Disturbances Generated by two Identical Converters Connected to a Line Impedance Stabilization Network

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Abstract **-** Electromagnetic conducted emissions are a phenomenon that is difficult to predict, particularly within a complex power grid which includes static converters, considered to be the origin of these disturbances. This work concerns the study of disturbances generated by two converters connected to a line impedance stabilization network (LISN) through two distinct connexions. The study is particularly focused on high frequency HF modeling of power converters with the aim of investigating the propagation of conducted disturbances (harmonics in particular) to the power grid using a LISN**.**

Keywords **-** Compatibility electromagnetic, static converters, modeling, conducted disturbances, LISN.

I. INTRODUCTION

EMC frequency based modeling offers a number of advantages. It allows for the direct visualization of the spectrum of conducted emissions. Furthermore, frequency domain modeling targets linearization of the system, thus making it easier and faster for analyzing disturbances; unlike time domain analysis which requires a longer simulation time and sometimes a large data storage capacity. Despite that, the frequency domain method needs prior theoretical study. In this study, we shall review a frequency domain modeling for an excitation source [1-3] applied to base commutation cells (DC/DC converter type).

This method aims at replacing the commutation cell by 2 generators representing power signals (voltage source, current source) which generate common and differential disturbances modes. In this paper, we shall review the behavior of the 5- parameters model when the two converters are connected to the same line impedance stabilization network (LISN) [4-7].

The use of passive components in static converters requires an understanding of the behavior of these components at high frequency to take them into consideration when studying the disturbances.

II. MEASUREMENTS ON PASSIVE COMPONENTS

A) Defining the S-parameters in A Port Network

This method is primarily used for coaxial cables. S_{ij} parameters are often employed in the area of radio frequencies and high frequencies. They permit, by analogy with transmission lines, to define a 2-port network in terms of transmission and reflection (Fig.1).

The underpinning principle of this method is as follows: a 2-port network is traversed by direct waves (incoming) and reverse waves (outgoing). In this 2-port network, it represents the *S* matrix (scattering) or the distribution matrix as shown in figure 1

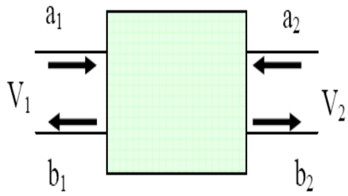

Fig.1. Conventions used for 2-port network (distribution parameters).

The matrix associating the outgoing waves b_1 and b_2 to the incident waves a_1 and a_2 takes the following form:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (1)$$

S_{ij} matrix parameters are referred to as the « *S* » parameters.

❖ *The physical meaning of the S* -parameters

The physical meaning of the *S*- parameters is as follows:

- Input reflection factor S_{11} which is calculated by:

$$S_{11} = \left[\frac{b_1}{a_1} \right]_{a_2=0} \quad (2)$$

- Transmission factor S_{21} which is calculated by:

$$S_{21} = \left[\frac{b_2}{a_1} \right]_{a_2=0} \quad (3)$$

- Output reflection coefficient S_{22}, which is calculated by:

$$S_{22} = \left[\frac{b_2}{a_2} \right]_{a_1=0} \quad (4)$$

- Reverse transmission coefficient of the line S_{12}, which is calculated by:

$$S_{12} = \left[\frac{b_1}{a_2} \right]_{a_1=0} \quad (5)$$

B) Network Analyzer

The network analyzer is the main measurement equipment for microwave frequencies. Contrary to what the name might suggest, it is not intended for telecom systems. in fact, it's used for determining the *s* parameters for active and passive 1-port or 2-port networks. it is also possible to characterize multi-port networks by multiplying the measurements in some particular conditions.

Network analyzers fall into two main categories: scalar network analyzers (SNA) which only allow the measurement of the magnitude of the *s* parameters, and vector network analyzers (VNA) which permit the measurement of both magnitude and phase. The first can only provide some of the information, but has the advantage of being inexpensive. Its working principle is based on a combination of couplers and receivers. The frequency sweep can be set to either linear or logarithmic scales.

Different measurements can be taken with this analyzer on passive components (resistance, inductance, and capacitance) to better understand their behavior over a wide frequency range.

The network analyzer (Fig.2) gives the measurement points and then by means of the Matlab software, the results can be visualized as curves.

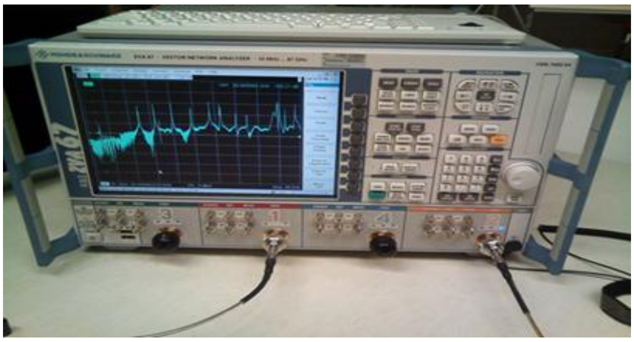

Fig. 2. Vector Network Analyzer (VNA).

To take a measurement using a network analyzer, we need to perform the following procedure:

- We set the frequencies (high or low) depending on our needs.
- Frequency sweep and input signal: we set the number of points, preferably to the maximum (1601) to obtain better results. Next, select the type of frequency sweep (linear or logarithmic). The logarithmic sweep is preferred. Finally, set the power, the maximum value being 10 dBm.
- Display selection: we select the type and number of paths and also the layout of the diagrams.
- Calibration: to prevent errors, a calibration of the measured components is necessary. There are two ports on the network analyzer (port 1 and port 2).
- The calibration is conducted in three steps:

- Port 1 (reflection mode) : after connecting the board to Port 1 in open circuit mode, we press the Open key (channel 1) of the VNA, and then after connecting the board to Port 1 in short-circuit mode, we press the short key channel 1. Next, we connect the board to port 1in a matched load of 50 Ω and press the load key (channel 1)
- Port 2 (reflection mode): after connecting the board to Port 2 in open circuit mode, we press the open key channel 2 of the VNA. Then, we connect the board to Port 2 in short-circuit mode and press the Short key (channel 2), and after connecting the

board to port 1 in matched load mode (50 Ω), we press the load key (channel 2).

- Port 1 and Port 2 (transmission mode): after connecting the board to Port 1 on one end and to Port 2 on the other at the same time in transmission mode, we press the key through Port 1-2.

The results are saved on a USB stick.

C) *Resistance measurement*

To measure resistance (Fig. 3) of an electrical component, the two connectors of an ohmmeter are connected to the terminals of the dipole and the measurement is read.

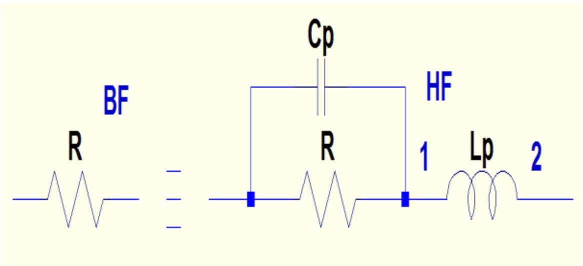

Fig. 3. Electrical diagram of a resistor at both high and low frequencies.

Measuring resistance with a network analyzer enables us to understand its actual variation at both low and high frequencies.

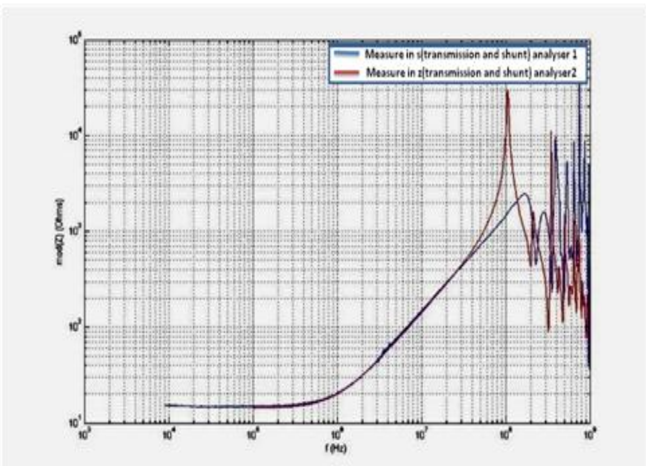

Fig. 4. Variation of a resistance with frequency

Figure 4 shows the variation of resistance with frequency. One can clearly see that in the 10 kHz-1 MHz range, resistance exhibits a normal behavior, but changes when the frequency exceeds 1 MHz, parasitic inductance affects the value of resistance and the inductive effect can clearly be seen. This changes when resonance frequency is attained at around 200 MHz; at this point parasitic capacitance influences resistance and one can observe the appearance and dominance of the capacitive effect.

As can be seen resonance frequency is different for the two measurements, for the *z* impedances or for the s-parameters; beyond that frequency, the behavior of resistance is disturbed due to the influence of unknown external factors at high frequency.

D) *Inductance Measurement*

A coil, also called a self-inductance, is generally made up of a conducting wire helically wound, forming a solenoid. When the coil is traversed by current, the magnetic field that is induced opposes the current that generated it (Lenz's law). The coil is characterized by its inductance *L*, defined as the ratio between the magnetic field and the current intensity. The unit is expressed in Henry (*H*).

At high frequency (> 300MHz) the space between one loop and another represents a parasitic capacitance C_p which may take significant proportions with respect to the desired inductive effect. The behavior of the coil may be represented by an ideal coil in parallel to an ideal capacitor in terms of reactance effects.

The electrical diagram is completed with a parallel resistor R_p, which reflects the magnetic circuit losses, and a resistor in series R_s, which reflects the wound electric wire's resistance (Fig.5).

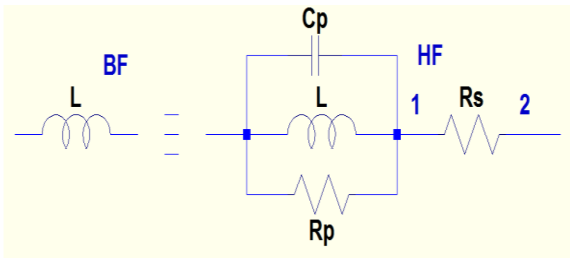

Fig. 5. Electrical diagram of an inductor at high and low frequency

Measuring the inductance with a network analyzer enables us to get an insight into the actual behavior of the inductor in relation to variation in frequency.

Figure 6 shows the behavior of the inductor in relation to frequency. One can clearly see that in the frequency range of 100 kHz - 2 MHz, the inductor exhibits a normal inductive behavior, but this changes when the frequency exceeds 2 MHz, which is the resonance frequency. Indeed, the parasitic capacitance seems to affect both the inductance and the capacitive effect. The capacitive effect changes when the frequency approaches 100 MHz where a repetitive shift between a capacitive and an inductive effect can be observed.

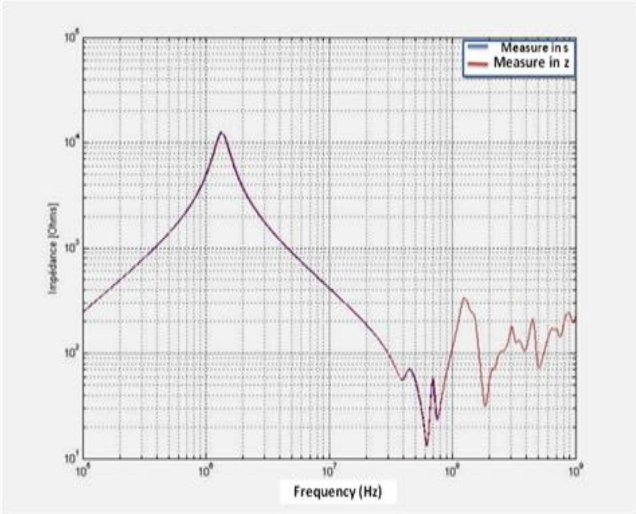

Fig. 6. Behaviour of an inductor as a function of frequency.

As one can see, the resonance frequency is different for the two measurements, i.e. *Z* or *S* due to the influence of unknown external factors at high frequency.

E) Capacitance Measurement

A capacitor (Fig. 7) is a component which can store electric energy. It is generally composed of two electrodes which are separated by an isolating layer (air or dielectric material). It is characterized by its capacitance, expressed in Farad. This is a simplification since some or all of the parasitic elements associated with its constituents have been ignored for low frequency, but not for high frequency:

- L_p : inductance of the conductors (armatures, connections).
- R_p : equivalent series resistance, representing all the losses in the components.

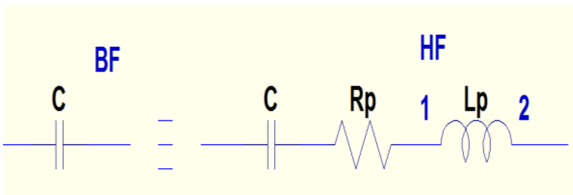

Fig. 7. Electrical diagram of a capacitor at low and high frequency

Measuring capacitance with a network analyzer (Fig. 8) enables us to better understand the actual behavior of the capacitor as a function of frequency.

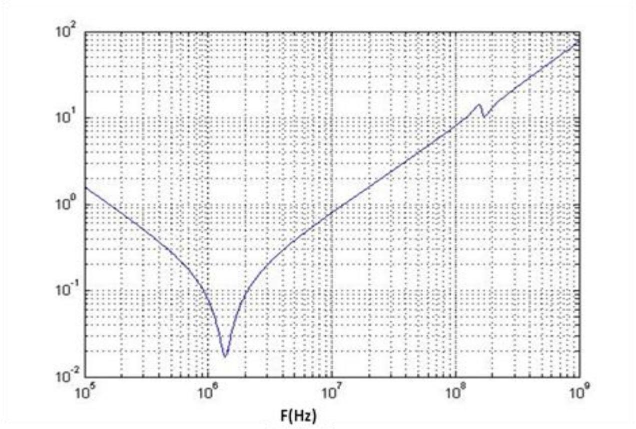

Fig. 8. Behaviour of a capacitor as a function of frequency.

Figure 8 shows the capacitive behavior of the capacitor as a function of frequency. One can see that from 100 kHz up to 2 MHz, the capacitor exhibits a normal capacitive behavior, but beyond that value, parasitic inductance affects inductance, and the inductive effect can clearly be seen. A repetitive shift between a capacitive effect and an inductive effect can be observed. The latter, starting from ~200 MHz shows a repetitive change between a capacitive effect and an inductive one.

III. ANALYSIS OF THE DISTURBANCES OF TWO IDENTICAL CONVERTERS

The two selected converters are identical (chopper series) and operate at the same commutation frequency. They are composed of a MOSFET IRFP240 transistor which commutates at a frequency of 10 kHz, and a 1N914 diode. The former is connected directly to the LISN whereas the latter is connected to the LISN via a shielded twisted cable. In the first case, the analysis is carried out at the same switching frequency while in the second, different switching frequencies are used for the two converters so as to see their behavior over a wide frequency range. Figure 9 illustrates the electrical diagram of the simulation [7-9].

To predict the LISN voltage, representative of conducted disturbances, is determined from the electrical diagram (Fig.10) made up of the models of the 2 converters. The 5 parameters of each converter comprise 3 impedances that allow for a representation of the propagation paths, and the 2 current sources representing the disturbances sources [7]. The connection is composed of coupled series inductors (L = 710 nH), a mutual inductance (M = 295 nH) and capacitor of 32 pF between the positive line and the negative one and 2 capacitors of 202 pF between the positive-GND and the negative-GND.

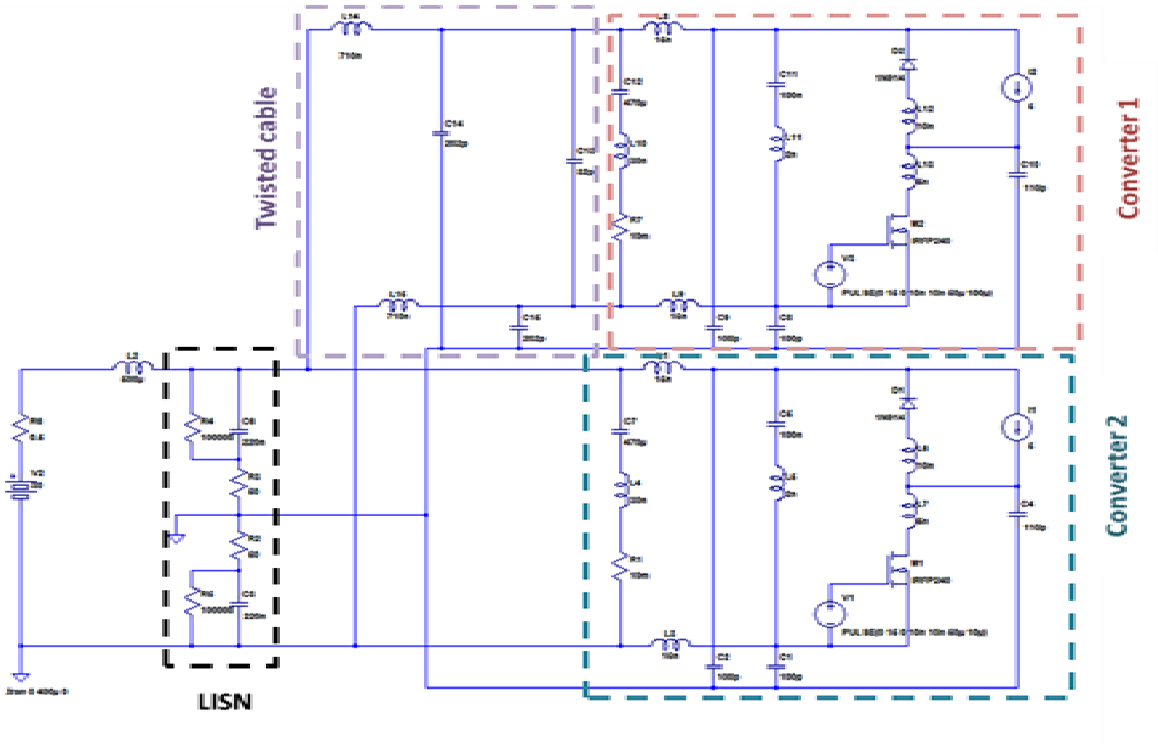

Fig. 9. Electrical diagram for the simulation of two converters by using Ltspice software.

This connection is a simplified representation of a twisted cable [7]. In figure 11, prediction of LISN voltage is consistent with the simulation, although some errors can be observed starting from 15 MHz Indeed, the network impacts the behavior of the converters and the interaction between these 2 converters is not well accounted for in this modeling. When the two converters are connected to the same network, the available propagation paths are more numerous and are not taken into account during the identification [7].

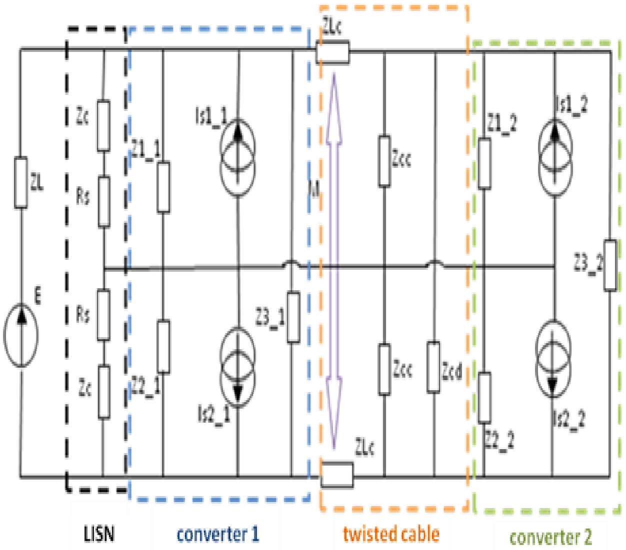

Fig. 10. Electrical equivalent diagram of two converters connected to a LISN

With : Z_{1_1}, Z_{2_1}, Z_{3_1}, Is_{1_1}, Is_{2_1} : the 5 parameters identifying the converter 1.

Z_{1_2}, Z_{2_2}, Z_{3_2}, Is_{1_2}, Is_{2_2} : the 5 parameters identifying converter 2.

Z_{LC}, Z_{CC}, Z_{Cd} : impedance modeling characterizing the twisted cable.

Z_{LC} and Z_{CC} : impedances in common mode.

Z_{Cd} : impedance in differential mode.

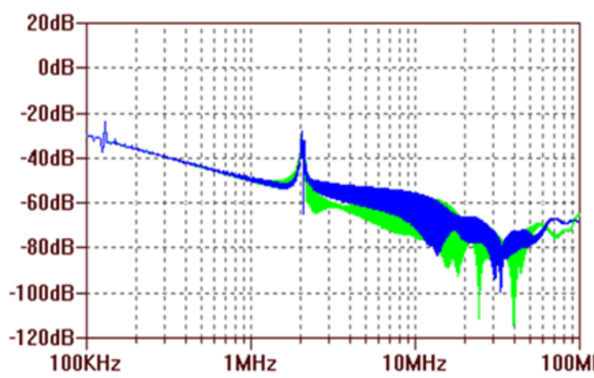

Fig. 11. Comparison between the simulated and the predicted voltages of the LISN by using Ltspice software.

A) Black Box Type Model

The presented model (Fig. 10) allows for a good prediction of conducted disturbances of a converter on a LISN, despite some limitations observed at high frequency. It permits the prediction of conducted disturbances emitted by the studied converter with respect to the EMC current standards. EMC filters may be added if necessary. However, the increased number of converters in the on-board network (Fig.12) may compel us to review the method used to predict conducted electromagnetic disturbances. Indeed, predicting the overall electromagnetic emissions of a system with the associated interaction seems to be inevitable.

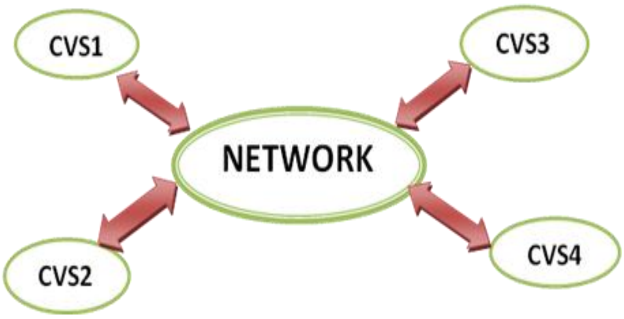

Fig.12. Simple diagram of network comprising 4 converters [11]

The EMC study of a converter on a LISN remains simple provided that the internal characteristics of the converter are fully or partially known. But this method becomes problematic when a number of converters are connected to the network. Moreover, an understanding of all the internal elements of the converters is required, making the study complex and laborious.

A black box model (Fig.13) does not require an understanding of the internal working of a converter [7-9].

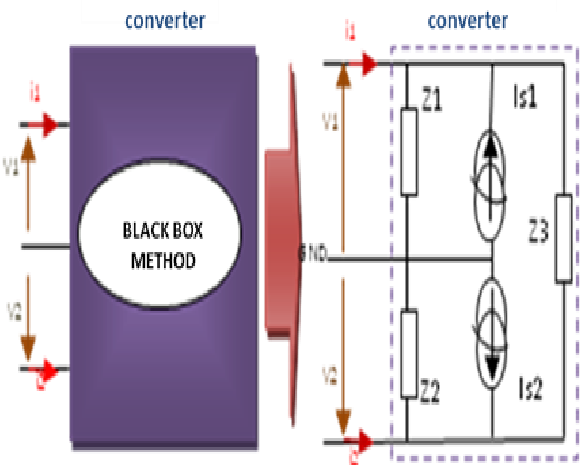

Fig. 13. A 5- Parameters Black Box Model [7, 10].

The aim of this work is to propose a simple but accurate EMC model of a converter to facilitate the overall study of a network with its converters.

This generic model is based on the principle of a two-port network that includes one input and one output (Fig.13). Any EMC analysis should take into account the ground potential (GND). As a result, an electronic power converter supplied by one phase or by a line with a DC voltage can be considered as a 2-port network. We can then consider the basic π electric diagram of a 2-port network (Fig. 14) whose lower input and output terminals are at the same potential, which in our case is the ground potential.
Since the converter can be considered as a generator of disturbances, some other sources should be included in the π model representation of the 2-port network. This allows turning the passive 2-port network representation to an active representation which corresponds to our converter (Fig. 14). We added current sources and as a result, the generic EMC model for the power converter is the one shown in Fig.13.

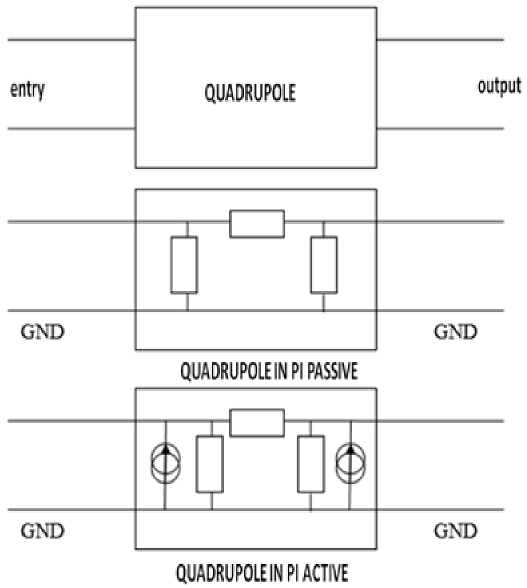

Fig. 14. Representation of a 2-port network model [7, 12].

B) Identification

The identification is conducted using 3 tests which yield 6 different combinations. It is necessary then to select the appropriate data set to be retained so as to obtain a model that provides great accuracy. A set of data concerning the short-circuit test is not retained since it concerns tests in a configuration that is seldom used and will only generates subsequent prediction errors.

The identification consists of determining the 3 impedances Z_1, Z_2 and Z_3, along with the 2 current sources I_1 and I_2 (Fig. 13) [7, 12]. The impedances of the model do not correspond to a simple set as for a capacitor, but reproduces the behavior of the converter with all its parasitic elements and not of single one. Even though impedances are more complex, this allows us to get closer to a behavioral model, and the same applies to the current sources. Once the model is identified [7, 11, 12], we need to model the connection so as to proceed subsequently to the prediction of the disturbances. Indeed, it is essential to show the connection and the network in order to perform the matrix calculation that gives us the prediction. The model (Fig.10) allows the correct prediction of the electromagnetic disturbances for a certain range of uses which are limited by the conditions of the 3 identification tests. As we have seen in the twisted cable example, the model was sensitive to important variations in the capacitance of the common mode connection, and to a lesser extent to the differential mode connection and inductors.

C) Simulation of a model with two converters operatin at two diffrent frequencies

The electrical diagram of the simulation is similar to the one in figure 9, except that the converter connected via a shielded twisted cable connection has a switching frequency which differs from that of the other converter by 100 kHz. The identification method used is the direct identification of the converter without a complex connection between the converter and the LISN [13-20]. The first selected frequencies were 100 and 110 kHz. On the other hand, the identification of the converters at those frequencies is correct with regard to the predictions in those identification conditions (Figs 15 and 16).

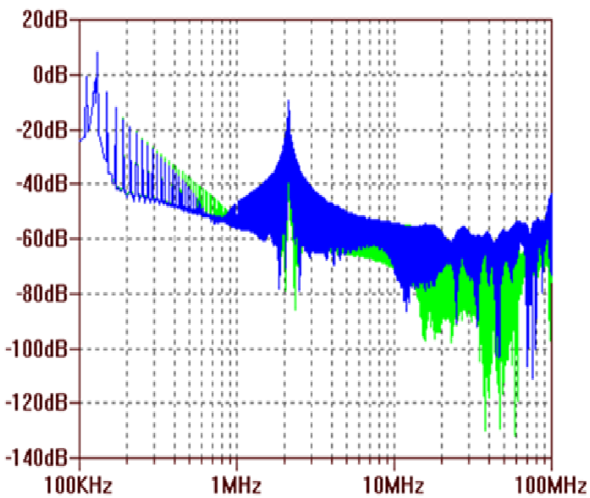

Fig.15. Comparison of the simulated LISN voltage and the predicted voltages based on the converter model at 100 kHz in the identification conditions by using Ltspice software

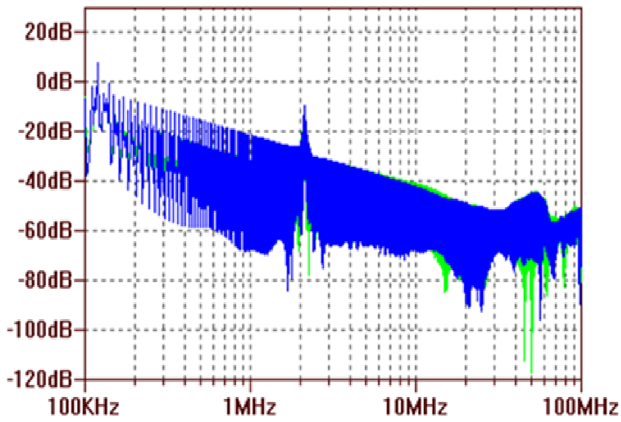

Fig. 16. Comparison of the LISN simulated and the predicted voltages based on the converter model at 110 kHz in the identification conditions by using LTspice software.

Predicting the LISN voltage for the overall system is not error free (Fig. 17). Although the modulation envelope seems to be correct, it is not so starting from 40 MHz, and the values at intermediate frequencies are generally wrong. This error in the intermediate frequencies stems from a calculation error during identification, because at those frequencies the magnitudes are very low and may cause divisions close to zero in the calculation. So, the sources of electromagnetic disturbances due to commutation at different frequencies are not easy to predict within a network.

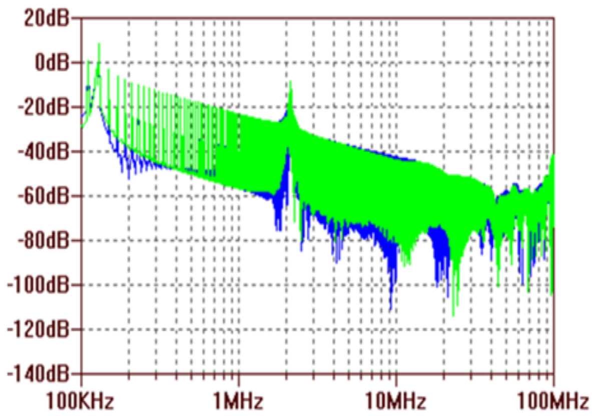

Fig.17. Comparison of the simulated and predicted LISN voltages based on the model of converters operating at different frequencies i.e., 100 kHz, 110 kHz by using LTspice software.

To correctly visualize the predictions while taking into account that the switching frequencies were different, we had to take a significant number of points during the FFT (smaller re-sampling periods) for more complex simulations keeping the same simulation step.

The first simulation represented only a slight discrepancy of 10% from the 100 kHz reference frequency of one of the converters. In case of a more significant discrepancy (Figs 18 and 19) the predictions of the LISN voltage become wrong on different frequency ranges. For the simulation with the converter operating at 100 kHz and the other at 10 kHz (Fig. 18), the error becomes significant starting from 4 MHz. In this case, we face the problem of the number calculation points, but in this time more errors are generated.

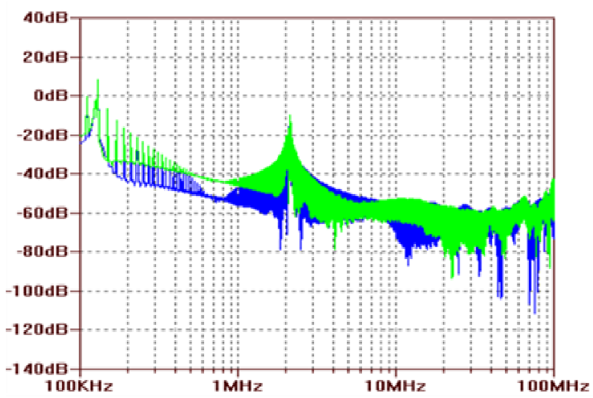

Fig. 18. Comparison of the simulated and predicted LISN voltages based on the model of converters operating at different frequencies (10 and 100 kHz) by using LTspice software.

When doubling the frequency, i.e., one converter operates at 100 kHz whereas the other operates at 200 kHz (Fig. 19), the prediction of the measured disturbances on the LISN is ~10 MHz by carrying out an identification of the converter operating at 200 kHz with a twisted cable type connection.

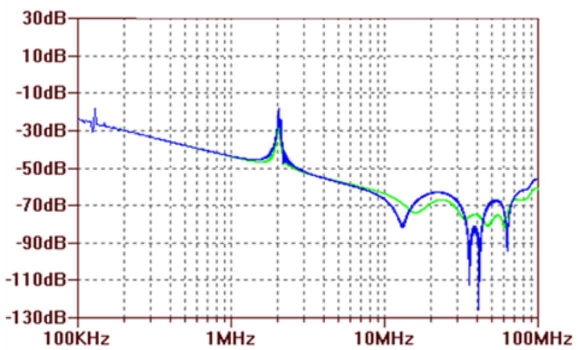

Fig. 19. Comparison of the simulated and predicted LISN voltages based on the model of converters operating at different frequencies (100, 200 kHz) by using LTspice software.

IV. CONCLUSION

This paper focuses on applying the model defined as a network with at least 2 converters. We have chosen to implement the model of 2 converters connected to a LISN through different connections, the network being composed of a LISN and connections. When 2 converters operate at the same commutation frequency, the models directly identified on the LISN allow obtaining a good prediction of disturbances within the LISN.

However, when the commutation frequencies are different, the prediction becomes less accurate at high frequency ranges. Indeed, the difference in frequency reveals the impact of the interaction between the two converters and between the network and the converters.

The complexity of the circuits to be simulated over 100 kHz- 100 MHz frequency range leads to small time steps and the simulation is as a result time consuming and costly in terms of IT resources. Furthermore, the simulations do not necessarily converge. Direct investigation at operating frequency is the best currently available solution but necessitates the development of models and an identification methodology.

The methods currently used require a thorough knowledge of the converters to model, i.e., the different internal parasitic elements of the converter. On the other hand, applying this model does not require knowledge of the network, to which the converter is connected, in order to determine the investigated values, in our case the LISN voltage. This voltage represents the EMC disturbances.

This method may enable us to visualize the main source of the EMC disturbances over the overall system and to determine the filter, which will be the subject of a subsequent study.

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