## A practical example:
## An EMC filter for a switched-mode power supply unit

In this article, an EMC filter for a specific switching power supply is developed and calculated step by step. The power supply operates with the following electrical parameters:

- **Input voltage:** 115 - 230 V AC
- **Nominal power:** 100 W
- **Efficiency:** 85 %
- **Switching frequency:** 75 kHz
- **Topology:** Fly-Back

The analysis of interference, the selection of suitable filter components and the optimization of the filter for the respective application are systematically addressed. Particular attention is paid to differentiating between common mode and differential mode interference in order to develop a targeted and standard-compliant filter solution.

How exactly such a filter is created, which components are required and which challenges arise during implementation are dealt with in the following sections.

In the first step, the voltage curve through the bridge rectifier is measured and the pulse duration ($\boldsymbol{\tau}$) and the rise time of the pulse ($\mathbf{t}_r$) are determined.

Recording the voltage signal results in a pulse duration of :

$$\tau = 2{,}1\ \mu s$$

The edge rise time is:

$$t_r = 1{,}3\ \mu s$$

Assuming a trapezoidal shape of the voltage and current curve through the bridge rectifier, the EMC spectrum can be estimated before the use of a mains filter and without Fourier transformation. To do this, the peak voltage (Vp) is calculated first:

$$V_p = \sqrt{2} \times V_{rms}$$

$$V_p = \sqrt{2} \times 230\ V \approx 325\ V$$

The corner frequencies of the enveloping amplitude density curve are then determined:

$$f_1 = \frac{1}{\pi \times \tau}$$

$$f_1 = \frac{1}{\pi \times 2{,}1\ \mu s} = 151{,}58\ kHz$$

$$f_2 = \frac{1}{\pi \times t_r}$$

$$f_1 = \frac{1}{\pi \times 1{,}3\ \mu s} = 244{,}85\ kHz$$

If the curve of the envelope is now sketched graphically, the course shown in Figure 1 results:

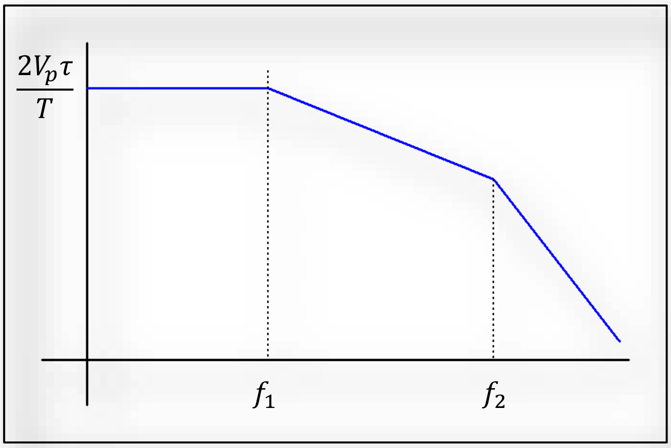


Figure 1: Sketch of the envelope curve

EN 55014 is used in this example for the subsequent estimation of the interference emission. It describes an EMI standard QP limit of 66 dBμV. The first odd harmonic above 150 kHz and the subsequent frequency spectrum are relevant for the evaluation of the interference emission. For the example, this means that the 3rd harmonic of the switching frequency, i.e. 225 kHz ($f_{n=3}$), must be considered. The frequency lies between the corner points $f_1$ und $f_2$. Therefore, the expected amplitude of the harmonic can be calculated approximately as follows:

$$V_3 = \frac{2 \times V_p}{\pi} \times \left(\frac{f_0}{f_{n=3}}\right)$$

$$V_3 = \frac{2 \times 325\ V}{\pi} \times \left(\frac{75\ kHz}{225\ kHz}\right) \approx 68{,}97\ V$$

A coupling impedance is also required to calculate the common mode current ($I_{cm}$). As an example, a coupling capacitance ($C_p$) of 20 pF is assumed. In practice, similar values are often found between the drain of the IGBT and the heat sink used. If this is connected to the protective conductor, the common mode current calculated below can occur.

$$I_{cm} = \frac{V_3}{X_c}$$

$$I_{cm} = V_3 \times 2\pi f C$$

$$I_{cm} = 68{,}97\ V \times 2\pi \times 225\ kHz \times 20\ pF \approx 1{,}95\ mA$$

A network simulation and an EMC measuring receiver are used to measure the conducted interference voltage. The following total impedance results from the parallel connection of the output impedance of the network simulation and the input impedance of the EMC measuring receiver:

$$Z = 50\ \Omega\ \|\ 50\ \Omega = 25\ \Omega$$

The expected interference voltage ($V_{cm}$) can now be calculated:

$$V_{cm} = Z \times I_{cm} = 25\ \Omega \times 1{,}95\ \text{mA} = 48{,}75\ \text{mV}$$

Converted to dBµV, this results in an interference level of:

$$V_{db\mu V} = 20 \times log\left(\frac{48{,}75\ mV}{1\mu V}\right) = 93{,}76\ dB\mu V$$

The last relevant variable required is the cut-off frequency of the filter to be used. The required attenuation is decisive here. It is calculated from the expected interference level, the normative limit value and a safety margin of 3 dBµV:

$$Dämpfung\ A = 93{,}76\ dB\mu V - 66\ dB\mu V + 3\ dB\mu V = 31\ dB\mu V$$

The filter to be developed should attenuate the interference with an attenuation of +40 dB per decade. From this, the approximate cut-off frequency of the mains filter can be determined:

$$f_c = f_{n=3} \times 10^{\frac{-A}{40}} = 225\ kHz \times 10^{\frac{-31}{40}} = 37{,}78\ kHz$$

Once all the necessary variables have been determined, the mains filter can be developed. In this example, a common-mode choke with an inductance value of four millihenry is selected as the choke. The decisive factor for the choke is not only the inductance, but also the current carrying capacity. The largest input current of the switching power supply occurs under full load at the minimum input voltage and is calculated as follows:

$$I_{max} = \left(\frac{P}{\eta}\right) \div V_{min} = \left(\frac{100\ W}{0{,}85}\right) \div 150\ VAC = 1{,}02\ A$$

This means that the current carrying capacity of the push-pull choke must be greater than 1.02 A. In practice, a choke with a load capacity of 2 A at 230 VAC at an ambient temperature of 40°C is usually selected in such a case. The selected common-mode choke has the impedance characteristics shown in Figure 2:

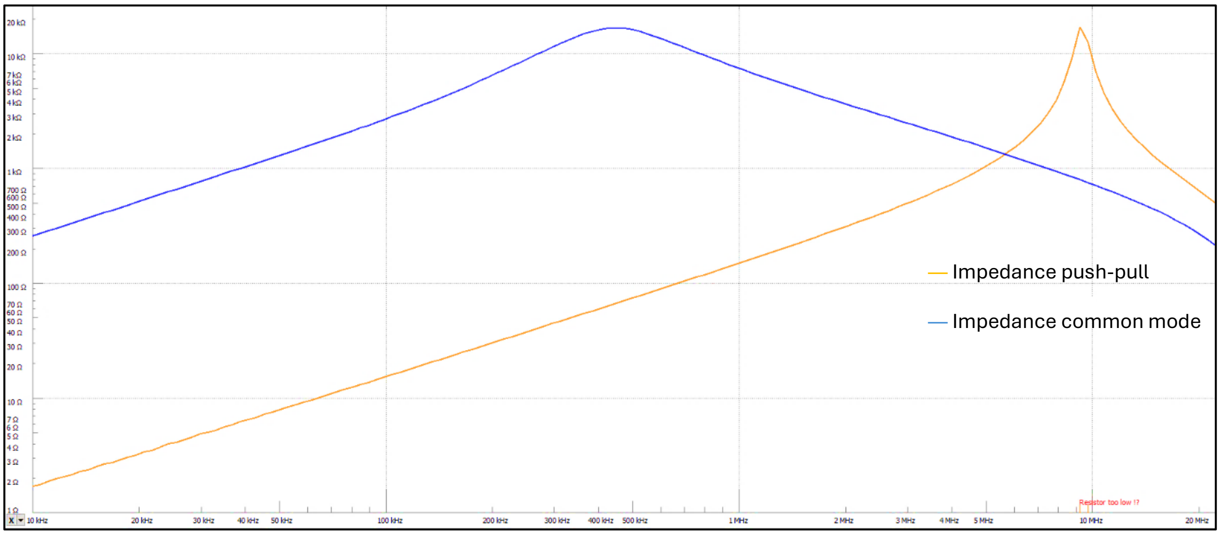


Figure 2: Impedance curve common mode choke 4 mH

Y2 capacitors are used in the mains filter to make optimum use of the attenuation of the choke and to ensure a high attenuation curve of the common mode interference up to the MHz range. These can be determined using Thomson's oscillation equation:

$$f_c = \frac{1}{2\pi \times \sqrt{L \times C}}$$

This oscillation equation is now rearranged according to the capacitance, in this case according to the capacitance of the Y2 capacitors:

$$C_y = \frac{1}{(2\pi \times f_c)^2 \times L_{cm}}$$

$$C_y = \frac{1}{(2\pi \times 37{,}78\ kHz)^2 \times 4\ mH} \approx 4{,}4\ nF$$

As two Y2 capacitors are used in the mains filter, the calculated value is divided by two. This results in a capacitance value of 2.2 nF. In this case, a capacitance value of 2.2 nF would be selected according to the E24 series. When selecting the Y2 capacitors, care must always be taken not to exceed the legally prescribed leakage currents.

To further complete the mains filter, an X1 capacitor is required, which is connected between the L and N mains lines. The X1 capacitor can also be determined using the oscillation equation. In practice, the leakage inductance of the common mode choke is assumed as the inductance. The leakage inductance can be measured using an LCR meter. In this example, the measured value corresponds to approximately 26.6 μH. Using these values, a suitable X1 capacitance can be calculated as follows:

$$C_x = \frac{1}{(2\pi \times f_c)^2 \times L_{leak}}$$

$$C_x = \frac{1}{(2\pi \times 36\ kHz)^2 \times 26{,}6\ \mu H} \approx 667{,}17\ nF$$

In practice, the next highest capacitance value in the E24 series is selected in such a case. In this case, the selected X1 capacitance is 680 nF.

Higher push-pull inductances are often required for lower cut-off frequencies $f_1$ in order to keep the X1 capacitance low. In this case, the options for using the leakage inductance for push-pull suppression are very limited. This makes it necessary to use separate common-mode chokes for the L and N conductors. Hybrid chokes, which combine the elements of push-pull and common-mode chokes, are an interesting approach here.

In most mains filters, a discharge resistor is placed on the mains side, parallel to the X1 capacitor, for safety reasons. This enables the capacitors to discharge the X1 capacitor primarily. According to DIN EN 60335-1, a safe voltage level (less than 50 V) should be reached within one second.

In this example, a resistance of 680 kΩ is suitable. It allows the X1 capacitor to discharge within 0.88 s.

Finally, the mains filter can be extended with a varistor connected between the mains lines to ensure protection against transient overvoltages from the mains.

The final result of the step-by-step development of the mains filter for the above example is the following structure for the filter shown in Figure 3:

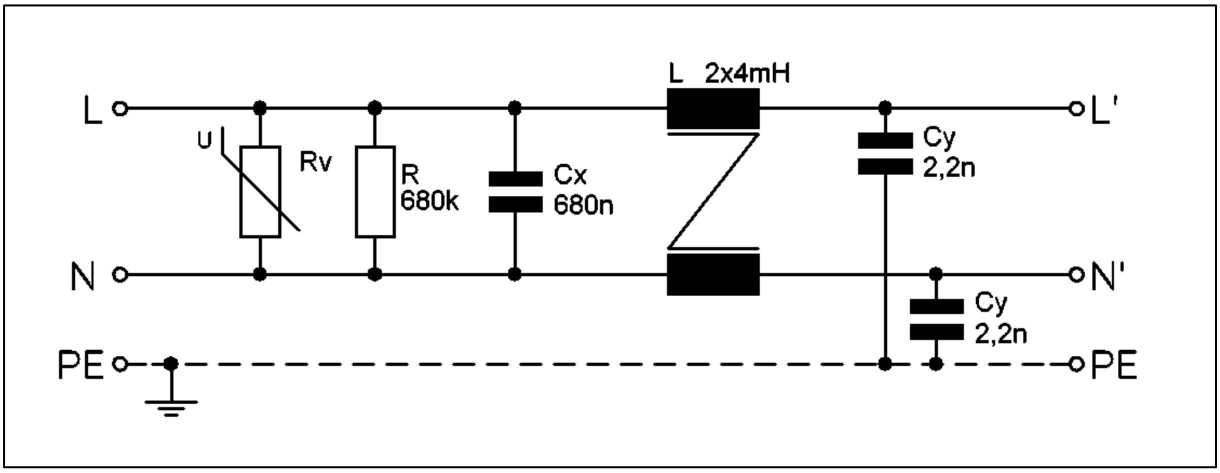


Figure 3: Circuit diagram of the example filter

It was shown how an effective mains filter for a switching power supply can be specifically developed using basic mathematical estimates and simple measurement technology. The aim was to ensure compliance with relevant EMC standards without having to accept unnecessary complexity or oversized components. By taking a differentiated view of common-mode and differential-mode interference, the filter could be adapted to the specific interference spectrum of the switching power supply.

The mathematical determination of relevant variables - such as cut-off frequency, capacitance values for Y2 and X1 capacitors, inductance values of the common-mode choke and its current carrying capacity - enabled a targeted selection of components and a standard-compliant design of the filter.

The combination of a common-mode choke, X1 and Y2 capacitors and a varistor results in a practical design, which was supplemented by a discharge resistor in accordance with the standard. In practice, hybrid choke concepts can also be used to efficiently suppress both common-mode and differential-mode interference.

The methodology described in the article thus provides a clearly structured guideline for developers to equip switch-mode power supplies with EMC-compliant equipment and to implement filter solutions functionally and economically.