Design of a Hybrid Integrated EMC Filter for a DC–DC Power Converter

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Abstract—This study focuses on the design and the realization of an integrated EMI filter embedded in an aircraft power supply. The first part of the study is dedicated to the modeling of the dc–dc power, based on a “black box” representation: the converter is represented by an association of sources and impedances that reflect its external EMI behavior. This initial step enables us to define the electrical structure of the filter and the component values; a hybrid solution (active plus passive) can be effective for optimal filtering while minimizing the size and mass. The second part of the study is devoted to its realization, based on the integration of capacitive and inductive components inside a printed circuit board structure. This technology is named hybrid integration. Some technological difficulties are highlighted regarding the geometry of the components and their manufacture using this technology. Finally, filter architecture is proposed and a functional prototype is realized. Experiments show that significant gains in volume are achieved while compliance with the DO 160 standard (aeronautics) is obtained.

Index Terms—Common and differential mode interferences, electromagnetic compatibility, electromagnetic interference (EMI) hybrid filter, integration of passive components.

I. INTRODUCTION

T he use of semiconductor components (SiC/GaN) in power electronics can reduce the volume of equipment, increase their operating temperature, and improve their energy efficiency [1], [2]. However, due to very fast changes in voltages and currents in the switching components (dV/dt, dI/dt), conducted and radiated electromagnetic disturbances occur at high frequencies [3], [4]. To protect the network from these emissions and meet the standards for electromagnetic compatibility (EMC) including the aeronautic standard “DO160F (150 KHz, 30 MHz),” an EMC filter is absolutely necessary [5], [6].

The EMC filter requires a specific design for the two modes of propagation of parasitic currents, i.e., common mode (CM) and differential mode (DM). The design is based on the use of an accurate electromagnetic model of the converter. The behavioral model has proved its efficiency in representing accurately electromagnetic interferences [7], [8]. This kind of model is constituted by disturbance equivalent sources and CM and DM equivalent impedances. In recent years, several studies have shown the interest but also the limitations of EMC active filters in a frequency range up to several megahertz [9], [10]. Other research has show a reduction of the efficiency of EMC filters due to their parasitic components and to imperfections in materials [11]. Thus, to exploit the performances of each technology, a hybrid optimized EMC filter, that is composed of an active part for low frequencies and a passive part for high frequencies, is the most compact solution [12]–[14]. The integration of the passive part of this hybrid filter will be presented in this paper.

First, the electromagnetic characterization of the converter under test is presented. In order to increase the effectiveness of the passive part of a hybrid filter and to reduce its volume, a full integration of this part in the printed circuit board (PCB) is proposed. Its implementation requires the choice of a magnetic material which can be integrated and the use of high permittivity dielectric materials in order to achieve high value of planar capacitances. Taking into account the brittleness of magnetic materials (ferrites), several tests for their integration into a PCB have been done. A planar geometry that meets the specifications is then chosen. After characterization of the materials that are used in this new architecture, its modeling by the finite element method (FEM) is presented. Measurements of the attenuations in CM and DM of the integrated passive filter are then compared with those of identical discrete ones.

II. CHARACTERIZATION AND MODEL OF ELECTROMAGNETIC INTERFENCES GENERATED BY THE POWER CONVERTER

The power converter considered in this paper is a dc–dc power supply designed to equip a civil aircraft. Aeronautic standards must be therefore be respected and in particular the DO160F standard, which defines the maximum allowable levels for electromagnetic interferences. The specifications of the power converter are given in Table I.

The intrinsic level of conducted electromagnetic interferences generated by a power converter can be identified and separated into two contributions, i.e., CM and DM. In this section, an
equivalent behavioral EMC model is proposed with a limited number of parameters that can be identified by analytical calculations, simulations, or electrical measurements [15], [16]. This model includes two parts: an equivalent impedances circuit [17] associated with equivalent sources of voltage (CM) and current (DM) (see Fig. 1). This model allows the calculation of the emission level of the converter regardless of the configuration of the EMC filter placed at the input. Note that the identification of impedances and sources is realized without EMC filter and, in this model, the equivalent noise sources are placed according to their mode of propagation [18], [19]. In the proposed method, the power converter is considered a “black box” with two input ports, respectively; between line 1 and mass, and between line 2 and mass (see Fig. 2). The development of this equivalent model will be discussed in the following sections.

### A. Impedance Modeling

In this section, the identification procedure of the EMC black box impedances is described. The system to be identified has two ports. Therefore, there are four impedances to define, namely $Z_{11}$, $Z_{22}$, $Z_{12}$, and $Z_{21}$, i.e., the four values of the impedance matrix

$$V = ZI \Rightarrow \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}.$$  \hspace{1cm} (1)

In order to perform both the direct measurements of impedance and transimpedance of the system under test, an impedance analyzer HP4194a configured for transfer mode measurement (T/R) is used. A current is, therefore, injected by the source generator of the analyzer in one of the input ports of the off-state converter board. The resulting voltage is then measured in port T. The injected current is measured using a current sensor with a large bandwidth (Tektronix CT2: 1 mV/1 mA, loaded with 50 $\Omega$) and connected to port R. This protocol requires corrections that depend on imperfections due to connections and transfer functions of the current and voltage probes used.

The equipment under test is shielded to avoid the influence of external fields. This measurement bench also guarantees a stable configuration of connections, and thus, the parasitic impedances of connections are almost invariant (see Fig. 2).

Using this test bench, three impedances are measured, i.e., the impedance between line 1 and mass, between line 2 and mass, and between line 1 and line 2 corresponding, respectively, to $Z_{11}$, $Z_{22}$, and the differential impedance $Z_{DM}$. These impedances are shown in Fig. 3.

From these measurements, the impedances $Z_{11}$ and $Z_{22}$ are clearly identical leading to the same CM impedance. In addition, the transimpedances $Z_{12}$ and $Z_{21}$ are also identical, which allows us to propose a simple electrical model with only three localized impedances (see Fig. 4).

The proposed model consists basically of two parasitic inductances of equal value, i.e., $L_1$ and $L_2$ placed on both lines in series with two parasitic resistances $R_{LS}$. This model is supplemented by two identical CM capacitances ($C_1$ and $C_2$) placed between each line and the mass. The DM impedance $Z_{DM}$ is represented by a capacitance $C_0$ connected in parallel with a resistor $R_0$, and parasitic components $R_{ps}$ and $L_{ps}$.

Measurements and identifications led to determination of the value of each element of the model [20]. These values are shown in Table II.

The theoretical impedances corresponding to each measurement configuration have been calculated from this model. The experimental results presented in Fig. 3 are clearly in good agreement with simulated results.
B. CM and DM Sources Model

The EMC “black box” model must be completed by equivalent CM and DM sources. The symmetry of the DM and CM impedances limits the phenomena of mode conversion. This simplifies the extraction of the equivalent sources.

In order to realize this extraction, the power converter is fed through two identical line impedance stabilization network (LISN) placed on each line. They meet the recommendations of standard DO160F and they stabilize the impedances of the power source. According to the complete model given in Fig. 5, the equivalent sources can be extracted by measuring the two line currents. The equivalent CM voltage source and the differential current source can be determined by

\[ V_{CM} = \left( \frac{Z_{L} + Z_{L} + Z_{C}}{2} \right) (I_1 + I_2) \] (2)

\[ I_{DM} = (I_1 - I_2) \left( \frac{Z_{L} + Z_{L} + Z_{C}}{2Z_{C}} + \frac{Z_{L} + Z_{L}}{Z_{DM} + \frac{1}{2}} \right) \] (3)

In order to improve the accuracy in the calculation of the two equivalent sources, currents “I_1 + I_2” and “I_1 - I_2” have been directly measured on the test bench using two identical current probes. The acquisitions at this step are performed using an oscilloscope (Tektronix DPO 7104 “1 GHz”). The data are then processed using MATLAB. In this software, the current sensor voltages are first corrected by applying the inverse transfer function of the sensors, leading to the current values, i.e., “I_1 + I_2” and “I_1 - I_2”. The CM and DM sources are then calculated using (2) and (3).

The calculated spectra corresponding to CM and DM sources can be seen in Fig. 6.

C. EMC Model Validation

To verify that the proposed model can correctly represent the levels of electromagnetic interference (EMI) generated by the power converter, the LISN voltages have been calculated from this model. Experimental and calculated LISN voltage spectra corresponding to \( V_{Rrsil1} \) and \( V_{Rrsil2} \) are shown in Fig. 7. Experimental spectra are measured using an HP4195A spectrum analyzer. They are in good agreement with the simulated levels. This agreement proves that the proposed model as well as the method of identification of its parameters are correct.

This model provides a relevant way to calculate and to optimize the EMC filter. In the next section, it will be shown how the required attenuations can be calculated to meet the DO160F standard required levels.

![Converter equivalent model of impedance for EMI analysis.](image1)

![CM and DM sources associated with the power converter equivalent model of impedance.](image2)

![Calculated spectra of CM and DM sources (fast Fourier transform (FFT)) in the EMI model of the power converter.](image3)
The first step of the design of the EMC filter is to set the required attenuation levels for CM and DM. The previous model in Fig. 5 can be split into two configurations corresponding to DM and CM as presented in Fig. 8. Because the DO160F standard gives the limit levels in terms of current rather than voltage, it is better to reason with current sources of disturbances. Thus, the model of CM can be rearranged to bring up an equivalent source of CM current, denoted $I_{CM}$.

The theoretical required levels of attenuation can now be calculated from the previous models by determining the levels of emission associated with the CM current source only, then those related to the DM current source.

From the spectra of $I_{DM}$ and $I_{CM}$ (see Fig. 9), the required attenuation level can be determined on the DO160F frequency range by

$$\text{Att}_{DM} = I_{DM}(\text{dB} \mu\text{A}) - \left( \text{Limit (DO160F)}(\text{dB} \mu\text{A}) - 6 \text{ dB} \right)$$

$$\text{Att}_{CM} = I_{CM}(\text{dB} \mu\text{A}) - \left( \text{Limit (DO160F)}(\text{dB} \mu\text{A}) - 6 \text{ dB} \right).$$

An extra 6 dB reduction of the standard level is justified because the overall level of disturbances of CM and DM may add up in the worst case. This gives, for the same amplitude of the two contributions, twice the level of each emission.

The attenuation provided by an EMC filter is a smooth continuous function; thus, the attenuations required are given by the envelopes of the calculated attenuations. They are plotted by the continuous line in Fig. 10.

Without a filter, the attenuations provided by the structural elements of the power converter (impedances network of the “black box”) for both modes are calculated using the...
Fig. 11. (a) Schematic of a single-stage passive EMI filter. (b) Magnetic behavior of coupled inductors for CM and DM currents.

electrical model given in Fig. 8. The corresponding attenuations are plotted by the dotted line in Fig. 10. It can be seen from this figure that the attenuation introduced by the structural passive elements does not achieve the required attenuations. For frequencies above 1 MHz, these attenuations will be provided by the passive filter and the values of the passive filter components can be calculated to ensure these required attenuations [21].

In this paper, the necessary attenuation on the frequency band of the DO160F standard is obtained, thanks to a hybrid filter. Such hybrid architecture is known to be the best approach to optimizing EMI filtering [12], [22]. For one part of the frequency band, an active filter compensates parasitic signals, but the limitations of the active filter begin to be significant beyond a few megahertz. To cover the entire frequency band, the active filter must be associated with a passive filter giving the required attenuation in the HF frequency range, for example [2–30 MHz].

In a hybrid filtering structure, the architecture of the passive filter can be simpler than in a purely passive structure. A single-stage structure, as shown in Fig. 11, is sufficient in this case. The CM filter consists of two symmetrical capacitors between each line and ground, associated with two coupled inductors. The leakage inductance of the coupled inductor constitutes, with the capacitor added between the two lines, a DM filter. In an integrated view of this passive filter, values of capacitive or magnetic components depend on their geometry and they can be determined from the required theoretical attenuation. This theoretical attenuation can be calculated using the “black box” model.

Electric models that represent the filter are added to the previous DM and CM models (see Fig. 12). In these models, the position of the capacitances $C_{CM}$ and $C_{DM}$ can be modified: they can be placed at one end or the other of the coupled inductor. These DM and CM capacitances are, however, defined by the limits of the chosen technology for integration in PCB. In our case, capacitances are made of thin layers of high-k material embedded in the PCB, leading to $C \approx 1.7 \text{ nF/cm}^2$. For an available area of 4 cm $\times$ 5 cm for the PCB, the capacitances of the proposed design will be limited to 20 nF for DM and 10 nF for CM, leading to an equivalent 20 nF capacitance in CM and 25 nF capacitance in DM.

Based on the previous values of DM and CM capacitances, the parametric calculation of the attenuations can be achieved by varying the inductance values for both modes. The attenuations calculated in Fig. 13 show the existence of optimum values for $L_{CM}$ and $L_{DM}$, namely $L_{CM} = 3 \mu H$ and $L_{DM} = 3 \mu H$, achieving the requirements of DO 160 over the entire frequency range for
CM and in the range [2.5–30 MHz] for DM. In this last case, the associated active filter will have to effectively reduce the DM disturbances from 150 kHz to 2.5 MHz. This is reasonably possible with suitable electronics.

Therefore, for the converter considered in this paper and the structure chosen for the passive filter, the theoretical required values are given in Table III.

However, the effectiveness of the passive filter is often degraded by imperfections of the passive components i.e., parasitic elements, interconnections, and materials properties. To control and manage these effects, the integration of the passive components within the PCB is proposed in the next section.

IV. INTEGRATION OF THE PASSIVE FILTER

Integration of passive components for power electronic converters and in particular of EMC filters is the main focus of this section. In recent years, several integration technologies [23], [24] and multilayer structures embedded in PCB have been studied [25]–[27]. In order to meet the application constraints (EMC, volume, mass, mechanics, environment, etc.), planar passive components embedded within a PCB will be proposed to use.

The passive EMI filter structure, proposed in Fig. 14, consists of an inductive part, i.e., a coupled inductor, and two capacitive parts \( C_{\text{CM}} \) and \( C_{\text{DM}} \). In this section, the technological feasibility of each part will be discussed separately. The design of this structure requires a global approach to achieve the specifications and, at the same time, minimize mass and volume.

A. Impedance Modeling

1) Proposed Design: In the proposed filter, the CM and DM capacitors are made from a material known as C-Ply [28]. This material is sandwiched between two copper plates [see the cross section of this assembly in Fig. 15(b)]. It enables the design of planar capacitors compatible with PCB technologies. The only constraint in the implementation of such a material is to place these layers symmetrically in the PCB stacking. In our design, there are two capacitive layers. One layer is dedicated to the DM capacitor and the other to the CM capacitors. As a consequence of this design, the total area dedicated to the DM capacitor is twice that of the CM capacitors leading to an equal equivalent capacitance in CM and in DM.

In Fig. 15(a), a PCB prototype can be seen including two capacitive layers with, on the top, six connections including two central connections to ground on both sides of the filter and four input and output connections. The total area of this integrated filter is 20 cm². The dielectric material used for the capacitors is 16 \( \mu \text{m} \) thick and its main characteristics are summarized in Table IV.

2) Main Characteristics of the Integrated Capacitors: A capacitor is usually modeled by a capacitance in series with an
equivalent series resistor (ESR) and an equivalent series inductance (ESL) [29]. If the capacitor is connected using the four-point transmission line connection method, like in Fig. 16, the ECLs will add up to CM and DM inductances and the filtering efficiency will not be degraded by the parasitic elements [23].

The impedance measurements of CM and DM capacitors are shown in Fig. 17. From these measurements, the equivalent electrical model can be identified leading to \( C_{\text{CM}} = 9 \, \text{nF} \), \( C_{\text{DM}} = 18 \, \text{nF} \), \( \text{ESR} = 3 \, \text{m\Omega} \), \( \text{ESL} = 0.78 \, \text{nH} \).

**B. Inductive Part of the Integrated EMC Filter**

Regarding the CM passive filtering, two coupled inductors using a common magnetic material with a high permeability and a high saturation level are designed. In the configuration of Fig. 11(b), the leakage flux determines the DM inductances. These inductances must be controlled by correct design of the magnetic core.

1) **Choice of Magnetic Material and Core Design**: Magnetic materials often used for filtering EM interferences are ferrite materials. Their magnetic properties vary with frequency [30]. For EMC filtering applications, materials with high losses at high frequencies have been sought.

The first design for testing integration of a magnetic component in the PCB led us to integrate a component that contains two magnetic plates and two vertical legs (see the cross section in Fig. 18). In this magnetic structure, windings are integrated in the PCB around the two vertical legs leading to the required magnetic structure, i.e., two coupled inductors. But this first design also highlighted some technological problems namely difficulties in ensuring proper contact between the top and bottom parts of the magnetic core and the presence of numerous fractures near the overhanging portions.

After this initial feedback, a new design of magnetic component has been proposed. In this design, the magnetic core is a planar ring core (see Fig. 19). This design lowers the constraints arising from the need to ensure a contact between different portions of the magnetic circuit and reduces the risk of fractures in overhanging parts.

For such a magnetic core, the windings have to be designed on two copper layers connected by vias. This core has been obtained from a ferrite material dedicated to high-frequency filtering applications and the dimensions have been defined to meet the MC and MD attenuation requirements.

2) **Characterization of Material Properties**: From (6) and the impedance spectrum measurement (realized with an
From these measurements, it was found that the proposed design, reducing the turn-to-turn parasitic capacitance as well as the interwinding capacitances, leads to maintenance of the inductive behavior of the magnetic component on the entire frequency range of the DO160 standard.

The behavior of the magnetic component has also been calculated using a simulation software based on the FEM (COMSOL 3-D). Fig. 24(a) and (b) shows the simulated behavior of the magnetic component in the two current configurations in Fig. 22.

It can be seen in these figures that the field distributions are very different in the two configurations. For CM currents, flux density flows entirely within the magnetic circuit; for DM currents, magnetic field lines are closed in the air, outside the core. These behaviors are consistent with our expectations.

C. Performances of the Integrated Passive Filter

The performances of a filter can be determined, for a defined source and load impedance, by measuring the attenuation introduced by the filter in this configuration. This attenuation is given as the ratio between the filter input voltage and the filter output voltage. This measurement is performed using an HP4195A frequency analyzer used in transfer mode configuration. The measurement configurations are shown in Fig. 25(a) and (b) for CM and DM, respectively.
To demonstrate the benefits realized by the integration of an EMC filter, an equivalent discrete filter with identical component values at low frequencies was constructed [see Fig. 25(c)]. In Fig. 26, the attenuations obtained, respectively, with the discrete and integrated filters are compared. For frequencies between 500 kHz and 10 MHz, attenuations for DM and CM are higher with the discrete filter. This relative lack of performance in this frequency band is linked, for the integrated passive filter, to the reduction of inductance with frequency due to the reduction of the real part of relative permeability with frequency (see Fig. 20). Therefore, these lower performances are due to material properties and are not due to design. Nevertheless, the main advantages of integration can be seen beyond 10 MHz as controlled and lower inductive and capacitive parasitic effects lead to much higher resonant frequencies. Thus, attenuations obtained at high frequencies are higher for the integrated passive filter.

The interconnection parasitic inductances $L_{via}$ between the integrated capacitors are minimized due to the use of via with low lengths [see Fig. 27(a)]. In contrast, the parasitic inductances

![Fig. 25. Configuration for measurement of (a) CM attenuation and (b) DM attenuation. (c) Photograph of the discrete EMC filter (volume = 3.5x3.2x1.2 = 13.44 cm$^3$).](image)

![Fig. 26. CM and DM attenuation measurement for (a) discrete passive filter and (b) passive integrated filter.](image)
of the discrete capacitors and the interconnection wires make the parasitic inductive effects important in the discrete EMC filter. The parasitic capacitive effect in an integrated winding is shown in Fig. 27(b). This effect can be optimized by a calculation of the wire-to-wire spacing D and the wire-to-core spacing d. The minimal controlled value of “D and d,” in the current integration process, is 200 μm. Moreover, the high resistivity of the ferrite lowers the effect of the wire-to-core capacitance. Due to the thinness of the copper, the global ESR of the embedded choke increases for the dc current. To overcome this disadvantage, an additional metallization is recommended.

The resulting embedded choke volume is 63% lower than the equivalent discrete choke. It can also be emphasized that the total volume of the integrated filter is 58% lower than the equivalent discrete filter. The proposed integrated structure is also shielded by the two ground planes located at the top and bottom of the PCB stacking.

The global behavior of the integrated filter is, therefore, better than its equivalent using discrete components.

The integrated filter is now set up to reduce the interferences generated by the converter used to support our study. It can be shown in Fig. 28 that, as expected, the integrated filter reduces CM and DM interferences in the frequency range that extends from 2.5 to 30 MHz.

An active filter must be added to reduce EMI interferences due to switching in the frequency band up to 2.5 MHz. Possible topologies of active filters are proposed in [33] and [34]. For our application, the chosen topology uses a voltage compensation effect generated by an auxiliary winding added to the coupled inductor. This topology will be described in a future paper.

V. CONCLUSION

Reducing the volume and improving the efficiency of EMC filters for power electronics devices are strategic issues particularly in the case of complex systems such as those found in the aerospace or automotive industries. In this paper, a characterization procedure for a power supply has been presented. This method allows constructing an electromagnetic behavioral model of the converter. From this model, it is possible to define the characteristics of an EMC filter optimized to meet the specifications given by a standard. The proposed EMC filter is designed to be integrated into the thickness of a PCB. One of the main challenges of such a design is the integration of magnetic components. The proposed design reduces the volume of the filter by 58% and improves the CM and DM attenuations at high frequency compared to the same filter made of discrete components. The proposed structure optimized for filtering high-frequency interferences (beyond 2.5 MHz) must be supplemented by a low-frequency active filter. It is easy to use the PCB board incorporating the passive filter as a support to this new role. This architecture, thus ensures maximum efficiency and optimum compactness for the EMC filter.

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