Finite element models for studying the capacitive behaviour of wound components

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Finite element models of increasing accuracy are proposed for the study of the capacitive behaviour of wound magnetic components. Simple models, which are based on the classical assumption of a decoupling between electric and magnetic fields, are first described. Formulations which enable such a coupling are then presented. The models are tested on various coreless inductors, made of round conductors or copper sheets. The results are discussed and compared with experimental data measured with an impedance analyzer.

***Index Terms*—Computational electromagnetics, Finite element analysis, Electromagnetic compatibility, Engineering education**

I. Introduction

OVER the last years, our transportation system has been subject to an important electrification in order to benefit from the flexibility of the electrical energy. A critical issue consists in reducing the weight and volume of the electrical equipments as much as possible, regardless of the application (automotive, railway, aeronautic or space). For instance, modern power electronics converters embedded in such systems work with high switching frequencies (up to several MHz), in order to reduce their volume and mass. This gives rise to frequency effects which are not correctly represented by classical models. In particular, the wound magnetic components in the converters show a capacitive behaviour (*e.g.* resonances due to parasitic capacitances) which cannot be neglected at the considered frequencies, for electromagnetic compatibility issues for instance.

Such a problem has already been addressed in the literature. In [1], a review of available analytical models for the computation of the capacitances of wound components is proposed. A Finite Element (FE) approach is also described in [2], for multiwinding transformers. These works propose static models, which is equivalent to neglect the coupling between electric and magnetic (EM) fields, a common assumption among the power electronics scientific community.

In this paper, various FE models of increasing accuracy are implemented, which progressively enable a coupling between EM fields. The objective is to discuss the validity of the common hypothesis of EM decoupling, by considering the frequency and the components characteristic lengths as parameters. Experimental evidence, obtained using an Agilent4294A impedance analyzer, is also provided in order to support the discussion. The models will be tested on single winding coreless inductors, made of round conductors or copper sheets.

II. Formulations

The implemented FE models are presented in Fig. 1. The objective is to generate impedance curves (module and phase) which will be compared with measurements in section III.

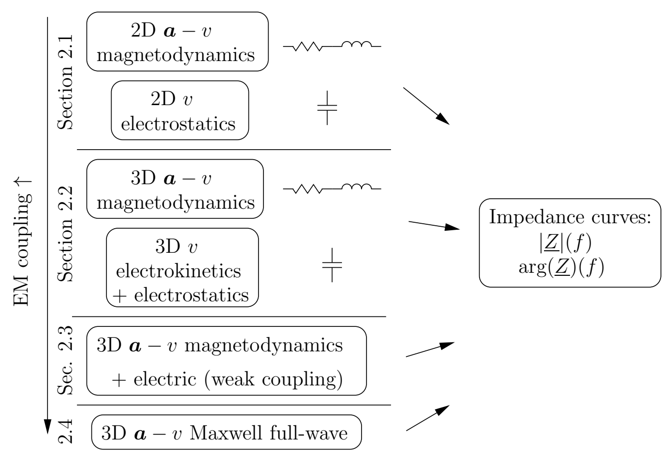

Figure 1: FE models for the computation of the Bode curves of wound inductors.

A. A 2D static model

A 2D v axisymmetric electrostatic model, with v the electric scalar potential, is employed to compute the winding stray capacitance. A linear variation of the potential along the winding is assumed [3], which is equivalent to neglect the coupling between EM fields. This characteristic is common to the two static models presented in this paper (see section II-B). An impedance curve is obtained by placing this capacitance in parallel with the resistive-inductive circuit computed using a 2D $\mathbf{a}-v$ magnetodynamic formulation, with $\mathbf{a}$ the magnetic vector potential. Massive conductors are considered, in order to take the skin and proximity effects into account.

B. A 3D static model

In [3], the authors showed that a 2D representation of the windings was not sufficient for a correct modeling of the capacitive effects in the inductor. Indeed, a 2D model considers a winding as a stack of turns, each at a constant electric potential. However, in 3D, the winding can be modeled as a helix, along which the potential varies linearly in a continuous way, which is closer to reality. Therefore, a two step procedure has been proposed for the computation of the capacitance. First, a 3D electrokinetic problem is solved so as to find v in the winding. This solution is then extended by solving a 3D electrostatic problem in the dielectrics, using the solution of the first problem as a source via a boundary condition.

C. A 3D weakly coupled model

The two static models presented above assume that the potential varies linearly along the winding. However, this is not necessarily the case at the considered frequencies, as it is shown in Fig.2(a), which depicts the potential v of each turn of a single layer winding in elevation, for the frequencies $f = 50\,\mathrm{Hz}$ and $f = 1\,\mathrm{MHz}$. At $1\,\mathrm{MHz}$, the gradients of potential between the turns are less important at the extremities of the winding, which is due to the skin and proximity effects. This phenomenon modifies therefore the capacitive behaviour of the components, and highlight the need to take EM coupling into account. In [4], a weakly coupled FE model is described, which is decomposed in two steps. First, a 3D $\mathbf{a}-v$ magnetodynamic model is employed in order to obtain the electric field in the conducting parts. Then, the electric field in the dielectrics is obtained by solving an electric problem, using the solution of the first problem as volume and surface sources.

D. A 3D full-wave model

Finally, a 3D $\mathbf{a}-v$ full wave model (strong EM coupling) is applied, based on reference [5].

III. Test cases and perspectives

The models are tested on two inductors: one of 96 turns made of round conductors of $0.63\,\mathrm{mm}$ diameter arranged in two layers, and one of 14 turns of copper sheets ($0.03\,\mathrm{mm}$ thickness, $20\,\mathrm{mm}$ height) insulated by Kapton (see Fig.2(b)).

For the inductor with round conductors, it can be seen that the 3D weakly coupled model accurately predicts the first capacitive resonance which occurs at approximately $1\,\mathrm{MHz}$ (see Fig.3, blue crosses). This model seems therefore to be the best suited for our purpose, given the switching frequencies which are in application in modern power electronics converters. For the resonances at higher frequencies, a more critical study will be proposed in the full paper, since the Maxwell full-wave model has not yet been implemented at the time of writing.

In case of inductors made of copper sheets, it has been shown that the 3D static model is sufficient for the first resonance. Indeed, the potential gradients between each turn are approximately the same, regardless of the frequency, even if the skin and proximity effects appear. This is due to the particular geometric configuration of copper sheets.

A more complete parametric study will be proposed in the full paper, by considering the frequency as a parameter and studying more test cases of different characteristic lengths. The goal is to propose a rigorous procedure for selecting the appropriate model, depending on these parameters. Moreover, the evolution of the field models and their relations to each other could be very useful in the educational point of view as well, by highlighting the effects on the same object of different neglections at various frequencies.

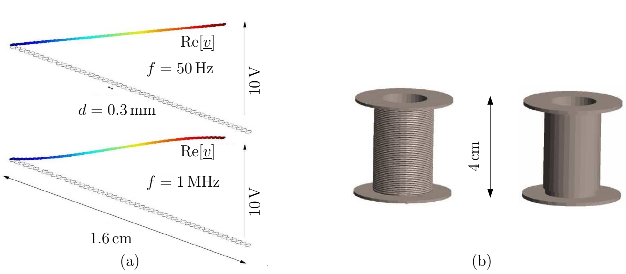

Figure 2: (a) Distribution of the electric potential along a winding (in elevation) and (b) test inductors (round conductors and copper sheets).

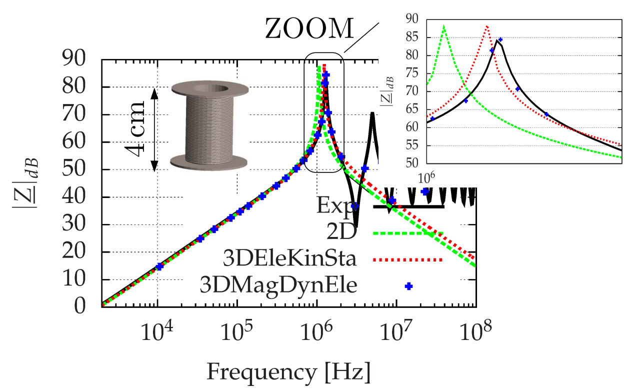

Figure 3: Module of the impedance as function of the frequency for the inductor with round conductors. The black plain lines depict experimental data, green dashed lines the 2D static model results, red dashed lines the 3D static model results, and blue crosses the 3D weakly coupled model results.

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