University of Colorado
Boulder

Photovoltaic Power Electronics
ECEA 5717 Close-Loop Photovoltaic Power Electronics Laboratory
Converter Small-Signal AC Transfer Functions

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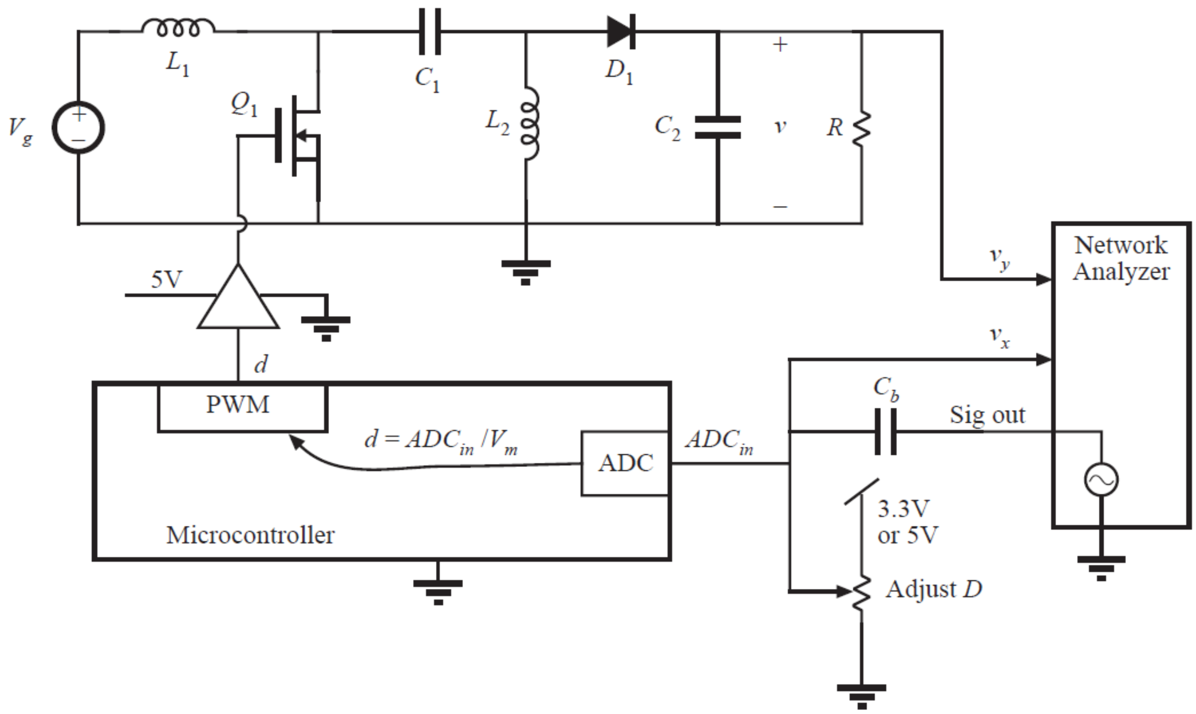


1. Measurement of original $G_{vd}(s)$

- Report multimeter readings of quiescent values of V_g and V. Values should be within ±1V of the required values.

Measurement Equipment:
FLUKE 289 TRUE RMS MULTIMETER (Calibrated by TRANSCAT on 06/15/2021)

INPUT VOLTAGE (V)		LOAD (Ω)		ADC Voltage (V)	ADC Read	DUTY CYCLE	OUTPUT VOLTAGE (V)	
DESIRED	READING	DESIRED	READING				DESIRED	READING
17	17.001	30	30.15	1.4133	1764	0.425	12.50	12.51

Expression	Type	Value	Address
Voltage2	unsigned int	1764	0x00000602@Data
DutyCycle	unsigned int	51	0x00000603@Data
Voltage2/DutyCycle	unsigned int	34	
GRP(ADCRESULT).REG(ADCRESULT2)			
Add new expression			

- Measured Bode plot of magnitude and phase of G_{vd} / V_m. Some moderate noise in the plots is allowable, but the underlying magnitude and phase data should be discernable and should appear to represent a valid transfer function.

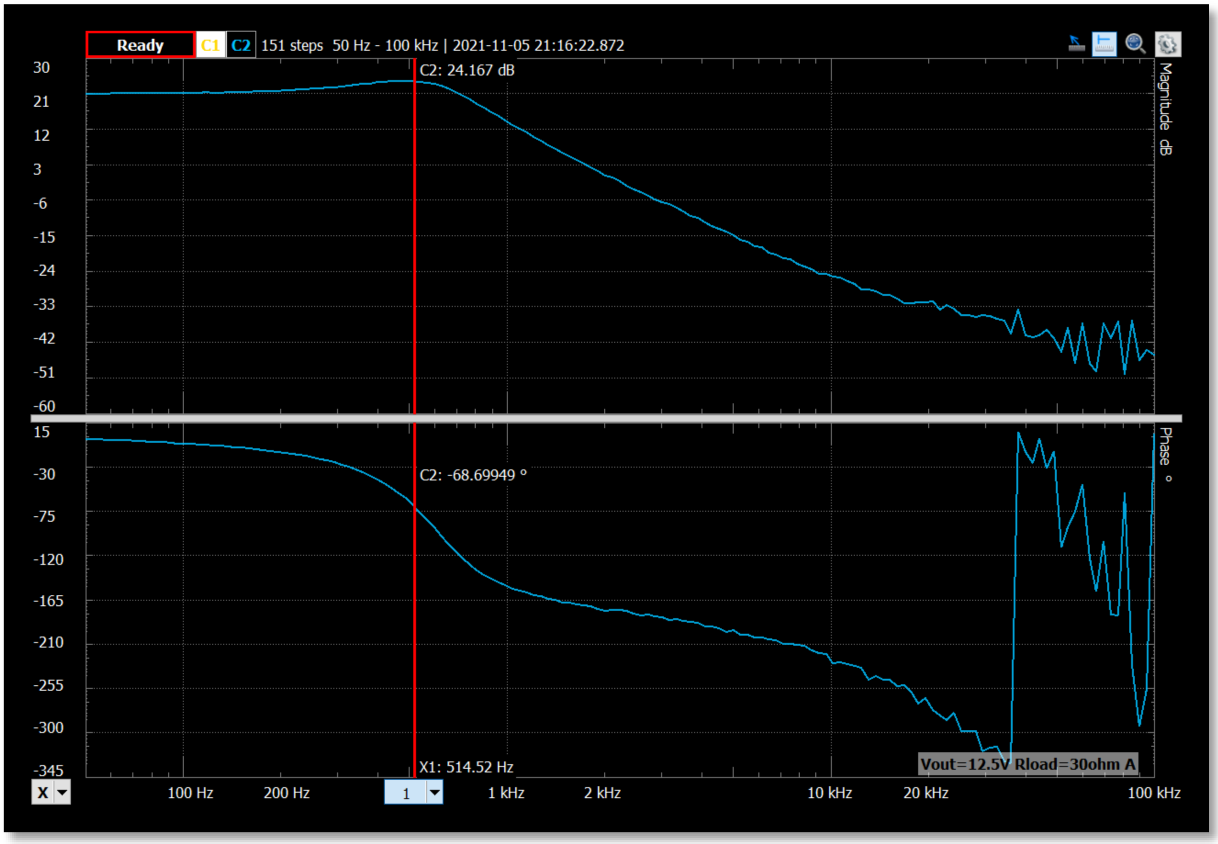


Figure 1. G_{vd} / V_m

By observing the graph, it has 2 poles and peaking at around 514Hz, RHP zero around 20kHz, DC gain is 19.935dB

- What is the numerical value of the PWM/ADC gain 1 / V_m? This is the gain from a perturbation in the ADC input voltage to the resulting perturbation in the PWM output duty cycle. It can vary depending on the selected switching frequency and on any scale factors employed in the interrupt service routine. The calculation of this gain should be documented briefly.

Switching Frequency: 500kHz, therefore ePWM1 should be 120

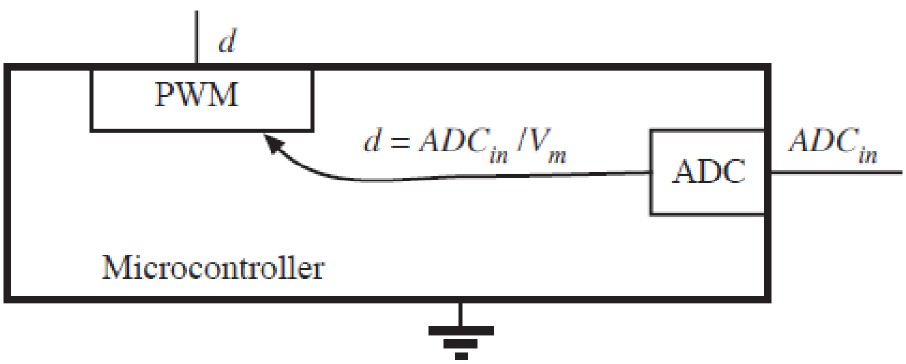
$$ePWM1 = \frac{\frac{1}{500kHz}}{\frac{1}{60MHz}} = 120$$

```
PWM_setPeriod(myPwm, 120);                     // Set period for ePWM1
```

To achieve 3.3V at 100% duty, the scale factor should be:

$$\frac{PWM_{max}}{ADC_{max}} = \frac{120}{2^{10} - 1} = \frac{1}{34.125} \approx \frac{1}{34}$$

```
Voltage2 = ADC_readResult(myAdc, ADC_ResultNumber_2);        //
DutyCycle = Voltage2/34;                                     //
PWM_setCmpA(myPwm, DutyCycle);                               //
```



$$d = \frac{ADC_{in}}{V_m}$$

$$V_m = \frac{ADC_{in}}{d} = \frac{1.4133}{0.425} = 3.3254$$

2. Simulation of $G_{vd}(s)$

- Document your LTspice simulation of your SEPIC. Include your LTspice schematic or netlist.

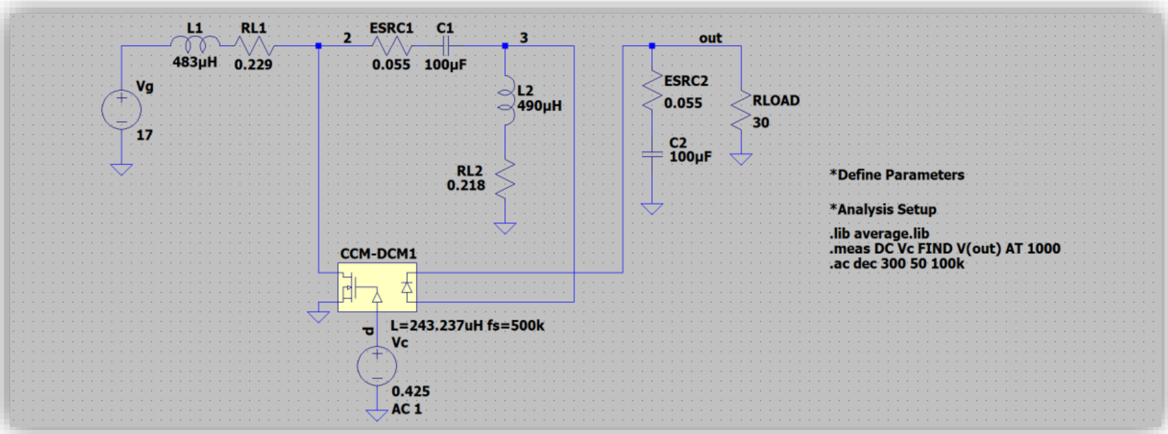


Figure 2. Diagram of my SEPIC including losses elements

- Include your output Bode plots of the magnitude and phase of $G_{vd}(s)$.

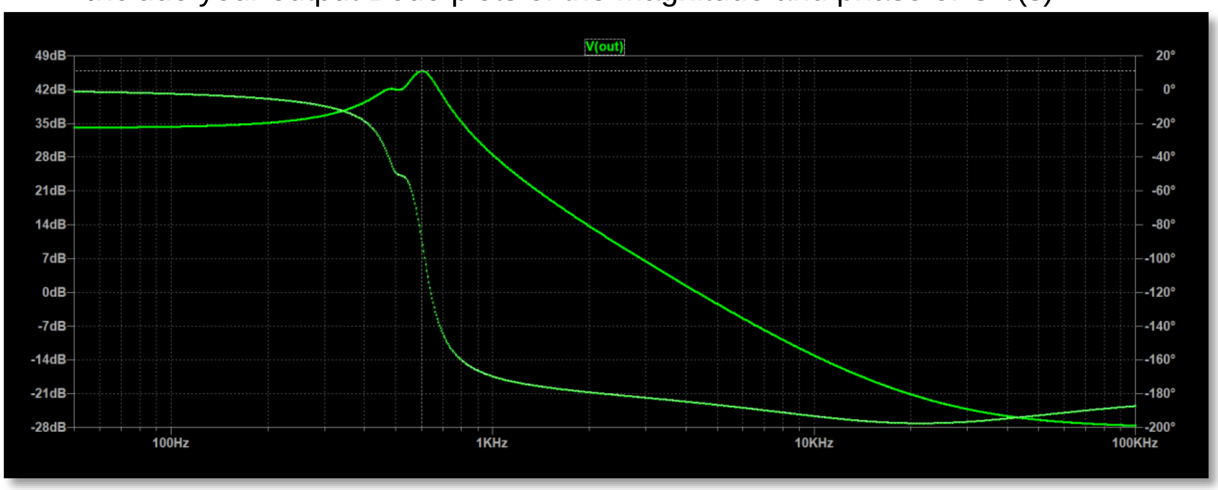


Figure 3. Gvd(s)

- Briefly discuss any deviations between your simulation and your measurement of part 1.

In LTSpice, the magnitude and phase also appear similar to actual measurement, where the LTSpice can see some resonance around 500Hz

3. Damping the internal resonance

- Evaluate the $G_{vd}(s)$ transfer function of the effective buck-boost converter model, described in the accompanying lecture. Give numerical values for the salient features (poles, zeroes, dc gain). Compare with your measurements of part 1: how do those measurements deviate from the predictions of the effective buck-boost model?

Below calculations of the effective buck-boost are based on lossless model:

$$G_{vd-bb} = \frac{V_g}{D'^2} \frac{1 - s\frac{L_1}{R}(\frac{D}{D'})^2}{1 + s\left(\frac{L_2 + (\frac{D}{D'})^2 L_1}{R}\right) + s^2 C_2 (L_2 + (\frac{D}{D'})^2 L_1)}$$

L_1	L_2	C_1	C_2	D	R	V_g
483µH	490µH	100µF	100µF	0.425	30	17

DC Gain

$$20\log(\frac{V_g}{D'^2}) = 34.22dB$$

By observing the result from the measurement $G_{vd}(s)/V_m$, DC gain is around 19.935dB

$$20\log(\frac{V_g}{D'^2} \cdot \frac{1}{V_m}) = 20\log\left(\frac{17}{0.575^2} \cdot \frac{1}{3.3254}\right) = 23.7854$$

The lossy elements are around 3.8dB

Zero

$$f_z = \frac{\omega_z}{2\pi} = \frac{1}{2\pi \cdot [\frac{L_1}{R}\left(\frac{D}{D'}\right)^2]} = 18kHz$$

We can observe a slight RHP behavior around 20kHz

Pole

$$f_p = \frac{1}{2\pi\sqrt{C_2(L_2 + (\frac{D}{D'})^2 L_1)}} = 580Hz$$

We can observe the two poles peaking at around 515Hz

- Evaluate the internal resonance frequency, Eq. (1). Discuss whether you observe evidence of this resonance in your experimental measurements of part 1, or in your simulation of part 2.

$$f_{int} = \frac{1}{2\pi\sqrt{C_1(L_2 + L_1)}} = \frac{1}{2\pi\sqrt{100\mu F \cdot (483\mu H + 490\mu H)}} = 510Hz$$

With the measurement of AD2, I did not see any observable resonance, but we can see some resonance around 500Hz in LTSpice. I removed all losses element below in LTSpice and we can further observe the effect. Just another point to proof the losses damped the internal resonance. Trade-off of stability vs efficiency.

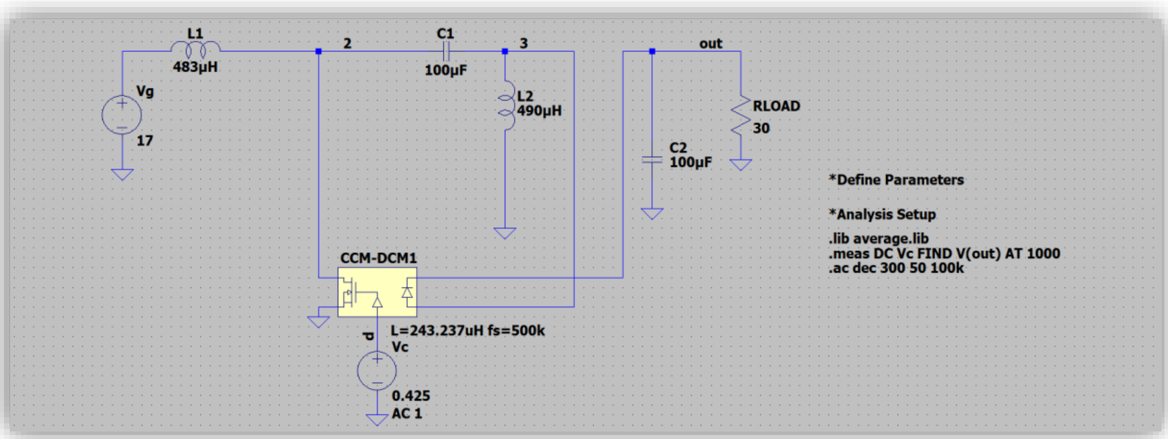


Figure 2. Diagram of my SEPIC removing losses elements

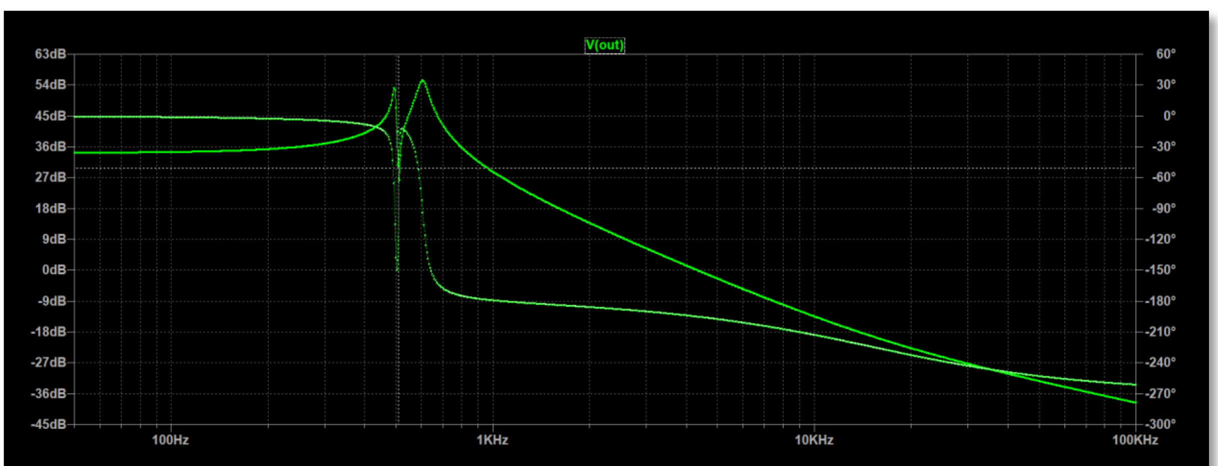


Figure 5. Gvd(s) (Lossless)

- Plot the magnitudes of the impedances Z_L and Z (Eqs. (2) and (5)) for your final design, and report your element values.

$$Z_L = (sL_1 + sL_2)$$

$$f_L = \frac{Z_L}{2\pi(L_1 + L_2)} = \frac{1}{2\pi(483\mu H + 490\mu H)} = 163.571Hz \ @ \ Z_L = 1\Omega$$

$$Z_{C1} = \frac{1}{sC_1}$$

$$f_{C1} = \frac{1}{2\pi Z_{C1} C_1} = \frac{1}{2\pi \cdot 1 \cdot 100\mu F} = 1.592kHz \ @ \ Z_{C1} = 1\Omega$$

By choice, I picked C_b = 220µF

$$Z_{Cb} = \frac{1}{sC_b}$$

$$f_{Cb} = \frac{1}{2\pi Z_{Cb} C_b} = \frac{1}{2\pi \cdot 1 \cdot 220\mu F} = 723.453Hz \ @ \ Z_{Cb} = 1\Omega$$

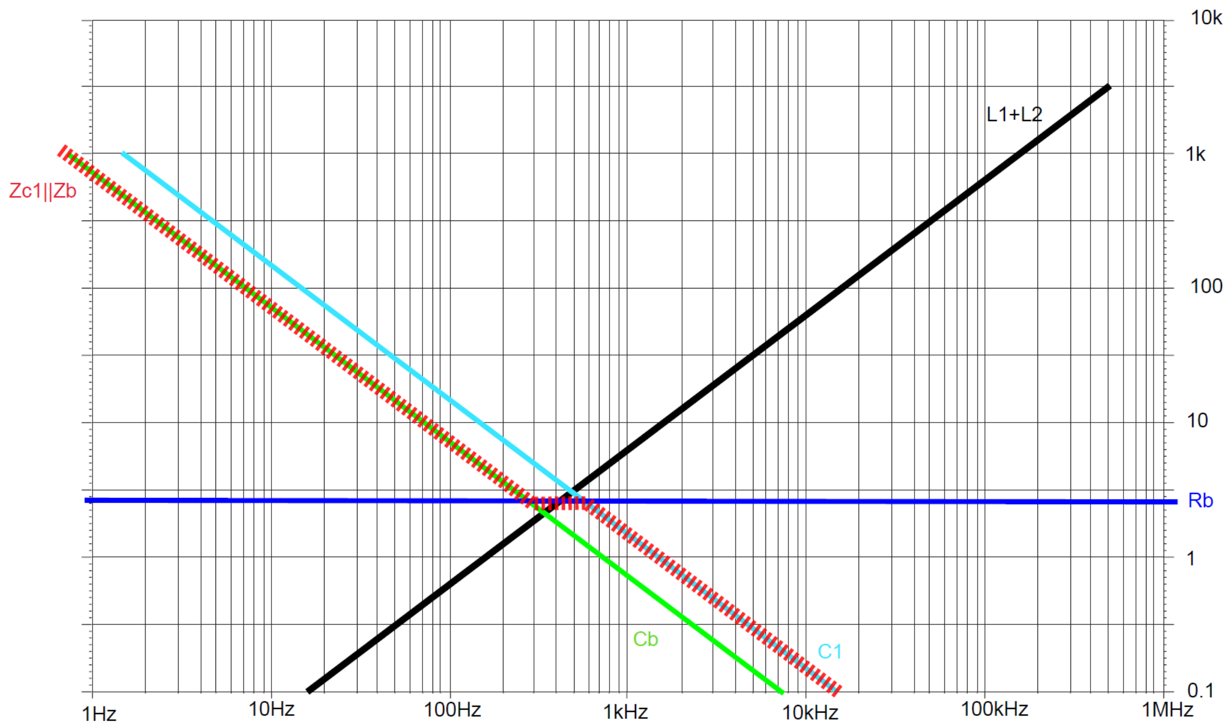


Figure 6. Z_{C1}, Z_{Cb}, Z_L, Z

We can find the secondary intersection

$$f_{int2} = \frac{1}{2\pi\sqrt{C_b(L_2+L_1)}} = \frac{1}{2\pi\sqrt{220\mu F \cdot (483\mu H + 490\mu H)}} = 344Hz$$

The choice of R_b in Z_b should have intersect between f_{int} and f_{int2}

$$R_{b\,min} = 2\pi f_{int2}(L_2+L_1) = 2\pi \cdot 344 \cdot (483\mu H + 490\mu H) = 2.10\Omega$$
$$R_{b\,max} = 2\pi f_{int}(L_2+L_1) = 2\pi \cdot 510 \cdot (483\mu H + 490\mu H) = 3.12\Omega$$

$$2.10\Omega < R_{b\,min} < 3.12\Omega$$

By choice, I picked R_b = 2.5Ω

- Document your LTspice simulation of your damped SEPIC of part 3. Include your LTspice schematic or netlist. Include your output Bode plots of the magnitude and phase of $G_{vd}(s)$.

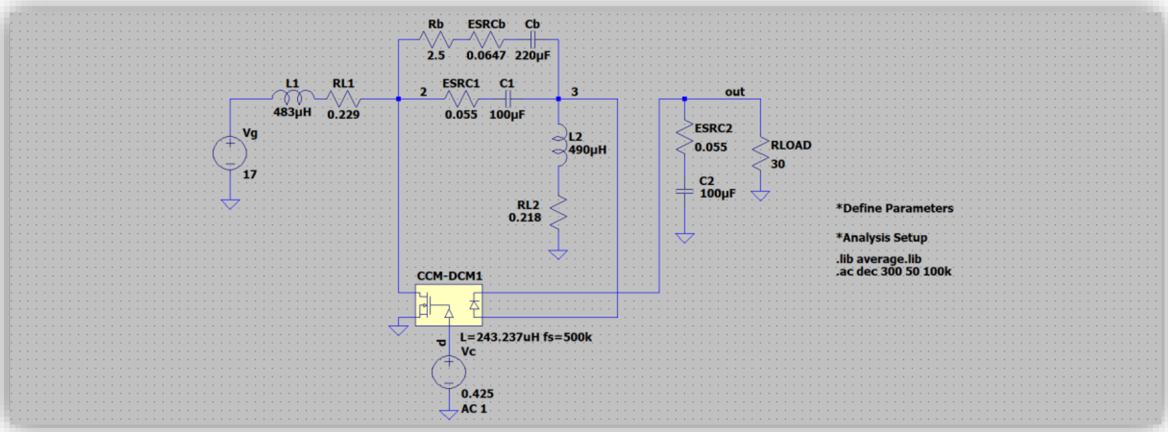


Figure 7. Diagram of my damped SEPIC

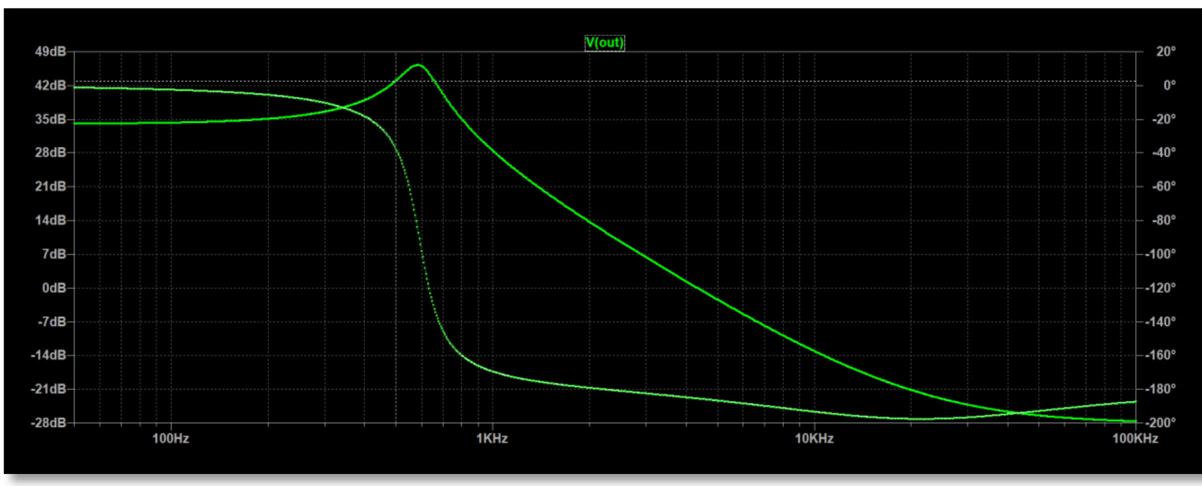


Figure 8. Gvd(s) (damped)

- Give your measured Bode plot of the damped $G_{vd}(s)$ magnitude and phase for your experimental SEPIC with damping network. Is the internal resonance sufficiently damped?

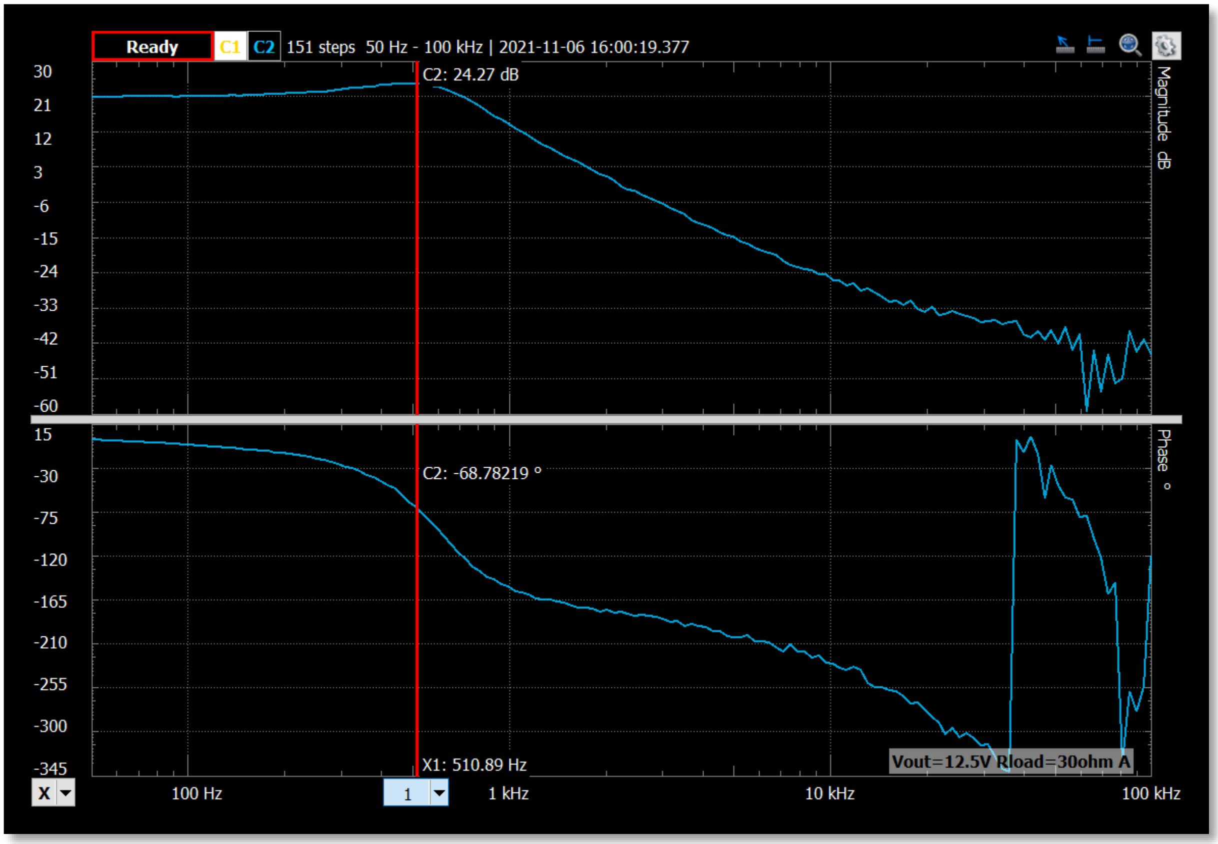


Figure 9. G_{vd} / V_m (with damping elements)

Magnitude and Phase remain similar, two poles and RHP zero behavior, the peaking of the two poles shift slightly to 510Hz.

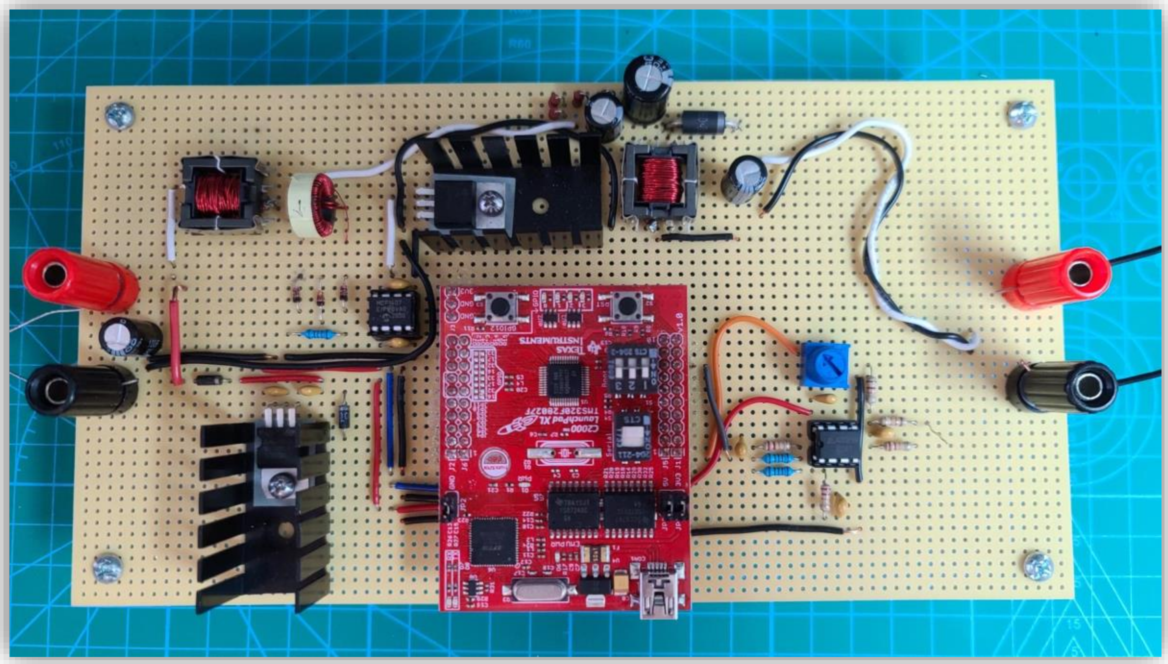


Figure 10. My SEPIC

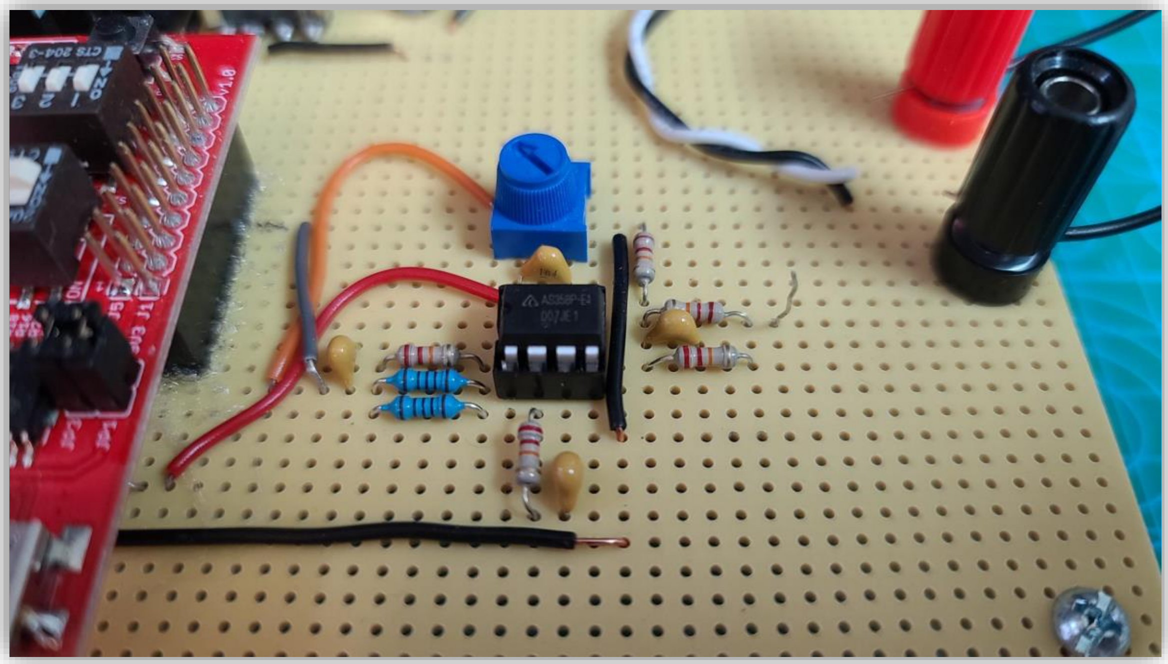


Figure 11. OP-amp Circuit

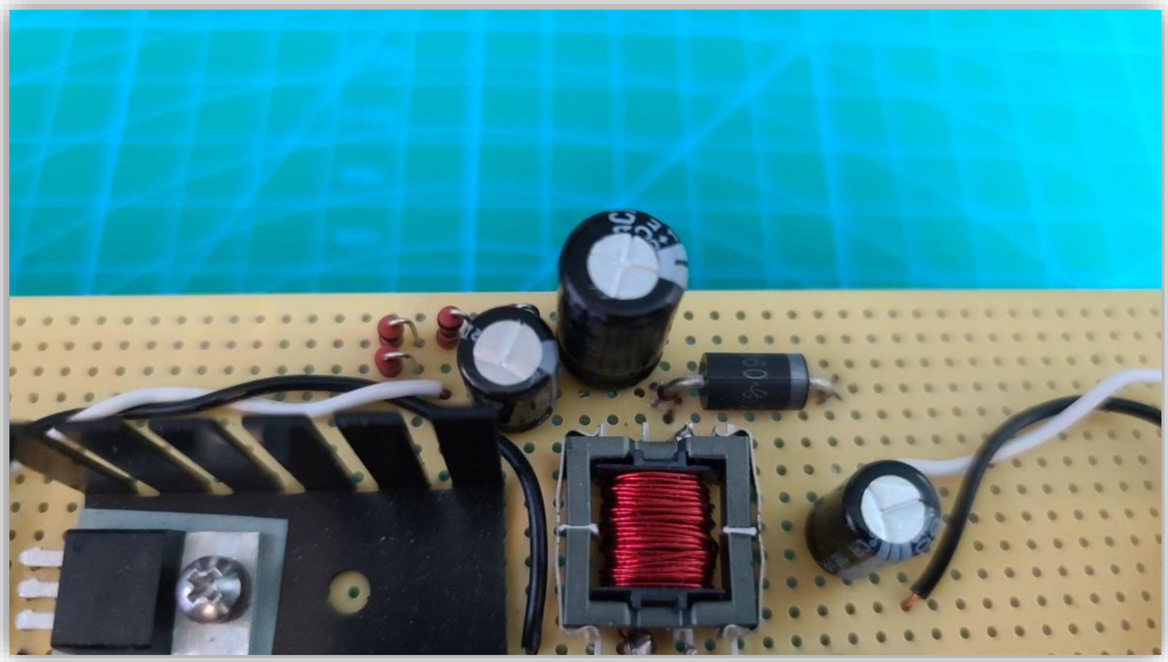


Figure 12. C_1, R_b, C_b