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Simulation Tool for Conducted EMI and Filter Design

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Abstract - **In this paper a simulation tool that allows us to determine the conducted Electromagnetic Interference (EMI), generated for the basic PFP converters (Cuk, Buck, Boost, Buck-Boost, Sepic, and Zeta converters) will be presented. Using this Software, we can determine full EMI spectrum in dB/µV in accordance with the CISPR 16 standard. An EMI filter design methodology that allow us to accommodate the conducted Electromagnetic Interference (EMI) generated by power factor correctors to international standards in the design step is also presented. Therefore, this can be an useful aid for power electronics designers.**

Keywords EMI, PFPs, Filter.

I. Introduction

A crucial task in the recent years has been the reduction of the product development time, because the product lifetime has become shorter quickly. Keeping this in mind, is important to minimize the EMI failures in the design time, because the real cost of EMI compliance failing is not the charge made to EMC credential laboratories for testing and re-testing, that can be expensive, with Test House fees up to U$ 1,500.00 per day. These fees fade into insignificance when compared with the impact of the resulting delay on product time to market [1].

The influence of the EMI injected into the AC line by the power converters working as Power Factor Pre-regulators (PFP) in the electronic design is becoming more and more important. This is because the converters need to fulfil the international standards for EMI of current and future regulation limits of conducted and radiated noise generation. These regulations also limit the minimum power factor for the equipment connected to the AC line.

All these facts demonstrate the importance of the EMI analysis of power converters working as Power Factor Pre-regulator (PFP).

A method for determination of PFP conducted Electromagnetic Interference (EMI) emission was presented by Dos Reis, J. Sebastián and J. Uceda [2], which was based in a group of curves as you can see in Fig. 1, that allow us to determine the amplitude (first harmonic) of the conducted EMI (dB/µV) in Differential Mode (DM) x frequency (MHz), in accordance with the International Special Committee on Radio Interference publication 16 (CISPR 16) [3] standard, for (Cuk, Buck, Boost, Buck-Boost, Sepic and Zeta) converters working as PFP, in all operate modes: Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM) and Frequency Modulation (FM), as proposed by Albach [4]. In that work the authors only present the first harmonic approach. The curves are made taking into account a simulation of the measuring apparatus in accordance with CISPR 16. A very good method for this simulation was presented by Albach [4].

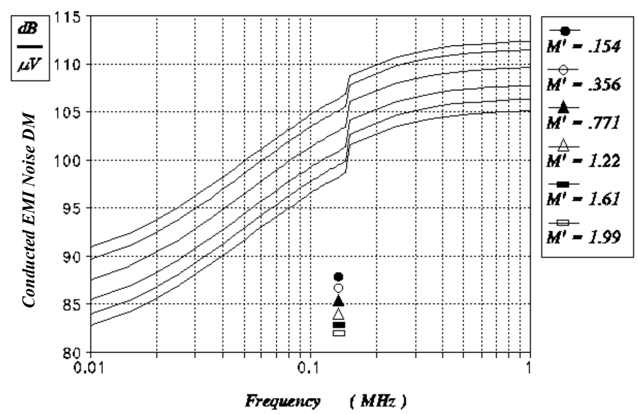


Fig. 1: Example of EMI design curves.

In this work a full simulation tool is presented. This tool was developed in order to run in a Personal Computer and can simulate the entire EMI spectrum for the following converters working as PFP: Cuk, Buck, Boost, Buck-Boost, Sepic and Zeta. Using this Software, is possible to determinate with very good accuracy, the conducted EMI before build a prototype. This information can contribute to reduce the product development time and therefore the cost of the final product.

This software permit the simulation of the Line Impedance Stabilization Network (LISN) and the EMI receiver. A simplified electrical circuit and the transfer function of the LISN is shown in Fig. 2. The EMI receiver parts (input filter, demodulator, Quasi-Peak Detector and Mechanical Measurement Apparatus) can be seen in Fig. 3, in accordance with the CISPR 16 standard [3]. Using the proposed software tool, the EMI curves can be obtained from simulation analysis. The CISPR 16 establish a standardized way to determinate the EMI spectrum [3]. In order to comply with CISPR 16 standards [3], an EMI receiver must include a filter with specified bandwidths and shapes, an envelope detector, a quasi-peak detector and a meter with time constants specified like in Table I. In the follow section the analytical harmonic analysis adopted of the input current obtained for Sepic and Cuk converters is presented.

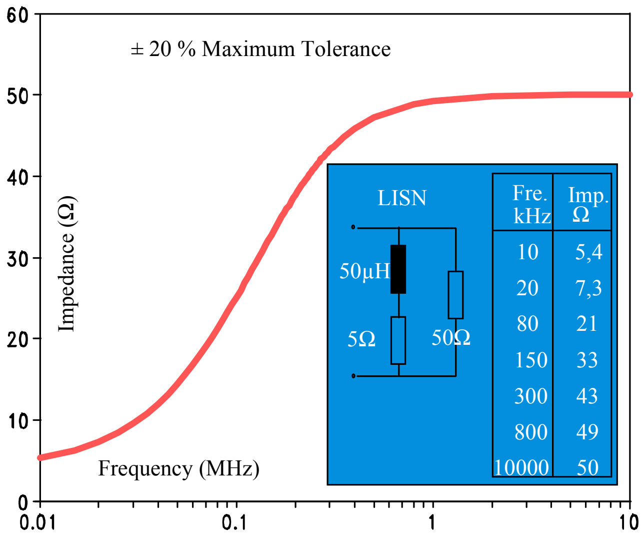


Fig. 2. Line Impedance Stabilization Network.

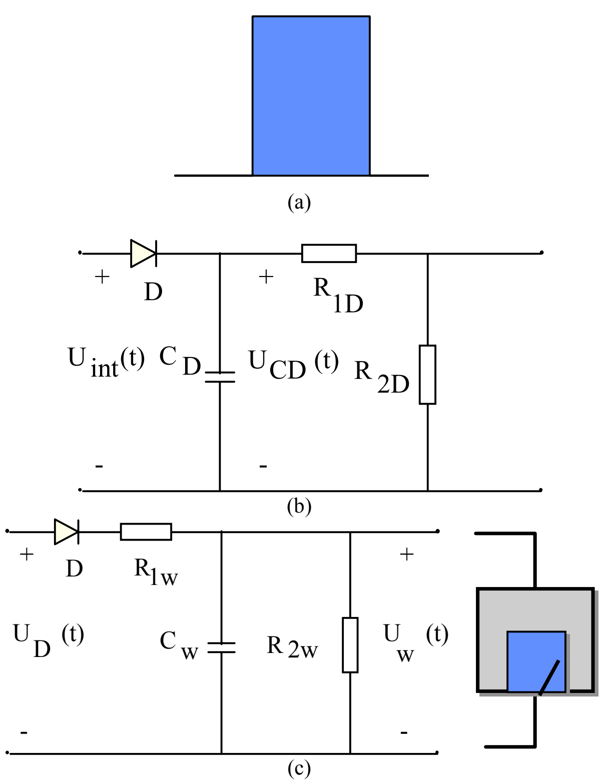


Fig. 3. EMI receiver parts (a) input filter, (b) demodulator, (c) quasi-peak detector and mechanical measurement apparatus.

TABLE I
MEASUREMENTS SPECIFICATIONS ACCORDING TO CISPR 16

Characteristics	Range of frequency		
	.10 to 150 kHz	0.15 to 30 MHz	30 to 1000 MHz
BANDWIDTH	220 Hz	9 kHz	120 kHz
Charge time constant (τ_1)	45 ms	1 ms	1 ms
Discharge time constant (τ_2)	500 ms	160 ms	550 ms
Mechanical time constant (τ_m)	160 ms	160 ms	100 ms

II. ANALYTICAL HARMONIC ANALYSIS OF THE INPUT CURRENT FOR SEPIC AND CUK CONVERTERS

The EMI interference is obtained from the analytical harmonic analysis of the input current of all studied converters and by the simulation of the LISN and EMI receiver. The high frequency current harmonics (obtained by analytical analysis) flows through the LISN, which is a current-voltage transducer (Fig. 2), is converted in a voltage. The voltage at the output of the LISN is applied to the EMI input filter receiver (Fig. 3-a). After that, the interference voltage $U_{int}(t)$ is applied to the envelope detector (Fig. 3-b). Then, the demodulated voltage U_D (t) is applied to the quasi-peak detector and finally the result is shown in the meter (Fig. 3-c). In this section we will present the analytical harmonic analysis of the input inductor current i_{L1} for Sepic and Cuk converters like PFP in Discontinuous Conduction Mode (DCM). An equivalent analysis can be extended to the others basic PFP converters working in all operation modes.

The basic structures of the Sepic and Cuk converters are shown in Fig. 4.

For the present analysis, the elements in Fig. 4 will be considered as follows:

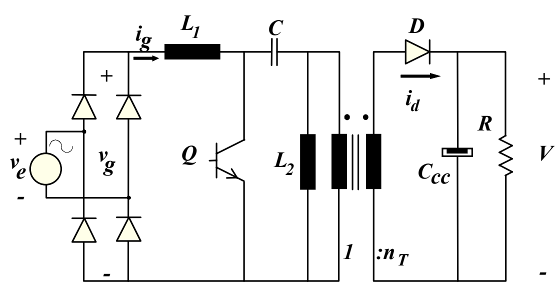
a) Inductors L_1 and L_2 will be represented by its inductance.

b) The output capacitor C_{CC} is represented as a voltage source, because C_{CC} is large enough.

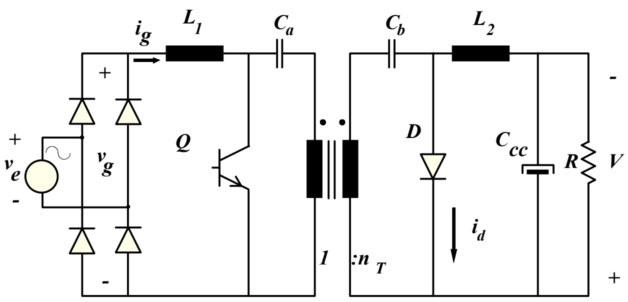
c) All semiconductors are ideal switches.

d) The voltage v_g denotes the rectified mains input voltage $v_g = V_e \mid \sin \omega t \mid$, where V_g is the peak value of the mains input voltage (v_e), $\omega = 2\pi f$ and f is the line voltage frequency. In a S.F. period we consider v_g constant and its value is $v_g = Vg \,|\sin \omega\, t_{1i}|$. We can make this simplification because the line voltage has a frequency (50 - 60 Hz) which is much lower than the S.F.

e) The capacitor C voltage follows the input voltage in a line period as described by Simonetti [5].



(a)



(b)

Fig. 4. Sepic and Cuk converters (a) and (b) respectively.

The Sepic and Cuk converters in DCM present an average input current proportional to the input voltage in a switching period as shown by Liu & Lin [6]. Can be demonstrated that, Sepic and Cuk converters when operating as PFP in DCM have the same input current. Therefore, the analysis made for Sepic converter is also valid for Cuk converter. Throughout this paper, the results obtained for Sepic converter are the same that the results obtained for Cuk converter.

The input current for Sepic and Cuk converters as PFP in DCM, within a S.F. period, is given as a function of the time instants t_{1i}, t_{2i}, t_{3i} and t_{4i}. The index i = 1, 2 ... I, represent the numbers of the S.F. periods within one half-wave period of the input voltage v_g. The I value is defined as $I = f_s / (2.0\ f)$, in the case of constant switching frequency. In Fig. 5 is shown the input current as a function of the time instants t_{1i}, t_{2i}, t_{3i} and t_{4i}, for one switch period of a Sepic or Cuk converter as PFP in DCM. In the Table II, the time intervals are best explained.

TABLE II
TIME INTERVALS

t_{1i} transistor becomes conducting.
t_{2i} transistor becomes non-conducting.
t_{3i} currents i_{L1} and i_{L2} becomes equal.
t_{4i} transistor becomes conducting again.
$t_{4i}-t_{1i} = T = 1 / f_s$ high frequency period.
$t_{2i}-t_{1i} = t_{on} = dT$ on time of the transistor.

To know the conducted EMI DM generated by these converters, we need to know the high frequency Fourier coefficients. The Fourier expansion of the input current can be expressed by equation (1) as:

$$i_{L1}(t) = \frac{a_o}{2} + \sum_{n=1}^{\infty}\left(a_n \cos\frac{n\pi t}{\tau} + b_n \sin\frac{n\pi t}{\tau}\right) \qquad (1)$$

The coefficients a_n and b_n have been calculated as in [4], where:

$$a_n = \frac{2}{\tau}\sum_{i=1}^{I}\int_{t_{1i}}^{t_{4i}} i_{L1i}(t)\cos n\omega t\, dt \qquad (2)$$

$$b_n = \frac{2}{\tau}\sum_{i=1}^{I}\int_{t_{1i}}^{t_{4i}} i_{L1i}(t)\sin n\omega t\, dt \qquad (3)$$

$$\tau = \frac{\pi}{\omega} \quad \ldots\ldots \quad \omega = 2\pi f \qquad (4)$$

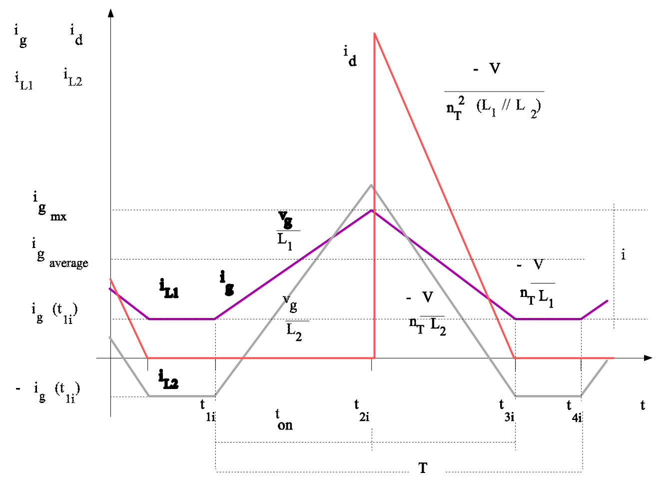


Fig. 5. Input current as a function of time intervals.

III. EMI TOOL DESCRIPTION

In this section will be presented a description of the software that allows to determine the conducted EMI (dB/μV) for the more employed PFP converters, in accordance to the CISPR 16 standard [3]. This tool can be used for development of the Boost, Buck, Buck-Boost, Zeta, Sepic and Cuk PFPs converters.

The main parts of the software are described in the follow steps:

1. Input data for a desired PFP converter and design of the input inductor as shown in Fig. 6 and 7 respectively.
2. To Calculate the Fourier coefficients a_n and b_n of the input current. The coefficients a_n and b_n are obtained using analytical expressions. To check the obtained coefficients, the tool supply an output window of the input current in time domain. An example of this feature is shown in Fig. 8.
3. Simulation of the LISN and the EMI receiver. The interference voltage is obtained by simulation of the input current across LISN. To simulate measurements apparatus in accordance to CISPR 16, using the characteristics shown in Table I.
4. Finally the tool provides a graphical output of the interference voltage (in dB/μV). An example for the Buck converter is showed in Fig. 9.

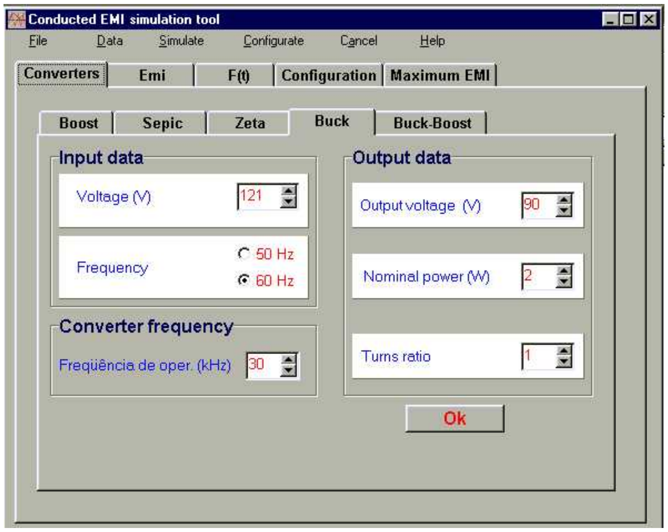


Fig. 6: Input data for Buck PFP converter.

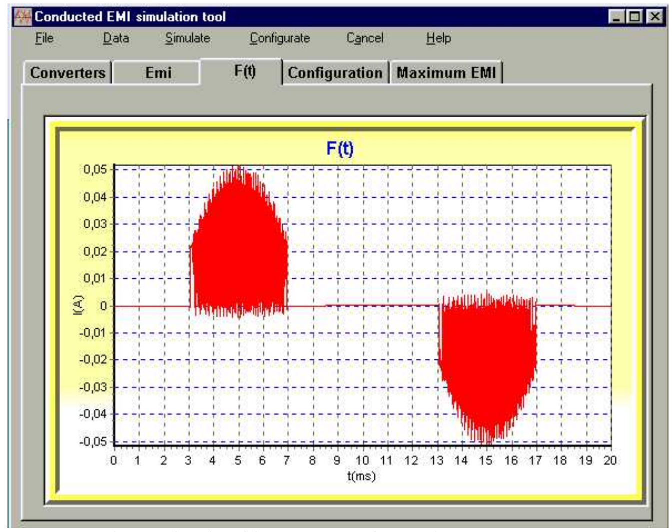
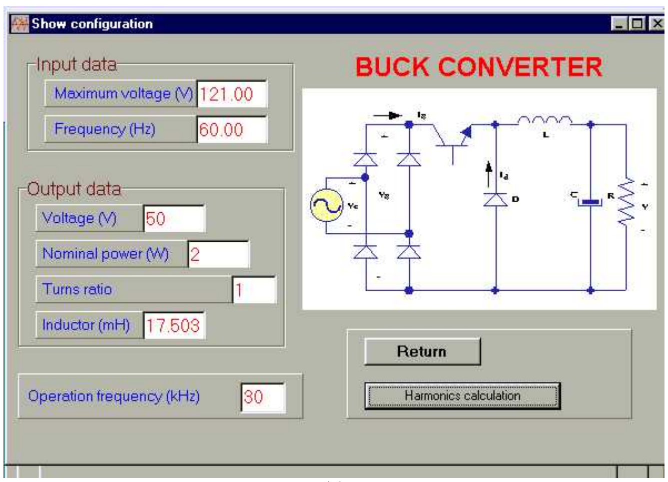
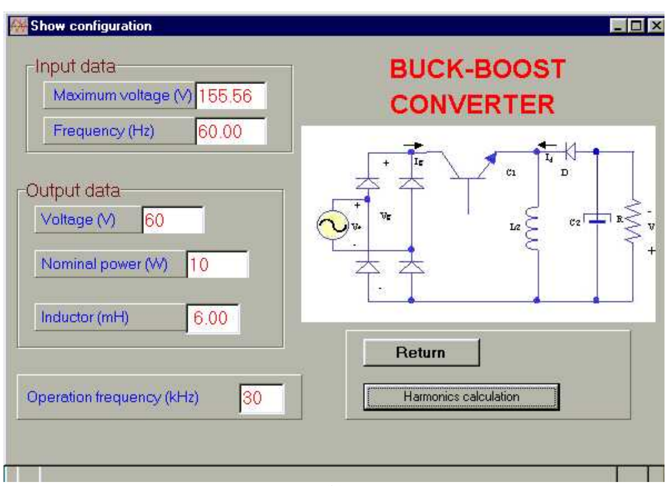


Fig. 8: Simulated input current for Buck PFP converter.

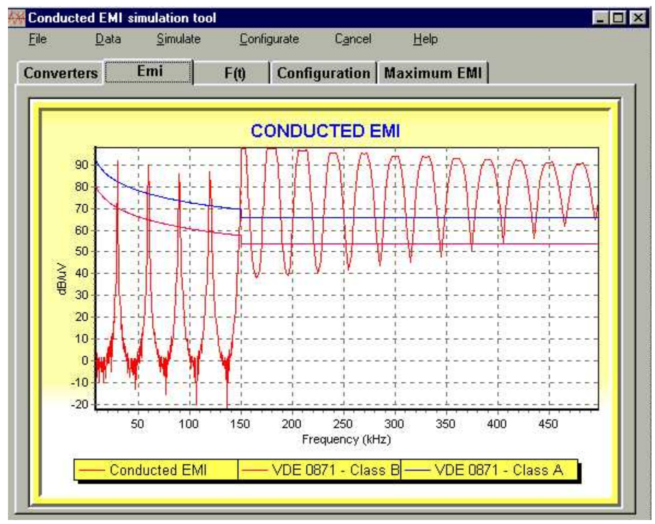


(a)



(b)

Fig. 7: Output window data for Buck and Buck-Boost PFP converters.



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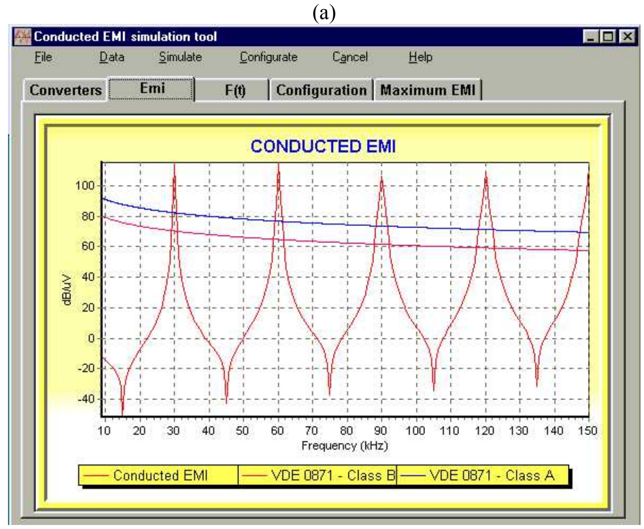


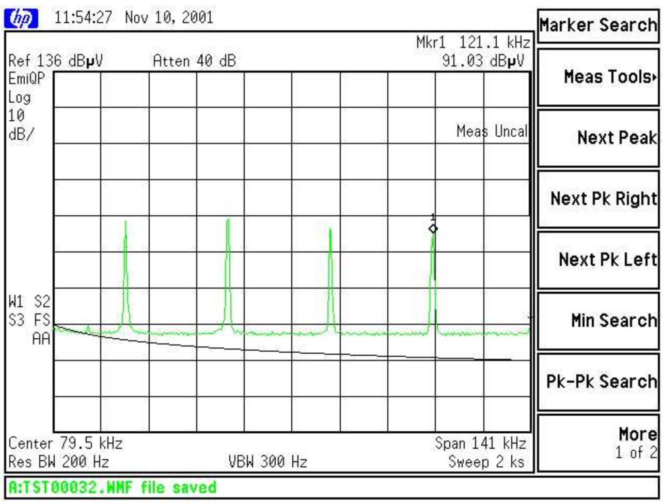
(b)

Fig. 9: Conducted EMI output for Buck and Buck-Boost PFP converters.

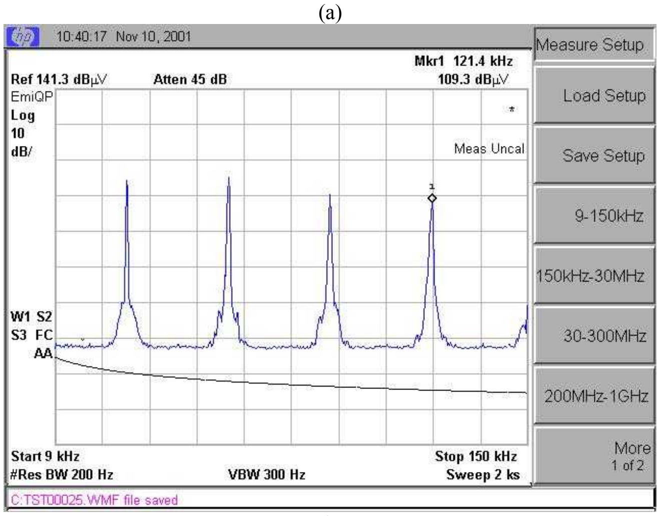
It is important to observe that at f_s = 150 kHz the curves have a discontinuity. This discontinuity at 150 kHz has origin in the CISPR 16, which establishes changes in the measurement apparatus at this frequency. The most important change occurs in the bandwidth of the receiver that changes from 200 Hz to 9 kHz.

IV. Experimental Results

For experimental validation of the proposed tool, a Buck, and a Buck-Boost PFP converters prototypes were implemented and tested at Labelo (a credential measurement laboratory). Underwriters Laboratories Inc., of the USA, recognize this Laboratory. The prototypes specifications are shown in Fig. 7. The experimental EMI results for both PFP converters are shown in Fig. 10.



(a)



(b)

Fig. 10. Experimental EMI test for Buck and Buck-Boost PFP converters.

The results obtained in the lab were compared with the results from simulation and are presented in the Table III for Buck and Buck-Boost converters respectively.

TABLE III
COMPARISON BETWEEN LAB AND PROPOSED TOOL RESULTS.

Buck PFP converter

FREQUENCY (kHz)	CONDUCTED EMI GENERATED BY A BOOST CONVERTER (dB/ μV)	
	LAB'S RESULTS	RESULTS OF THE PROPOSED TOOL
30	94.7	92.7
60	95.3	95.1
90	92.7	92.6
120	91.0	88.6
150	91.3	88.8

Buck-Boost PFP converter

FREQUENCY (kHz)	CONDUCTED EMI GENERATED BY A BOOST CONVERTER (dB/ μV)	
	LAB'S RESULTS	RESULTS OF THE PROPOSED TOOL
30	115,2	113,9
60	116,4	113,3
90	111,6	110,6
120	109,3	105,4
150	117,4	95,8

V. EMI Filter Design Considerations

The design of a suitable EMI filter can be done according different approaches [7-9]. Usually a high-order filter is used to reduce inductance and capacitance values.

Ideally it could be considered that no harmonic components exist in the frequency range between the line and the switching frequencies. This fact would allow to centre the filter resonance at a suitable frequency in order to guarantee the required attenuation. In this ideal situation the filter could be undamped.

In the Continuous Conduction Mode the input rectified voltage is usually used to create the current reference waveform. In this case the presence of instabilities in the filter output (converter side) can lead to severe converter malfunction [10].

As the input voltage waveform is not so important for the proper operation of the PFC in the Discontinuous Conduction Mode, some damping effect is necessary to avoid oscillations in the average input current produced by transient situations, like load or line changes.

According to the paper proposition, the filter will be designed considering only the differential mode EMI noise produced by the converter. For this type of filter, not only the required attenuation but also other restrictions must be taken into account. For example, VDE standard specifies a maximum x-type capacitance of 2.2 μF [8] in order to limit the line current (50/60 Hz component) even at no load situation. The maximum capacitance should be used to minimise the inductance value.

Let us consider the damped second order filter topology shown in Fig. 11. This filter attenuates 40 dB/dec. For a given necessary attenuation, the cut-off frequency is given by:

$$f_c = \frac{f_x}{10^{A_1/A_2}} \tag{5}$$

where f_c is the cut-off frequency, f_x is the frequency in which the required attenuation (A_1) is determined. A_2 is the filter characteristic attenuation.

The inductance value is given by:

$$L_f = \frac{1}{4\pi^2 C_1 f_c^2} \tag{6}$$

The maximum C_1+C_2 value is 2.2 µF [8], and for a proper damping effect, $C_2=10C_1$. The damping resistance can be calculated as:

$$R_d = \sqrt{\frac{L_f}{C_2}} \tag{7}$$

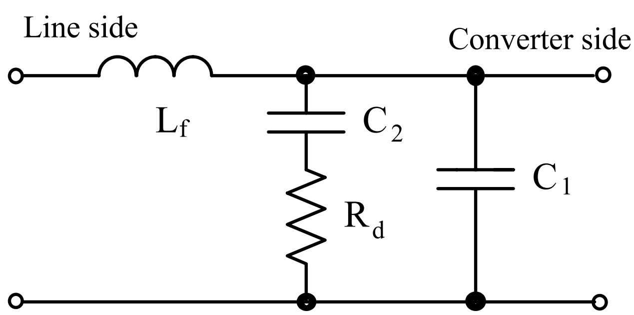


Fig. 11. EMI differential mode filter.

VI. Filter Design Examples

The standard VDE 0871 determine limits for conducted noise in industrial (class A) and home equipment (class B). The standard VDE 0871 limits for mains terminal disturbance voltage (in dB/µV) in the frequency band between 9 kHz and 150 kHz is shown in Fig. 9-a.

Let us consider the Buck-Boost PFC converter described in Table III, in DCM and the 92.7 dB/µV predicted EMI level in 30 kHz, measured according to CISPR 16 [3]. From Fig. 9 the VDE 0871 class B limit in 30 kHz is 70 dB/µV. Therefore, the required filter attenuation is 22.7 dB/µV. A filter attenuation of the 25 dB/µV was adopted, to obtain this attenuation in 30 kHz. The proposed second-order filter must have a cut-off frequency at 7.1 kHz using equation (5). Adopting C_1=220 nF and C_2=2 µF, the inductance utilizing equation (6) and damping resistance applying equation (7) are, respectively, L_f = 2.27 mH and R_d = 33.7 Ω. Figure 12 shows the filter frequency response, given the 26.7 dB attenuation in 30 kHz.

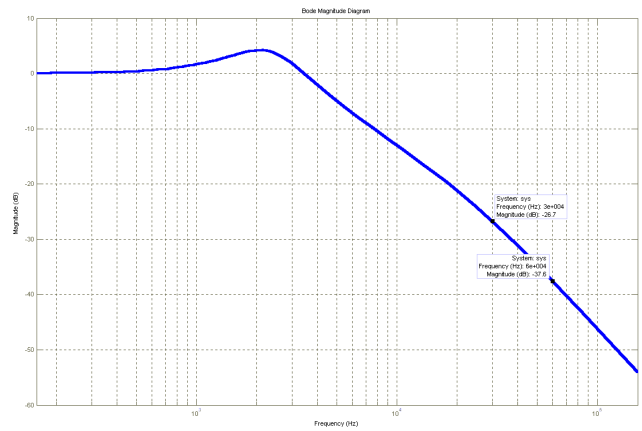


Fig. 12 – EMI filter attenuation.

VII. Conclusions

The presented tool is very important to the development of projects of conducted EMI filter, reducing the steps of cut-and-trial, that normally are used to solve conducted EMI problems.

This tool can contribute to the reduction of the product development time, reducing this way, the cost of development and providing a quick return of investments, with the advantage that the product can be sold before the similar product of the competitor are on the market.

In the research, this software helps the development of more efficient and suitable converters according to the international standard rules and the consumer market. Besides of this, the software is also very helpful tool for Power Electronic learning.

The proposed second-order filter cut-off the fundamental harmonic interference and its high order components properly as could be observed at Fig. 12, where the attenuation in 30 kHz and 60 kHz are 26.7 dB and 37.6 dB respectively.

Acknowledgements

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