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Fast integral modeling approach for the characterization of a superconductor stabilizer in DC electric grid

Sara FAWAZ, Hocine MENANA and Bruno DOUINE

Université de Lorraine, GREEN, F-54000 Nancy, France.

name.surname@univ-lorraine.fr

Objective –The objective of this paper is to develop a fast integral modeling approach for the design and characterization of a superconductor stabilizer (SS) that is embedded in DC electric grid. The SS consists of a large scale non-inductive high temperature superconducting (HTS) coils. The modeling approach is combined with a far tape approximation strategy, which enables the estimation of losses and the determination of current density distribution in the coil by modeling a progressively reduced set of consecutive tapes instead of the entire coil.

Findings –The model has been tested where the calculated AC losses show a good agreement with those obtained with Norris ellipse formula and measurements. This highlights the importance of considering the elliptical section of the superconductor in the tape. Additionally, some noteworthy phenomena were observed, which are related to the current distribution in the tapes.

Originality –Integral approaches are used due to their advantages of limiting the discretization to the active parts of the system. However, these approaches can still encounter difficulties when modeling coils composed of a large number of turns. Consequently, a far-tape approximation strategy is employed to reduce the size of matrices and computation time.

Keywords – Large scale non inductive HTS coils, AC Losses, Modeling, Measurements, Superconducting stabilizer.

1. Introduction

High temperature superconducting (HTS) coils present a great interest for electric power applications, such as electrical machines, superconducting stabilizer and energy storage systems. These devices are designed to operate in dc and/or ac conditions, therefore, hysteretic losses (AC losses) are expected in both steady and transient state operation. For the application of a superconducting stabilizer consisting of a non-inductive HTS coil, these losses are crucial for stabilizing the DC electric grid. Therefore, accurately estimating these losses is important for evaluating the coil's performance and designing it effectively. However, due to the nonlinear properties of HTS materials, calculating AC losses for coils composed of hundreds of tapes can be a challenging task, requiring significant computing time and memory space.

Several approaches have been developed for the modeling of HTS. The most commonly used approach is the finite element method based on H formulation. However, this method becomes costly in terms of memory space and computation time when dealing with systems consisting of distributed sources and has multi-scale dimensions, such as HTS coils. In such cases, integral methods that limit the discretization to the active parts of the system are more suitable [1-2]. However, even the integral approaches face difficulties when modeling large HTS coils due to the large number of discretization elements. Therefore, modeling strategies such as the fast multipole method [3] can be used to reduce the size of matrices and computation time, leading to a far-tape approximation strategy in this case [4].

In this work, the far-tape approximation is applied to model a large scale non-inductive HTS coil carrying AC currents, leading to a successive modeling of a very reduced set of tapes of the HTS coil.

2. The modeling approach

The modeled system consists of a non-inductive coil of inner and outer radii noted R_{int} and R_{out} , respectively, and composed of an N_t -turn wound with a first generation HTS tape (BSCCO tape) as illustrated in Fig. 1, where H_t and W_t are the width and the thickness of the tape respectively. The non-inductive coil is constructed in such a way that the current flows in opposite directions in two consecutive turns.

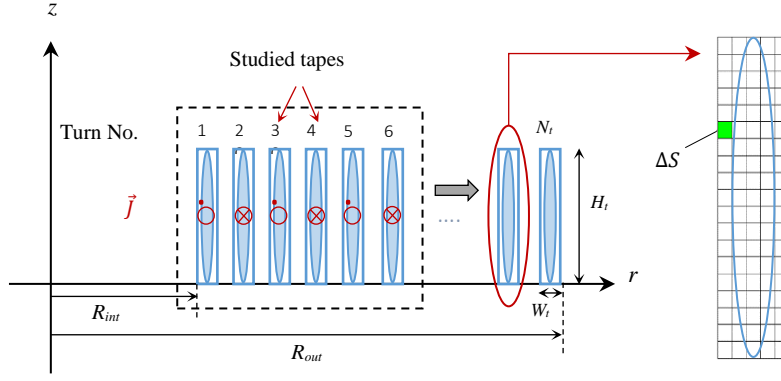


Figure 1 : The cross-section geometry of the HTS coil and its discretization.

The local electric field E is expressed as a function of the local current density J ($E = \rho J$), where ρ is the electric resistivity of the material.

The resistivity of the silver at 77 K is imposed outside the elliptical section: $\rho_{Ag(77K)} = 0.27 \times 10^{-8} \Omega \cdot m$ [5], while the electric resistivity of the HTS material is modeled by the E - J power law [6], associated with the Kim's law to consider the $J_c(B)$ dependency [7], given in (1), where E_c is the critical electric field; n is the creep exponent; J_{c0} is the critical current density at the zero magnetic field; B_0 and β are physical parameters depending on the considered superconducting material; and k is a parameter of anisotropy.

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

The modeling approach is based on numerical integration of the Biot-Savart equation to evaluate the distribution of the magnetic flux density (MFD), using cylindrical coordinates (r, θ, z) . The current is imposed in the coil and since the coil is non-inductive, the far-tape approximation allows to transform the whole coil modeling to a successive modeling of an even number of consecutive tapes (n_t), wherein the physical quantity of interest is evaluated in the two central tapes. The sequence is then repeated by sliding consecutive n_t tapes by two tapes in each iteration to process all the tapes of the coil. The discretization leads thus to a specific number ($N_e = n_t \times N_r \times N_z$) of elementary sections (ΔS) for each computation sequence. The distributions of the magnetic vector potential \vec{A} , and both of the radial and axial components (\vec{B}_r, \vec{B}_z) of the MFD in the tapes section are given in (2), where $\overline{G}_A, \overline{G}_{BR}$ and \overline{G}_{BZ} are integral matrices and \vec{J} is a vector containing the current densities of the N_e elementary sections.

$$\{ \vec{A} = \overline{G}_A \vec{J}; \quad \vec{B}_r = \overline{G}_{BR} \vec{J}; \quad \vec{B}_z = \overline{G}_{BZ} \vec{J} \} \quad (2)$$

The AC modeling approach is based on the expression of the electric field as function of the magnetic vector and electric scalar potentials (\vec{A}, V) given by (3), considering the non-linear $E(J)$ characteristic.

$$\partial_t \vec{A} + E_c \left| \frac{J}{J_c} \right|^n \frac{\vec{J}}{\|\vec{J}\|} + \vec{\nabla} V = \vec{0} \quad (3)$$

The value of $\vec{\nabla} V$ is constant over the entire cross section of a tape and can be used to impose the conservation of the current in each tape [8]. The matrix form of (3) can thus be expressed as follows:

$$\overline{G}_A \partial_t \vec{J} = -E_c \{ \vec{J} / J_c \}^n - \gamma \vec{S} \{ \vec{J} - \vec{J}_a \} \quad (4)$$

where γ is a feedback constant, and \bar{J}_a is applied in such a way that the current flows in the opposite direction in two consecutive turns. The matrix system (4) is solved using the ODE solver “ode15s” in Matlab [9].

3. Results and discussions

A pancake insulated non-inductive HTS coil wound with a dynamically innovative Bi-2223 tape (DI-BSCCO) has been constructed and characterized. The parameter specifications are given in Table 1. The Kim’s parameters in a non-inductive coil are determined using the approach developed in [2] with a non-uniform current density distribution in the coil. The measured critical current of the coil is 167 A, while that of the tape is 170 A. The slight decrease in I_c suggests that the magnetic field applied to a tape in the non-inductive coil is close to the self-field of a tape sample.

The developed approach is applied to the HTS coil for the determination of the evolution of the AC losses and the current density J distribution at different applied AC current.

The instantaneous losses in a single tape can be evaluated as follows:

$$P = 2\pi \sum_{i=1}^{N_r \times N_z} E_i J_i r_i \Delta S_i \quad (5)$$

The AC losses are obtained by averaging the second half of the period.

Table 1. Parameters specifications

Parameter	Value	Description
I_c (77K)	170 A	Tape critical current at zero external field
L	102 m	Length of the superconducting tape
W_t/H_t	0.23/4.3 mm	Tape thickness / Tape width
R_{out}/R_{int}	27 / 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	9/13	Number of elements along the r/z axis
E_c	1 μ V/cm	Critical electric field
n	15	Creep exponent
I_{c0}	184.51 A	Critical current at zero MFD
k	0.14	Parameter of anisotropy
B_0/β	0.14 T / 2.25	Constants used in (1)
γ	100 V/(A.m)	Feedback constant

The AC losses dissipated in the HTS coil, for a frequency of 40 Hz, using the proposed modeling approach are reported in Fig. 2, compared to the measurements and losses calculated with the Norris formulas at the same frequency. The losses using the Norris formulas are calculated with the critical current of the tape at zero external field provided by the manufacturer ($I_c = 170$ A), and with the critical current I_{c0} , which is a Kim parameter determined for the HTS coil ($I_c = 184.51$ A). The results obtained from the numerical approach show a good agreement with the Norris formulas and the measurements, emphasizing the significance of considering the elliptical section of the superconductor in the tape.

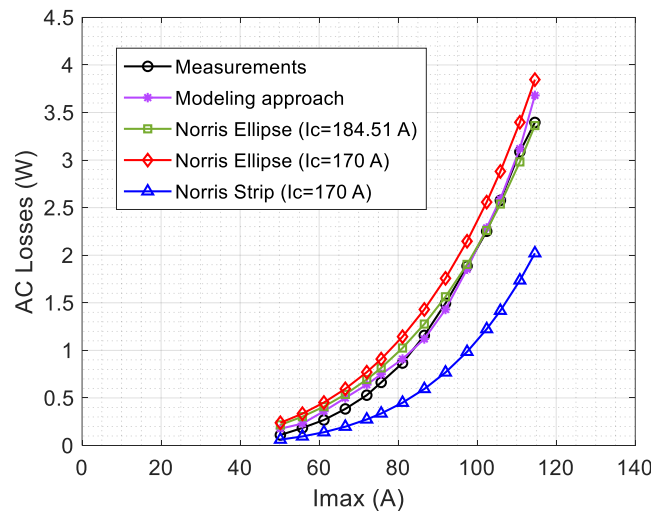


Figure 2 : Comparison between the numerical and experimental AC losses and the losses calculated with Norris formulas for a frequency of 40 Hz.

Figure 3 illustrates the distribution of J in the last sequence (last six tapes), for a sinusoidal applied current of 120 A amplitude and 40 Hz frequency, at three different instants: $t=T/4$, $t=T/2$, and $t=3T/4$, where T is the period. The thickness of the tapes has been expanded in the r -direction in the plots to emphasize the current repartition. Since the coil is non-inductive, we can notice that the current flows in the opposite direction in two consecutive turns and penetrates each tape from the outside, until it reaches a distance dependent on the critical current. When the current decrease, an inverse current is induced from the outside, so that when the applied current is zero at $t=T/2$, the current density in each tape is not locally nil (Fig. 3-b), but its integral over the surface of each tape is nil. At $t=3T/4$, the situation is reversed compared to $t=T/4$.

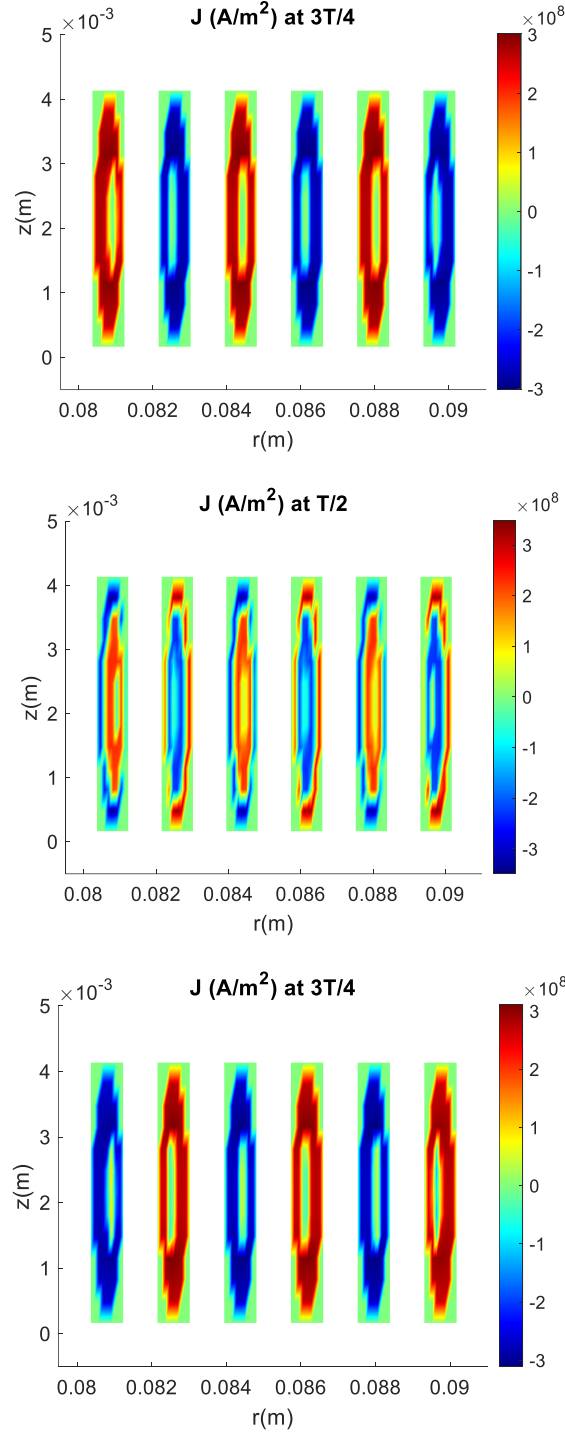


Figure 3 : Distribution of the electric current density in the last 6 tapes cross section at 40 Hz, for an applied current $i(t) = 120 \sin(2\pi ft)$ @ $t=T/4$, $t=T/2$ and $t=3T/4$.

The computation time using the modeling strategy based on the subdivision into sectors for an applied current is around 30 min, whereas modeling the entire coil, with the same discretization lasts 12h. Figure 4 shows the instantaneous AC losses for a sinusoidal applied current with an amplitude of 120 A and a frequency of 40 Hz.

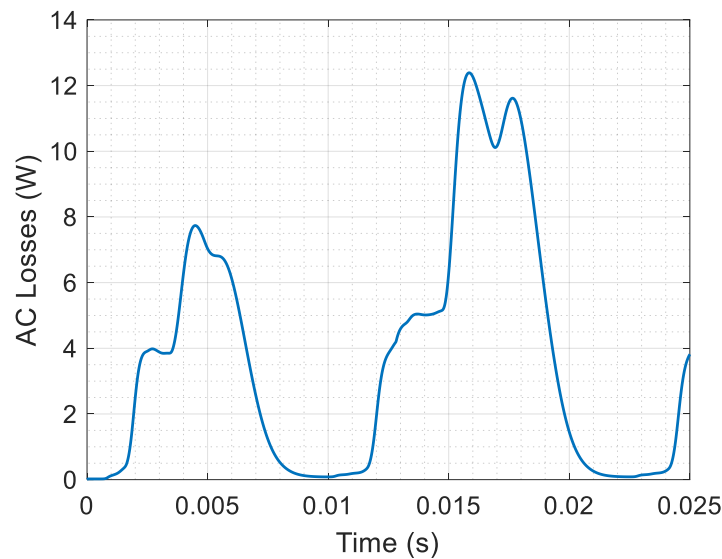


Figure 4 : Instantaneous AC losses for an applied current $i(t) = 120 \sin(2\pi ft)$ at 40 Hz.

4. Conclusion

In this paper, a fast integral modeling approach is proposed for the design and characterization of large scale HTS coils, specifically non-inductive coils. The approach relies on a sequential modeling strategy of a set of tapes, considering a far tape approximation, leading to the cancellation of the magnetic field of the far tapes in the context of non-inductive coils.

Integral equations are used to evaluate the electromagnetic quantities, enabling to discretize only the active parts of the reduced modeled system. The modeling strategy is applied to model the losses in a non-inductive coil for different current supply. The results of the numerical AC losses show good agreement with the measurements and the losses calculated with the Norris ellipse formula, highlighting the effectiveness of considering the elliptical cross-section of the superconductor in the tape. Norris ellipse formula can be used to predetermine the losses in AC mode in non-inductive coils, as the magnetic field applied to the coil tape is close to the self-field of a tape sample. However, the evaluation of local quantities such as the current density repartition and the determination of the losses in a coil under different current supply can only be performed numerically. The approach proposed in this paper significantly reduces the computation time compared to simulating the entire non-inductive coil. Future research could explore losses in the AC+DC mode using the proposed approach, particularly in non-inductive coils which can be used as stabilizers in DC electric grids.

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