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 US$ 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 Preregulators (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 Preregulator (PFP).

A method for determination of PFP conducted Electromagnetic Interference (EMI) emission was presented by Dos Reis et al [2]. Which it was based, in a group of curves as you can see in figure 1, that allow us to determine the amplitude of the conducted EMI Differential Mode (DM) (first harmonic) in dB/µV 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 operates 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 [4]. 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].

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. Using this Software it 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.

This software permit the simulation of the Line Impedance Stabilization Network (LISN) like you can see in figure 2 and the EMI receiver parts (input filter, demodulator, Quase-Peak Detector and Mechanical Measurement Apparatus) like you can see in figure 3, in accordance with the CISPR 16 standard. Using the proposed software tool, the EMI curves can be obtained from simulation analysis. The CISPR 16
establish a standardized way to determine the EMI spectrum. In order to comply with CISPR 16 standards, 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 1. In the follow sections an example of the mathematical harmonic analysis obtained for Sepic and Cuk converters is presented.

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<tr>
<th>Characteristics</th>
<th>Range of frequency</th>
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<td>Bandwidth</td>
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II. HARMONIC ANALYSIS OF THE INPUT CURRENT FOR SEPIC AND CUK

The EMI simulation is obtained from the input current harmonic analysis of the studied converter and from the simulation of the LISN and EMI receiver. The high frequency current harmonics flows through the LISN which is a current voltage transducer (fig. 2) 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), 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 present the harmonic analysis of the input inductor current $i_{L1}$ for Sepic and Cuk converters as PFP in Discontinuous Conduction Mode (DCM). The same 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. In order the results obtained for the Boost converter are showed in this paper, thereunto, the buck converter results are showed too.

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 $C_f$ is represented as a voltage source, because $C_f$ is large enough.

c) All semiconductors are ideal switches.

d) The voltage $v_g$ denotes the rectified mains input voltage $v_g = V_g | \sin \omega t |$, where $V_g$ is the peak value of the mains input voltage ($v_m$), $\omega = 2\pi f$ and $f$ is the line voltage frequency. In a S.F. period we consider $v_g$ constant and its value is $v_g = V_g | \sin \omega t_{1i} |$. 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 $C_1$ voltage follows the input voltage in a line period as described by Simonetti et al [5].

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Fig. 2. Line Impedance Stabilization Network.

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

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TABLE I

MEASUREMENTS SPECIFICATIONS ACCORDING TO CISPR 16

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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).

\[
i_{L_i}(t) = \frac{a_n}{2} + \sum_{n=1}^{\infty} \left( a_n \cos \frac{n\pi t}{\tau} + b_n \sin \frac{n\pi t}{\tau} \right)
\]

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

\[
a_n = \frac{2}{\tau} \sum_{i=1}^{I} i_{L_i}(t) \cos n \omega t \, dt
\]

\[
b_n = \frac{2}{\tau} \sum_{i=1}^{I} i_{L_i}(t) \sin n \omega t \, dt
\]

\[
\tau = \frac{\pi}{\omega} \quad \omega = 2\pi f
\]

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 in [6]. It 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 is the same as 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 \(i = 1, 2, \ldots, I\), 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 \(I = \frac{f_s}{(2.0 \ f)}\), in the case of constant switching frequency. In Fig. 5 we show 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.

**III. EMI TOOL DESCRIPTION**

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

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

- The calculation of input current for the cited converters in high frequency (h.f.). An example of input data is shown in the figure 6.
- To obtain the Fourier coefficients \(a_n\) and \(b_n\) of the input current. This coefficients for all converters can be obtained as for Sepic and Cuk converters. To check the obtained coefficients the tool supply an input current time domain as shown in figure 7.
• To obtain the interference voltage, simulating the input current across of the artificial mains network (LISN).
• To simulate measurements apparatus in accordance to CISPR 16, using the characteristics of the table 1.
• To show in graphic forms the conducted EMI. An example is showed in figure 8.

It is important to observe that at \( f_s = 150 \text{ kHz} \) the curves have a discontinuity. This discontinuity at 150 kHz has its 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.

For validation of this tool, results obtained in [4] and [7] were compared and showed that for few steps of calculation, they are very good.

**IV. 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 center 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 \( \mu \text{F} \) [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 figure 9. This filter attenuates 40 dB/dec. For a given necessary attenuation, the cut-off frequency is given by:

\[
 f_c = \frac{f_x}{10^{A_1/A_2}}
\]  

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:

$$L_f = \frac{1}{4\pi^2 C_1 f_c^2}$$  \hspace{1cm} (2)

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

$$R_d = \sqrt{\frac{L_f}{C_2}}$$  \hspace{1cm} (3)

For experimental validation of the proposed tool, a Boost, a Buck, a Sepic and a Zeta converters prototypes were implemented and tested at Labelo (a credential measurement laboratory). Underwriters Laboratories Inc. of the USA recognize this Laboratory. The experimental EMI result for the Boost converter are shown in Fig. 11.

The results obtained by the proposed EMI tool for Boost converter are shown in Fig. 8. The simulations and the implemented prototype for Boost converter was made using the specifications shown in the input panels of the Fig. 6. The results obtained in the lab were compared with the results of the simulation and are presented in the Table III.

Let us consider a boost PFC, in DCM, and the 102 dB/\(\mu\)V predicted EMI level shown in Fig. 8. The required filter attenuation is 36 dB/\(\mu\)V. To have this value at 150 kHz, a second-order filter must have a cut-off frequency at 18.9 kHz (equation (38)). Adopting $C_1=220$ nF and $C_2=2$ \(\mu\)F, the inductance (equation (39)) and damping resistance (equation (40)) are, respectively, 322 \(\mu\)H and 38 $\Omega$. Figure 10 shows the filter frequency response, given the 36 dB attenuation at 150 kHz.

VI. EXPERIMENTAL RESULTS

For experimental validation of the proposed tool, a Boost, a Buck, a Sepic and a Zeta converters prototypes were implemented and tested at Labelo (a credential measurement laboratory). Underwriters Laboratories Inc. of the USA recognize this Laboratory. The experimental EMI result for the Boost converter are shown in Fig. 11.

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V. FILTER DESIGN EXAMPLE

The standard IEC CISPR 11 [11] determines limits for conducted noise for industrial, scientific and medical equipment (ISM). The limit for mains terminal disturbance voltage in the frequency band 150 kHz to 500 kHz is 66 dB/\(\mu\)V (average level), measured according to CISPR 16.

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VII. ACKNOWLEDGMENTS

The authors gratefully acknowledges the support of the Brazilian agency FAPERGS for their financial support to this work.
VIII. 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 to teach the Power Electronic discipline.

The simulation time is short, if considered that the software executes thousands of interactions, converging to the values with an acceptable precision and running complex equations at the same time.

IX. REFERENCES