A Full PEEC Modeling of EMI Filter Inductors in Frequency Domain

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Abstract — In this paper, we present the performance of the 3D Partial Element Equivalent Circuit–Boundary Integral Method (PEEC-BIM) coupled model of toroidal inductors used typically in EMI filter applications. The presence of magnetic materials is modeled by replacing the surface of magnetic regions with equivalent distributions of fictitious currents. It is shown that the influence of the magnetic core on the impedance and the stray field of EMI filter inductors can be explained in detail by PEEC-BIM simulation results. The developed PEEC-BIM approach is verified by both 3D FEM simulations and near-field measurements. Regarding the computational complexity, the suggested PEEC-BIM method applied to toroidal inductors demonstrates to have good performance. The reduction of the calculation time by a factor of 5 compared to a corresponding FEM simulation enables the simulation of the entire EMI filter.

I. INTRODUCTION

Power electronic systems typically require an input filter to meet the electromagnetic compatibility (EMC) standards. The prediction of the electromagnetic (EM) behavior prior to hardware prototyping is a critical design step to reduce the development time. It was shown that both self parasitic and mutual EM coupling effects have influence on the filter attenuation characteristic and must be taken into account [1]. The Partial Element Equivalent Circuit (PEEC) method has proven to be an efficient approach for solving the circuit-field problems e.g. for PCB layouts, EMI filters etc. [2]. Accordingly, the presented research is focused on developing a 3D PEEC tool for EMI filter design. The first step towards this tool is the verification of the 3D PEEC model of filter inductors performed in this paper.

II. STATE-OF-ART

The PEEC method is derived from the integral formulation of Maxwell's equations. In comparison to the differential field solvers like the Finite Element Method (FEM), the PEEC method does not require to mesh air volume but just the conducting, dielectric and/or magnetic regions. This reduces significantly its computational complexity. Furthermore, the PEEC method leads to an equivalent electric circuit problem that can be easily interfaced to any circuit solver e.g. SPICE. On the other hand, the main difficulty for the PEEC modeling approach is the presence of non-linear magnetic materials like ferromagnetic cores used in many EMI filter applications. Regarding EMI noise prediction, the major limitation is the modeling of the stray field of passive filter components [3]. Namely, a clear understanding of the stray field generated by toroidal inductors is still missing and the corresponding PEEC models have been only approximatively developed. In [4], the PEEC modeling of the stray field of common-mode (CM) toroidal inductors was performed under the assumption that the magnetic core does not change the direction of magnetic field lines and that the influence of the core is described by the effective permeability μ_{eff}, which was considered to depend only on the geometry of the core and coil. In [5], the authors ignored the presence of the core assuming that it has insignificant influence on the magnetic coupling. In this paper, the coupled PEEC and Boundary Integral (PEEC-BIM) method introduced in [6] is used to model the stray field of magnetic inductors with more accuracy, which also enables an evaluation of the previously mentioned approximations.

III. PEEC-BIM METHOD FOR EMI FILTER INDUCTORS

The theory behind the PEEC-BIM model was introduced and verified for a toroidal inductor impedance in [6]. The magnetic core is modeled as a linear material defined by its permeability $\mu_r(f)$. In this paper, two main aspects are investigated: a) PEEC modeling of differential-mode (DM) inductors and of single-phase CM inductors including the CM and DM impedances (Fig. 1) and b) PEEC modeling of the mutual coupling between an inductor and a pick-up coil. The specification of the inductors used in the PEEC simulation is given in Table I. The frequency range of interest is from 150 kHz to 30 MHz defined by the EMC standards for HF conducted emission.

TABLE I
MODELED DM AND CM INDUCTORS

Inductor	Core	Windings (wire diameter)
CM_1	Vacuumschmelze (VAC), VITROPERM 500F, W380 [7]	2x7 turns (1.4mm)
CM_2	Air (plastic), W380 core dimensions	2x7 turns (1.4mm)
DM_1	Micrometals, iron-powder, T94-26 [8]	22-turns uniform winding (1.4mm)

A. *Impedance: PEEC Simulations vs. Measurements*

For the sake of brevity, only the calculated and measured impedances of the CM Inductor CM_1 are presented in Fig. 1.

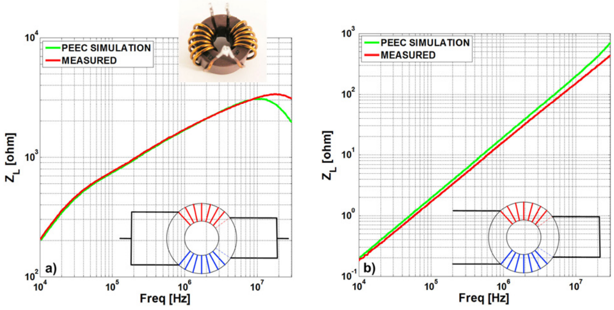

Fig. 1. The PEEC simulation vs. measurements of inductor CM_1: a) common-mode impedance b) differential-mode impedance.

For better results above the resonant frequency more accurate measurements of the permeability $\mu_r(f)$ are needed which will be carried out in the course of future research.

B. EM Coupling: PEEC Simulation vs. Measurements

For modeling and calculation of magnetic coupling, the DM winding configuration of a single-phase CM inductor (i.e. leakage inductance, Fig. 1b) is observed. The test set-up for the field measurements consists of a power amplifier impressing a sinusoidal source signal at the terminals of the inductor and a pick-up coil to verify the magnetic flux density by measuring the induced voltage using a high precision oscilloscope. The single-layer pick-up coil is built of 15 turns (copper wire diameter 0.2 mm) on a cylindrical coil former (diameter 8 mm). To investigate the influence of the magnetic core on the stray field, the injected current, I_{in}, the input voltage, V_{in}, and the induced sensor voltage, V_{ind} are measured for both inductors CM_1 and CM_2. In Fig. 2, the comparison between the PEEC-BIM simulation and the measurements at e.g. $f = 77$ kHz is presented and shows excellent agreement between the simulated and measured values.

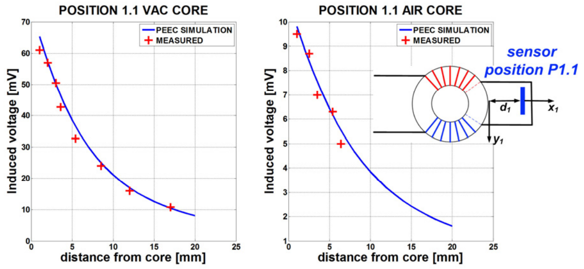

Fig. 2. The PEEC simulation vs. measurements of the induced voltage for the sensor position P1.1 ($f = 77$ kHz, $I_{in} = 600$ mA): a) VAC W380 core b) air (or plastic) W380 core.

Following the same methodology as the authors in [4], i.e. tracking the ratio V_{ind} / V_{in}, the influence of a magnetic core on the stray field could not be directly evaluated. Therefore, the simulation of magnetic field lines is performed in the following section.

C. Stray Field of a Toridal Inductor

The PEEC-BIM and a corresponding Maxwell3D Finite Element (v13.0) simulation of the near magneto-static field were performed at different directions and distances from the inductor. The developed PEEC-BIM simulation provides an explanation of the EM behavior of inductors: the major core contribution to the magnetic stray field can be ascribed to the magnetic surface currents forming loops around the core [6]. The strength of these currents is higher on the parts of core covered with the windings, and they are proportional to the core permeability. It is demonstrated that in the case of a lower number of turns, the stray field lines are modified due to the presence of the core especially near the parts which are not covered with the coil. The influence of the magnetic core decreases if the core is fully covered with windings and additionally diminishes with distance (Fig. 3). Consequently, the analysis shows that neglecting the presence of the core is not a comprehensive approach and that at least a modification of the factor μ_{eff} is required [4]. Keeping a constant flux, i.e. V_{in} constant as in [4], implies that the ratio V_{ind}/V_{in} is not changed due to the presence of the core but that clearly a higher current is required for the air core inductor in order to maintain V_{in} constant. The calculation of the factor μ_{eff} is not straight-forward and it cannot be easily determined in advance which emphasizes the advantage of the suggested PEEC-BIM approach, i.e. the possibility to directly calculate the EM behavior of the filter inductors.

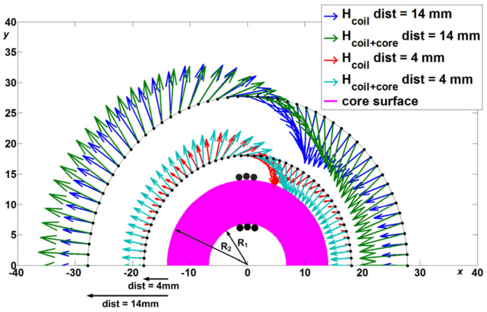

Fig. 3. Direction of the magnetic field lines at the distance of 4 mm and 14 mm from the core surface in the xy-plane ($z = 0$) for highly permeable core ($\mu_r = 35\,000$) and air core.

IV. PEEC-BIM SIMULATION PERFORMANCE

The mesh of the magnetic surface in φ-, θ- and z-directions (n_φ, n_θ, n_z) determines the computational complexity of the implemented PEEC-BIM method [6]. The simulations were performed on standard PCs with a 64-bit Win OS, and a CPU clock frequency of 3GHz. Obtaining similar accuracy of magnetostatic field results, the simulation of a single-phase CM inductor based on the PEEC-BIM method is approximately 5 times faster than the corresponding FEM simulation in Ansoft Maxwell3D v13.0 (≈ 4 min vs. 20 min). The PEEC-BIM simulation of the impedance $Z_{CM(DM)}(f)$ in $N_f = 200$ frequency points takes approximately 5 min, which can be divided into 4 min for the pre-calculation of matrix elements and 1 min for the calculation over the frequency range.

V. REFERENCES

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