3D Numerical Modeling of AC Losses In Multi-filamentary Superconductors

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MgB_2 superconductors show great potential for the high current compact power cables. Throughout the design of the cooling system for a 12 kA cable, the losses has to be calculated as close as possible. This article focuses on the calculation of AC losses generated by a time varying environment as AC current or/and external magnetic field. The superconductor AC loss modeling problem can be formulated as an eddy current problem in which the resistivity of the superconducting region is modeled with a power law characteristic. However, the calculation of AC losses for superconductors in 3-D, using the finite element method, is time consuming and leads to convergence issue due to the very nonlinear nature of the power law E-J characteristic, as well as the singular behavior of the flux/current front everywhere where the current density is zero. In this paper, two electromagnetic formulations as well as two different E-J models have been studied and compared in order to model a basic 3-filaments wire. Although most results are coherent which each other, there is still optimization to do in order to find a computationally efficient approach to solve this problem and scale up to more realistic multi-filamentary wires.

***Index Terms*—Superconducting numerical models, Multifilamentary superconductors, AC losses.**

I. INTRODUCTION

Since the discovery of superconductivity, the capability of carrying large currents without any resistance have raised the interest of cable manufacturers. However, this desired behavior is only achievable under a critical surface delimited by a critical temperature, current and magnetic field. A wire made of 36 filaments of superconducting compound MgB_2 embedded in a nickel matrix is today a realistic option for the creation of high current compact power cable, and was even successfully tested in 2014 [1]. It is worth mentioning that this material must be cooled at a temperature below 25 K, but the high cryogenic cost of gaseous Helium is compensated by the low MgB_2 cost, at least for DC conditions. Indeed, AC losses exist even when electrical resistivity is zero, when superconductors are exposed to a time-varying magnetic field and/or when the transport current varies with time. Even in a DC application, the current always contain AC components and generates losses inside the conductors. The total heat load inside a fully operating power cable consists therefore of the sum of the heat influx through the cryogenic envelope, the heat influx through the cross-section of the current leads, and the AC losses generated in the cable sub-conductors themselves, composed of superconducting filaments and a normal metal matrix.

To minimize the cost of the cooling system, the AC losses must be minimized as much as possible, and this task is made easier during the design process if one can predict the losses by means of numerical simulations.

In the case of simple geometries, AC losses can be computed using analytical solutions, but in the general case, numerical methods must be used, the most popular being the finite element method.

The physics of AC losses can be well described with Maxwell equations together with appropriate constitutive laws for the materials. In current literature, the problem is most frequently expressed in terms of so-called the H-formulation [2][3], where H is the magnetic field. This formulation, which works quite well in 2-D, imposes the use of a finite though dummy resistivity in the non-conducting regions (air for example), and may lead to unphysical currents in the air regions when modeling 3-D devices [4].

In more traditional eddy current formulations, and especially in the time-harmonic regime, the problem is formulated in terms of the magnetic vector potential A and electric scalar potential V (A-V formulation), or alternatively, in term of the current vector potential T and magnetic scalar potential ϕ (T-ϕ formulation) which provides a good convergence with the E-J characteristic of superconductors. Those formulations have the advantage of providing means to avoid considering dummy resistivities in non-conducting regions, but they have seldom been applied to superconducting problems, which must be simulated as time transient problems due to their highly nonlinear nature. Still we can find some instances of use of those formulations for superconductor modeling, e.g. in [5]. The peculiarities of the nonlinear dynamics of superconductors give rise to new modeling challenges, and this commands for a detailed investigation of various electromagnetic formulations and numerical simulation parameters for this particular case.

As a first step along this direction, in this paper, we study and compare two finite element formulations for modeling superconductor AC losses: T–ϕ vs. the H formulation. We also compare two types of E-J characteristics based on the power law model in order to account for the nonlinear electrical behavior of superconductors. The properties of the formulations and their suitability for studying 3-D twisted superconducting wire are discussed based on the benchmark case of a 3-filaments wire.

II. ELECTROMAGNETIC MODELING OF SUPERCONDUCTORS

To model the electromagnetic behavior of the superconductor, a nonlinear E-J relationship is used. Two formulations were tested, i.e. the classic power law (1), which is widely used in the superconducting community, and an alternative power law (2), known as *percolation law*, as suggested by the University of Geneva [6] and used for the modelling of quench propagations [7]. It was also successfully applied to AC losses calculations in 2-D problems and confirmed by experiments [8]. It has the advantage of respecting the zero resistivity under a critical current density J_{c0}. The equations are displayed below

$$E = E_c \left(\frac{\left|\vec{J}\right|}{J_c} \right)^n \qquad with\ n = 30 \qquad (1)$$

$$E = 0 \qquad when \left|\vec{J}\right| \le J_{c0} \qquad (2a)$$

$$E = E_c \frac{1}{\left(\frac{J_c}{J_{c0}} - 1\right)^{n_1}} \cdot \left(\frac{\left|\vec{J}\right|}{J_{c0}} - 1\right)^{n_1}\ with\ n_1 = 2\ when \left|\vec{J}\right| > J_{c0} \qquad (2b)$$

In (1) and (2), $J_c = 2.84.10^8$ A/m^2 is the critical current density and E_c=1 μV/cm is the electric field at which the critical current is reached. J_{c0} was set at $2.78.10^8$ A/m^2.

To model this electromagnetic problem, two software packages were used. The first one was FLUX® [9], developed by G2Elab and CEDRAT. It uses the T-ϕ formulation for solving 3-D eddy current problems. The second software package was Daryl Maxwell, a FEM software developed in Polytechnique Montreal, and devised for modeling large 3-D, nonlinear electromagnetic problems with the FEM, using the H formulation. We have implemented the two power law in these software.

III. STUDIED PROBLEM

The 3-D problem investigated here is a 3-filaments superconducting wire with a filament diameter of 1 mm and a twist pitch of 20 mm, subjected to an AC transport current and/or external field. The geometric model and the mesh used are showed in Fig. 1.

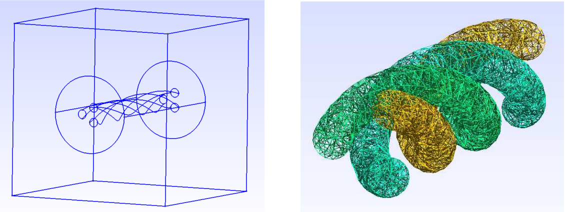
(a) (b)

Fig. 1. (a) Geometry and (b) mesh of the 3-filaments problem.

In order to compare the two formulations with the two implemented power laws, we first compute the AC losses in the case of a transport current only (no external field is applied). The simulation was realized with the two codes for both E-J relationships. The results corresponding to a transport current amplitude of 560 A (I_c = 700 A) are shown in in Fig. 2, and the AC losses are shown in Table I.

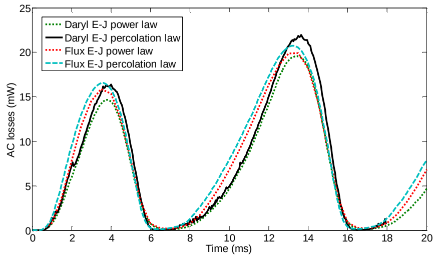

Fig. 2. Transport current AC losses with the two E-J formulations.

The AC loss values are very close to each other, and they do not depend much on the E-J relationship in the case of *Flux* (difference of 0.23 %). In the case of Daryl-Maxwell though, we observe a difference between the two E-J characteristics. Even with a relative tolerance of the Newtown-Raphson set at 10^{-6}, oscillations of in the loss curve appear (see Fig. 1). This has to be further investigated. Overall, we remark that the losses are in the same range with both software packages.

TABLE I
AC LOSSES CALCULATIONS

Software and E-J	AC losses at 50 Hz (mJ/cycle)
Daryl power law	7.75
Daryl percolation law	8.69
FLUX power law	8.68
FLUX percolation law	8.66

In the full paper, more details on the implementation and on the comparison in terms of computation performance will be provided. The case including applied external field combined with transport current will be included.

IV. REFERENCES

[1] “CERN MgB2.” [Online]. Available: http://home.web.cern.ch/fr/about/updates/2014/04/world-record-current-superconductor.

[2] F. Grilli, E. Pardo, A. Stenvall, D. N. Nguyen, W. Yuan, and F. Gomory, “Computation of Losses in HTS Under the Action of Varying Magnetic Fields and Currents,” *IEEE Trans. Appl. Supercond.*, vol. 24, no. 1, pp. 1–33, Feb. 2014.

[3] V. M. R. Zermeno, F. Grilli, and F. Sirois, “A full 3D time-dependent electromagnetic model for Roebel cables,” *Supercond. Sci. Technol.*, vol. 26, no. 5, p. 052001, May 2013.

[4] V. Lahtinen, M. Lyly, A. Stenvall, and T. Tarhasaari, “Comparison of three eddy current formulations for superconductor hysteresis loss modelling,” *Supercond. Sci. Technol.*, vol. 25, no. 11, p. 115001, Nov. 2012.

[5] F. Grilli, S. Stavrev, Y. Le Floch, M. Costa-bouzo, E. Vinot, I. Klutsch, G. Meunier, P. Tixador, and B. Dutoit, “Finite-Element Method Modeling of Superconductors : From 2-D to 3-D,” vol. 15, no. 1, pp. 17–25, 2005.

[6] M. Decroux, L. Antognazza, N. Musolino, E. De Chambrier, S. Reymond, J. Triscone, W. Paul, and M. Chen, “Properties of YBCO Films at High Current Densities: Fault Current Limiter Implications,” *IEEE Trans. Appl. Supercond.*, vol. I, no. 1, pp. 0–3, 2001.

[7] A. Badel, L. Antognazza, M. Therasse, M. Abplanalp, C. Schacherer, and M. Decroux, “Hybrid model of quench propagation in coated conductors for fault current limiters,” *Supercond. Sci. Technol.*, vol. 25, no. 9, p. 095015, Sep. 2012.

[8] G. Escamez, A. Badel, P. Tixador, B. Ramdane, G. Meunier, A. Allais, and C. Bruzek, “Numerical modelling of AC losses in HTS tubes,” *IEEE Trans. Appl. Supercond.*, vol. Accepted.

[9] “FLUX software.” [Online]. Available: http://www.cedrat.com/.