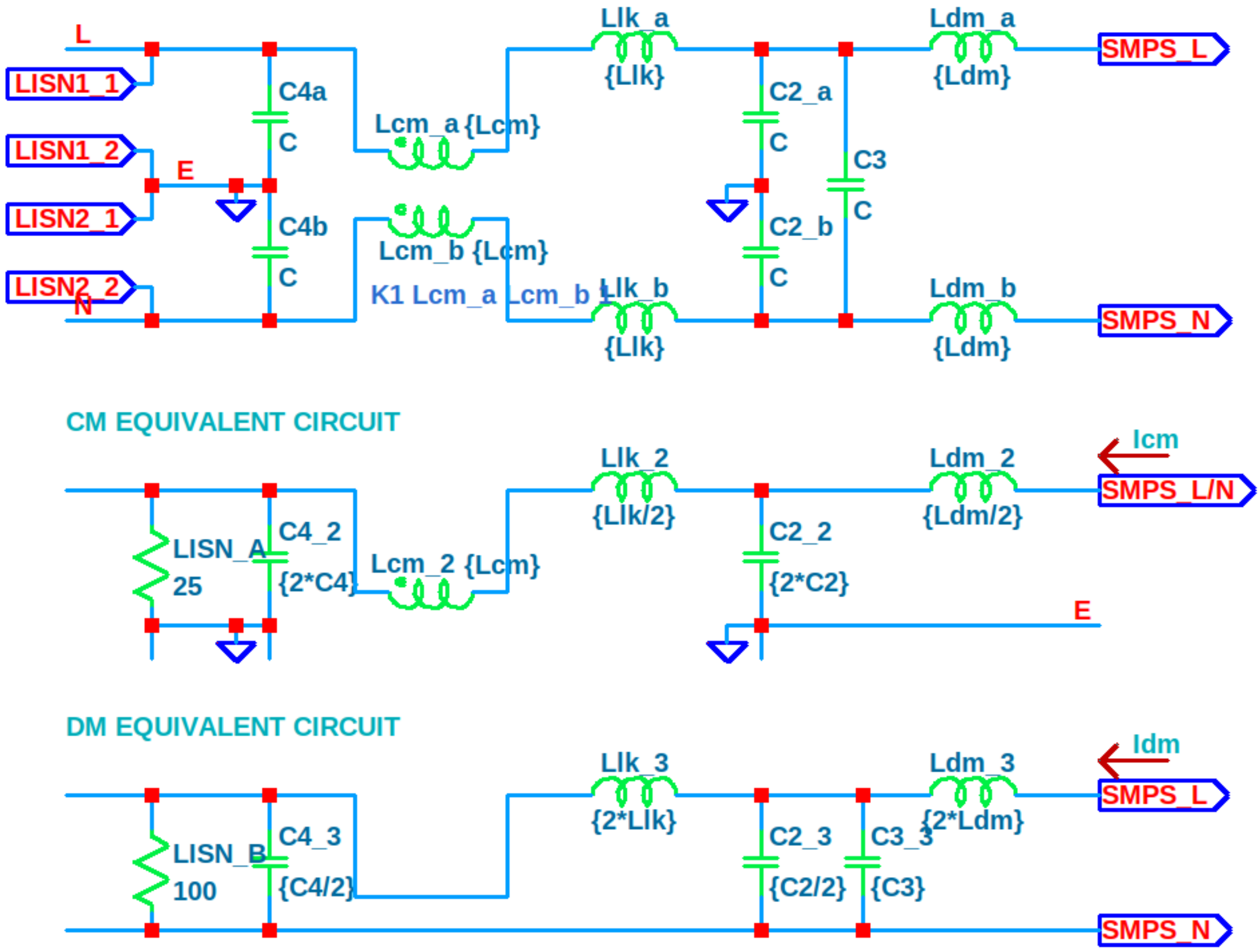
EMI_FILTER_FLYBACK_85_275VRMS_5V_6A_30W_CM_CCM

Note that this is a preliminary model. CM and DM noise must be measured on a prototype model and account for them respectively.

(reference EMI filter circuit)



(we are using CISPR-22 CLASS B LIMITS to account for the EMI filter parameters)

DM Filter Design

$$DM\ noise\ source\ V_{dm}=I_{SW}\cdot ESR\ ,\ where\ I_{SW}\ here\ refers\ \text{to}\ average\ \text{or}\ center\ of\ ramp\ of\ the\ switch$$

(Assuming CBULK is very large, and that it has no ESL, and also that its ESR is much less than 100 Ω, all being reasonable assumptions.)

Without an EMI filter present, the switching noise current received by the LISN would be

$$I_{LISN}=\frac{V_{dm}}{Z_{LISNDM}}=\frac{I_{SW}\cdot ESR}{100}\ Amps$$

(since the LISN has an impedance of 100 Ω for DM noise)

However, the analyzer measures the noise across one of the two effective series 50 Ω resistors in the LISN (Note to disable the series LISN resistance of the respective channel when connecting the spectrum analyzer). So, the measured level of noise is

$$V_{\mathrm{LISN\_DM\_NOFILTER}} = I_{LISN} \cdot 50 = \frac{I_{SW} \cdot ESR}{2} \, Volts$$

DM Filter Design at High Line

Duty-Cycle

The maximum peak rectified voltage is 265 * sqrt(2) = 374 V. The VOR is by definition 5 V * 1/0.073 = 68.5 V. The lowest duty cycle (highest input) at CCM is

$$D = \frac{V_{\mathrm{OR}}}{V_{\mathrm{IN}} + V_{\mathrm{OR}}} = \frac{68.5}{374 + 68.5} = 0.154$$

Load current of 6 A translates to the following switch current pedestal:

$$I_{SW} = \frac{N_S}{N_P} \frac{I_O}{1-D} = \frac{0.073 \cdot 6}{1 - 0.154} = 0.517 \, A$$

Breakpoints (in the Fourier series of the DM noise - (here we find the harmonics amplitude based on breakpoints or on the exact equation))

$$nbreak\,1 = \frac{1}{\pi f \, t_{on}} = \frac{1}{\pi D} = \frac{1}{\pi \cdot 0.154} = 2.066$$

$$nbreak\,2 = \frac{1}{\pi t_{cross} f} = \frac{1}{\pi \cdot 0.2\text{e-}6 \cdot 65\text{e}3} = 24.48$$

(considering rise and fall times of the Vds waveforms of 0.2e-6 s)

$$fbreak\,1 = \frac{1}{\pi t_{on}} = \frac{1}{\pi D} f = \frac{1}{\pi \cdot 0.154} \cdot 65\text{e}3 = 134\text{e}3 \, Hz$$

$$where\, nbreak\,1 = fbreak\,1/f$$

$$fbreak\,2 = \frac{1}{\pi t_{cross}} = \frac{1}{\pi 0.2\text{e-}6} = 1.592\text{e}6 \, Hz$$

We see that fbreak1 exceeds the fundamental frequency of 65 kHz, so its amplitude will get clamped. We use the following envelope equations, to find out the exact amplitude of the first harmonic.

$$c\_estimated\,1 = \frac{2A}{nbreak\,1 \cdot \pi} = \frac{2 \cdot 0.517}{2.066 \cdot \pi} = 0.159$$

(where A = ISW (center of ramp))

Note that we can use the exact equation to find all harmonics amplitude (for n = 1 (not the approximated value), and n = 2 etc.):

$$|c_n| = 2A \cdot \frac{t_{on}}{T} \cdot \left| \frac{\sin(n \pi t_{on}/T)}{n \pi t_{on}/T} \right| \cdot \left| \frac{\sin(n \pi t_{cross}/T)}{n \pi t_{cross}/T} \right| \approx 2A \cdot \frac{t_{on}}{T} \cdot \left| \frac{\sin(n \pi t_{on}/T)}{n \pi t_{on}/T} \right|$$

$$i.e.,|c_{n1}|=2A\cdot\frac{t_{on}}{T}\cdot\left|\frac{\sin(n\pi t_{on}/T)}{n\pi t_{on}/T}\right|=2\cdot0.517\cdot0.154\cdot\left|\frac{\sin(1\cdot\pi\cdot0.154)}{1\cdot\pi\cdot0.154}\right|=0.153$$

The second Fourier harmonic (based on envelope) found at 130 kHz has an amplitude of

$$i.e.,|c_{n2}|=2A\cdot\frac{t_{on}}{T}\cdot\left|\frac{\sin(n\pi t_{on}/T)}{n\pi t_{on}/T}\right|=2\cdot0.517\cdot0.154\cdot\left|\frac{\sin(2\cdot\pi\cdot0.154)}{2\cdot\pi\cdot0.154}\right|=0.135$$

The third Fourier harmonic (based on envelope) found at 3 * 65 kHz = 195 kHz has an amplitude of

$$i.e.,|c_{n3}|=2A\cdot\frac{t_{on}}{T}\cdot\left|\frac{\sin(n\pi t_{on}/T)}{n\pi t_{on}/T}\right|=2\cdot0.517\cdot0.154\cdot\left|\frac{\sin(3\cdot\pi\cdot0.154)}{3\cdot\pi\cdot0.154}\right|=0.108$$

EMI Spectrum with no filter (note again that this can be measured with a spectrum analyzer)

Above, we have calculated the harmonic current amplitudes based on an envelope estimate. When these current harmonics reach the LISN, still assuming no EMI filter, we get the following voltages:

(here the Cbulk ESR is assumed 5.64 Ω/2 = 2.82 Ω at 50 Hz and at high frequencies this value is assumed to decrease. We’ll take it aproximately 0.94 Ω)

$$V_{\mathrm{dm\_1}}=\frac{I_{\mathrm{SW\_1}}\cdot ESR}{2}=\frac{0.153\cdot0.94}{2}=0.071\,V\rightarrow 20\log(0.071/1\text{e-}6)=97\,dBuV$$

$$V_{\mathrm{dm\_2}}=\frac{I_{\mathrm{SW\_2}}\cdot ESR}{2}=\frac{0.135\cdot0.94}{2}=0.063\,V\rightarrow 20\log(0.063/1\text{e-}6)=96\,dBuV$$

$$V_{\mathrm{dm\_3}}=\frac{I_{\mathrm{SW\_3}}\cdot ESR}{2}=\frac{0.108\cdot0.94}{2}=0.051\,V\rightarrow 20\log(0.051/1\text{e-}6)=94.1\,dBuV$$

Required Filter Attenuation

From the equation representing the CISPR-22 Class B limits over the range 150 – 500 kHz we know that

$$dBuV\_QP=-20\log(f_{MHz})+50(almost\;exact)$$

At the third harmonic of the no filter spectrum (195 kHz, i.e., 3 * 65 kHz), this limit is

$$dBuV\_QP=-20\log(0.195)+50=64.2\,dBuV$$

Now we get the required filter attenuation as 94.1 dB uV – 64.2 dB uV = 29.9 dB uV at 195 kHz. We are ignoring the first and second harmonic since it lies outside of the CISPR-22 Class B limits.

Filter Components at Stated Line Condition

We need to pick a low-pass filter with an appropiate corner frequency that provides this attenuation. If we are using a one-stage LC low-pass filter, we know it has an attenuation characteristic of about 40 dB.decade above its corner frequency (i.e., 1/(2πsqrt(LC))).

$$slope=\frac{dB_{att}}{logf_{att}-logf_{pole}} \rightarrow f_{pole}=10^{[logfatt-(dBatt/slope)]}$$

Note that this equation is the same as asking what fpole we need to get an attenuation of 29.9 dB at 195 kHz.

Therefore, solving we get

$$f_{pole}=10^{[logfatt-(dBatt/slope)]}=10^{[\log 195k-(29.9/40)]}=34.8\,kHz$$

We therefore need a filter that has an LC of

$$LC=\left(\frac{1}{2\pi 34.8\text{e}3}\right)^2=2.1\text{e-}11\,s^2$$

For example, if we have picked the X-cap C3 as 0.22 uF, the net DM inductance is L (twice the individual DM inductances in each line). We get

$$L\equiv 2L_{dm}=\frac{2.1\text{e-}11}{0.22\text{e-}6}=95\,uH \rightarrow L_{dm}=48\,uH$$

Before we build this filter, we need to repeat all the above steps at low line too (90 VAC). We will get another inductance recommendation.

DM Filter Design at Low Line

Duty-Cycle

The minimun peak rectified voltage is 90 * sqrt(2) = 127 V (Note that from the design file we have Vmin = 95 Vdc). The VOR is by definition 5 V * 1/0.073 = 68.5 V. The highest duty cycle (lowest input) at CCM is

$$D=\frac{V_{\mathrm{OR}}}{V_{\mathrm{IN}}+V_{\mathrm{OR}}}=\frac{68.5}{95+68.5}=0.42$$

Load current of 6 A translates to the following switch current pedestal:

$$I_{SW}=\frac{N_S}{N_P}\frac{I_O}{1-D}=\frac{0.073\cdot 6}{1-0.42}=0.755\,A$$

Breakpoints (in the Fourier series of the DM noise)

$$nbreak\,1=\frac{1}{\pi f\,t_{on}}=\frac{1}{\pi D}=\frac{1}{\pi\cdot 0.42}=0.757$$

$$nbreak\,2=\frac{1}{\pi t_{cross} f}=\frac{1}{\pi\cdot 0.2\text{e-}6\cdot 65\text{e}3}=24.48$$

(considering rise and fall times of the Vds waveforms of 0.2e-6 s)

$$fbreak\,1=\frac{1}{\pi t_{on}}=\frac{1}{\pi D}f=\frac{1}{\pi\cdot 0.42}\cdot 65\text{e}3=49\text{e}3\,Hz$$

$$where\; nbreak\,1=fbreak\,1/f$$

$$fbreak\,2=\frac{1}{\pi t_{cross}}=\frac{1}{\pi 0.2\text{e-}6}=1.592\text{e}6\,Hz$$

We see that fbreak1 is below the fundamental frequency of 65 kHz,so, it will not affect any harmonic amplitudes. The amplitude of the first harmonic (at 65 kHz) is then just based on the simple equation below

$$c\_estimated\,1 = \frac{2A}{n\cdot\pi} = \frac{2\cdot 0.755}{1\cdot\pi} = 0.48$$

(where A = ISW (center of ramp))

Note that we can use the exact equation to find all harmonics amplitude (for n = 1 (not the approximated value), and n = 2 etc.):

$$|c_n| = 2A\cdot\frac{t_{on}}{T}\cdot\left|\frac{\sin(n\pi t_{on}/T)}{n\pi t_{on}/T}\right|\cdot\left|\frac{\sin(n\pi t_{cross}/T)}{n\pi t_{cross}/T}\right| \approx 2A\cdot\frac{t_{on}}{T}\cdot\left|\frac{\sin(n\pi t_{on}/T)}{n\pi t_{on}/T}\right|$$

$$i.e., |c_{n1}| = 2A\cdot\frac{t_{on}}{T}\cdot\left|\frac{\sin(n\pi t_{on}/T)}{n\pi t_{on}/T}\right| = 2\cdot 0.755\cdot 0.42\cdot\left|\frac{\sin(1\cdot\pi\cdot 0.42)}{1\cdot\pi\cdot 0.42}\right| = 0.47$$

We will continue to use the estimated one as it give more pessimistic values.

$$c\_estimated\,2 = \frac{2A}{n\cdot\pi} = \frac{2\cdot 0.755}{2\cdot\pi} = 0.24$$

$$c\_estimated\,3 = \frac{2A}{n\cdot\pi} = \frac{2\cdot 0.755}{3\cdot\pi} = 0.16$$ found at 195 kHz, i.e., 3 * 65 kHz

EMI Spectrum with no filter (note again that this can be measured with a spectrum analyzer)

$$V_{\mathrm{dm\_1}} = \frac{I_{\mathrm{SW\_1}}\cdot ESR}{2} = \frac{0.48\cdot 0.94}{2} = 0.22\,V \rightarrow 20\log(0.22/1\text{e-}6) = 107\,dBuV$$

$$V_{\mathrm{dm\_2}} = \frac{I_{\mathrm{SW\_2}}\cdot ESR}{2} = \frac{0.24\cdot 0.94}{2} = 0.11\,V \rightarrow 20\log(0.11/1\text{e-}6) = 100\,dBuV$$

$$V_{\mathrm{dm\_3}} = \frac{I_{\mathrm{SW\_3}}\cdot ESR}{2} = \frac{0.16\cdot 0.94}{2} = 0.075\,V \rightarrow 20\log(0.075/1\text{e-}6) = 97.5\,dBuV$$

Required Filter Attenuation

From the equation representing the CISPR-22 Class B limits over the range 150 – 500 kHz we know that

$$dBuV\_QP = -20\log(f_{MHz}) + 50(almost\ exact)$$

At the third harmonic of the no filter spectrum (195 kHz, i.e., 3 * 65 kHz), this limit is

$$dBuV\_QP = -20\log(0.195) + 50 = 64.2\,dBuV$$

Now we get the required filter attenuation as 97.5 dB uV – 64.2 dB uV = 33.3 dB uV at 195 kHz. We are ignoring the first and second harmonic since it lies outside of the CISPR-22 Class B limits.

Filter Components at Stated Line Condition

$$f_{pole} = 10^{[logfatt-(dBatt/slope)]} = 10^{[\log 195k-(33.3/40)]} = 28.6\,kHz$$

We therefore need a filter that has an LC of

$$LC = \left(\frac{1}{2\pi 28.6\text{e}3} \right)^2 = 3.1\text{e-}11\, s^2$$

For example, if we have picked the X-cap C3 as 0.22 uF, the net DM inductance is L (twice the individual DM inductances in each line). We get

$$L \equiv 2L_{dm} = \frac{3.1\text{e-}11}{0.22\text{e-}6} = 141\, uH \rightarrow L_{dm} = 70\, uH$$

At high line we had 48 uH, at low line we get 70 uH on account of the higher currents at low line. Our final choice is the greater of the two, that is 70 uH.

Note that CISPR-22 limits include both the CM and DM noise. Here we have neglected the CM noise in the DM filter design calculation as it is only preliminary. To account for, we can add another 10 dB of attenuation needed.

CM Filter Design (at high line)

Duty Cycle

The maximum peak rectified voltage is 265 * sqrt(2) = 374 V. The VOR is by definition 5 V * 1/0.073 = 68.5 V. The lowest duty cycle (highest input) at CCM is

$$D = \frac{V_{\text{OR}}}{V_{\text{IN}} + V_{\text{OR}}} = \frac{68.5}{374 + 68.5} = 0.154$$

The VDS amplitude for a flyback is VIN + VOR = 374 + 68.5 = 442.5 V. (This “A” (pulse amplitude) in the Fourier expansion)

Breakpoints (here we find the harmonics amplitude based on breakpoints or on the exact equation)

$$i.e., |c_{n3}| = 2A \cdot \frac{t_{on}}{T} \cdot \left| \frac{\sin(n\pi t_{on}/T)}{n\pi t_{on}/T} \right| = 2 \cdot 442.5 \cdot 0.154 \cdot \left| \frac{\sin(3 \cdot \pi \cdot 0.154)}{3 \cdot \pi \cdot 0.154} \right| = 93\, V \quad \text{at 195 kHz}$$

EMI Spectrum with no Filter (can be measured with a spectrum analyzer too)

Above, we have calculated the harmonic voltage amplitudes based on an envelope estimate. These generate harmonic currents in the line, based on the impedance in the path including the LISN. These harmonic currents flow through the 25 Ω equivalent CM LISN impedance and get converted into voltage picked up by the spectrum analyzer as per Vcm = 25 * Icm. Here we will approximate Vcm by using that fact that we have a total of 100 pF mounting capacitance (Y capacitor) connected to earth in SMPS:

$$V_{cm} = \frac{100 \cdot A \cdot C_P}{T} = \frac{100 \cdot 442.5 \cdot 100\text{e-}12}{1/65\text{e}3} = 0.286\, V \rightarrow 20 \log(0.286/1\text{e-}6) = 109\, dBuV$$

(where A = VIN + VOR = 477 V)

The CM noise spectrum is flat-topped (clamped) at exactly 100 * A * CP/T, right up till the second breakpoint.

Required Filter Attenuation

At 195 kHz, the CISPR Class B (QP) limit is 64.2 dB uV.

So, we get the required filter attenuation of 109 – 64.2 = 44.8 dB uV

Filter Components at Stated Line Conditions

We need to pick a low-pass filter with an appropiate corner frequency that provides this attenuation. If we are using a one-stage LC low-pass filter, we know it has an attenuation characteristic of about 40 dB.decade above its corner frequency (i.e., 1/(2πsqrt(LC))).

$$f_{pole}=10^{[logfatt-(dBatt/slope)]}=10^{[\log 195k-(44.8/40)]}=14.8\,kHz$$

We therefore need a filter that has an LC of

$$LC=\left(\frac{1}{2\pi 14.8\text{e}3}\right)^2=1.15\text{e-}10\,s^2$$

For example, suppose we have finally picked two Y-caps marked “C4” as 2.2 nF each (note that Y capacitors are limited by regulatory standards). Then, as per the equivalent diagram, the effective C is therefore 4.4 nF. We can thus find Lcm as follows.

$$L\equiv L_{cm}=\frac{1.15\text{e-}10}{4.4\text{e-}9}=26.13\,mF$$

This is a high inductance and we may therefore consider two identical CM filters (LC stages) in cascade instead. We split the Y-cap into four 1.2 nF caps, so each stage gets a total Y-capacitance of 2.4 nF. That way we will not exceed the safety requirements.

Now, two LC filters in cascade will give us 80 dB/decade attenuation. Therefore, we get

$$f_{pole}=10^{[logfatt-(dBatt/slope)]}=10^{[\log 195k-(44.8/80)]}=53.7\,kHz$$

$$LC=\left(\frac{1}{2\pi 53.7\text{e}3}\right)^2=8.78\text{e-}12\,s^2$$

$$L\equiv L_{cm}=\frac{8.78\text{e-}12}{2.4\text{e-}9}=3.65\,mF$$