University of Colorado - Boulder

ECEN 2270
Electronics Lab | Spring 2024

ECEN 2270 Electronics Lab: Lab 0

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I. Experiment 0.A

A. 0.A.2 - A Simple RC LPF

In this experiment, we change the voltage source frequency and run a transient simulation for various frequencies. The change in frequency results in a of value of the amplitude.

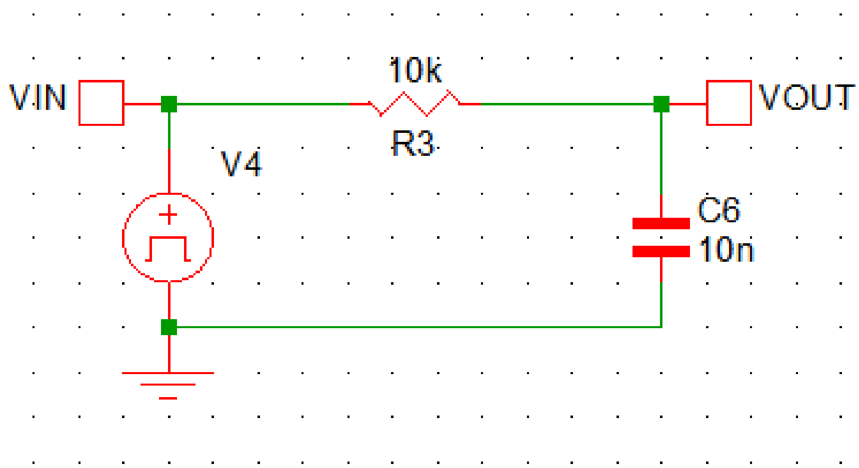


Fig. 1 LPF Circuit

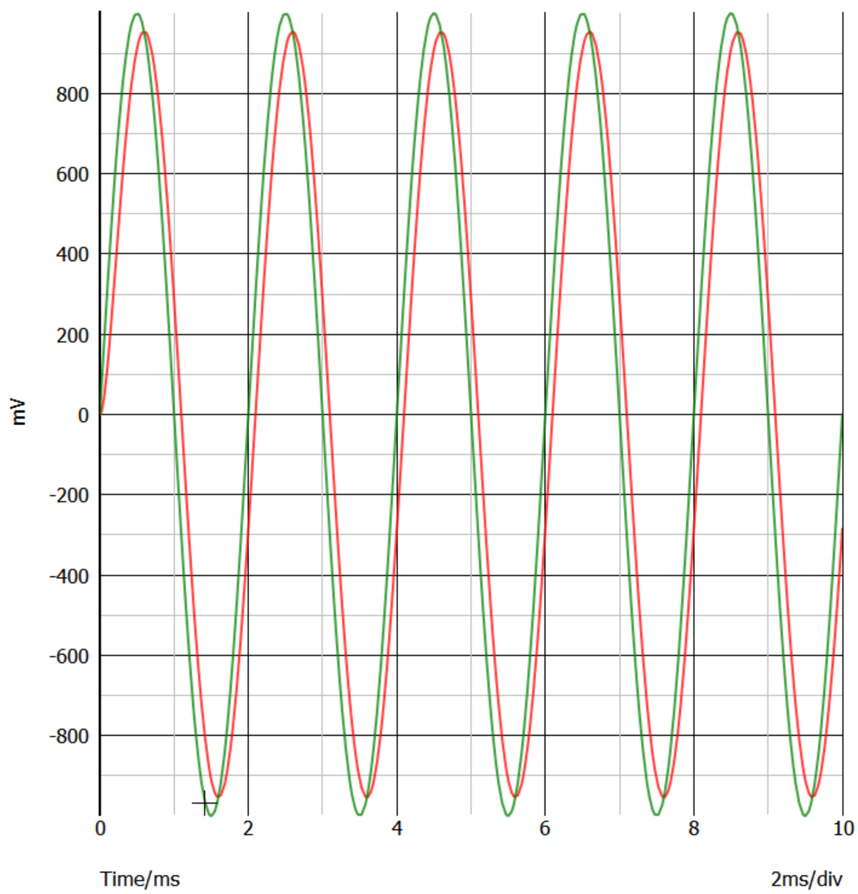


Fig. 2 V_{in} **(green) and** V_{out} **(red) for LPF**

We measured an amplitude at each frequency to see how the change looks like in a scatter plot:

Vin	Vout	f	H(f)
996.6	991.1	200	0.994481
1000	954.35	500	0.95435
996.58	853.33	1000	0.856258
996.58	688.72	2000	0.691084
996.58	419.58	5000	0.42102
996.58	252	10000	0.252865

Fig. 3 Freqency Response

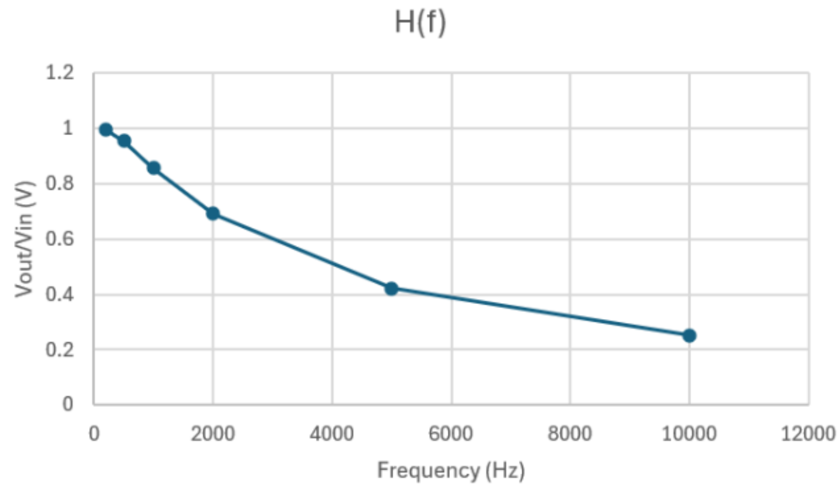


Fig. 4 V_{out} **vs frequency**

B. 0.A.3 - A Bode Plot for the LPF

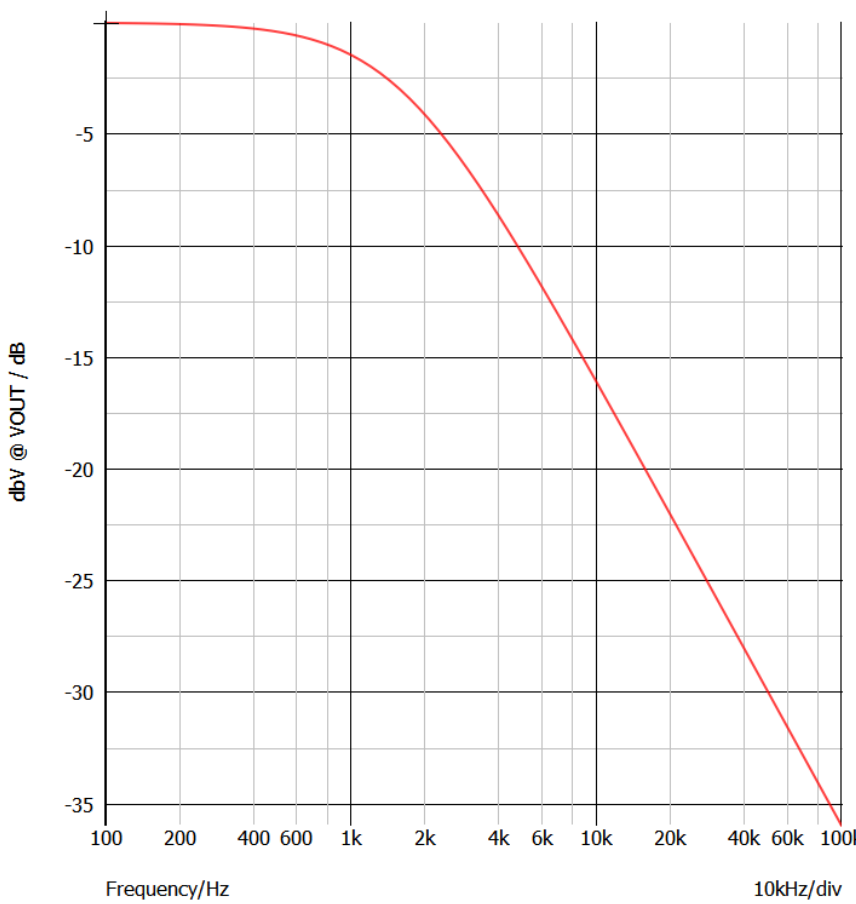


Fig. 5 LPF Bode Plot

Questions from Experiment:

What is the maximum gain of the circuit?
The maximum Gain is 0dB (or 1 Volt).

What is the -3 dB frequency (i.e., the frequency at which V_{out} has decreased by 3 dB from its maximum value) of the circuit?
The frequency at -3dB is about 1.6k Hz.

How is the -3 dB frequency related to R and C?

$$f_3 = \frac{1}{2\pi RC}$$

If you wanted f_3 to be equal to 1 kHz, how would you have to change R (or C)?
Increase the value of R or C to decrease the value of f_3.

How is the -20 dB frequency f_{20} related to f_3?
It is one order of magnitude higher in voltage.

What is the input impedance of the circuit, at low frequencies and at high frequencies?
At low frequencies, the impedance is mostly dependent on the capacitance modeled by $\frac{1}{j\omega C}$); the impedance at very low frequencies the impedance is very high. At high frequencies, the impedance is represented by the resistor, which is 10k ohms.

What would happen if you would use two such circuits in series?
The attenuation would be double. Meaning that on a bode plot its stopband attenuation would be -40 dB/dec; or -20N dB/dec (where N is the number of LPF circuits connected).

C. 0.A.4 - An OpAmp LPF

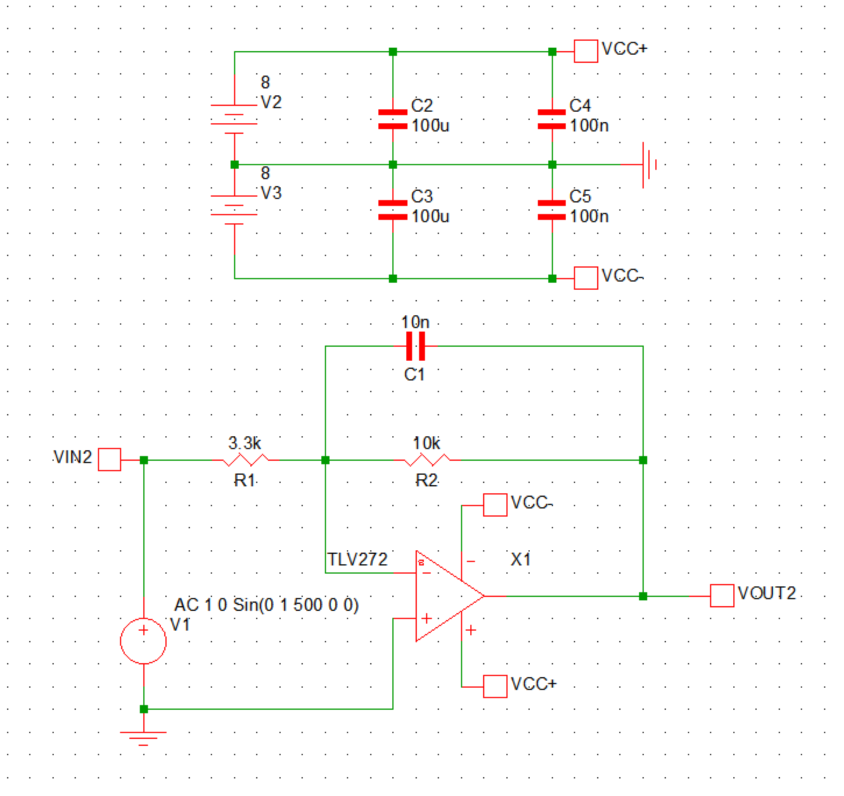


Fig. 6 OpAmp LPF Dual Power Supply

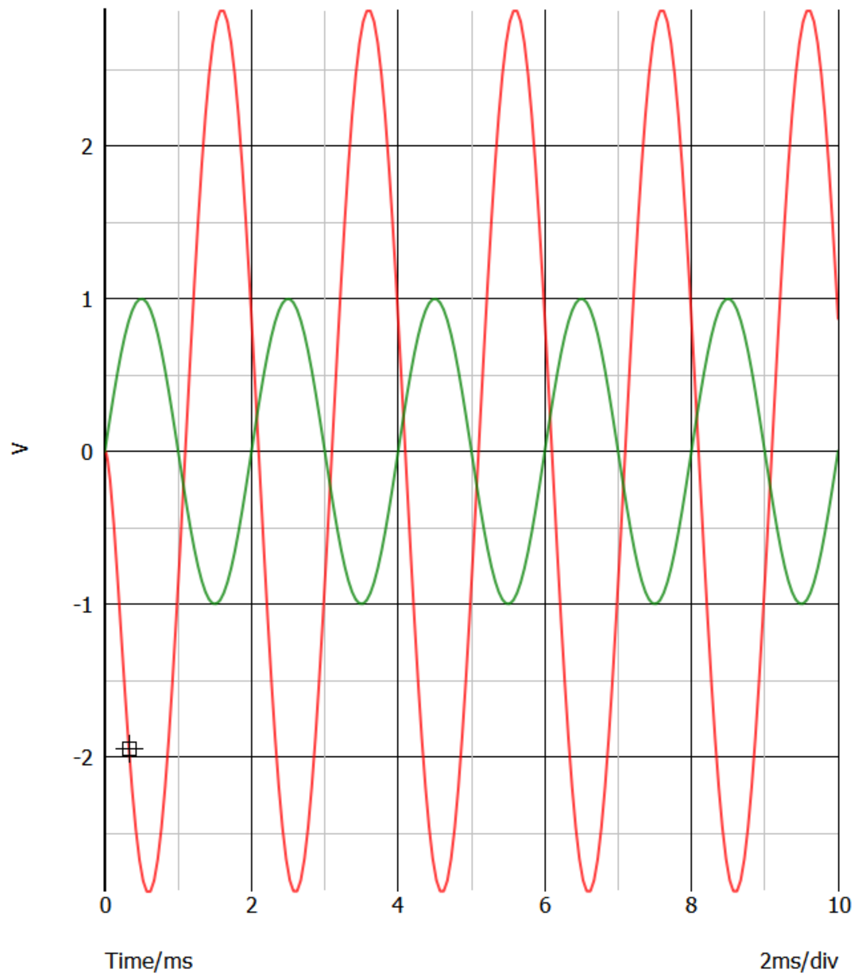


Fig. 7 V_{in} **(green) and** V_{out} **(red) for OpAmp LPF**

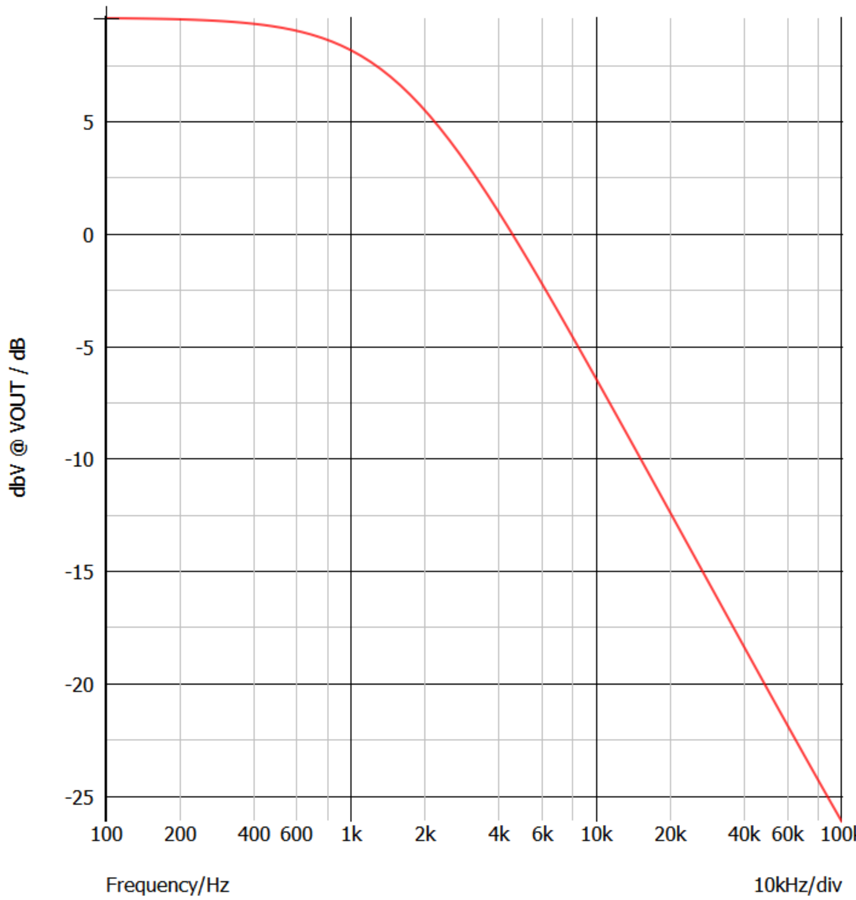


Fig. 8 Bode Plot for OpAmp LPF

Questions from Experiment:

What is the maximum gain of the circuit?
The maximum gain is about 9.6 dB.

What is the -3 dB frequency (i.e., the frequency at which V_{out} has decreased by 3 dB from its maximum value) of the circuit?
The -3 dB (below passband) frequency is about 1.56k Hz.

How is the -3 dB frequency related to R and C?

$$|H(s)| = \frac{R_2}{\sqrt{R_1^2 + (\omega R_1 R_2 C)^2}}$$

The above equation is the magnitude transfer function, which is used to create a bode plot. ω is angular frequency, or $2\pi f$. Thus, it can be seen that the shape of the bode plot (and thus its magnitudes at different frequencies) are directly related to both resistor and the capacitor values.

If you wanted f_3 to be equal to 1 kHz, how would you have to change R (or C)?
You can decrease the resistor values or increase the capacitor value.

How is the -20 dB frequency f_{20} related to f_3?
-20 dB (relative to the passband) is 1 decade past the corner frequency).

What is the input impedance of the circuit, at low frequencies and at high frequencies?

At low frequencies the capacitor becomes a short circuit and the resistors are unfazed. The same is to be said of high frequency except the capacitor now acts like a short circuit for most of the AC waves period.

What would happen if you would use two such circuits in series?

Once again, you would be creating a second order filter where the attenuation would be -20N dB where N is the number of circuits in series.

D. 0.A.5 - Single Supply OpAmp LPF

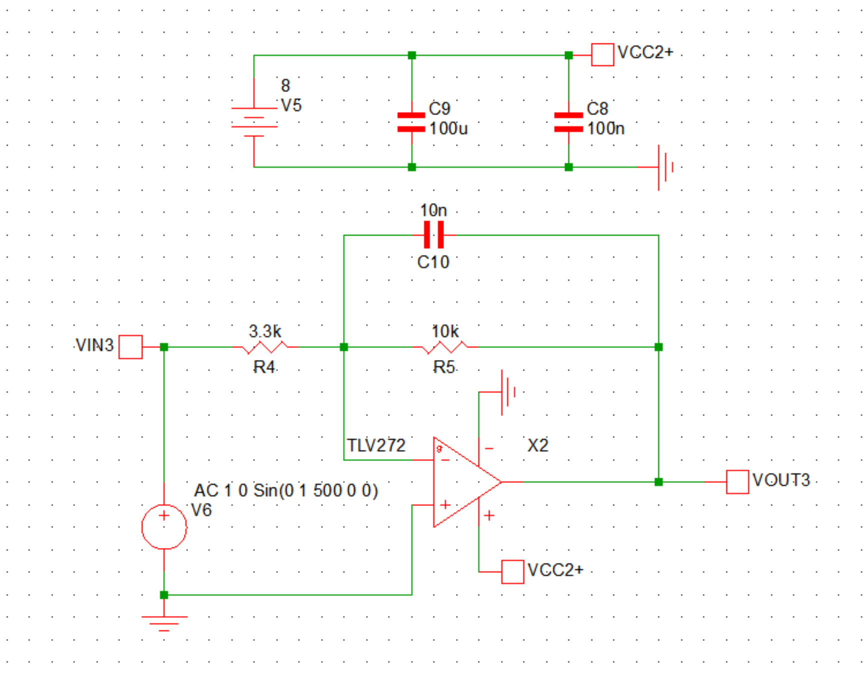


Fig. 9 OpAmp LPF Single Power Supply

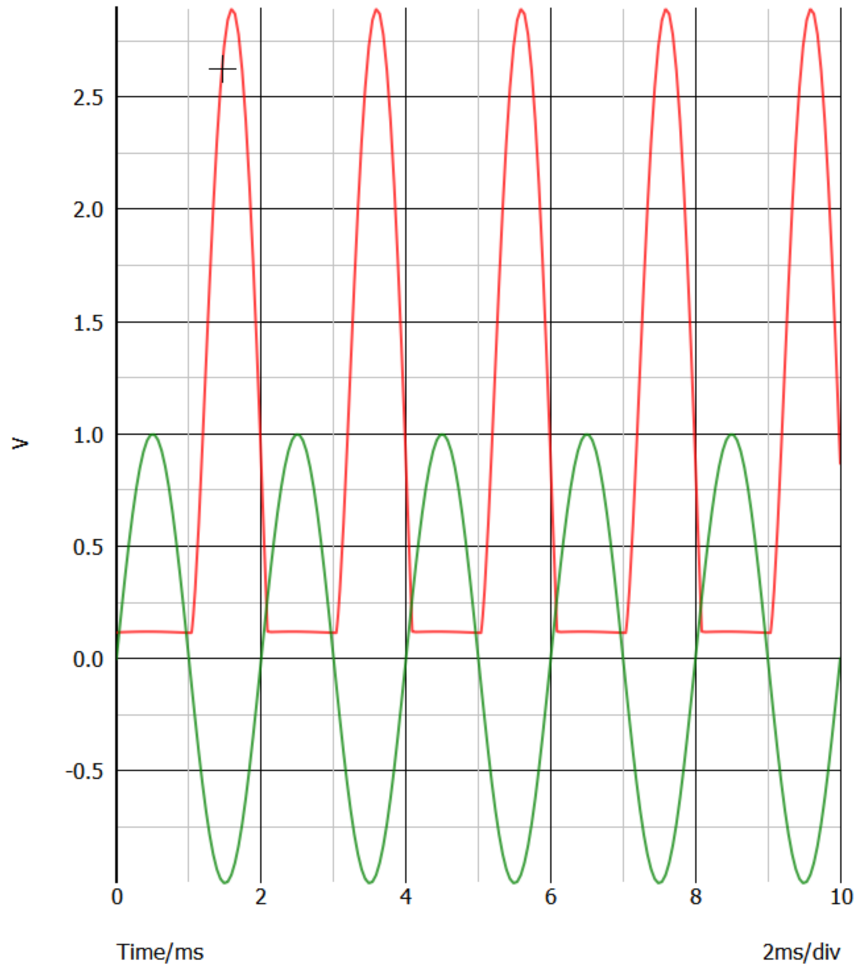


Fig. 10 V_{in} **(green) and** V_{out} **(red) for OpAmp LPF with a single power supply**

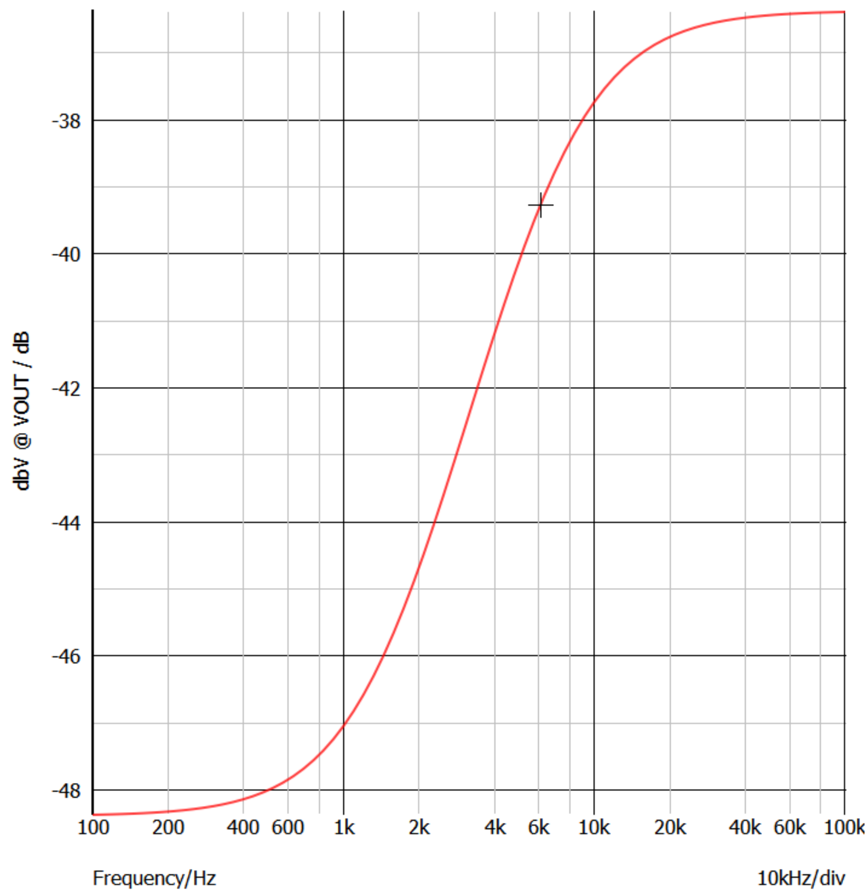


Fig. 11 Bode Plot for Single Power Supply OpAmp LPF

As seen from the output waveform, there is significant clipping from the OpAmp when the input waveform is roughly less than 0 V. This makes sense as when the negative terminal of the OpAmp sees a higher voltage than the positive terminal, it is restricted to not be higher than the negative power rail (which is set as 0 V). Thus half of the output waveform is clipped significantly skewing the bode plot.

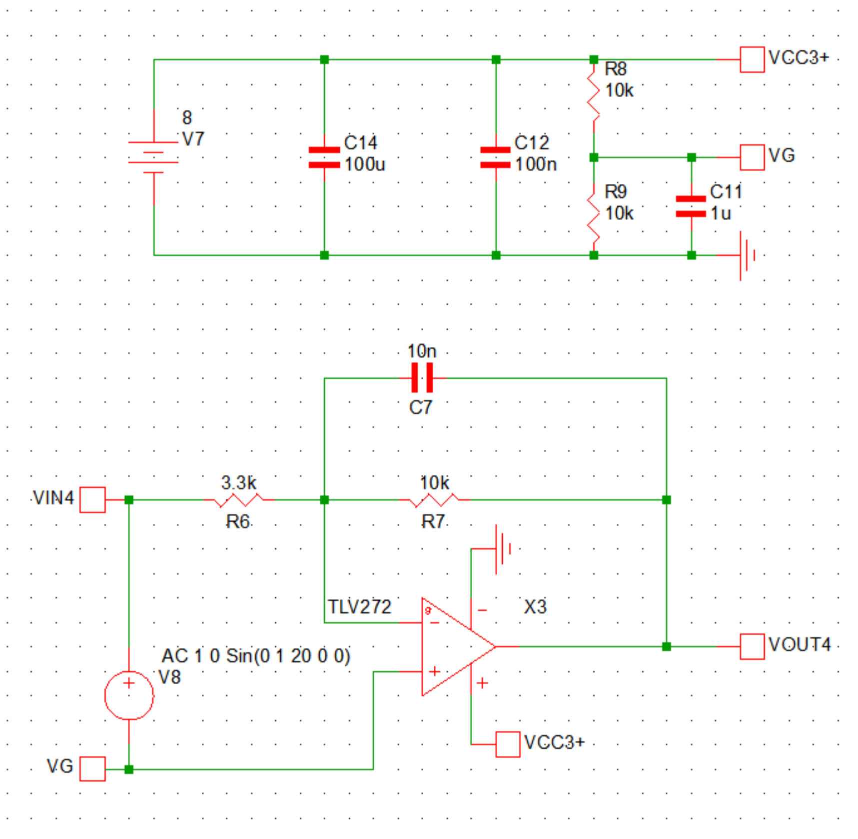


Fig. 12 OpAmp LPF Virtual Ground

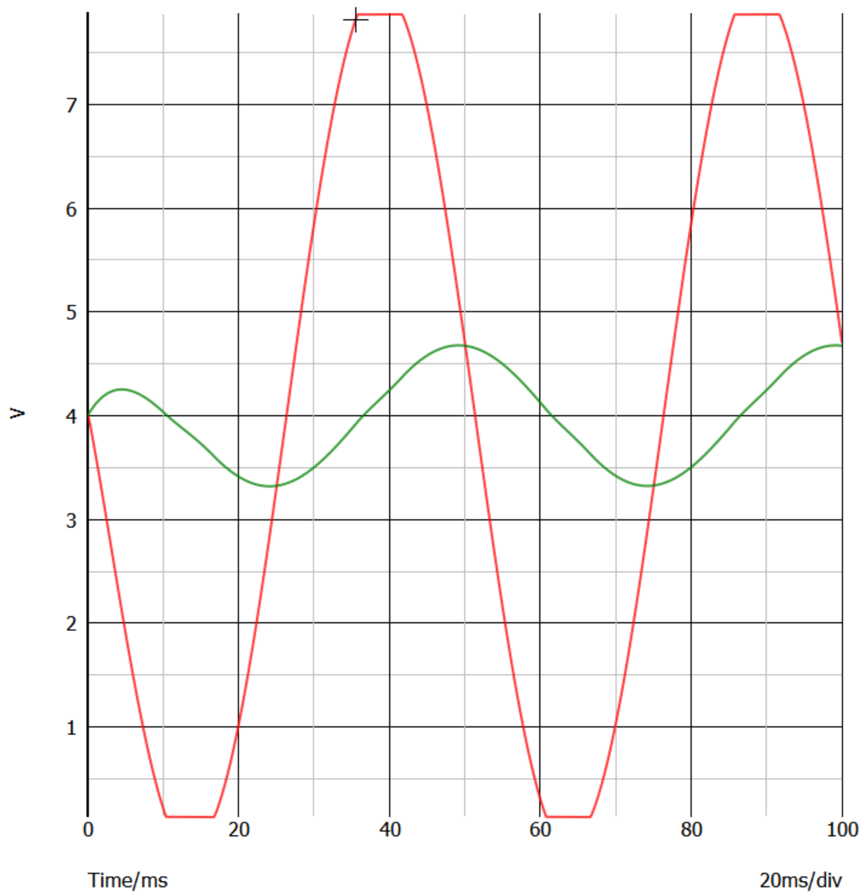


Fig. 13 V_{in} **(green) and** V_{out} **(red) for OpAmp LPF with a Virtual Ground**

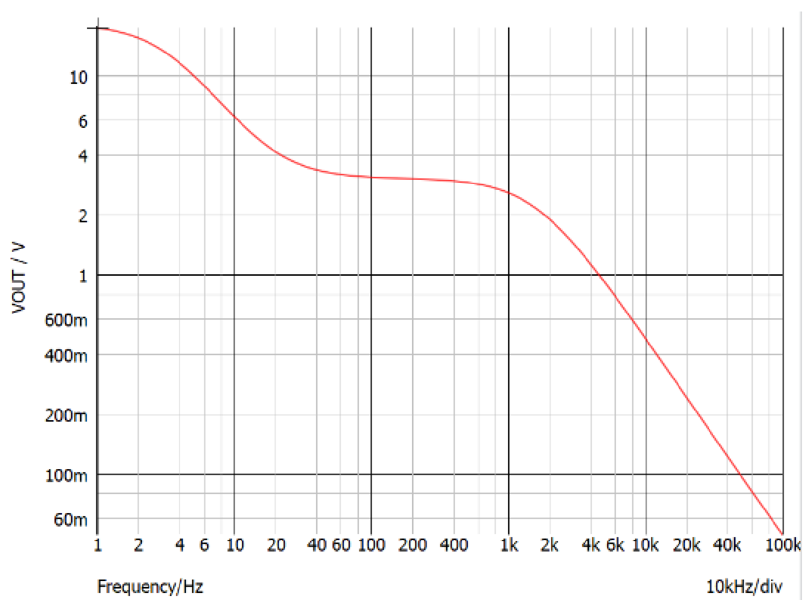


Fig. 14 OpAmp LPF with Virtual Ground Bode Plot

Naturally these results are unsatisfactory, but they can be rectified by reformatting the circuit:

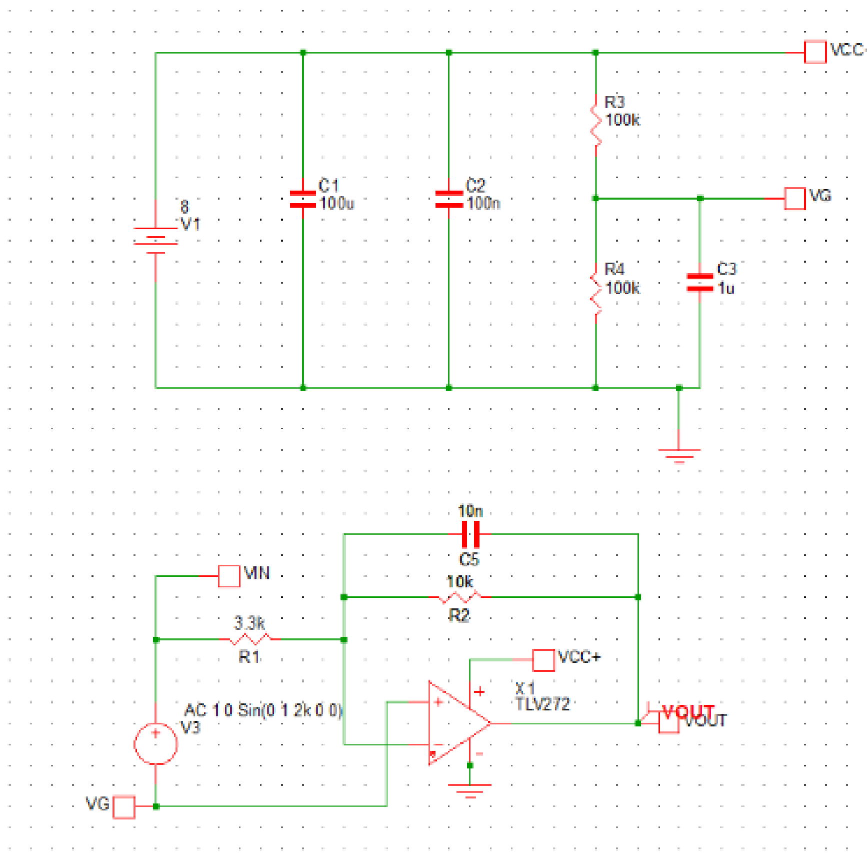


Fig. 15   Rectified Circuit

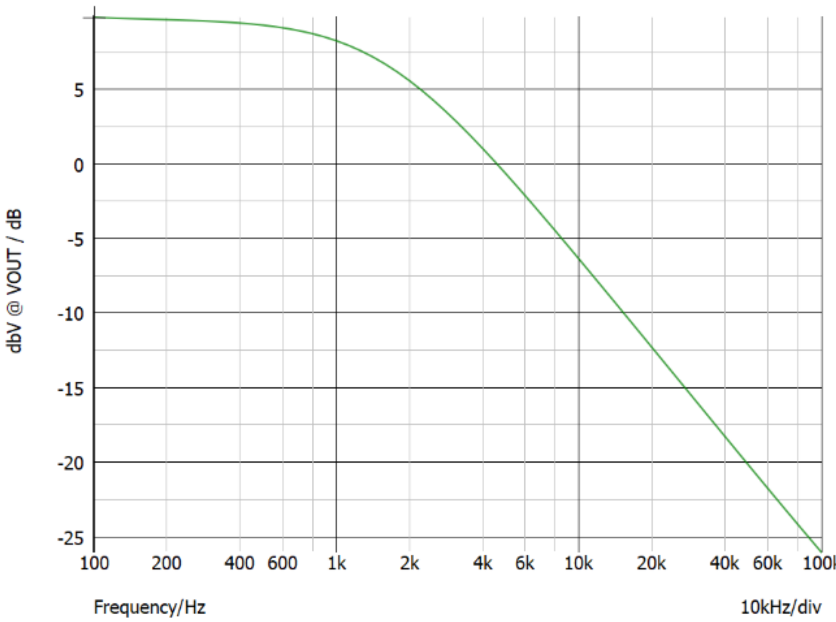


Fig. 16 Rectified Bode Plot

E. 0.A.6 - PWM

Fig. 17 Square-wave Generation and FFT

We may also not that the FFT representation changes with respect to the duty cycle of the PWM signal.

Fig. 18 25% Duty Cycle

Fig. 19 33.3% Duty Cycle

Fig. 20 50% Duty Cycle

Fig. 21 6ms Period

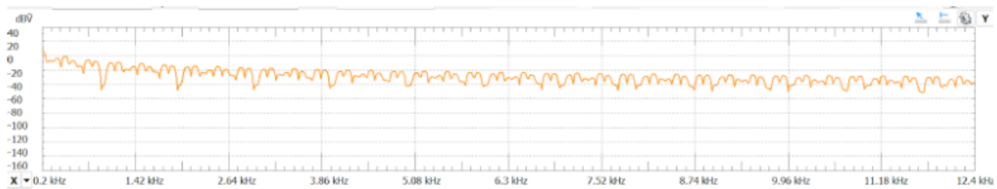


Fig. 22 10ms Period

Questions from Experiment:

How does the pattern of the Fourier series coefficients change when the duty cycle of the PWM waveform changes?
Due to the properties of signal modulation, natural harmonic frequencies will appear due to the frequencies used in order to build the signal using a discrete amount of sinusoidal Fourier series. Thus, as the duty cycle becomes less symmetrical, the resonant frequencies needed in order to represent that waveform increase.

How does the pattern of the Fourier series coefficients change when the period of the PWM waveform changes?
Naturally, as the period increases, the frequency decreases, and thus less Fourier series are needed in order to properly represent the desired signal. The opposite is true, as an increased frequency means that more Fourier series need to be implemented in order to accommodate for the higher frequency components of the wave.

What if a triangular waveform is used instead of the rectangular one?
A triangular wave will need more involved Fourier series signals as its wave-pattern is more complex than the up and down (binary) nature of a square or pulse wave. This is due to the falling edge of the triangular wave needing to be made of multiple harmonics to see a falling (small ripple voltage) AC signal that represents a flat falling slope.

F. 0.A.7 - DAC Using PWM and LPF
In order to achieve the desired attenuation and cutoff frequency, we need to determine the appropriate values of R and C.

$$|H(j\omega)| = \frac{1}{\sqrt{1 + \omega RC^2}}$$

If we set R = 1kΩ and the corner frequency at 100 Hz or 200π rad/s, we can solve for C, which should be equal to 1.6μF. Analytically, values of R = 1.01Ω and C = 1.58mF are valid, however resistor power ratings as well as the time constant ($\tau = RC$) of the circuit must be considered.

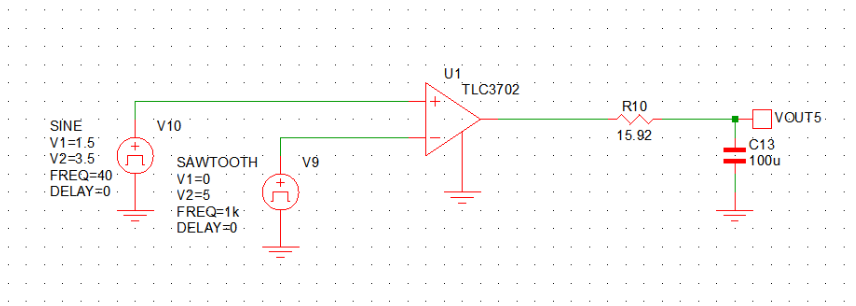
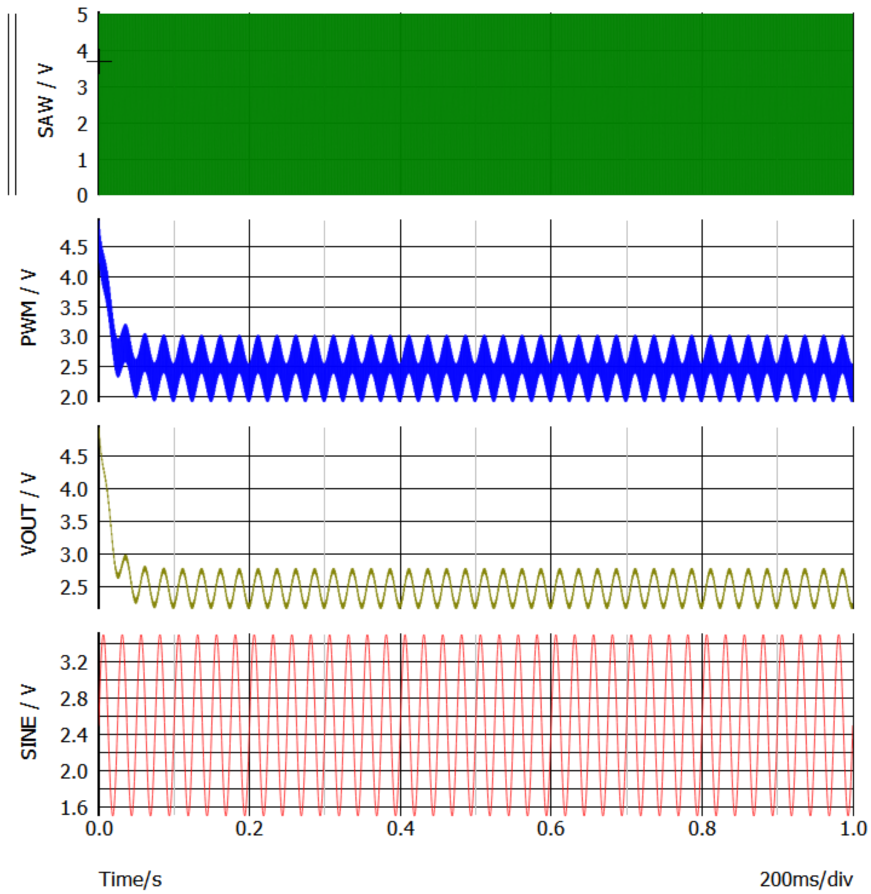


Fig. 23 LPF Digital to Analog Converter



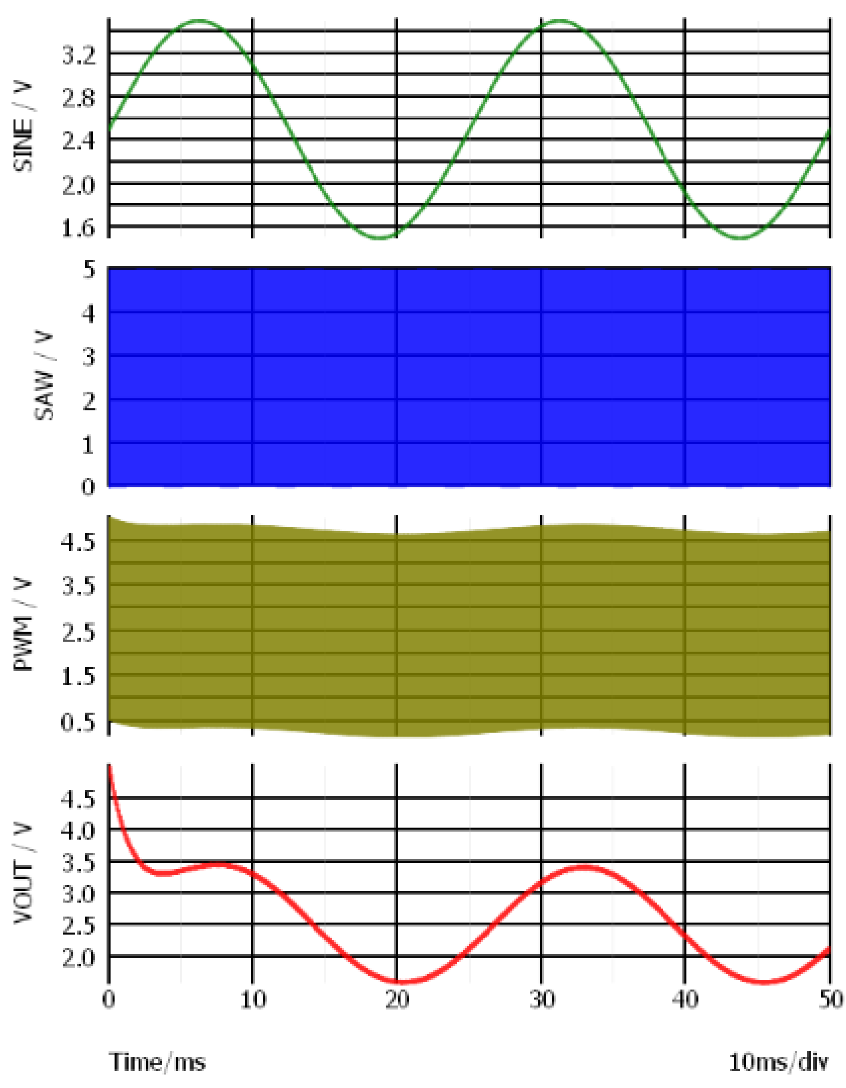


Fig. 24 LPF Applied to a Square-wave generator

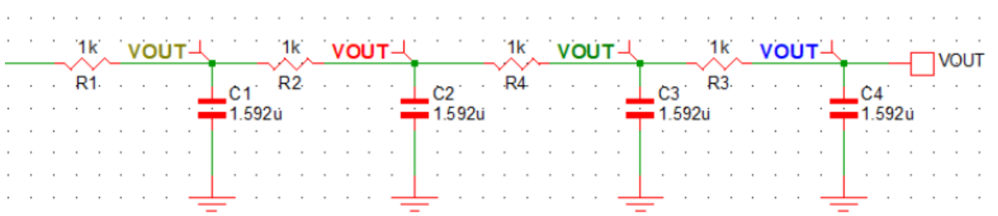


Fig. 25 Higher Order Filter Design

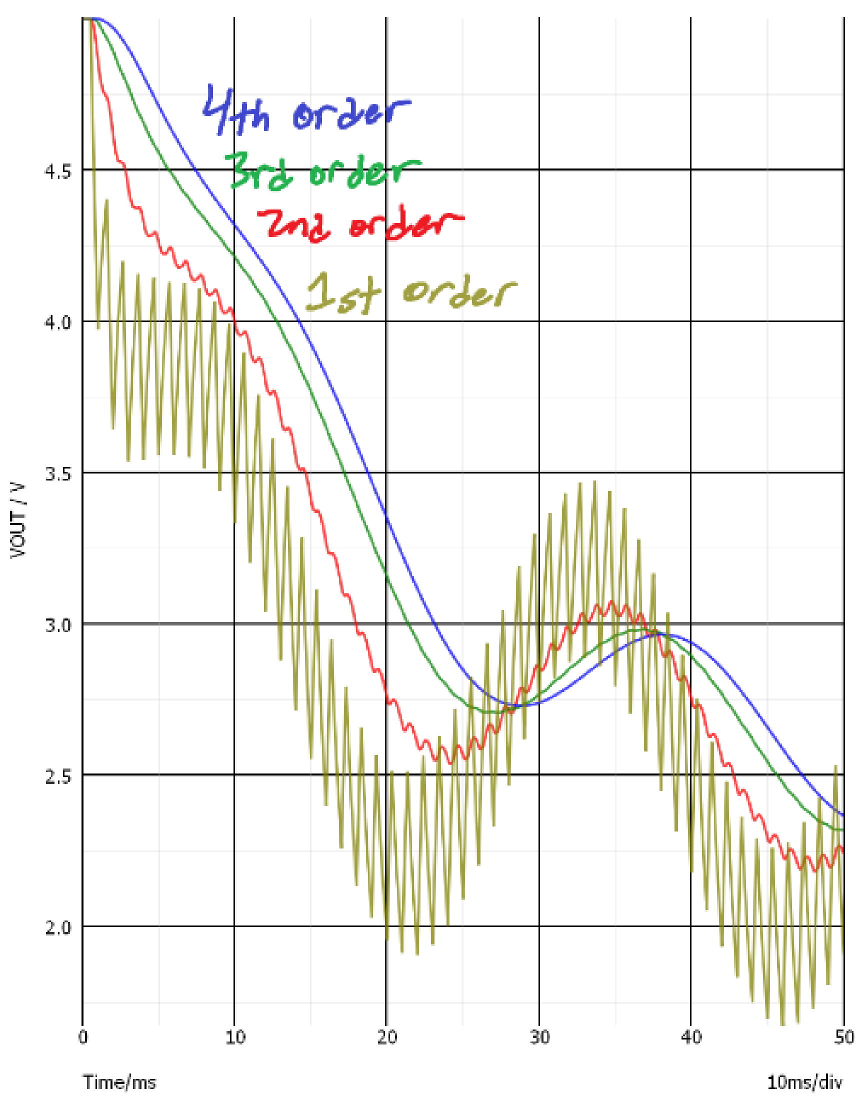


Fig. 26 Response to a higher order filter

II. Experiment 0.B

A. 0.B.2 - Determine Motor Parameter R_m

```
        Rm = [2.2083  2.3086   2.4314   2.4487   2.5800   2.6707   2.9486];
        Rm = polyfit(Idc , Vdc - Idc/6 , 1);
```

V_dc (V)	V_I (V)	R_1 (V)	I_dc (A)	V_M	R_M
0.57	0.04	0.17	0.240	0.53	2.971
1.5	0.101	0.17	0.606	1.399	
2.12	0.136	0.17	0.816	1.984	
3.06	0.195	0.17	1.170	2.865	
4.12	0.25	0.17	1.500	3.87	
4.92	0.289	0.17	1.734	4.631	
6.43	0.344	0.17	2.064	6.086	

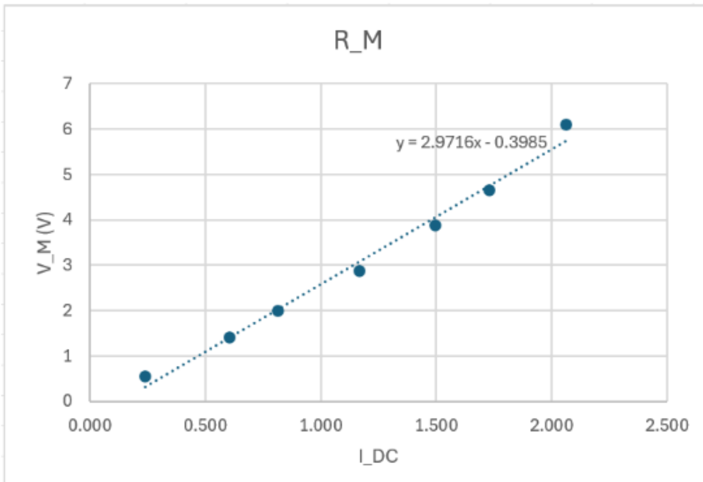


Fig. 27 Scatter Plot for R_m values

B. 0.B.3 - Determine Motor Parameters k, B and T_{int}

```

        Idc = VI.*6;
        Vemf = Vdc - Rm.*Idc - VI;

        k = [0.5714  0.5298  0.5839  0.4941  0.5454  0.5241  0.4795  0.5037
            0.4962  0.4664  0.4819  0.4925];

        k_avg = 0.5141; %(we will proceed with this value for now)
        k_y_int = 0.5705;

        polyfit(omega , k.*Idc , 1);
        T_int = 0.1396;
        B = 0.0064;
```

V_dc (V)	V_I (V)	R_1 (V)	I_dc (A)	V_M	f_enc	w[rad/s]	V_EMF	k	Average k
1.55	0.043	0.17	0.258	1.507	198	1.30	0.74	0.57	0.514
1.98	0.049	0.17	0.294	1.931	305	2.00	1.06	0.53	
2.36	0.047	0.17	0.282	2.313	386	2.53	1.48	0.58	
2.68	0.052	0.17	0.312	2.628	526	3.44	1.70	0.49	
3.36	0.052	0.17	0.312	3.308	667	4.37	2.38	0.55	
3.8	0.055	0.17	0.33	3.745	806	5.28	2.76	0.52	
3.97	0.058	0.17	0.348	3.912	917	6.00	2.88	0.48	
4.49	0.059	0.17	0.354	4.431	1025	6.71	3.38	0.50	
4.94	0.064	0.17	0.384	4.876	1150	7.53	3.74	0.50	
5.26	0.067	0.17	0.402	5.193	1310	8.57	4.00	0.47	
5.67	0.07	0.17	0.42	5.6	1380	9.03	4.35	0.48	
6.14	0.071	0.17	0.426	6.069	1490	9.75	4.80	0.49	

w[rad/s]	T	T_INT	B	Average B
1.30	0.147	0.1396	0.00604	0.00654
2.00	0.156		0.00809	
2.53	0.165		0.00992	
3.44	0.154		0.00423	
4.37	0.170		0.00700	
5.28	0.173		0.00632	
6.00	0.167		0.00455	
6.71	0.178		0.00577	
7.53	0.191		0.00677	
8.57	0.187		0.00558	
9.03	0.202		0.00695	
9.75	0.210		0.00720	

Fig. 28 Intermediate values

C. 0.B.4 - Determine Motor Parameter *J*

```

tau = 3.3;
w0 = (2.*pi.*1490)./(960);
J = -(B.*tau)./(log((T_int)./(B.*w0 + T_int)));
J = 0.0572;
```

D. 0.B.5 - Validate Motor Parameters

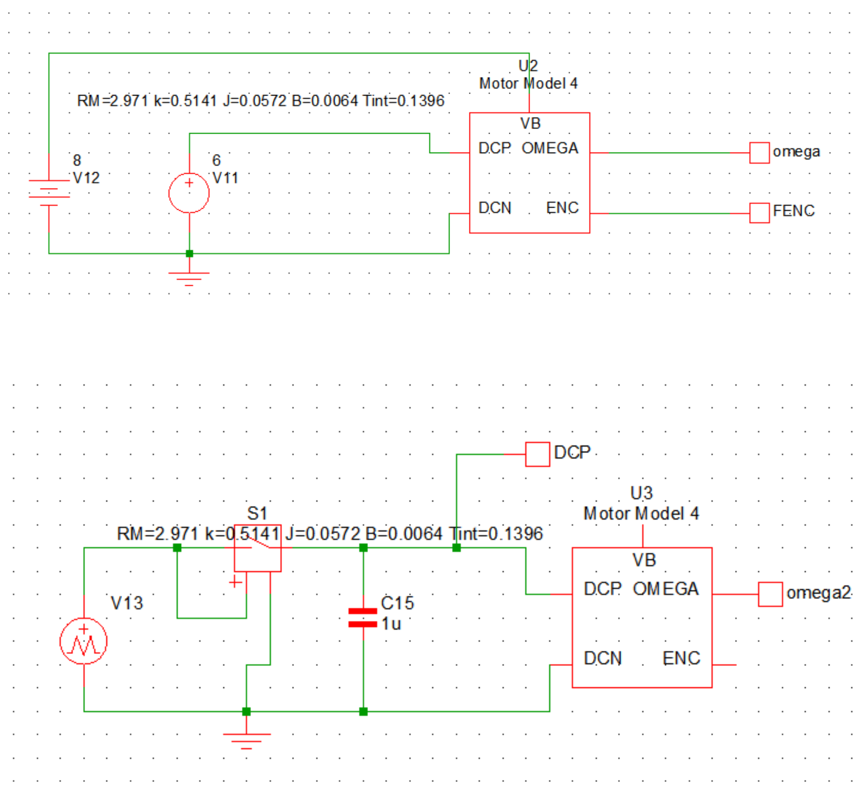


Fig. 29 Validation of Motor Parameter Circuits

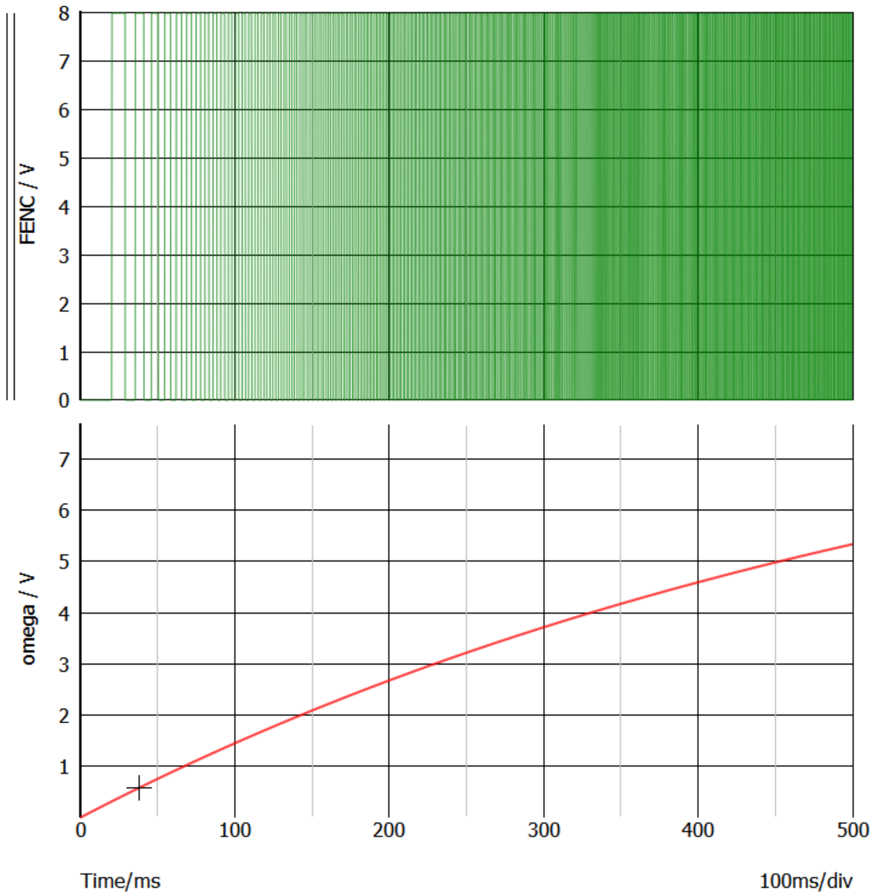


Fig. 30 Encoder Frequency vs Spin Frequency

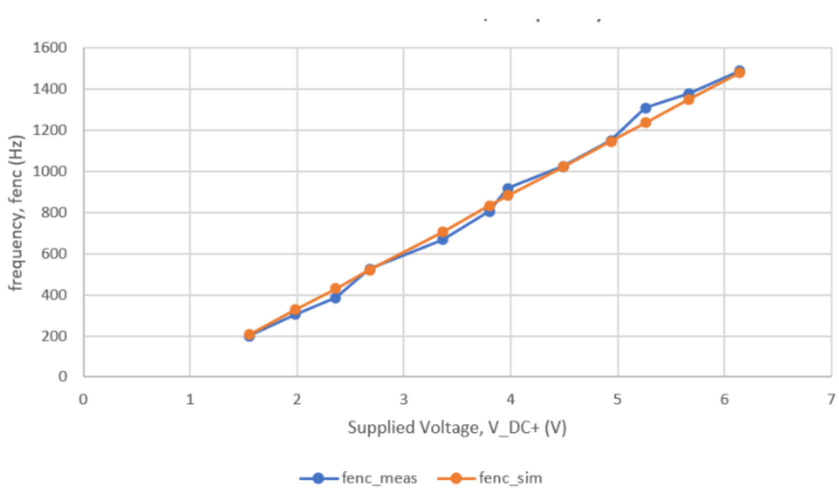


Fig. 31 Measured vs Simulated Frequency

This graph show the differences between the measured values and the simulated values. This validates the accuracy of the parameters.

E. 0.B.6 - Extra Credit

Procedure:

1) Connect the motor in a test circuit with a DC power supply set to a medium voltage (3 to 4 Vdc).
2) Use a current sensing resistor to measure the armature current, and an oscilloscope to capture the current waveform.
3) Apply a step change in V_{dc} while the motor runs at medium speed.
4) Capture the transient response of the armature current using the oscilloscope.
5) Calculate dI/dt from the initial slope of the current response.
6) From the captured transient response, use the initial linear portion of the current ramp to calculate dI/dt. Knowing V_{dc}, R_M, and E_b (if speed is constant, E_b can be estimated), rearrange the formula to solve for L_M.

$$V_{dc} = L_M(dI/dt) + R_M I + E_b$$

Theory: To measure L_M you apply a voltage change and observe the current. The inductance can be calculated from the above formula using the rate of change of current.

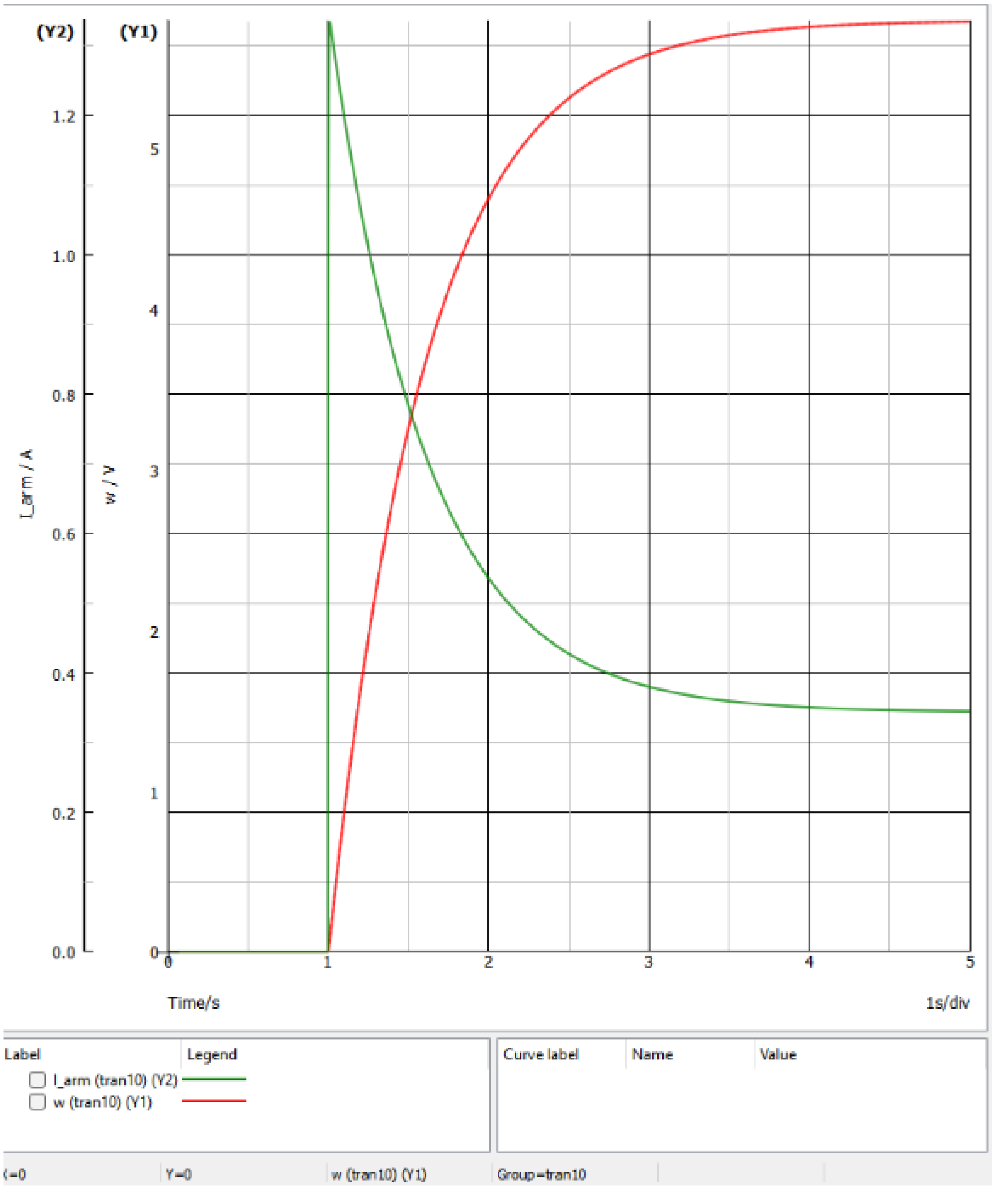


Fig. 32

dI/dt = (1.3345-0)/(1.0086-1) = 155.174

Now we isolate and calculate for L_M, at t = 1 I = I_max and V_emf = 0

$$V_{dc} = R_M I_{dc} + L_M(dI/dt) + V_{emf}$$

$$4 = 2.971 * 0.345 + L_M * 155.174$$

L_M = 19.172mH