

AC Losses Modeling in ReBCO Superconducting Coils Using the Volume Integral Method

S. Fawaz¹ and H. Menana²

¹ESME, ESME Research Lab, Campus de Lille, F-59000 Lille, France, sara.fawaz@esme.fr

² Group of Research in Electrical Engineering of Nancy, GREEN, F-54000 Nancy, France; hocine.menana@univ-lorraine.fr

In this work, different strategies are compared for AC losses modeling in superconducting coils made of Rare-earth Barium Copper Oxide (ReBCO) tapes, using the volume integral method. These strategies explore the possibilities of homogenization of the electromagnetic properties of the tape, in order to reduce computation time. The modeling results are compared to measurements.

Index Terms—AC losses, HTS Coils, Homogenization, REBCO tapes, Volume integral modeling.

I. INTRODUCTION

HIGH temperature superconductors (HTS) hold significant potential for applications in electrical power systems, primarily due to their relatively low cryogenic costs. However, the main limitations are related to AC losses, and to the pronounced local dependence of the critical current density on the magnetic field. Consequently, modeling approaches based on local quantities are essential for the design and characterization of superconducting systems [1]. The structural complexity of HTS involving heterogeneities, anisotropies and multi-scale dimensions, combined with the strong nonlinearity of their electromagnetic properties, makes their modeling within systems, often greedy for IT resources. Therefore, specific modeling approaches are required [2].

In a two-dimensional approach, strategies for modeling the AC losses in HTS coils made of Rare-earth Barium Copper Oxide (ReBCO) tapes are developed considering the possibilities of homogenization at the tape and coil scales. The volume integral method is used, enabling to discretize only the active parts of the modeled system. The modeling results are then compared to experimental measurements.

II. MODELED SYSTEM

The modeled system consists of a single layer pancake inductive coil of inner and outer radii denoted as R_{int} and R_{ext} , respectively, and composed of N_t turns of ReBCO tape as shown in Fig. 1, where H_t and W_t represent the width and the thickness of the tape. Such tape has a multilayer structure where the superconducting layer thickness is about $2\mu\text{m}$ [3].

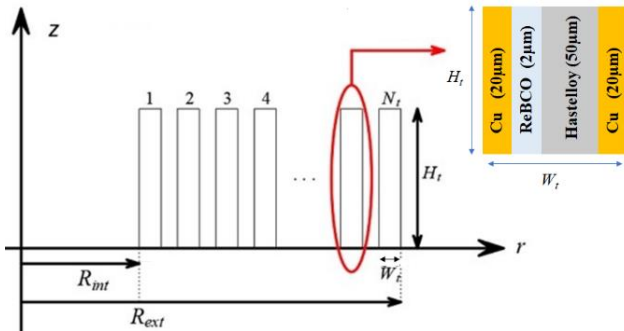


Fig. 1. Modeled system with a schematic layout of the considered multilayer structure of the REBCO tapes.

The modeling strategies consider three tape configurations : the multilayer tape configuration, which explicitly represents the main tape layers (Copper, Re-BCO and Hastelloy); the homogenized tape configuration, where the tape is treated as a single, uniform superconducting entity; and the single-layer superconducting tape configuration, which focuses solely on the superconducting (Re-BCO) layer. In the multilayer tape model, the resistivity values of Copper and Hastelloy at cryogenic temperatures are used [4]. The electric resistivity of the superconducting region is nonlinear modeled by a power law relation (1) where, E and E_c represent the electric field and its critical value; J and J_c are the electric current density and its critical value; n is the creep exponent characterizing the steepness of the transition from the superconducting to the normal state; J_{c0} is the electric current density at zero magnetic field; B_r and B_z are respectively the components of the magnetic field in the radial and axial directions; and B_0 , k and β are parameters depending on the material. The superconducting and normal regions are denoted respectively by Ω_s and Ω_n . All regions of the system are characterized by the vacuum magnetic permeability μ_0 .

$$\begin{cases} \vec{E} = E_c (J_c(B))^{-n} J^{n-1} \vec{J} \\ J_c(B) = J_{c0} \left(1 + B_0^{-1} \sqrt{k^2 B_z^2 + B_r^2} \right)^{-\beta} \end{cases} \quad (1)$$

The modeling approach uses the expression of the electric field as a function of the magnetic vector and electric scalar potentials ($\vec{E} = -\partial_t \vec{A} - \vec{\nabla} V$).

In 2D, the term $\vec{\nabla} V$ is replaced by an integral ensuring the current conservation. Expressing the magnetic vector potential $\vec{A}$ in an integral form as function of the electric current density, we obtain the following equation:

$$E_{(\vec{p})} + \iint_{\sum S_i} G_{(\vec{p}, \vec{q})} \partial_t J_{(\vec{q})} ds + \gamma \sum_{N_t} \iint_{S_i} (J - J_a) ds = 0 \quad (2)$$

where, G is the Green's function, J_a is the applied current density assumed to be uniform, S_i is the tape section and γ is a feedback constant [5]. The AC losses are evaluated as follows:

$$P = 2\pi \sum_{N_t} \iint_{S_i} r_{(\vec{p})} E_{(\vec{p})} J_{(\vec{p})} ds \quad (3)$$

Each tape section is discretized into $N_r \times N_z$ rectangular

elements of surface ΔS along the radial and axial directions, respectively. Introducing (1) in (2), the matrix form of the resulting equation is given as follows:

$$\bar{G}\partial_t \bar{J} + \bar{S} \cdot E_c [\bar{J} / \bar{J}_c]^n - (\bar{S} - 1) \cdot \bar{\rho} \bar{J} + \gamma \bar{S}_t \{ \bar{J} - \bar{J}_a \} = \bar{0} \quad (4)$$

The matrix $\bar{\rho}$ represents the resistivity of the normal regions, and the matrix $\bar{S}$ is introduced to distinguish between the superconductive and normal regions: $S_{(i,j) \in \Omega_s} = 1$ and $S_{(i,j) \in \Omega_n} = 0$. The matrix system (4) is solved using the “ode15s” solver in Matlab.

III. RESULTS AND DISCUSSIONS

The parameter specifications of the modeled system are given in Table 1. A sinusoidal current is applied: $I_a = I_{\max} \sin(2\pi ft)$.

TABLE I
PARAMETERS SPECIFICATION

Parameter	Value	Description
W_t / H_t	0.92/4 mm	Tape thickness / Tape width
R_{ext} / R_{int}	6.2 / 6 cm	External/Internal radius of the coil
N_t	6	Number of the coil turns
$\rho_{Cu(77K)}$	$0.19 \times 10^{-8} \Omega \cdot m$	Electrical resistivity of Copper at 77K
$\rho_{Hast(77K)}$	$124 \times 10^{-8} \Omega \cdot m$	Electrical resistivity of Hastelloy at 77K
E_c	1 $\mu V/cm$	Critical electric field
n	18/30	Creep exponent for the multilayer/homogenized and superconducting layer tape model
I_{c0}	140 A	Critical current at zero magnetic field
k	0.15	Parameter of anisotropy used in (1)
B_0 / β	0.14 T/1.39	Kim's parameters used in (1)
γ	100 V/(A.m)	Feedback constant

The instantaneous AC losses of the coil for a sinusoidal applied current of 110 A amplitude and 40 Hz frequency is reported in Fig. 2. The steady state regime is obtained at the second half period. The average AC losses are then obtained by averaging the instantaneous losses on the second half of the period. The AC losses obtained in the different tape configurations are compared to measurements for different applied currents at a frequency of 40 Hz. As shown in Fig. 3, the three tape configurations lead to very close results highlighting the possibility of the tape homogenization, or that of simply neglecting the normal regions. This also means that the hysteresis losses in the HTS part are predominant at low frequencies. The origin of the hysteresis losses are explained in Fig. 4, showing the distribution of the electric current density in the homogenized superconducting tapes at the half period where the applied current is nil ($I_a = 0$). When in a normal conductor, this situation would lead to a zero current density, in a superconductor, two currents of the same amplitude flow in opposite directions in each tape section which densities depending on the strength of the local magnetic flux density. This maintains a certain magnetic energy in the tapes which is not returned to the source. The difference with the measurements may be due to uncertainties in the Kim's parameters used in (1) which are obtained for applied magnetic fields, while the coil is in the self field.

Compared to the multilayer tape configuration, the computation time is reduced by a factor 20 considering the

homogenized configuration, and by a factor of 1300 considering the single-layer superconducting tape configuration, due to the reduced discretization in the radial direction in this case ($N_r=1$).

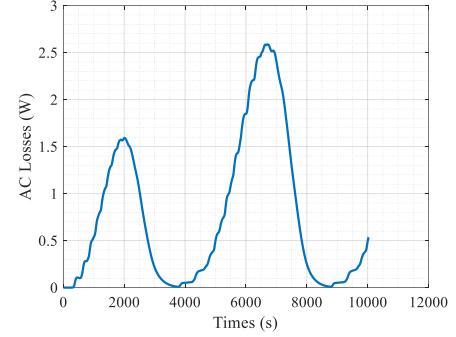


Fig. 2. Instantaneous AC losses ($I_{\max}=110A$, $f=40Hz$).

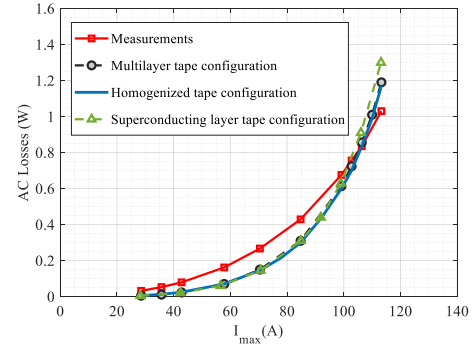


Fig. 3. Comparison between experiments and the numerical results of AC losses obtained for the different tape configurations ($f=40$ Hz).

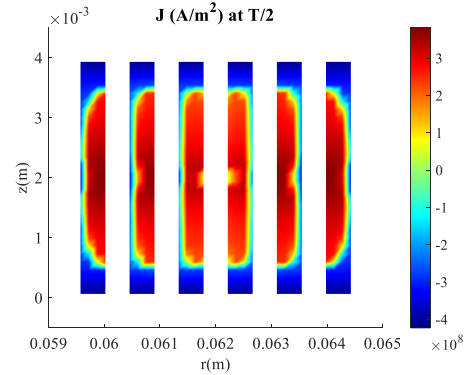


Fig. 4. Distribution of the electric current density in the HTS coil cross section using the homogenized tapes configuration, at half a period ($I_{\max}=110A$, $f=40Hz$).

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