

BUCK_4_20VDCINPUT_3V3_4A_13W_VM_CCM

SPECIFICATIONS

V _{inmin}	4 VDC
V _{inmax}	20 VDC
V _{out}	3.3 V
V _{ripple}	125 mV
V _{out_drop}	0.25 V from I _{out} = 200 mA to 3 A in 1 us
I _{outmax}	4 A
F _{sw}	100 kHz
I _{ripplepeak}	15 mA, input current maximum ripple

VM CCM

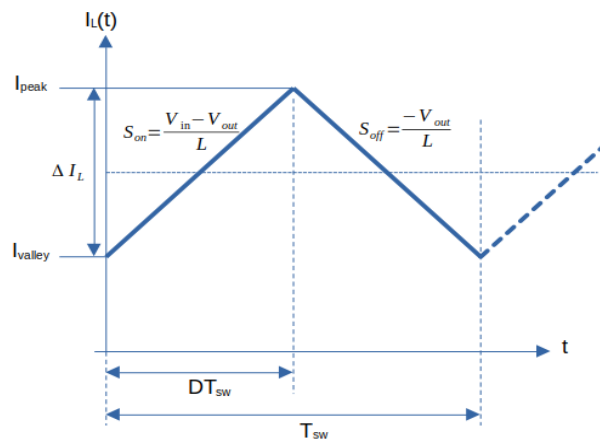
$$D_{min} = \frac{V_{out}}{V_{inmax}} = \frac{3.3}{20} = .165$$

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

→ 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 C_{out} without ESR effect)



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

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

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

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

with δI_r of 10%

$$L = \frac{3.3 \cdot (1 - 0.165)}{0.1 \cdot 100e3 \cdot 4} = 69 \mu H$$

At maximum load current, the peak current will increase to

$$I_{peak} = I_{L,avg} + \frac{V_{out}(1-D_{min})}{2 L F_{sw}} = I_{out} + \frac{V_{out}(1-D_{min})}{2 L F_{sw}} = 4 + \frac{3.3 \cdot (1 - 0.165)}{2 \cdot 69e-6 \cdot 100e3} = 4 + 0.2 = 4.2 A$$

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

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

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

4.7 μF Panasonic 10SVP4R7M

$I_{C,rms} = 670 mArms$

$RESR_{max} = 0.24 \Omega$ at $T_A = 20^\circ C$, 100 kHz to 300 kHz

SVP series, 10 V

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

AC ANALYSIS

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

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

$$C_{out} = \frac{\Delta I_{out}}{2\pi f_c \Delta V_{out}} = \frac{2.8}{2\pi \cdot 10e3 \cdot 0.25} = 200 \mu F$$

470 μF Vishay 54471E3

$I_{C,rms} = 630 mArms$ at $T = 105^\circ C$

$RESR_{low} = 0.120 \Omega$ at $T_A = 20^\circ C$

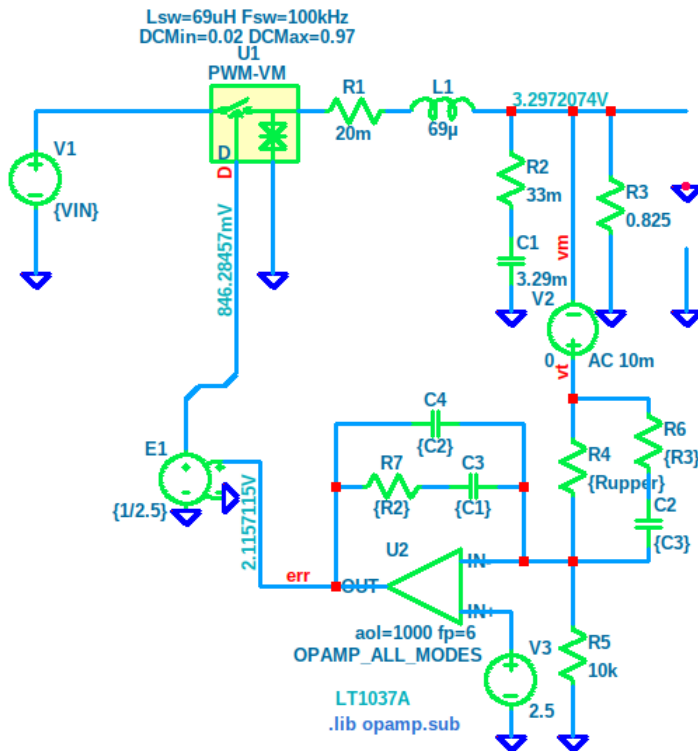
$RESR_{max} = 0.240 \Omega$ at $T_A = -10^\circ C$

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:

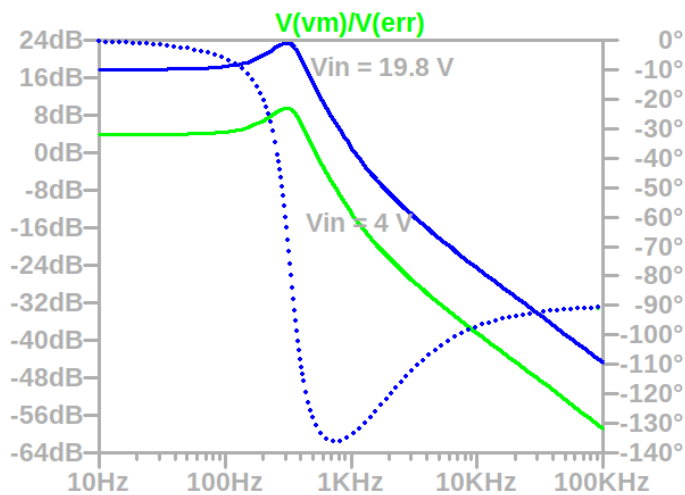
$$R_{ESR} < \frac{1}{2\pi f_c C_{out}}$$

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

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



→ open-loop (control-to-output) transfer function (at $V_{IN} = 4\text{ VDC}$ and 19.8 VDC)



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

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

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

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

→ our LC circuit resonates at

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

From the open-loop sweep we can see that the the required gain at f_c of 10 kHz is 38 dB worst case at V_{in} 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

$R_2 = 30.5 \text{ k}\Omega$

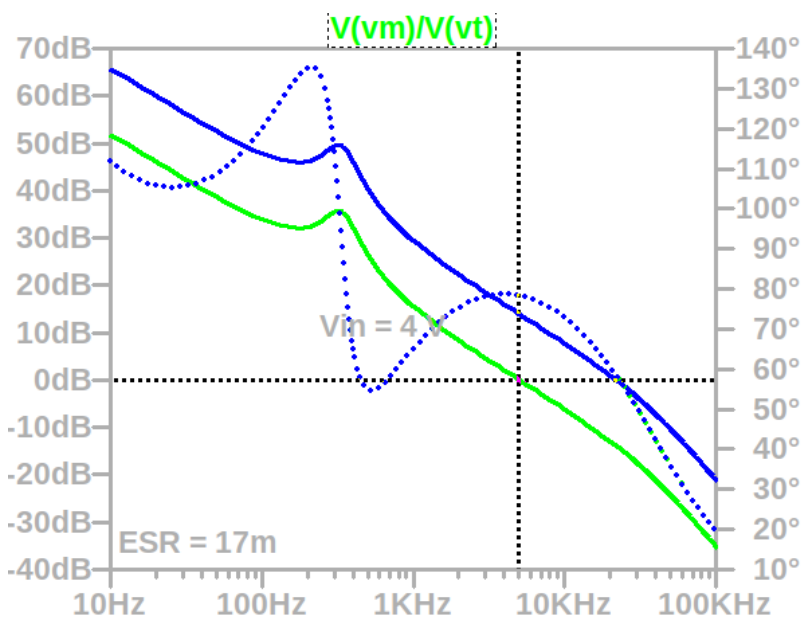
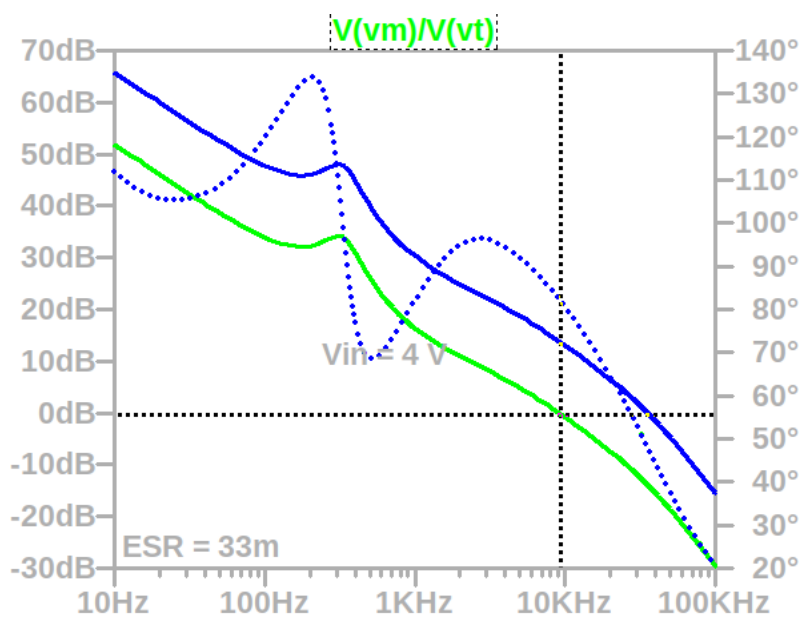
$R_3 = 19.7 \text{ }\Omega$

$C_1 = 17 \text{ nF}$

$C_2 = 1.83 \text{ nF}$

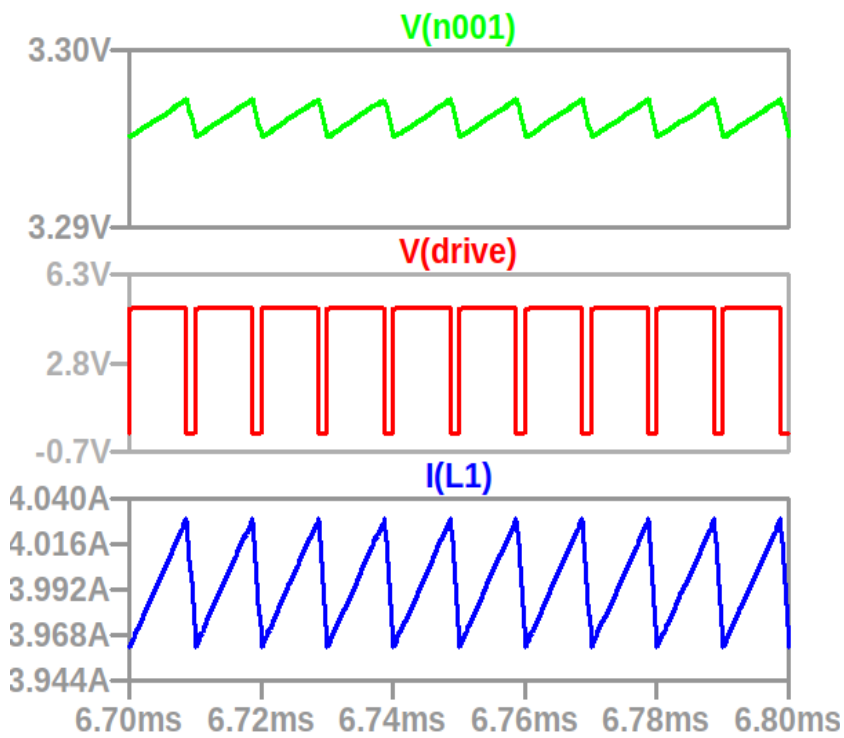
$C_3 = 161 \text{ nF}$

→ loop-gain transfer function at $V_{in} = 4 \text{ VDC}$ and 19.8 VDC



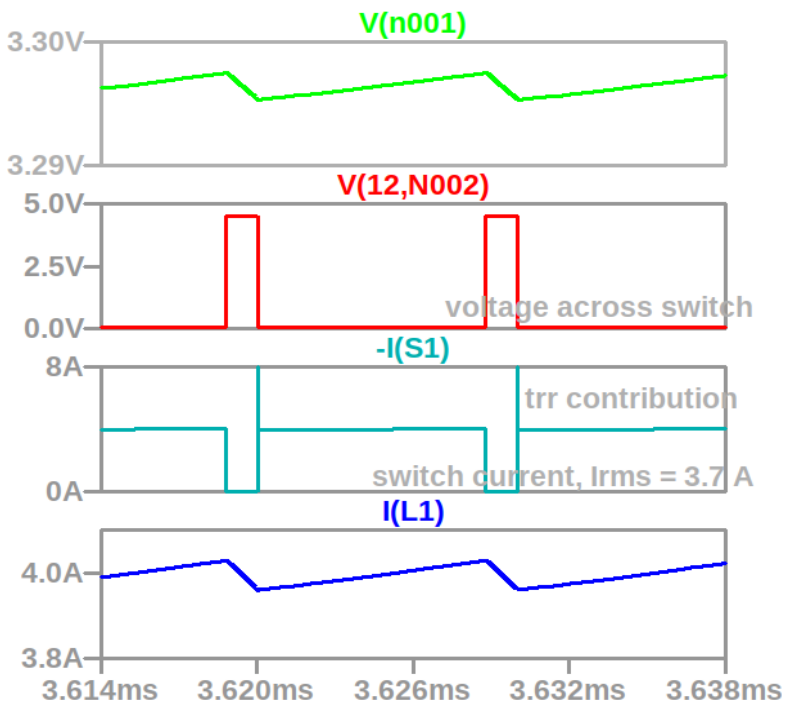
TRANSIENT ANALYSIS

(transient simulation at VIN = 4 VDC)



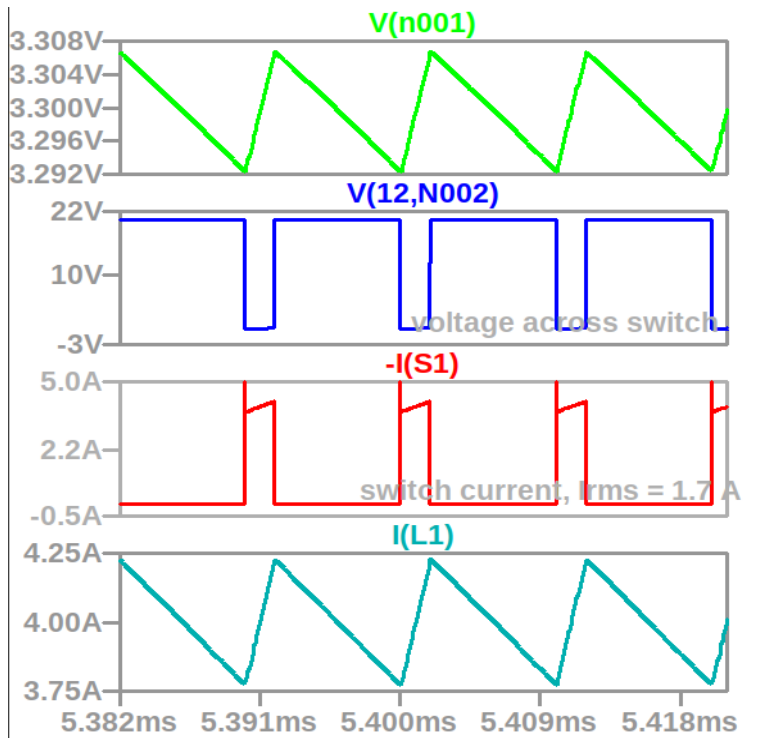
MOSFET STRESS

(MOSFET waveforms at $V_{in} = 4 \text{ VDC}$)



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

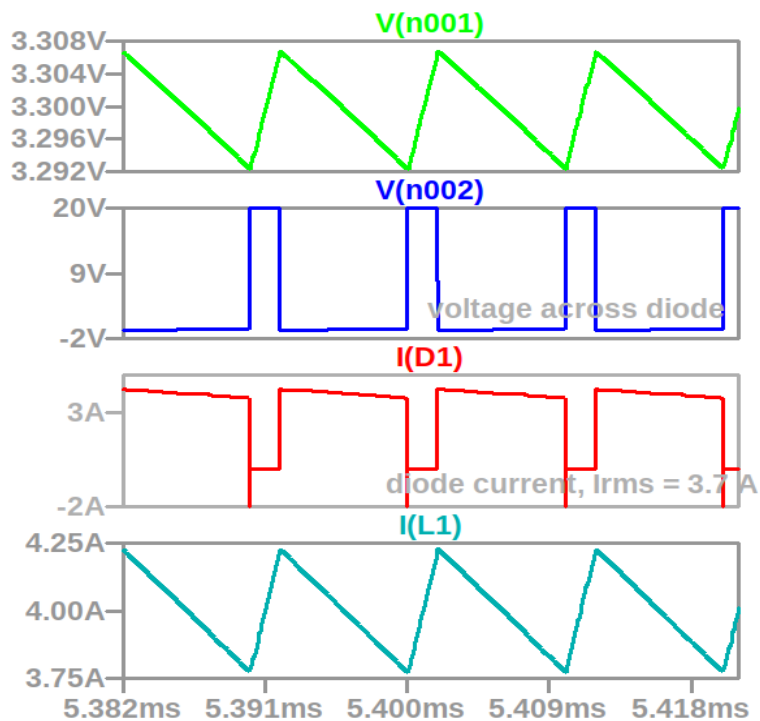
(MOSFET waveforms at $V_{in} = 20 \text{ VDC}$)



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*.)

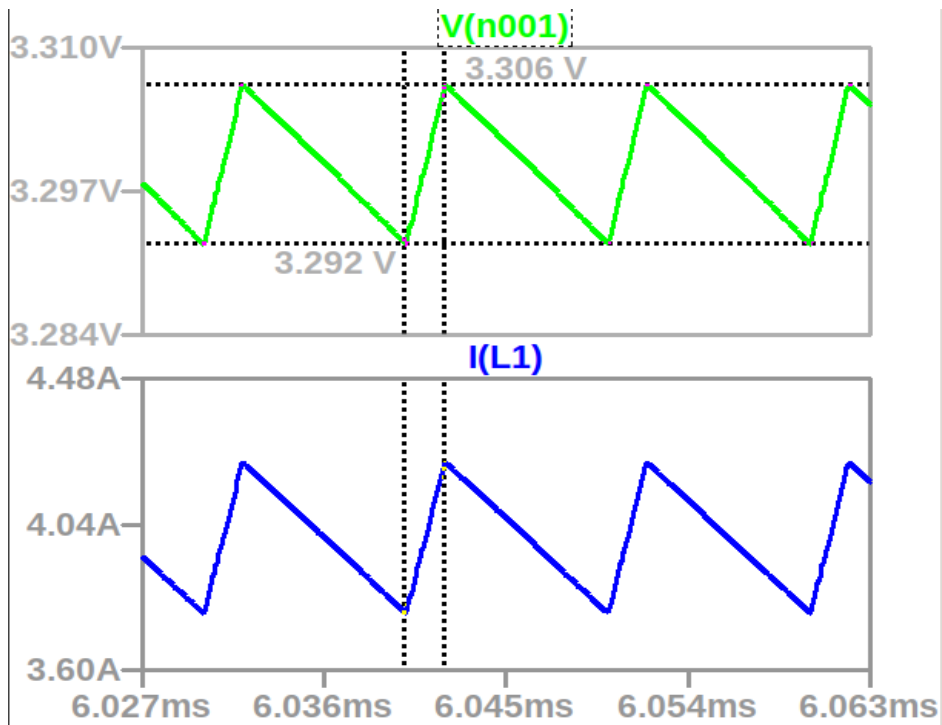
(diode waveforms at $V_{IN} = 20\text{ VDC}$)



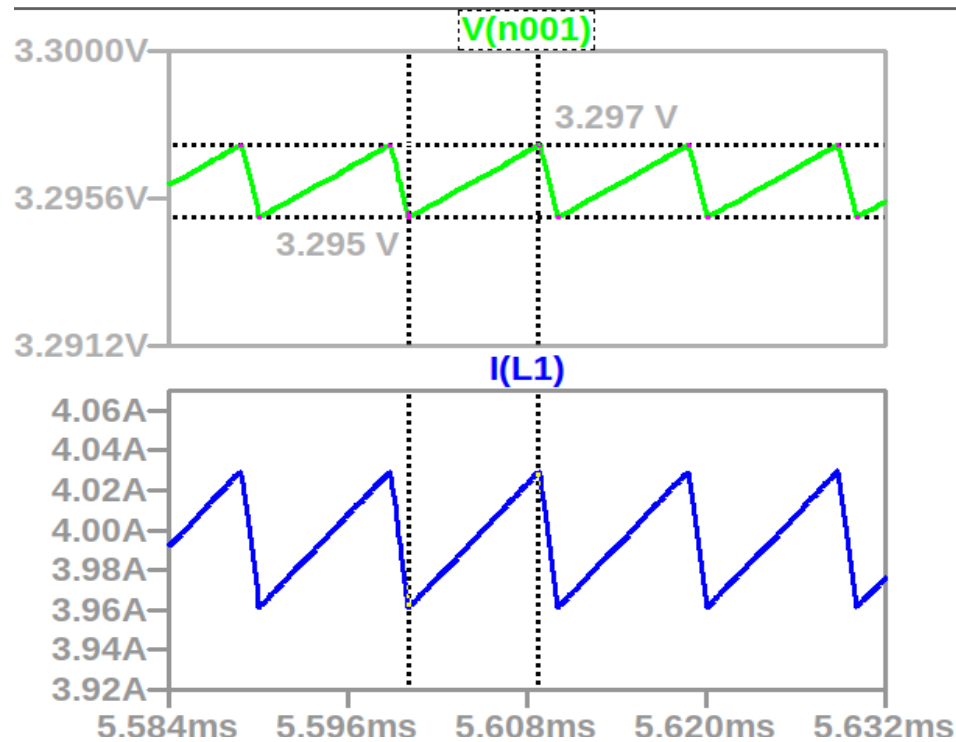
$$P_{cond} = V_f I_{d,avg} + R_d I_{d,rms}^2 \approx V_f I_{d,avg} \approx 0.7 \cdot 3.3 = 2.31\text{ W}$$

OUTPUT RIPPLE AND TRANSIENT RESPONSE

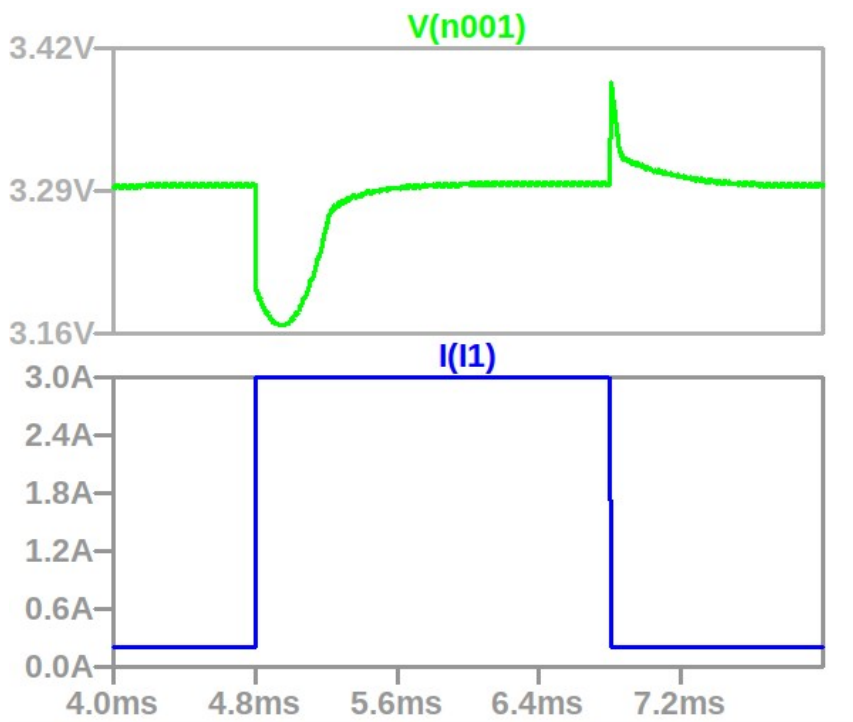
(output ripple at VIN 20 V and full load of 4 A ~ 14 mV)



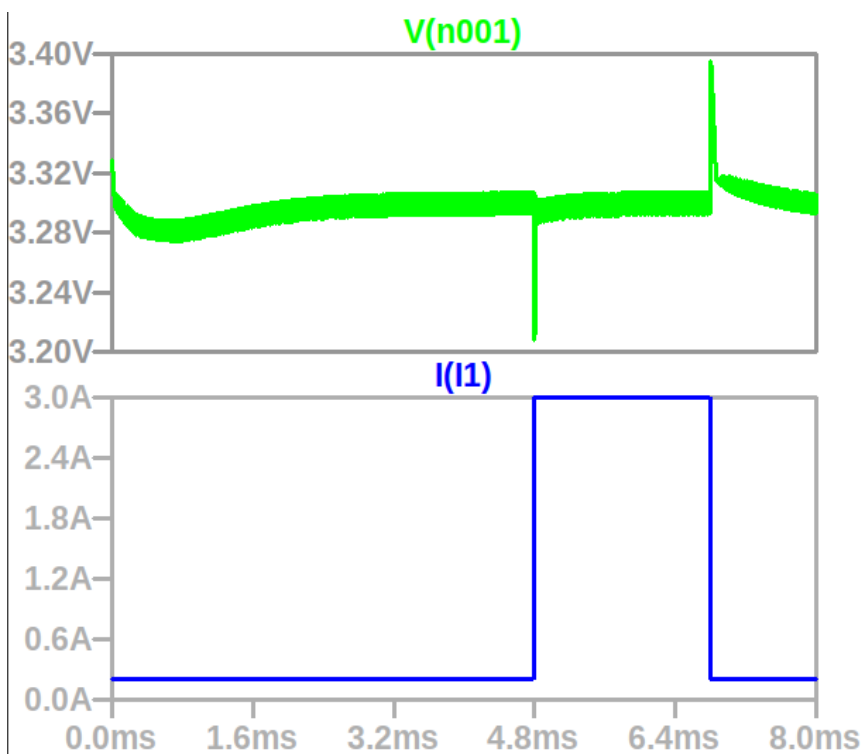
(output ripple at VIN 4 V and full load of 4 A ~ 1.4 mV)



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



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



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

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

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

INPUT FILTER

(buck input current signature at VIN 20 VDC)

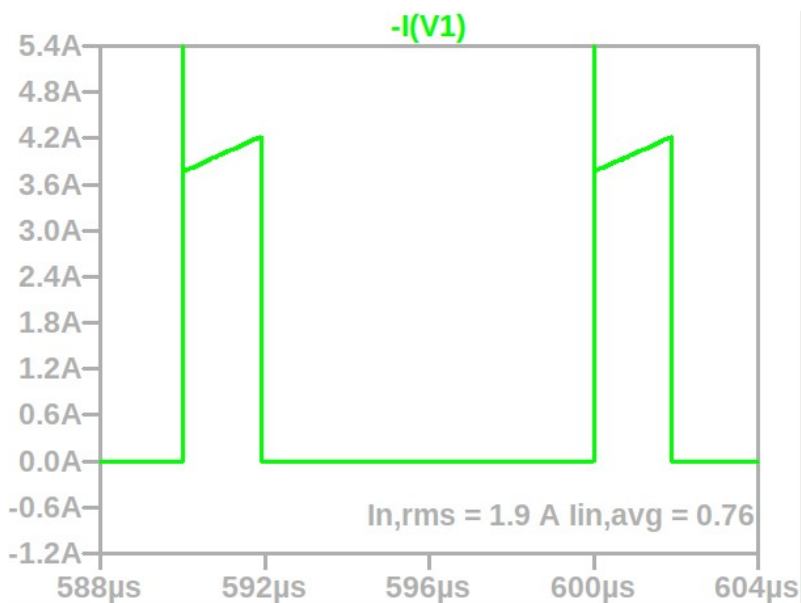
Fourier components of I(v1)

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%



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

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

$$f_0 < \sqrt{0.01} \cdot F_{sw} < 10 \text{ kHz}$$

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

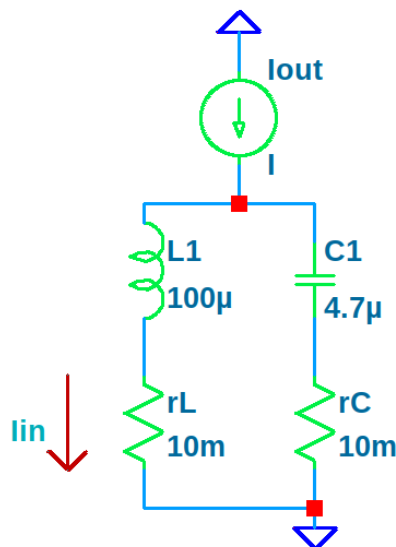
$$I_{in,rms}^2 - I_{in,ac}^2 - I_{in,dc}^2 = 0$$

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

For L = 100 uH we get,

$$C = \frac{1}{4 \pi^2 f_o^2 L} = 2.53 \mu F$$

or 4.7 uF for the normalized value.



I_{in} (the current going through the 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)

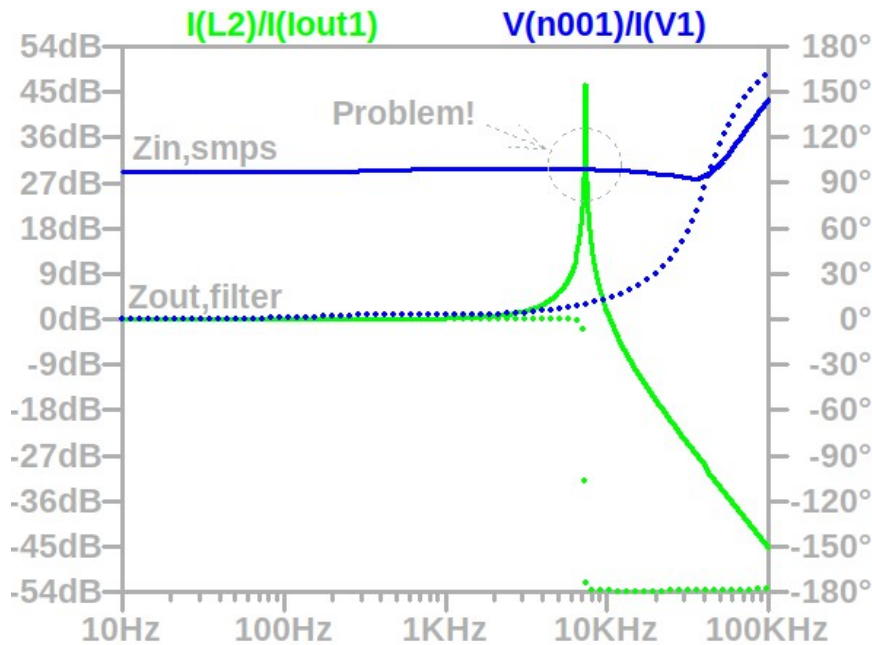
$$\left\| \frac{I_{in}}{I_{out}} \right\|_{at 100 \text{ kHz}} = \sqrt{\frac{r_C^2 + \frac{1}{(\omega C)^2}}{(r_L + r_C)^2 + \frac{1}{(\omega C)^2} - \frac{2L}{C} + (\omega L)^2}} = \dot{c}$$

$$= \sqrt{\frac{0.01^2 + \frac{1}{(2\pi \cdot 100e3 \cdot 4.7e-6)^2}}{(0.01 + 0.01)^2 + \frac{1}{(2\pi \cdot 100e3 \cdot 4.7e-6)^2} - \frac{2 \cdot 100e-6}{4.7e-6} + (2\pi \cdot 100e3 \cdot 100e-6)^2}} = \dot{c}$$

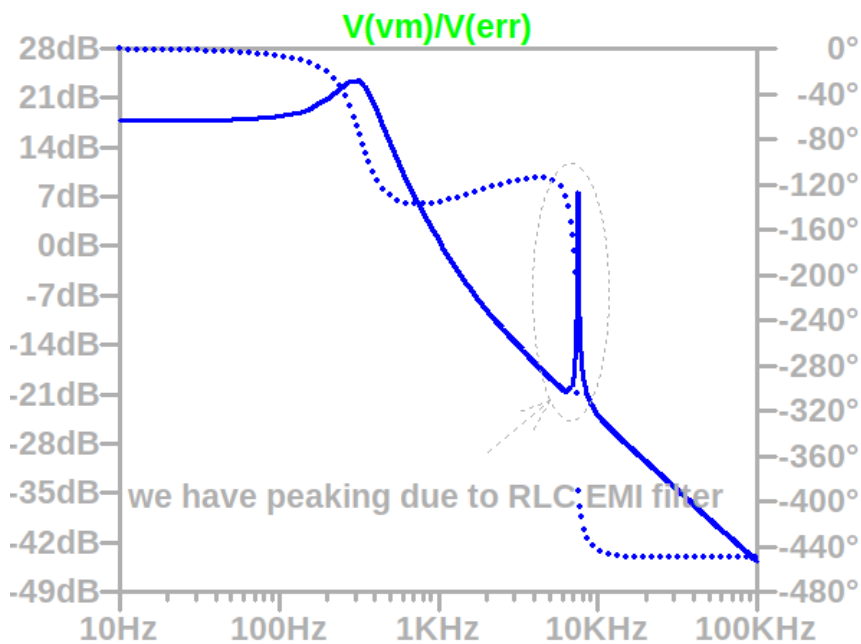
$$= \sqrt{\frac{1.14e-1}{400e-6 + 1.14e-1 - 42.55 + 3.94e3}} = 5.4m$$

which is below the 10m specification previously calculated.

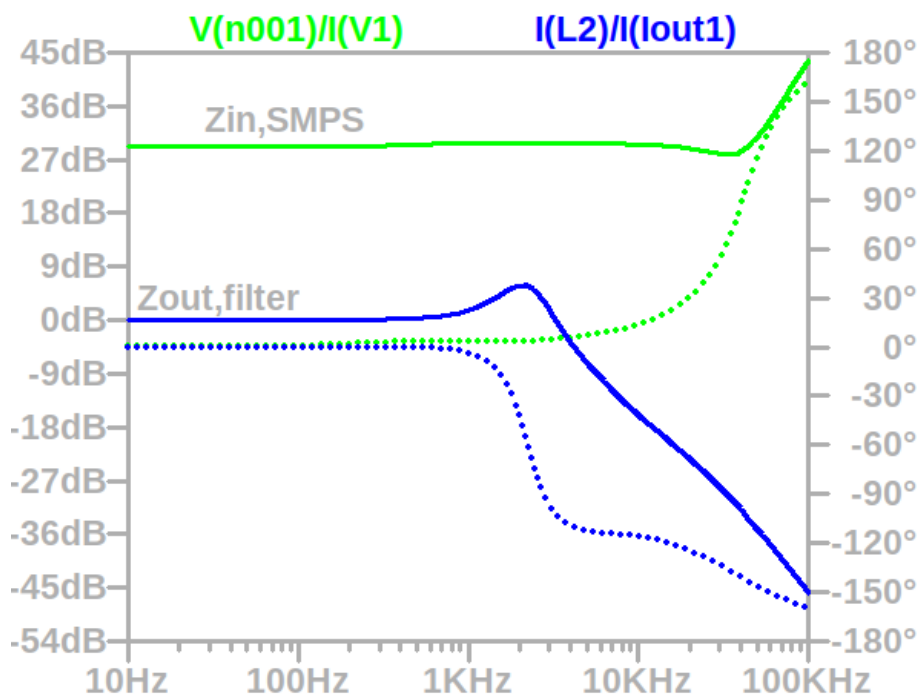
(both ac converter input impedance and filter output impedance are shown in the following graph)



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:

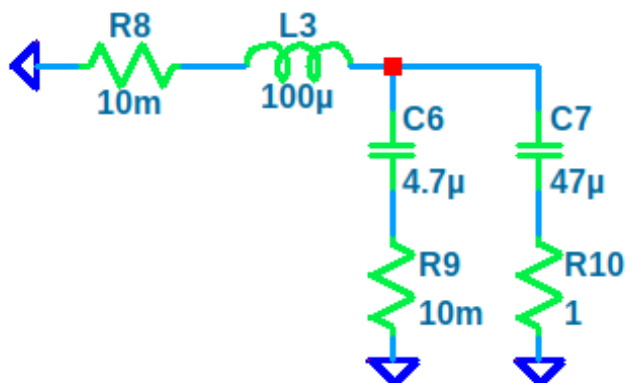


(filter circuit $R_{damp} \sim \sqrt{L/C}$) i.e., the characteristic impedance of L3 and C6

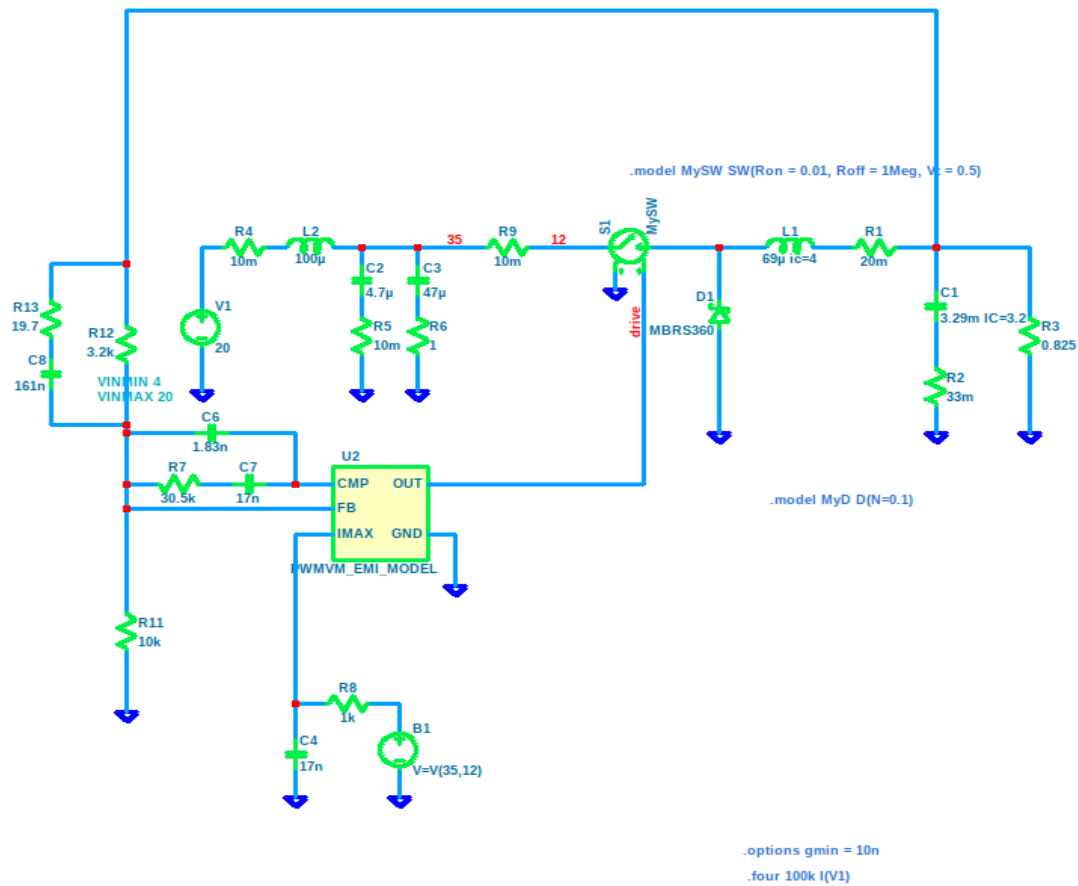
C7 should be chosen to have lower impedance than R10 at the approximate resonance pulsating frequency of $1/\sqrt{L3 \cdot C6}$

$$X_C = 1/(2\pi f_f C_7) \rightarrow C_7 = 1/(2\pi f_f X_C) = 1/(2\pi \cdot 7.34e3 \cdot 1) = 21.69e-6 F$$

$$\text{where } f_f = \frac{1}{2\pi\sqrt{L3 \cdot C6}} = 7.34 \text{ kHz}$$



(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%