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Compact EMC model of power electronics converter for conducted EMC studies in embedded networks

M. Foissac¹, J.L. Schanen¹, C.Vollaire²

1 G2ELab – UMR 5269 INPG-UJF-CNRS

2 Ampère – UMR 5005 - University of Lyon

Abstract This paper presents a "black box" model for EMC prediction of power electronics converters. Unless previous work, this compact representation does not necessitate the precise knowledge of the internal behaviour inside the converter. The methodology for identifying the model parameters will be given, as well as the model validation. One of the most promising applications of such a simple model is the forecast of ElectroMagnetic Compatibility behaviour at system level in embedded networks.

Keywords: EMC, EMI, Power Electronics

1. Introduction

With the generalization of the "Power by Wire" concept, especially in aircraft and automotive applications, the electrical consumption is growing dramatically. This leads to new problems when designing electrical networks. Modern embedded networks become more complex since the power input stage of the majority of loads is composed of switched mode power converters. Even if this allows a better power management, power electronics generates high EMI (ElectroMagnetic Interferences) level, which must be forecasted accurately, in order to avoid disturbance of the complete system.

To quantify the EMC (ElectroMagnetic Compatibility) behaviour of an embedded network, on both conducted and radiated aspect, it is mandatory to determine the current flowing in the networks, on a wide frequency range. The time simulation of a complete network including many power electronics converters is too complex to reach a sufficient accuracy in the high frequency range. Indeed, precise cabling models, as well as semiconductor models are needed. Simulation time step must be kept low (some nanoseconds) in order to keep convergence and to reach high frequency. Even for a single converter, the task is not easy at all.

To overcome the drawbacks of time simulation, models in the frequency domain have been proposed [1]. They start from the knowledge of the converter intrinsic behaviour, replacing the semiconductors by equivalent sources. Even if good results have been obtained, the location of the source is arbitrary and does not correspond to the actual behaviour of the converter. Furthermore, the proposed model still necessitates a very good knowledge of the internal cabling of the converters. Thus, another modelling method will be proposed in

this paper. It is based on a "black box" approach, and aims to replace the converter by a simple equivalent scheme, generating the same disturbance as the converter, with no need of knowing what is exactly inside it.

The model topology will be first presented, as well as the method proposed for parameters identification. A simplified application to differential mode and common mode only will be presented in section 3 and 4, in order to focus on the main difficulties of the identification. Section 5 will then detail the complete identification method for a whole converter. Results are used in section 6, on a simple chopper cell.

This work is part of the PEPS CEM project, supported by the competitiveness cluster MOVEO, and the Rhone Alpes "Transportation" cluster. PEPS CEM is the development of a platform for EMC prediction of complex systems. It will provide all necessary models and simulation tools for EMC investigation of embedded networks.

2. Converter Model

Any EMC analysis must account for the ground potential. Therefore, a power electronics converter, fed by a single phase or a DC power line, has to be considered as a quadropole: two power access and a reference potential. Since the converter can be considered as an EMI generator, some sources have to be added to the conventional quadropole representation. We chose to add current sources. Therefore, the generic EMC model for a power converter is the one presented in Figure 1. In comparison with other work [2-3], it accounts for all necessary parameters, without any redundancy or approximation. Other representations using voltage source can also be used; they can be easily obtained from the proposed Norton scheme.

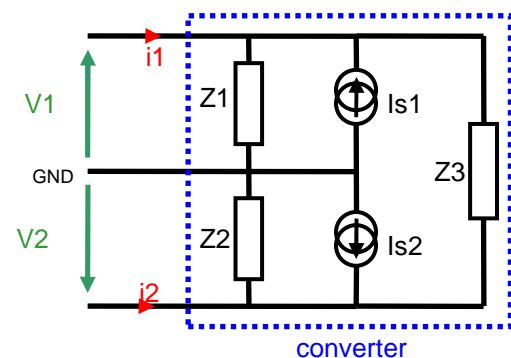


Fig. 1 : Model of a converter

Three impedances and two current sources have thus to be identified on the whole frequency range of interest. To achieve this task, one possible solution is to measure the input voltage and currents for several operating conditions, obtained by varying line impedance, as illustrated in Fig. 2. Any line impedance can be changed, either Common Mode, or Differential Mode. To be noticed that this change in power line impedance must not affect the switching behaviour of the converter, in order the sources can be properly identified. Therefore, this method is more adapted for identifying a power converter rather than a switching cell, as proposed in [3]. Further works of [3] have indeed been oriented to power converter modelling [4].

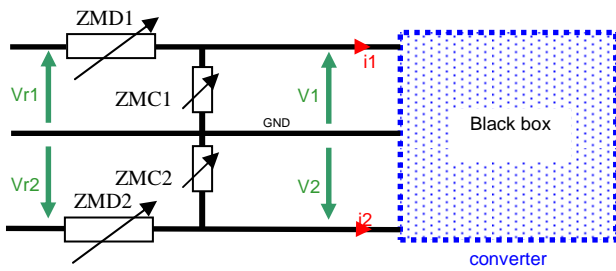


Figure 2. Line impedance variation for parameters identification

The values of V_1 , V_2 , I_1 , I_2 are linked to the parameters of the model by equation (1). Each operating point is characterised by a set of measurements V_{1i} , V_{2i} , I_{1i} , I_{2i} , whatever the power line impedance. These measurement results allow obtaining a set of two equations for each line impedance. To obtain the five parameters, it is therefore necessary to achieve three different measurements, for three different operating points. However, before addressing the complete problem, some preliminary studies must be achieved. Indeed, in such inverse problems, there is strong risk of identification failure due to unavoidable measurement inaccuracies.

Therefore, in a preliminary step (section 3), a simplified problem will be detailed: by removing the ground potential. The converter in Differential Mode only becomes a simple dipole, which can be represented by only two parameters (one impedance Z and one current source I_s). In a second step only Common Mode generation, between one power line and the ground, will be considered (section 4). Once again this implies a dipole model only. The conclusions of these two simple cases will be used in section 5, where a complete converter will be considered.

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} Z_1 \cdot \frac{Z_2 + Z_3}{Z_1 + Z_2 + Z_3} \cdot I_1 + Z_1 \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3} \cdot I_2 + Z_1 \cdot \frac{Z_2 + Z_3}{Z_1 + Z_2 + Z_3} \cdot I_{s1} + Z_1 \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3} \cdot I_{s2} \\ Z_1 \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3} \cdot I_1 + Z_2 \cdot \frac{Z_1 + Z_3}{Z_1 + Z_2 + Z_3} \cdot I_2 + Z_1 \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3} \cdot I_{s1} + Z_2 \cdot \frac{Z_1 + Z_3}{Z_1 + Z_2 + Z_3} \cdot I_{s2} \end{pmatrix} \quad (1)$$

3 Simplified Model for Differential Mode

For this preliminary study, we have chosen a simple chopper cell. This simplified case is especially interesting since the equivalent circuit can be easily identified by investigating the chopper topology: the impedance Z corresponds mainly to the input capacitor, and the current source simply corresponds to the current in the power switch [5]. To be noticed that this is a first order approximation, just to check the impact of the link on the precision of the identification. Indeed, for an actual converter, the value of Z and I_s should represent all parasitics in the chopper cell, and not only the input capacitor. However, in this preliminary step, we suppose an ideal circuit composed of a current source and the input capacitor, and we try to identify them.

Figure 3 shows the converter model inserted in a standard environment (using a Line Impedance Stabilization Network, LISN), with a variable link. It has been chosen to modify the parallel impedance in this case. Indeed, modifying the series impedance generates less impact on V_1 and I_1 values, since it is in series with the equivalent impedance of the LISN (ranging from 10 to 100 Ω).

The variable impedance is composed of a CI-LI series association.

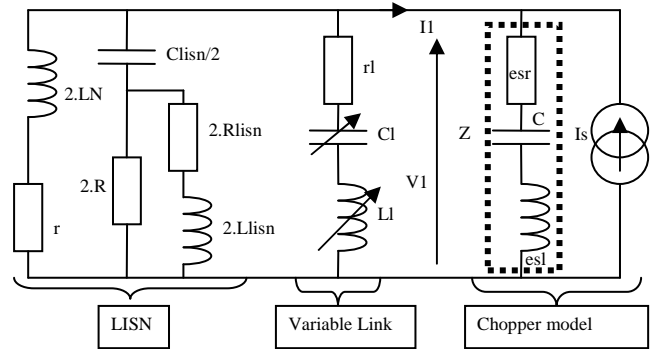


Figure 3. Chopper model in Differential Mode connected to a LISN, with a variable parallel impedance for parameter identification.

The measurement of V_1 and I_1 brings only one equation:

$$I_1 = -I_s + \frac{V_1}{Z} \quad (2)$$

Therefore, two different operating conditions must be considered, leading to two different values (V_{11} , I_{11}) and (V_{12} , I_{12}). Thus, the parameters Z and I_s can be expressed with the following (3) and (4) equations:

$$I_s = \frac{V_{11} \cdot I_{12} - V_{12} \cdot I_{11}}{V_{12} - V_{11}} \quad (3)$$

$$Z = \frac{V_{I_1} - V_{I_2}}{I_{I_1} - I_{I_2}} \quad (4)$$

It is clear from these expressions that the determination can be effective only if the two operating conditions give different values to V_{I_1} , V_{I_2} and I_{I_1} , I_{I_2} . A sensibility study on CI-LI variation has been carried out, using precise simulations in the time domain, with accurate models of layout and semiconductors (Figure 4). It shows clearly that the high frequency precision is governed by LI, whereas CI imposes the low frequency behaviour.

This is not surprising since the equivalent scheme of Figure 3. is simply a current divide.

After this investigation, the operating conditions $CI=470nF$, $LI=10nH$ and $CI=100nF$, $LI=100nH$ has been chosen for identification. The results for Z and I_s are plotted on Figure 5, in comparison with the expected results (Z should corresponds to the input capacitor, I_s to the Mosfet current). The concordance is good until several tenth of MHz, except in some local points for Z . Around 50MHz, the accuracy becomes poor. This may be attributed to identification inaccuracy.

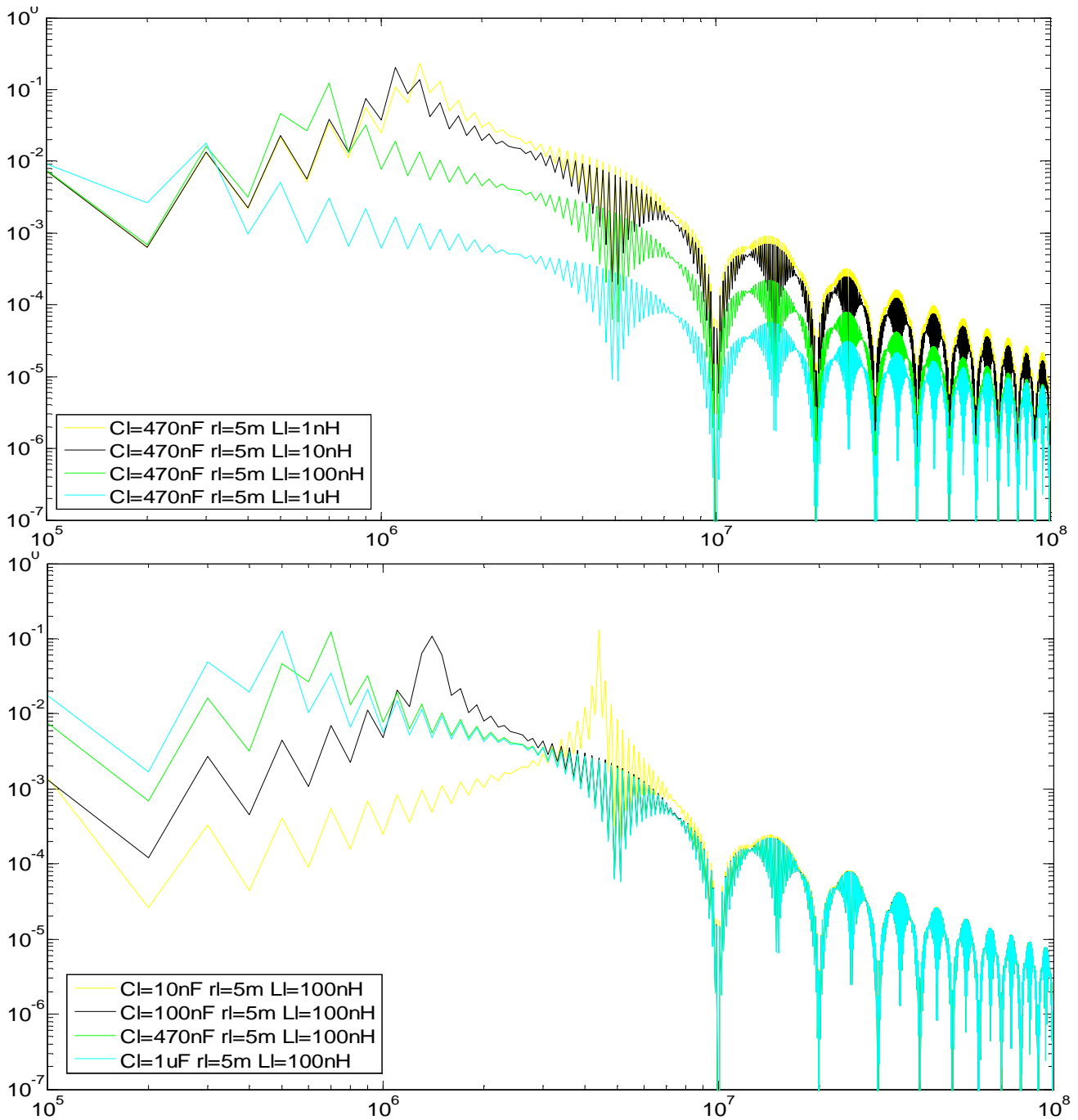


Figure 4. Sensibility study on input current (I_1): top variation of L – Bottom variation of C

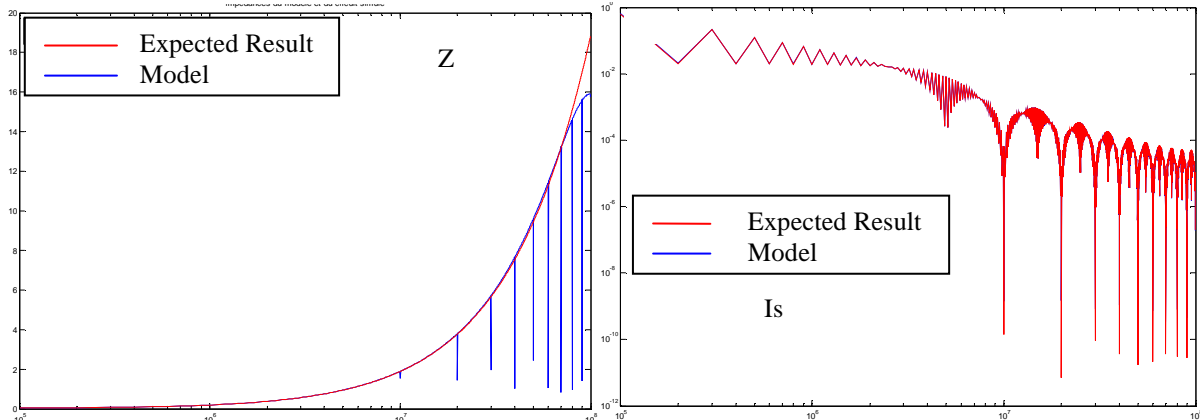


Figure 5. Result of model identification in comparison with expected results: left: Z, right: Is.

4 Simplified model for Common Mode

The usual representation for common mode generation uses a voltage source, to apply a common mode excitation to a floating capacitor C. Figure 6 illustrates an equivalent circuit; between a power line (plus or minus for the example of a DC bus) and the ground. The LISN is represented, as well as the variable link. A simple transformation can change this scheme into a Norton equivalent source, what corresponds to the topology of the equivalent circuit we are looking for (Figure 7).

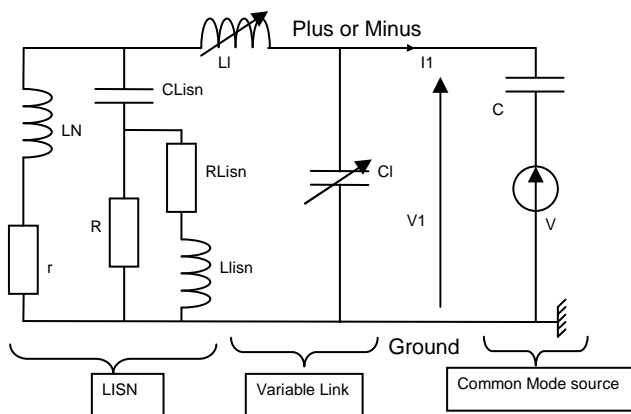


Figure 6. Equivalent circuit for common mode.

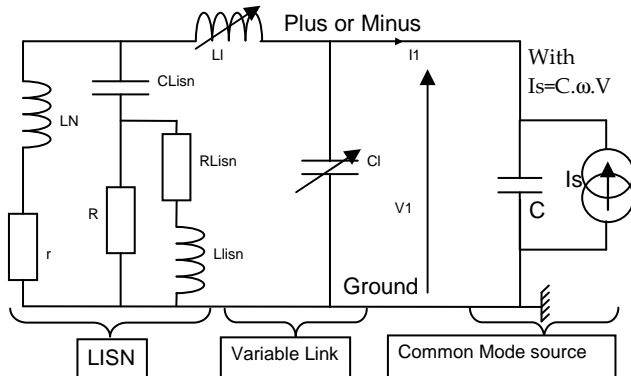


Figure 7. Equivalent circuit for common mode, deduced from Figure 6 using the desired dipole representation

As for differential mode, we will change the impedance of the link between the LISN and the converter, in order to identify the values of the chopper equivalent circuit (impedance Z and current source Is). Due to the usually low value of the stray capacitance C, the associated impedance is high, and a change of series and parallel impedance of the link has been considered useful.

Figure 8 illustrates the impact of LI and CI variation for the input current I1. It shows that a good difference can be obtained on the whole frequency range, using two different values of LI and CI. Therefore, a good identification may be obtained, what is clearly shown on Figure 9

5 Complete model identification

After the study of simple cases, which have shown the importance of line impedance selection to identify the system, an actual converter can then be addressed, including both common and differential mode EMI generation. As mentioned in section 2, the complete model implies five parameters, therefore, three operating points are necessary. One equation is thus redundant. Depending on the combination of equations used for the parameter determination, several different expressions can be found for Z1, Z2, Z3, Is1 and Is2. Hereafter are given the 6 key equations, where Z1, Z2, Z3, Is1 and Is2 are the model parameters to be determined, and V1i, V2i, i1i, I2i (i=1 to 3) are the different voltage and currents measured for three different line impedance.

$$I1_1 = \frac{V1_1}{Z1} - Is1 + \frac{V1_1}{Z3} - \frac{V2_1}{Z3} \quad (5)$$

$$I2_1 = \frac{V2_1}{Z2} - Is2 - \frac{V1_1}{Z3} + \frac{V2_1}{Z3} \quad (6)$$

$$I1_2 = \frac{V1_2}{Z1} - Is1 + \frac{V1_2}{Z3} - \frac{V2_2}{Z3} \quad (7)$$

$$I2_2 = \frac{V2_2}{Z2} - Is2 - \frac{V1_2}{Z3} + \frac{V2_2}{Z3} \quad (8)$$

$$I_{13} = \frac{V_{13}}{Z_1} - I_{s1} + \frac{V_{13}}{Z_3} - \frac{V_{23}}{Z_3} \quad (9)$$

$$I_{23} = \frac{V_{23}}{Z_2} - I_{s2} - \frac{V_{13}}{Z_3} + \frac{V_{23}}{Z_3} \quad (10)$$

After some algebra, by considering 5 among the 6 preceding equations, different expressions can be found for the various parameters of the model. Four different expressions can be deduced for Z1, Z2, Is1, Is2 and only two for Z3.

If the line impedance are well chosen in the three measurements, all results should match perfectly together and provide unique values for the model parameter. If it is not the case, some equations should suit better than others for model identification.

That is why the previous study on simplified model was useful in order to select the best line impedances, for identifying the model in the easiest way.

The proposed method necessitates thus the knowledge of the order of magnitude of the converter impedance in differential mode (Z3) and in common mode (Z1 and Z2). Usually, it is not a problem, and this is even simpler if the converter has an EMC input filter, which hides all the converter behaviour. Contrary to conventional methods [1] where this knowledge must be precise enough in order to provide accurate results, the presented method only needs to determine the order of magnitude. After identification, the model will then account for all stray elements inside the converter.

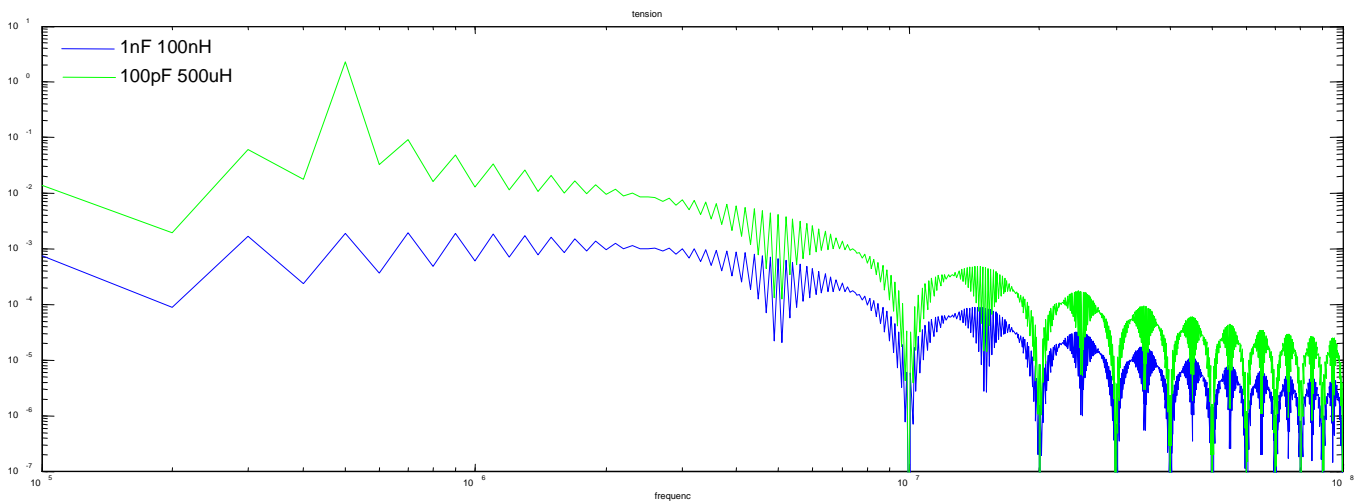


Figure 8. Two couples of values for LI and CI allowing a good difference for input current I1 on the whole frequency range. This provides a good identification.

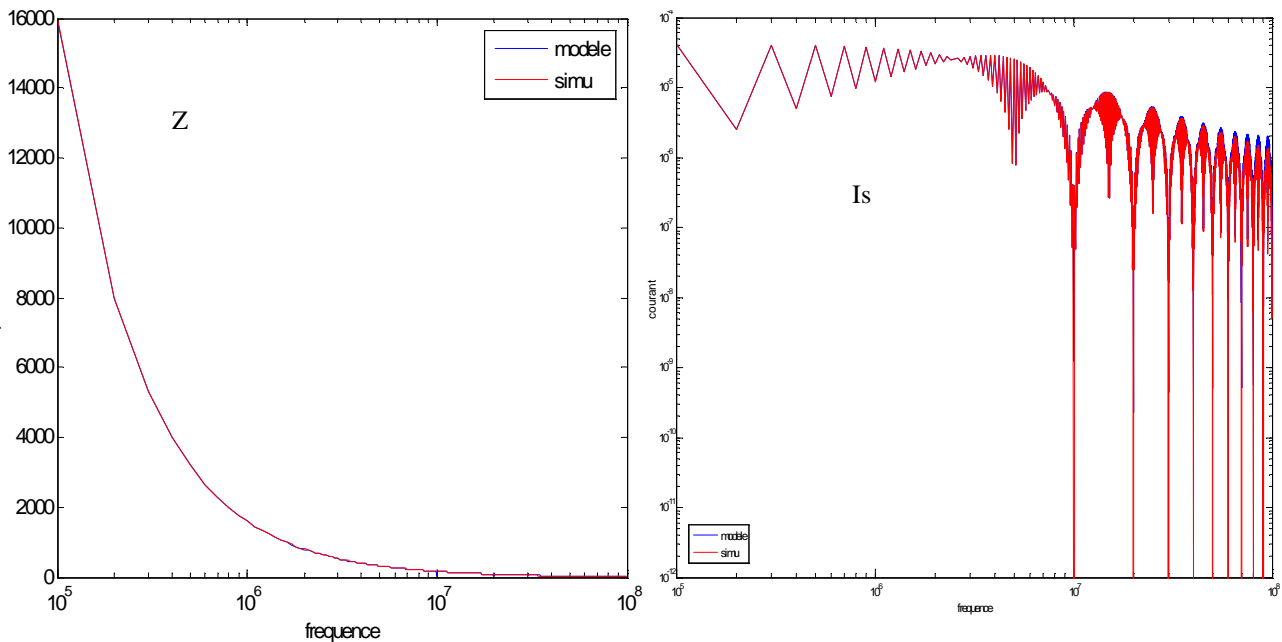


Figure 9. Result of the identification, in comparison with the expected values

6 Application to a Chopper Cell

The proposed method has been applied to a complete chopper, described in Figure 10. The conventional EMC model of this chopper, depicted in Figure 11, would replace the semiconductors with equivalent sources. However, depending on the sources position, different results may be obtained using the model, mainly in the high frequency range. This is illustrated in Figure 12, and is especially true if the converter layout leads to non symmetrical stray elements. In the results of Figure 12, the MOSFET voltage and current have been recorded, and injected in the circuit of Figure 11 to obtain the results (voltage across LISN). However a voltage source replaces the MOSFET, and the diode has disappeared (or may be replaced by its stray capacitor in the off state); this does not correspond to the actual switching behaviour of the converter, therefore, the results cannot be reproduced exactly. By using the proposed method, the converter will be represented by the equivalent scheme presented at the beginning of the paper (Figure 1). The parameter identification has been achieved by using three different simulations, for three different line impedances. Care has been taken to keep small time step, in order to reduce the simulation errors in the high frequency range. Fast Fourier Transform has been used to convert the time simulation results into the frequency domain.

After identification, the LISN voltage has been compared to the actual result of the time simulation, for a line impedance value **different from the ones used for the identification**.

The results are shown on Figure 13, and prove the validity and robustness of the proposed model.

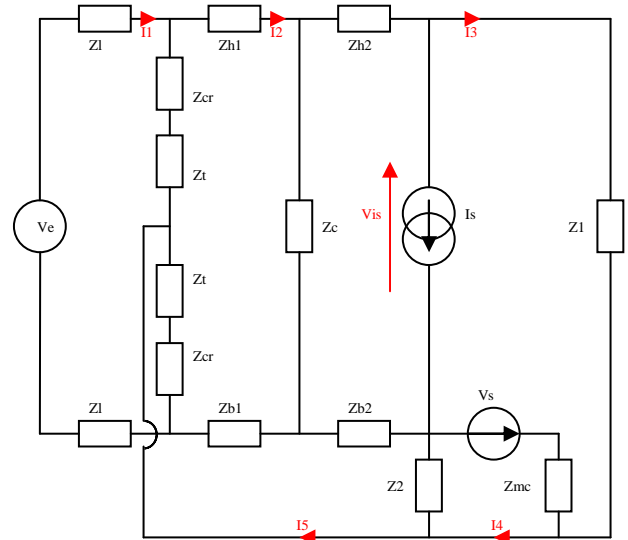


Figure 11. Equivalent circuit of the chopper of Figure 10, replacing the semiconductors by equivalent sources.

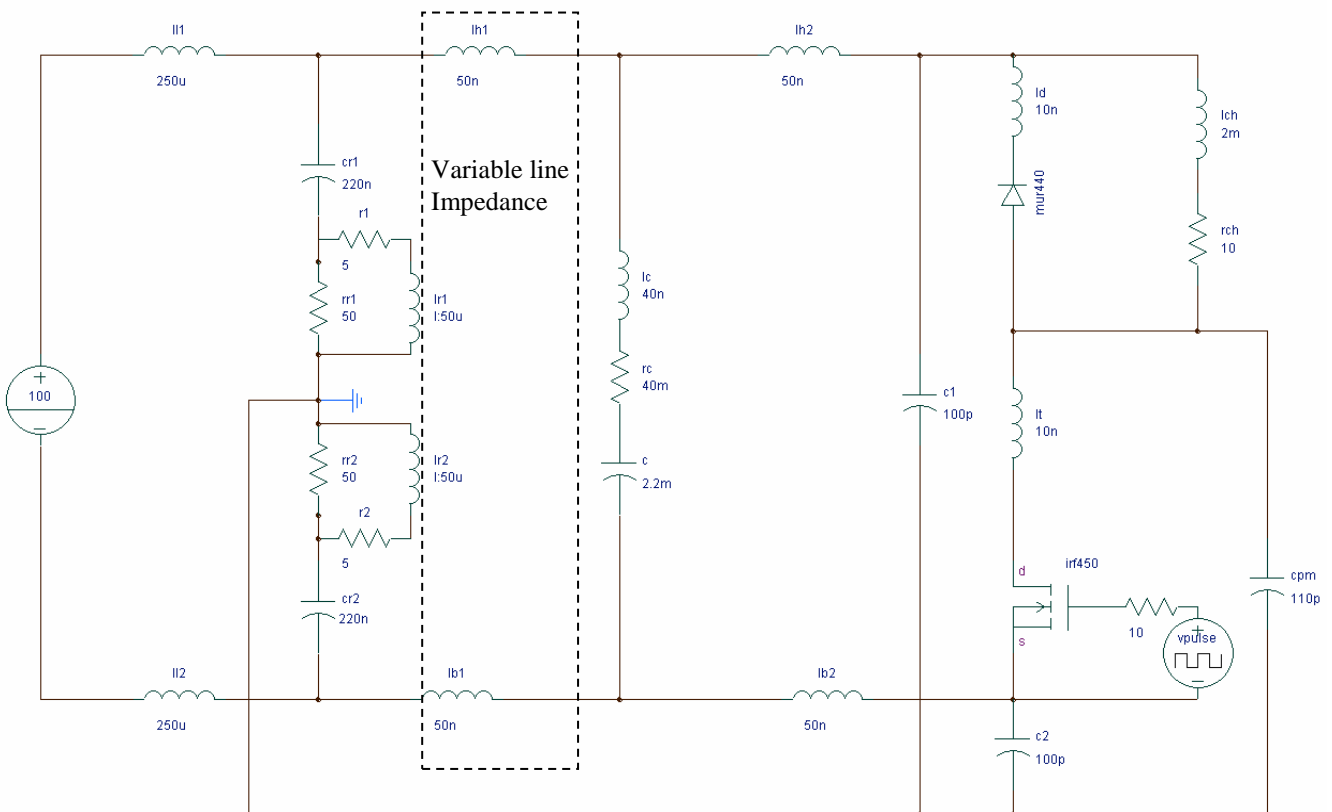


Figure 10. A chopper cell with stray elements and LISN.

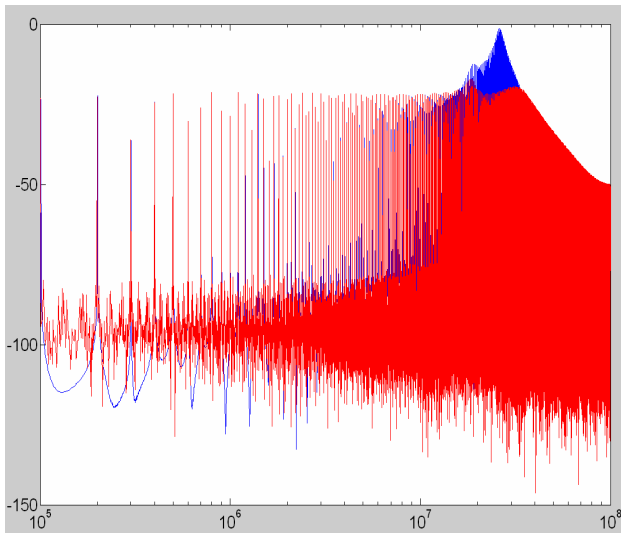


Figure 12. Comparison of LISN voltage obtained by the model, by modifying the source position.

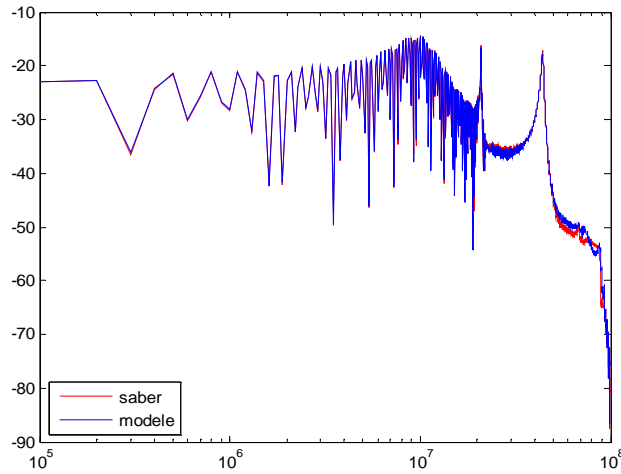


Figure 13. Comparison of the prediction identified using 500nH, 750nH and 1000nH and the simulation, for a 1500nH line impedance

7 Conclusion

A compact EMC model for a power electronics converter, based on a black box approach, has been proposed, as well as the identification method. The difficulties of model identification have been studied in a simplified case. The application to a complete chopper shows the ability of this model to generate the same disturbances as the actual converter, even for other line impedances than the ones used for identification.

The obtained model is compact and allows very quick simulations, even if several converters are to be handled. It should thus be a good method to forecast EMI in embedded networks.

8 References

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9 Glossary

EMC: ElectroMagnetic Compatibility
 EMI: ElectroMagnetic Interferences
 LISN: Line Impedance Stabilization Network