

1909751

by Alex Williams

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

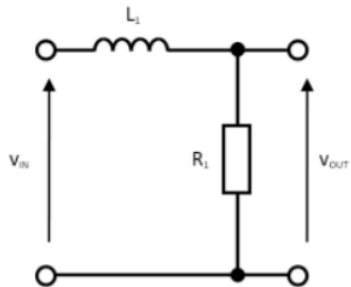


Figure 1: Task 1 RL circuit

The following values were chosen for the components in the circuit shown in Figure 1.

$$R1 = 20\Omega$$

$$L1 = 0.2H$$

$$\tau = \frac{L}{R} = \frac{0.2}{200} = 0.01 \text{ Seconds}$$

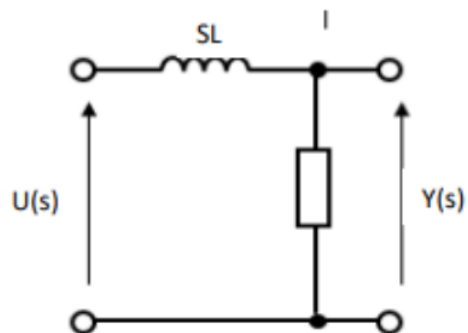


Figure 2: Laplace model

Figure 2 shows the Laplace model of the circuit with the transfer function as followed below.

$$\frac{Y(s)}{U(s)} = \frac{1}{sL + 1} = \frac{1}{\tau + 1}$$

$$\text{Time response } y(t) = 1 - e^{-t/\tau}$$

New to MATLAB? See resources to

```
>> num = [1];  
>> den = [0.01 1];  
>> step(num,den);  
grid
```

Figure 3: Task 1 MATLAB code

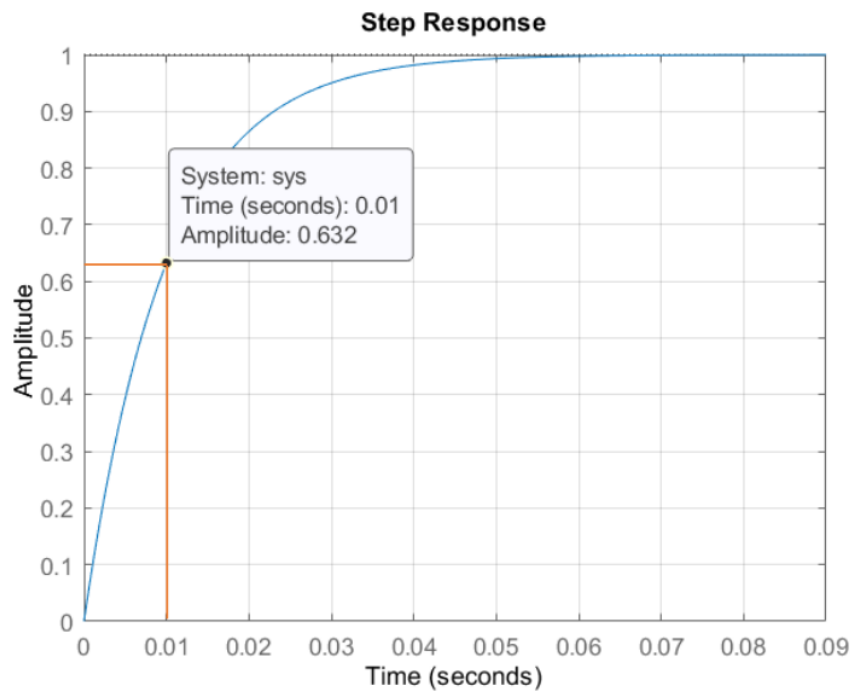


Figure 4: Task 1 step response

	Theory	Simulation
Time Constant	0.01	0.01

Table 1: RL Transient Results

Tau is one time constant. It can be measured on a graph when the amplitude is at 63.2% of the exponential growth in a transient. This comes from the formula $y(t) = 1 - e^{-t/\tau}$ as when $t=\tau$ the answer to the formula comes out at 63.2%. Theoretically it can be calculated by dividing the inductor



by the resistor using the formula $\tau=L/R$. Both my theory results and simulation results are the same. As a transient, at 5τ the amplitude is 1.

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

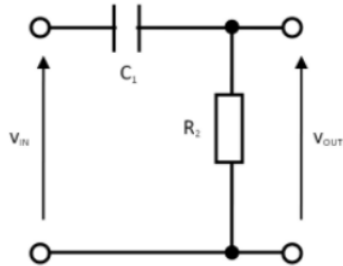


Figure 5: Task 2 RC circuit

The following values were chosen for the components in the circuit shown in Figure 5

$$R_2 = 300\Omega$$

$$C_1 = 20\mu\text{F}$$

$$\tau = C \times R = 20 \times 10^{-6} \times 300 = 0.006 \text{ seconds}$$

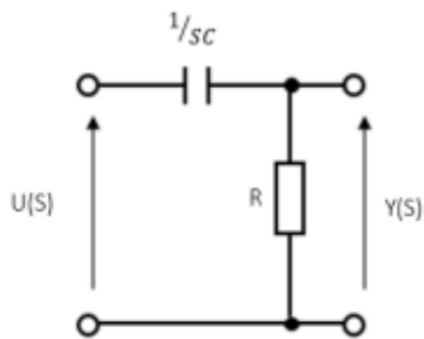


Figure 6: Laplace model

Figure 6 shows the Laplace model for a RC circuit with the transfer function as followed below.

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

A step response simulation was carried out on MATLAB using the code in Figure 7 and the response is shown in Figure 8.

```
>> num = [0.006 0];
>> den = [0.006 1];
>> step(num,den);
grid
```

Figure 7: Task 2 MATLAB code

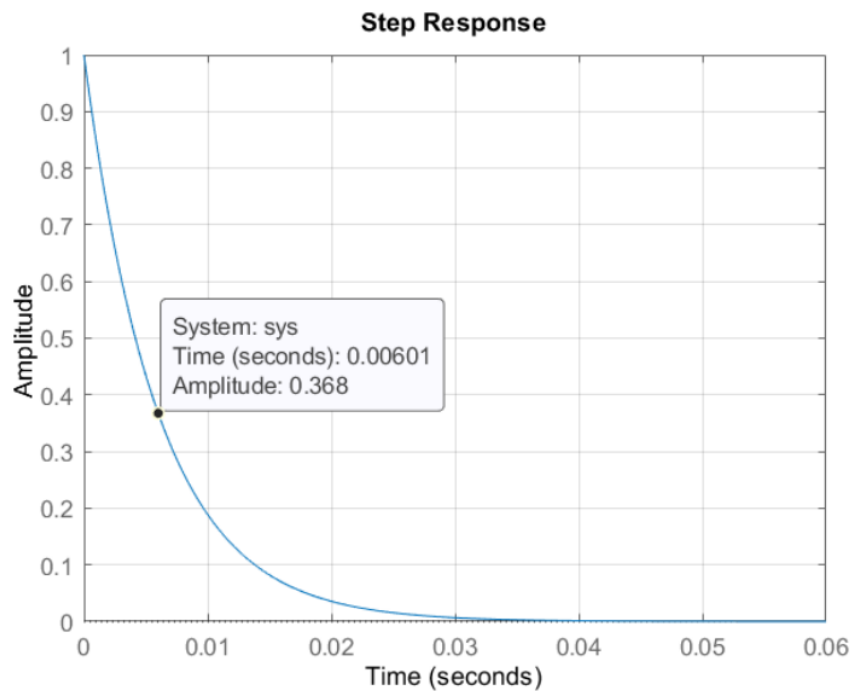


Figure 8: RC circuit step response

	Theory	Simulation
Time Constant	0.006	0.006

Table 2: RC Transient Results

The simulated and theory results are the same. The amplitude is also should be at 0.362 at 1 time constant as explained in task 1. Due to human error on highlighting the close values on the simulation it is showing a 0.006 discrepancy which is down to human error on annotation and not theory or simulation.

Task 3 – Frequency Performance Analysis of a First Order RL Electrical Circuit

Using the same circuit (Figure 1) and values as task 1. The transfer function would be found using the potential divider rule. The following process would be followed.

$$\text{Transfer function: } Y(s) = \frac{R}{sL + R} X(s) = \frac{20}{s0.2 + 20} X(s)$$

$$\therefore \frac{Y(s)}{X(s)} = \frac{\frac{R}{L}}{s + \frac{R}{L}} = \frac{\frac{20}{0.2}}{s + \frac{20}{0.2}}$$

$$H(s) = \frac{\omega_C}{s + \omega_C} = \frac{1}{s + 100}$$

This can be compared to the transfer function of a low pass filter. ω_C is the cut off frequency which can be calculated by dividing the inductance by the resistance.

$$\omega_C = \frac{1}{\tau} = \frac{1}{0.01} = 100 \text{ rad/s}$$

$$\theta(j\omega) = -\tan^{-1}\left(\frac{\omega L}{R}\right)$$

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

This can then be put into MATLAB to be compared against simulation. Cut off frequency is -3dB so at -3dB the expected out is 100 rad/s and a phase shift of -45° . The roll off which is the difference in magnitude per decade should be -20dB per decade as it is first order.

```
>> num=[100];
>> den=[1 100];
>> bode(num,den)
>> grid
```

Figure 9: Task 3 MATLAB code

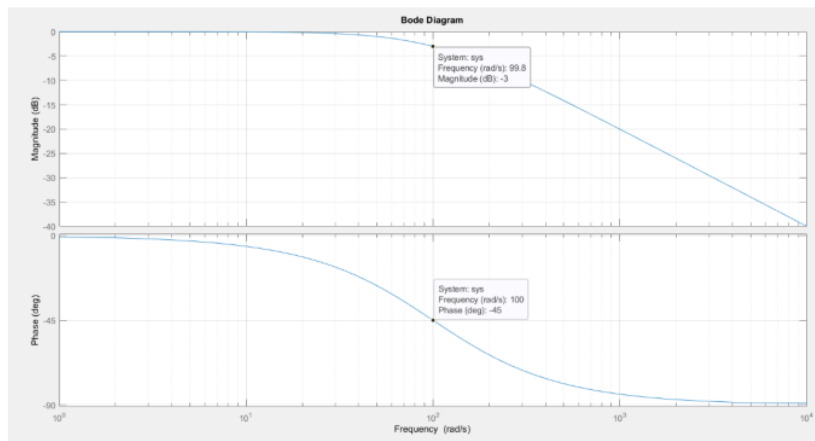


Figure 10: Task 3 Bode plot for frequency response

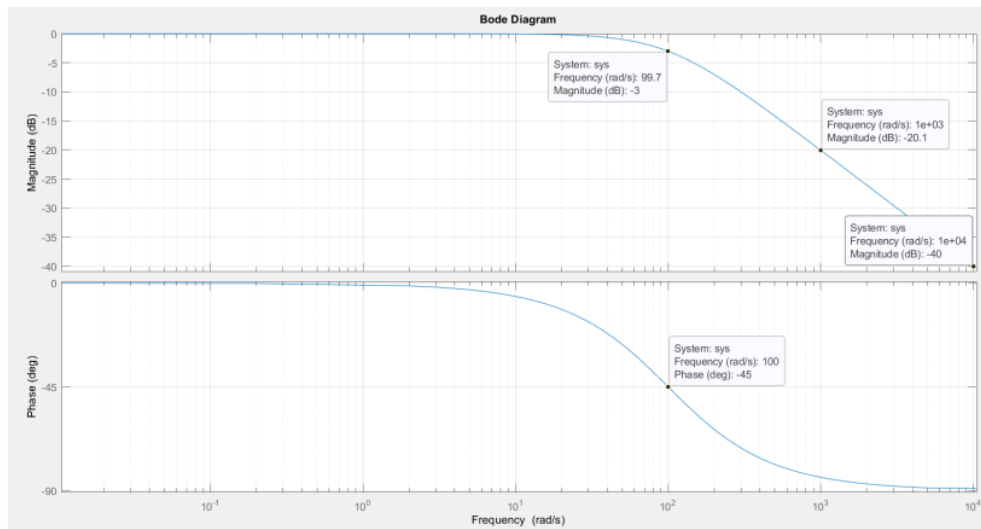


Figure 11: Task 3 Bode plot for frequency response

	Calculated	Simulated
Cut off frequency(rad/s) at -3dB	100	99.7
Magnitude difference per decade	-20dB	-19.9dB
Phase shift	-45°	-45°

The results are very accurate when compared to the simulation. There are slight discrepancies in the roll off and in the cut off frequency. However, these are very marginal to the point they would not have any significant impact.

Task 4 – Frequency Performance Analysis of a First Order RC Electrical Circuit

Using the same circuit (Figure 5) and values as task 2.

The time constant is the same as task two calculated by:

$$\tau = C \times R = 20 \times 10^{-6} \times 300 = 0.006 \text{ seconds}$$

$$\text{The cut off is calculated by using } \omega_c = \frac{1}{\tau} = \frac{1}{0.006} = 166.6 \text{ rad/s}$$

$$\text{The transfer function is } H(s) = \frac{s}{s + \omega_c} = \frac{s}{s + 166.6}$$

The phase shift is calculated as followed:

$$\theta(j\omega) = \tan\left(\frac{1}{\omega RC}\right)$$

$$90 - (\tan - 1(\omega RC)) = 90^\circ - 45^\circ = 45^\circ$$

```
>> num=[1 0];
>> den=[1 166.6];
>> bode(num,den)
>> grid
```

Figure 12: Task 4 MATLAB code

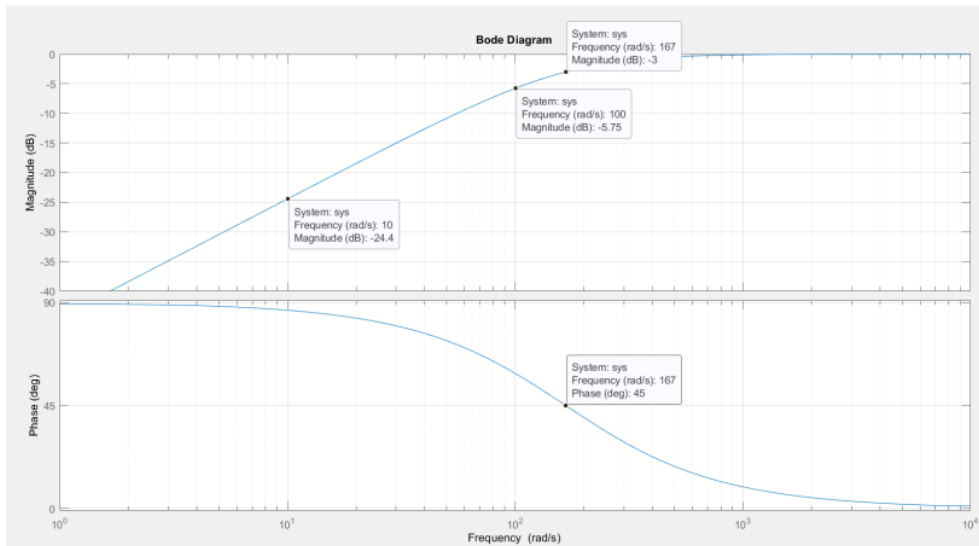


Figure 13: Task 4 Bode plot for frequency response

	Calculated	Simulated
Cut off frequency(rad/s) at -3dB	166.6	167
Magnitude difference per decade	-20dB	-18.65dB
Phase shift	45°	45°

The results are yet again very similar and are expected. The cut off frequency would match if rounded to the same decimal place. The difference in not rounding could be MATLAB is not displaying to a decimal place or the discrepancy is with the calculation vs simulation. However, yet again a 0.4 rad/s discrepancy would have no significant impact.



Task 5 – Transient Performance Analysis of a Second Order Series Electrical Circuit

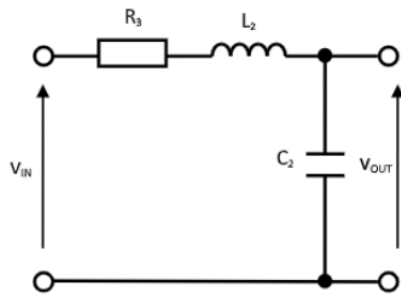


Figure 14: RLC Series Circuit

$$R_3 = 375\Omega$$

$$L_2 = 0.2\text{H}$$

$$C_2 = 35\mu\text{F}$$

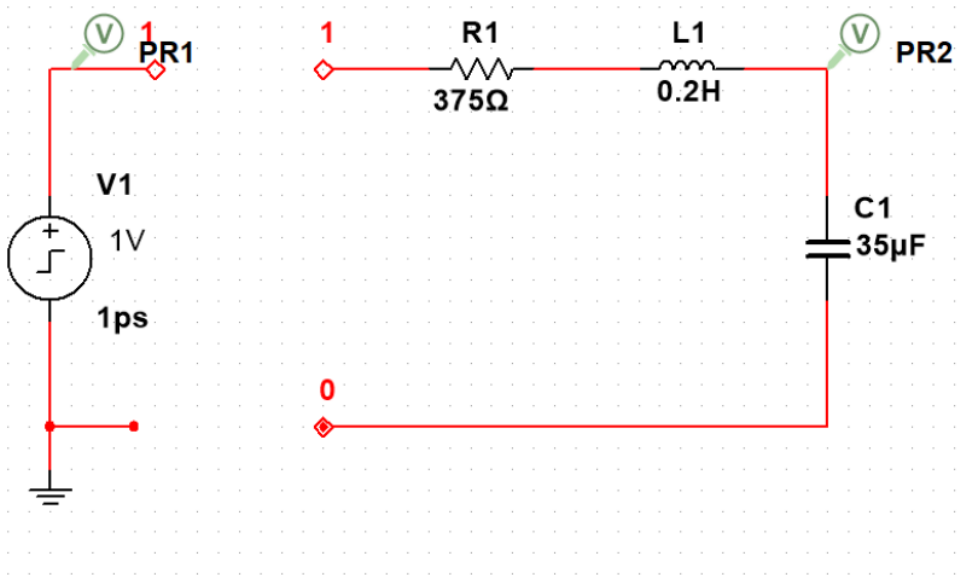


Figure 15: RLC circuit with initial values

Laplace model, $H(s) = \frac{\frac{1}{LC}}{s^2 + s\frac{R}{L} + \frac{1}{LC}}$. This can be compared to the second order transfer function which

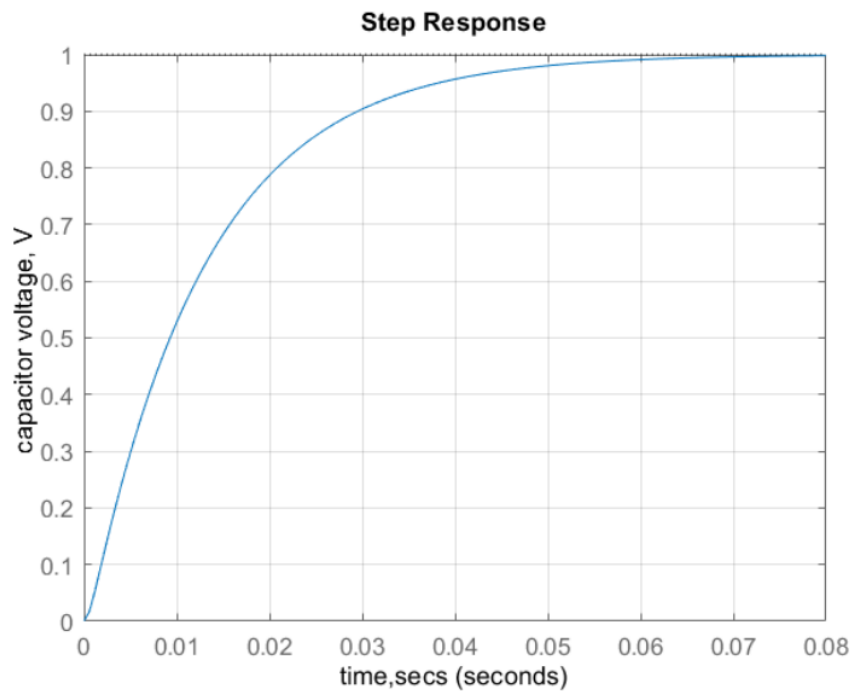
$$\text{is } H(s) = \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$\omega_n = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.2 \times (35 \times 10^{-6})}} = 377.96 \text{ rad/s}$$

$$\text{Sigma}, \Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{375}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 2.48 \text{ System is overdamped}$$

$$H(s) = \frac{142853.762}{s^2 + 1874.682s + 142853.762}$$

```
>> %code for second order transfer function
>> %RLC response to step input
>> % R=375, L=0.2, C=35u
>> num = [142853.762];
>> den = [1 1874.682 142853.762];
>> step(num,den);
grid;
>> xlabel ('time,secs');
>> ylabel ('capacitor voltage, V');
```



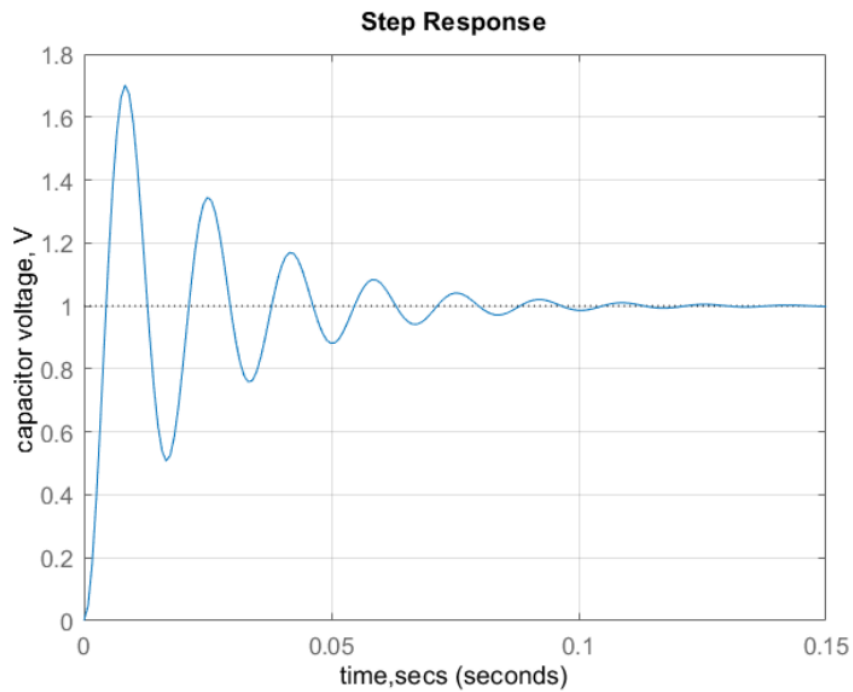
Value of R is changed to 17Ω.

$$R = 17\Omega$$

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{17}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0.112 \text{ System is underdamped}$$

$$H(s) = \frac{142853.762}{s^2 + 84.663s + 142853.762}$$

```
>> %Second order transfer function
>> %RLC response to step input
>> %R=17, L=0.2, C=35U
>> num = [142853.762];
>> den = [1 84.663 142853.762];
>> step(num,den);
grid;
```



Value of R is changed to 151Ω.

R = 151Ω

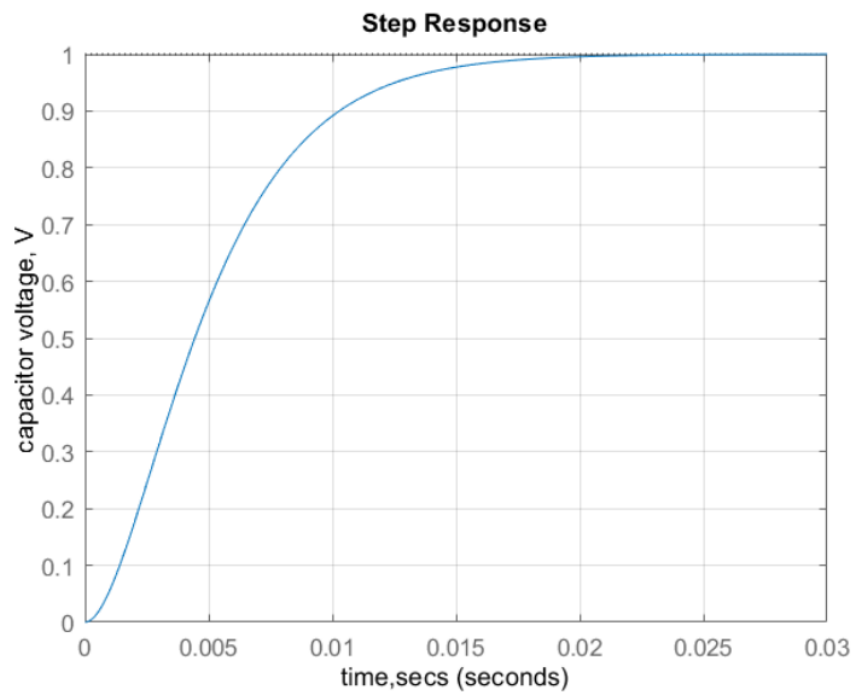
$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{151}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0.999 \text{ System is critically damped}$$

$$H(s) = \frac{142853.762}{s^2 + 755.16408s + 142853.762}$$

```

>> %second order transfer function
>> %RLC Circuit response to step input
>> %R=151 L=0.2 C=35u
>> num = [142853.762];
>> den = [1 755.16408 142853.762];
>> step(num,den);
>> grid;
>> xlabel ('time,secs');
>> ylabel ('capacitor voltage, V')
>> |

```



Value of R is changed to 2Ω .

$R = 2\Omega$

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{2}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0.01 \text{ System is not damped}$$

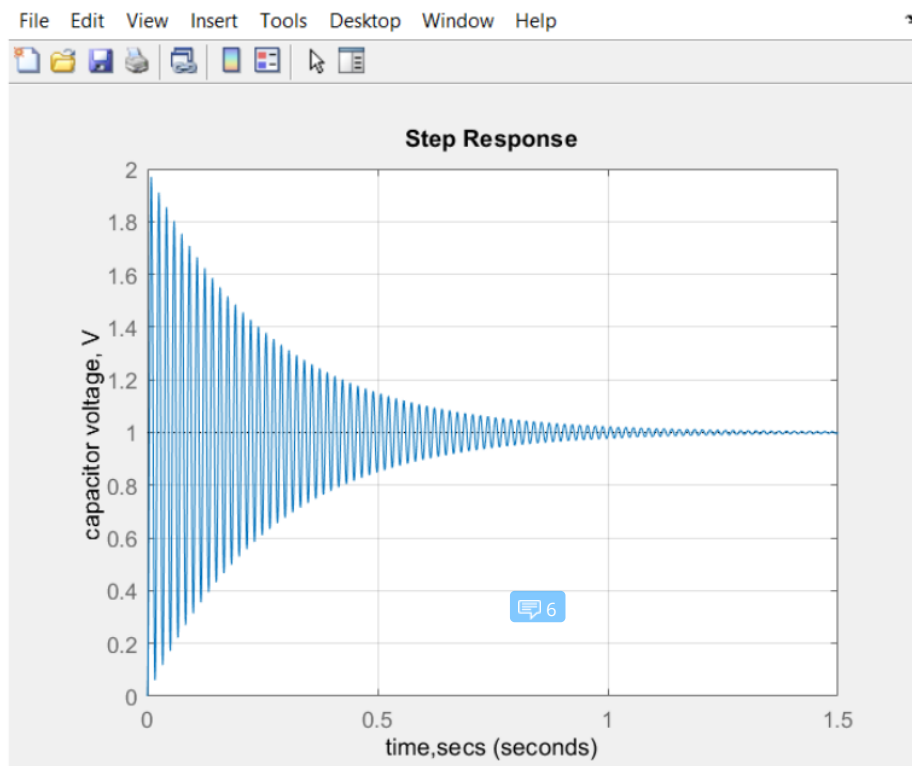


$$H(s) = \frac{142853.762}{s^2 + 7.5592s + 142853.762}$$

```

>> %Second Order Transfer Function
>> %RLC Series Response to set input
>> %R=2 Ohm L=0.2H C=35uF
>> num=[142853.762];
>> den=[1 7.5592 142853.762];
>> step(num,den);
>> grid;
>> xlabel ('time,secs');
>> ylabel ('capacitor voltage, V')

```



Resistance (Ω)	Σ	Type of damping
375	2.48	Overdamped
17	0.112	Underdamped
151	0.999	Critically damped
2	0.01	No damping

Table 3: Task 5 results

The theory and simulation match which proves the calculation are correct. It also shows that altering the resistance will change the outcome of the damping factor. The relationship between the two is that as the resistance is lowered the damping factor also decreases.

You have worked this out correctly, well done!

Task 6 – Transient Performance Analysis of a Second Order Parallel Electrical Circuit

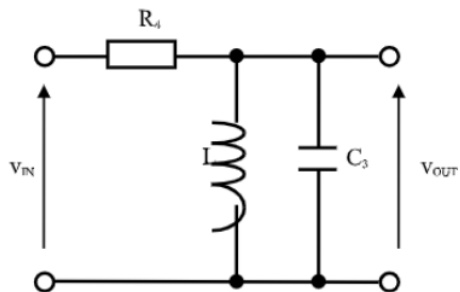
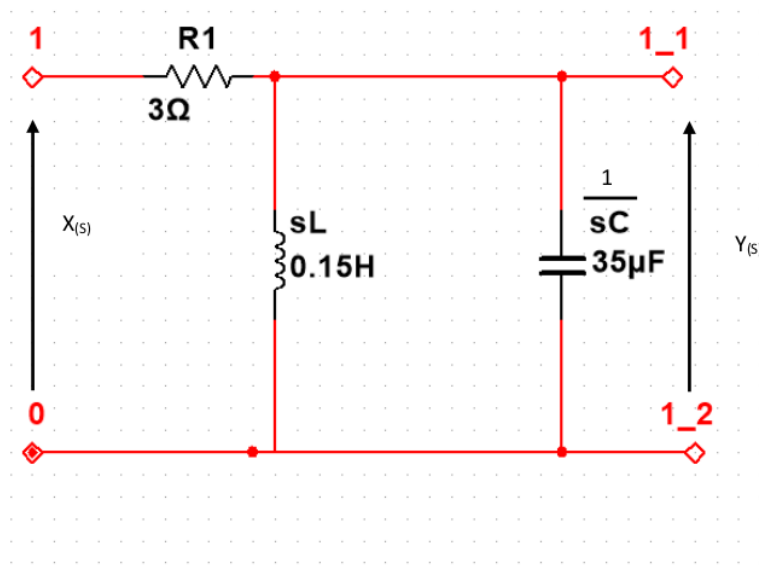


Figure 16: RLC Parallel Circuit

$$R = 3\Omega$$

$$L = 0.15\text{H}$$

$$C = 35\mu\text{F}$$



The potential divider rule is required:

$$Y(s) = \frac{Z_P(s)}{R + Z_P(s)} \times X(s) \quad Z_P \text{ is the parallel impedance of } sL \text{ and } \frac{1}{sC}$$

$$Z_P(s) = \frac{sL \times \frac{1}{sC}}{sL + \frac{1}{sC}} = \frac{sL}{s^2 LC + 1}$$

The transfer function can then be found by substituting back into the potential divider.

$$Y(s) = \frac{\frac{sL}{(s^2 LC + 1)}}{R + \frac{sL}{(s^2 LC + 1)}} \times X(s)$$

$$\frac{Y(s)}{X(s)} = \frac{sL}{R(s^2 LC + 1) + sL}$$

Divide top and bottom by RLC

$$H(s) = \frac{s \times \frac{1}{RC}}{s^2 + \frac{1}{RC} + \frac{1}{LC}}$$

This can be compared to the second order transfer function which is $H(s) = \frac{k\omega n^2}{s^2 + 2\Sigma\omega n s + \omega n^2}$

$$\omega n = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.15 \times (35 \times 10^{-6})}} = 436.436 \text{ rad/s}$$

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{3}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.15}} = 0.023 \quad \text{System is not damped.}$$

$$H(s) = \frac{s \times \frac{1}{3 \times 35 \times 10^{-6}}}{s^2 + \frac{1}{3 \times 35 \times 10^{-6}} + \frac{1}{0.2 \times 35 \times 10^{-6}}} = \frac{s \times 9523.810}{s^2 + 9523.810 + 142857.143}$$

```
>> %RLC Parallel Response
>> %L=0.15 C=35uF
>> %No damping R=3
>> num=[9523.810 0];
>> den=[1 9523.810 142857.143];
>> step(num,den);
>> grid
>> xlabel ('time,secs');
>> ylabel ('capacitor voltage, V')
```

Figure 17: Task 6 step response MATLAB code - No damping

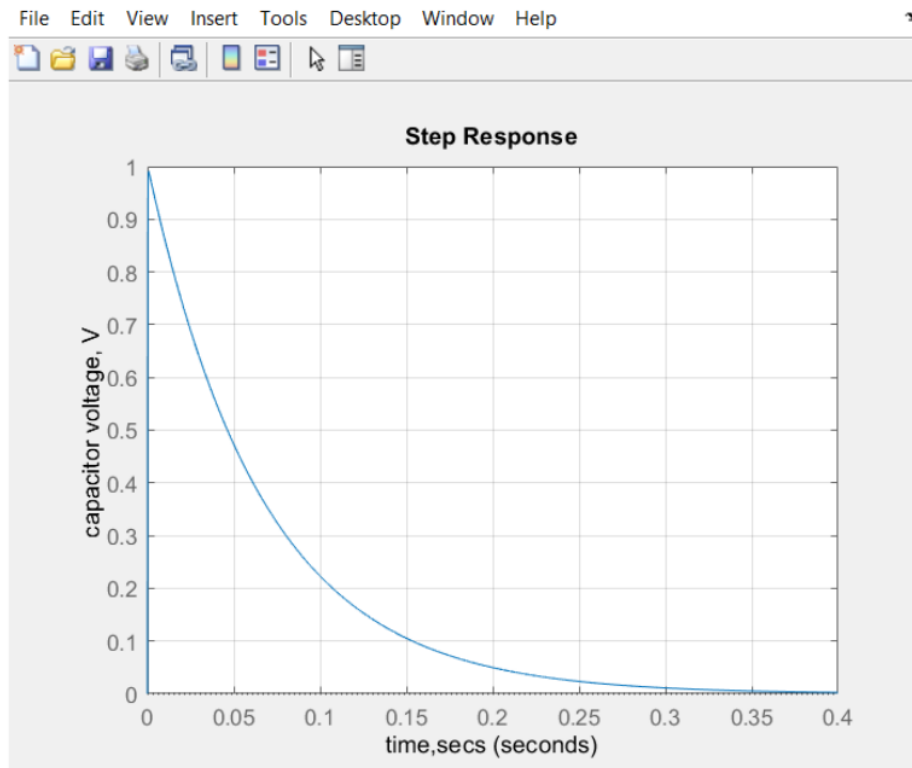


Figure 18: Task 6 step response - No damping

Change value of R to 375Ω

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{375}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.15}} = 2.864 \text{ System is over damped.}$$

$$H(s) = \frac{s \times \frac{1}{375 \times 35 \times 10^{-6}}}{s^2 + \frac{1}{375 \times 35 \times 10^{-6}} + \frac{1}{0.2 \times 35 \times 10^{-6}}} = \frac{s \times 76.19}{s^2 + 76.19 + 142857.143}$$

```
>> %RLC Parallel Response
>> %L=0.15 C=35uF
>> %Overdamped R=375
>> num=[76.19 0];
>> den=[76.19 142857.143];
>> step(num,den);
>> grid
>> xlabel('time,secs');
>> ylabel('capacitor voltage, V')
```

Figure 19: Task 6 step response MATLAB code - Overdamped

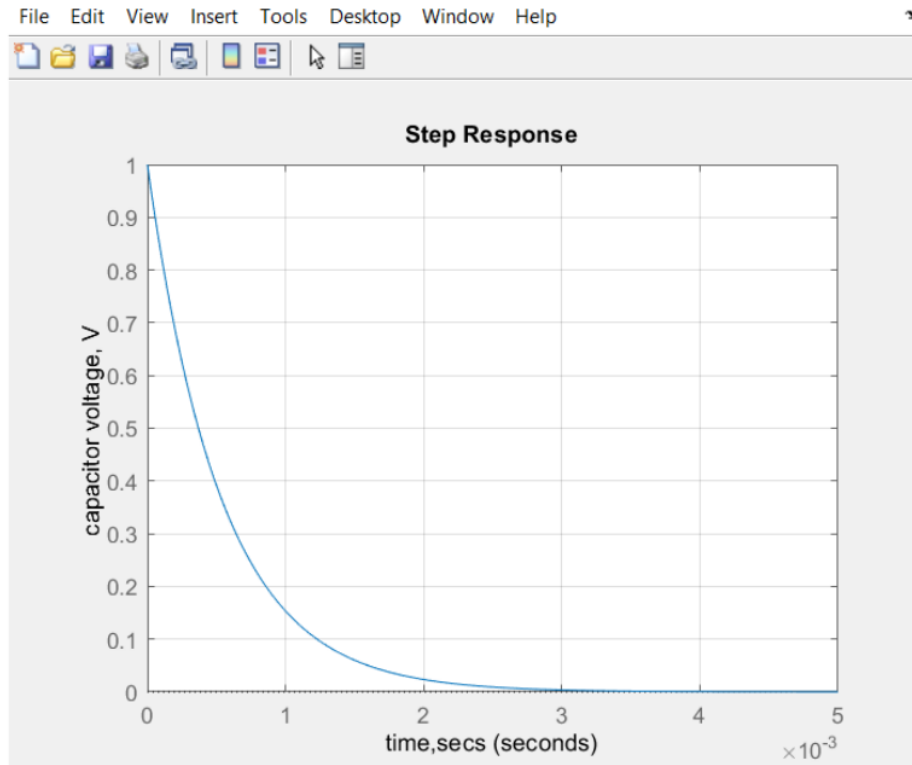


Figure 20: Task 6 step response - Overdamped

Value of R is changed to 17Ω.

$$R = 17\Omega$$

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{17}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0.112 \text{ System is underdamped}$$

$$H(s) = \frac{s \times \frac{1}{17 \times 35 \times 10^{-6}}}{s^2 + \frac{1}{17 \times 35 \times 10^{-6}} + \frac{1}{0.2 \times 35 \times 10^{-6}}} = \frac{s \times 1680.672}{s^2 + 1680.672 + 142857.143}$$

```

>> %RLC Parallel Response
>> %L=0.15 C=35uF
>> %Underdamped R=17
>> num=[1680.672 0];
>> den=[1680.672 142857.143];
>> step(num,den);
>> grid
>> xlabel ('time,secs');
>> ylabel ('capacitor voltage, V')

```

Figure 21: Task 6 step response MATLAB code – Underdamped

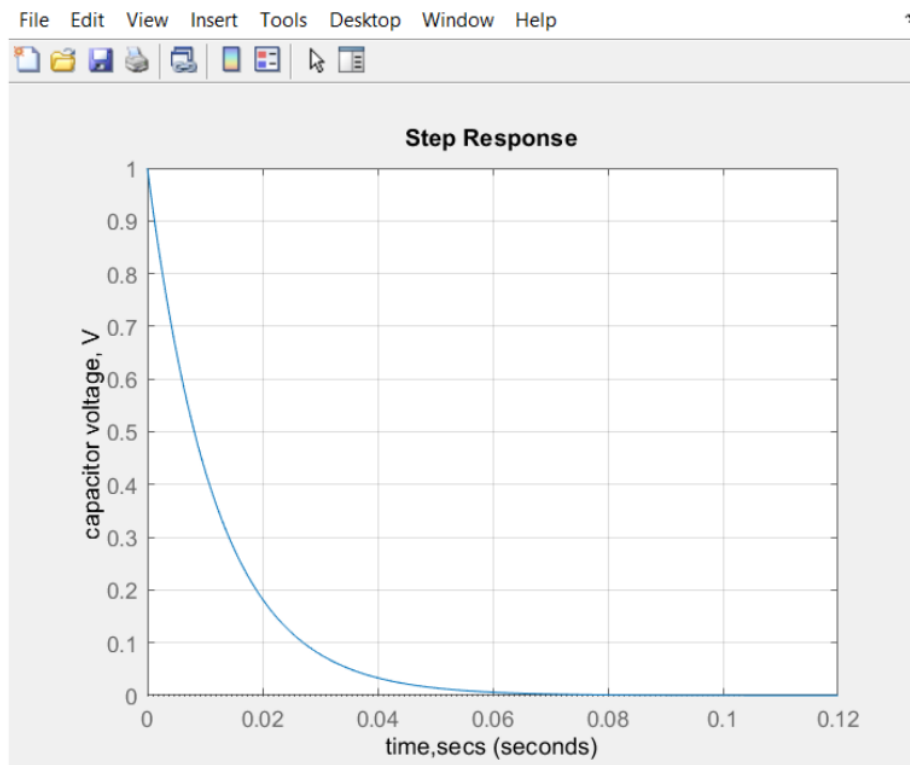


Figure 22: Task 6 step response - Underdamped

Value of R is changed to 151Ω.

R = 151Ω

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{151}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0.999 \text{ System is critically damped}$$

$$H(s) = \frac{s \times \frac{1}{151 \times 35 \times 10^{-6}}}{s^2 + \frac{1}{151 \times 35 \times 10^{-6}} + \frac{1}{0.2 \times 35 \times 10^{-6}}} = \frac{s \times 189.215}{s^2 + 189.215 + 142857.143}$$

```
>> %RLC Parallel Response
>> %L=0.15 C=35uF
>> %Critically damped R=151
>> num=[189.215 0];
>> den=[189.215 142857.143];
>> step(num,den);
>> grid
>> xlabel ('time,secs');
>> ylabel ('capacitor voltage, V')
```

Figure 23: Task 6 step response MATLAB code – Critically damped

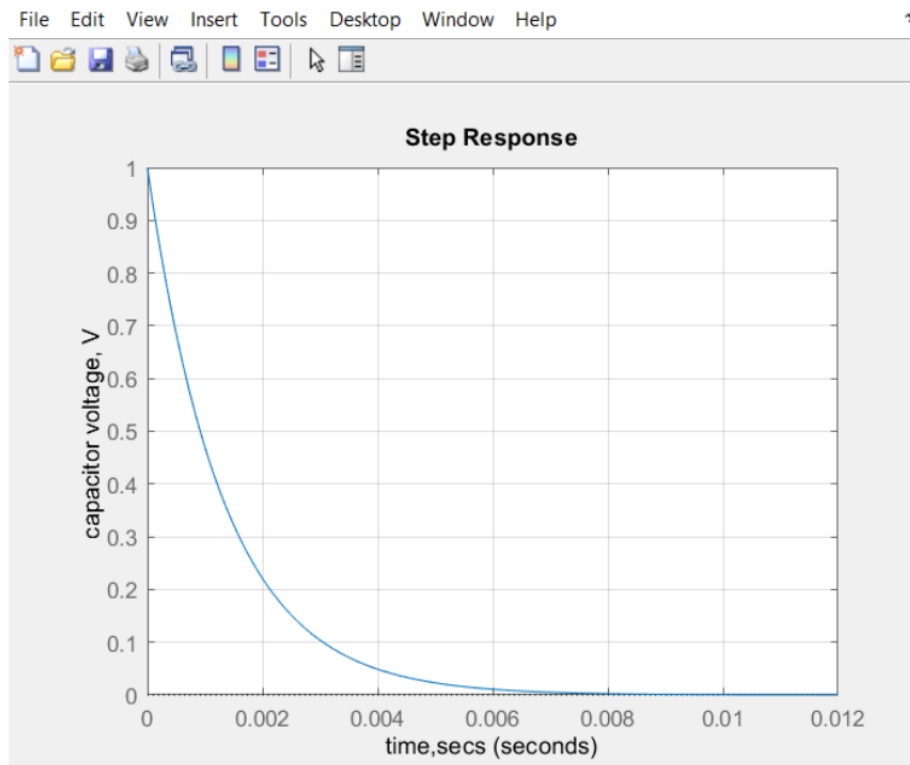


Figure 24: Task 6 step response - Critically damped

Resistance (Ω)	Σ	Type of damping
3	0.023	Not damped
375	2.864	Overdamped

17	Incorrect	0.112	Underdamped
151		0.999	Critically damped

Table 4: Task 6 results

The theory matches the simulation proving the calculations are correct. The relationship between the resistance and the damping is the same in both series and parallel circuits. Therefore, the relationship is the same as task 5.

Task 7 – Frequency Performance Analysis of a Second Order Series Electrical Circuit

Using the same circuit in task 5 (Figure 14) and the same values. The frequency performance will be analysed.

$$R3 = 375\Omega$$

$$L2 = 0.2H$$

$$C2 = 35\mu F$$

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

$$H(s) = \frac{\frac{1}{0.2 \times (35 \times 10^{-6})}}{s^2 + \frac{375}{0.2}s + \frac{1}{0.2 \times (35 \times 10^{-6})}} = \frac{142857.143}{s^2 + 1875s + 142857.143}$$

$$\frac{1}{LC} = \frac{1}{0.2 \times (35 \times 10^{-6})} = 142857.143$$

$$\frac{R}{L} = \frac{375}{0.2} = 1875$$

$$\text{Resonant } \omega_0 = \sqrt{\frac{1}{LC}} = \sqrt{\frac{1}{0.2 \times 35 \times 10^{-6}}} = 377.96 \text{ rad/s}$$

$$Q = \frac{1}{R} \sqrt{\frac{L}{C}} = \frac{1}{375} \times \sqrt{\frac{0.2}{35 \times 10^{-6}}} = 0.202$$

$$\text{Gain(dB)} = 20 \log\left(\frac{V_{in}}{V_{out}}\right) = 20 \log(0.202) = -13.893 \text{ dB}$$

$$\Sigma = \frac{R}{2} \times \sqrt{\frac{C}{L}} = \frac{375}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 2.48 \text{ system is over damped}$$

Change R to 17Ω

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{17}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0.112 \text{ System is underdamped}$$

$$H(s) = \frac{\frac{1}{0.2 \times (35 \times 10^{-6})}}{s^2 + \frac{17}{0.2}s + \frac{1}{0.2 \times (35 \times 10^{-6})}} = \frac{142857.143}{s^2 + 85s + 142857.143}$$

Change R to 151

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{151}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0.999 \text{ System is critically damped}$$

$$H(s) = \frac{\frac{1}{0.2 \times (35 \times 10^{-6})}}{s^2 + \frac{151}{0.2}s + \frac{1}{0.2 \times (35 \times 10^{-6})}} = \frac{142857.143}{s^2 + 775s + 142857.143}$$

Change R to 0

$$\Sigma = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{0}{2} \times \sqrt{\frac{35 \times 10^{-6}}{0.2}} = 0 \text{ System has no damping}$$

$$H(s) = \frac{\frac{1}{0.2 \times (35 \times 10^{-6})}}{s^2 + \frac{0}{0.2}s + \frac{1}{0.2 \times (35 \times 10^{-6})}} = \frac{142857.143}{s^2 + 0s + 142857.143}$$

```
>> %Overdamped R=375, L=0.2 C=35uF
>> num=[142857.143 ];
>> den=[1 1875 142857.143];
>> bode(num,den);
hold on
grid
>> %underdamped R=17
>> den=[1 85 142857.143];
>> bode(num,den);
>> %Critically Damped R=151
>> den=[1 775 142857.143];
>> bode(num,den);
>> %No damping
>> den=[1 0 142857.143];
>> bode(num,den);
```

Figure 25: Task 7 MATLAB code

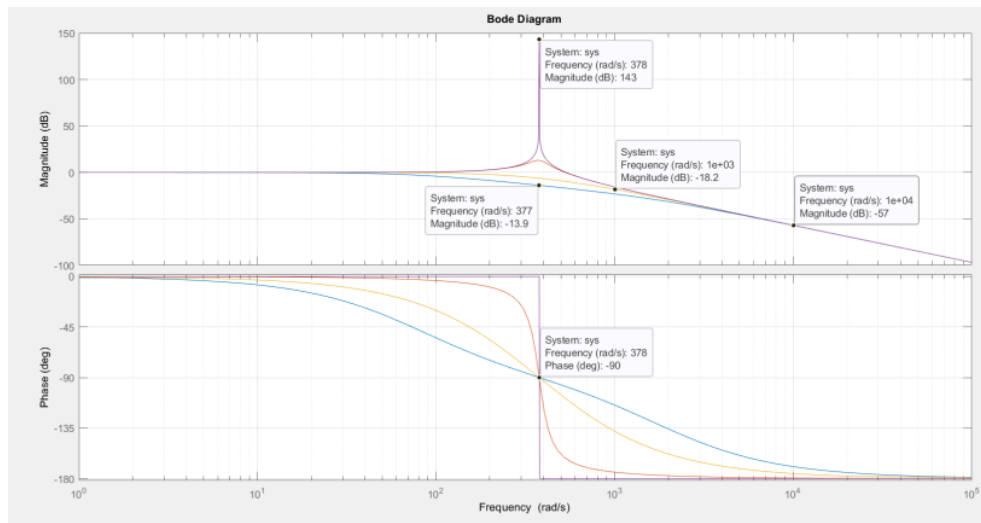


Figure 26: Task 7 Bode Plot

The theory matches the simulation. The altering of the resistance also changes the value of the damping factor. The magnitude at resonant matches which is expected proving the calculations are correct.

Task 8 – Frequency Performance Analysis of a Second Order Parallel Electrical Circuit

The same RLC parallel circuit (Figure 16) and values that are in task 6 is used again looking at the frequency performance.

The transfer function is found as followed for the parallel RLC circuit:

$$\text{Transfer function: } H(s) = \frac{sL}{R(s^2LC+1)+sL}$$

Divide top and bottom by RLC

$$H(s) = \frac{sL}{s^2RLC+R+sL}$$

$$H(s) = \frac{s \times \frac{1}{RC}}{s^2 + s \frac{1}{RC} + \frac{1}{LC}}$$

The centre frequency of the bandwidth can be found using: $\frac{s\beta}{s^2+s\beta+\omega_0^2}$

$$\omega_0 = \sqrt{\frac{1}{LC}} = \sqrt{\frac{1}{0.15 \times 35 \times 10^{-6}}} = 436.435 \text{ rad/s}$$

The bandwidth can be calculated by the following equation:

$$\beta = \omega_{c2} - \omega_{c1}$$

$$\beta = \frac{1}{2RC} - -\frac{1}{2RC}$$

$$\beta = \frac{1}{RC}$$

When $R = 3\Omega$

$$H(s) = \frac{s \times \frac{1}{3 \times (35 \times 10^{-6})}}{s^2 + s \frac{1}{3 \times (35 \times 10^{-6})} + \frac{1}{(0.15) \times (35 \times 10^{-6})}} = \frac{s \times 9523.8095}{s^2 + (s \times 9523.8095) + 190476.1905}$$

$$\beta = \frac{1}{RC} = \frac{1}{3 \times (35 \times 10^{-6})} = 9523.8095 \text{ rad/s}$$

```
>> %R=3
>> %L=0.15;
>> %C=35u
>> num=[9523.8095 0];
>> den=[1 9523.8095 190476.1905];
>> bode(num,den);
>> grid
```

Figure 27: MATLAB code $R=3\Omega$

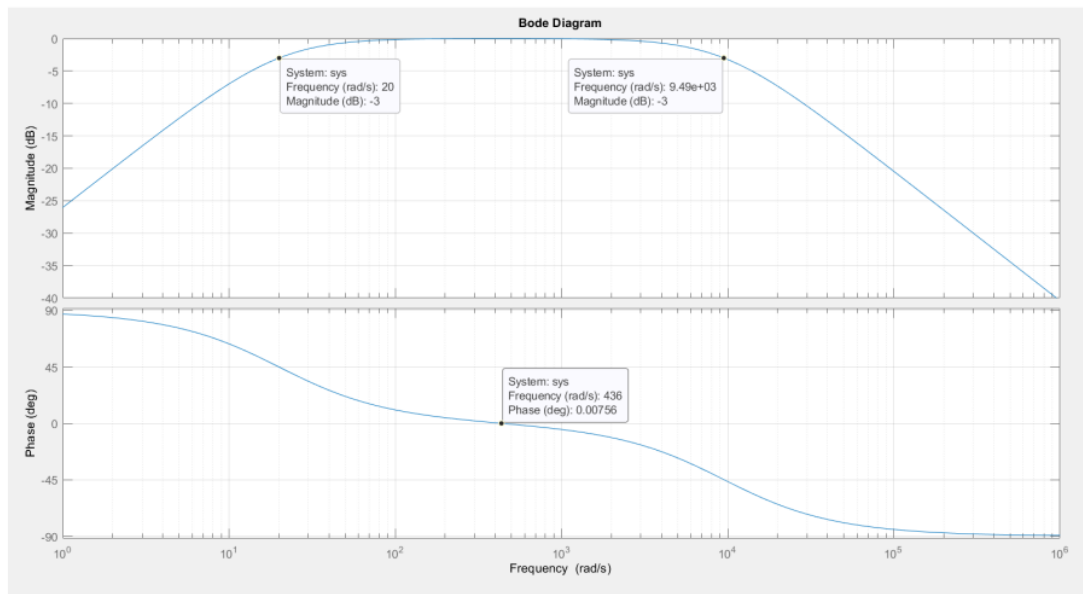


Figure 28: Bode plot $R=3\Omega$

When $R = 375\Omega$

$$H(s) = \frac{s \times \frac{1}{375 \times (35 \times 10^{-6})}}{s^2 + s \frac{1}{375 \times (35 \times 10^{-6})} + \frac{1}{(0.15) \times (35 \times 10^{-6})}} = \frac{s \times 76.19}{s^2 + (s \times 76.19) + 190476.1905}$$

$$\beta = \frac{1}{RC} = \frac{1}{375 \times (35 \times 10^{-6})} = 76.19 \text{ rad/s}$$

```
>> %R=375
>> %L=0.15
>> %C=35u
>> num=[76.19 0];
>> den=[1 76.19 190476.1905];
>> bode(num,den);
>> grid
```

Figure 29: MATLAB code $R=375\Omega$

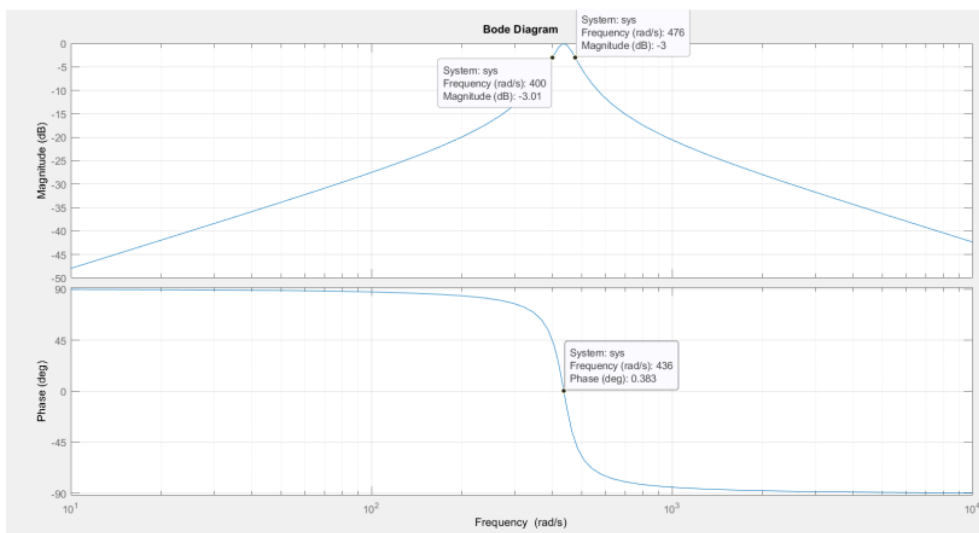


Figure 30: Bode plot $R=375\Omega$

When $R = 17\Omega$

$$H(s) = \frac{s \times \frac{1}{17 \times (35 \times 10^{-6})}}{s^2 + s \frac{1}{17 \times (35 \times 10^{-6})} + \frac{1}{(0.15) \times (35 \times 10^{-6})}} = \frac{s \times 1680.672}{s^2 + (s \times 1680.672) + 190476.1905}$$

$$\beta = \frac{1}{RC} = \frac{1}{17 \times (35 \times 10^{-6})} = 1680.672 \text{ rad/s}$$

```
>> %R=17
>> %L=0.15
>> %C=35u
>> num=[1680.672 0];
>> den=[1 1680.672 190476.1905];
>> bode(num,den);
>> grid
```

Figure 31: MATLAB code $R=17\Omega$

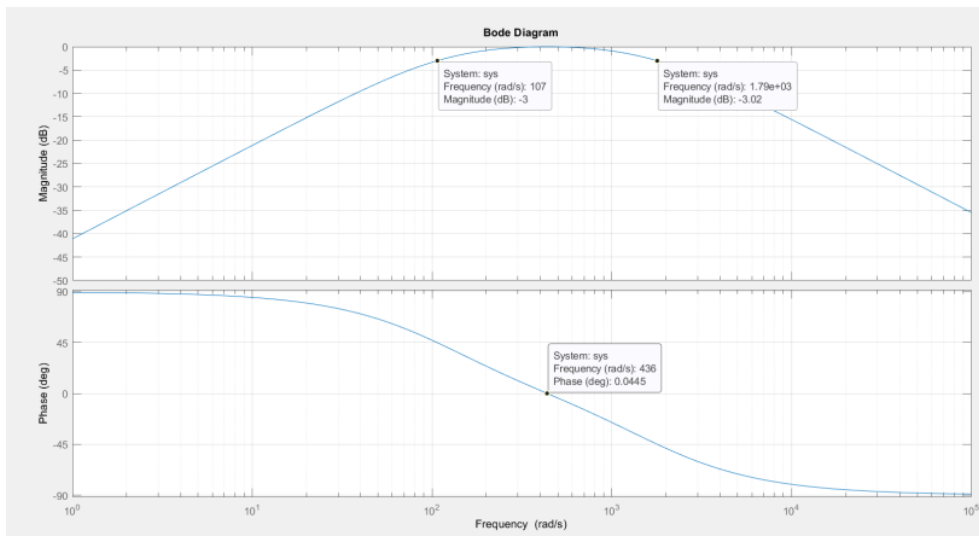


Figure 32: Bode plot $R=17\Omega$

When $R = 151\Omega$

$$H(s) = \frac{s \times \frac{1}{151 \times (35 \times 10^{-6})}}{s^2 + s \frac{1}{151 \times (35 \times 10^{-6})} + \frac{1}{(0.15) \times (35 \times 10^{-6})}} = \frac{s \times 189.215}{s^2 + (s \times 189.215) + 190476.1905}$$

$$\beta = \frac{1}{RC} = \frac{1}{17 \times (35 \times 10^{-6})} = 189.215 \text{ rad/s}$$

```
>> %R=151
>> %L=0.15
>> %C=35u
>> num=[189.215 0];
>> den=[1 189.215 190476.1905];
>> bode(num,den);
>> grid
```

Figure 33: MATLAB code $R=151\Omega$

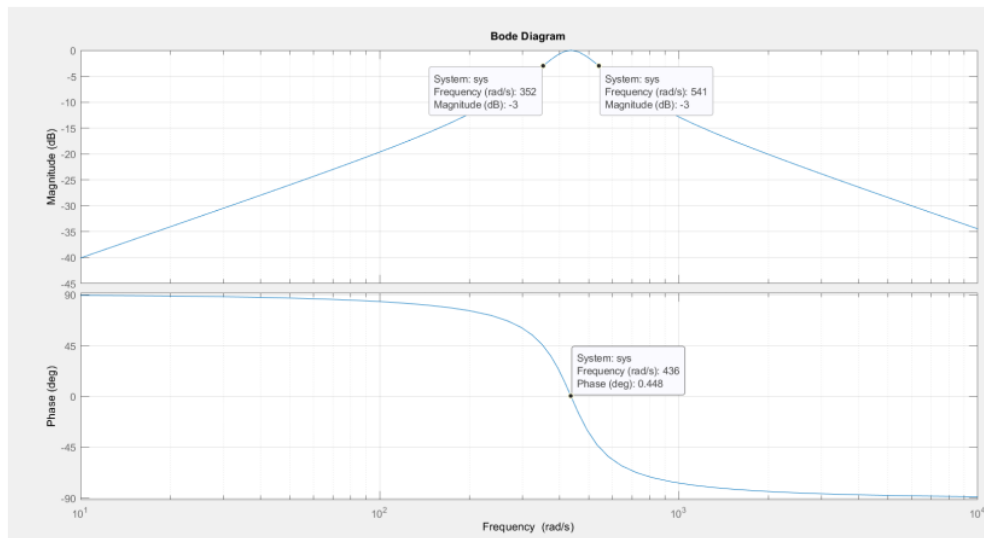


Figure 34: Bode plot $R=151\Omega$

Resistance Ω	Bandwidth (rad/s) Calculation	Bandwidth (rad/s) Simulation
3	9523.809	9470
375	76.19	76
17	1680.672	1683
151	189.214	189

$R=3\Omega$ the bandwidth doesn't match but could be down to how MATLAB displays data with rounding errors. All the other bandwidth match apart from marginal decimal places which would not have a big impact on results. In this circuit when the resistance is small there is a much larger bandwidth. Increasing the resistance has a direct impact on making the bandwidth smaller.

Task 9 – Frequency Performance Analysis of a First Order Electronic System

Figure 35 shows the circuit for the low pass op amp.

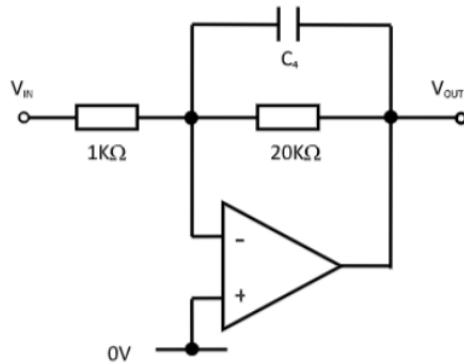


Figure 35: Task 9 Circuit

$$R_1 = 1k$$

$$R_2 = 20k$$

$$C = 350nF$$

$$k = \frac{R_2}{R_1} = \frac{20}{1} = 20$$

$$\omega_c = \frac{1}{CR_2} = \frac{1}{(350 \times 10^{-9}) \times (20 \times 10^3)} = 142.857 \text{ rad/s}$$

$$H(s) = -k \left[\frac{\omega_c}{s + \omega_c} \right] = -20 \left[\frac{142.857}{s + 142.857} \right]$$

$$\text{Num} = -20 \times 142.857 = -2857.14$$

$$\text{Gain} = 20 \log(20) = 26.02 \text{ dB}$$

$$\text{Cut off frequency } 26.02 - 3 = 23.02 \text{ dB}$$

```

s MATLAB
Command Window
New to MATLAB? See resources for Getting Started.
>> num = [-2857.14];
>> den = [1 142.857];
>> bode(num,den);
grid
fx >> |

```

Figure 36: MATLAB code task 9

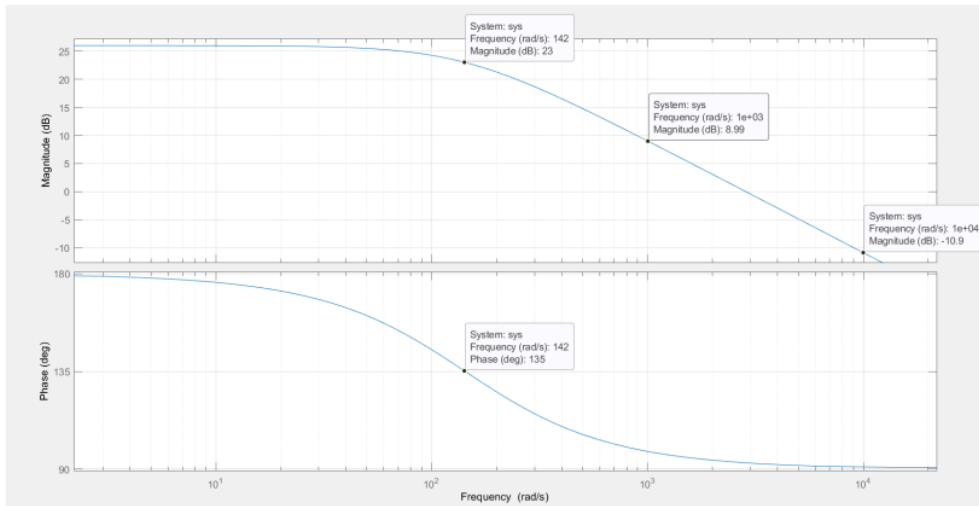


Figure 37: Task 9 Bode Plot

Figure 37 shows the bode plot for the low pass filter. Table 5 shows the results from task 9 the comparison between the calculated and simulated results.

-3dB	Calculated	Simulated
ω_c rad/s	142.857	142
Phase shift	180-45=135	135
Roll off	20dB per decade	19.89dB per decade

Table 5: Task 9 Results

The simulated results match the calculated results which proves the calculations are correct. There is a slight variation in the roll off but this could be due to the placement of the cursors while trying to read off the graph. However, 0.11dB is negligible and would have no great significant on any results.



Task 10 – Frequency Performance Analysis of a First Order Electronic System

Figure 38 shows the circuit for the high pass op amp.

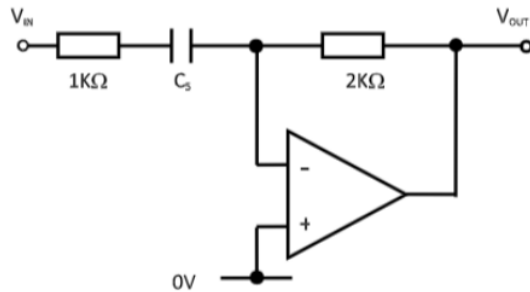


Figure 38: Task 10 Circuit

$$R_1 = 1k$$

$$R_2 = 2k$$

$$C = 350nF$$

$$k = \frac{R_2}{R_1} = \frac{2}{1} = 2$$

$$\omega_c = \frac{1}{CR_1} = \frac{1}{(350 \times 10^{-9}) \times (1 \times 10^3)} = 2857.143 \text{ rad/s}$$

$$H(s) = -k \left[\frac{s}{s + \omega_c} \right] = -2 \left[\frac{s}{s + 2857.143} \right]$$

$$\text{Gain} = 20 \log(2) = 6.02 \text{ dB}$$

$$\text{Cut off frequency } 6.02 - 3 = 3.02 \text{ dB}$$

```
>> %High Pass Filter
>> num=[-2 0];
>> den=[1 2857.143];
>> bode(num,den);
>> grid
```

Figure 39: Task 10 MATLAB Code

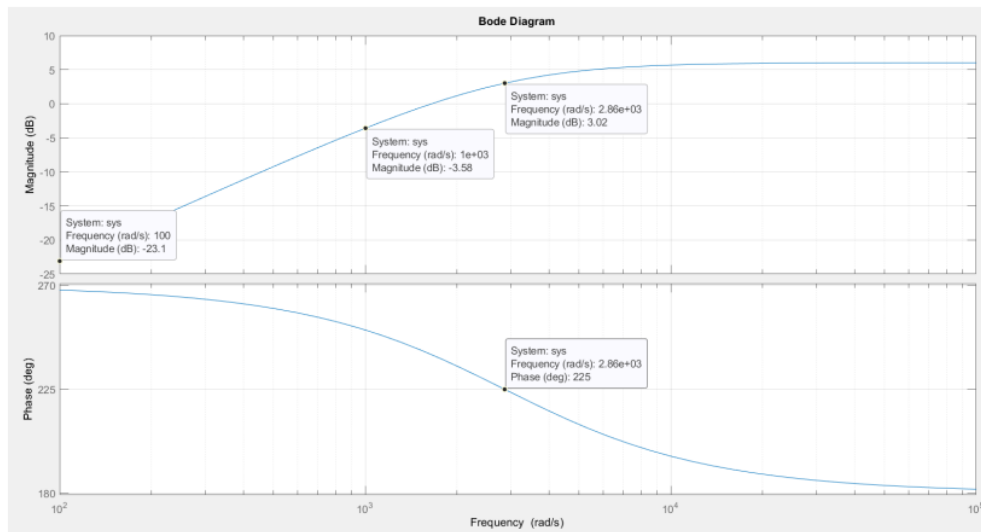


Figure 40: Task 10 Bode Plot

Figure 40 shows the bode plot for the low pass filter. Table 6 shows the results from task 9 the comparison between the calculated and simulated results.

-3dB	Calculated	Simulated
ω_c rad/s	2857.143	2860
Phase Shift	$180+45=225$	225
Roll off	20dB per decade	19.52 per decade

Table 6: Task 10 Results

The simulated results almost match the calculated results. The roll off and phase shift match but the frequency in ω_c is slightly out. This could be due to simulation error or rounding. As seen in the bode plot ω_c is shown as $2.86e + 03$. If my calculated ω_c is converted into standard form then the results will match. How the result is displayed on the plot is why there is an error due to rounding. A first order should have a roll off of 20dB, the error in the simulation model is down to human error in the placement of the cursors to collect the data.

Task 11 – Frequency Performance Analysis of a Fourth Order Electronic System

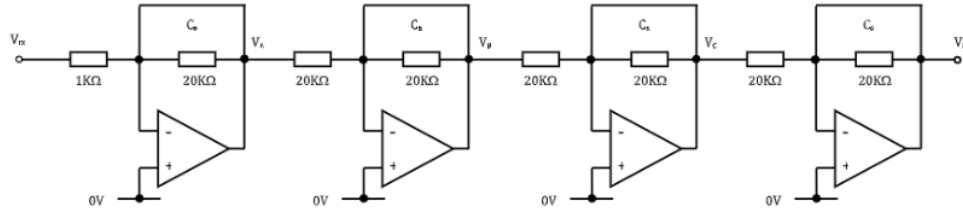


Figure 41: 4th order cascading filters

Figure 41 shows a 4th order filter. The cut of frequency can be shown as $\omega_{cn} = \sqrt[n]{\sqrt{2} - 1} \times \omega_c$ where n is equal to the filter order.

$$C = 35nF$$

$$\omega_c = \frac{1}{R_2 C} = \frac{1}{20 \times 10^3 \times 35 \times 10^{-9}} = 1428.671 \text{ rad/s}$$

$$H(s) = K \frac{\omega_c^2}{s^2 + 2\omega_c s + \omega_c^2}$$

$$K = \text{gain} = \frac{R_2}{R_1} = \frac{20}{1} = 20$$

$$\text{Gain in dB} = 20 \log_{10}(20) = 26.02$$

$$H(s) = 20 \times \frac{1428.671^2}{s^2 + 2 \times 1428.671s + 1428.671^2}$$

$$= 20 \times \frac{2041100.826}{s^2 + 2857.342s + 2041100.826}$$

N	$\omega_{cn} = \sqrt[n]{\sqrt{2} - 1} \times \omega_c$	$\frac{1}{\omega_{cn}}$	$\text{new } \omega_c = \frac{1}{\omega_{cn}} \times \omega_c$
2	919.84	1.087×10^{-3}	1.553 rad/s
3	728.37	1.373×10^{-3}	1.962 rad/s
4	621.44	1.609×10^{-3}	2.299 rad/s

$$n=2$$

$$H(s) = 20 \frac{\omega_c^2}{s^2 + 2\omega_c s + \omega_c^2}$$

$$n=3$$

$$H(s) = -20 \frac{\omega_c^3}{s^3 + 3\omega_c s^2 + 3\omega_c^2 s + \omega_c^3}$$

$$n=4$$

$$34$$

$$H(s) = 20 \frac{\omega_c^4}{s^4 + 4\omega_c s^3 + 6\omega_c^2 s^2 + 4\omega_c^3 s + \omega_c^4}$$

```

>> %Cascade 4th Order Low Pass Filter
>> %First Stage
>> wc1=1428.671;
>> wc=wc1;
>> k=20;
>> num1=[-k*wc];
>> den1=[1 wc];
>> bode(num1,den1);
>> grid on
>> hold on
>> %Second Stage
>> %To get the same cut off as wc, use scaling factor 1.087e-3
>> wc=wc1*1.087e-3;
>> num2=[k*wc^2];
>> den2=[1 2*wc wc^2];
>> bode(num2,den2);
>> %Third Stage
>> %To get the same cut off as wc, use scaling factor 1.373e-3
>> wc=wc1*1.373e-3;
>> num3=[-k*wc^3];
>> den3=[1 3*wc 3*wc^2 wc^3];
>> bode(num3,den3);
>> %Fourth Stage
>> %To get the same cut off as wc, use scaling factor 1.609e-3
>> wc=wc1*1.609e-3;
>> num4=[k*wc^4];
>> den4=[1 4*wc 6*wc^2 4*wc^3 wc^4];
>> bode(num4,den4);

```

Figure 42: MATLAB code cascading filters

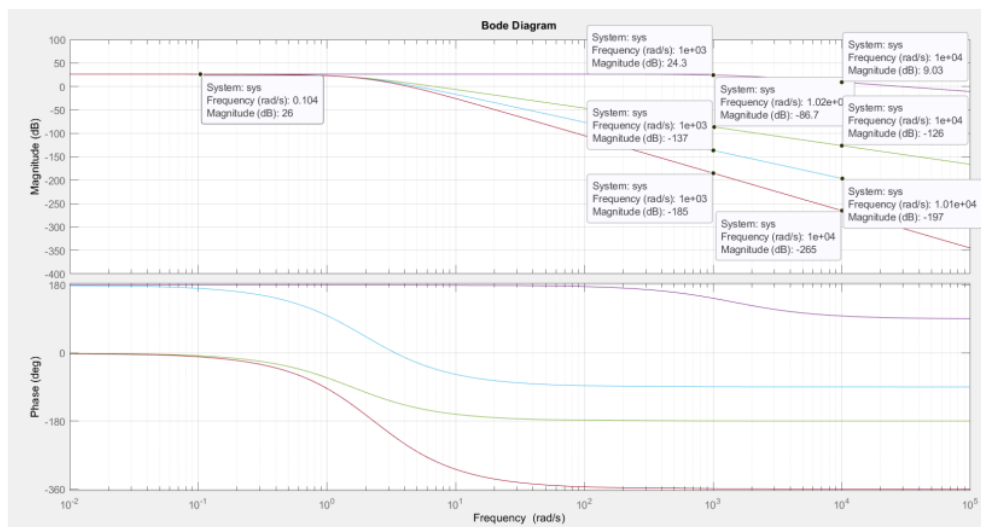


Figure 43: 4th Order filter bode plot

Colour	Order	Roll off theory (dB)	Roll off simulation (dB)
Purple	1 st	20	15
Green	2 nd	40	40
Red	3 rd	60	60
Red	4 th	80	80

The 2nd, 3rd and 4th order filters have the expected outcome with the correct roll off as expected. The gain was measured correctly. The roll off for the first filter was different on the simulation.

Task 12 – First Order Control System Analysis

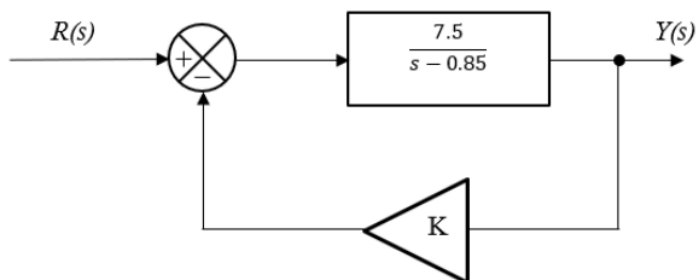


Figure 44: Task 12 closed loop circuit

The circuit can be seen below above in Figure 44. From the circuit the transfer function can be arranged and the prediction made of the stability of the circuit.

$$H(s) = \frac{7.5}{s - 0.85}$$

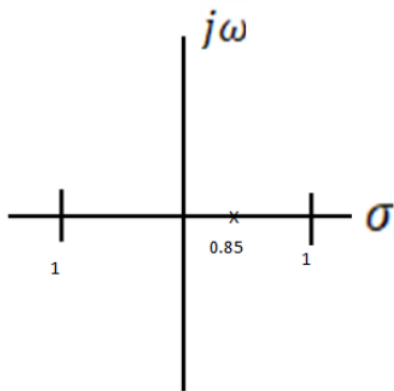


Figure 45: Argand Diagram

Poles are in the right hand side therefore the system is unstable.

$$H(s) = \frac{G}{1+GH}$$

$$= \frac{\frac{7.5}{s-0.85}}{1+k(\frac{7.5}{s-0.85})}$$

$$= \frac{7.5}{s-0.85+7.5K}$$

You have worked this out correctly, well

Equate to zero

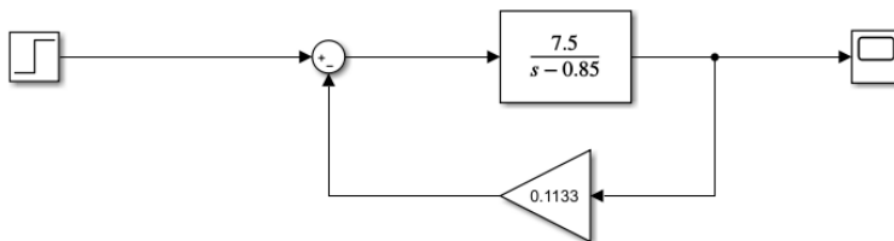
$$s + 7.5k - 0.85 = 0$$

$$s = -(7.5k - 0.85) = 0$$

For Poles

$$\therefore 7.5k = 0.85$$

$$k = \frac{0.85}{7.5} = 0.1133$$



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Figure 46: Closed loop circuit design

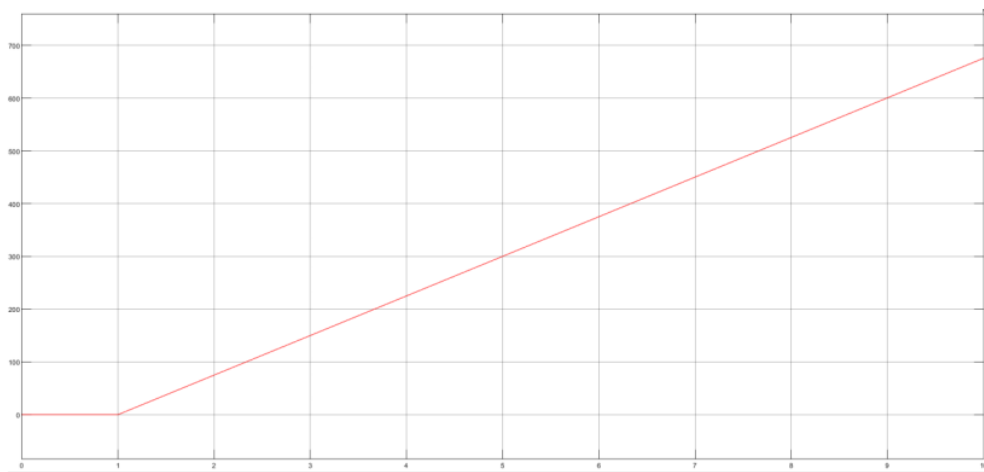


Figure 47: Unstable System

To make stable make $k > 0.85$

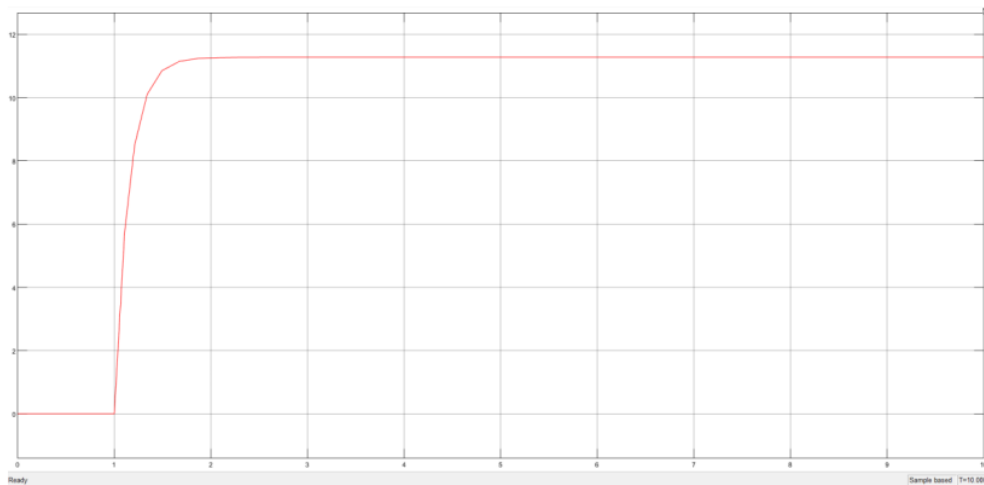


Figure 48: Stable system

Figure 48 shows the system with negative feedback and a gain of one. This makes the system stable as shown as the curve goes stable. The minimum value of k is equal to 0.1133.

If $k > 0.1133$

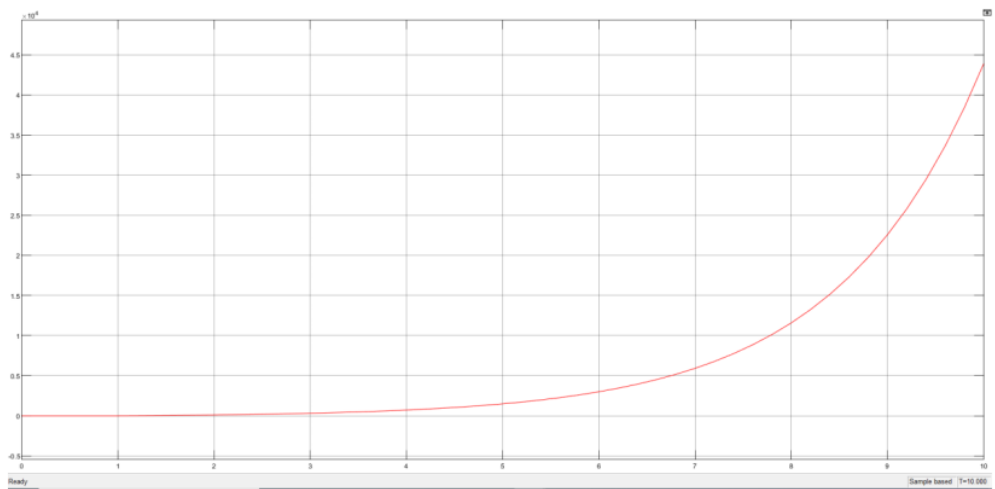


Figure 49: Exponential Rise

When $k > 0.1133$ there is an exponential rise which still makes the system unstable as the output is still increasing.

	Calculation	Simulation
Gain	0.1133	0.1133
Stability	Unstable	Unstable

Table 7: Results when $K=0.1133$

	Calculation	Simulation
Gain	>0.1133	1
Stability	stable	stable

Table 8: Results when $K > 0.1133$

	Calculation	Simulation
Gain	<0.1133	0.1133
Stability	Unstable	Unstable

Table 9: Results when $K < 0.1133$

```
>> num=[7.5];
>> den=[1 -0.85];
>> rlocus(num,den);
grid
```

Figure 50: Root Locus MATLAB Code

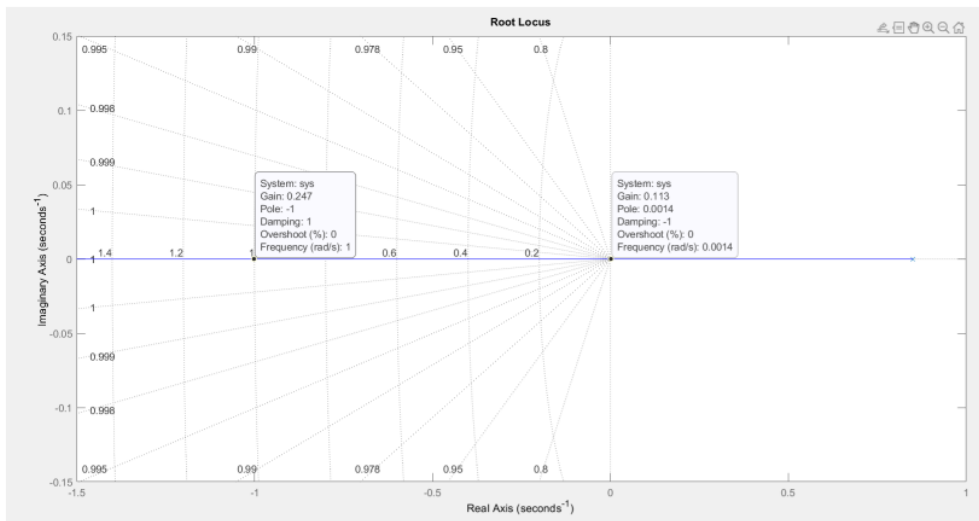


Figure 51: Root Locus

Figure 51 shows the root locus. This proves the theory that a gain above 0.1133 will make a stable system and a gain below 0.1133 will make an unstable system.

Task 13 – DC Motor Model Analysis

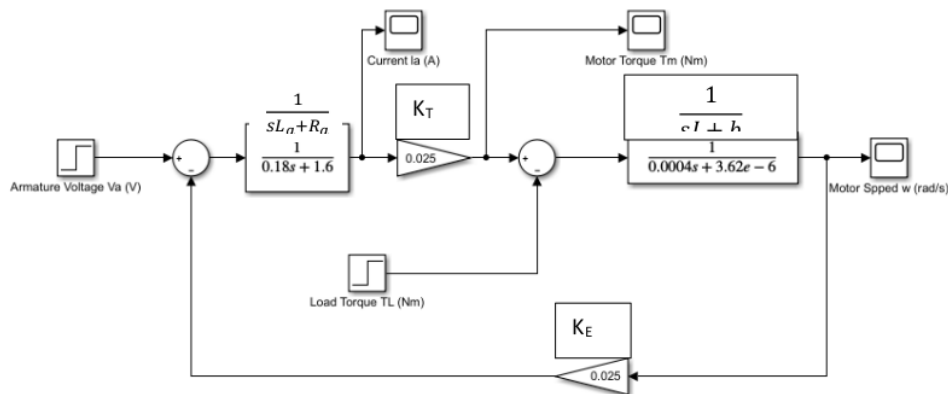


Figure 52: Mathematical DC Motor Model

Figure 52 shows the mathematical model for the DC motor.

$$\text{Time constant } 2\Sigma\omega_n = \frac{b}{J} + \frac{R_a}{L_a} = \frac{4.6 \times 10^{-6}}{0.00042} + \frac{1.5}{0.165} = 9.102s$$

$$\omega_n^2 = \frac{R_a \times b \times K_T \times K_E}{L_a \times J \times L_a \times J}$$

$$\omega_n^2 = \frac{1.5 \times (4.6 \times 10^{-6})}{0.165 \times 0.00042} \frac{0.062 \times 0.063}{0.165 \times 0.00042} = 56.36$$

$$\omega_n = \sqrt{56.36} = 7.507$$

$$2\Sigma\omega_n = \frac{b}{J} + \frac{R_a}{L_a} = \frac{4.6 \times 10^{-6}}{0.00042} + \frac{1.5}{0.165} = 9.102$$

$$\therefore \Sigma = \frac{9.102}{2 \times \omega_n} = \frac{9.102}{2 \times 7.507} = 0.606 \text{ System is underdamped}$$

$$T_{stall} = \frac{K_T \times V_a}{R_a} = \frac{0.062 \times 15}{1.5} = 0.62 Nm$$

$$\text{Theoretical friction-less no-load-speed } \Omega_{no \text{ load}} = \frac{V_a}{K_E} = \frac{15}{0.063} = 238.095 \text{ rad/s}$$

$$\text{Finding Poles using } x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = 0$$

$$a = 1 \quad b = 2 \times \Sigma\omega_n = 2 \times 0.606 \times 7.507 = 9.098 \quad c = \omega_n^2 = 56.36$$

$$x = \frac{-(7.507) \pm \sqrt{(7.507)^2 - 4(1)(56.36)}}{2(1)}$$

$$x = \frac{-7.507 \pm \sqrt{56.355 - 225.44}}{2}$$

$$x = \frac{-7.507 \pm \sqrt{-169.1}}{2}$$

$$x = \frac{-7.507 \pm 169.1j}{2}$$

You have worked this out correctly, well

$$P_1 = -3.75 + 84.54j \text{ or } P_2 = -3.75 - 84.54j$$

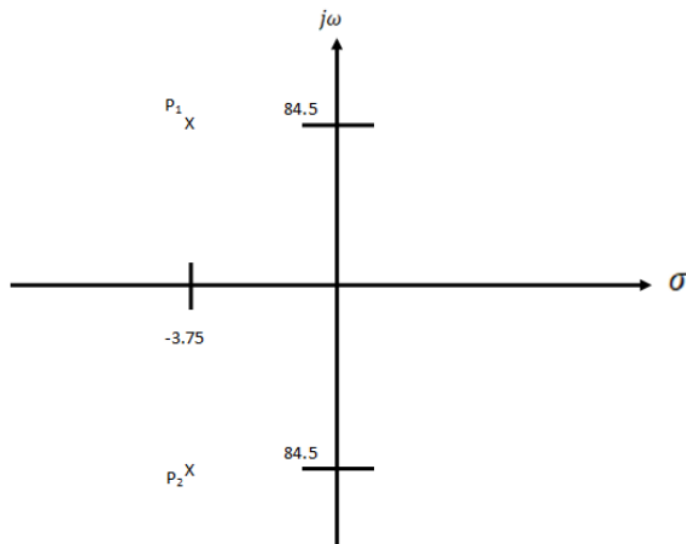


Figure 53: Task 13 Argand Diagram

As shown in Figure 53, the poles are in left hand plane so the prediction is a stable response.

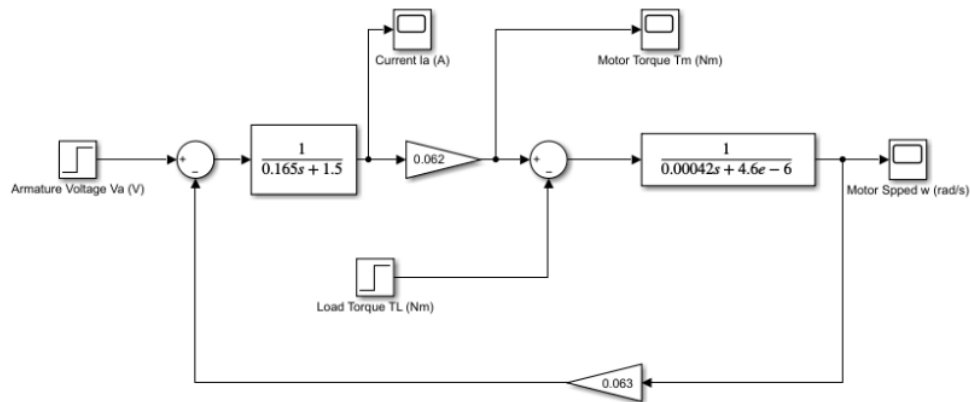


Figure 54: DC Motor Model

Figure 54 shows the DC motor model built on Simulink

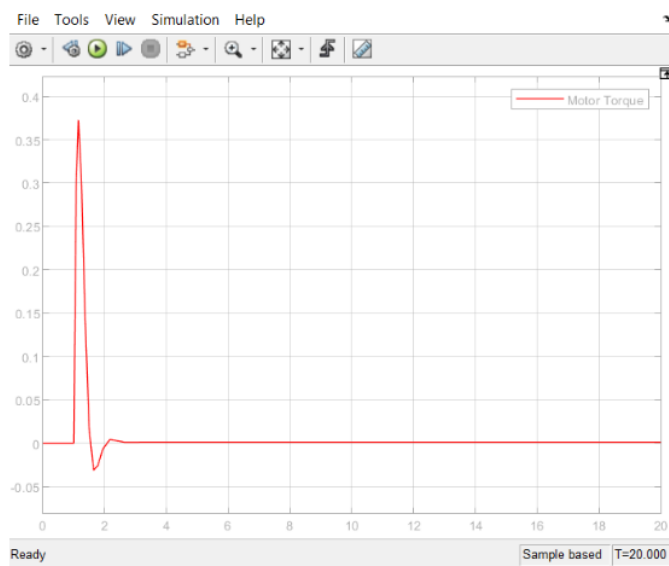


Figure 55: Motor Torque (Nm) no disturbance

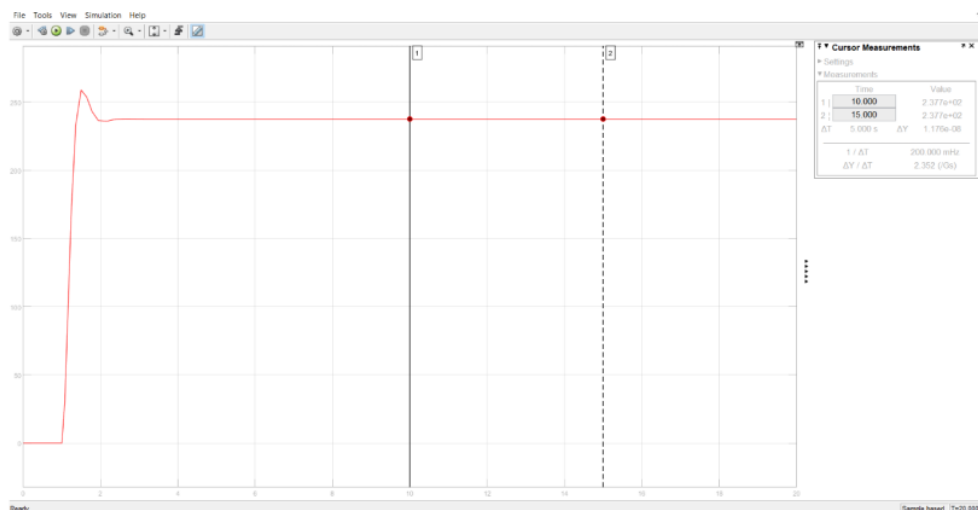


Figure 56: Motor no-load speed

	Calculated	Simulated
Motor Torque (Nm)	0.62	0.34
Motor no load speed (rad/s)	238.095	237.7

Table 10: Task 13 results no disturbance

Table 10 shows the results from task 13. Analysing the results there is a difference between the calculated and simulated result for the no load speed of the motor. The discrepancy is due to friction being included in the simulation. The formula $\frac{K_T V_a}{bR_a + K_T K_e}$ can be used to calculate the no load speed with friction.

$$\therefore \frac{K_T V_a}{bR_a + K_T K_e} = \frac{0.062 \times 15}{4.6 \times 10^{-6} \times 1.5 + 0.062 \times 0.063} = 237.67 \text{ rad/s which matches the simulated model.}$$

You have worked this out correctly, well

Using the motor speed in Figure 56 the settling time can be measured using the cursors. The cursors would go at the start of the peak and when the speed settles. This equates to approximately 1.5 seconds.

Figure 55 shows the torque being applied to the motor. The torque is applied after the voltage where the first peak occurs. After the start up there is undershoot on the way back down then levels off. The torque where it levels off is due to friction.

Voltage applied, have torque then undershoot then Torque after undershoot is due to friction.

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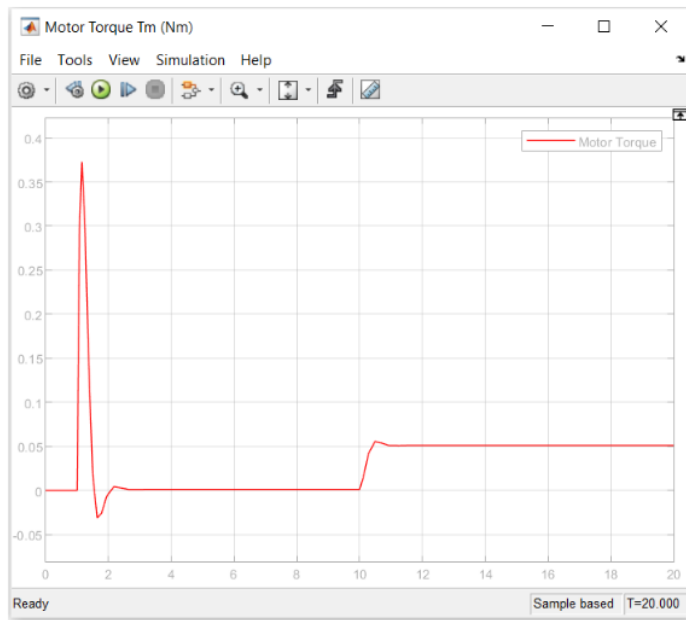


Figure 57: Motor Torque T_m (Nm) with disturbance

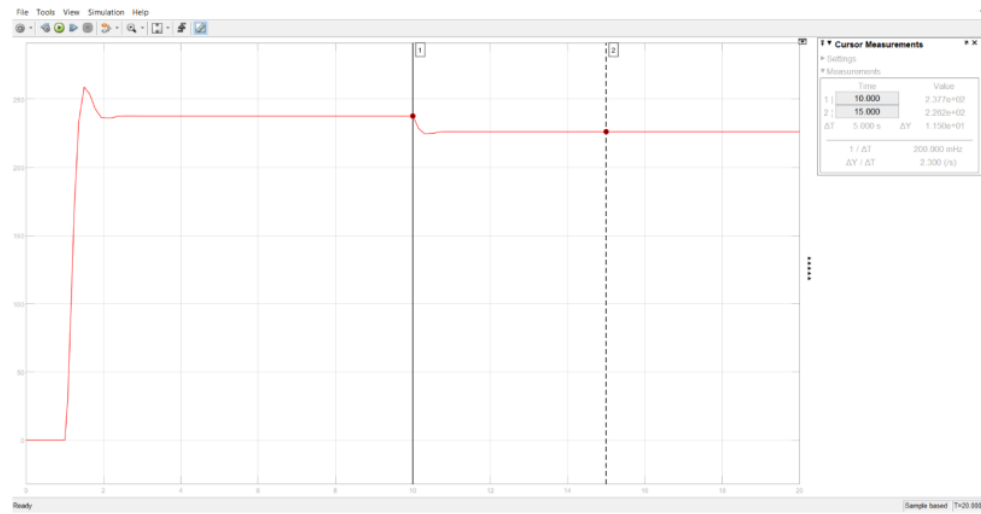


Figure 58: Motor speed with disturbance

$$\text{Speed with load } \Omega_{Load} = \frac{V_a \frac{R_a \times T_L}{K_T}}{\frac{R_a \times b}{K_T} + K_e} = \frac{15 \frac{1.5 \times 0.03}{0.062}}{\frac{1.5 \times 4.6 \times 10^{-6}}{0.062} + 0.063} = 233.35$$

	Calculated	Simulated
Motor Speed (disturbance) (rad/s)	226.175	226.2

The speed is initially the same as previously with no load, however after 10 seconds the disturbance is introduced which can clearly be seen by the dip in the graph in Figure 58. This brings the speed down to 226.2 rad/s which is the same as my calculated results when rounded to the same decimal place.

The peak in current is due to the initial start up of the motor. The motor will then settle and run steady until the load is applied in which the current will increase. The trace of the current is identical to the trace of the motor torque. This is due to their proportional relationship.

Task 14 – Proportional Speed Control System

The motor model was then put into a sub-system and a PID controller added that was configured only for the Proportional. The controller was replicated three times with values above and below K_p . The model can be seen in Figure 59.

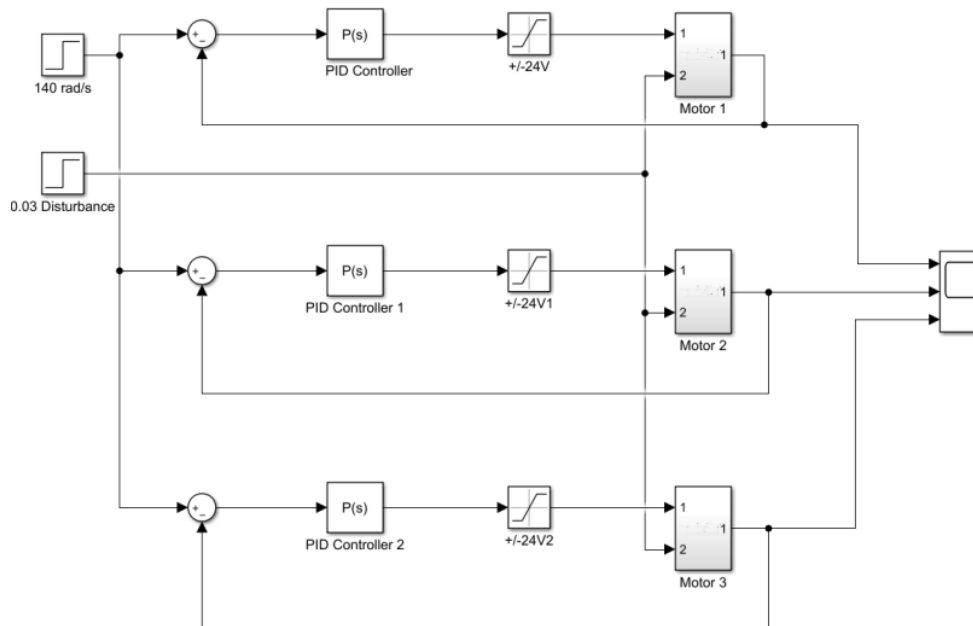


Figure 59: Proportional controller model

The auto tune feature was run to get the optimum value for K_p . The value of K_p was then both increased and decreased to see what effect it had on the outcome.

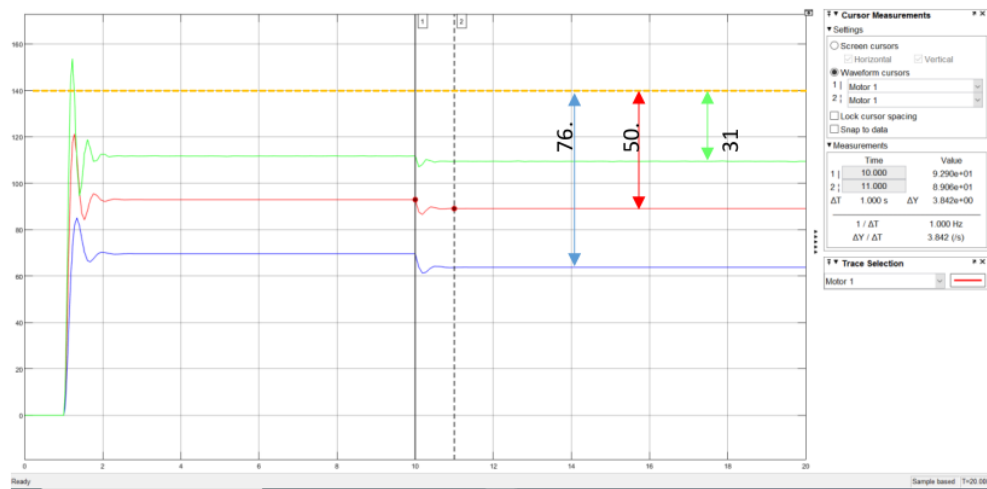


Figure 60: Proportional speed control trace

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	$K_p = 0.12447$	$\frac{1}{2}K_p$	$2K_p$
Steady state error (rad/s)	50.97	76.28	30.6
Rise time (s)	1.280	1.332	1.214
Overshoot (rad/s)	-20.3	-55.5	12.6

Table 11: Proportional speed control results

Altering the value of K_p has a direct impact of the steady state error. The steady state error was reduced when K_p was increased however it did introduce an overshoot at the start on build up where as when K_p was reduced the error increased but there was no overshoot but an undershoot instead. Steady state error cannot be eliminated with only proportional control.

You have worked this out correctly, well

Task 15 – Proportional-Integral Speed Control System

The Integral was then added to the controller. Research suggests that when integral is added so the controller now has proportional and integral control it will eliminate the steady state. The value of the proportional will be kept the same on all three controllers with the value of the integral altered. The trace can be seen in Figure 61.

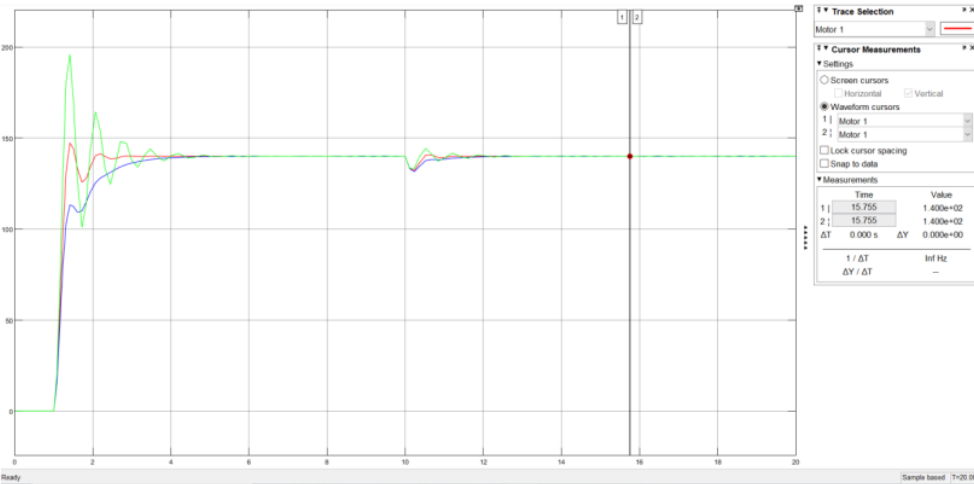


Figure 61: Proportional and Integral Control Trace

	$KI = 0.3043$	$\frac{1}{2} KI$	$2KI$
Steady state error (rad/s)	0	0	0
Rise time(s)	1.371	5.84	1.253
Overshoot Percentage	$\frac{7}{140} \times 100 = 5\%$	No overshoot	$\frac{55.8}{140} \times 100 = 39.8\%$
Settling Time(s)	1.25	5.84	6.28

Table 12: Proportional and Integral Control Results

As seen in the results of the Table 12. The introduction of the integral has eliminated the steady state error with all three achieving the steady state value. The data suggests that increasing the integral reduces the rise time but makes the settling time longer but introduces a big overshoot. Reducing the value of the integral has increased the rising and settling time but there is no overshoot. It is a much slower but more steady and smoother increase. It also brings the speed back to 140 rad/s after the torque is applied.

Task 16 – Proportional-Integral-Derivative Speed Control System

The derivative was then added to make up the complete PID controller. The proportional and Integral values are kept the same but the values of 'D' are changed in the same pattern as before with one higher and one lower.

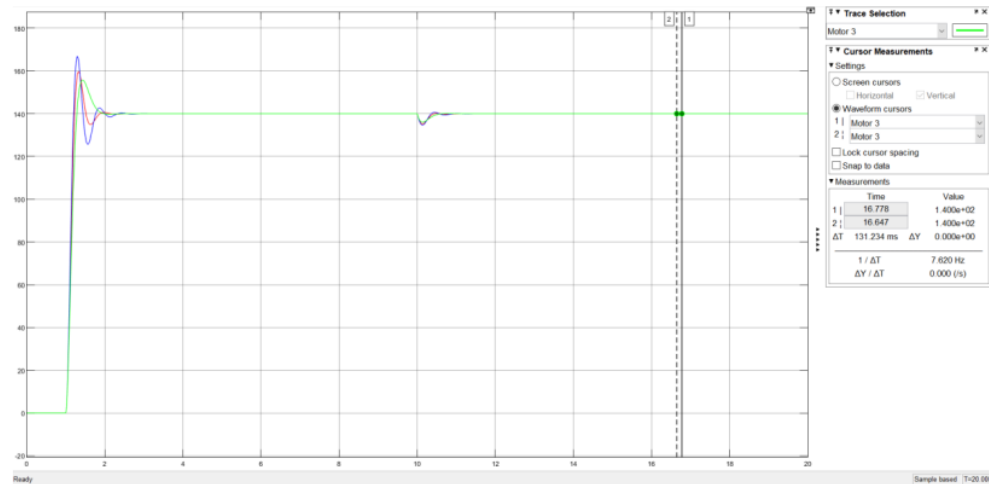


Figure 62: PID Controller Trace

	$KD = 6.6179 \times 10^{-3}$	$\frac{1}{2} KD$	$2KD$
Steady state error (rad/s)	0	0	0
Rise time(s)	1.227	1.201	1.280
Overshoot Percentage	$\frac{19.6}{140} \times 100 = 14\%$	$\frac{26.8}{140} \times 100 = 19\%$	$\frac{15.8}{140} \times 100 = 11\%$
Settling Time(s)	2.461	2.881	2.434

Table 13: PID Controller Results

Adding the derivate into the controller has decreased the settling time and also has decreased the rise time so all motors reach 140 rad/s in a quicker time frame. As with the PI controller, the PID controller also returns the speed to 140 rad/s after the load is applied.

Task 17 – Controller Comparisons

Each controller was changed and auto tuned for its optimal performance. One of each type of controller. This can be seen in Figure 63.

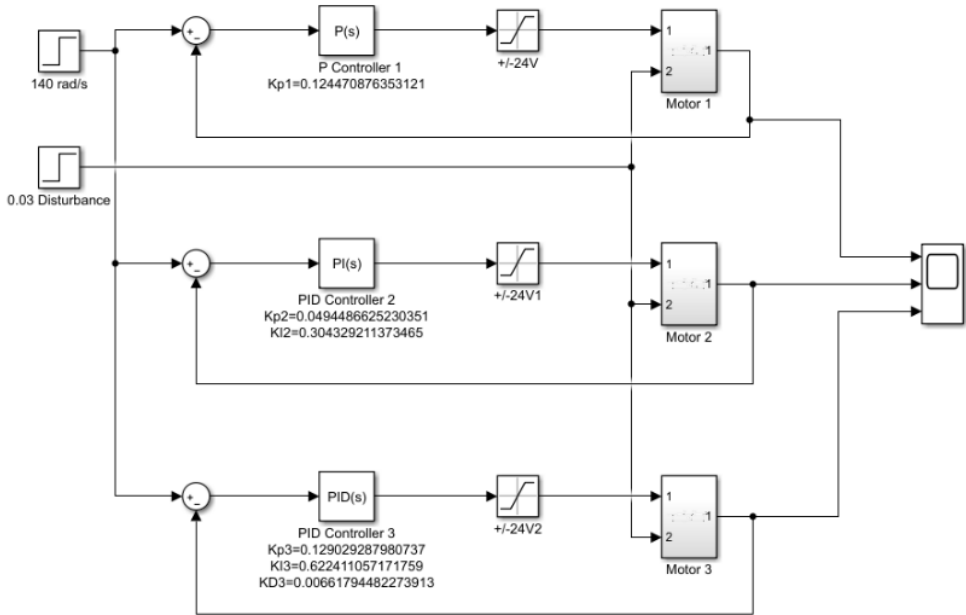


Figure 63: P, PI, PID Controller

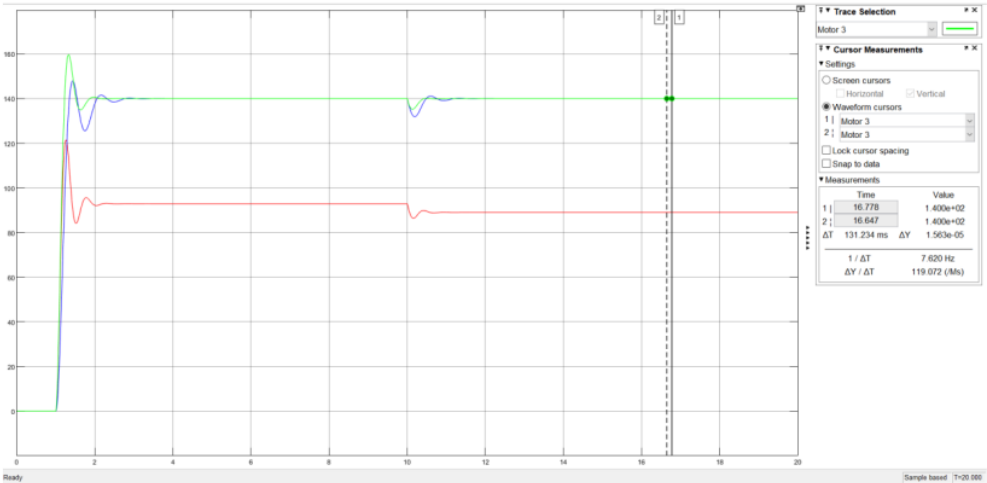


Figure 64: P, PI, PID Trace

	P	PI	PID
Steady state error (rad/s)	47.1	0	0
Rise time(s)	1.253	1.345	1.227

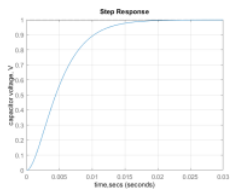
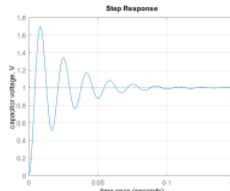
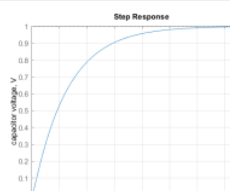
Overshoot Percentage	No overshoot	$\frac{7.8}{140} \times 100 = 5.5$	$\frac{19.63}{140} \times 100 = 11.8\%$
Settling Time(s)	2.539	3.342	2.448

Table 14: PID Controller Results

Motor 1 is only a proportional controller so steady state error has been reintroduced. The PI controller eliminates the steady state error but the settling time has increased and an overshoot is introduced. The PID controller then reduces the rise and settling time but at the expense of a higher overshoot.

Task 18 – Overall Conclusions and Recommendations

When looking at the transient response when the results are exponential, 1τ will always fall on 0.632% or 0.368% depending if the curve is raising or falling. This comes from the formula $y(t) = 1 - e^{-t/\tau}$. All first order systems will have a roll off of 20dB per decade and will increase by 20dB for each order, example that a fourth order system will have a roll of 80dB. This was also proved in simulation in Figure 43. When a system requires damping, sigma is the damping factor. There are four types of damping. This is shown in Table 15. The type of damping can also be seen by the bode plot response.

Sigma	Type of damping	
=1	Critically damped	
<1	Underdamped	
>1	Overdamped	

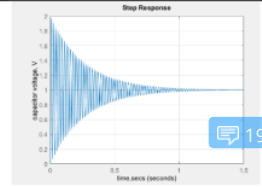
=0	No damping	
----	------------	--

Table 15: Types of Damping

When looking at closed loop system the poles can reflect if the system will be stable or unstable. If the poles are in the left hand plane the system is going to be stable. If they are in the right hand plane the system is going to be unstable.

On DC motor control, calculations didn't match the simulation for no load speed, this was due to friction. In the analysis of the task it was explained that this was because friction is used in the simulation and the calculation was then done to prove this. All other results matched with the speed of the motor dropping after the load was applied which is as expected. To combat the reduction in speed, PID controllers can be added to bring the speed back to the required speed. How effective the controller will depend on how it is tuned. Having just a proportional controller still means the system has a steady state error. Making it a PI controller removes the steady state error but can have an overshoot. If a PID controller is used, there is no steady state error, a faster rise and settling time but there is an overshoot. A PID controller is probably the best to use as it has no steady state error and a faster settling time.

1909751

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

78/100

PAGE 1

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Comment 1

% or 0.632

PAGE 7



Comment 2

from pot divider?

PAGE 8

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PAGE 10



Comment 3

state circuit type - LPF

PAGE 11



Comment 4

state circuit type - HPF

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Comment 5

R would need to be 0

PAGE 16



Comment 6

there is damping here

PAGE 17



You have worked this out correctly, well

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PAGE 20

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PAGE 23



Incorrect

You have worked this out wrongly. It is not correct, check work more carefully.



Comment 7

you have made mistakes for no damping R would need to be very large

PAGE 24

PAGE 25



Comment 8

tabulate R values and Damping results



Comment 9

this is a LPF with a resonant point of magnitude



Comment 10

more analysis required, e.g. Q factor and effect on max gain frequency moving to ω_n

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Comment 11

Very good conclusion and analysis

PAGE 30

PAGE 31



Comment 12

good conclusion, state circuit type

PAGE 32

PAGE 33



Comment 13

good work

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Comment 14

explain what the scaling factor does and how

PAGE 37



You have worked this out correctly, well



Comment 15

exaplain -ve fback effect

PAGE 38

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QM

You have worked this out correctly, well

PAGE 42

PAGE 43

QM

You have worked this out correctly, well



Comment 16

number sub parts of tasks for clarity

PAGE 44

PAGE 45



Comment 17

Good analysis

PAGE 46



Comment 18

good annotation on graph, order Kp increasing in table for trend transparency

QM

You have worked this out correctly, well

PAGE 47

QM

You have worked this out correctly, well

PAGE 48

PAGE 49

**Well done**

Well done

**Comment 19**

if there were no damping here it would not converge on zero

**Well done**

Well done

GRADING FORM: NEW CSG-RUBRIC

ALEX WILLIAMS**78****1. ENGAGEMENT WITH LITERATURE**

NA

2. KNOWLEDGE AND UNDERSTANDING

Excellent explanations given which shows your understanding. 26/30

26**3. COGNITIVE AND INTELLECTUAL**



Excellent analysis given save a few areas, see comments. This shows your analytical skills, along with a good overall conclusion. 23/30

23

4. PRACTICAL APPLICATION



Excellent simulations and testing results given and clear presentation. 22/30

22

5. TRANSFERABLE SKILLS



Very good report. 7/10

7