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EMI modeling method of AC-AC power converters

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Abstract: This paper presents a new model for simulation of Electromagnetic Interference (EMI) in power converters. Despite the fact that a Matrix Converter (MC) has been selected, such methodology can be applied to other converter topologies. The EMI model relies on a combination of time and frequency domain techniques in order to not only reduce the computational complexity but also to avoid convergence problems. Common Mode (CM) leakage current, which lays basically in A band (10 kHz to 150 kHz), is simulated and such results are compared with those obtained from the MC prototype showing a good concordance in terms of peak value.

Keywords: EMI, EMC, HF circuit modeling, Common Mode, Matrix Converter, conducted emissions

Classification: Electromagnetic compatibility (EMC)

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1 Introduction

The existing methods to calculate conducted EMI generated by power converters can be broadly classified in two categories: Field computation methods and equivalent circuit methods. The former rely on the solution of Maxwell's equations using either Finite Element Methods in time domain (FEM, FDTD, etc.) or Finite Elements Integral Methods (e.g. MoM) [1], whereas the equivalent circuit methods, using "source-path-victim" approaches, rely on time, frequency or combined time-frequency domain circuit analysis. Time domain approaches yield to high resolution and accuracy but at the expense of very large computational complexity, simulation time and possible convergence problems. Alternatively, frequency domain procedures [2, 3, 4], not only introduce a remarkable simplicity, in terms of modeling, but also they drastically reduce the computational effort required for its simulation. The problem for the last is the difficulty of accurately simulate the EMI sources. Combined methods [5], on which this paper is based, integrate the advantages of both time and frequency domain procedures. Following a primitive version of this approach, the analysis of a three phase Voltage Source Inverter (VSI) was presented in [3] introducing analytical, and therefore simplified, sources models to study the CM perturbations. In [4], not only the VSI itself is modeled but also the cabling, the motor and plane ground link were considered. The CM EMI disturbances, when using indirect MC fed wind turbines, are addressed in [6] obtaining just a single-phase model.

This work presents the EMI analysis of a direct MC drive, using a combined time-frequency approach to successfully address the study of CM disturbances, The EMI sources used in the proposed model, are obtained from accurate simulation of the whole three-phase drive system.

2 Combined Time-Frequency method

Modeling conducted EMI is essentially based on the solution, over the whole frequency range of interest of an equivalent circuit. In our case the equivalent circuit for CM disturbances is illustrated in Fig. 1.

Since this work is focused on modeling CM disturbances, EMI sources are due to fast voltage changes between certain points of the converter, i.e., large dv/dt, causing leakage currents through parasitic capacitive couplings. In the simulation stage, voltages at such points are obtained from a Matlab-Simulink model. A long term simulation (several periods) low sampling frequency is performed, obtaining voltage values at the points of interest. Such voltages present square commutation shapes, and, in case of a discrete simulation, are

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recorded in an array of samples for each of the voltages. In order to get a more accurate sources model, the rise and fall commutations times (typically 1 μs) must be considered yielding a better approach up to 1 MHz. As regards the EMI A band, it is enough to substitute the square shapes (sharp commutation) by a ramp commutation. The Fast Fourier Transform (FFT) of the above described synthesized waveform will be used as a frequency dependant source to supply the equivalent circuit. Notice that in the matrix converter the commutation times may change depending on the voltage step in each commutation. Notice also, that the modeling at higher frequencies (B band) requires more precise models of the transients and is out of the scope of this paper.

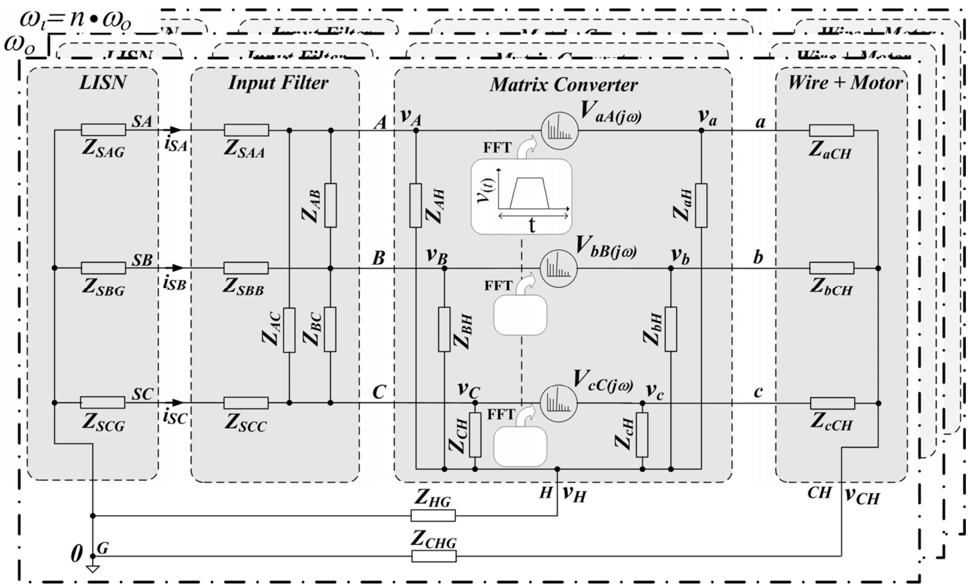

Fig. 1. Combined time-frequency model.

The wave-shapes in experimental tests were measured directly on the prototype at the same points having fast dv/dt. In the case of a matrix converter, the points suffering fast dv/dt changes are the output phases. So the sources to be considered are three sources between output and input phases.

In a second stage, the equivalent circuit is drawn, including the impedances of real components, connected according to the prototype topology, plus the parasitic impedances involved in the CM current leakage. Notice that for CM simulation, we must consider one impedance between each node pair, including ground as a node. In our study case, the impedances were obtained from several measurements performed with an impedance analyzer (Fluke PM6306), which allows impedance measurements up to 1 MHz. Finally, each impedance $Z(\omega)$, will be represented by an array of module – phase values along the frequency range.

Finally, the simulation is performed in frequency domain by solving Kirchhoff laws in the equivalent circuit for each particular frequency ω_i. The entire

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procedure is illustrated in Fig. 1 and can be formulated as:

$$i_{(\omega_i)} = \frac{v_{(\omega_i)}}{Z_{(\omega_i)}} \quad (1)$$

Notice that the dimensions of arrays $v_{(\omega_i)}$ and $Z_{(\omega_i)}$ must be equal.

3 Plant description

The described method has been applied to obtain the common mode leakage current $i_{CM} = i_{HG} + i_{CHG}$ of an MC drive, which schematic is shown in Fig. 2 (a). The system setup used for the model validation is formed, at the supply side, by an isolation transformer plus a Line Impedance Stabilization Network (LISN), an input low pass filter and the MC itself (matrix of switches). At the load side, we have the cabling and the motor.

In this work the LISN has been used just to obtain standard and repeatable test conditions. The equivalent circuit of the LISN has been modeled as three lumped impedances placed between each of the input phases of the MC filter and ground. These impedances are identified in Fig. 1 as Z_{SAG}, Z_{SBG} and Z_{SCG}.

The MC has a low pass input filter consisting of an LC circuit with a parallel damping resistor as show in Fig. 2 (a). The filter has been modeled as two lumped impedances per phase:

1) The serial impedances Z_{SAA}, Z_{SBB} and Z_{SCC}, which account for the set R_f, L_f and the respective High Frequency (HF) parasitic impedances.

2) Parallel impedances that appear between phases, which are due to C_f capacitors Z_{AB}, Z_{BC} and Z_{AC}.

The MC employed in this work is an all silicon solution which packs all the bidirectional switches in a single power module, hence reducing the possible parasitic inductances that could appear because of wiring. The characteristic impedances of the power module have been measured for each individual phase, as Fig. 2 (b) illustrates. Impedances Z_{AH} and Z_{aH}, connected by dashed lines, represent the parasitic elements that appear between the power module input/output terminals and ground (mainly the heat sink). Therefore, the power module has been modeled just as three EMI sources without any additional impedance.

The cabling and the load is another path through which EMI disturbances can flow to ground. In this work the load was a Permanent Magnet Synchronous Machine (PMSM). For proper EMI modeling, the power transmission cables, the internal motor coupling path and ground cable were characterized.

In Fig. 2 (c), Z_{wireA} and Z_{ParA} represent the cable parasitic impedances, Z_{La} is the impedance of the motor and Z_{CM} is the coupling impedance between motor winding and ground motor frame [7]. Nevertheless, since the wires in the experimental setup were short, the motor and its connections to the MC were simplified to single impedance for each phase Z_{aCH}, Z_{bCH} and

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Z_{cCH} plus ground impedance Z_{CHG} as it is shown in Fig. 1. Impedances Z_{HG} and Z_{CHG}, represent the coupling impedances between heat sink and ground plane and motor stator and its ground connection respectively as indicated in Fig. 2 (a).

The disturbance sources for the CM model are placed at the points where fast changes of voltage (dv/dt) occur, usually between each one of the output phase pairs a-b, b-c and c-a. This configuration requires modeling the whole semiconductor module, hence increasing the complexity of the model since all the impedances between phases and the state of each bidirectional switch must be necessary known. However, this paper proposes the treatment of the MC module as a multi-source generator that implies a wide simplification of the model. Three voltage sources between input and output phases (v_{aA}, v_{bB} and v_{cC}) allow modeling the MC semiconductor module without knowing the internal IGBT impedances. Fig. 1 shows the equivalent circuit model of the proposed MC. Applying Kirchhoff's law to such equivalent circuit it is derived the system equations (2). The simulation simply consists on solving (2), obtaining the node voltages. Leakage currents for each frequency are then easily obtained applying (1).

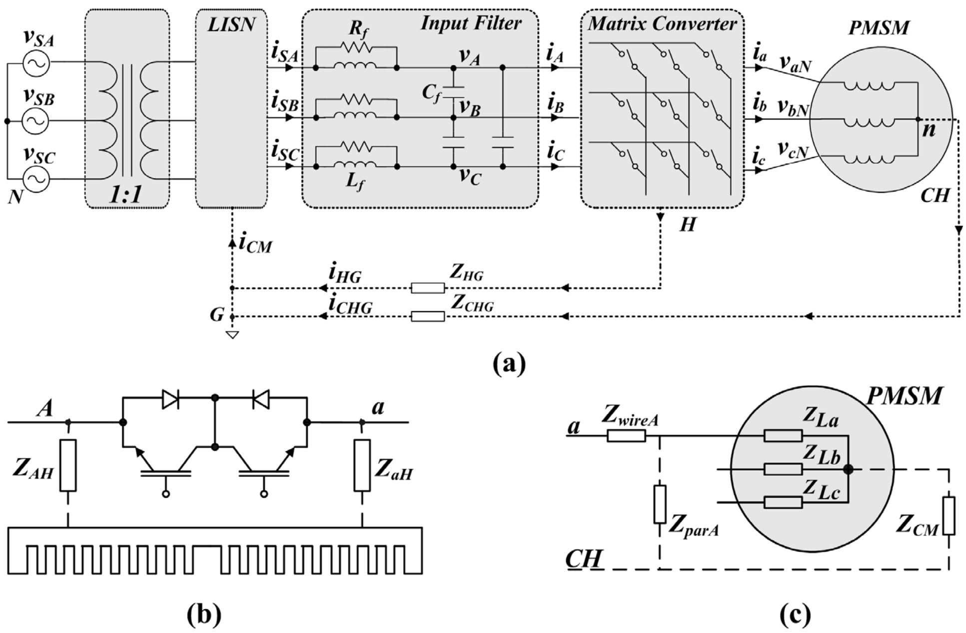

Fig. 2. Plant description. (a) Experimental rig and CM leakage current paths. (b) Characteristic impedances of the power module. (c) Parasitic impedances of the connection cable and load.

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$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ v_{aA} \\ v_{bB} \\ v_{cC} \end{bmatrix} = \begin{bmatrix} Y_{11} & \left(\frac{1}{Z_{aH}} + \frac{1}{Z_{aCH}}\right) & \frac{-1}{Z_{AB}} & 0 & -\left(\frac{1}{Z_{aH}} + \frac{1}{Z_{AH}}\right) & \frac{-1}{Z_{AC}} & 0 & \frac{-1}{Z_{aCH}} \\ \frac{-1}{Z_{AB}} & 0 & Y_{32} & \left(\frac{1}{Z_{bH}} + \frac{1}{Z_{bCH}}\right) & -\left(\frac{1}{Z_{AH}} + \frac{1}{Z_{bH}}\right) & \frac{-1}{Z_{BC}} & 0 & \frac{-1}{Z_{bCH}} \\ \frac{1}{Z_{AH}} & \frac{1}{Z_{bH}} & \frac{1}{Z_{BH}} & \frac{1}{Z_{bH}} & Y_{53} & \frac{1}{Z_{CH}} & \frac{1}{Z_{cH}} & 0 \\ \frac{1}{Z_{AC}} & 0 & \frac{1}{Z_{BC}} & 0 & \left(\frac{1}{Z_{CH}} + \frac{1}{Z_{cH}}\right) & Y_{64} & -\left(\frac{1}{Z_{cH}} + \frac{1}{Z_{cCH}}\right) & \frac{1}{Z_{cCH}} \\ 0 & \frac{1}{Z_{aCH}} & 0 & \frac{1}{Z_{bCH}} & 0 & 0 & \frac{1}{Z_{cCH}} & Y_{85} \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \end{bmatrix} \bullet \begin{bmatrix} v_A \\ v_a \\ v_B \\ v_b \\ v_H \\ v_C \\ v_c \\ v_{CH} \end{bmatrix} \quad (2)$$

Where

$$Y_{11} = \left(\frac{1}{(Z_{SAG} + Z_{SAA})} + \frac{1}{Z_{AC}} + \frac{1}{Z_{AB}} + \frac{1}{Z_{AH}}\right)$$

$$Y_{32} = \left(\frac{1}{(Z_{SBG} + Z_{SBB})} + \frac{1}{Z_{BC}} + \frac{1}{Z_{BH}} + \frac{1}{Z_{AB}}\right)$$

$$Y_{53} = -\left(\frac{1}{Z_{HG}} + \frac{1}{Z_{AH}} + \frac{1}{Z_{aH}} + \frac{1}{Z_{BH}} + \frac{1}{Z_{bH}} + \frac{1}{Z_{cH}} + \frac{1}{Z_{CH}}\right)$$

$$Y_{64} = -\left(\frac{1}{(Z_{SCG} + Z_{SCC})} + \frac{1}{Z_{AC}} + \frac{1}{Z_{BC}} + \frac{1}{Z_{CH}}\right)$$

$$Y_{85} = -\left(\frac{1}{Z_{aCH}} + \frac{1}{Z_{bCH}} + \frac{1}{Z_{cCH}} + \frac{1}{Z_{CHG}}\right)$$

Notice that the upper five rows are the Kirchhoff's nodal equations and the last three rows are the voltages relations.

4 Experimental results

In order to validate the proposed EMI model, simulations have been carried out supplying the model with voltages sources containing the waveform data captured between each input/output terminals (v_{aA}, v_{bB} and v_{cC}) from the experimental setup shown in Fig. 2 (a). The leakage current (I_{CM}) obtained from this simulation has been compared to the one directly measured from the experimental MC prototype and are shown in Fig. 3. The CM EMI current was measured using a HF current probe (Röhde & Schwarz *ESH 2-Z1*).

Since this work is concerned with the CM currents which are predominant in the range of 9 kHz to 150 kHz when power converters are used, results within this range of frequencies are presented.

It should be noted that both spectrums accurately matches validating the proposed EMI model for MCs. The divergence between both spectrums

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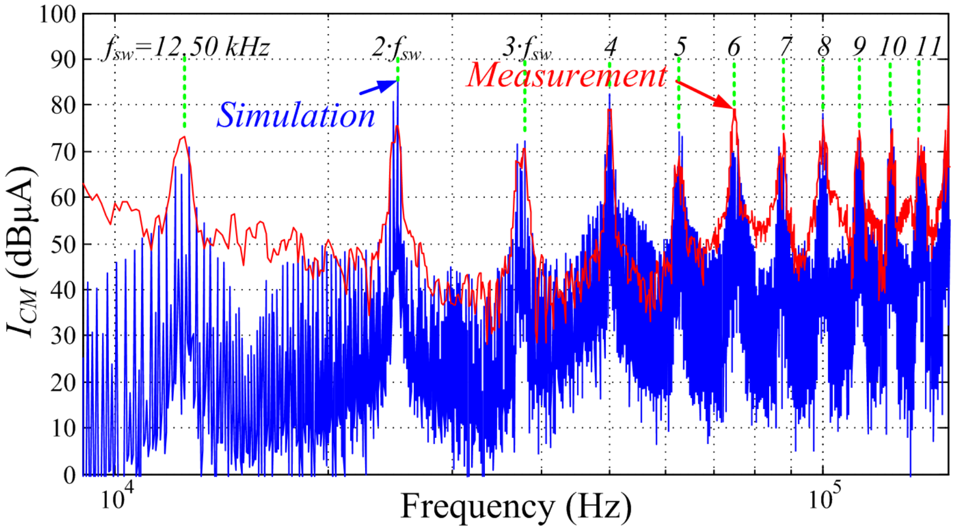

Fig. 3. Common mode current I_{CM} spectrum frame.

has been shown to be less than 6 dB which is an acceptable margin usually attributed to the uncertainty of the measurement procedure. As expected in any commutated power converter, the main leakage frequency components appear at the PWM frequency (f_{sw}) and its harmonics. Due to the varying nature of both, the duty cycle and amplitude of the PWM pattern, the spectrum shape spreads along the whole frequency range.

5 Conclusion

A combined time-frequency simulation method that allows an accurate calculation of the A band CM EMI produced by direct MCs has been presented in this paper. The method, which requires a low computational complexity, has been validated comparing the peak values in the spectrum of both, simulated and experimentally measured CM currents flowing through the ground path. The results have shown a maximum divergence between peak values of 6 dB, which can be considered acceptable for a first approach model. Better approximation can be obtained if the simulation results are passed through a filter equal to the input filter of EMI receiver.

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