3D multi-strands inductor modeling : influence of complex geometrical arrangements

R. Scapolan, A. Gagnoud, Y. Du Terrail
Laboratoire SIMaP/EPM, Grenoble INP, UJF, CNRS,
BP 75, 38402 Saint Martin d'Hères cedex
raphael.scapolan@simap.grenoble-inp.fr

***Abstract*—We study multi-strands inductors, in the context of high frequency induction processes. They present the advantage to reduce Joule losses compare to solid inductors. We remind why that type of cable seems to be promising and what electromagnetic effects are already identified.**

We have developed an electromagnetic software based on integral method using classical Biot and Savart law. We applied this model for the simulation of multi-strands cables. Numerical simulation of the electromagnetic behavior of these objects is complicate due to the complexity of their 3D geometry and to the size of the generated numerical system. Specific tools are developed for the 3D geometric modeling of Litz wires. Execution time is reduced by parallelization of system construction and solver. We have to understand precisely what happens inside the inductor. We present some results obtained with 3D simulations using integral method.

***Index Terms*—Numerical analysis, parallel algorithms, electromagnetic induction, proximity effect, energy efficiency.**

I. Introduction

Electromagnetic induction is widely used in heating industrial processes because it allows a precise control of heating parameters. In metallurgy, the control of the frequency of the inductor supply permits to make precise surface treatment of pieces. This process exploits the skin depth effect which is the result of the concentration of electric Eddy currents in a layer near the surface of the heating piece (the load). The thickness of this layer depends on the frequency of the electromagnetic field seen by the piece. The expression of skin depth is $\delta = \sqrt{2/\sigma\,\mu\,\omega}$ where σ is the material's electric conductivity, μ its magnetic permeability and ω the inductor's pulsation.

As a result of Eddy currents, the piece is heated due to Joule effect. This effect also appears in the solid inductor and could increase power losses. Depending on the installation geometry, the heating yield could be low ($\approx 30\%$). A way to improve the efficiency is to reduce Joule losses in the inductor by using multi-strands cable which is less sensitive to skin effect.

A multi-strands cable, also called Litz wire, is made with hundreds or thousands of thin strands. The objective is to obtain approximately a constant current density through the cable so the diameter of strands is chosen to be around the order or smaller than the skin depth corresponding to the working frequency. But, all strands interact between themselves that produces an other effect, called proximity effect. It has been already studied by some authors (e. g. [1] - [3]).

In [4] we showed, using a 2D model, that proximity effect creates a global skin effect on the cable. This approach corresponds to a geometrical parallel arrangement of strands which leads to the worst efficiency. In [5], we exposed a method to estimate, in a 3D configuration, the maximal efficiency which could be obtained if the current density would be homogeneous through a multi-strands inductor. For that, we studied a device with an inductor wounded around a cylindrical hollow load. We deduced, in an ideal case and in that configuration, that the yield could reach 80 % at 50 kHz, instead of 30 % with a solid inductor.

Our aim is to develop a 3D numerical model to study multi-strands inductors.

II. Numerical modeling of multi-strands inductor

A. Existing methods and limits

Lot of studies have been led to build homogenization models to replace the real geometry by a simple one and reduce the size of the problem. In [1] - [3], authors used semi-analytical approaches to simulate Litz wires. In [4], we used an equivalent electric conductivity, inspired by [6] where authors established equivalent properties taking into account some characteristics of a transformer coil. But all these approaches are limited. For complex geometries, they introduce approximations which hide influence of the real geometry. To be able to build optimized inductors, it is essential to understand the influence of all wires arrangement, which is 3D.

B. 3D modeling constraints

We can identify two difficulties for simulating that kind of inductive systems. First, the geometry is 3D and complex. Indeed, multi-strands inductor is an assemblage of many strands twisted in a packet, which packet is assembled with others similar packets in a bigger one, and so on to obtain the complete cable. Secondly, for any numerical method chosen for simulation, the matrix system is very large. Even with Finite Elements Method (FEM), the necessity to mesh all space between strands with a satisfying quality produces a big mesh. The scale ratio between diameter of strands (10-100 μm) and the diameter of the inductor (*cm*) is very important.

C. 3D modeling with integral method

We developed an integral method [7] to simulate 3D multi-strands cable. This method is based on the local Ohm's law

(1) and the conservation of current (2).

$$\vec{J} = -\sigma\vec{\nabla}V - \sigma\frac{\partial\vec{A}}{\partial t} \quad (1)$$

$$\vec{\nabla}\cdot\vec{J} = 0 \quad (2)$$

where $\vec{J}$ is the current density, V is the electrical potential and $\vec{A}$ the magnetic potential vector. Biot and Savart law is used to compute $\vec{A}$.

This method requires to mesh only the conductors, so it is possible to describe more complex geometry with less constraints than FEM. Unknowns of the linear system are $\vec{J}$ and V. At the extremities of wires we imposed Dirichlet condition on V and normal direction on $\vec{J}$. As Biot and Savart law is computed on all nodes, the system is non-sparse, non-symmetric and badly conditioned. We use maximal Gauss pivot algorithm to solve it. Simulation of multi-strands cables involves memory constraints and a long computation time.

We developed a C++ parallel code using MPI library. Time computation is reduced by using parallelism for system building and solving. To describe geometry and mesh of complex objects as multi-strands cables, we developed a specific tool.

III. Numerical results

We study two types of cable : with straight wires (C1) and with helical arrangement (C2) (pitch = 1mm). Cable radius is 178.5 μm in the two cases. Wires are in copper and diameter is 50 μm < $\delta \approx$ 150 μm. Cable is built with 4 concentric layers of wires : (C1) counts 37 wires and (C2) 28. To diminish system size, we simulate a cable portion of 0.5 mm length. Matrix size is 28897 for (C1) and 29688 for (C2). Rms supply voltage is 0.07 mV and frequency is 200 kHz.

Table I shows the total current and the impedance computed in the two cables. Fig. 1 and Fig. 2 show the Joule power density, respectively for (C1) and (C2). In Fig. 1, global skin effect appears clearly : current is higher through peripheral wires. In Fig. 2, helical arrangement leads to the opposite behavior : current is higher in the central wire. This effect occurs because wire length increases with helix radius, so the resistance also increases. Moreover, helical arrangement increases this effect for high frequency.

Table I: Total current and impedance for two cables.

Cable	Rms total current (A)	Impedance (Ω)
(C1)	3.62	1.21e-04 + 1.52e-04j
(C2)	2.62	2.08e-04 + 1.71e-04j

IV. Conclusion

We developed an integral method parallel code to compute electromagnetic behavior of a portion of a multi-strands cable in 3D. This method doesn't require to mesh space between conductors. So, it is well fitted to simulate multi-strands cables with small space between wires. We showed the effect of geometrical arrangement of wire on the repartition of Joule power density.

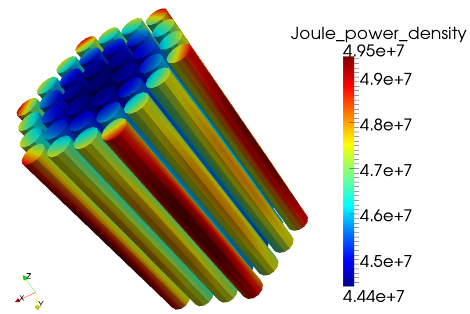

Figure 1: Joule power density for a 4-layers cable with straight wires (C1) (Post-processing realized with Paraview®). [8]

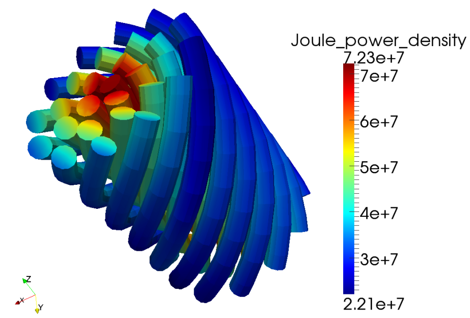

Figure 2: Joule power density for a 4-layers cable with helical arrangement (C2).

V. Acknowledgments

This study is led as a task of the ANR project ISIS (Innovative Solutions for Induction Systems) regrouping EDF, Fives CELES and SIMaP/EPM.

References

[1] C. R. Sullivan, "Optimal Choice for Number of Strands Litz-Wire Transformer Winding", IEEE Transactions on Power Electronics, vol. 14, no. 2, pp. 283291, 1999.

[2] F. Tourkhani, P. Viarouge and J. C. Fagundes, "Dimensioning of a magnetic component taking into account the effect of currents induced in the winding", Electrical and Computer Engineering, 1995. Canadian Conference on, vol. 1, pp. 268-271, 1995.

[3] J. Acrero, R.l Alonso, J. M. Burdío, L. A. Barragán, and D. Puyal, "Frequency-Dependent Resistance in Litz-Wire Planar Windings for Domestic Induction Heating Appliances", IEEE Transactions on Power Electronics, vol. 21, vo. 4, pp. 856-866, 2006.

[4] R. Scapolan, A. Gagnoud and Y. Du Terrail, "Simulation of multi-strands conductors thanks to equivalent electric conductivity", Proceedings of Numelec 2012, pp. 98, 3-5 July 2012.

[5] R. Scapolan, A. Gagnoud and Y. Du Terrail, "Estimation of optimal gain in induction heating with multi-strands inductor", 9th International Symposium on Electric and Magnetic Fields, EMF 2013, Bruges, April 2013, submitted for publication.

[6] G. Meunier, AT. Phung, "Propriétés macroscopiques équivalentes pour représenter les pertes dans les bobines conductrices", Revue Internationale de Génie Electrique, vol. 11, no. 6, pp. 675-694, 2008.

[7] A. Gagnoud, "Three-dimensional integral method for modelling electromagnetic inductive processes," IEEE Transactions on Magnetics, vol. 40, n 1, pp. 29-36, 2004.

[8] Paraview®, www.paraview.org