DC modeling & characterization of HTS coils with non uniform current density distribution

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***Abstract*—In this paper, a DC modeling approach is proposed for the calculation of current density distribution in a 1G HTS pancake coils taking into consideration the non-uniformity of *J* in the HTS tape section using a power minimization criterion. Integral equations are used to evaluate the magnetic flux density, enabling to discretize only the active parts of the system.**

Keywords—DC modeling, characterization, high temperature superconductors (HTS), superconducting coils, $J_c(B)$ dependency.

I. Introduction

Direct Current (DC) characterization is important for high temperature superconducting (HTS) coils in electrical power applications such as electrical machines, fault current limiters and energy storage systems. In particular, it allows to determine the critical operating current.

In principle, the operating current can be obtained from experiments where the current density distribution *J* is considered uniformly distributed in the coil cross-section [1]. However, this is not realistic due to the dependence of the critical current density J_c on the magnitude and orientation of the local magnetic flux density (*B*). This dependence can be considered by combining experiment with modeling [2]. However, DC models do not directly involve the non-linear *E(J)* characteristic [3], nevertheless the latter can be artificially introduced [4].

In this work, we developed a fast and realistic DC modeling approach that considers the *E(J)* relation including the $J_c(B)$ dependency, with a non-uniform distribution of *J*, based on a power minimization criterion.

The model is applied to predict the voltage-current *(U-I)* characteristics of a non-inductive pancake coil. Such coil structure presents weak local magnetic flux densities (MFD), below the values considered in the experimental models giving $J_c(B)$ dependency. We found that the extrapolation of such models does not provide satisfying results, and thus we solved an inverse nonlinear problem using the least squares method (LS) to determine, at the same time, the parameters of the Kim's model giving the $J_c(B)$ dependency and that of the power law giving the *E(J)* characteristic, from the measured *U-I* curve.

II. The Modeling Approach

The modeled system consists of a N_t turns circular pancake coil wound with a 1G HTS tape. Using cylindrical coordinates (r,θ,z), the modeling approach is based on a numerical integration of the Biot-Savart equation to calculate the MFD distribution, combined with a strategy considering the non-uniform distribution of *J* due to the $J_c(B)$ dependency.

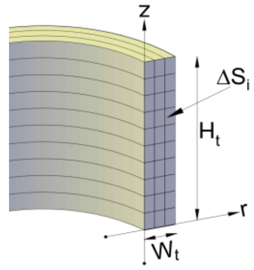

Fig. 1. Two-dimensional (2D) axisymmetric model of a discretized superconducting tape used as a basis for this analysis.

Each coil turn (tape) is discretized into $N_r \times N_z$ elementary sections, in the *r-z* plan (Fig. 1), leading to $N_e = N_t \times N_r \times N_z$ elementary sections for the coil. The distribution of the magnetic vector potential $\bar{A}$, as well as the radial and axial components $(\overline{B_r}, \overline{B_z})$ of the MFD in the coil section are then given by (1), where, $\overline{\overline{G_A}}, \overline{\overline{G_{BR}}}$ and $\overline{\overline{G_{BZ}}}$ are $(N_e \times N_e)$ matrices and $\bar{I}$ is a vector containing the current in each elementary section.

$$\left\{ \bar{A} = \overline{\overline{G_A}}\,\bar{I};\quad \overline{B_r} = \overline{\overline{G_{BR}}}\,\bar{I};\quad \overline{B_z} = \overline{\overline{G_{BZ}}}\,\bar{I} \right\} \tag{1}$$

The *E(J)* characteristic is modeled by the power law, associated with Kim's law to consider the $J_c(B)$ dependency, both given in (2), where *E* and E_c are the electric field and its critical value; *n* is the creep exponent; J_{c0} is the critical current density at zero MFD; B_0 and β are physical parameters depending on the considered HTS material, and *k* is a parameter of anisotropy.

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

The coil is fed by a current I_a. To consider the influence of the MFD on the current distribution in the coil section, the current I_i flowing in an elementary section ΔS_i, in a tape of section S_t, located at a radial coordinate r_i, is given by (3), where B_i and $J_c(B_i)$ are respectively the MFD and the critical current density evaluated at the center of ΔS_i, while $\langle J_c(B) \rangle_t$ and $\langle r \rangle_t$ are respectively the mean values of the critical current density and the radial coordinates in the tape.

$$I_i = \frac{\Delta S_i \langle r \rangle_t\, J_c(B_i)}{S_t\, r_i \langle J_c(B) \rangle_t} I_a \times \frac{|I_a|}{\sum |I_i|} \tag{3}$$

Equation 3 is solved iteratively until convergence. The stop criterion is based on minimizing the power (*P*) dissipated in the coil, as shown in Fig. 2.

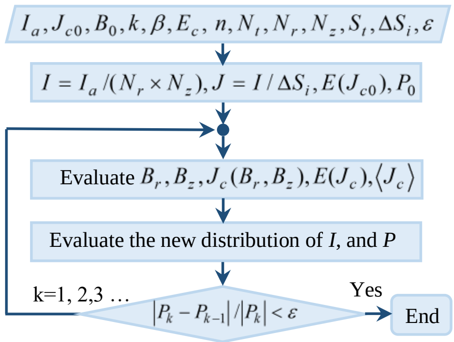

Fig. 2. Flow chart of the modeling approach.

III. Application

The model is used for the characterization of the local properties: $E(J)$ and $J_c(B)$, of a non-inductive HTS pancake coil wound with dynamically innovative Bi-2223 tape (DI-BSCCO), starting from the measured *U-I* curve. The aim is to determine the parameters J_{c0}, B_0, k, β and n, which are unknown, and not correctly given by the experimental $J_c(B)$ curves of such material, since the local MFD is low, close to the self-field of the tape. The modeling approach is thus combined with a LS method to determine these parameters using the experimental *U-I* curve as shown in Fig. 3.

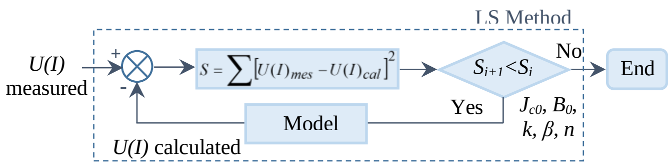

Fig. 3. Parameters identification using the LS method.

The parameters specifications are given in Table I. The *U-I* curves obtained by numerical analysis and measurements are shown in Fig. 4. The experimental result indicates a critical current of 167.27 A, whereas the simulation gives 167.44 A. Fig. 5 shows the distribution of B_r, B_z and J in the inner tape for an applied current of 150 A. As we can notice, B_r affect more significantly the distribution of J. The central regions, subjected to lower values of B_r, carry larger currents. At the edges, the situation is reversed i.e., B_r is maximum and the current is minimum.

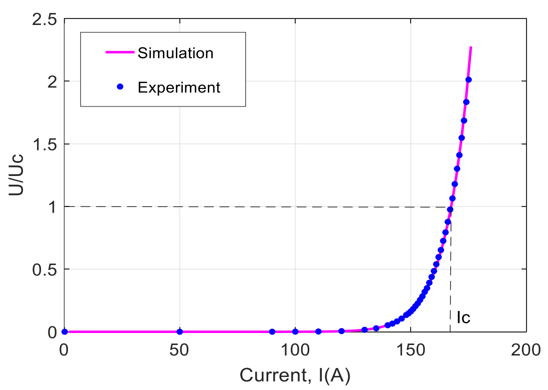

Fig. 4. Calculated and measured *U-I* curves of the HTS coil

Figure 6 presents the evolution of the power losses (P) in the iterative procedure given in Fig. 2, for an applied current of 150A. The first value is obtained using the critical current density at zero MFD (J_{c0}), the second one is obtained by considering a uniform J distribution in the tape section.

TABLE I
Parameters Specification

	Parameter	*Value*	*Description*
Given parameters	I_c *(77K)*	170 *A*	Tape critical current at zero external field
	L	102 *m*	Length of the superconducting tape
	W_t	0.23 *mm*	Tape thickness
	H_t	4.3 *mm*	Tape width
	R_o/R_i	27 *cm* / 9 *cm*	Outer/Inner radius of the coil
	N_t	92	Number of the coil turns
	d	1.7 *cm*	Distance between tapes
	N_r/N_z	5/20	Number of elements along the r/z axis
	E_c	1 $\mu V/cm$	Critical electric field
Identified	n	15	Creep exponent
	I_{c0}	184.82 *A*	Critical current at zero MFD
	k	0.14	Parameter of anisotropy
	B_0/β	0.14 T /2.26	Constants used in (2)

The latter is the maximal value obtained in the iterative solving. After the third iteration, the power tends to decrease and becomes stable after 10 iterations for a relative error of 10^{-6}.

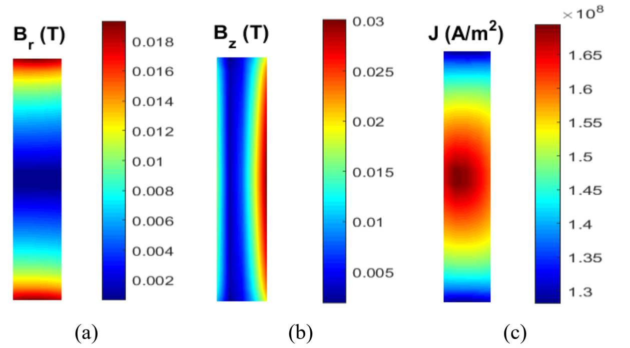

Fig. 5. Distributions, in the inner tape section, of: (a) the radial component of the MFD, (b) the axial component of the MFD, (c) electric current density *J*.

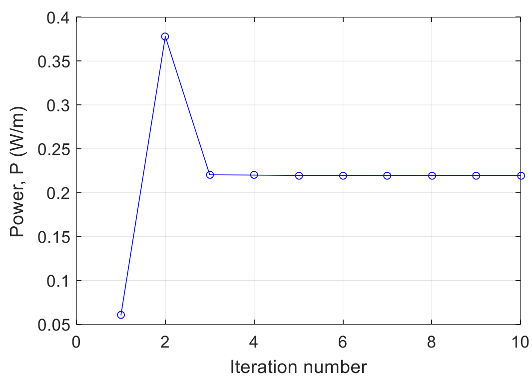

Fig. 6. Evolution of the power dissipated in the iterative solving ($\varepsilon=10^{-6}$)

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