Computer Aided Optimal Design of High Power Density EMI Filters

***Abstract*—Power density of power converter systems is becoming an increasing crucial design constraint for a wide range of technical applications. Size reduction of EMI filter in power converters is an important challenge due to its significant impact on the overall converter volume and weight. In order to take on this issue, a computer aided procedure for a fast selection of optimal discrete EMI filter components and layout is described in this paper. The proposed technique is a rule-based automatic procedure based on a suitable database that considers the commercially available data sheets of passive components (e.g. magnetic cores, capacitors). It allows the minimization of the filter's volume and therefore the improvement of the converter's power density. The size and the performance of an EMI filter designed by using the proposed procedure, have been compared with those of a conventionally designed one. The comparison demonstrates the effectiveness of the proposed method.**

Keywords—EMI filter; Power converter; Power density; Optimal design

I. INTRODUCTION

High-speed switching operations of power electronic converters usually cause relevant electromagnetic interference (EMI), potentially affecting other devices placed in their proximity. For this reason EMI is one of the major issues in power electronic systems design, particularly when dealing with stringent standard limits [1]-[2].

The size of the EMI filter can contribute up to 30% of the total size and weight of the converter system, therefore a filter design that realizes the maximum power density is strongly desired, especially for applications in which compactness and low weight are primary issues (e.g., in airplanes, electrical vehicles, etc.) [3]-[5].

In scientific literature, several techniques are reported, specifically tailored to an efficient power-density-design of discrete EMI filters for power electronic converters [4]-[10]. Some techniques are simply based on setting up a compact layout by using suitable winding structures and high performance magnetic materials for the inductance cores [4]-[6]. Other approaches, starting from an accurate high frequency modeling of the system under investigation, propose the use of optimization algorithms to suitably minimize either the volume of the whole EMI filter or the volume of some parts of it. But in order to provide accurate high frequency models for each part of the system, a relevant computational effort is usually needed [7]. Furthermore, some other authors introduce the use of heuristic procedures, mostly genetic algorithms (GA), to perform an EMI filter design oriented to the maximum power density [8]. In this case the high number of iterations, usually needed to obtain the optimal or sub-optimal solution, results in a high time consuming procedure. Finally, a PC-based automatic EMI filter design method without any volume minimization implications is proposed in [9], whereas an optimization of the DM EMI filter utilizing some constant factors has been done by minimizing the filter volume function [10], where it is demonstrated that an optimal number of filter stages leads to the minimal occupied volume.

It is worth noting that, regardless of the used approach, once the filter topology is chosen and the values of its common mode/differential mode (CM/DM) inductors/capacitors are defined, there are manifold possibilities for practical layouts. Moreover, the identification of the layout leading to the minimum volume is a nontrivial task. Therefore, in order to reduce the effort and the time needed for properly selecting the filter components, a rule-based computer aided procedure for the optimal design of EMI filters in terms of power density is proposed in this paper. Both CM and DM sections of the EMI filter are considered within the optimized procedure.

For a given basic filter configuration, starting from the EMI noise to be attenuated, the proposed procedure extracts the filter components (type and values of electric parameters) from suitable databases of commercially available devices and finds the optimal number of filter stages. The automatic procedure can be implemented in any open source/commercial environment and it exhibits low computational demand. Therefore, it can be advantageously used by both EMI engineers for obtaining an optimized filter design and scientists/experts for the evaluation of filter performance vs. layout and power density features.

A preliminary experimental assessment of the proposed technique is performed. In particular, a comparison of EMI filter volume, weight and performance with those of an EMI filter designed according to a conventional procedure is done. Further results will be given in the final paper.

II. BASIC PRINCIPLES OF EMI FILTER DESIGN

The first step of an EMI filter design is the identification of the crucial point on the experimental curve of the EMI emission, i.e., the emission peak at the lowest frequency in the EMI range (150kHz - 30MHz). Therefore, it is necessary to separately measure the CM and DM components and to obtain their frequency spectra as the initial step of the design. The required attenuation for the CM and DM noise are expressed in (1) and (2), respectively:

$$A_{req\_att\_CM}[dB\mu V] = A_{h\_att\_CM}[dB\mu V] - Limit[dB\mu V] + 6dB\mu V \quad (1)$$

$$A_{req\_att\_DM}[dB\mu V] = A_{h\_att\_DM}[dB\mu V] - Limit[dB\mu V] + 6dB\mu V \quad (2)$$

where A_{h_att} is the amplitude of the harmonic to be attenuated, *Limit* is the maximum amplitude allowed by the reference standard at the frequency of interest and $6\ dB\mu V$ specifies an additional safety margin.

The cutoff frequency of the CM or DM filter is then expressed by (3).

$$f_{o\_CM/DM} = f_{h\_att} / 10^{\frac{A_{req\_att}}{filt\_att}} \quad (3)$$

where f_{h_att} is the harmonic frequency to be attenuated and *filt_att* is the filter inherent attenuation. When both corner frequencies are known, the inductance and capacitance values of the CM/DM sections of the EMI filter can be determined. Furthermore, in order to obtain an effective attenuation by the used chokes, the magnetic cores must be accurately chosen. In particular, both geometrical dimensions and magnetic properties of the material must be appropriately selected so to prevent magnetic saturation.

III. The Proposed Rule-based Procedure

The optimized EMI filter design proposed in this paper relies on a rule based algorithm taking into account the main characteristics of the power electronic system under study, the design constraints (including minimum volume) and the parameters/features of the EMI filter to be optimized. The concept of the proposed technique is summarized in Fig.1.

In order to properly select the most suitable components for the EMI filter, two databases of commercially available devices have been created. The first one is a database of magnetic cores including 110 toroidal cores, with both nano-crystalline (Vitroperm 500F) and ferrite (N30) materials. On the other hand, a suitable database of capacitors, including Y-type (for the CM noise mitigation) and X-type (for the DM noise mitigation) has been built, as well.

The following input data are requested to run the rule-based algorithm:

- Supply voltage (V_{grid})
- Number of phases of the power electronic system (n_{phase})
- Operating temperature (T)
- Maximum operating current (I_{max_phase}) and maximum CM and DM currents (I_{CM_max} and I_{DM_max})
- Required attenuation for both CM and DM EMI (Att_{req_CM}, Att_{req_DM})
- Frequencies of the CM and DM EMI spectra to be attenuated (f_{CM_att}, f_{DM_att})
- Inherent attenuation of the EMI filter, tied to its topology ($Att\_intr_{CM\_flter}$, $Att\_intr_{DM\_filter}$)
- Capacitance of signal/ground lines capacitors (C_{y_value}).

Sometimes, depending on the components which are used, multi-stage filter can occupy a smaller volume than single stage one; therefore, the proposed optimized design procedure considers the possibility to span a number of filter stages, *n*, ranging from 1 to 5. Once the input information are given, the algorithm is run according to the following steps:

1. CM section design. For *n=1,…,5*, the following quantities are computed: the cutoff frequency, the CM inductance, the number of turns (N_{CM}) needed to set up the required inductance for any core in the database. Then, the cores which allow the practical realization of the CM choke according to the required value of CM inductance and to the condition $N_{CM}< N_{max}$, are selected from the database. Finally the volume of whole CM section of the EMI filter in computed,

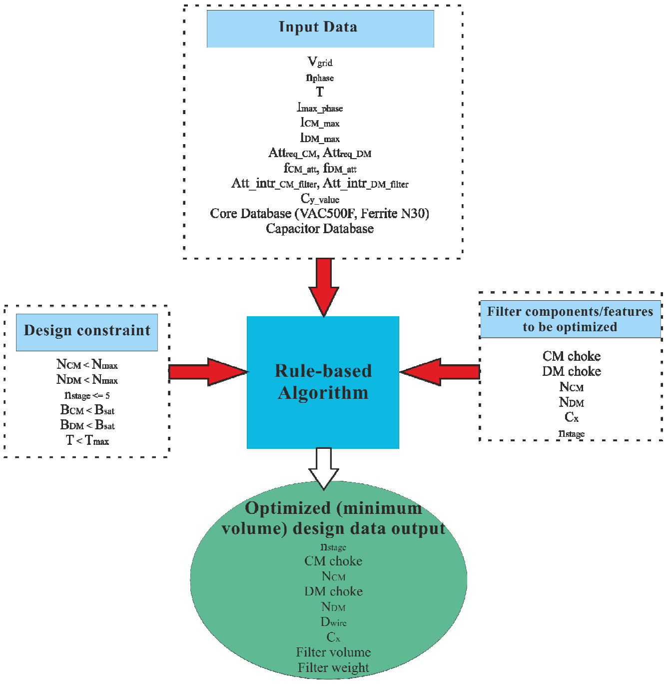

Fig. 1. Concept of the proposed technique.

including the volume of Y-capacitors whose capacitance has been previously fixed as an input parameter.

2. *DM section design*. The cutoff frequency vs. the number of stages is computed. The DM inductance values are obtained on the basis of the X-capacitors values in the database (ranging between 33nF and 10µF). Then dealing with DM noise, either the leakage inductance of the CM choke or the use of separate DM inductors can be selected. If the use of separate DM inductors is chosen, the number of turns for the DM inductors are calculated. Then, the cores allowing a practical realization, according to the condition $N_{DM}<N_{max}$, are selected from the database. Finally, the volume of the selected cores and capacitors are computed for *n=1,…,5*, and the combination of components permitting the implementation of the DM section with the minimum volume is selected.

Saturation of the magnetic core has been verified in both the CM and DM section design procedures. In particular, the fulfillment of the conditions $B_{CM}<B_{sat}$ and $B_{DM}<B_{sat}$ has been verified for the considered magnetic materials (nano-crystalline or ferrite). In this way the EMI filters designed according to the proposed procedure are free from saturation issues with no degrading of the desired performance. Finally, the algorithm calculates the EMI filter weight of the selected configuration.

IV. Preliminary Validation and Discussion

In order to validate the proposed computer aided procedure, a preliminary experimental investigation has been carried out on a suitably devised test bench. The test arrangement is composed of a PWM IGBT Voltage Source Inverter (VSI), based on a STGIPS10K60A module; an Altera Cyclone III FPGA board equipped with a Nial Stewart GPIB expansion board, implementing the PWM modulator; a three phase low power resistive load. The VSI switching frequency is equal to

20 kHz. A dual DC Line Impedance Stabilization Network (LISN) with a voltage capability up to 600V has been set-up and used to measure the conducted EMI. Starting from the measured values, the data needed by the proposed automatic design procedure have been computed. For the case study, the automatic procedure described in Section III has been implemented and run in Matlab environment. Fixing a Γ topology, the automatic procedure selected a double stage configuration. The optimized filter features are the following (for each stage): L_{CM}=50μH, C_{CM}=200nF, L_{DM}=242μH, C_{DM}=33nF. The filter designed according to the described procedure has been experimentally set up.

In order to validate the proposed design procedure, a single stage EMI filter designed according to the well-known conventional procedure [4]-[5], [11] has been built as well, as a benchmark. A comparison of the two filters in terms of size and performance has been performed.

As far as the volume and weight of the two filters are concerned, it is possible to observe that the optimized design leads to a reduction of 68.3% in volume and of 68.57% in the weight with respect to the conventionally designed filter. In Fig. 2 photos of the magnetic cores (a) for the CM chokes and of the DM capacitors (b) used in the conventional (components on the left) and optimized (components on the right) EMI filters, are shown to give an idea of the improved compactness.

Experimental tests have been performed to verify the performance of the realized EMI filter. A RF current probe R&S EZ-17 that allows measurements in the frequency range 20Hz-100MHz with a maximum DC current of 300A and an R&S FSH4 (100kHz-3.6GHz) spectrum analyzer have been used for the RF measurements. In order to evaluate the EMI filter mitigation performance, EMI measurements with each input filter have been carried out. As expected, both filters exhibit a satisfactory behavior since the filtered EMI is below the standard limit (Military Standard 461F [12]), as shown in Fig. 3. Therefore, the compliance of the power electronic system under study with the standard limit is satisfied with an EMI filter whose compactness and power density are significantly improved without significant computational effort.

V. CONCLUSIONS

This work deals with the power density issue in EMI filters used for mitigating EMI in power electronic systems. In detail, this paper proposes an automatic procedure for the optimal and fast selection of discrete EMI filter components and layout, aiming at obtaining the minimum volume.

The proposed procedure relies on a suitably devised rule-based algorithm and on databases of commercially available magnetic cores and capacitors. It takes as inputs some parameters computed from noise measurements and others that define the system configuration; after the computation, it outputs the optimal filter components and the whole filter volume and weight. The rule-based algorithm is run with Matlab environment and does not require significant computational effort. A preliminary experimental assessment demonstrates the effectiveness and usefulness of the proposed method.

(a) (b)

Fig. 2. Comparison of magnetic cores (a) for CM choke and of DM capacitors (b) used in the realized EMI filters.

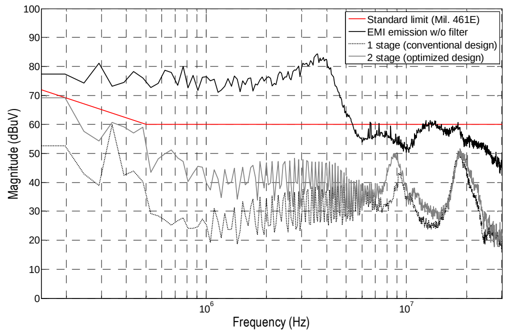

Fig. 3. Comparison of optimized and conventional EMI filter performance.

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