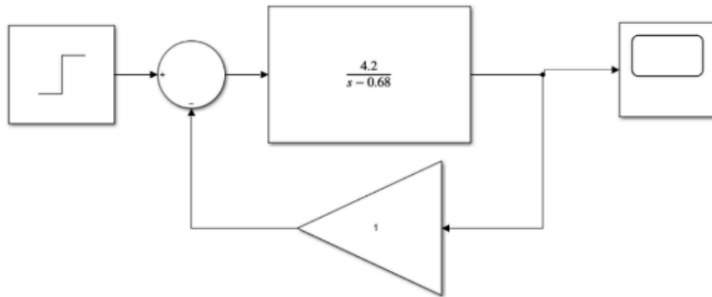


Figure 39 - Closed loop circuit $K=1$

The transfer function for the closed loop circuit was calculated.

$$22 \quad \frac{\frac{4.2}{s - 0.68}}{1 + \frac{4.2k}{(s - 0.68)}} = \frac{4.2}{s - 0.68 + 4.2 \times 1}$$

$$H(s) = \frac{4.2}{s + 3.52}$$

Figure 40 - Closed loop TF when $K = 1$

When $K=1$ the pole is -3.52, which means the system is stable. An argand diagram was created to plot the pole.

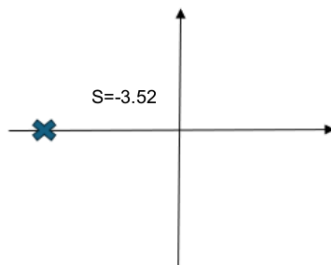


Figure 41 - Argand diagram $K=1$

From the T.F. the step response and root locus was created using matlab.

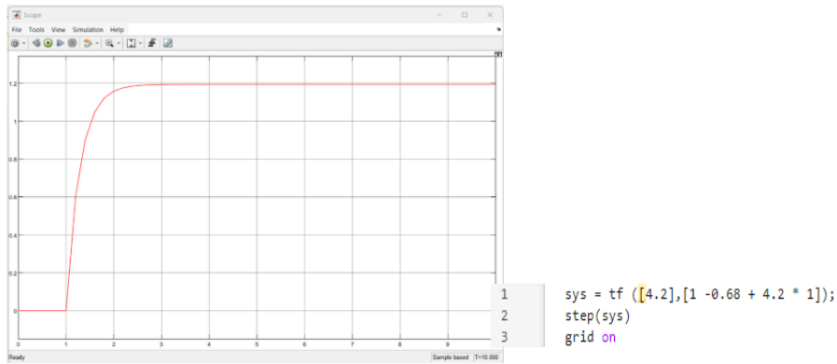


Figure 42 - Stable step response

The MATLAB code was also used to create the root locus. Root locus can be used in a closed loop system to show how the poles move in a complex plane.

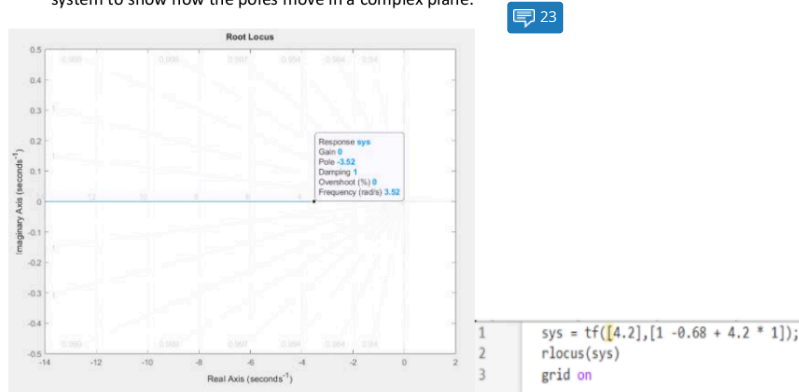


Figure 43 - Stable root locus

Rearranged to find the value of K to create a marginally stable circuit

$$S = 0.68 - 4.2k$$

$$4.2k = 0.68$$

$$k = \frac{0.68}{4.2} = 0.162$$

Equation 60 - Minimum value of K

$$\frac{4.2}{s - 0.68 + 4.2 \times 0.162}$$

Equation 61 - Marginally stable TF

This value was inputted into the feedback control.

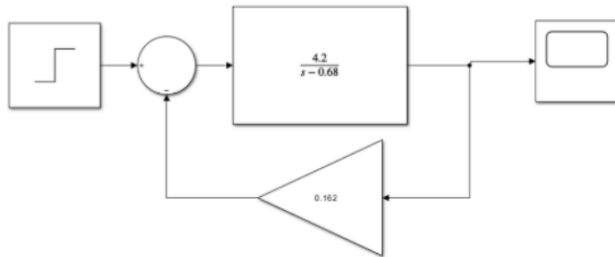


Figure 44 - Closed loop circuit with minimum value of K

The new transfer function was used on MATLAB to create a marginally stable circuit.

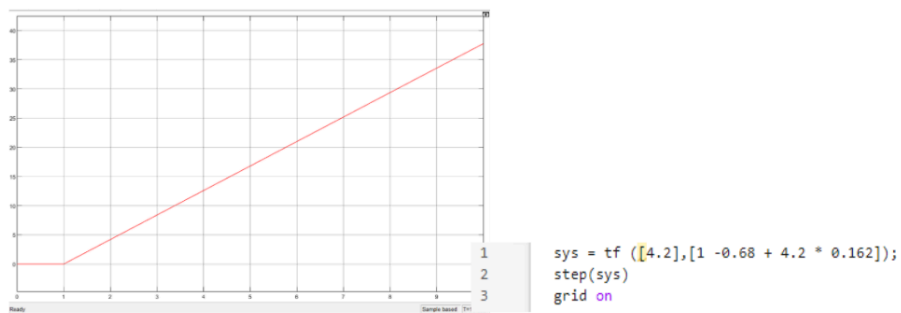


Figure 45 - Marginally stable step response

The root locus was also created on MATLAB. The pole is barely negative, near marginal stability, making the system stable but very slow.

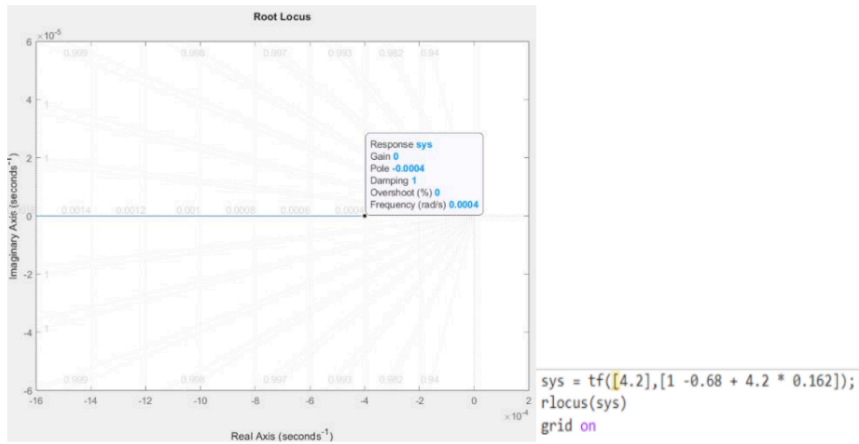


Figure 46 - Marginally stable root locus

The transfer function was used to create a root locus where the K value was either side of the value where the system was marginally stable to see how the impact it has on the poles.

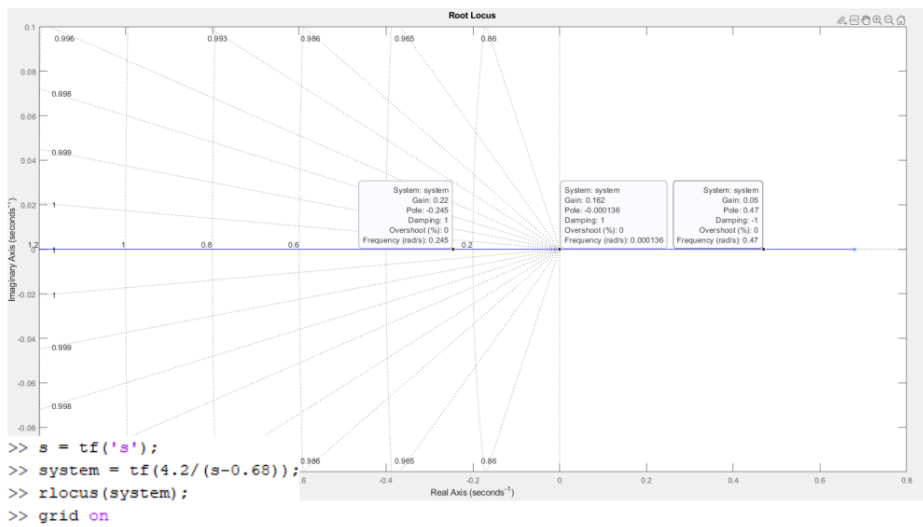


Figure 47 - Changing K values root locus

The results were recorded in the table below.

Gain (K)	Pole	Response
0.22	-0.245	Stable
0.162	0	Marginally Stable
0.05	0.47	Unstable

Table 8 - Changing gain for pole response

Gain (K) was added to stabilise the open loop circuit, without the feedback control the pole was plotted at 0.68 which is in the RH plane and is unstable. The pole placement determines if the system is stable or not so the pole must be in the LHS plane to insure stability.

The closed loop system where $K=1$ shows the pole as negative and plotted in the LHS plane meaning the system is stable (no oscillations). The step response shows rise in output until the steady state value is achieved.

The minimum value of K was calculated to create a marginally stable circuit. In a marginally stable circuit the pole (s) = 0, the graphs show the output does not exponentially grow and it does not decay either, the system is barely stable, and the slow response is because the pole is so close to 0. A small change in the pole will either make the system stable or unstable, if the feedback control is increased the pole will move further left and the system response would be faster and more stable, and a decrease would cause a move to the right and an unstable system as shown in the table and graphs.

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Task 10 - DC Motor Model Analysis

Given DC permanent magnet motor parameters:

Armature resistance (R_a) = 1.50 Ohms

Armature Inductance (L_a) = 0.2H

Rotor inertia (J) = 0.00035 Kg m^2

Friction coefficient (b) = 3.68×10^{-6} Nm / rad/s

Motor voltage constant (K_e) = 0.025V / rad/s

Motor torque constant (K_t) = 0.025Nm / A

Maximum armature voltage = 24V

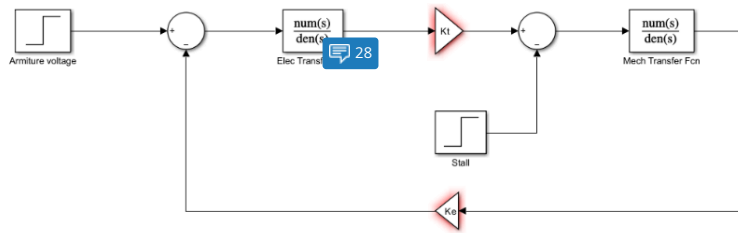


Figure 48 - DC motor model

To determine the transfer function when the disturbance is initially set to zero the DC motor can be shown by two first-order differential equations.

$$L \frac{di}{dt} + Ri = V - K_e \omega$$

Using Laplace TF can be seen as:

$$G(s) = \frac{1}{sLa + Ra} = \frac{1}{0.2s + 1.5}$$

Equation 62 - Electrical transfer function

$$J \frac{d\omega}{dt} + b\omega = K_t i - T_L$$

Using Laplace TF can be seen as:

$$T(s) = \frac{1}{sJ + b} = \frac{1}{0.2s + 1.5}$$

Equation 63 - Mechanical transfer function

After taking the Laplace transform and combining both dynamics the second order transfer function of the motor model with zero disturbance can be seen as:

$$H(s) = K \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2}$$

Using the given parameters can be derived from

$$H(s) = \frac{\frac{K_t}{La \times J}}{s^2 + s \left(\frac{b}{J} + \frac{Ra}{La} \right) + \frac{(Ra \times b + K_t \times K_e)}{La \times J}}$$

$$= \frac{\frac{0.025}{0.2 \times 0.00035}}{s^2 + s \left(\frac{3.68 \times 10^{-6}}{0.00035} + \frac{1.5}{0.20} \right) + \left(\frac{1.5 \times 3.68 \times 10^{-6} + 0.025 \times 0.025}{0.2 \times 0.00035} \right)}$$

$$H(s) = \frac{357.14}{s^2 + 7.51s + 9.01}$$

Equation 64 - Motor model transfer function

The following was calculated:

$$\omega_n = \frac{1}{\sqrt{LC}} = \sqrt{\left(\frac{Ra \times b}{La \times J} + \frac{K_t \times K_e}{La \times J} \right)} = \sqrt{\left(\frac{1.5 \times 3.68 \times 10^{-6}}{0.2 \times 0.00035} + \frac{0.025 \times 0.025}{0.2 \times 0.00035} \right)} = 3.0 \text{ rad/s}$$

Equation 65 - Natural frequency

$$T_m = \frac{K_t \times Va}{Ra} = \frac{0.025 \times 14}{1.5} = 0.233 \text{ Nm}$$

Equation 66 - Stall torque

$$\Omega_{NL} = \frac{Va}{K_e} = \frac{14}{0.025} = 560 \text{ rad/s}$$

Equation 67 - No load speed with no friction

$$NL\Omega = \frac{K_t \times Va}{b \times Ra + K_t \times K_e} = \frac{0.025 \times 14}{3.68 \times 10^{-6} \times 1.5 + 0.025 \times 0.025} = 555 \text{ rad/s}$$

Equation 68 - No load speed with friction

$$\Omega_L = \frac{Va - \frac{Ra T_L}{K_t}}{\frac{Ra \times b}{K_t}} + K_e = \frac{14 - \frac{1.5 \times 0.04}{0.025}}{\frac{1.5 \times 0.00035}{0.025}} + 0.025 = 464 \text{ rad/s}$$

Equation 69 - Loaded speed

$$\zeta = \frac{Ra \times J + La \times b}{2\sqrt{La \times J(Ra \times b + K_t K_e)}} = \frac{1.5 \times 0.00035 + 0.2 \times 3.68 \times 10^{-6}}{2\sqrt{0.2 \times 0.00035(1.5 \times 3.68 \times 10^{-6}) + 0.025 \times 0.025}} = 1.25$$

Equation 70 - Damping factor (overdamped)

The poles were located using the quadratic equation with the denominator from the TF

$$H(s) = \frac{357.14}{s^2 + 7.51s + 9.01}$$

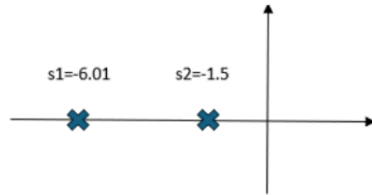
$$\sqrt{\frac{-7.51 \pm (7.51)^2 - 4(1)(9.01)}{2(1)}}$$

$$P1 = \frac{-7.51 - 4.51}{2} = -6.01 \text{ AND } P2 = \frac{-7.51 + 4.51}{2} = -1.5$$

Equation 71 - Poles of motor model



The poles were plotted on an argand diagram. The argand diagram shows both poles are real and negative which means the system is stable.



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Using the parameters a model of this motor system using MATLAB Simulink.

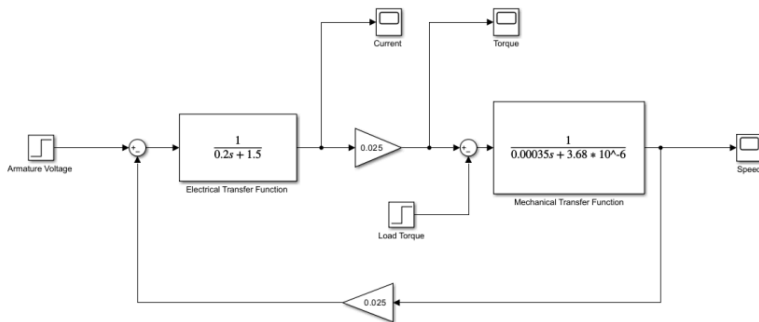


Figure 49 - DC motor model with load

Scopes were used to show the response of the motor whilst operating without load, the responses of speed, current and torque of the motor over 20 seconds with an armature voltage step input of 14Vdc with the disturbance set to zero. After 10 seconds the stall torque was applied.

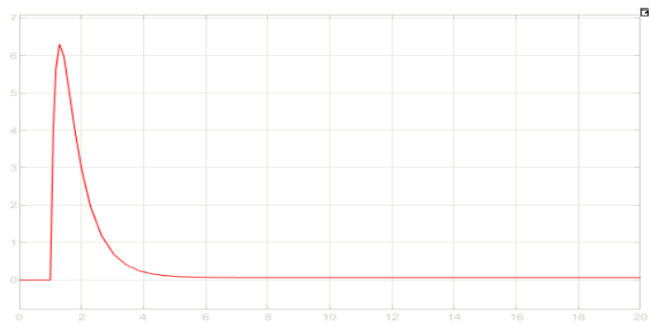


Figure 50 - Current scope with no load

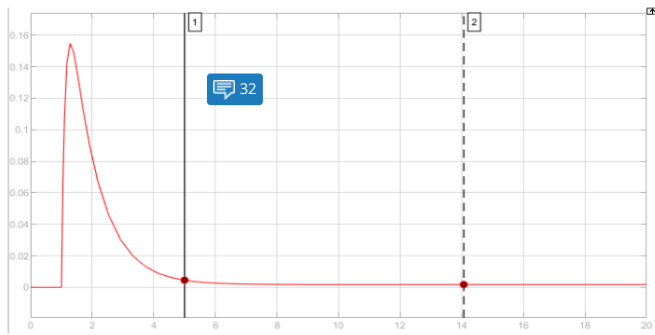


Figure 51 - Torque scope with no load

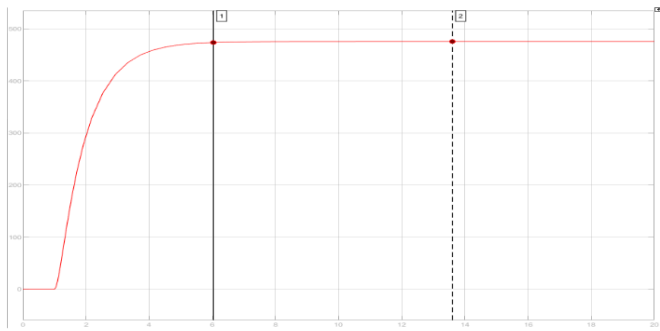


Figure 52 - Speed scope with no load

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A disturbance of 0.04Nm was introduced on MATLAB:

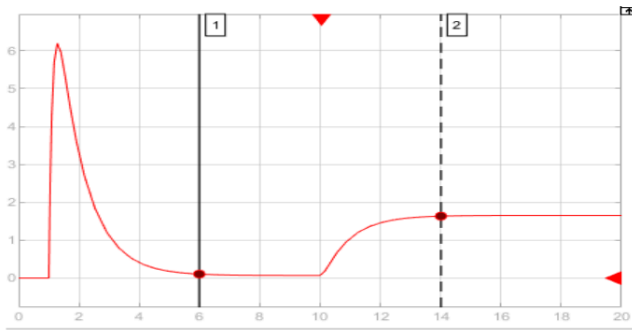


Figure 53 - Current scope with load

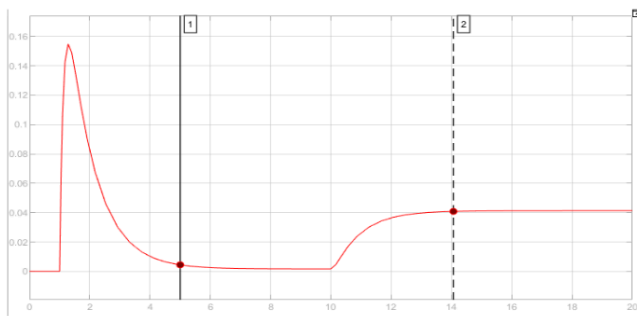


Figure 54 – Torque scope with load

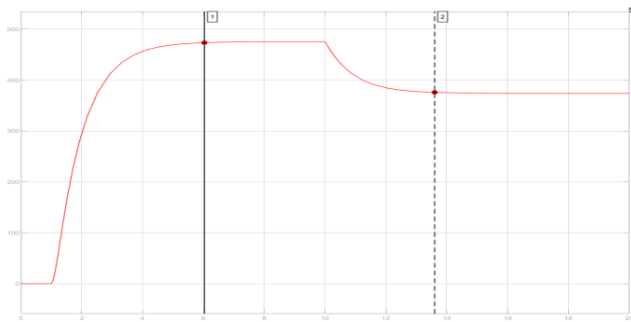


Figure 55 - Speed scope with load

Table shows predicted and simulated results with and without load.

Speed	Predicted rad/s	Simulated rad/s	Error rad/s
No load speed with friction	555	555.02	+0.02
Under load speed	464	464.09	+0.09

Table 9 - Motor speed with and without load

The transfer function was derived from the given parameters and used to find both poles which are real and negative which means the system is stable.

When there is no load, the motor is operating with low current as the torque demand is low. The speed rises smoothly until the steady state is achieved. When a disturbance of 0.04 is applied the current increases alongside the increased demand for torque to maintain the speed. The speed drops although the motor is working harder and will slowly settle at the slightly slower speed.



Task 11 - Proportional Speed Control System

The motor model was converted into a subsystem then an outer loop was added to include a proportional controller for speed control. Given values:

Armature voltage = ± 24

Setpoint = 140 rad/s

Speed feedback disturbance 0.03Nm.

The control system was replicated to feed the speed output signals to a 3-input scope.

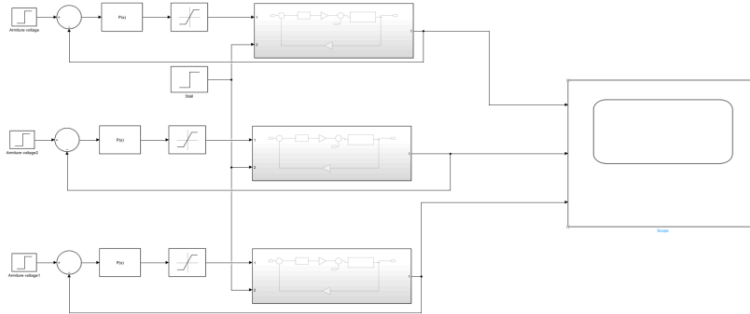


Figure 56 - P controller subsystems

The controller type (P) was selected and tuned to find the optimum Kp value. The Kp was manually adjusted above and below either side of the tuned value to analyse the response.

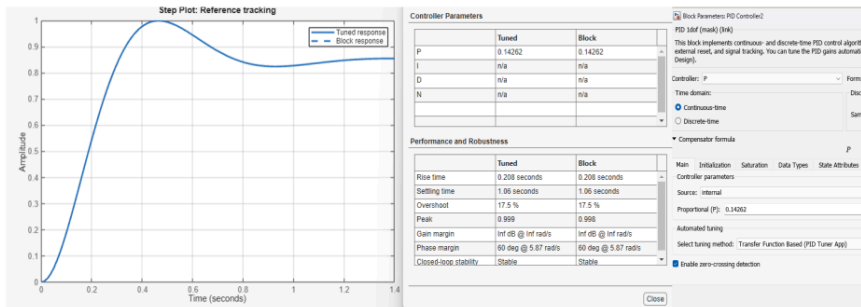


Figure 57 - Autotuned proportional gain

The Simulink simulation was used to measure the rise time, settling time and overshoot for the responses in figure.

The steady state error (SSE) was taken from the cursors values in figure which is the difference between the set point and the desired value.

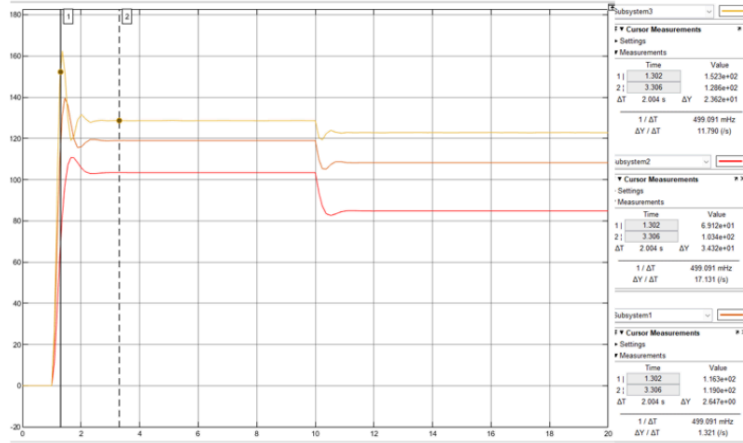


Figure 58 - P controllers' response

The simulation shows that when the K_p is increased the overshoot increases whilst the steady state error and the rise time decreases. There is also a slight increase in settling time which measures the speed the oscillations in a system will settle after the disturbance. This has the opposite effect for all parameters when the K_p is decreased.

The modified K_p results were recorded in table.

Proportional Gain (K_p modified)	Overshoot %	Rise Time (sec)	Settling Time (sec)	Steady State Error (rad/s)
Subsystem 1 Tuned (0.14262)	17.15	0.208	1.06	21
Subsystem 2 Low (0.07131)	7.33	0.333	1.04	37
Subsystem 3 High (0.28524)	30.1	0.133	1.08	12

Table 10 - K_p parameter results

For the P controller the tuned circuit is where the system is most balanced in terms of response time and steady state error. Although the SSE decreases when the K_p is increased, there can be more instability and oscillation in the system. The P controller responds to current error and alone cannot eliminate SSE.



Task 12 - Proportional-Integral Speed Control System

Each controller was converted to PI, the integral (I) responds to the accumulation of errors to eliminate SSE.

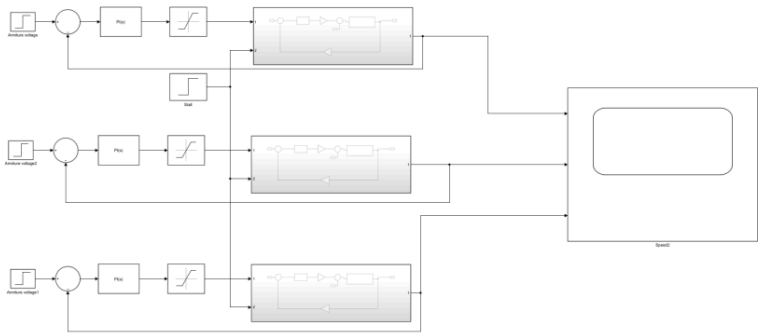


Figure 59 - PI controller subsystems

The first system was auto tuned to find the optimum Kd and Ki parameters.

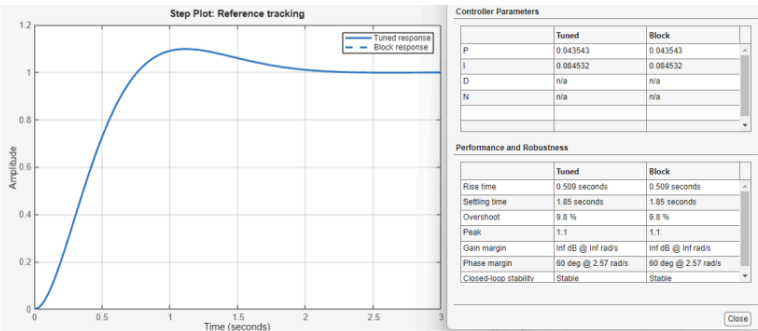


Figure 60 - Tuned PI parameters

Whilst the same value of Kp was used, a unique Ki value was used in all three systems to analyse the impact modifying Ki had on the systems.

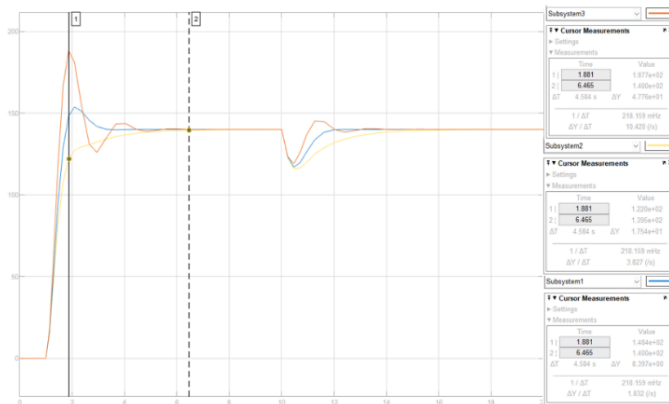


Figure 61 - PI controllers' response

When the K_i was increased the system responds faster, however this leads to increased overshoot and settling times.

The modified K_i results were recorded in table.

Proportional-Integral (K_i modified)	Overshoot %	Rise Time (sec)	Settling Time (sec)	Steady State Error (rad/s)
Subsystem 1 Tuned (0.084532)	9.8	0.509	1.85	0
Subsystem 2 Low (0.042266)	4.5	0.888	3.26	0
Subsystem 3 High (0.16906)	34.8	0.366	3.13	0

Table 11 - K_i parameter results

By converting to a proportional-integral speed control system error has been eliminated as the setpoint of 140 is achieved and the overshoot has been reduced, but when the system poorly tuned can lead to instability in the system response.



Task 13 - Proportional-Integral-Derivative Speed Control System

Each controller was converted to PID, the derivative (D) responds to the rate of change in error.

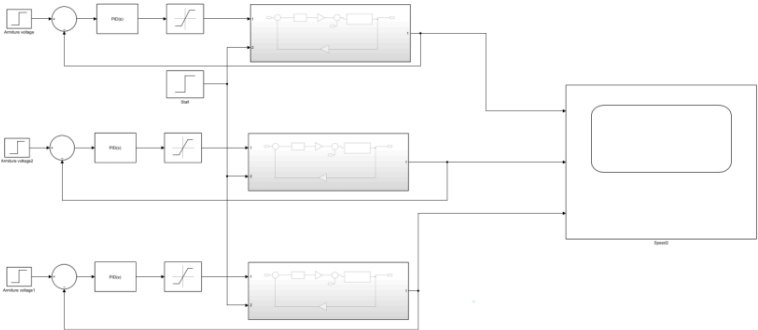


Figure 62 - PID controller subsystems

The first system was auto tuned to find the optimum Kp, Ki and Kd parameters.

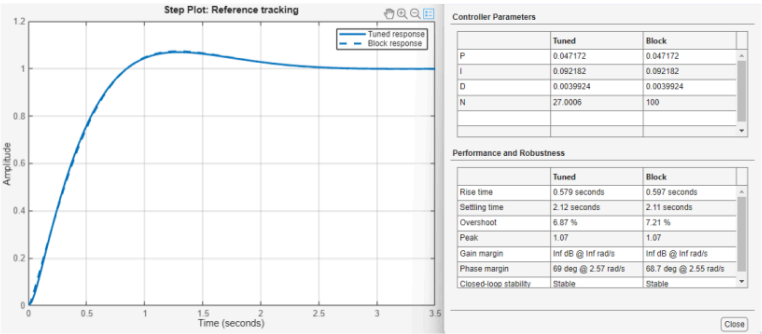


Figure 63 - Tuned PID parameters

This time the same value of Kp and Ki was used, and a unique Kd value was used in all three systems to analyse the effect of changing the Kd.

This time the same value of K_p and K_i was used and a unique K_d value was used in all three systems to analyse the affect of changing the K_d .

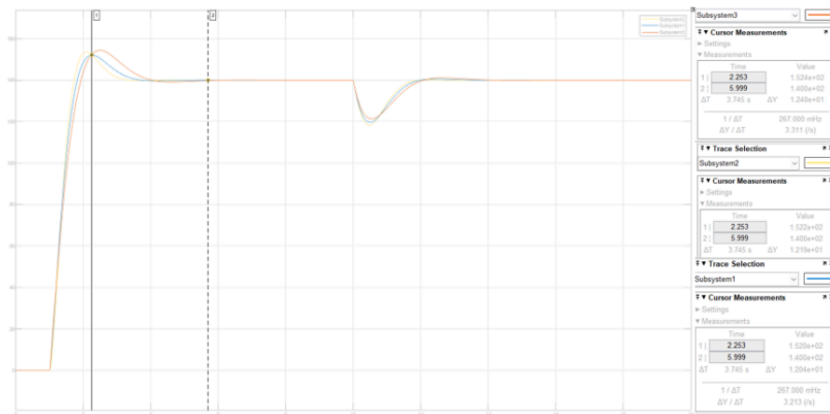


Figure 64 - PI controllers' response

When the derivative gain (K_d) is increased the overshoot decreases. This also leads to an increase in rise time and settling time.

The modified K_d results were recorded in table.

Proportional-Integral-Derivative (K_d modified)	Overshoot %	Rise Time (sec)	Settling Time (sec)	Steady State Error
Subsystem 1 Tuned (0.0039924)	6.87	0.579	2.12	0
Subsystem 2 Low (0.001)	9.8	0.505	1.84	0
Subsystem 3 High (0.01)	5.5	0.734	2.58	0

Table 12 - K_i parameter results

38

This controller also has no error as the set point is 140 due to the integral.

The PID controller responds to the rate of slope in the error and adjusts to minimize error and disturbance, so there is less error and overshoot which can lead to longer response times to achieve the smoother setpoint.

Task 14 - Controller Comparisons

Each controller was converted one last time to show a P, PI and PID controller.

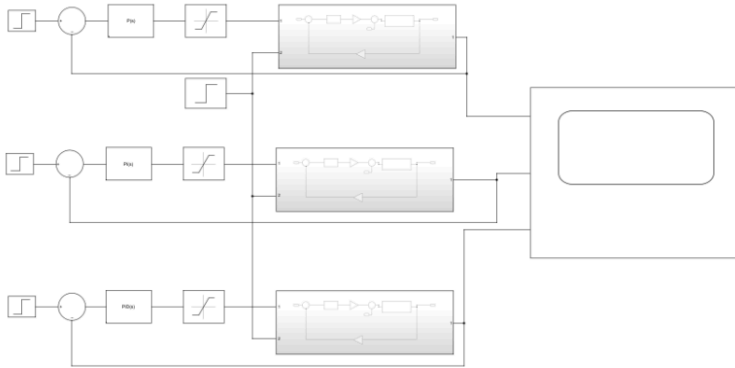


Figure 65 - P, PI, PID controllers

The response of each controller was shown on the same scope.

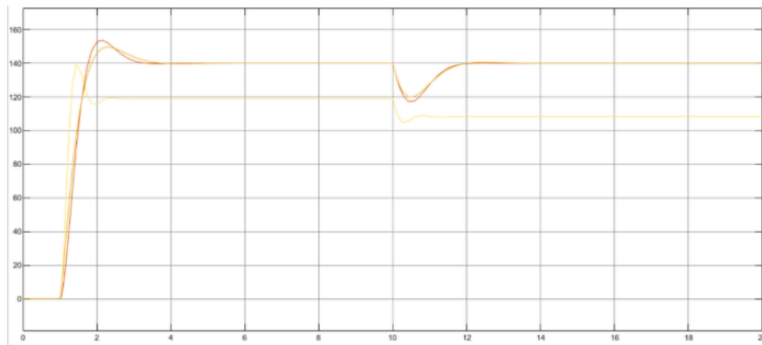


Figure 66 - Response of all tuned controllers

The results from all three tuned controllers were recorded in table.

Controller	Overshoot %	Rise Time (sec)	Settling Time (sec)	Steady State Error
P	17.15	0.2068	1.06	21
PI	9.8	0.509	1.85	0
PID	6.87	0.579	2.12	0

Figure 67 - Combined tuned controller parameters

The P controller takes the least time to settle and the fastest rise time, but it has the highest overshoot and the only one with steady state error.

The PI controller eliminated the steady state error as the integrator over time accumulates the error and increases the control signal to reduce the error to zero. The overshoot is also lower which would improve the efficiency and smoothness for the motors.

The PID benefits from all the actions of each of the controllers and additionally uses the derivative to predict how the future trend of the error to add damping, reduce overshoot and oscillation in the system. The settling time is slightly increased but is a result of a tighter control.



Task 15 - Conclusions and Recommendations

The first part of this assignment showed that the Laplace domain can be used with differential equations to find the time constant and the affect any input has on the transient response for first order reactive electrical circuits. The calculated results from the RL and the RC circuits matched the simulated results once the transfer function was used in MATLAB, as seen from the step response plots with an exponential rise and decay respectively.

The next part looked at the frequency performance again using the Laplace domain and the time constant and cutoff frequency to find the transfer function and to simulate the magnitude and phase functions of frequency and identify the different types of filters. The Bode plots showed the expected -cut-off frequencies and find where frequencies are attenuated, which followed the -20dB decade rule where the frequency moves at a factor of 10 for every 20dB (magnitude). The phase plot proved predictions of the phase shift for the high and low filters. The bode diagrams also proved that th6e circuits with the smaller resistor values will have a lower damping value and will have a sharper peak whilst the phase plots shift appears sharper as the resistor value decreases.

Finally the control system analysis was carried out using gain to ensure negative poles meaning the system is stable with no oscillation, which was proved using a step response. The DC motor model was constructed successfully using the given parameters and combining multiple systems to analyse the different types of controllers. The P controller was not precise enough as it does not use integral to reduce the error. The PI reduced the overshoot and had no error but had a slightly higher settling time. Using the PID was the smoothest and most balanced controller.

In the future it would be desirable to include hardware testing, after the simulations were completed to physically inspect and test the DC motor model and controllers.



Bibliography

Kuo, B.C. and Golnaraghi, F., 2017. *Automatic Control Systems*. 10th ed. New York: Wiley.

82/100

PAGE 1

PAGE 2

PAGE 3

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PAGE 8



Comment 1

This is good, I would suggest adding a labelled circuit diagram.



Comment 2

This part is too brief for the reader to gain an understanding of the closed loop system.

PAGE 9



Comment 3

Excellent work here and well laid out.

PAGE 10



Comment 4

Excellent results and graph.

PAGE 11



Comment 5

Good analysis.

PAGE 12



Comment 6

Excellent work here.

PAGE 13



Comment 7

Very good results and graph , laid out very professionally.



Comment 8

Good work.

PAGE 14

PAGE 15



Comment 9

Possible the pass/fail column is either unnecessary or should be clarified.



Comment 10

typo



Comment 11

Very good analysis.

PAGE 16

PAGE 17



Comment 12

Very good work in this task also.

PAGE 18



Comment 13

uF

PAGE 19

PAGE 20

PAGE 21

PAGE 22

PAGE 23



Comment 14

Again, very good work, maybe contextualise with a real world example of the phenomenon.

PAGE 24

PAGE 25

PAGE 26



Comment 15

Discussion on magnification?, Q factor and relevant theory missing here in this task.

PAGE 27

PAGE 28



Comment 16

x2 phase plots?!



Comment 17

A shame the magnitude plot with cursor measurements is not shown.

PAGE 29

PAGE 30



Comment 18

Written poorly, leaves the reader confused.



Comment 19

Rather brief and a lot of information is lacking.

PAGE 31



Comment 20

denominator



Comment 21

Good annotations and predictions.

PAGE 32



Comment 22

State the negative feedback equation $G/(1+GH)$

PAGE 33



Comment 23

Move because?



Comment 24

Requires further explanation.

PAGE 34

PAGE 35

PAGE 36



Comment 25

Stability and oscillations are mixed up here in this context.



Comment 26

Good work overall in this task.

PAGE 37



Comment 27

A circuit diagram would be useful here.



Comment 28

Expand these blocks to allow the TF to be shown.



Comment 29

Again the use of a circuit diagram would greatly enhance the understanding of the source of these equations.

PAGE 38



Comment 30

For extra marks the derivation should be shown.

PAGE 39



Comment 31

Good work here.

PAGE 40



Comment 32

Cursor could have placed to measure peak torque?



Comment 33

You should show the actual cursor values.

PAGE 41



Comment 34

All your response graphs are missing measured values!

PAGE 42



Comment 35

Correct analysis, however lacking a table of results.

PAGE 43

PAGE 44



Comment 36

Excellent work which is clearly set out.

PAGE 45

**Comment 37**

Excellent work.

**Comment 38**

A good application of method and well structured.

**Comment 39**

Excellent work.

**Comment 40**

A reasonable and fair conclusion which sums up the work well.

GRADING FORM: NEW CSG-RUBRIC

LUKE BOWEN

82

1. ENGAGEMENT WITH LITERATURE

NA

0

2. KNOWLEDGE AND UNDERSTANDING

Excellent detailed knowledge is shown in the report and the work is coherent, accurate and detailed. There are some areas for improvement as commened. 24/30

24

3. COGNITIVE AND INTELLECTUAL



Analysis is sound and critical of concepts with good data in the most part to back up the arguments. 24/30

24

4. PRACTICAL APPLICATION



Advanced application of techniques used in the matlab and simulink tasks. Mostly well annotated and presented response graphs, the calculations are good and the whole piece of work shows a very good application of the required techniques. 26/30

26

5. TRANSFERABLE SKILLS



Communication is professional, confident, and displays a high level of fluency. well laid out and clear throughout. Some areas for improvement as commented. 8/10

8