Time-Domain Finite-Element Modelling of Laminated Iron Cores – Large Skin Effect Homogenization considering the Jiles-Atherton Hysteresis Model

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Abstract— This paper deals with the incorporation of the Jiles-Atherton (J-A) hysteresis model in a time-domain finite-element homogenization technique for laminated iron cores. The separate discretization of each lamination is avoided by using dedicated skin-effect basis functions, which also serve to interpolate the J-A hysteretic material law. As validation test case, a stacked ring core surrounded by a toroidal coil is considered.

I. INTRODUCTION

Many techniques have been proposed for dealing with lamination stacks in finite-element models: anisotropic surrogate material laws, embedded lower dimensional models, *a posteriori* loss estimation, ... (see [1] for an overview). Homogenization methods accounting for hysteresis are mostly limited to time-harmonic analysis [2], [3].

In this paper, the authors extend the time-domain homogenization technique proposed in [4] and include a vectorized Jiles-Atherton (J-A) model [5].

II. HOMOGENIZATION AND JILES-ATHERTON MODEL

Starting from the 1-D eddy-current model of a lamination, i.e. the diffusion equation for the magnetic field, dedicated skin-effect basis functions (even orthogonal polynomials up to order n) are chosen to interpolate the magnetic induction and field. Then the magnetic constitutive law, whether linear or not, is weakly imposed [4]. For a prescribed accuracy, the order n of the interpolation has to be increased with the frequency.

The analysis is now further enhanced by considering a more involved constitutive law: we adopt a J-A hysteresis model [5]. This model, based on a true energy interpretation and with a few physical related parameters, is straightforwardly integrated by replacing the non-hysteretic law treated in [4] by the J-A type hysteretic law.

The time-domain homogenization approach consists then in embedding this 1-D lamination model in a higher dimension finite-element implementation. In practice, this amounts to adding $n/2$ degrees of freedom per mesh element in the homogenized core. Further, we must keep track of the history of the magnetic field when integrating along the thickness of the lamination. The system can be solved by the Newton-Raphson method [5].

III. APPLICATION EXAMPLE

As validation test case, we study a stacked ring core (20 laminations, thickness 0.5 mm, $\sigma = 5$ MS/m, separated by 0.02 mm thick airgaps) surrounded by an inductor [4] (homogenized model, exploiting symmetry, depicted in Fig. 1). The parameter values of the J-A model are those of the steel in [5]. Time-stepping simulations with imposed sinusoidal current of same amplitude but different frequencies are carried out. A brute-force FE approach with a sufficiently fine discretization of each lamination (10 layers of elements) serves as reference solution. A good convergence towards the reference results ("fine") is observed for all considered frequencies (Fig. 1). The effect of the eddy currents when increasing the frequency is evident in the global hysteresis loci (flux linkage versus current) shown in Fig. 2. Further, the higher the frequency, the more additional basis functions (higher n) are to be included for a precise homogenization.

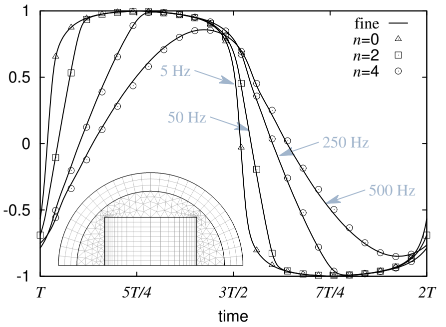

Fig. 1. Normalized flux linkage versus time in steady state (second period). Mesh of the homogenized model.

Further details and results will be given in the full paper.

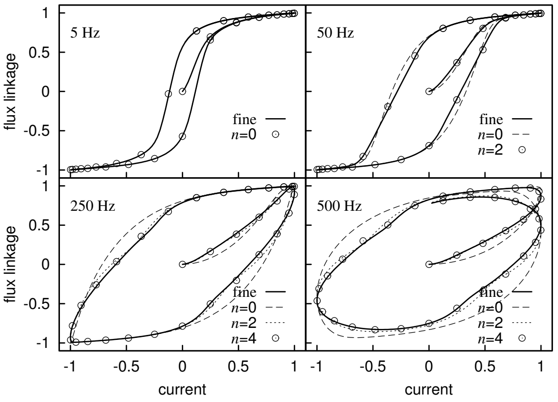

Fig. 2. Normalized flux linkage of the inductor versus normalized current.

IV. REFERENCES

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