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Design of Differential Mode Filters for Two-Level and MultiCell Converters

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Abstract—Faster switching devices like WideBandGap semiconductors allow increasing the switching frequency that can be used for a given efficiency, and they are sometimes (often?) presented as the solution to increase power density. However, using these components in standard structures can bring far-from-optimal results since they require bigger filters resulting in poor power density. By contrast, we will show that using these components in multicell converters allows increasing the cutoff frequency of the filters.

Keywords—filter; standard; two_level; multilevel

I. INTRODUCTION

Increasing the switching frequency allows using smaller passive to obtain a given peak-peak ripple, and it has therefore often been presented as a way to reduce the size of the filters. However, the standards do not limit pkpk ripples, they limit the value of the ripple at specified frequencies that do not vary with the switching frequency. This difference is big enough to invert the direction of variation of the cutoff frequency with respect to the switching frequency of two-level converters. This effect depends on the standard and of the slopes of its limit curves ; it will be quantified for different cases in the first section of this paper with two-level converters in mind. In the second section of the paper, we will show that the behavior can be very different when multicell converters are used.

II. FILTERING OF TWO-LEVEL CONVERTERS

A. Harmonic spectrum generated by a commutation cell

A two-level switchmode converter needs two filters, one on the High Voltage side, one on the Low Voltage side. In order to design these filters, the commutation cell can be represented as a set of square current and voltage sources, both of them controlled by the control signal (Fig. 1).

If the converter is a chopper with a duty cycle D , the harmonics X_f of these two sources can be easily calculated as :

$$\begin{cases} I_{n.f_{sw}}^{chop} = \frac{2I_{LV}}{n\pi} \cdot \sin(n\pi \cdot D) \\ V_{n.f_{sw}}^{chop} = \frac{2V_{HV}}{n\pi} \cdot \sin(n\pi \cdot D) \end{cases} \quad \text{for } n=1, \dots, \infty$$

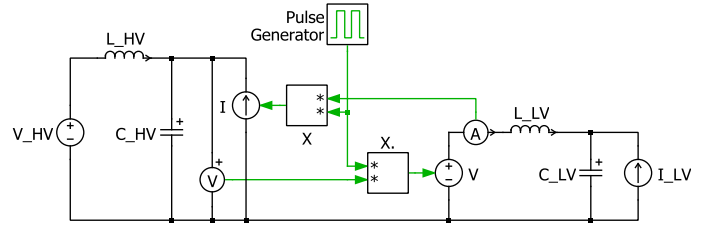
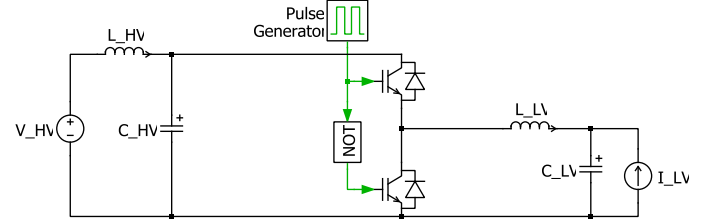


Figure 1. Commutation cell and its model

Assuming that f_0 the cutoff frequency of the filter is much less than the switching frequency f_{sw} , we can use the asymptotic response of the second order filter to evaluate the harmonics after filtering:

$$\begin{cases} I_{n.f_{sw}}^{HV} = \left(\frac{f_0^{HV}}{n.f_{sw}} \right)^2 \frac{2I_{LV}}{n\pi} \cdot \sin(n\pi \cdot D) \\ V_{n.f_{sw}}^{LV} = \left(\frac{f_0^{LV}}{n.f_{sw}} \right)^2 \frac{2V_{HV}}{n\pi} \cdot \sin(n\pi \cdot D) \end{cases} \quad \text{for } n=1, \dots, \infty$$

Based on the symmetry of the system and formulas, in the following we will use a general formulation to describe both sides:

$$X_{n.f_{sw}}^{filtered} = \left(\frac{f_0}{n.f_{sw}} \right)^2 \frac{2X}{n\pi} \cdot \sin(n\pi \cdot D)$$

And the worst case amplitudes of harmonics are :

$$X_{n \cdot f_{sw}}^{wc} = \left(\frac{f_0}{f_{sw}} \right)^2 \frac{2X}{n^3 \pi}$$

From this formula, it can be seen that the envelope of the harmonics is a straight line decreasing with a slope of -60dB/decade when a second order filter is used, which is the case in this paper.

B. Filter design governed by a “salient” point

When the limit curve starts flat at a frequency that is higher than the switching frequency, only the first limit point determines the filter requirement (Fig. 2). The cutoff frequency required to withstand the standard is obtained by intersecting the envelopes of the unfiltered and filtered spectra (respectively -20dB/decade and -60dB/decade) since the attenuation of the filter cancels at the cutoff frequency.

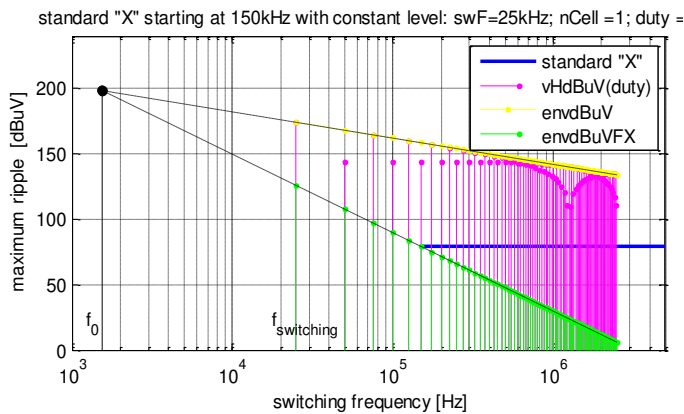


Figure 2 Harmonics, envelope and filtered envelope corresponding to a standard starting at 150kHz

A similar behavior is observed when the standard involves a point with a left slope that is less than -60db/decade and a right slope that is greater than -60dB/decade (Fig 3).

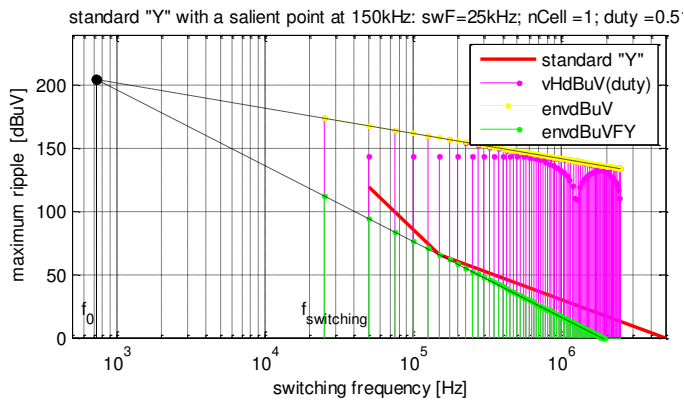


Figure 3 Harmonics, envelope and filtered envelope corresponding to a standard with a salient point at 150kHz

More generally, when using a N^{th} order filter, we can define a “salient point” as follows :

- the left slope is not existing, (or is less than $-20(1+N)$ dB/decade),
- the right slope is greater than $-20(1+N)$ dB/decade.

For switching frequencies smaller than the frequency of the salient point, the filter requirement is governed by this point. If the switching frequency is *increased*, the envelope of the unfiltered harmonics slides horizontally to the right and the cutoff frequency must *decrease* to respect the limit value at the salient point and a *bigger* filter is needed.

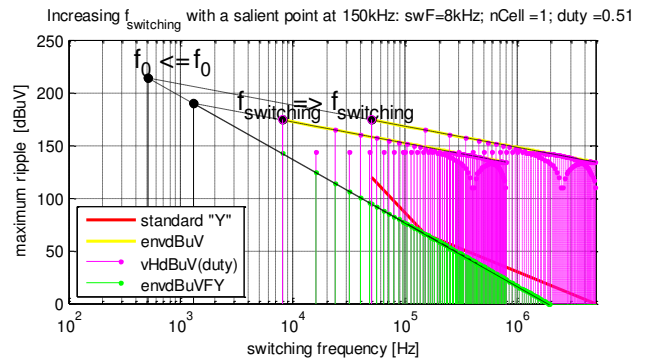


Figure 4 Increase of switching frequency in presence of a salient point

In practice, such salient points can be observed in standards EN55022. This is illustrated in figures 5a and 5b corresponding to a switching frequency of 25kHz and showing respectively examples with classes A and B.

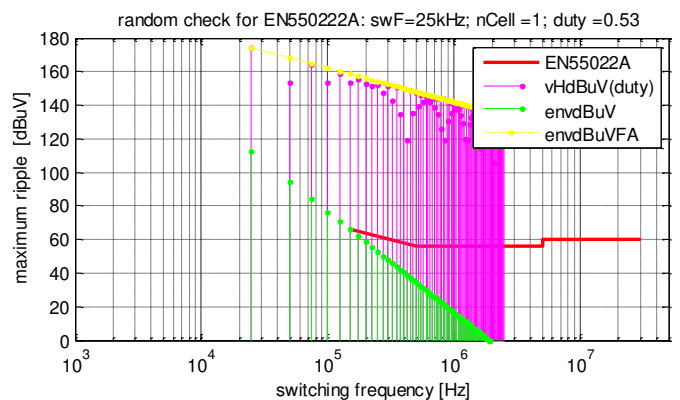
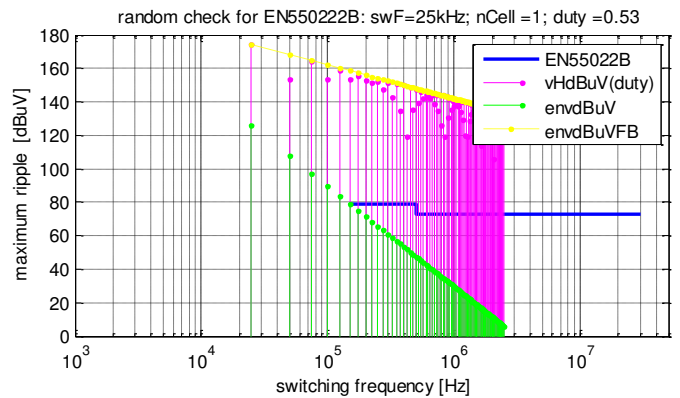


Figure 5 Salient points in standard EN55022

C. Filter design governed by the first harmonic of the switching frequency

When the limit curve starts at a frequency lower than the switching frequency and the limit is flat, the cutoff frequency is imposed by the amplitude of the first harmonic only. The cutoff frequency f_0 is found by intersecting the line corresponding to the envelope of the spectrum with a -60dB/decade line crossing the limit at the switching frequency (Fig. 6).

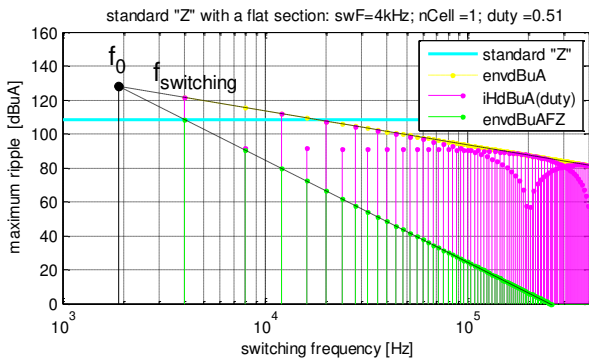


Figure 6 Increase of switching frequency in presence of a flat limit

Using this graphical construction, it can be seen that if the switching frequency is increased, the cutoff frequency can be increased in the same proportion.

More generally, the design of a N^{th} order filter for a standard starting below the switching frequency is governed by the first harmonic if the $-(2N+1).20$ dB/decade lines going through each salient point cross the limit at a frequency higher than the switching frequency. Under such circumstances, the cutoff frequency can vary in the same direction as the switching frequency as long as the right slope of the limit at the switching frequency is greater than $-(2N+1).20$ dB/decade, and for slopes less than this value switching frequency and cutoff frequency must vary in opposite directions.

In practice, when the limit is made of several segments, the limiting factor can be a salient point for certain combinations of switching frequency and order of the filter and the first harmonic for other cases.

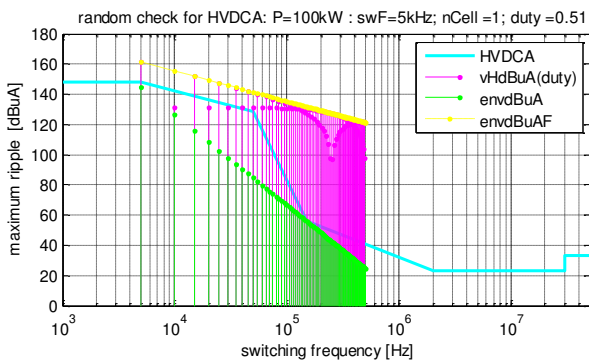


Figure 7 Example of filter design dominated by the first harmonic

For example, with the standard “HVDC540V” shown in Fig. 7 for a 100kW system, it can be seen that for a switching frequency lower than 5kHz (value used for this figure), the filter will be chosen with respect to the first harmonic, and for a higher switching frequency it would be ruled by the salient point at 150kHz.

The low frequency part of this standard depends on the power of the equipment and is plotted in Fig. 8 for a 1kW system. In this case, the left slope at 150kHz is very close to -60dB/decade, so the salient point is “activated” only for switching frequency between 40kHz and 150kHz.

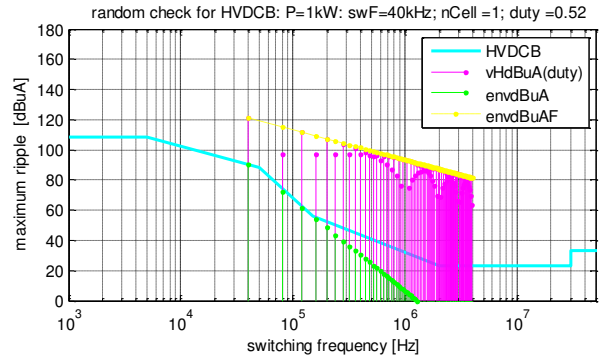
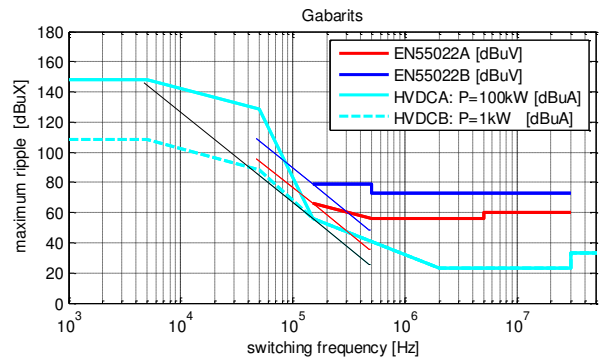
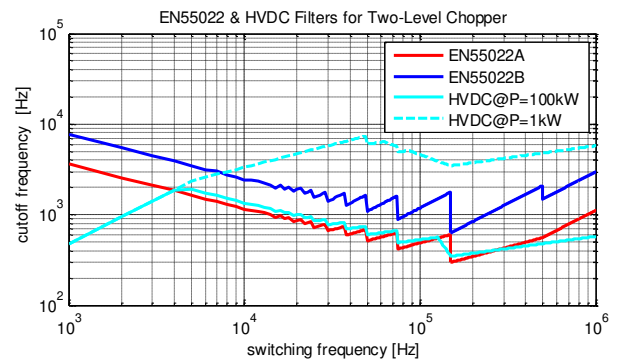


Figure 8 Example of filter design dominated by the salient point



a : four examples of standard



b : cutoff frequency vs switching frequency

Figure 9 Standards and corresponding the cutoff frequency (2-level converter; 2nd order filter)

Using a simple routine to calculate the voltage harmonics at the output of a two-level converter at a given input voltage (or the current harmonics at the input of a two-level converter for a given power) it is possible to determine numerically the cutoff frequency of the second order filter required as a function of the switching frequency. Such results for the four different standards recalled in Fig. 9a are given in Fig. 9b.

It can be seen that EN55022A, EN55022B and HVDCA are mainly governed by the salient point at $f_{corner}=150\text{kHz}$. For this reason, the general trend is a decrease of f_0 for f_{sw} increasing from 1kHz up to 150kHz and the slope is -10dB/decade because :

$$X_{f_{corner}}^{wc} = \left(\frac{f_0}{f_{sw}} \right)^2 \frac{2X}{n_{f_{corner}}^3 \pi} \Rightarrow f_0 = f_{sw} \sqrt{\frac{X_{f_{corner}}^{wc} n_{f_{corner}}^3 \pi}{2X}} = \sqrt{\frac{X_{f_{corner}}^{wc} f_{corner}^3 \pi}{2X f_{sw}}}$$

$$n_{f_{corner}} = \frac{f_{corner}}{f_{sw}}$$

Unfortunately, the switching frequency of converters is limited by acoustic noise on one side and switching losses on the other side, and in the allowed region (typically 15-100kHz) the switching frequency giving the filter with the highest frequency is the lowest, i.e. 15kHz.

When HVDCB is applied, the behavior is quite different because up to a switching frequency of 40kHz the cutoff frequency is imposed by the first harmonic, not by the one at f_{corner} .

In addition to the general shape that is in accordance with previous analysis, oscillations can be observed, especially before reaching the salient point at 150kHz. These oscillations are due to the discrete nature of the spectrum which allows avoiding the salient point for certain values of the switching frequency. For example, in Fig. 10, the harmonic at the switching frequency (140kHz) is not addressed by the standard, and the filter can be designed for the maximum value of the harmonic at 280kHz, thus reducing the filtering requirement. This effect also exists for the salient point in HVDCA but it is less pronounced than for the one in HVDCB because of the slope which is close to -60dB/decade.

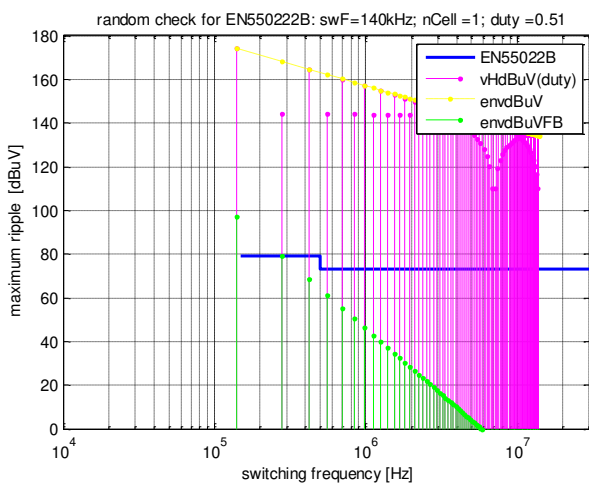


Figure 10 : Design case taking advantage of the discrete nature of the spectrum

Preliminary conclusion

If a new generation of components allowing a much higher switching frequency is introduced (WBG for example), we can also see from figure 9 that the switching frequency needed to allow using a filter with a cutoff frequency that is higher than for a 15kHz switching converter is:

- around 800kHz for EN55022A,
- around 600kHz for EN55022B,
- above 1MHz for HVDCA(100kW).

When HVDCB is considered, the situation is somewhat different; however, in this case too, a switching frequency well beyond 1MHz is needed to have a chance to beat a 40kHz design.

III. FILTERING OF MULTICELL CONVERTERS

These principles can be easily generalized to design filters for multicell converters. The harmonics generated by a multicell converter with n_{Cell} are :

- 0 for the frequencies that are not an integer multiple of $n_{Cell}f_{sw}$,
- those of a two-level converter for frequencies that are an integer multiple of $n_{Cell}f_{sw}$.

Taking this property into account, the characteristic curves for giving the cutoff frequency of the filter as a function of the switching frequency and of the number of cells can be computed. These curves are given in fig. 11 for each of the four standards discussed previously.

A better understanding of these curves is gained by noting that for multicell converters it is much easier for the first non-zero harmonic (frequency $n_{Cell} f_{sw}$) to jump over the salient point at 150kHz. And as soon as this is realized, the cutoff frequency starts increasing with the switching frequency. As a consequence, multicell converters provide many design options (combination of switching frequency and number of cells) allowing cutoff frequency of the filter to be raised above that of a reference two-level design. In general it is possible to propose such a multicell design with a reduced switching frequency (maximizes efficiency), with a higher switching frequency (maximizes the increase of cutoff frequency) or with the same frequency (tradeoff between the two factors).

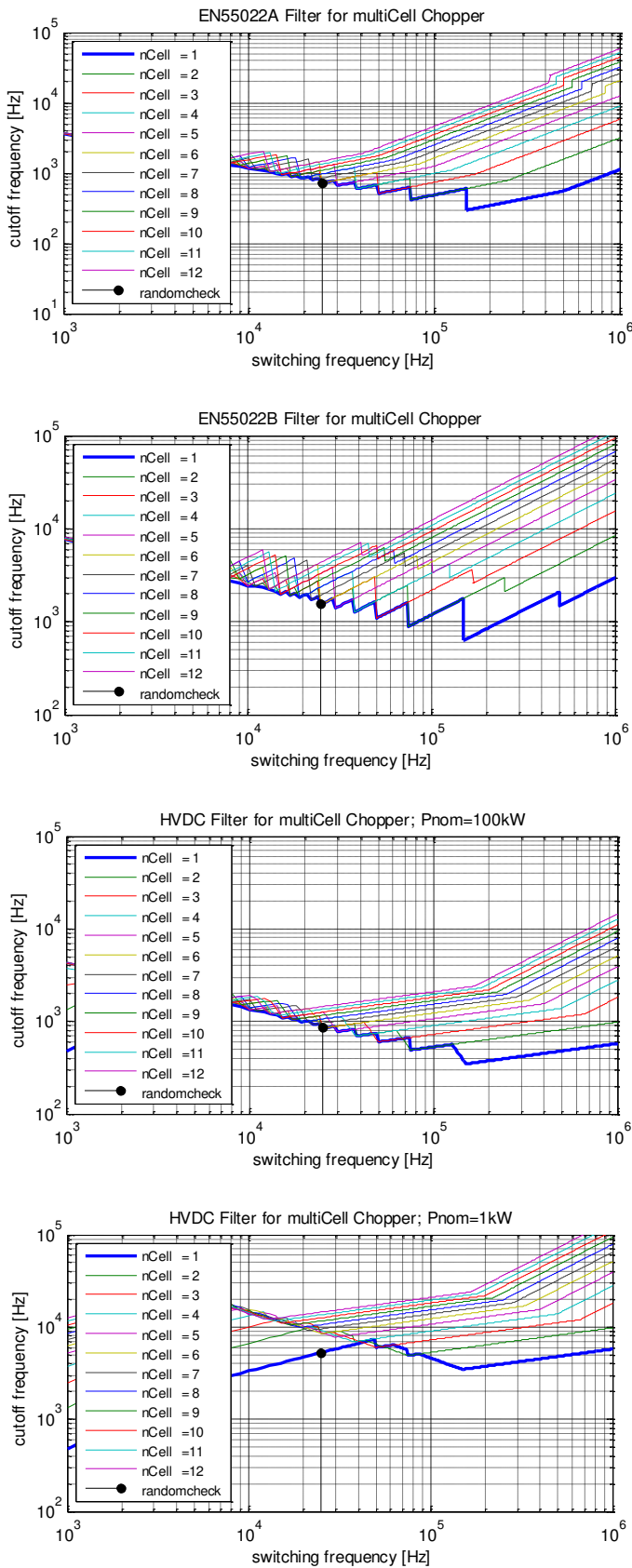


Figure 11 : Cutoff frequency vs switching frequency (multilevel converter; 2nd Order filter)

Another way to present the same results is given in Figure 12. Assuming a reference design in the form of a 1-cell (2-level) converter switching at 16kHz, it can be seen that:

- with one cell and EN55022A or 5022B, the cutoff frequency of the filter can be increased only by lowering the switching frequency or by setting it at more than 1MHz,
- when the number of cells increases there is a wider range of switching frequencies allowing an increase of the cutoff frequency.

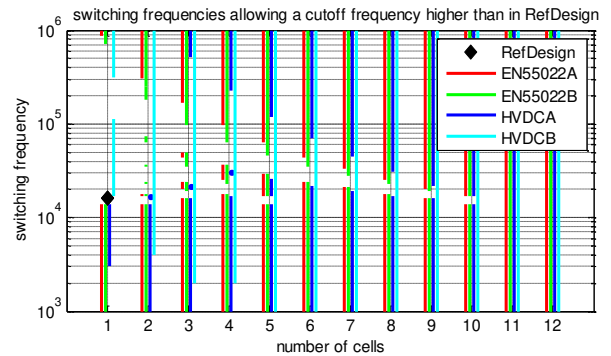


Figure 12 Switching frequencies allowing an increase of the cutoff frequency

IV. CONCLUSION

With most existing standards, increasing the switching frequency does not allow reducing the size of the filter, at least in the band 10-150kHz. The switching frequencies that might provide a benefit in terms of filter reduction are typically in the MHz range which is not practical for most applications, even with promises of wide bandgap semiconductors.

However, multicell topologies (in its widest meaning) change the game, especially as far as filter design is concerned ; in particular, with these topologies it is possible to increase the cutoff frequency of filters by increasing the typical switching frequency of 10-100kW converters from 20kHz to 50 or maybe 100kHz, which probably allows reducing the volume of the filters. Therefore WideBandGap semiconductors and multilevel topologies should be considered as two inseparable ingredients of the next generation of converters.

Factors contributing to making this a realistic option are:

- availability of various proven series multicell/multilevel topologies (coming mainly from the high power field),
- availability of proven parallel multicell/interleaved topologies (coming mainly from the low power VRM field),
- possibility of combining them,
- availability of faster and more reliable silicon discrete devices to replace power modules,
- development of wide band gap power semiconductors (GaN, SiC) providing high efficiency at switching frequency of 100kHz (and above?).

V. APPENDIX : CURVES FOR A 4TH ORDER FILTER

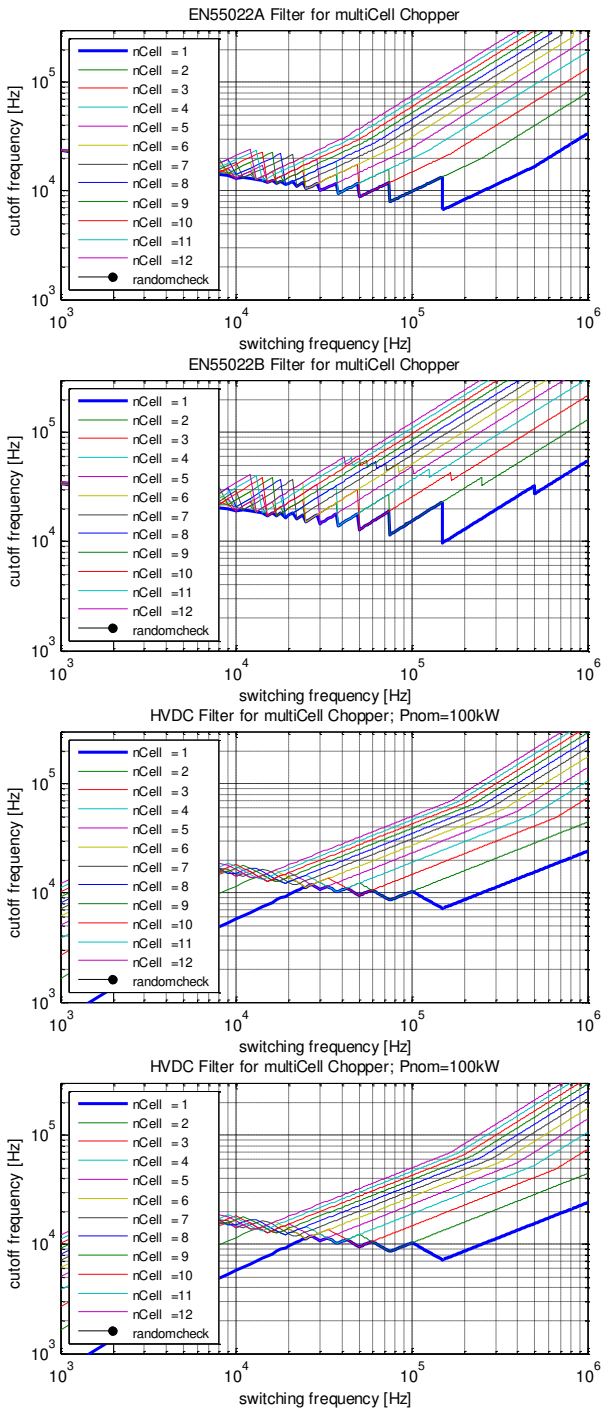


Figure A1 Cutoff frequency vs switching frequency (same four standards as in fig 11 but 4th order filter)

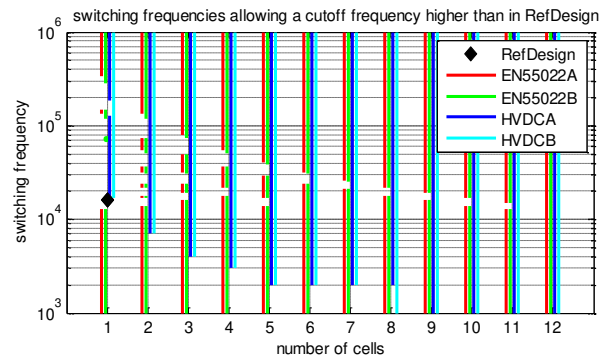


Figure A1 Switching frequencies allowing an increase of the cutoff frequency (same four standards as in fig 12 but 4th order filter)

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