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Electromagnetic modeling with 3D integral method

A. Gagnoud^{1,2a}, R. Scapolan^{1,2b} and Y. Du Terrail Couvat^{1,2c}

¹ Univ. Grenoble Alpes, SIMAP, F-38000 Grenoble, France

² CNRS, SIMAP, F-38000 Grenoble, France

Corresponding author : annie.gagnoud@simap.grenoble-inp.fr

Abstract

The present work focus on numerical modeling of electromagnetic phenomenon in the inductive processes. Our objective is to be able to model 3D configurations, taking into account high number of objects, small space between active elements of the installation and multi-scale. To achieve this goal we develop an integral method with parallel computing. The obtained results show the efficiency of this approach.

Key words : integral method, electromagnetic modeling, parallel computing, induction

Introduction

The use of induction in materials heat treatment and materials elaboration industrial processes presents some significant advantages like precision, rapidity and control. In the context of reducing energy consumption, it is important to optimize processes and design new configurations. One solution is obtained by the development of adapted numerical modeling. Various inductive configurations must be implemented as cold crucible, electromagnetic levitation, Litz coil... Furthermore a large range of frequencies of power supply has to be treated.

Usually, the finite element method is used to model electromagnetic phenomenon. Various 3D potential formulations are available [1]. Various kinds of elements can be used : node or edge elements. Boundary impedance formulations can be applied to model thin skin depth [2], [3]. The management of all these possibilities is really complex.

The present work focuses on the electromagnetic modeling of inductive processes. Our goal is to be able to model 3D configurations, taking into account high number of objects, small space between active elements of the installation and multi-scale. Compared to finite element method, the integral method presents great advantages linking to the fact that the mesh is limited to the conductors. So the air or isolating materials between conductors is not meshed. Easily, with this method, we can take into account small air gap between conductors. In case of large electromagnetic skin depth we use volume mesh and in case of thin skin depth we use surface mesh. We have developed two softwares : MIGEN used for classic devices like cold crucibles [4], inductors [5] and MODELITZ which is a parallel software used for Litz coils [6].

Principle of integral method

The integral method is developed for electromagnetic modelling of inductive processes. This numerical method is based on the local Ohm's law (1) and the equation of conservation of the current (2). The power source supplies an alternative sinusoidal current in the inductor coil, thus the equations are written in their complex form :

$$\mathbf{J} = -\sigma \nabla V - i_c \sigma \omega \mathbf{A} \quad (1)$$

$$\nabla \cdot \mathbf{J} \quad (2)$$

where \mathbf{J} is the complex current density, σ is the electrical conductivity of the material, V is the complex electrical potential, i_c the imaginary number, ω the angular frequency and \mathbf{A} the complex magnetic potential vector. We use Biot and Savart law to express the magnetic vector potential :

$$\mathbf{A} = \frac{\mu_0}{4\pi} \iiint_{\Omega} \frac{\mathbf{J}}{r} dv \quad (3)$$

where Ω is the volume of the electrical conductors, μ_0 the magnetic permeability of vacuum and r the distance between a point of the conductor and the calculation point of \mathbf{A} . In the equation (1), we replace the magnetic potential vector by it's expression (3) and we obtain the following relation :

$$\mathbf{J} = -\sigma \nabla V - i_c \sigma \omega \frac{\mu_0}{4\pi} \iiint_{\Omega} \frac{\mathbf{J}}{r} dv \quad (4)$$

The equations (4) and (2) are defined in the conductive regions of the installation, so the study domain is limited to the conductors. Added to these equations we defined the boundary conditions. Firstly, the boundary condition at infinity is

natural and is given by the Biot and Savart law (3). Secondly, for the load region, the current density must be tangential to the surface of the conductor, so the following condition is imposed :

$$\mathbf{J} \cdot \mathbf{n} = 0 \quad (5)$$

where \mathbf{n} is the external normal vector to the surface of the conductor. Thirdly, for the inductor, we imposed at its extremities, Dirichlet conditions for the electrical potential and normal direction for the current density. On the other faces of the inductor, we imposed tangential direction for current density. The unknowns are the complex current density and the complex electrical potential.

We develop this method for 3D configurations. A library of geometrical objects is available and permits to describe various 3D configurations. A specific modulus is implemented for the description of Litz coil, with different number of twist levels. Each object is meshed in first order elements. For each object, the electromagnetic skin depth is calculated:

$$\delta = \sqrt{2 / \mu_0 \sigma \omega} \quad (6)$$

We distinguish two cases :

- the case of small skin depth, the mesh is limited to the surface of the object, and we take into account a decay law for the current density,
- the case of large skin depth, the object is meshed in volume.

The equations (4) and (2) are written at each node of the mesh. We use the classical numerical techniques which are used in finite element method : Gauss integration method on the reference element, Lagrange polynomial interpolation on the reference element. We obtain a linear system constituted with a full and non symmetric complex matrix. To solve it, we apply a Gauss pivot algorithm with a research of the maximal pivot. After resolution of this system we obtain the electrical potential and the electrical current density. The Joule power density is calculated on each node of the mesh. Magnetic field and electromagnetic forces can also be calculated. 3D visualisations are realized thanks to Paraview®. We calculate too, global quantities such as the current in the inductor, Joule power in the different objects, equivalent impedance of the devise.

Actually, two software are available:

- a sequential software MIGEN. It permits to model classical installations like cold crucibles, electromagnetic levitation... With this software it is possible to take into account thin and large skin depths regions.
- A parallel software MODELITZ, which permits to model multi-strand inductors. This code has a specific geometrical toll for the construction of Litz coil with various arrangements. Building and solving the linear system are computed in parallel. This implementation is realized with MPI library.

Numerical results obtained with MIGEN software

We consider a cold crucible configuration : constituted by an eight sectors copper cold crucible, a copper inductor coil and an stainless steel load. The external radius of the crucible is equal to 4.2cm. Its height is equal to 20cm. The radius of the load is equal to 3cm, and its height is 15cm. The inductor coil has 4 turns. Two calculations are realized, one with a circular coil section and one with a rectangular coil section. 100V is applied to the inductor. The frequency is equal to 100kHz. In the Fig. 1, Fig. 2 we present the Joule power density distribution in the two configurations.

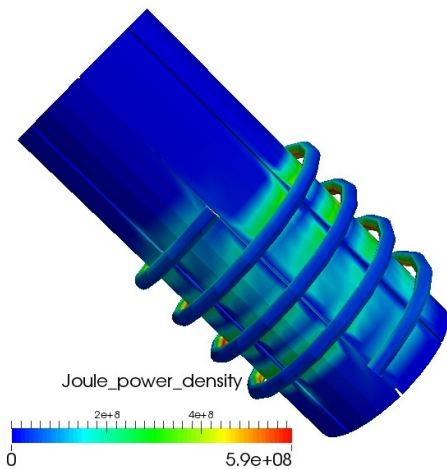


Fig. 1: Cold crucible device in the case of a circular section coil : Joule power density.

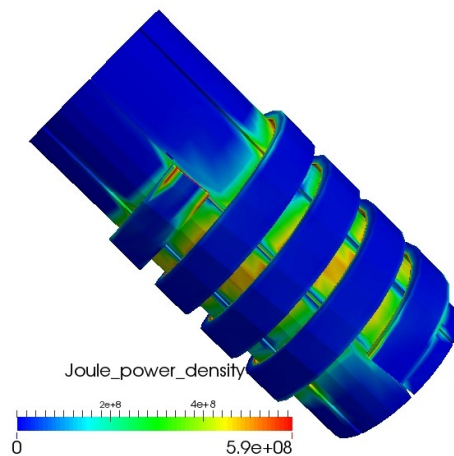


Fig. 2: Cold crucible device in the case of a rectangular section coil : Joule power density.

These two figures show the 3D effects on the external surface of the crucible. The maximum value of the Joule power density is on the internal face of the coil. In the same condition the Joule power density is more important on the cold crucible in the case of an inductor with a rectangular section. On the table 1, we present the percentage of Joule power in the elements of the installation for the 2 cases. The second configuration has a better efficiency.

Table 1 : Percentage of Joule power in the elements of the installation

	Coil with circular section	Coil with rectangular section
Load	44.03 %	49.63 %
Crucible 8 sectors	30.56 %	32.42 %
Inductor	25.41 %	17.95 %

Numerical results obtained with MODELITZ software

We study Litz wire cable. We consider the case of a 3x4 strands cable (12 strands). The two level of twist are in the opposite direction. The radius section of strand is $25\mu\text{m}$. The imposed electrical potential gradient is equal to 0.5V.m^{-1} . The frequency is 300kHz. On the Fig. 3 we present the Joule power density distribution in a part of this cable. Some variations in the section of strands appear. The minimum value of the Joule power density is on the external part of the cable. With the software MODELITZ we study various multi-strand configurations. We analyse the influence of the arrangements and the influence of the frequency. The maximal number of strands that we can model is around 60.

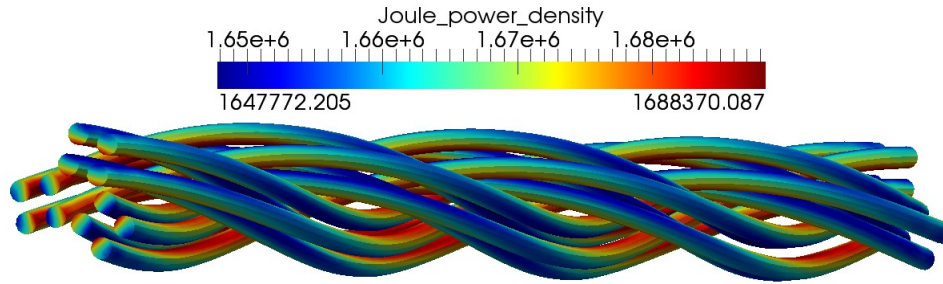


Fig. 3 : Litz cable 3*4 strands: Joule power density distribution at 300kHz.

MODELITZ is a parallel software. To test the efficiency of our parallel development we study the time of computation of a given configuration on various numbers of processes. This study has been executed on various clusters. For all tests we obtain similar results. The acceleration is linear for the building of the linear system. The acceleration of the solving is less efficient. Globally, the acceleration law for the total computation has a power 0.8 to 0.9. On the Fig. 4 we give an example of a test on a cluster of 8 CPU Intel® Xeon® E5-2620. For this study the number of degree of freedom is 19866.

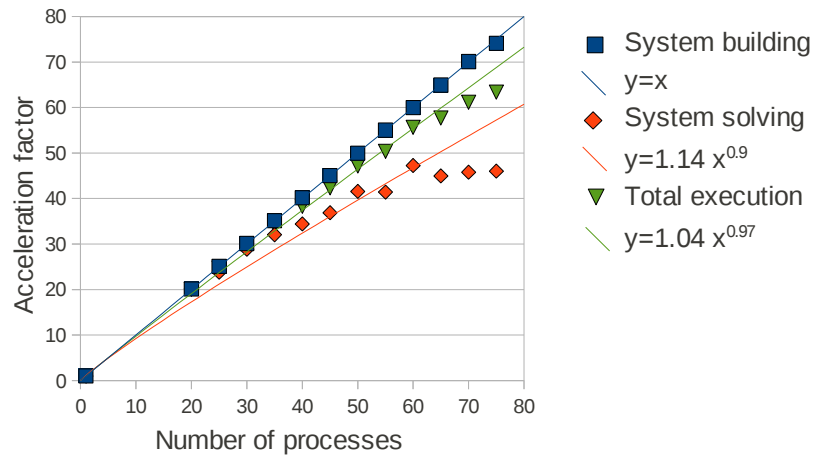


Fig. 4 : Acceleration of the computation with parallel MODELITZ software in function of the number of parallel processes.

Advantages and drawbacks

In the integral method the mesh is limited to the conductive regions of the device. Consequently this method presents important advantages compared to the finite element method. It is possible to take into account in a same configuration objects with different size, small air gap. The size of the mesh is smaller compared to the finite element method and present a good quality. Furthermore, the thin skin depth regions are meshed on the surface. In this method the presence of large skin depth regions and small skin depth regions can be easily modeled in a same configuration. Another advantage of the integral method concerns the description of the boundary conditions. Some boundary conditions are intrinsic like the condition at the infinity and the tangential condition at the surface of conductors which must be applied to the current density. These two points constitute the main advantages of this numerical method for electromagnetic modeling.

In the integral method the linear system is stored in a full non-symmetrical matrix. Even if the size of the matrix is smaller compared to the finite element method, this point is the main drawback of this method. We must use a direct method for solving system and it costs time and memory.

With this method the inductor coil can be modeled. The impedance of the device is directly obtained. Moreover, the repartition of the Joule power in the elements of the device are obtained by integration. So, this method is well adapted to optimize installations and to define parameters of the power supply of the system.

Conclusions

The integral method is well adapted to model electromagnetic phenomena in inductive processes. With this method it is more simple to describe a 3D problem than with finite element method. Various scales, small air gap and thin electromagnetic skin depth can easily be modeled with this numerical technique. The local and global results have a good precision. The limit of this method is due to the full matrix of the linear system. Consequently in the MODELITZ software we implement a parallel approach. The results obtained with MODELITZ demonstrates the possibilities of this method to take into account an important number of objects and small air gap between these objects.

Our objective is now to merge MIGEN and MODELITZ in one parallel software and to coupled it with finite element method and finite volume method for multi-physic computing.

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