An Extension of PEEC Method for Magnetic Materials Modeling in Frequency Domain

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Abstract— In this paper, a novel extension of the Partial Element Equivalent Circuit (PEEC) method for modeling magnetic components in the frequency domain is presented. The electromagnetic problem is solved by replacing the magnetized object with a fictitious magnetic current distribution in free space. The derived PEEC model is verified on the example of a magnetic toroidal inductor by experimental impedance measurements. Methods of applying the PEEC modeling approach for other magnetic geometries are analyzed.

I. INTRODUCTION

As electronic devices must comply with electromagnetic compatibility (EMC) standards, a comprehensive knowledge of their high frequency electromagnetic (EM) behavior in advance to final design decisions is of great importance. The Partial Element Equivalent Circuit (PEEC) approach is a method well-suited for numerical simulation of EM field problems concerning electrical circuits such as EMI filters, power converters, printed circuit boards, etc. The PEEC method is based on the integral formulation of Maxwell's equations and their interpretation in terms of partial circuit elements. It can be used to model comprehensive EM effects i.e. skin and proximity effects in both time and frequency domains, with significantly less computational effort than the Finite Element Method (FEM). So far several extensions were added to the standard PEEC method e.g. modeling in the presence of dielectrics and a PEEC solver for non-orthogonal geometries [1]-[2]. However, PEEC models of standard magnetic components are missing as there is a difficulty to apply the PEEC approach in the presence of magnetic materials. Therefore, further extensions to the PEEC method have to be determined to enable EM modeling of complex power systems consisting of standard magnetic circuit components like inductors, transformers, etc. In this paper, the geometry of interest is a coil wrapped around a toroidal core with a rectangular cross section.

II. PEEC AND MAGNETIC MATERIALS

In the presence of magnetic materials, a proper modification of the electric field integral equation based on Maxwell's theory is required to keep the PEEC equation system suitable for a circuit description. The change of the EM field due to magnetic materials can be assigned to a distribution of bounded magnetic currents and/or charges in free space of permeability μ_0. For linear homogeneous magnetic materials, the magnetic volume has no contribution to the total EM field and only the magnetic surface needs to be modeled. Typically used magnetic cores like powder, ferrite, and amorphous cores, are characterized by their permeability coefficient μ_r which is defined as a function of magnetic field strength and frequency. To model the main flux within a core, a correlation between surface magnetic quantities and the electric sources has to be defined. For a circular magnetic path, i.e. toroidal, we define it by the boundary element (BE) method applied at the interface of the magnetic medium. Accordingly, the standard PEEC system matrix [3] is modified by three matrices L_M, α_{MM} and λ_{MI} (1) defining the PEEC model of toroidal magnetic inductors,

$$\begin{bmatrix} -A & -(R+j\varpi L) & j\varpi L_M \\ (j\varpi P^{-1}+Y_L) & -A^T & 0 \\ 0 & \lambda_{MI} & \alpha_{MM} \end{bmatrix} \begin{bmatrix} V \\ I \\ I_M \end{bmatrix} = \begin{bmatrix} V_S \\ I_S \\ 0 \end{bmatrix} \tag{1}$$

where the unknowns I, V and I_M are respectively the winding currents, the potentials of PEEC nodes and the magnetic surface currents. The calculation of the new additional parameters is described in the full paper. Comparing to the approach in [4], (1) is also valid for non-conductive magnetic materials. PEEC modeling of other magnetic geometries via the magnetic current approach is analyzed in the full paper.

III. EXPERIMENTAL MEASUREMENTS

The results for a Magnetics T94-26, 22 turns inductor are presented in Fig. 1. In the full paper, core losses are included by using a complex permeability. To verify the PEEC modeling approach several other cores and coil arrangements are examined and modeled in the whole frequency range in order to show the agreement with measurements up to higher frequencies.

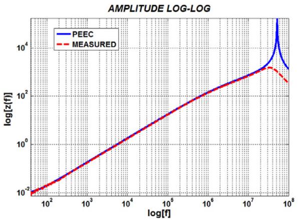

Fig. 1. Comparison of the PEEC modelling impedance and measurement result for an inductor Magnetics T94-26 core, 22 turns, neglecting losses in core at high frequencies.

IV. REFERENCES

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