McMaster Solar Car Electrical Design Challenge: Upper Year Challenge

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Contents

Introduction:

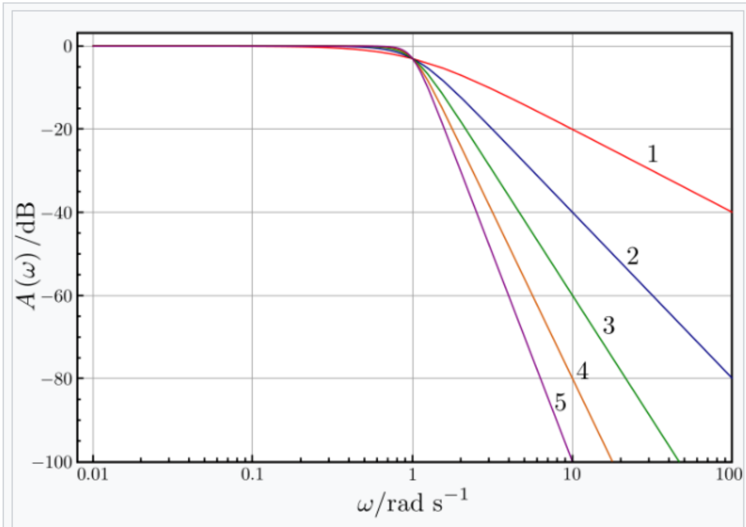
The upper year design challenge requires the development of a circuit which will take a given input signal with lots of noise and cut-off any high frequencies above 1.87kHz with a sharp roll-off. The design requirements are as follows:

- Cutoff frequency of 1.87 kHz
- Signals are within 10 -15V range
- Indicator lights for demonstrating board status
- Reverse polarity protection on the input side
- Minimize the voltage drop and power draw from your device
- BONUS: Design a PCB with your chosen components (preferred EasyEDA)

Design Process:

Butterworth Filter

The circuit discussed in this design challenge is a low-pass filter, which has been previously explored in many circuit design courses at McMaster and specifically ELEC 3TR3. In the first lab we were tasked with designing a 2nd order Butterworth filter, unfortunately such a design will not work for this design challenge. To meet the "sharp roll-off" requirement, a higher order filter is required. The following figure depicts this relation:



Butterworth Filter Gain Plot with Order 1 to 5. [1]

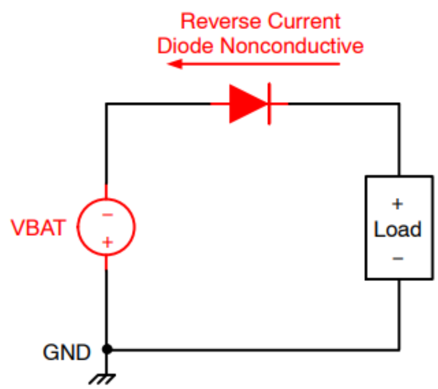
As shown above, to achieve a sharp roll-off, a high order is required. This will be explored further in the calculations portion of the report.

Indicator Light

This is an easy implementation into the circuit where an LED with a series current limiting resistor is placed between the power supply. This way when the circuit is powered on, the LED will indicate this. Note the resistor value will need to be calculated to the LED does not reach its voltage limits, given the high supply voltage of 10-15V. For this design a 10k resistor was used.

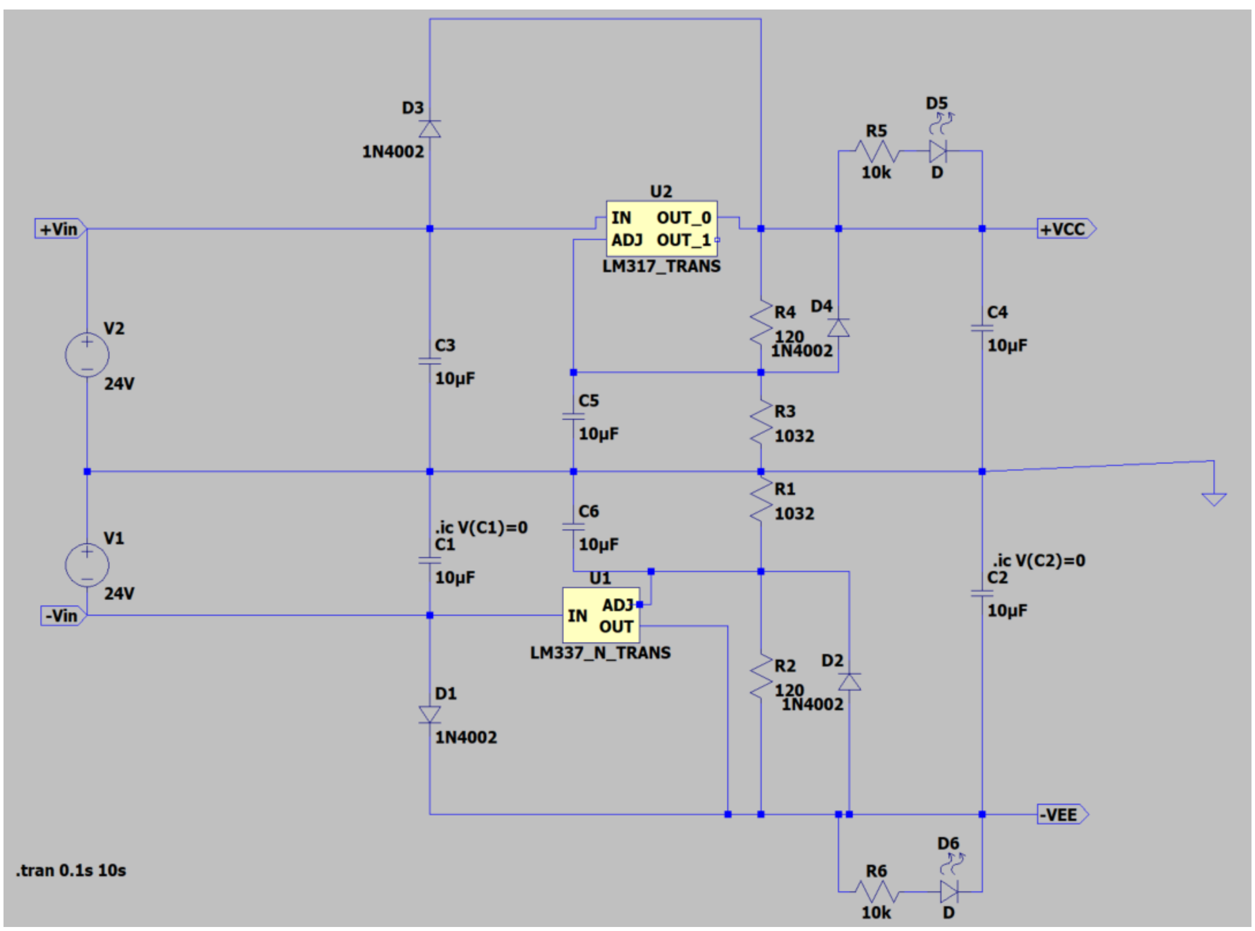
Reverse Polarity

There are many ways to implement reverse polarity protection, with the most common being a simple Schottky diode which will prevent current from flowing through the circuit if its polarity is reversed. The Schottky diode provides a lower voltage drop which fits the design requirements, with the addition of a voltage regulator to help regulate the voltage. Another option for reverse polarity protection would be using a P-Channel MOSFET design would be used, but with a lower voltage drop.

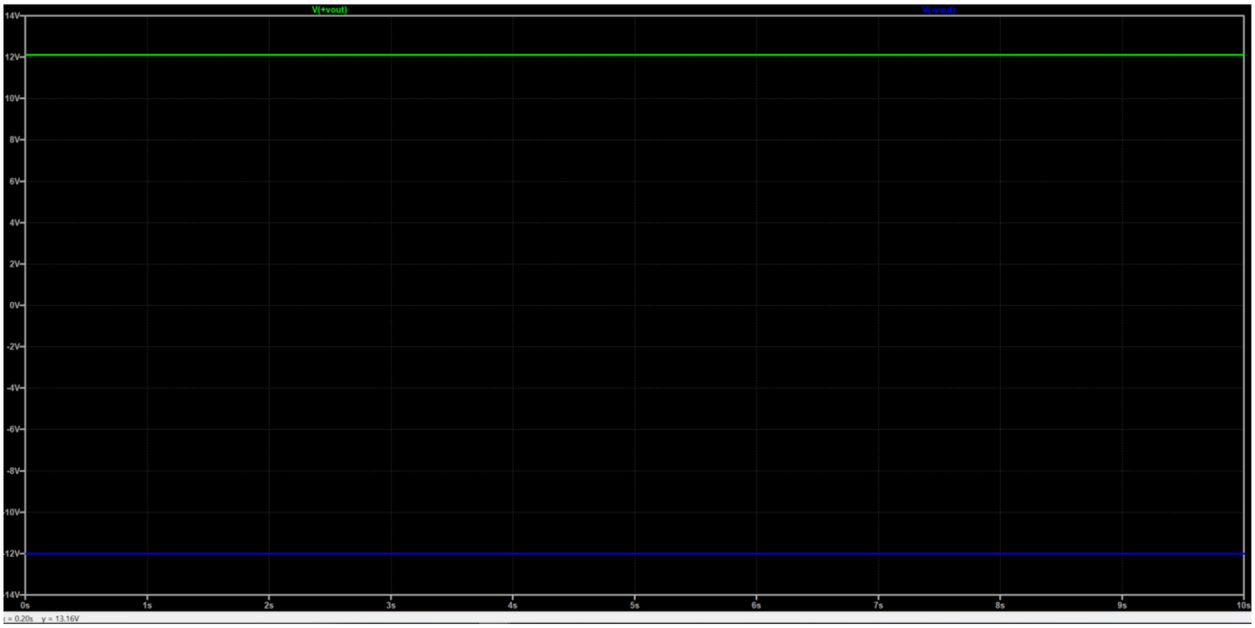


Reverse Polarity Protection Using a Diode. [1]

We can incorporate this property of a diode with voltage regulators to create a rail splitter circuit, which will provide +12V and -12V as Op-amps typically require dual supplies to operate. Using the LM337 (Negative voltage regulator) and LM317 (Positive voltage regulator) and a common ground point, I was able to create a dual power supply with D1 and D3 as reverse polarity. Capacitors were placed for capacitor discharge protection and decoupling.



<u>*Dual Rail Power Supply*</u>



Output Voltage +12 and -12V

Design Component Selection

Component	**Part Number**	**Features**
Diode	1N5819	Reverse voltage = 40V
Op-Amp	LM358	Supply Range = 3V to 36V
Positive Voltage Regulator	LM317	Supply Range = 4V to 40V
Negative Voltage Regulator	LM337	Supply Range = -4V to -40V

Calculations and Simulations:

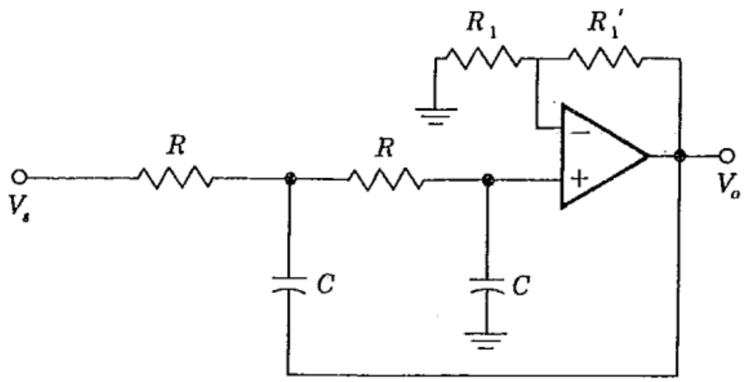
Butterworth Filter

A Butterworth Filter design was used due to its noise reduction applications and the ability to generate a steep roll off at the cut off frequency by simply cascading multiple lower order filter stages. For example, to create a 4th-order filter, we can cascade two 2nd-order sections together using the following equations which are derived from the factors of polynomials of a Normalized Butterworth Filter:

TABLE 16-1 Normalized Butterworth polynominals

n	Factors of polynomial $P_n(s)$
1	$(s+1)$
2	$(s^2+1.414s+1)$
3	$(s+1)(s^2+s+1)$
4	$(s^2+0.765s+1)(s^2+1.848s+1)$
5	$(s+1)(s^2+0.618s+1)(s^2+1.618s+1)$
6	$(s^2+0.518s+1)(s^2+1.414s+1)(s^2+1.932s+1)$
7	$(s+1)(s^2+0.445s+1)(s^2+1.247s+1)(s^2+1.802s+1)$
8	$(s^2+0.390s+1)(s^2+1.111s+1)(s^2+1.663s+1)(s^2+1.962s+1)$

Butterworth Filter Polynomials [3]



Secord-Order Low-Pass Section [3]

Using n=4 for a fourth order polynomial we can obtain the following K values and thus find our resistor values for the filter:

Cutoff frequency: $\boxed{f_c = \frac{1}{2\pi RC}}$

To get a sharp roll off: 4th Order Butterworth Filter

$n = 4$

$$P_n(s) = (s^2 + 0.765s + 1)(s^2 + 1.848s + 1)$$

$K_1 = \frac{0.765}{2} = \boxed{0.3825}$

$Av_1 = 3 - 2K$

$= 3 - 2(0.3825)$

$\boxed{Av_1 = 2.235}$

$Av_1 = \frac{R_1 + R_1'}{R_1}$

$2.235R_1 = R_1 + R_1'$

$\boxed{R_1' = 1.235R_1}$

Let $R_1 = 10K\Omega$

$\therefore R_1' = 12.35K\Omega$

$K_2 = \frac{1.848}{2} = \boxed{0.924}$

$Av_2 = 3 - 2K$

$= 3 - 2(0.924)$

$\boxed{Av_2 = 1.152}$

$Av_2 = \frac{R_2 + R_2'}{R_2}$

$1.152R_2 = R_2 + R_2'$

$\boxed{R_2' = 0.152R_2}$

Let $R_2' = 1.52K$

$\therefore R_2 = 10K$

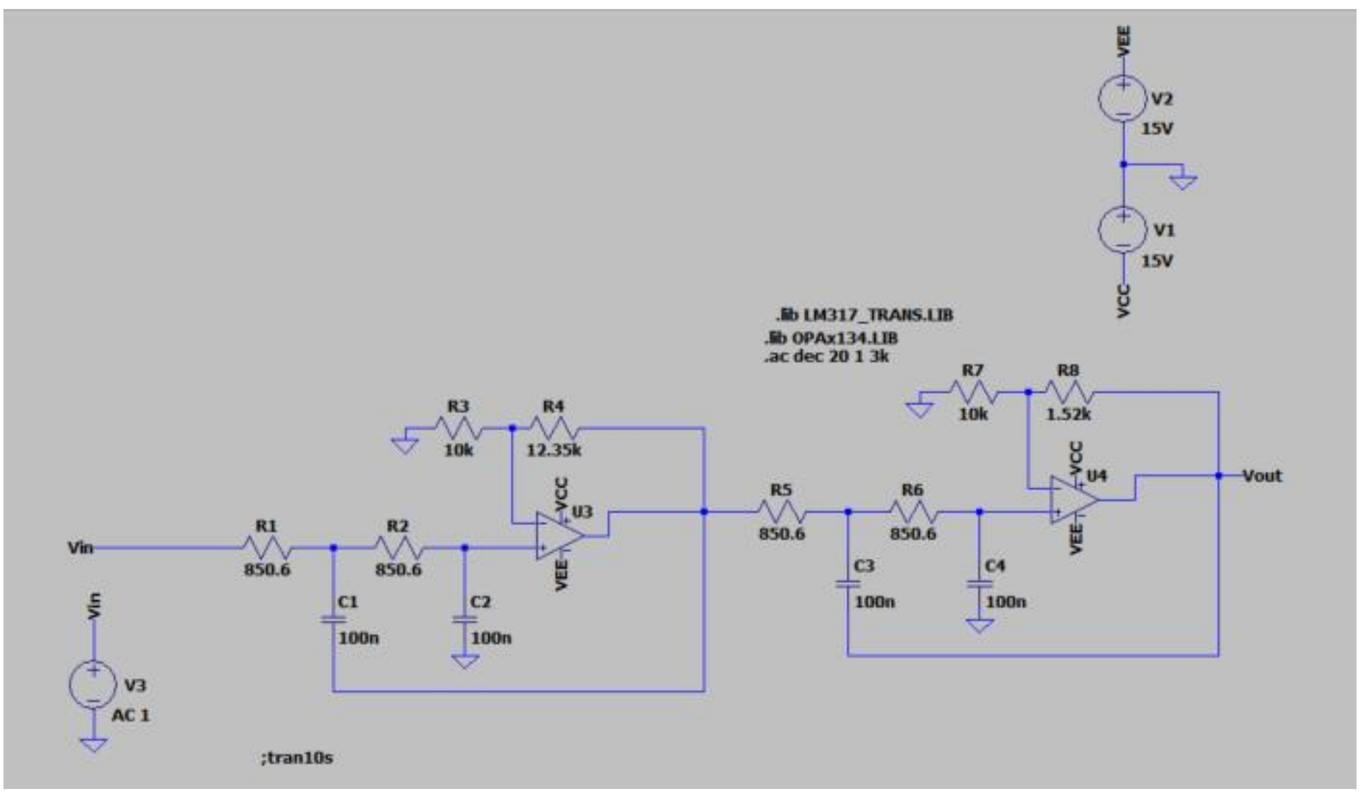
$$\boxed{f_c = \frac{1}{2\pi RC}}$$

$$1.87\,kHz = \frac{1}{2\pi RC}$$

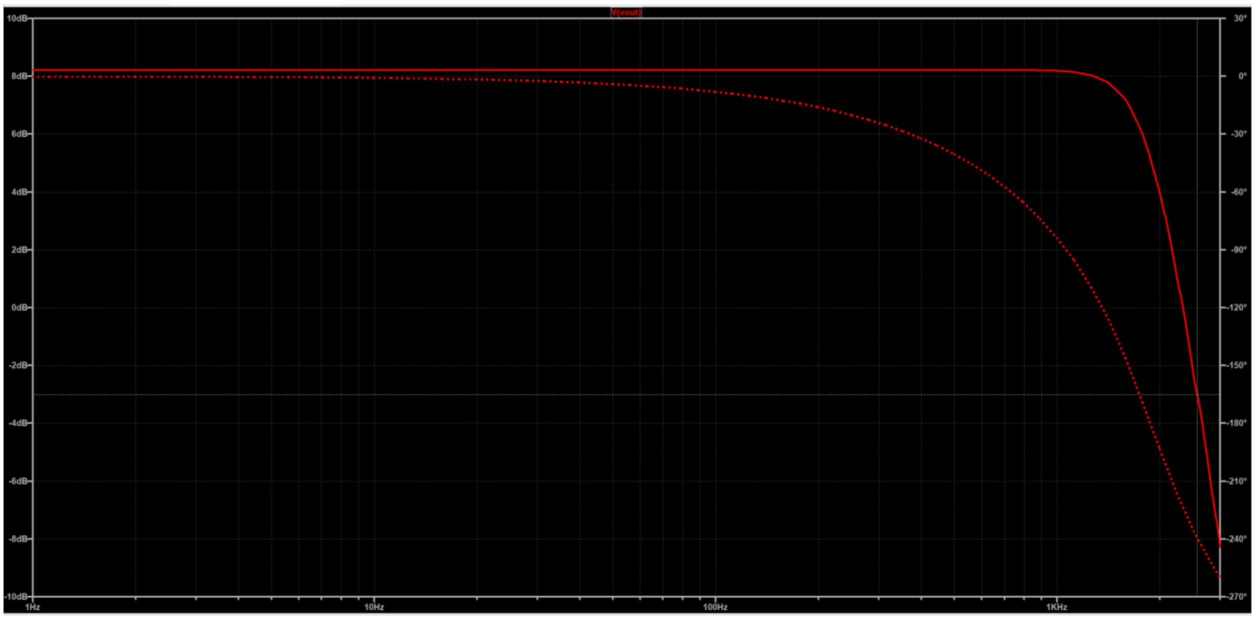
$\boxed{\text{Let } C = 100nF}$

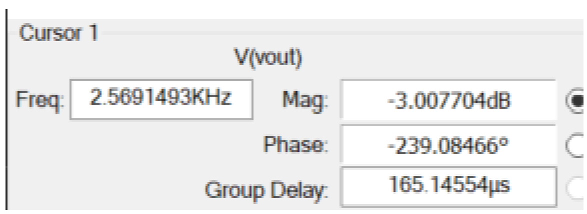
$$R = \frac{1}{2\pi \cdot 1.87k \cdot 100n}$$

$$\boxed{R = 850.6\Omega}$$



Fourth-Order Low-Pass Filter





Unfortunately, this 4th-order design does not meet our requirements of having a steep roll off, therefore we need to move up to a n=6 design and cascade another 2nd order filter. The calculations can be seen below:

$n=6$

$P_n(s)=(s^2+0.518s+1)(s^2+1.414s+1)(s^2+1.932s+1)$

$K_1=\frac{0.518}{2}$ $\quad K_2=\frac{1.414}{2}$ $\quad K_3=\frac{1.932}{2}$

$$A_{v_1}=3-2K_1 = 3-0.518 = 2.482$$

$$A_{v_2}=3-2K_2 = 3-1.414 = 1.586$$

$$A_{v_3}=3-2K_3 = 3-1.932 = 1.068$$

$$A_{v_1}=\frac{R_1+R_1'}{R_1} \qquad A_{v_2}=\frac{R_2-R_2'}{R_2} \qquad A_{v_3}=\frac{R_3-R_3'}{R_3}$$

$2.482R_1=R_1+R_1'$ $\quad 1.586R_2=R_2-R_2'$ $\quad 1.068R_3=R_3-R_3'$

$\boxed{R_1'=1.482R_1}$ $\quad \boxed{R_2'=0.586R_2}$ $\quad \boxed{R_3'=0.068R_3}$

$R_1=1K$, $R_1'=1.482K$

$R_2=1K$, $R_2'=586\Omega$

$R_3=1K$, $R_3'=68\Omega$

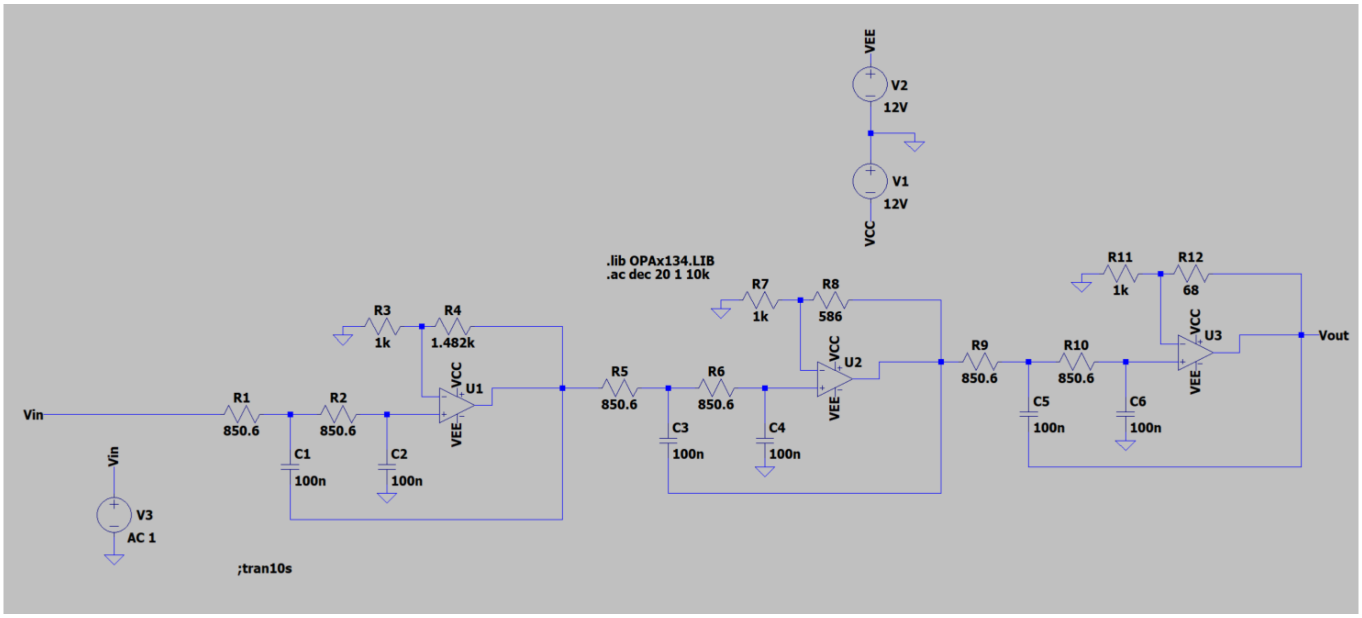
$$\boxed{f_c=\frac{1}{2\pi RC}}$$

$$1.87\,kHz=\frac{1}{2\pi RC}$$

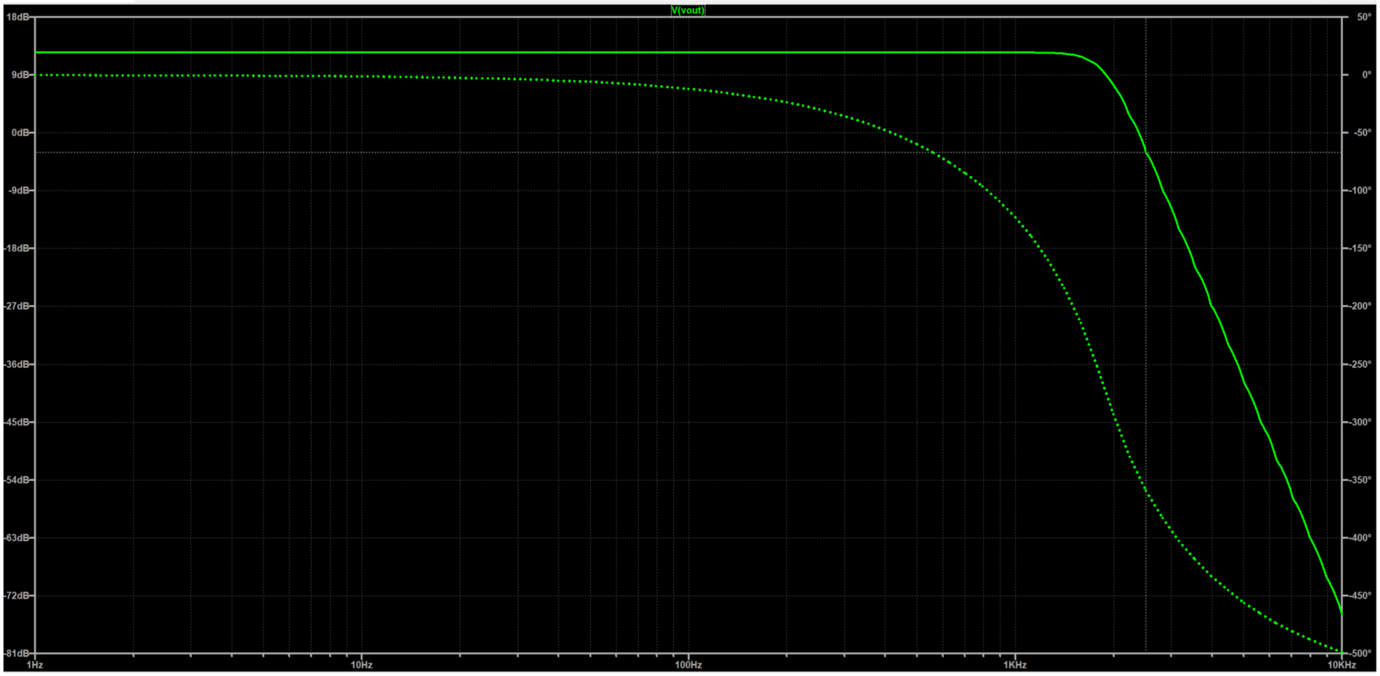
$\boxed{\text{Let } C=100nF}$

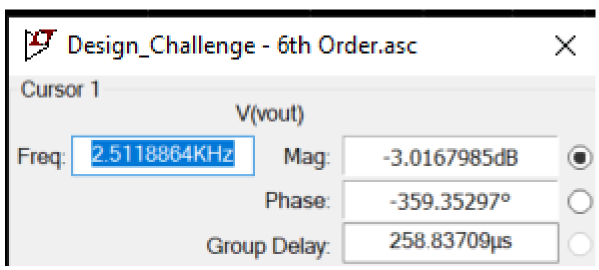
$$R=\frac{1}{2\pi\cdot 1.87k\cdot 100n}$$

$$\boxed{R=850.6\Omega}$$



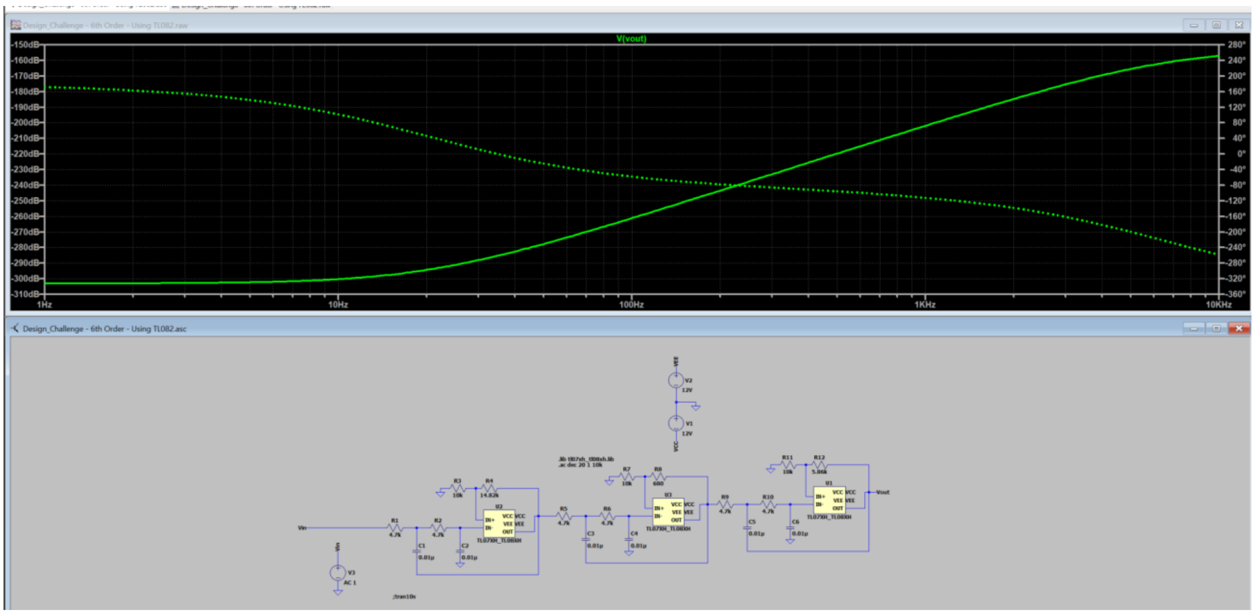
Six-Order Low-Pass Filter


V(vout)
18dB
9dB
0dB
-9dB
-18dB
-27dB
-36dB
-45dB
-54dB
-63dB
-72dB
-81dB
50°
0°
-50°
-100°
-150°
-200°
-250°
-300°
-350°
-400°
-450°
-500°
1Hz
10Hz
100Hz
1KHz
10KHz


Design_Challenge - 6th Order.asc
Cursor 1
V(vout)
Freq: 2.5118864KHz
Mag: -3.0167985dB
Phase: -359.35297°
Group Delay: 258.83709µs

Trouble Shooting:

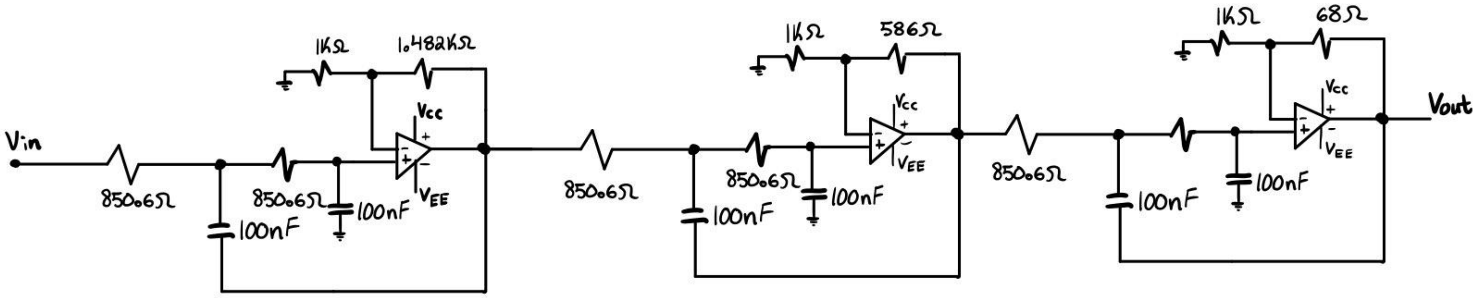
Unfortunately, despite using a 6th order butter worth filter, the cutoff frequency is not 1.87kHz and for some reason the roll-off has gotten less steep compared to the 4th order circuit design. Using validated resistor and capacitor values which should result in a 1.87kHz response still does not output the proper cutoff frequency. This issue may be attributed with the SPICE software, or the op-amps selected. Using a universal op-amp and importing a custom SPICE model for a Texas Instrument TL082 Op-amp did not resolve the issue.

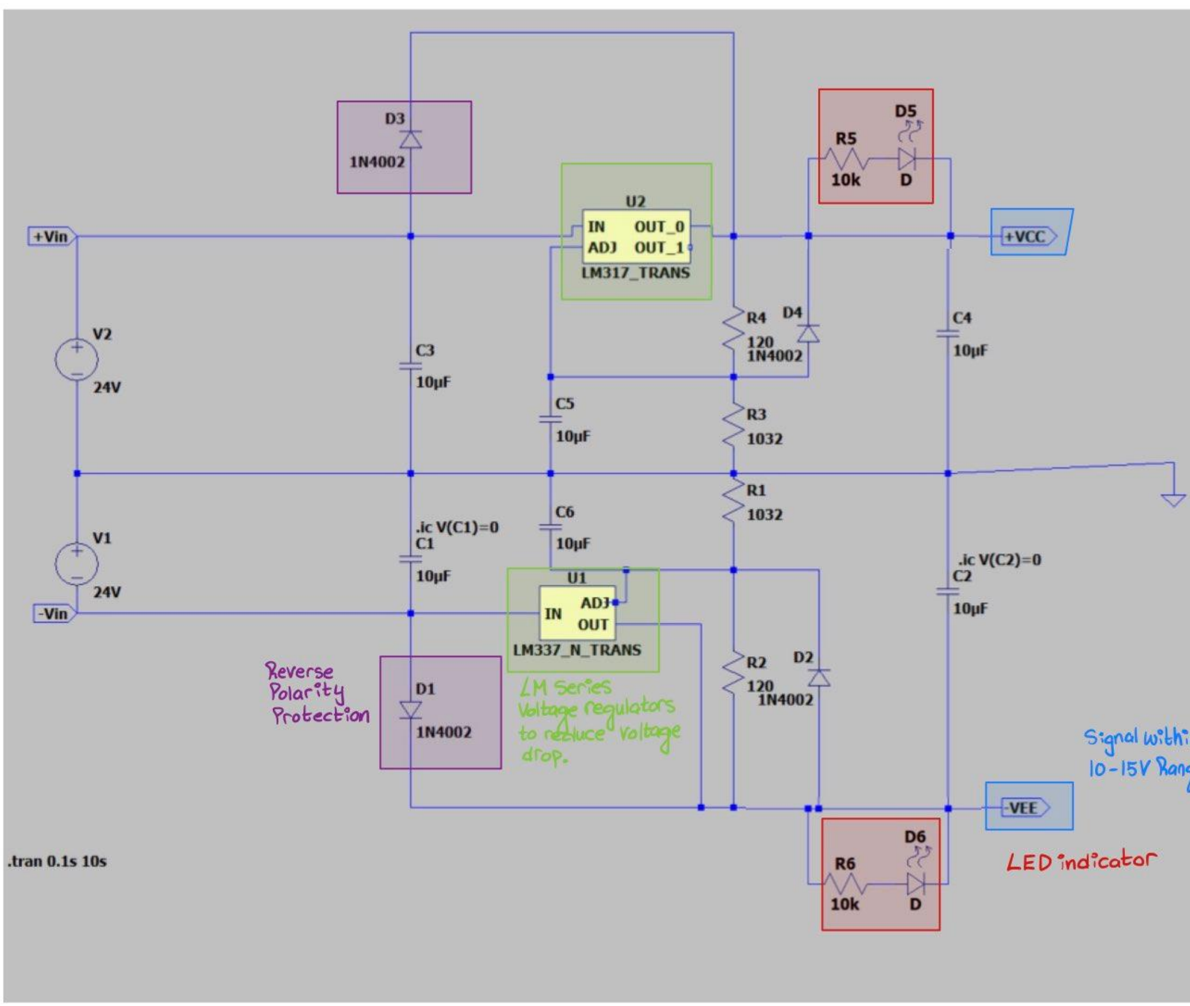


Incorrect Frequency Response Circuit

Final Design:

Despite not being able to simulate a working 6th order butter-worth filter, I continued the design to meet the rest of the design challenge requirements as shown below:

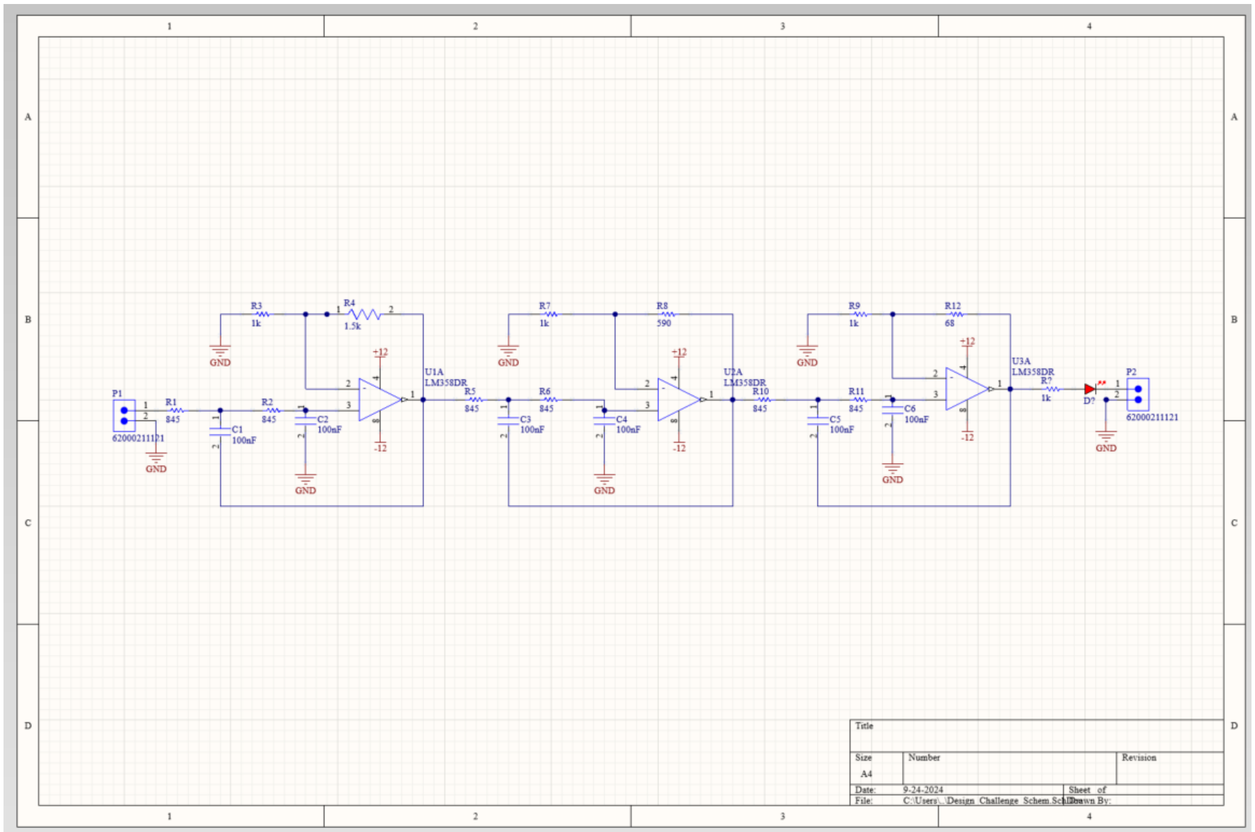


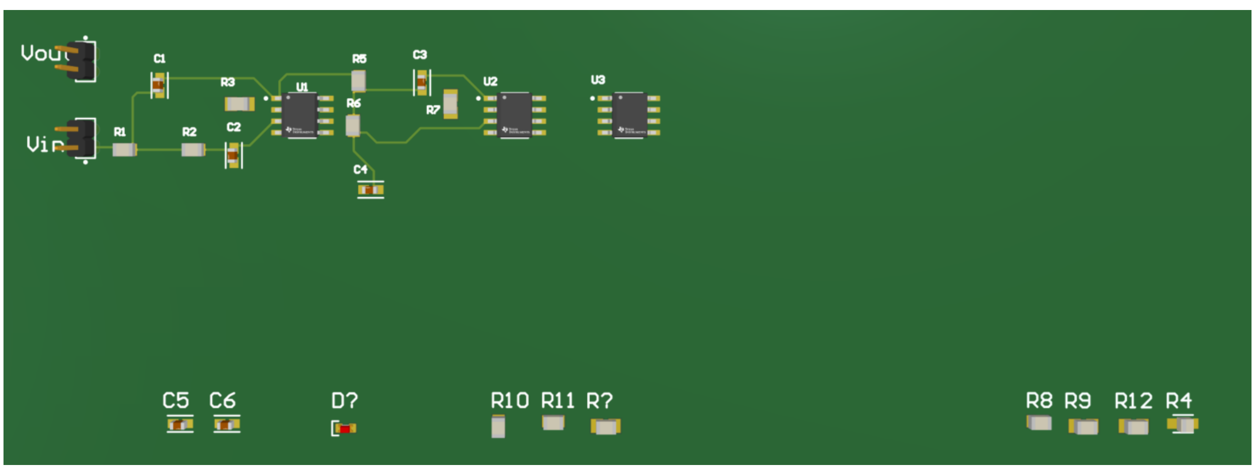


*All components are within Voltage range.

PCB Design:

Unfortunately, due to time constraints I was unable to complete the PCB bonus, however I began a brief design.





References:

AND90146 - MOSFET selection for reverse polarity … (n.d.-a). https://www.onsemi.com/download/application-notes/pdf/and90146-d.pdf

Butterworth filters. (n.d.-b). https://www.ece.mcmaster.ca/~kumars/Communication_System/LABS/appendix%20for%20Butterworth%20filters.pdf

Wikimedia Foundation. (2024, September 24). *Butterworth filter*. Wikipedia. https://en.wikipedia.org/wiki/Butterworth_filter