Model Based Optimization of EMC Input Filters

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***Abstract*– Input filters of power converters for compliance with regulatory electromagnetic compatibility (EMC) standards are often over-dimensioned in practice due to a non-optimal selection of number of filter stages and/or the lack of solid volumetric models of the inductor cores. This paper presents a systematic filter design approach based on a specific filter attenuation requirement and volumetric component parameters. It is shown that a minimal volume can be found for a certain optimal number of filter stages for both the differential mode (DM) and common mode (CM) filter. The considerations are carried out exemplarily for an EMC input filter of a single-phase power converter for the power levels of 100 W, 300 W, and 500 W.**

I. Introduction

For compliance with the high frequency EMC (electromagnetic compatibility) standards [1] in the range of 150 kHz – 30 MHz a filter circuit, which may consist of one or more filter stages (cf. Fig. 1), has to be inserted at the input of a power converter. With this, high frequency conducted emission (CE) noise occurring at multiples of the switching frequency shall be attenuated effectively and/or prevented from propagating towards the mains.

The design of the input filter of a power electronics converter is an important issue in the design process, since it has a strong impact on the achieved power density of the converter. In the past, a lot of research has been done in the area of filter topologies, noise emission estimation and minimization, e.g. by modulation concepts, control techniques and appropriate selection and/or dithering of the switching frequency [2]-[5]. However, a big potential for achieving a highly compact filter has been neglected so far, namely the optimization of the number of filter stages based on volumetric inductor core data. It is shown in this paper that this fact leads to a power converter with minimal filter volume.

Basically, the required filter attenuation Att_{req} depends on a series of parameters, such as the delivered power, the switching frequency, and the employed control and modulation of the converter. Within the whole frequency range 150 kHz – 30 MHz, wherein the standards have to be fulfilled, the filter requirement is usually most stringent for one certain frequency. For converters with constant switching frequency it is often sufficient to consider only the first multiple of the switching frequency (or the n^{th} multiple in case of n interleaved converter cells) within the measurement range of 150 kHz – 30 MHz as design point (especially for differential mode (DM) noise emissions), while for variable switching frequency the highest attenuation requirement may appear at a different location. In any case, for this frequency f_D a filter has to be designed, which delivers the required attenuation Att_{req} (f_D).

As has been shown in [6], an n-staged LC filter with the same inductance and capacitance values for all filter stages leads to a minimal filter volume, thus $L_1 = L_2 = ... = L_n = L$ and $C_1 = C_2 = ... = C_n = C$. With this, the attenuation Att_{LC} provided by the filter is given by

$$Att_{LC} = \frac{1}{(2\pi \cdot f_D)^{2n} \cdot L^n \cdot C^n} \overset{!}{\geq} Att_{req}(f_D) \tag{1}$$

Thus, for a certain attenuation requirement Att_{req} and design frequency f_D, there is an optimal selection of L and C in dependency of the number of filter stages n. However, only one filter stage number will lead to a global minimum of the filter volume. As will be shown in this paper, the optimal number of filter stages both for the differential mode (DM)

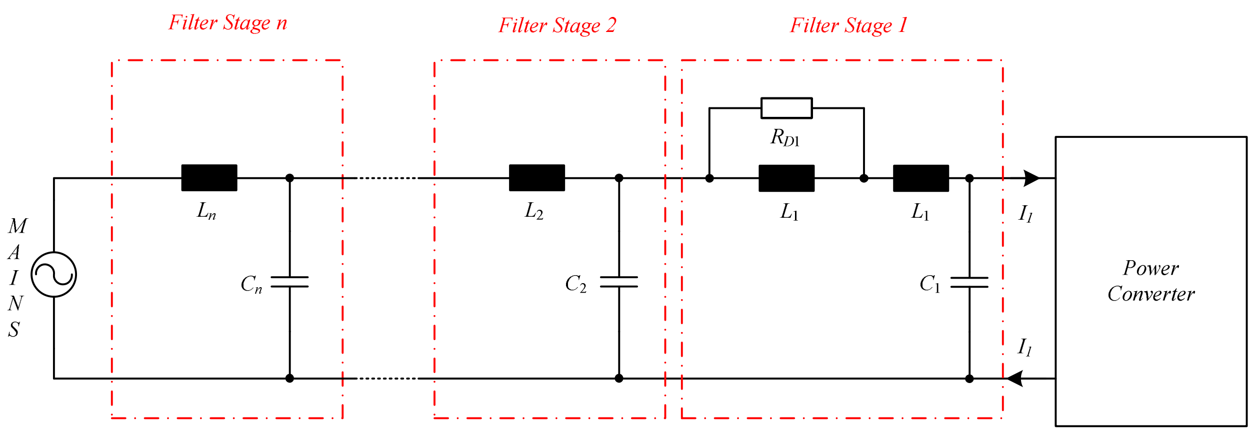

Fig. 1: Input filter structure consisting of several filter stages (1,2,..n) for a single-phase power converter. Here, only the differential mode (DM) part for a boost converter is shown exemplarily.

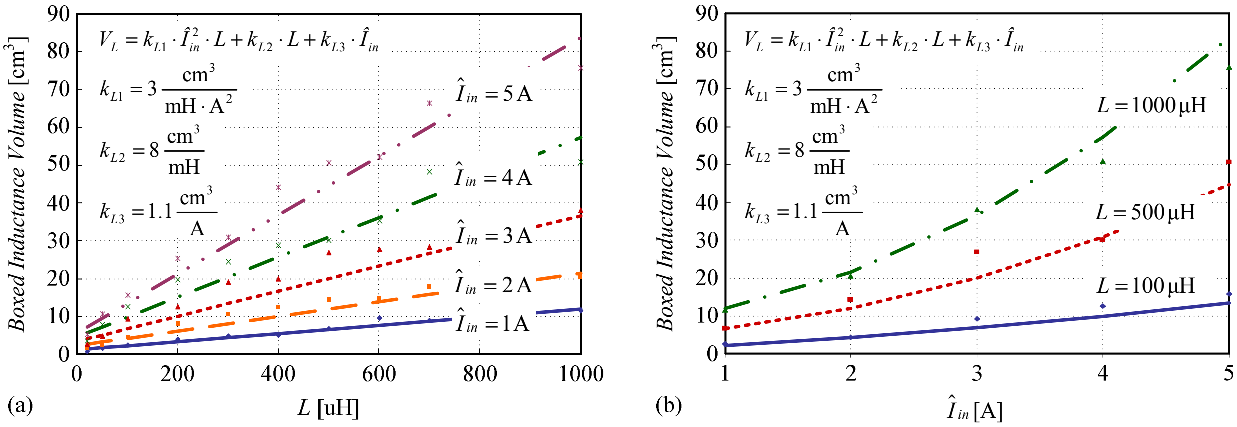

Fig. 2: Volume approximation for a DM filter inductance using *Magnetics* toroid cores [7].

filter and the common mode (CM) filter can be found based on specific volumetric data of the filter components. As will be shown, the optimal stage number depends on the attenuation requirement, the design frequency, and also on the delivered power of the converter[1]

II. Differential Mode Filter Optimization

The volume of the filter inductor is given in many sources as being proportional to the stored energy

$$V_L \sim k_L \cdot L_{DM} \cdot \hat{I}_{in}^2 \tag{2}$$

with the input current amplitude $\hat{I}_{in}$. However, a detailed analysis of different core types of various manufacturers reveals that also linear terms depending on the input current value and on the inductance value have to be taken into account in order to properly represent the inductor volume

$$V_L = k_{L1} \cdot L_{DM} \cdot \hat{I}_{in}^2 + k_{L2} \cdot L_{DM} + k_{L3} \cdot \hat{I}_{in}\,. \tag{3}$$

As a detailed analysis shows, this is the main reason for the fact that higher number of filter stages lead to a volume increase for low attenuation requirements. Exemplary curves for specific toroid cores being suitable as input filter inductors [7] are shown in Fig. 2 along with their specific volumetric values k_{L1}, k_{L1}, and k_{L3}. In order to achieve a realistic design, these values already represent the boxed volumes of the components.

On the other hand, the volume of the input capacitors mainly increases with the stored energy [6] plus a small offset (which is constant for a certain mains voltage $\hat{U}_{in}$)

$$V_C = k_{C1} \cdot C \cdot \hat{U}_{in}^2 + k_{C2}\,. \tag{4}$$

This dependency is shown in Fig. 3 along with the specific volumetric values k_{C1} and k_{C2}. With this, a total filter volume optimization utilizing the parameters k_{L1}, k_{L2}, k_{L3}, and k_{C1} and k_{C2} is possible and the filter volume can be minimized by

$$V_{DM} = (n+1) \cdot V_L + n \cdot V_C \rightarrow min \tag{5}$$

[1] It has to be stated that for very high switching frequencies (f_S > 500 kHz), also the parasitics of L and C have to be taken into account, which is not done here for the sake of brevity.

The term (n + 1) for the number of inductors is due to a passive damping network [8], which has to be inserted for the filter stage at the converter input (cf. Fig. 1) in order to passively damp input filter resonances and which is realized by a damping resistor R_D (not being accounted in the filter volume) and an additional inductor with the same inductor value as the filter inductors. The filter volume can now be minimized by rewriting (1), (3), (4) and (5) to

$$L_{DM} = a \cdot \frac{1}{C_{DM}} \tag{6}$$

and

$$V_{DM} = b \cdot L_{DM} + c + d \cdot C_{DM} + e \tag{7}$$

with

$$\begin{aligned} a &= \frac{1}{(2\pi \cdot f_D)^2 \cdot \sqrt[n]{Att_{req}}} \\ b &= (n+1) \cdot (k_{L1} \cdot \hat{I}_{in}^2 + k_{L2}) \\ c &= (n+1) \cdot k_{L3} \cdot \hat{I}_{in} \\ d &= n \cdot (k_{C1} \cdot \hat{U}_{in}^2) \\ e &= n \cdot k_{C2} \end{aligned} \tag{8}$$

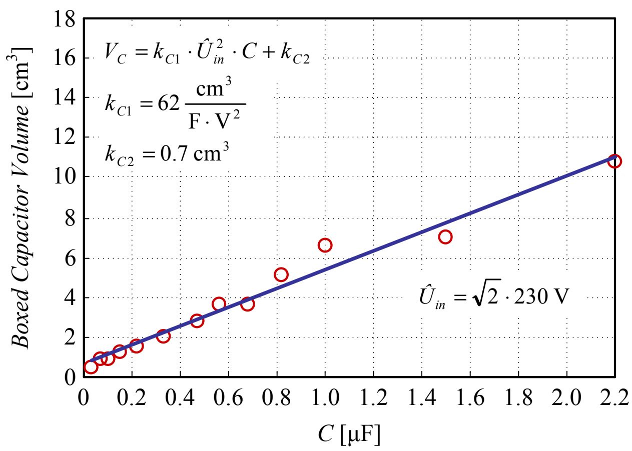

Fig. 3: Volumetric parameters of selected input filter capacitances.

Differentiation of (7) with respect to C_{DM} and equating with zero

$$\frac{\partial V_{DM}}{\partial C_{DM}} = 0 \tag{9}$$

leads to the optimal values of the input filter components

$$C_{DM} = \sqrt{\frac{a \cdot b}{d}}\ , \tag{10}$$

$$L_{DM} = \sqrt{\frac{a \cdot d}{b}}\ . \tag{11}$$

Replacing a, b and d reveals the dependency on various parameters, such as the converter input current and voltage, the attenuation requirement, the design frequency, and the selected number of filter stages:

$$C_{DM} = \sqrt{\frac{(n+1)\cdot\left(k_{L1}\cdot\hat{I}_{in}^{2}+k_{L2}\right)}{n\cdot\left(k_{C1}\cdot\hat{U}_{in}^{2}\right)\cdot\left(2\pi\cdot f_D\right)^2\cdot\sqrt[n]{Att_{req}}}}\ , \tag{12}$$

$$L_{DM} = \sqrt{\frac{n\cdot\left(k_{C1}\cdot\hat{U}_{in}^{2}\right)}{(n+1)\cdot\left(k_{L1}\cdot\hat{I}_{in}^{2}+k_{L2}\right)\cdot\left(2\pi\cdot f_D\right)^2\cdot\sqrt[n]{Att_{req}}}}\ . \tag{13}$$

The total DM filter volume is then given by

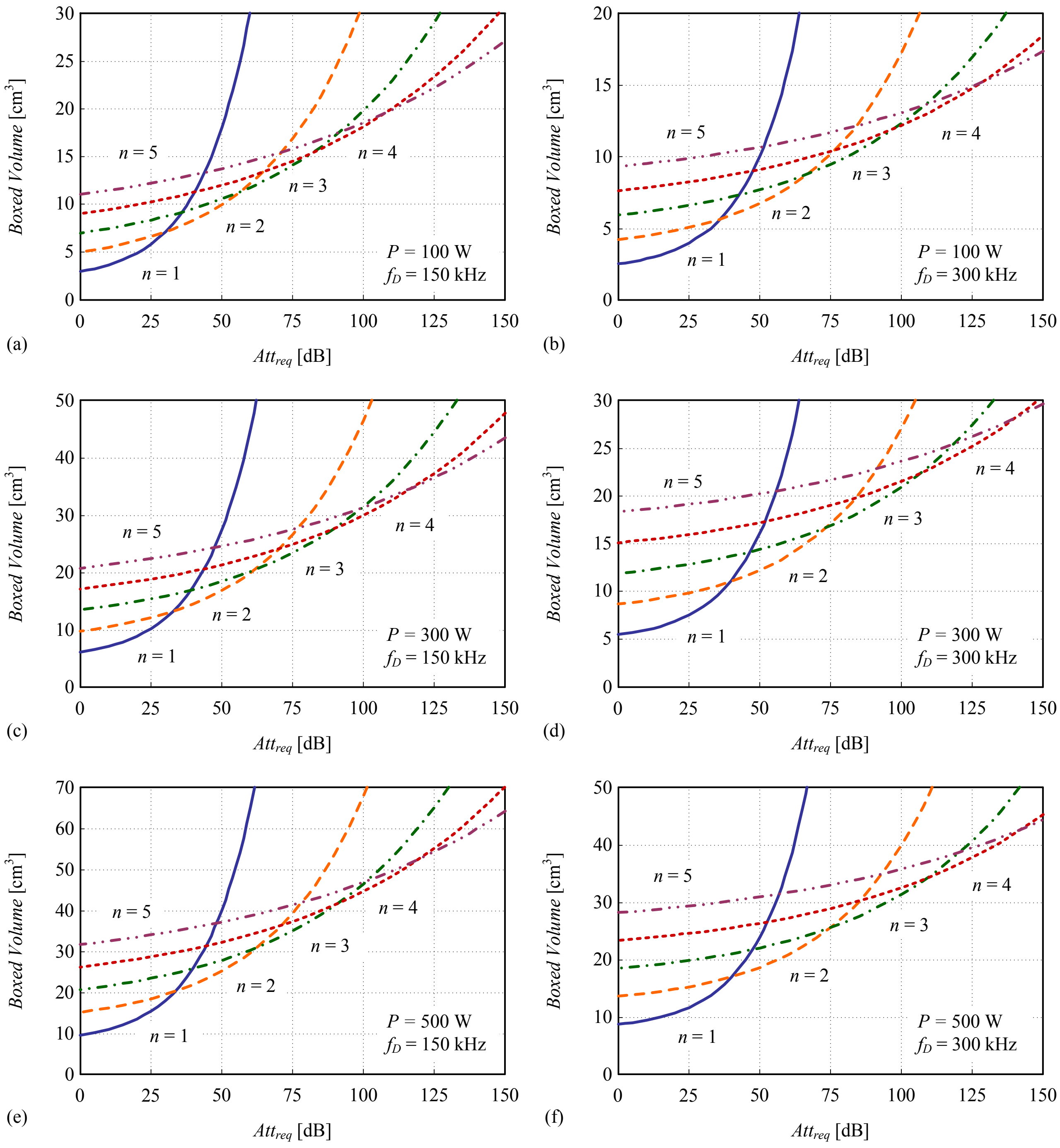

Fig. 4: Boxed volume curves of the differential mode EMC filter for a single-phase power converter for different input power levels P and design frequencies f_D in dependency on the required attenuation Att_{req} (for $U_{in,rms}$ = 230 V).

$$V_{DM} = n \cdot k_{C2} + (n+1) \cdot k_{L3} \cdot \hat{I}_{in} + 2 \cdot \sqrt{\frac{(n+1) \cdot \left(k_{L1} \cdot \hat{I}_{in}^2 + k_{L2}\right) \cdot n \cdot \left(k_{C1} \cdot \hat{U}_{in}^2\right)}{(2\pi \cdot f_D)^2 \cdot \sqrt[n]{Att_{req}}}} . \qquad (14)$$

Now the question arises, which number of filter stages n leads to a minimal filter volume. An analytical solving of this problem based on the previous equations results in an excessive mathematical effort. Therefore, the filter volumes according to (14) will be evaluated in the following numerically for a single phase power converter for different attenuation requirements, power levels and design frequencies.

In Fig. 4, the filter volume curves for different number of filter stages (n = 1,2,..,5) are plotted in dependency on the attenuation requirement Att_{req} in the range of (0…150) dB, two design frequency points f_D (150 kHz and 300 kHz) and three different input power levels P (100 W, 300 W, and 500 W). Hereby, the volumetric parameters k_{L1}, k_{L2}, k_{L3}, and k_{C1} and k_{C2} from Fig. 2 and Fig. 3 have been utilized and European mains voltage has been considered ($U_{in,rms}$ = 230 V).

As can be seen in Fig. 4, the optimum number of filter stages only slightly depends on the input power level, while it shows a clear dependency on the attenuation requirement and on the design frequency. This trend continues also for higher power levels, which are not shown in Fig. 4 for the sake of brevity. Anyway, converters for higher power levels typically feature a three-phase input and are equipped consequently with a three-phase input filter. Although this is not discussed here, it can be stated that an optimization can be carried out in an analogous manner and leads to comparable results. The attenuation requirement can be found by circuit simulations and frequency domain analysis of the spectrum of the EMC test receiver [8] or – if a prototype is present – by EMC measurements. Typical attenuation requirements for these power levels are in the range of 50 dB, which justifies the most commonly used selection of two DM filter stages (cf. Fig. 4).

As already mentioned before, for a fixed switching frequency the design frequency is the first multiple of the switching frequency (or the n^{th} multiple in case of n interleaved converter cells) within the EMC measurement band 150 kHz – 30 MHz. That means that e.g. a converter with a switching frequency of 30 kHz will have the same design frequency as a converter with 150 kHz, but will have a lower attenuation requirement, since the amplitudes of the harmonics are decreasing for higher frequencies. Furthermore, e.g. a converter with three interleaved cells switching with each 100 kHz has the same design point as a converter with 300 kHz, but has again lower attenuation requirements, since interleaving reduces the harmonic noise emission.

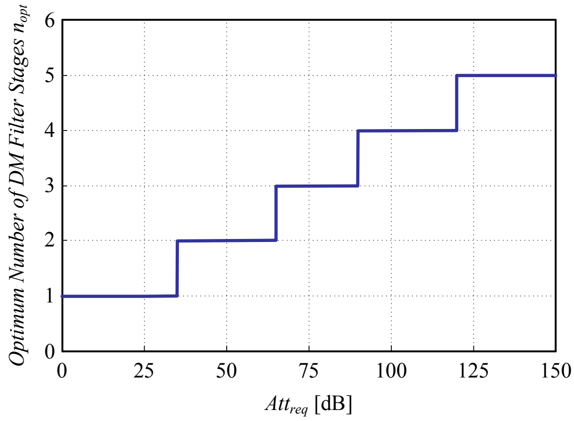

Fig. 5: Optimum number of DM filter stages for P = 300 W and f_D = 150 kHz in dependency on the required attenuation Att_{req}.

Exemplarily, for P = 300 W and f_D = 150 kHz the optimum number of filter stages n_{opt} is plotted in Fig. 5 in dependency on the required attenuation. With these results, an optimized DM filter can be designed very fast and comfortably. Furthermore, the considerations can be used for the selection of an appropriate switching frequency in the course of an overall optimization of a converter topology.

III. Common Mode Filter Optimization

For the design of the common mode filter, there are two main differences as compared to the DM filter design.

- First, a linearization and/or parameterization of the volume curves is not possible for most of the commercially available CM chokes. For the case at hand, nano-

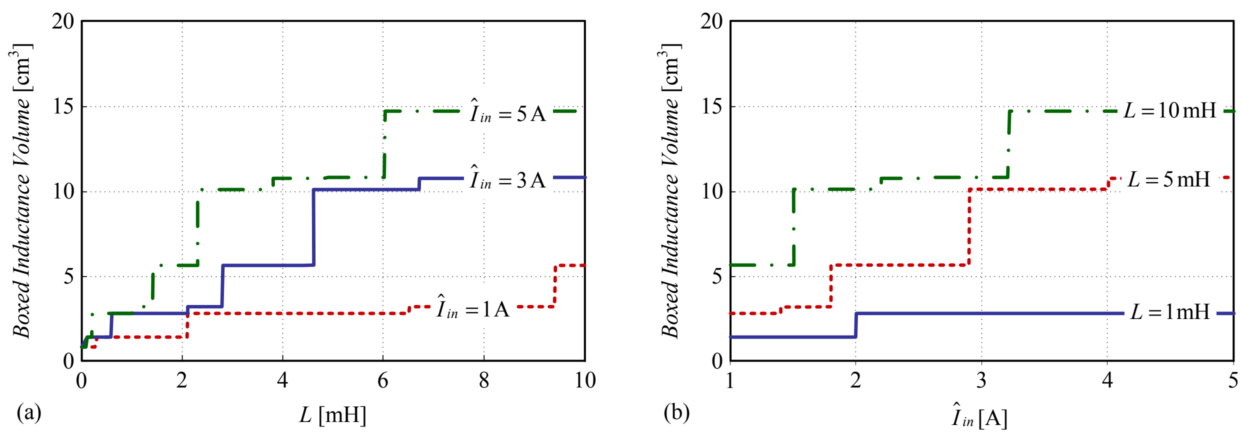

Fig. 6: Volume approximation for a CM filter inductance using *Vaccuumschmelze* nanocristalline cores [9].

cristalline cores [9] have been considered due to their good high frequency behavior and their high inductance-to-volume ratio. As can be seen in the volume curves Fig. 6, a parameterization is inappropriate due to the limited number of available core sizes.

- Secondly, the maximum CM capacitance is limited by the maximum allowed total leakage current to ground $I_{GND,max,rms}$ = 3.5 mA at 110% of the rated *rms* mains voltage [9]. Usually, the maximum allowable CM capacitance leads to a minimum total CM filter size. With the same capacitance values being employed for all filter stages between both power lines to ground, each CM capacitance value is then given by

$$C_{CM} \leq \frac{1}{2 \cdot n} \cdot \frac{I_{GND,\max,rms}}{1.1 \cdot U_{in,rms} \cdot \omega}. \quad (15)$$

With this, the CM filter volume is then given by

$$V_{CM} = V_{L,CM}(n, Att_{req}, \hat{I}_{in}, f_D) + V_{C,CM}(\hat{U}_{in}) \quad (16)$$

and can be evaluated in an analogous manner as for the DM filter. Due to the discrete steps caused by the steps in the inductor volume curves, now not necessarily a higher

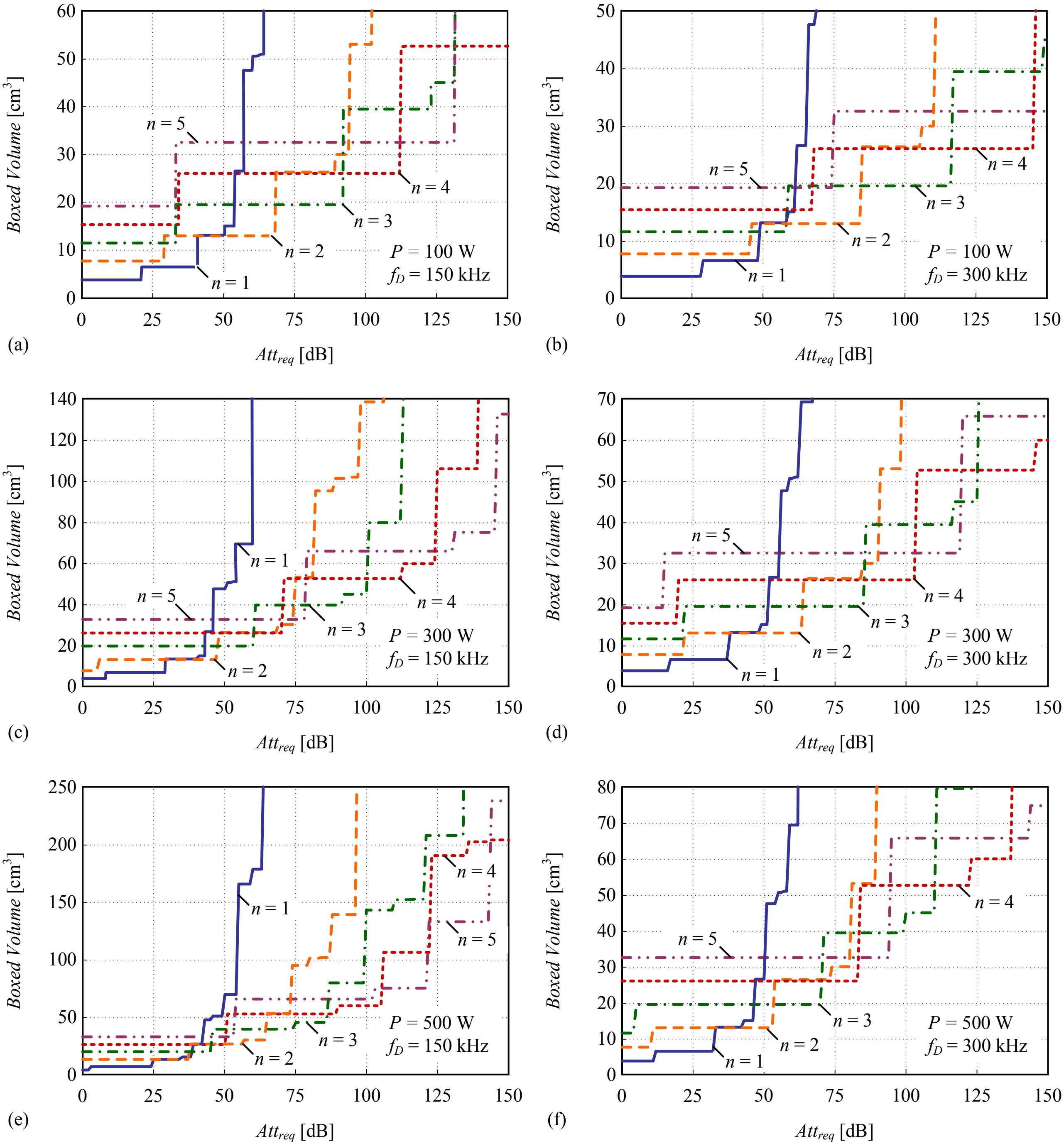

Fig. 7: Boxed volume curves of the common mode EMC filter for a single-phase power converter for different input power levels and design frequencies in dependency on the required attenuation (for $U_{in,rms}$ = 230 V).

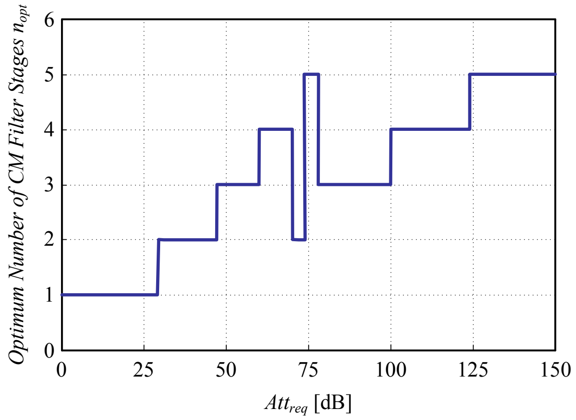

Fig. 8: Optimum number of CM filter stages for P = 300 W and f_D = 150 kHz in dependency on the required attenuation.

number of filter stages leads to a smaller filter volume for increasing attenuation requirements. For the exemplary case of P = 300 W and f_D = 150 kHz [cf. Fig. 7 (c)] an increase of the attenuation requirement leads to a continuous increase of the optimal number of filter stages until n = 4 at 70 dB (cf. Fig. 8), while for even higher attenuation requirements (80 to 100 dB) n = 3 is again the optimal filter stage number. However, for converters in this power range typically attenuation requirements below 50 dB occur (depending on the parasitic capacitance of the converter and load to ground), wherefore usually 1 or 2 filter stages are sufficient.

IV. Conclusions

In this paper, an optimization of the input filter of a single-phase power converter for compliance with EMC standards has been presented. For the differential mode filter part, the procedure is based on a volumetric model of the filter components. For the common mode components, a model-based approach is not possible due to the limited number of available cores and the limitation of the maximum leakage current to ground, which limits the maximum common mode filter capacitance.

However, in both cases filter volume curves can be plotted in dependency on the specific attenuation requirement at a certain design point frequency and on the number of filter stages. The specific attenuation requirement can be identified by circuit simulations and/or measurements. Thus, for a specific design point, a certain number of filter stages leads to a minimal total filter volume. This optimum filter stage number has been evaluated for some exemplary design points, i.e. the power levels of 100 W, 300 W, and 500 W, two design point frequencies 150 kHz and 300 kHz, and for attenuation requirements in the range of 0 dB up to 150 dB.

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