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"Black Box" EMC model for Power Electronics Converter

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Abstract -- The generalization of switched mode power conversion in embedded networks generates new problems at system level: the prediction of ElectroMagnetic Compatibility behaviour of the complete system. In order to forecast the conducted emissions in the power lines, compact models of the power converters are needed. This paper aims to propose a generic black box model for converters connected to an embedded network. The methodology for identifying the model parameters will be given, as well as the model validation.

Index Terms -- Power electronics, Electromagnetic compatibility, Reduced order systems, Parameter estimation.

I. 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. To save energy, 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 level, which must be forecasted accurately, in order to avoid disturbance of the complete system.

To quantify the EMC behaviour of an embedded network, on both conducted and radiated aspects, it is mandatory to determine the current flowing in the power lines, on a wide frequency range. The time simulation of a complete embedded 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 frequencies in the Fourier Transform. Even for a single converter, the task is not easy at all.

To overcome the drawback 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 inside it.

The model topology will be first presented, as well as the method proposed for parameters identification. A simplified application to differential mode only will be presented in section III, in order to focus on the main difficulties of the identification. Section IV will then illustrate the method on a complete chopper cell.

II. BLACK BOX EMC 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. Since the converter can be considered as an EMI (ElectroMagnetic Interferences) 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 Fig. 1. In comparison with other work [2-3], it accounts for all necessary parameters, without any redundancy or approximation.

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 voltages and currents for several operating conditions, obtained by varying line impedance, as illustrated in Fig. 2.

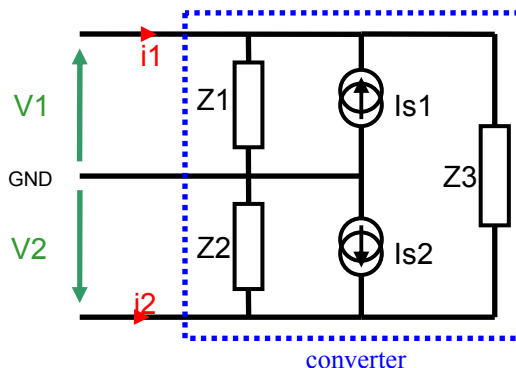


Fig. 1. Model of a converter

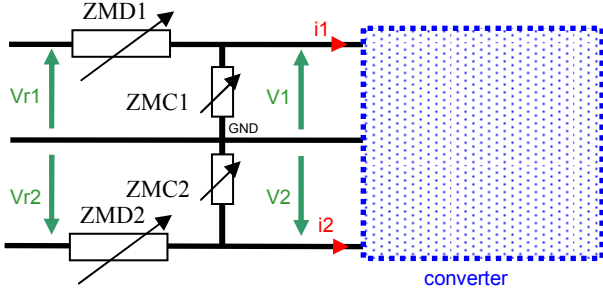


Fig. 2. Line impedance variation for parameters identification

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].

The values of V_1 , V_2 , I_1 , I_2 are linked to the parameters of the model I_{s1} , I_{s2} , Z_1 , Z_2 , Z_3 by the following equation:

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

$$\begin{pmatrix} Z_1 \cdot \frac{Z_2 + Z_3}{Z_1 + Z_2 + Z_3} \cdot I_{s1} + Z_1 \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3} \cdot I_{s2} \\ Z_1 \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3} \cdot I_{s1} + Z_2 \cdot \frac{Z_1 + Z_3}{Z_1 + Z_2 + Z_3} \cdot I_{s2} \end{pmatrix}$$

Each operating point is characterised by a set of measurements V_1 , V_2 , I_1 , I_2 , whatever the power line impedance. These measurement results allow obtaining a set of two equations (see (1)). To obtain the five parameters, it is therefore necessary to achieve three different measurements, for three different operating points. One equation is therefore redundant. After analysis, depending on the five chosen equations, several different expressions can be found for Z_1 , Z_2 , Z_3 , I_{s1} and I_{s2} . Four different expressions can be obtained for Z_1 , Z_2 , I_{s1} and I_{s2} , and only two for Z_3 . Numerically, the results must obviously be the same, but due to identification errors, some discrepancies may appear and will be illustrated in the following sections of the paper.

As mentioned before, in such inverse problems, there is strong risk of identification failure due to unavoidable measurement inaccuracies. Therefore, in a preliminary step, a simplified problem will be detailed: by removing the ground potential, the converter becomes a simple dipole, which can be represented by only two parameters (one impedance Z and one current source I_s).

III. SIMPLIFIED MODEL FOR DIFFERENTIAL MODE

For this preliminary study, we chose a simple chopper. This simplified case is especially interesting since the equivalent circuit can be easily identified by investigating the chopper topology: the impedance Z corresponds to the input capacitor, and the current source simply corresponds to the current in the power switch [5]. However, to avoid any switching modification when changing the line impedance, a decoupling capacitor has been taken into account, in parallel with the input capacitor.

Fig. 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. The variable impedance is composed of a C1-L1 series association.

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_1 , I_1) and (V_2 , I_2). Thus, the parameters Z and I_s can be expressed as follows:

$$I_s = \frac{V_1 \cdot I_2 - V_2 \cdot I_1}{V_2 - V_1} \quad (3)$$

$$Z = \frac{V_1 - V_2}{I_1 - I_2}$$

It is clear from these expressions that the determination can be effective only if the two operating conditions give different values to V_1 , V_2 and I_1 , I_2 .

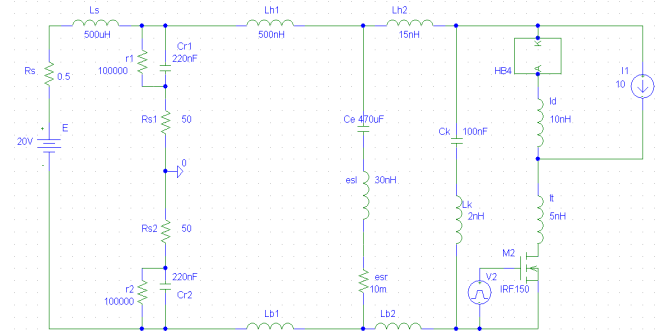
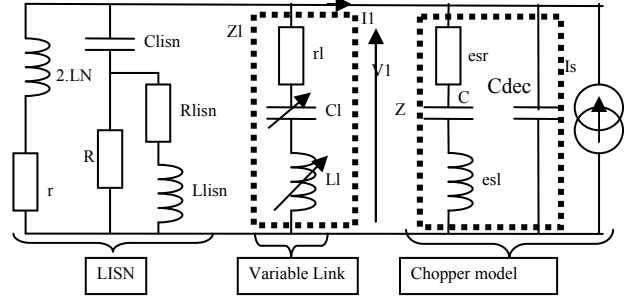


Fig. 3 : Top - Chopper model connected to a LISN, with a variable parallel impedance for parameter identification. Bottom - Pspice scheme for simulation

A sensibility study on the line impedance CI-LI variation has been carried out, using precise simulations in the time domain, with accurate models of layout and semiconductors (Fig. 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 Fig. 3. is simply a current divider.

After some simple computations, using the current divider, it appears that some criteria must be fulfilled in order to maximize accuracy during the identification process.

To reach different current values when varying the line impedance Zl:

- * the LISN impedance Z_r must not be negligible in comparison with the impedance Z to be identified.

- * the parallel association of Z_r and Z_l (line impedance) must not be negligible in comparison with Z

- * Z_l must not be too large in comparison with Z_r

To reach different voltage values when varying Zl:

- * The parallel association of Z_r and Z must not be negligible compared to Z_l

Therefore, the converter model is not really a black box, since the order of magnitude of the input impedance Z must be known. To maximize the identification accuracy, the preceding rules should be fulfilled.

The identification of the converter in differential mode has been carried out as follows:

- * V1, I1 measurement with no additional line impedance
- * V1, I1 measurement adding a Z_l line impedance composed of $C_l = 470\mu F$ and $L_l 20nH$, what fulfils the desired criteria.

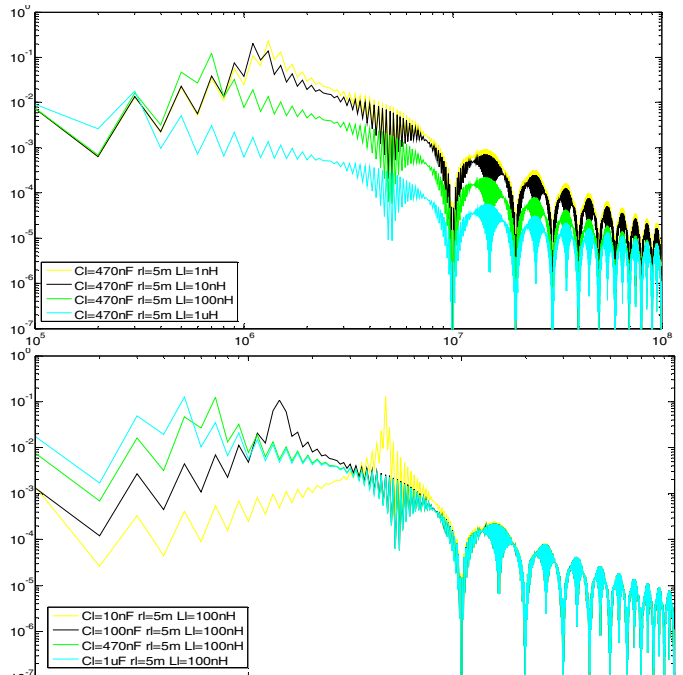


Fig.4. Sensibility study on input current (I_1): top variation of LI – Bottom variation of CI

The results for Z and I_s are plotted on Fig. 5, in comparison with the expected results (Z corresponds to the input capacitor, paralleled with the decoupling capacitor, I_s may be approximated to the current flowing through the Mosfet). The concordance is good until 10 MHz, but not perfect, especially for Z . Two explanations can be brought: first, the linear representation using the input impedance of the converter does not reflect exactly the converter behaviour, since it neglects the switches. This can explain the difference higher than 10 MHz. Second, especially at 10 MHz, there is a very poor accuracy in voltage measurement (see Fig. 4) that may explain identification errors.

Nevertheless, the global result on EMI emission is the only one we should care about: it is illustrated by the voltage across LISN (Fig. 6.). It shows that the model has been identified properly, since the correspondence is very good between the time simulation and the model prediction (in the case of no paralleled line impedance). Obviously, the good correspondence does not fully validate the model, since the results have been checked on a case used for identification. However, this section intended to validate the identification process, the sensibility study will be carried out on the full model, including common mode, in the following sections.

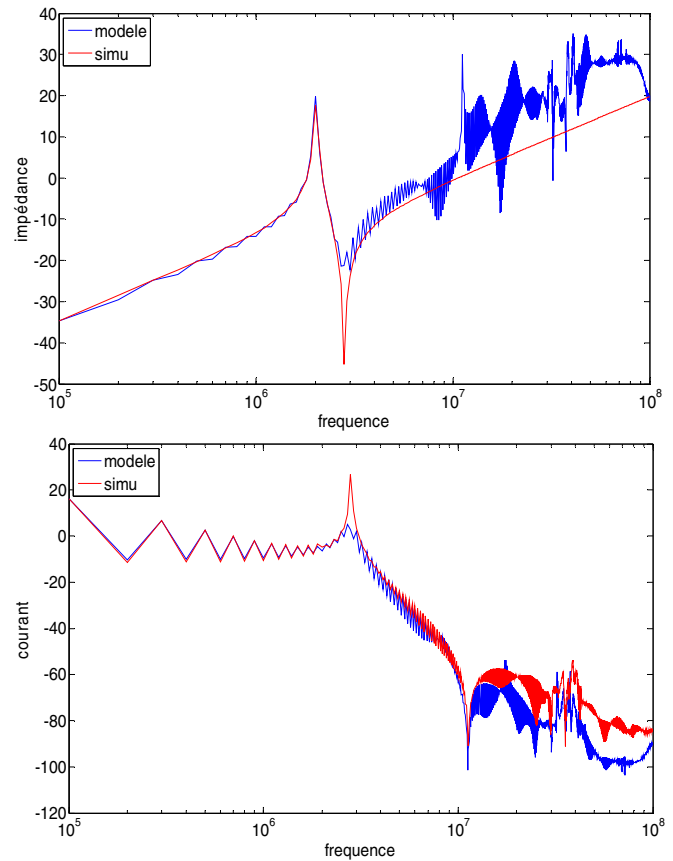


Fig.5. Result of model identification in comparison with expected results: top: Z , bottom I_s .

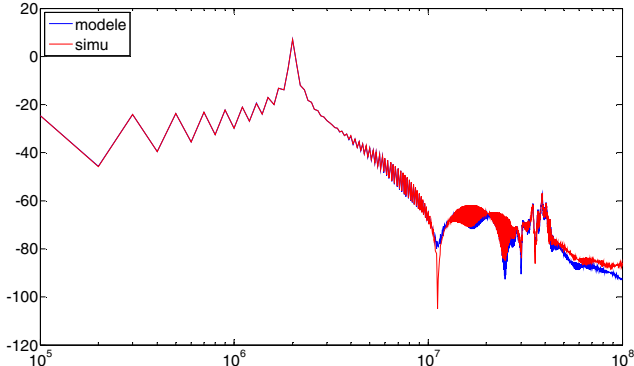


Fig.6. Prediction of LISN voltage [dB] in comparison with time simulation.

IV. COMPLETE MODEL INCLUDING COMMON MODE

A. Importance of Common Mode in the Model evaluation

The preceding section has just illustrated the identification method based on a pure differential approach. The complete model, presented in section II includes the ground potential. To show the big impact of the common mode current, the same identification in differential mode has been achieved, using power line current and voltage, with the ground connected to LISN, and capacitive propagation path included in the converter model (Fig. 7.). The obtained model composed of only one current source and one impedance cannot predict accurately any voltage across LISN, as illustrated in Fig. 8.

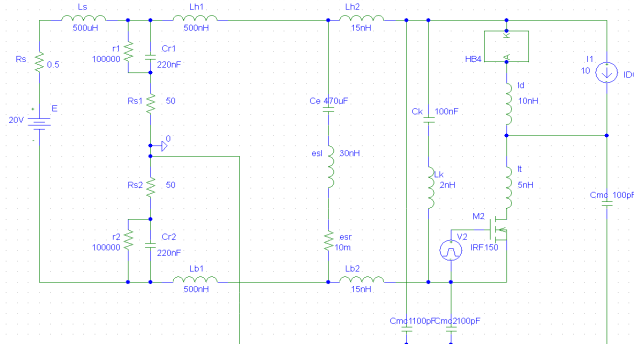


Fig.7. Simulation scheme of the converter including common mode propagation path.

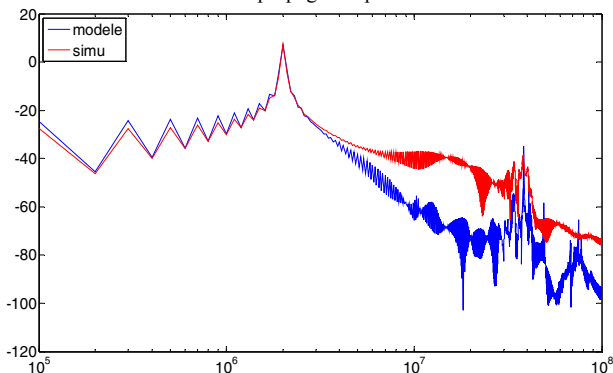


Fig.8. Prediction of a LISN voltage [dB] obtained with the simple model (identified with differential mode signals) in comparison with time simulation.

B. Complete Model Identification

As illustrated with the results of Fig. 8, the full model is necessary to account for the complete EMC behaviour of the converter. The model is composed of 3 impedances and 2 current sources, and necessitates 3 different operating conditions to be identified. To reach high accuracy, the same analysis as the one carried out in section III should be achieved. In this case, the line impedance has to be modified using both parallel and series impedances, in order to provide sufficient differences in the measured signals, between the three different operating points.

However, this may lead to difficult experimental setups, especially when adding series inductors, which should exhibit a good behaviour on a wide frequency range. Therefore, we chose the following procedure, in order to identify the model:

- * V1, V2, I1, I2 measurement using a direct connection between the source and the converter

- * Connection between plus wire and ground, and measurement of I1, V2, I2 (V1 = 0) (example in Fig. 9.)

- * Connection between minus wire and ground, and measurement of V1, I1, I2 (V2 = 0)

As mentioned in section II, different combinations of the six equations resulting from the 3 different operating points can be used. The global results, illustrated in Fig. 10. show the same behaviour, with however some discrepancies, due to identification inaccuracies. For instance, the use of a specific set of equations ("combi 5" in Fig. 10) is not the best one to obtain the good impedance. This combination does not use one equation provided by the operating point without short circuit, which corresponds to the "normal" behaviour of the converter. Consequently, the two corresponding equations must be kept in the identification process for better accuracy.

Since once again the main objective of the model is to obtain a good estimate of the EMI generation, the most important result is the one depicted in Fig. 11., where one voltage across the LISN, obtained using the model, has been plotted in comparison with the precise time simulation result. The accuracy is good, even if the model has been identified using very different operation points, using short circuits between power lines and ground, what does not bring the maximum accuracy on an identification point of view. Furthermore, if the model has been identified in such a large variation of power line impedance, it can be considered robust with respect to power line impedance change.

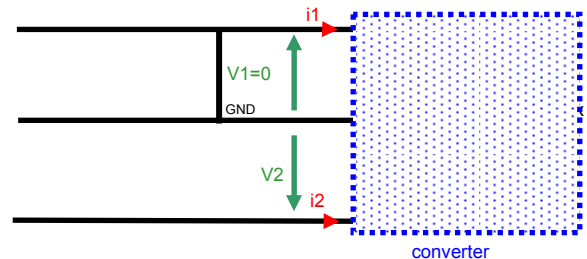


Fig. 9. Identification of the complete model: example with plus line and ground short circuited.

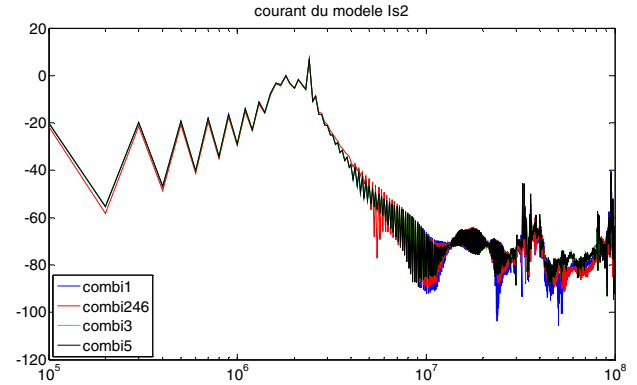
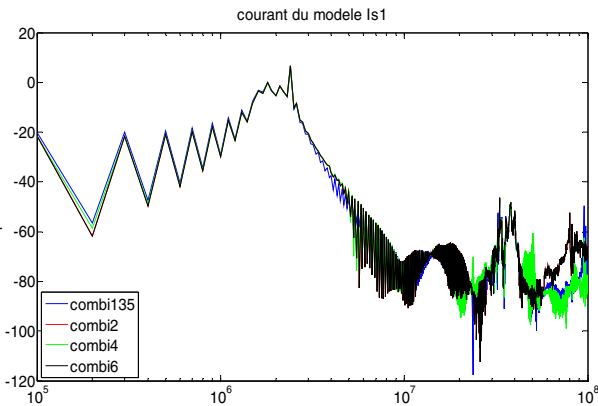
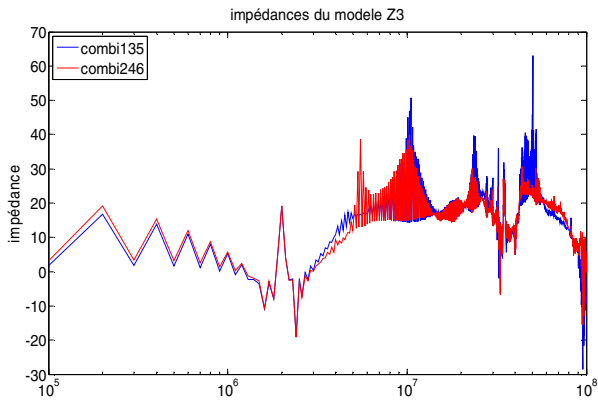
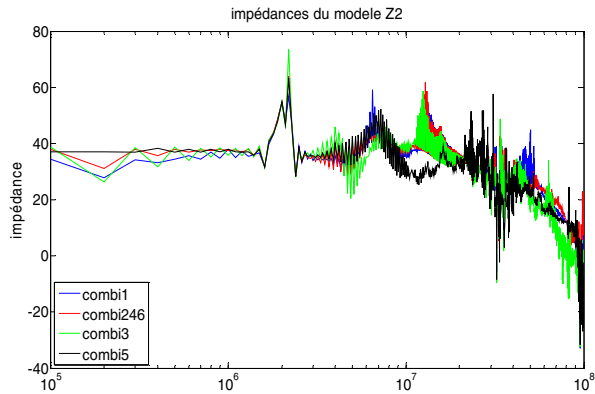
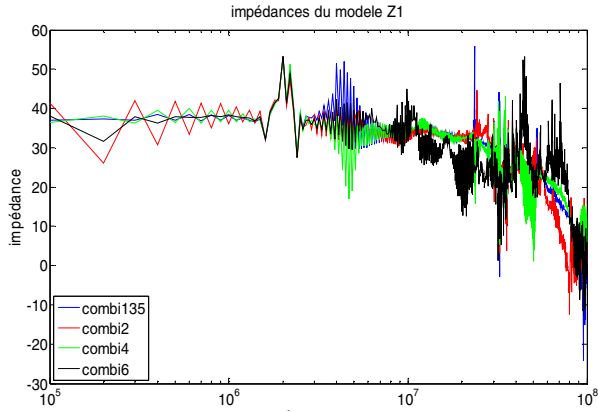


Fig. 10. Comparison between the different set of equations used for model identification on the model parameters Z1, Z2, Z3, Is1, Is2

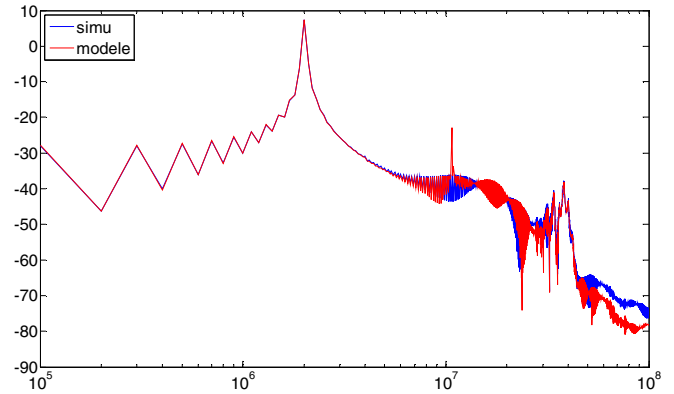


Fig. 11. Comparison between the model results and a precise time simulation on a LISN voltage

V. MODEL DISCUSSION

Another way of model validation, it to check if it can predict the EMI level in a different operating condition than the one used for identification. For this purpose, we simply disconnected the ground connection in Fig. 7. The LISN voltage should thus correspond to a pure Differential Mode perturbation what could also be predicted using the model presented in section II.

The comparison is illustrated in Fig. 12. It shows a quite good accuracy, despite a small shift in the 10MHz anti-resonance.

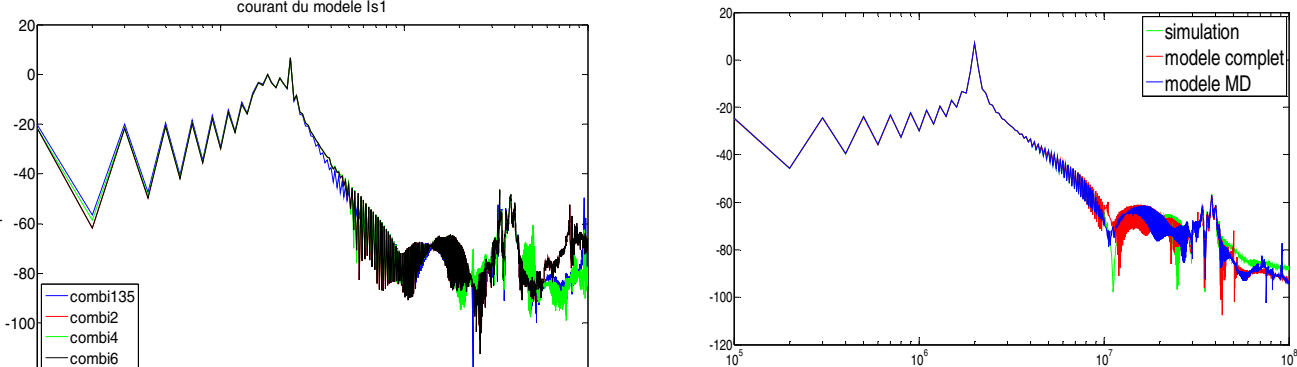


Fig. 12. Comparison of time simulation, DM model and complete model for ground disconnected.

VI. EXPERIMENTAL VALIDATION

The last validation will use experimental results. For this purpose, a 100W boost converter has been chosen. It is composed of an input electrolytic capacitor C_e , a Surface Mounted Device inductor L_e , a MOSFET and a Diode (Fig. 13). The input voltage is 14 V and output is 42 V. The switching frequency is roughly 100kHz. The power layout uses Insulated Metal Substrate (IMS). Stray capacitors are thus quite high, what impacts on common mode current emission.

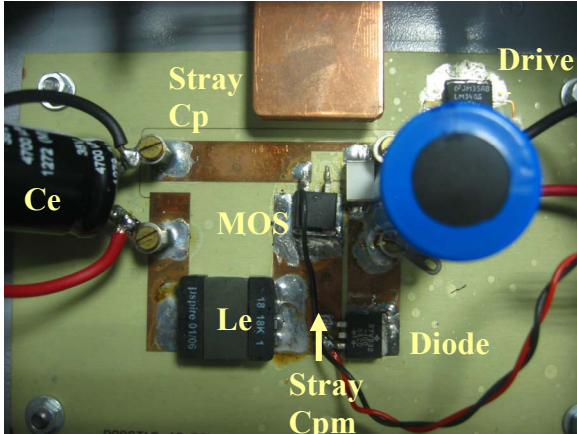


Fig. 13. Boost converter used for identification

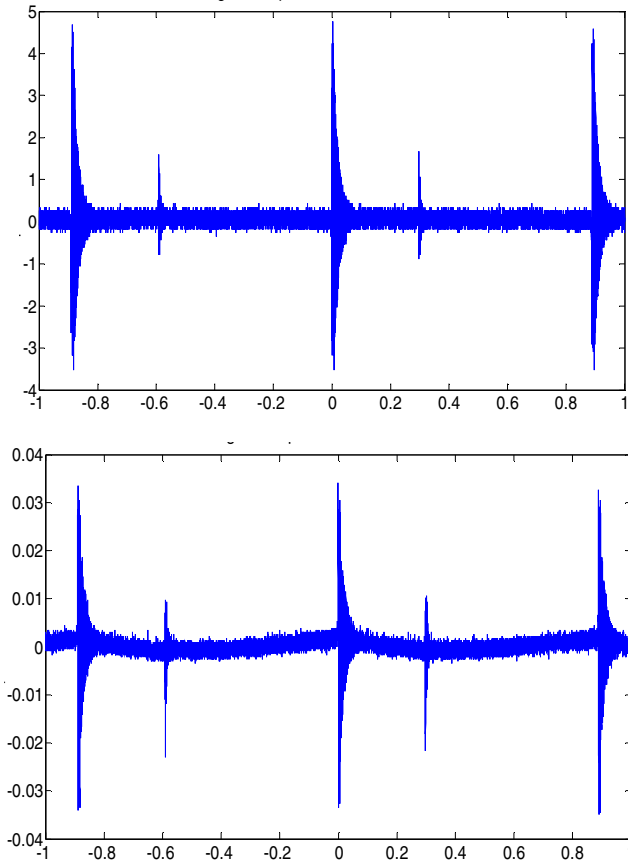


Fig. 14. Example of signal recording: voltage V_1 (top) and current I_1 (bottom). The DC values have been removed and time scale adjusted.

The converter is connected to a LISN using short wires and a copper plane, as described in EMC standards. Voltage and current probes have been used to record the V_1 , V_2 , I_1 , I_2 signals at converter input. A 4 channels oscilloscope has been used, using the maximum data points as possible with simultaneous acquisition: a sampling time of 200 ps has been reached. Some signals are illustrated in Fig. 14.

The method used for identification is the one presented in section IV, using short circuit to the ground. After recording the signals in the time domain, a Fast Fourier Transform has been achieved and the model identified. To be noted that it is not possible to use a spectrum analyzer since the recording of the four signals V_1 , V_2 , I_1 , I_2 must be synchronous, and the phase of the spectrum is also mandatory, and not provided by the spectrum analyzer.

Once identified, the model has been used to predict the LISN voltage, in comparison with the measured one. At this point, there is still some inaccuracy in the power wires impedance values. However, the global shape is quite good. Future work will have to impose a power line geometry, in order it can be easily identified. Additionally, some signal processing on the data acquisition may help in obtaining better results

VII. 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 the simplified case of a pure Differential Mode approach. In this case, the model can be reduced to a simple dipole. The application to a complete converter has been illustrated and a method proposed for identification, using simple short circuits between power lines and ground. After identification, the model shows a good ability to generate the same disturbances as the actual converter. It has been checked in other line impedance conditions (disconnecting the ground wire for example).

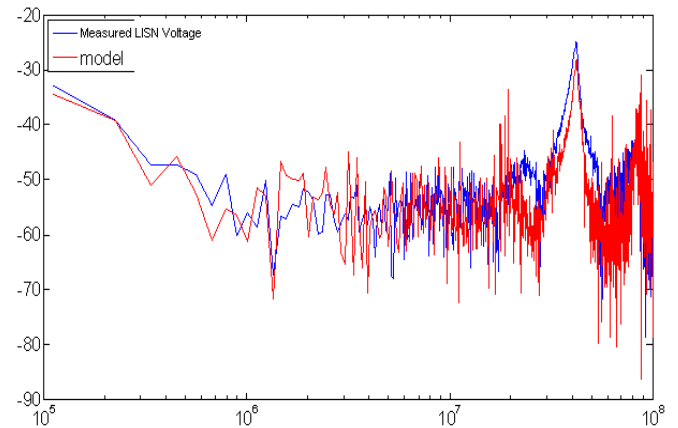


Fig. 15. LISN voltage obtained either using measurement or the model identified.

Last, the method has been applied to an experimental boost converter. Even if some improvement are still to be proposed, the method has shown a good potentiality for EMC study of power electronics converters, especially in the modern embedded networks.

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