STEP_DOWN_4_20VDCINPUT_3V3_4A_13W_VM_CCM

SPECIFICATIONS

Vinmin	4 VDC
Vinmax	20 VDC
Vout	3.3 V
Vripple	125 mV
Vout_drop	0.25 V from Iout = 200 mA to 3 A in 1 us
Ioutmax	4 A
Fsw	100 kHz
Iripplepeak	15 mA, input current maximum ripple

VM CCM

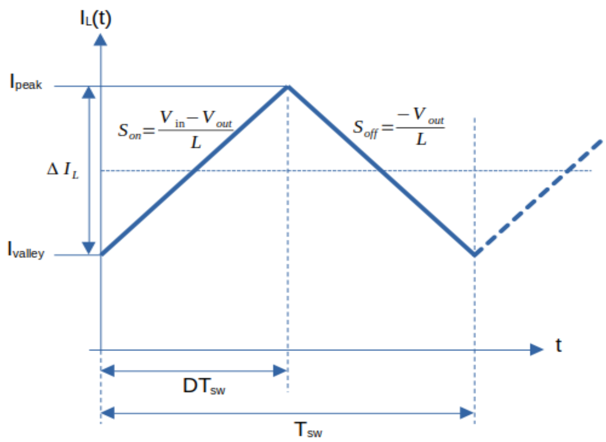
$$D_{min}=\frac{V_{out}}{V_{inmax}}=\frac{3.3}{20}=.165$$

$$D_{max}=\frac{V_{out}}{V_{inmin}}=\frac{3.3}{4}=.825$$

→ the corner frequency placement is defined by

$$f_0=F_{sw}\frac{1}{\pi}\sqrt{\frac{2\Delta V}{(1-D_{min})V_{out}}}=\frac{100e3}{3.14}\sqrt{\frac{0.25}{(1-0.165)3.3}}=9.6\,kHz$$

(the previous equation was derived from the ripple voltage across Cout without ESR effect)



$$I_{valley}=I_{peak}-S_{off}\cdot t_{off}=I_{peak}-\frac{V_{out}(1-D)}{L F_{sw}}$$

$$\Delta I_L=I_{peak}-I_{valley}=I_{peak}-I_{peak}+\frac{V_{out}(1-D)}{L F_{sw}}=\frac{V_{out}(1-D)}{L F_{sw}}$$

$$\frac{\Delta I_L}{I_{out}} = \delta I_r = \frac{V_{out}(1-D)}{L F_{sw} I_{out}}$$ which means that at Dmin we will have the highest ripple.

$$L = \frac{V_{out}(1-D_{min})}{\delta I_r F_{sw} I_{out}}$$

$$with\ \delta I_r\ of\ 10\%$$

$$L = \frac{3.3 \cdot (1-0.165)}{0.1 \cdot 100\text{e}3 \cdot 4} = 69\, uH$$

At maximum load current, the peak current will increase to

$$I_{peak} = I_{L,avg} + \frac{Vout(1-D_{min})}{2 L F_{sw}} = I_{out} + \frac{Vout(1-D_{min})}{2 L F_{sw}} = 4 + \frac{3.3 \cdot (1-0.165)}{2 \cdot 69\text{e-}6 \cdot 100\text{e}3} = 4 + 0.2 = 4.2\, A$$

$$C_{out} = \frac{1}{(2\pi f_o)^2 L} = \frac{1}{(2\pi \cdot 9.6\, e3)^2 \cdot 69\, e-6} = 4\, uF\, (can\, be\, increased)$$

$$I_{Cout,rms} = I_{out} \frac{1-D_{min}}{\sqrt{12}\, \tau_L}\ where\ \tau_L = \frac{L}{R_{load} T_{sw}}$$

$$I_{Cout,rms} = 4 \frac{1-0.165}{\sqrt{12} \frac{69\text{e-}6}{0.825 \cdot 10\text{e-}6}} = 0.115\, mArms$$

4.7 uF Panasonic 10SVP4R7M

IC,rms = 670 mArms

RESR,max = 0.24 Ω at T_A = 20 C, 100 kHz to 300 kHz

SVP series, 10 V

(https://ro.mouser.com/datasheet/2/315/AAB8000C193-947353.pdf)

AC ANALYSIS

$$f_c = \frac{\Delta I_{out}}{2\pi C_{out} \Delta V_{out}} = \frac{2.8}{2\pi \cdot 4.7\text{e-}6 \cdot 0.25} = 379\, kHz$$ (available for small ESR effects)

A cutoff frequency of 379 kHz is a large value, therefore by manipulating the previous equation we extract the Cout value for the required drop and select a cutoff frequency of 10 kHz.

$$C_{out} = \frac{\Delta I_{out}}{2\pi f_c \Delta V_{out}} = \frac{2.8}{2\pi \cdot 10\text{e}3 \cdot 0.25} = 200\, uF$$

470 uF Vishay 54471E3

IC,rms = 630 mArms at T = 105 C

RESR,low = 0.120 Ω at T_A = 20 C

RESR,max = 0.240 Ω at T_A = -10 C

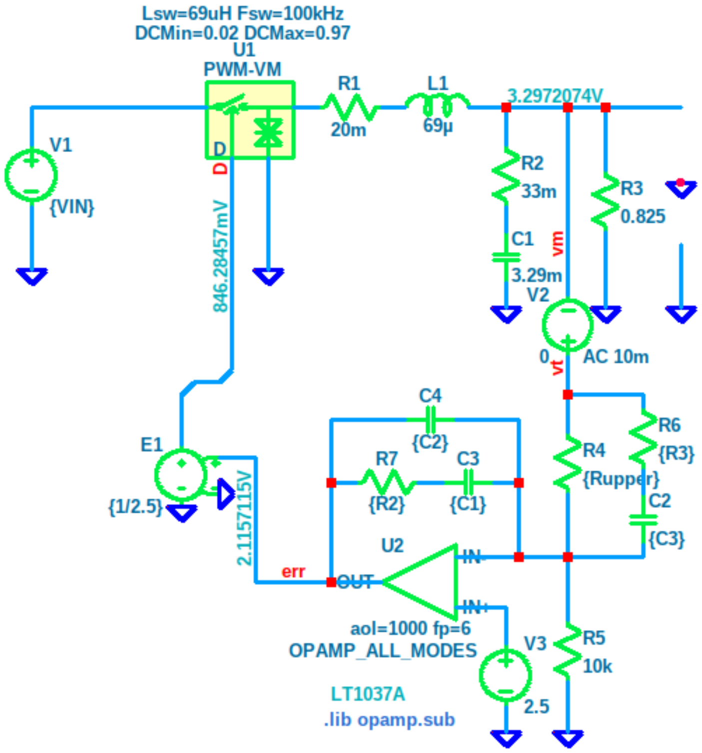
136 RVI, 10 V (https://www.vishay.com/docs/28321/136rvi.pdf)

We have to verify that the ESR value is less than the output capacitor impedance magnitude at the selected crossover frequency, to prove the equation conditions:

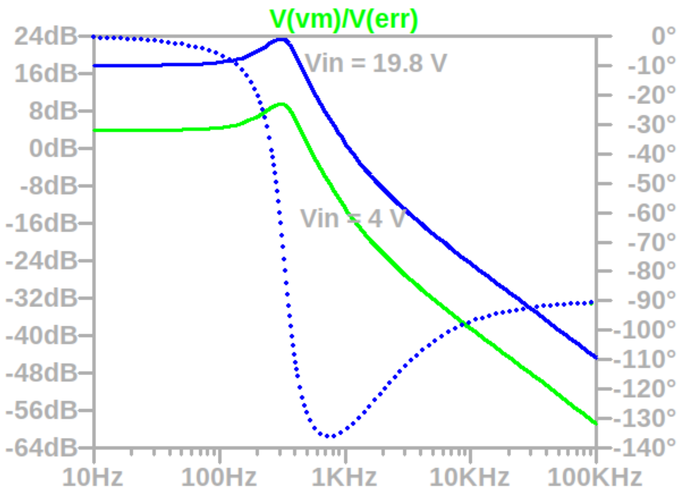
$$R_{ESR} < \frac{1}{2\pi f_c C_{out}}$$

$$240\,m\Omega < Z_{Cout}\,at\,10\,kHz\,(33\,m\Omega) \rightarrow No!$$

For a practical example we will have to search for a capacitor with a lower ESR. Here we will select 240/33 ~ 7, 470 uF Vishay 54471E3.



→ open-loop (control-to-output) transfer function (at VIN = 4 VDC and 19.8 VDC)



$$R_{ESR,low}=\frac{0.120}{7}=17\,m\Omega$$

$$R_{ESR,high}=\frac{0.240}{7}=34\,m\Omega$$

$$f_{z,low}=\frac{1}{2\pi R_{ESR,high}C_{out}}=\frac{1}{2\pi\cdot 34\text{e-}3\cdot 3.29\text{e-}3}=1.42\,kHz$$

$$f_{z,high}=\frac{1}{2\pi R_{ESR,low}C_{out}}=\frac{1}{2\pi\cdot 17\text{e-}3\cdot 3.29\text{e-}3}=2.84\,kHz$$

→ our LC circuit resonates at

$$f_0=\frac{1}{2\pi\sqrt{LC}}=\frac{1}{2\pi\sqrt{69\text{e-}6\cdot 3.29\text{e-}3}}=334\,Hz$$

From the open-loop sweep we can see that the the required gain at fc of 10 kHz is 38 dB worst case at Vin 4 VDC.

To cancel the LC filter peaking, we place the a double zero at the resonant frequency of 334 Hz.

First pole is placed at the highest zero position to force the gain to roll off, 2.84 kHz.

A second pole will be placed at one-half the switching frequency.

Using the manual placement, we have the following compensator elements

R2 = 30.5 kOhm

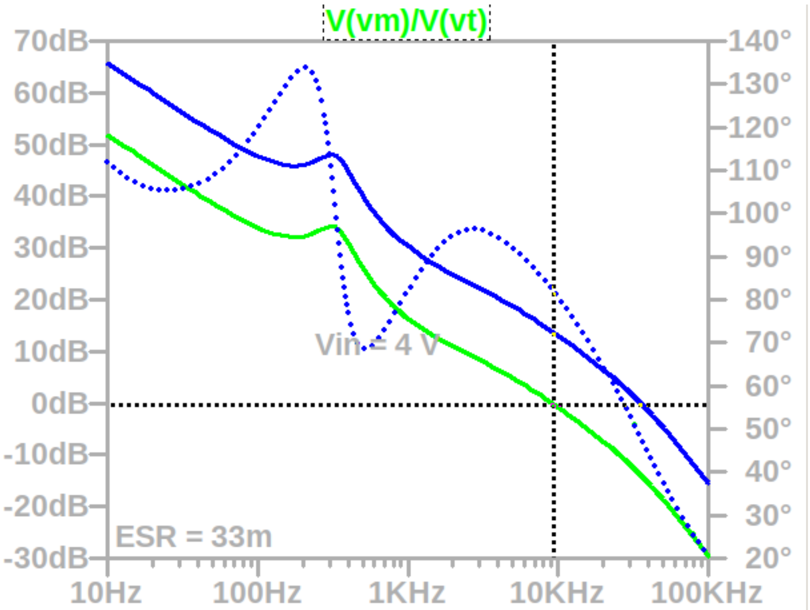
R3 = 19.7 Ohm

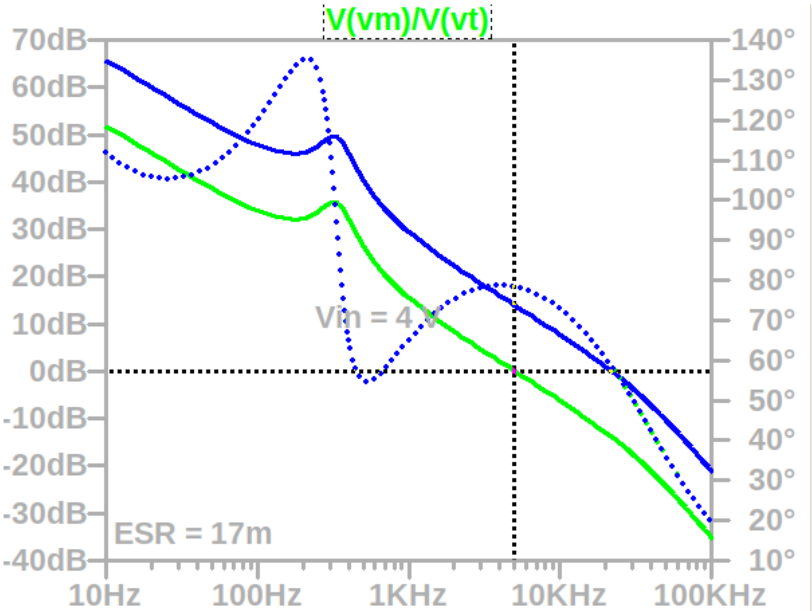
C1 = 17 nF

C2 = 1.83 nF

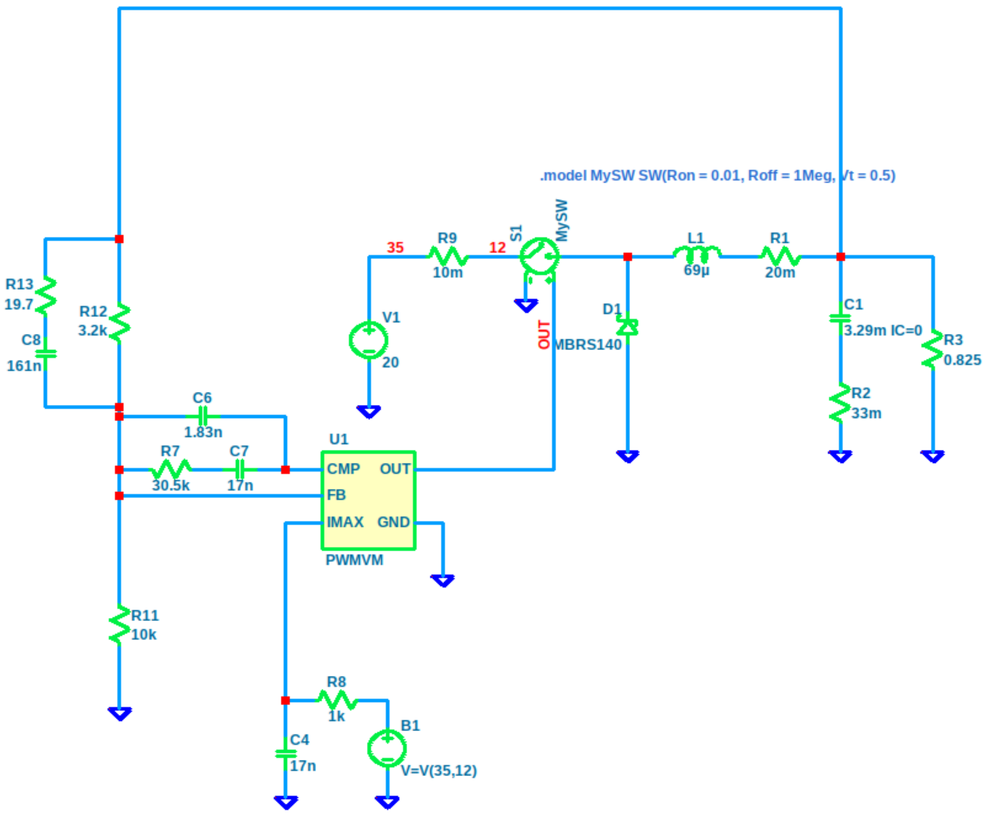
C3 = 161 nF

→ loop-gain transfer function at Vin = 4 VDC and 19.8 VDC

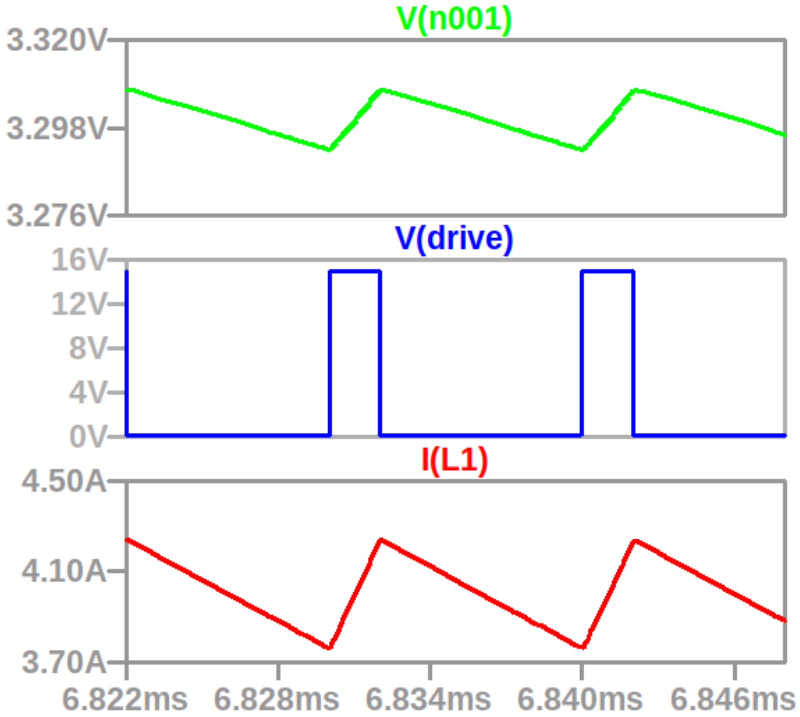




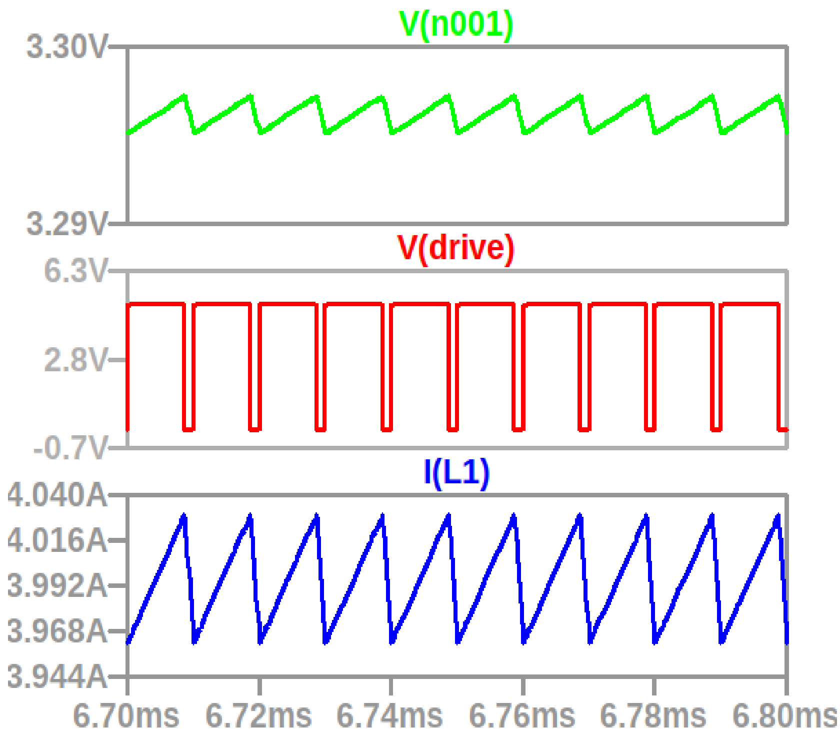
TRANSIENT ANALYSIS



(transient simulation at VIN = 20 VDC)

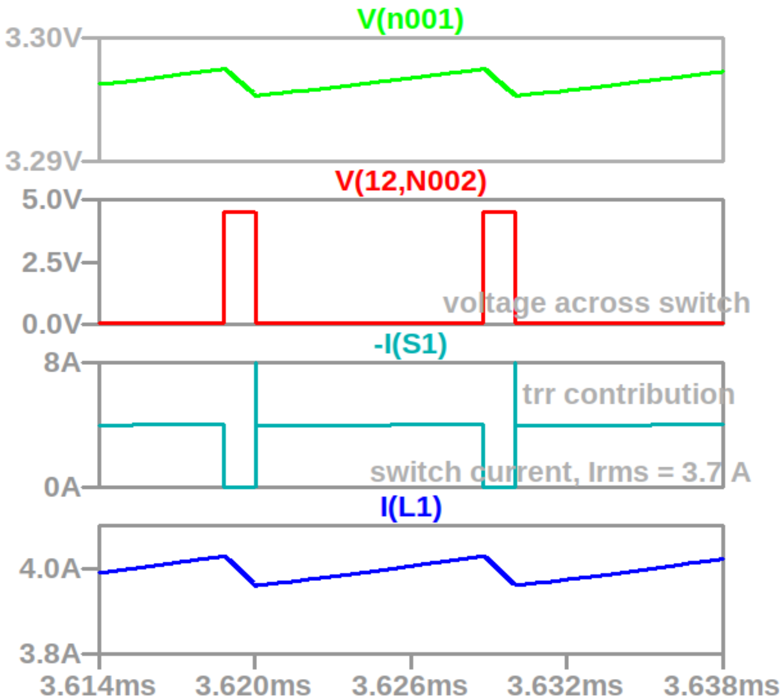


(transient simulation at VIN = 4 VDC)



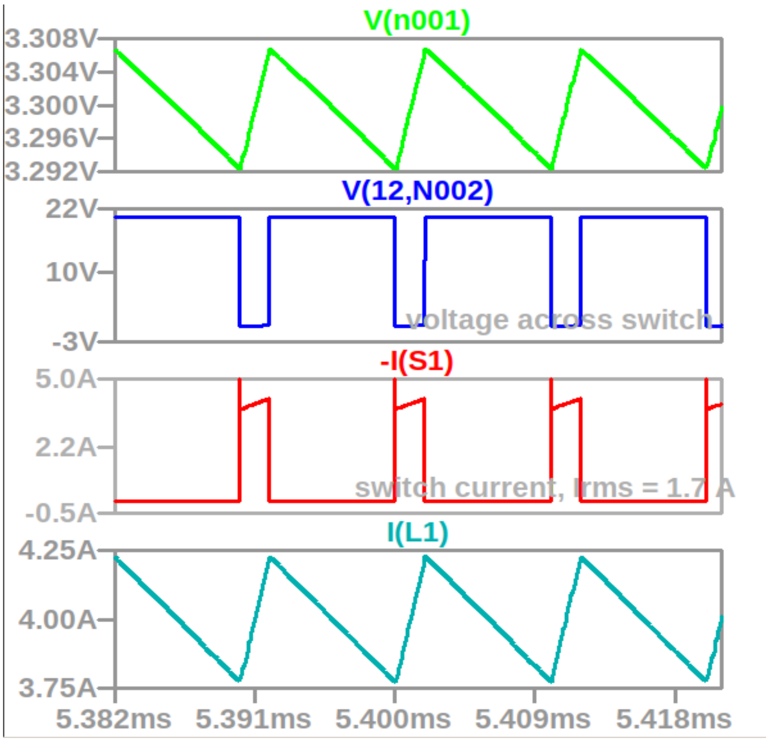
MOSFET STRESS

(MOSFET waveforms at Vin = 4 VDC)



$$P_{cond,MOSFET} = R_{DS(on),max} I_{D,rms}^2 = 0.1 \cdot 3.7^2 = 1.369\,W$$

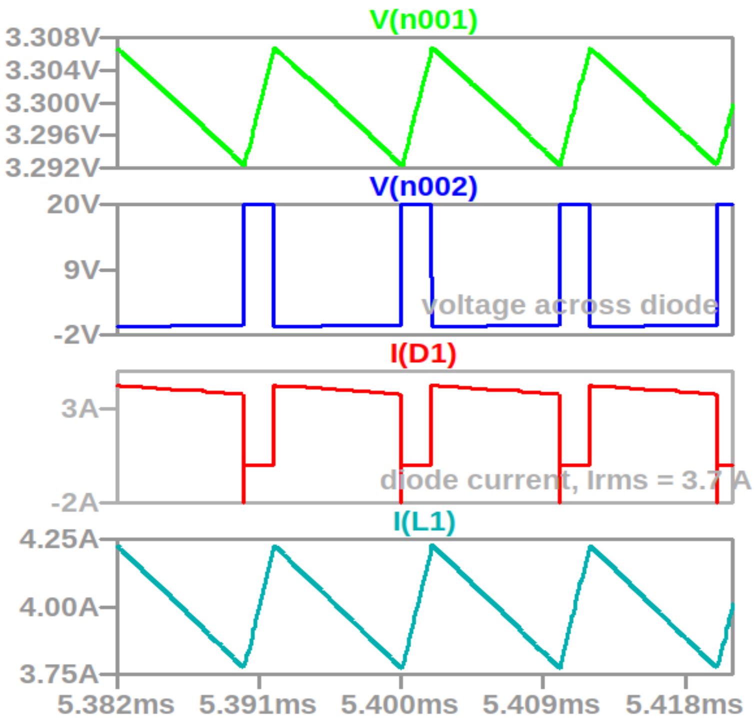
(MOSFET waveforms at Vin = 20 VDC)



DIODE STRESS

(The diode “sees” current during the off time only. As a result, in CCM, its dissipation increases as the duty ratio goes lower (off time goes up), at the *highest input voltage.*)

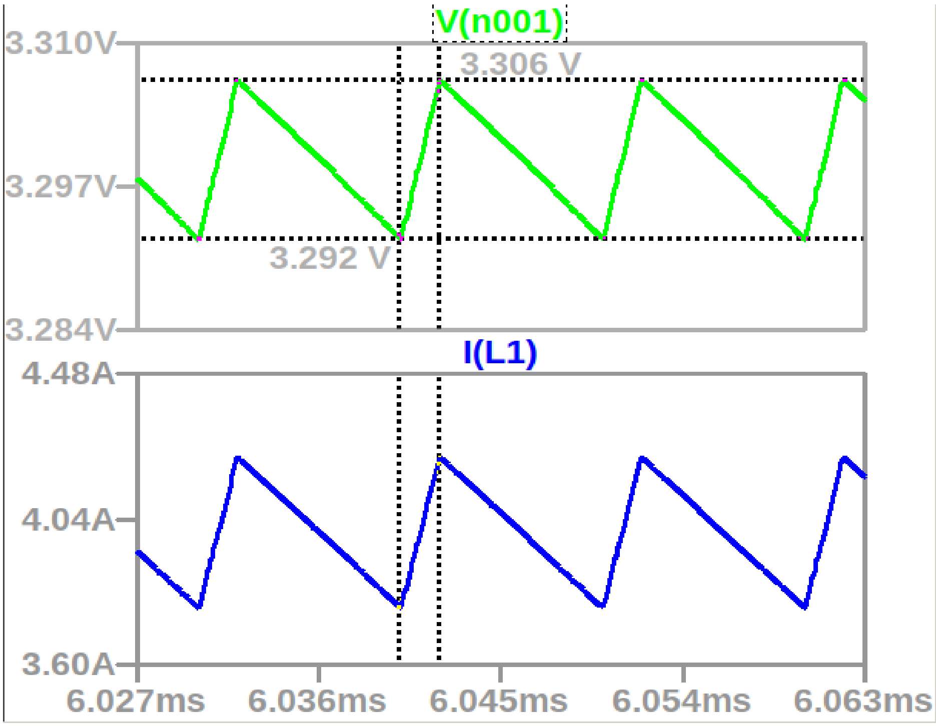
(diode waveforms at VIN = 20 VDC)



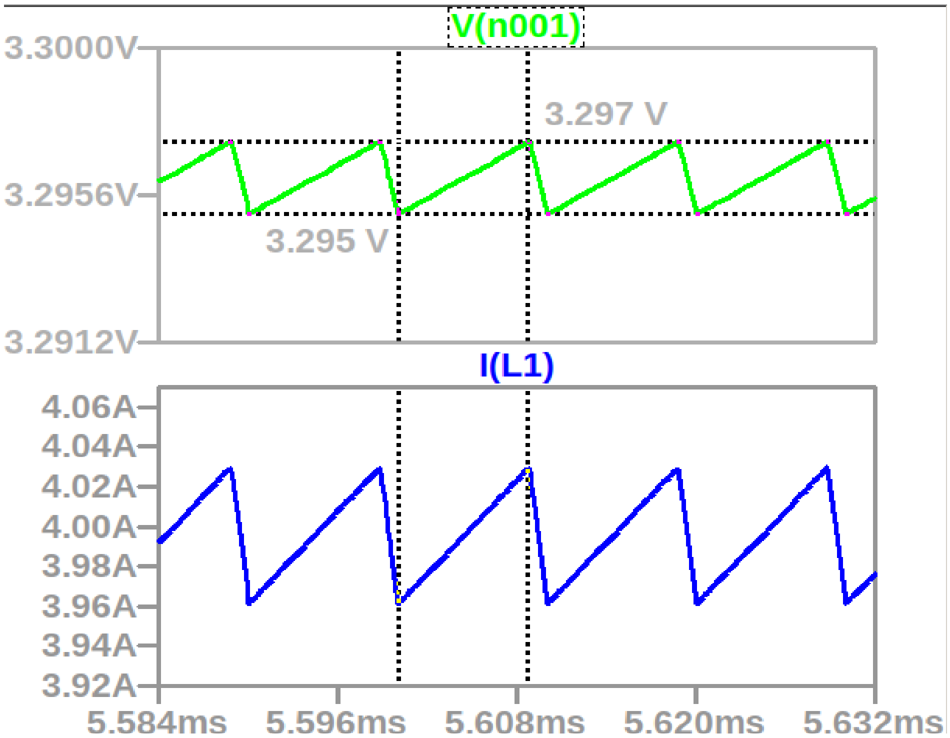
$$P_{cond} = V_f I_{d,avg} + R_d I_{d,rms}^2 \approx V_f I_{d,avg} \approx 0.7 \cdot 3.3 = 2.31\,W$$

OUTPUT RIPPLE AND TRANSIENT RESPONSE

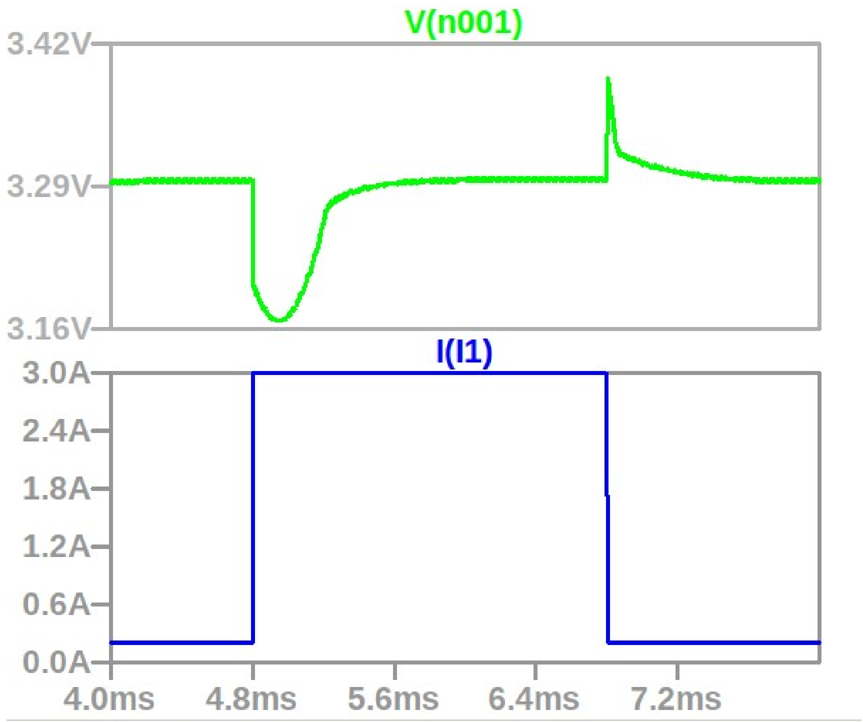
(output ripple at VIN 20 V and full load of 4 A ~ 14 mV)



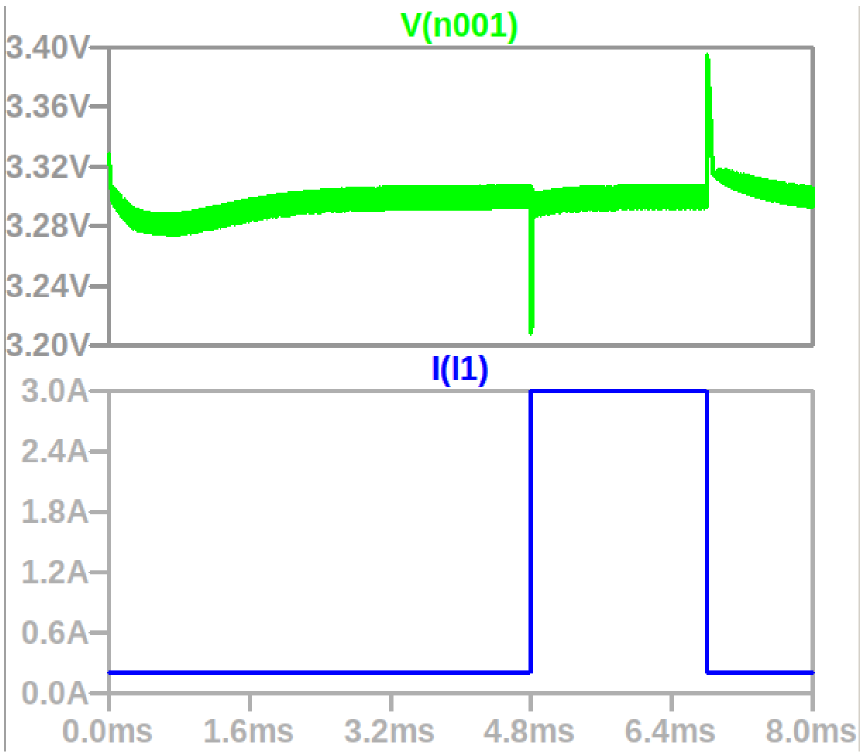
(output ripple at VIN 4 V and full load of 4 A ~ 1.4 mV)



(buck output voltage suddenly loaded from 200 mA to 3 A at VIN 4 V, with tr and tf 1us)



(buck output voltage suddenly loaded from 200 mA to 3 A at VIN 20 V, with tr and tf 1us)



The efficiency can be measured by displaying the product of I(Vin) and V(Vin). This gives you the instantaneous input power. Average it over one switching cycle, and you obtain the average input power Pin. Display the output voltage, square it, get the average value, and divide it by the load: This is the output power Pout. The efficiency is simply Pout/Pin.

$$\eta_{low,line} = \frac{\frac{3.3^2}{0.825}}{4 * 3.52} = \frac{13.2}{14.8} = 89.1\%$$

$$\eta_{high,line} = \frac{\frac{3.3^2}{0.825}}{20 * 0.8} = \frac{13.2}{16} = 82.5\%$$

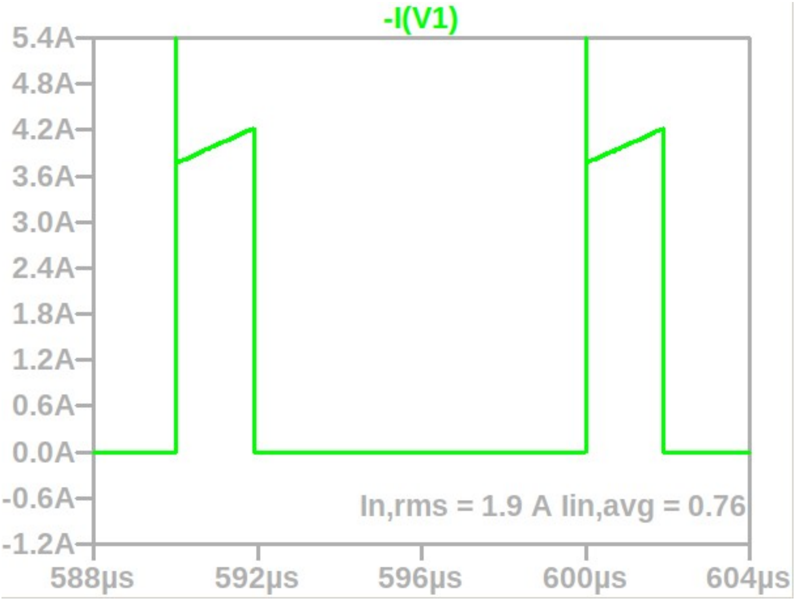
INPUT FILTER

(buck input current signature at VIN 20 VDC)

Fourier components of I(v1)
DC component:-0.761656

Harmonic Number	Frequency [Hz]	Fourier Component
1	1.000e+5	1.434e+0
2	2.000e+5	1.185e+0
3	3.000e+5	8.285e-1
4	4.000e+5	4.349e-1
5	5.000e+5	8.214e-2
6	6.000e+5	1.847e-1
7	7.000e+5	3.149e-1
8	8.000e+5	3.175e-1
9	9.000e+5	2.219e-1

Partial Harmonic Distortion: 111.798819%
Total Harmonic Distortion: 120.988400%



$$I_{peak}(fundamental) = 1.4\,A$$

$$Att_{filter} < \frac{15\,mA}{1.4\,A} < 0.01 \text{ or } better\ than\ a\ 39\,dB\ attenuation$$

$$f_0 < \sqrt{Att_{filter}} \cdot F_{sw} < 10\,kHz$$

A key selection criteria for selecting capacitors is its rms current folwing through it, so the current flowing through Cin will be

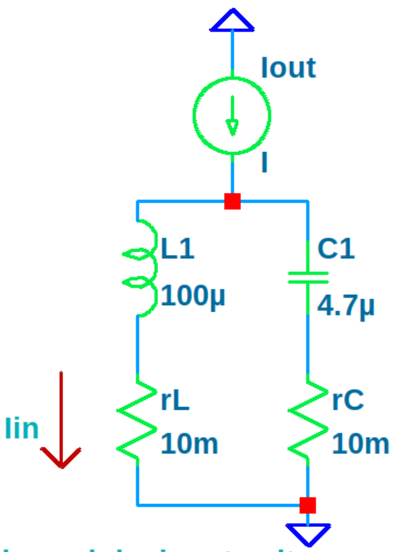
$$I^2_{\text{in,rms}} - I^2_{\text{in,ac}} - I^2_{\text{in,dc}} = 0$$

$$I_{Cin,rms} = I_{\text{in,ac}} = \sqrt{I^2_{\text{in,rms}} - I^2_{\text{in,dc}}} = \sqrt{1.9^2 - 0.762^2} = 1.74\,Arms$$

For L = 100 uH we get,

$$C = \frac{1}{4\pi^2 f_o^2 L} = 2.53\,uF$$

or 4.7 uF for the normalized value.



Iin (the current going through he input voltage source)

We verify the final attenuation at 100kHz of the filter with the parasitics added: (the transfer function can be derived by state-space matrix algebra or a simple current division)

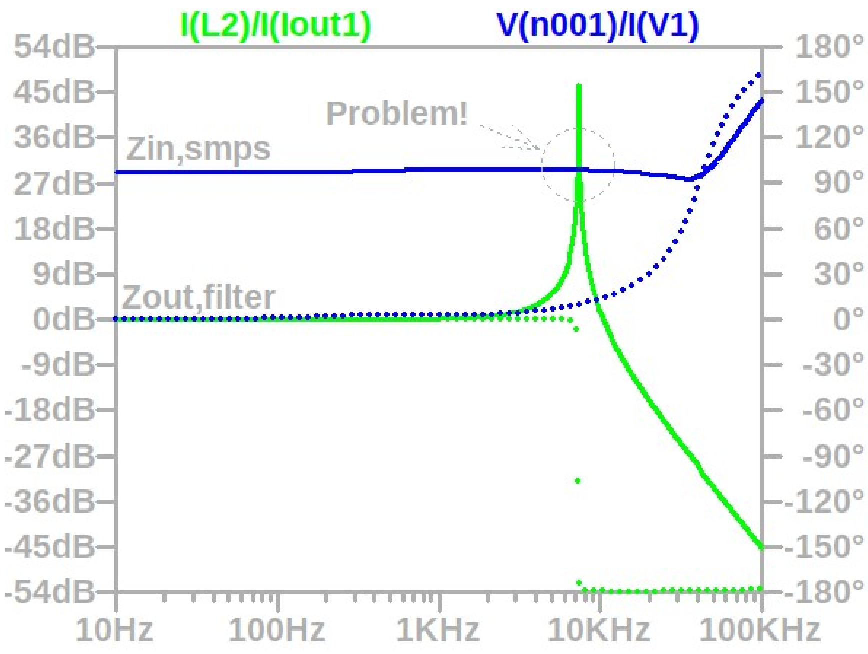
$$\left\| \frac{I_{\text{in}}}{I_{out}} \right\|_{at\,100\,kHz} = \sqrt{\frac{r_C^2 + \frac{1}{(\omega C)^2}}{(r_L + r_C)^2 + \frac{1}{(\omega C)^2} - \frac{2L}{C} + (\omega L)^2}} = \text{¿}$$

$$= \sqrt{\frac{0.01^2 + \frac{1}{(2\pi \cdot 100\text{e}3 \cdot 4.7\text{e-}6)^2}}{(0.01+0.01)^2 + \frac{1}{(2\pi \cdot 100\text{e}3 \cdot 4.7\text{e-}6)^2} - \frac{2 \cdot 100\text{e-}6}{4.7\text{e-}6} + (2\pi \cdot 100\text{e}3 \cdot 100\text{e-}6)^2}} = \text{¿}$$

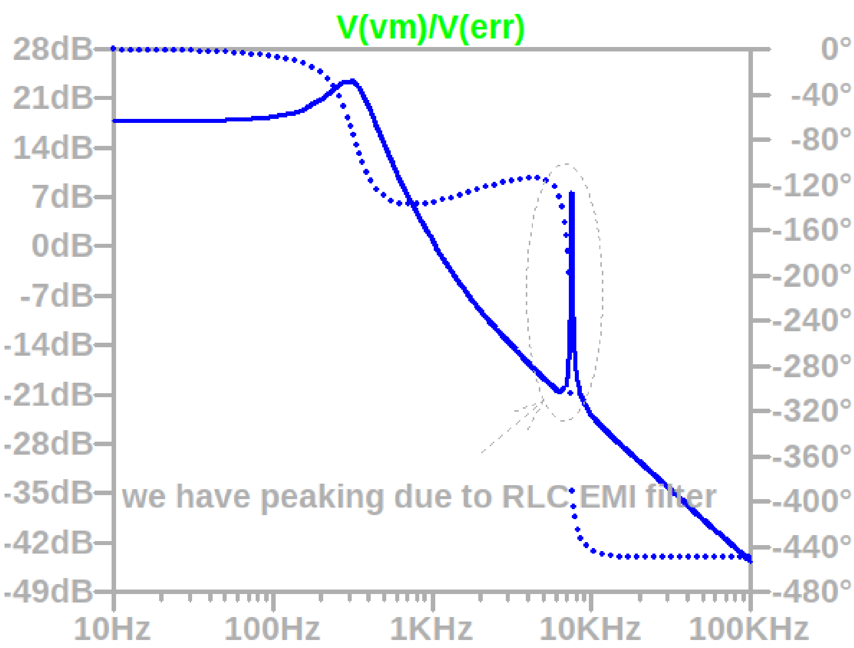
$$=\sqrt{\frac{1.14\text{e-}1}{400\text{e-}6+1.14\text{e-}1-42.55+3.94\text{e}3}}=5.4\,m$$

which is below the 10m specification previously calculated.

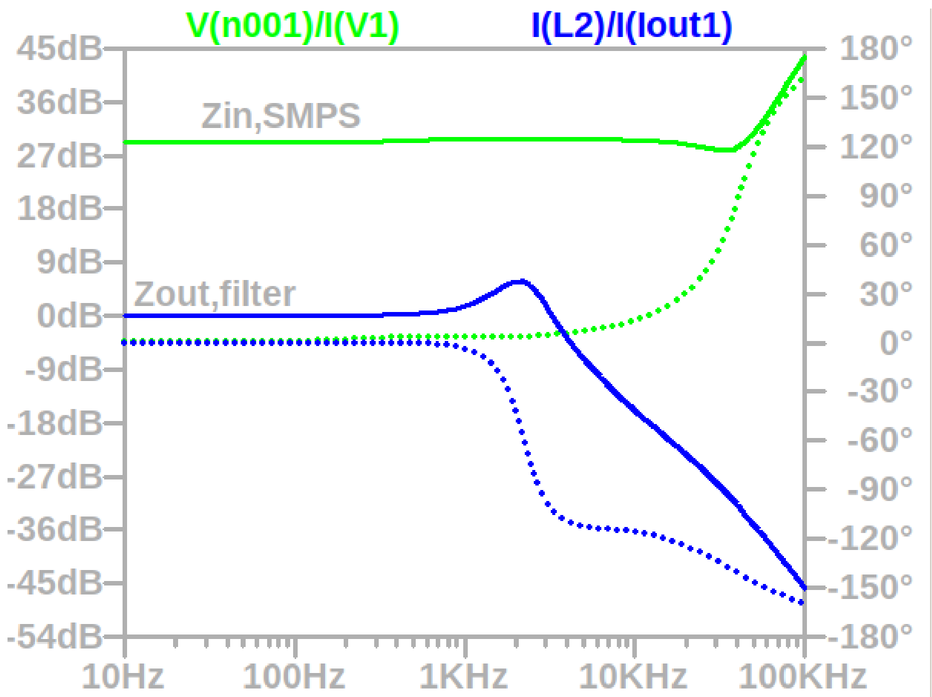
(both ac converter input impedance and filter output impedance are shown in the following graph)



Note that if we are not damping this filter, the open-loop gain or the control-to-output transfer function will reveal an aggravated phase degradation associated with RLC filter peaking (like in the following representation of the open-loop gain of this converter with EMI filter added).



After we added a damping network to EMI filter we get the following result:

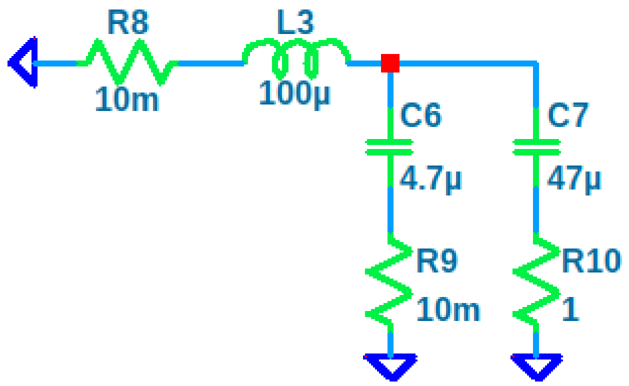


(filter circuit Rdamp ~ sqrt(L/C)) i.e., the characteristic impedance of L3 and C6

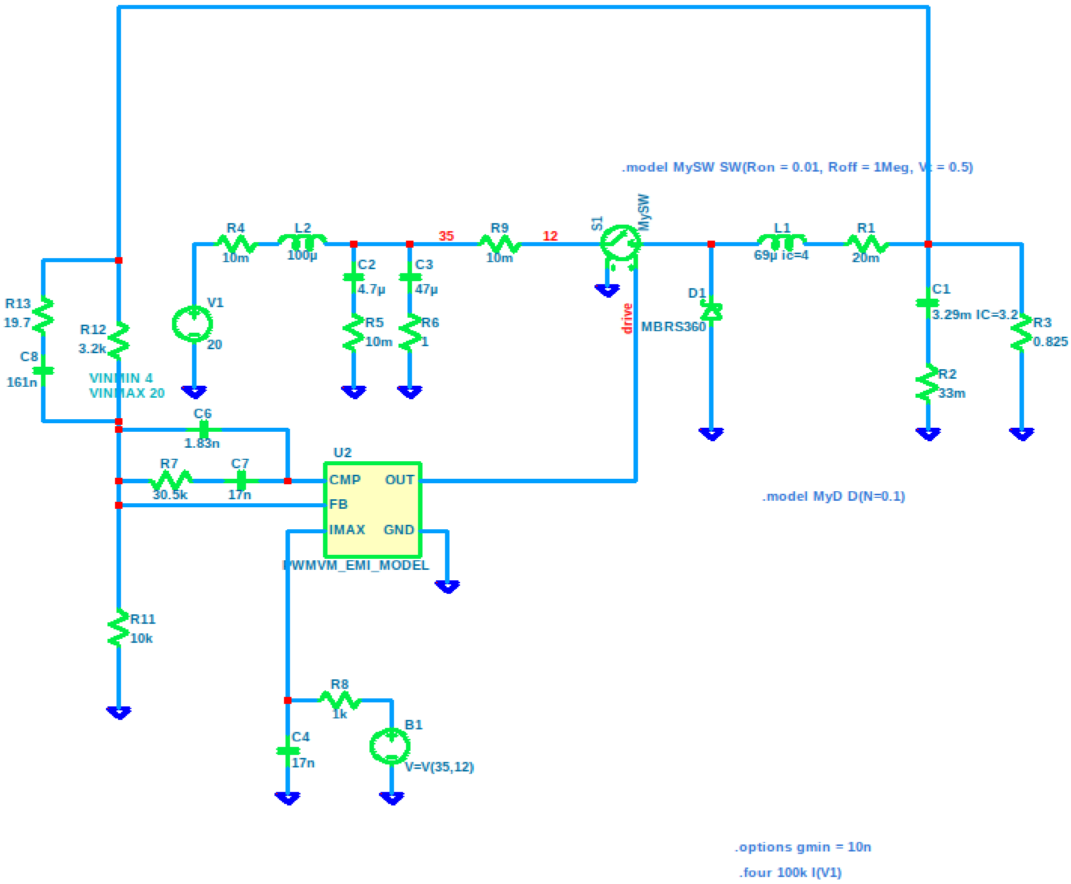
C7 should be chosen to have lower impedance than R10 at the approximate resonance pulsating frequency of 1/sqrt(L3*C6)

$$X_C = 1/(2\pi f_f C_7) \rightarrow C_7 = 1/(2\pi f_f X_C) = 1/(2\pi \cdot 7.34e3 \cdot 0.2) = 108e-6\,F \; where\; X_C \; was\; taken\; 0.2\,\Omega$$

$$where\; f_f = \frac{1}{2\pi\sqrt{(L3*C6)}} = 7.34\,kHz$$



(final circuit)



(input current harmonics simulation verifies our EMI filter)

Fourier components of I(v1)
DC component:-0.770244

Harmonic Number	Frequency [Hz]	Fourier Component
1	1.000e+5	7.217e-3
2	2.000e+5	1.550e-3
3	3.000e+5	4.937e-4
4	4.000e+5	1.402e-4
5	5.000e+5	3.527e-5
6	6.000e+5	3.538e-5
7	7.000e+5	3.959e-5
8	8.000e+5	5.145e-6
9	9.000e+5	1.274e-5

Partial Harmonic Distortion: 22.645434%
Total Harmonic Distortion: 22.658500%