

Towards Numerical Modeling of 3D Electromagnetic Devices in the Low-Frequency Regime Using the Numerical Homogenization Method

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The numerical modeling of 3D electrical devices that contain composite materials, such as electrical machines, transformers, and new devices made from soft magnetic and 3D-printed magnetic materials, has yet to be fully realized. Current modeling approaches mainly rely on homogenization methods applied to 2D sections of device components, such as 2D slices of a transformer core or portions of 3D magnetic composites. However, some effects can only be accurately captured using 3D multiscale models of the entire device. The challenges of applying these methods to 3D nonlinear eddy current problems in composites arise from the high computational cost due to the multiscale nature of the materials. The method must also be capable of handling nonlinear material laws. Furthermore, the presence of strong eddy currents may require advanced upscaling techniques that ignore the macroscale contribution of eddy currents confined within the cell. This paper combines the multiscale method with massive parallelization to produce first results for a 3D three-phase transformer.

Index Terms—Eddy Currents, Finite Element Method, Multiscale Models, Nonlinear Magnetics, Numerical Simulation.

I. INTRODUCTION

The numerical modeling of 3D real-life electrical devices with composite materials such as electrical machines, transformers, and new devices that contain soft magnetic materials and 3D-printed magnetic materials, is currently not feasible. Most existing modeling approaches rely on homogenization methods, using either $\mathbf{h}$ -conforming, $\mathbf{b}$ -conforming or mixed formulations [1–4], typically applied to 2D sections of device components, such as 2D slices of a transformer core or similar structures. Attempts have been made to homogenize portions of 3D magnetic composites, including sections of 3D laminated materials and idealized soft magnetic composites (SMCs) [3–5] but these efforts were primarily aimed at validating formulations. To the best of our knowledge, the numerical homogenization of an entire real-life 3D device such as a transformer has yet to be attempted.

The homogenization of 3D devices with pre-computation of homogenized material laws can be considered in the case of linear magnetodynamic or nonlinear magnetostatic problems. However, the presence of eddy currents together with nonlinearities introduces dynamic hysteresis that is not easy to take into account using classical homogenization techniques. The challenges of applying homogenization methods such as HMM [6] to solve 3D nonlinear problems with eddy currents arise from several factors. First, the high computational cost due to the multiscale nature of the materials is a significant issue. Additionally, the presence of strong eddy currents may require appropriate upscaling techniques to account for confined eddy currents within the cell, which should not contribute to the global magnetization [1], [7]. Furthermore, the homogenization method should be able to handle macroscale nonlinearities, induced by a subsequent nonlinear law or the influence of strong eddy currents in the mesoscale.

In this paper, we use recently developed multiscale formulations, coupled with massive parallelization, to model a 3D

three-phase academic transformer. The HMM approach can easily be extended to more realistic 3D transformers, unlike the brute-force approach which is not yet feasible for such devices due to a large number of degrees of freedom.

II. THE NUMERICAL HOMOGENIZATION METHOD

A. Overview of HMM for magnetodynamic problems

Recently, the authors developed $\mathbf{b}$ -conforming and $\mathbf{h}$ -conforming multiscale formulations [1], [5]. For brevity, we focus here on the $\mathbf{h}$ -conforming multiscale formulation as details of the $\mathbf{b}$ -conforming multiscale formulations can be found e.g., in [1].

We consider a multiscale problem with locally-confined eddy currents, which leads to the homogenized magnetic core being treated as non-conducting. The strong form of the homogenized problem reads:

Macroscale problem:

$$\begin{aligned} \partial_t(\mu \mathbf{h}_M) + \mathbf{curl}_x(\rho \mathbf{curl}_x \mathbf{h}_M) &= \mathbf{0} \text{ in } \Omega_s^M, \\ \mathbf{div}_x \mathbf{B}_M(\mathbf{h}_M, [\mathbf{h}_c]^{N^{GP}}) &= 0 \text{ in } \Omega \setminus \Omega^H, \\ \mathbf{div}_x(\mu \mathbf{h}_M) &= 0 \text{ in } \Omega \setminus \{\Omega_s^M \cup \Omega^H\}, \\ \mathbf{n} \times \mathbf{h}_M &= \mathbf{0} \text{ on } \Gamma, \\ \mathbf{h}_M(\mathbf{x}, t = 0) &= \mathbf{h}_0(\mathbf{x}) \text{ in } \Omega. \end{aligned}$$

Mesoscale problems:

$$\begin{aligned} \partial_t \mathbf{B}(\mathbf{h}_M + \mathbf{h}_c^{(i)}) + \mathbf{curl}_y(\rho \mathbf{curl}_y \mathbf{h}_c^{(i)}) &= \mathbf{0} \text{ in } \Omega_m, \\ \mathbf{h}_c^{(i)} &\text{ is tangentially periodic.} \end{aligned}$$

In these problems $\mathbf{h}$, $\mathbf{B}$ are the magnetic field and the magnetic induction respectively. The index $_M$ denotes quantities defined on the macroscale domain Ω with differential operators indexed by $_x$, while the index $_c$ is used for corrections fields defined on mesoscale domains Ω_m with differential operators indexed by

y . The subdomains Ω_s^M and Ω^H of Ω represent massive inductors and the homogenized subdomains, respectively. The vector $[\mathbf{h}_c]^{N^{GP}} := (\mathbf{h}_c^{(1)}, \mathbf{h}_c^{(2)}, \dots, \mathbf{h}_c^{(N^{GP})})$ is the set of mesoscale solutions computed on a periodic cell around points of interest of the homogenized domain, while ρ and μ are the electric resistivity and the magnetic permeability, respectively. In the context of the HMM method, these two problems are solved iteratively in a coupled manner until convergence.

B. Upscaling techniques

For $\mathbf{h}$ -conforming multiscale formulations, the macroscale magnetic induction $\mathbf{B}_M$ is upscaled as the volume average of $\mathbf{B}$ over Ω_m , whereas the macroscale differential reluctivity $(\partial \mathbf{B}_M / \partial \mathbf{h}_M)^{(i)}$ is upscaled using the solution of a mesoscale magnetostatic problem [5].

For $\mathbf{b}$ -conforming multiscale formulations, the upscaling of the magnetic field cannot merely involve averaging the total mesoscale magnetic field, especially when the average of the eddy currents within the cell is of a similar magnitude to the magnetic power. In such formulations, upscaling techniques involve face or edge averaging of the magnetic field along well-defined faces or curves on the boundary of the non-conducting domain [1], as well as defining a correction magnetic field or magnetization generated by confined eddy currents within the confined cell. These corrections can then be subtracted from the total magnetization in the cell, leading to a volume averaging that yields a more accurate homogenized magnetic field [1], [7].

III. NUMERICAL RESULTS

We consider an academic 3D three-phase transformer consisting of 3 primary inductors and 3 secondary inductors wound around a magnetic core. The magnetic core is made of 11 laminations, each 80mm thick, separated by insulators with a filling factor of 0.9. The columns of the core has a width of 300mm, and a height of 600mm, with a 260mm distance between vertical columns. An air layer and a spherical shell for infinite transformation are added around the device. The core is discretized using 12 elements along the thickness of each lamination as shown in the top-left image of Figure 1, resulting in a total of 934,683 elements and 164,992 nodes.

Both the reference and the homogenized problems are solved using GetDP [8]. The reference magnetodynamic problem is solved using the $\mathbf{h}$ -conforming multiscale formulation. The operating frequency is set at $f = 50$ Hz, with the relative permeability of the laminations $\mu_r = 1000$ and a fictitious conductivity $\sigma = 10^3$ S/m, ensuring that the skin depth is approximately 80% of the thickness of the lamination. A ramped-up three-phase current is imposed in the inductors, with the peak voltage $V_{\max} = 100$ V reached after 0.25 of the period. The same conditions are imposed for the homogenized problems, solved using the HMM method on a mesh with a total number of elements equal to 607,389 elements and 95,557 nodes as depicted in the top-right image of Figure 1. The number of macro-elements in the homogenized domain is equal to 240 which corresponds to 240 mesoscale problems to be solved.

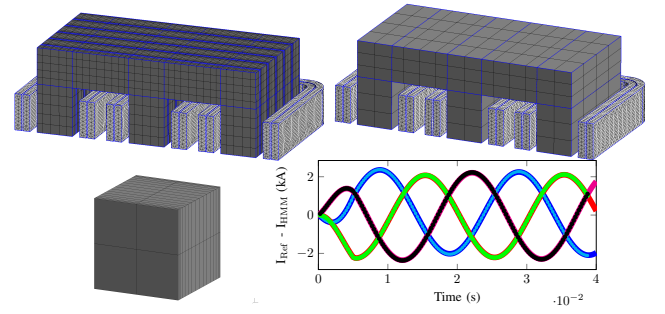


Figure 1: Top-left : mesh of the academic 3D three-phase transformer with 5 and a half laminations, each 80mm thick, and which is used for validation. Top-right : mesh of the academic 3D three-phase homogenized transformer. Bottom-left : mesh of the mesoscale domain made of 1 lamination surrounded by half of the insulator on both sides. Bottom-right : Three-phase electric currents in the primary inductors using the reference and the homogenized meshes. For reference results, phase 1 is depicted in blue, phase 2 is depicted in red and phase 3 is depicted in magenta. For homogenized results, phase 1 is depicted in cyan, phase 2 is depicted in green and phase 3 is depicted in black.

The bottom-right image of the Figure 1 shows electric currents flowing through the primary inductors by imposing a ramped-up voltage in the three inductors under the no-load test. As can be seen on this image, electric currents obtained using the homogenization method are in a good agreement with those obtained using the brute-force approach.

IV. CONCLUSIONS AND PERSPECTIVES

We have used the computational homogenization method to model electromagnetic fields in a three-phase transformer using the HMM method. The method relies on an appropriate definition of coupled macroscale and mesoscale problems, solved using a massive parallelization. The method provides accurate electric currents when a voltage is imposed in a no-load test. In the final paper, we consider nonlinear material laws at the mesoscale and explore the use of pre-computed BH magnetic laws for magnetostatic problems.

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