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ORIGINAL PAPER

A Comparative Study of AC Transport and Eddy Current Losses for Coil Made of HTS Tapes Coated with Copper Stabilizer

Muzaffer Erdogan[1] · **Serhat Tunc**[2] · **Sukru Yildiz**[3] · **Fedai Inanir**[2]

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Abstract In this work, the evaluation of AC loss of the pancake coils wound by HTS-coated conductors, by employing the finite element method in 2D, is presented. The transport current loss of the superconducting tape and the eddy current loss of the copper stabilizer as a function of the amplitude for four frequencies of the applied current are examined numerically by utilizing a newly developed calculation method based on the $A - V$ formulation embedded in COMSOL Multiphysics software with an AC/DC module. The number of the coil turn is 10, and the radius is about 60 mm. The superconducting layer width and height in the simulations are 12 and 1 mm, respectively. The width and height of the copper layers are 12 and 80 mm, respectively. The critical current density of tapes is taken as 300 A.

Keywords Superconductivity · Finite element method · Superconducting coil · 2G HTS tape · AC loss

✉ Fedai Inanir
inanirfedai@gmail.com

1 Department of Physics, Namik Kemal University, 59030, Tekirdağ, Turkey

2 Department of Physics, Yildiz Technical University, Esenler, 34420 Istanbul, Turkey

3 Department of Metallurgy and Materials Engineering, Ahi Evran University, Kırşehir, Turkey

1 Introduction

Recent developments on HTS technology have given us new opportunities for using long-length superconducting (SC)-coated conductors as core components in designing AC devices such as transformers, cables, and generators [1–3]. Conventional instruments are still superior to AC HTS apparatuses since the AC losses in windings of HTS could not been decreased sufficiently. AC loss mechanisms must be understood precisely in order to develop a new type of low-AC loss HTS coils for superconducting power devices. Predominant electromagnetic losses in a HTS coil are classified as hysteresis, coupling, eddy current, and ferromagnetic losses [4]. In a coated conductor, an alternating self-field due to the high current on a YBCO layer induces currents on metal layers which are responsible for eddy current loss. To our knowledge, eddy current losses in metallic layers in HTS coils have not yet been investigated sufficiently.

An alternating current passing through superconducting layers induces a magnetic flux inducing an electromotive force (emf). This emf creates a current flowing through the surface of copper conductor wound around a coated superconductor. The resulting induced emf has no contribution to the output of the coil; however, this will end up as heat and this type of energy loss is called "eddy current loss".

The investigation of AC loss in HTS tapes and coils was needed parallel to the progress of HTS apparatus. Many works have been dedicated on short samples of tapes and small coil assemblies [5, 6]. Loss mechanism study tendencies were focused on AC loss in an alternating magnetic

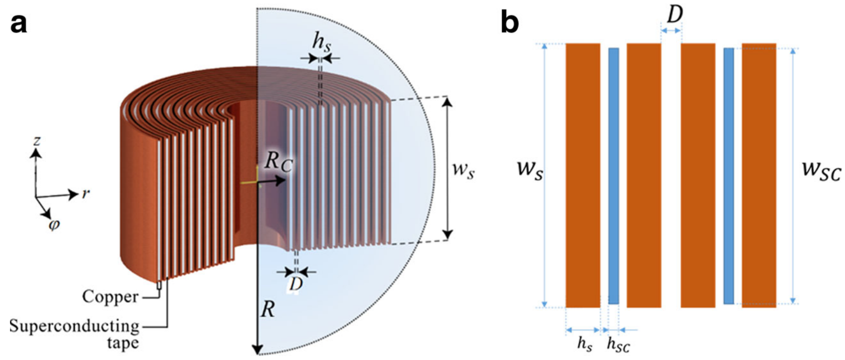

Fig. 1 **a** The system model used for electromagnetic calculations of superconducting tapes is designed using conductors coated with copper stabilizers. **b** Detailed cross-sectional view of the stabilizers and the superconducting tape

field or in the presence of transport current [7–9]. Critical-state model and E–J power law have been widely utilized for numerical modeling of AC losses [10–12]. The homogenization principle is employed in some modeling works to cope with calculating complexity of thousands of windings by reducing them to a small number of turns [13]. The modeling of superconducting-coated conductor tapes and coils under the working conditions has intensively been performed by the finite element method (FEM). Three major sets of equations derived from Maxwell equations based on different state variables have been embedded in the commercial FEM software. The magnetic vector potential ($\boldsymbol{A}$) is determined by the $A - V$ formulation [14, 15], and the current potential (T) is proposed by the $T - \Omega$ formulation [16]. The state variables are $\mathbf{A}$ in the $A - V$ formulation and T in the $T - \Omega$ formulation. Another formulation to calculate the critical state for coated conductors is the H formulation [17, 18]. The Faraday equation for specific boundary conditions in two or three dimensions can directly be resolved using the H formulation. The modeling calculations are mainly aimed on the interaction between tape stacks like HTS coil. In order to simulate the stack of YBCO-coated conductors, the vector potential is employed by Grilli et al. [19]. Ainslie et al. proposed to predict AC loss of HTS racetrack coils in the frame of H formulation [20]. Zhang et al. have developed an axial symmetric FEM model based on the H formulation for HTS pancake coils made of coated conductors [21].

Muller has evaluated analytically the eddy current and hysteresis losses of the metal-superconductor stripes in the

Table 1 The parameters chosen to compute the contribution of eddy currents on the Cu stabilizer to the AC loss

Quantity (unit)	Explanation	Value
I_c (A)	Critical current of the superconductor	300
w_{sc} (mm)	Width of the superconductor	12
w_s (mm)	Width of the copper stabilizer	12.1
h_{sc} (μm)	Thickness of the superconductor	1
h_s (μm)	Thickness of the copper stabilizer	40 + 40
R_c (mm)	Inner radius of the coil	60
D (mm)	Interwinding distance	0.4
J_{c0} (A/m^2)	K critical current density	2.5×10^{10}
B_0	Critical current density parameter	0.36
β	Critical current density parameter	1.2
T_c (K)	Critical temperature of YBCO tape	92
σ_b (S/m)	Conductivity of vacuum	1
R_u (cm)	Calculation domain radius	$\sim 150 \times R_c$
N	Number of windings	10
f (Hz)	Applied current frequency	1, 50, 100, and 1000
E_c (V/m)	Characteristic electric field	1×10^{-4}
n	Exponent for the E–J relation	21

low frequencies [22]. The eddy current loss contribution to the total loss of superconducting tapes has been investigated by several researchers [23–25]. The eddy current loss of the superconducting coil wound on silver-sheathed Bi-2223 tapes has been measured by Paasi et al. [26]. To our knowledge, the hysteresis loss of the superconductor and the eddy current losses of the metallic sheets of the HTS coils wrapped by the YBCO-coated conductors exposed to the transport current have not yet been investigated using numerical calculations.

In this work, we present the FEM calculation results of AC losses including both the transport in superconductors and the eddy current losses occurring in the metallic stabilizer of the coils made by a 2G HTS-coated conductor under acting time-varying transport current. We mean “the power dissipated per unit length of the cable” with the term “loss” in this manuscript. The calculated loss curves for the frequencies of the applied current have been introduced. The calculation is based on the $A-V$ formulation implemented into the COMSOL Multiphysics.

2 The Model

The 2D cross section of the coil employed in the numerical calculations is displayed in Fig. 1. The cross section of the coil is assumed to lie on the r–z plane and the current to flow in the φ-direction, in cylindrical coordinates. Current is applied only to superconducting layer, and eddy currents are induced on the Cu stabilizer due to the time-varying magnetic fields created by alternating current. The superconducting tape is chosen to be 12 mm wide. The coil has ten windings in order to reduce the computational time consumption and for more precise results. The physical parameters used in calculations are given in Table 1. FEM simulations have been carried out at COMSOL Multiphysics program.

The $A-V$ formulation is implemented in the AC/DC module, which is very effective to solve Maxwell equations.

A mapped mesh technique has been used in the simulations for each superconducting layer with a very large aspect ratio, and the number of slices that the tapes are divided is 150 widthwise and 4 along its height. Free triangular meshing is chosen for the calculation domain outside of the coated conductor such as 18168 in the SC layers and 10891 in the air subdomain outside of the cable cross section. The total number of mesh elements is 29059. For wires and coils with a small number of turns, the mesh can play an important role in the accuracy of the AC loss calculation [27]. The error can be large when not enough mesh elements are taken along the thickness of the superconducting layer, because of the high current density distribution is along the edges as well as top and bottom surfaces. For higher currents, this error is significantly reduced because the flux front moves from the edges towards the center.

The governing equation for the dynamical analysis is given by Ampere’s law

$$\frac{1}{\mu_0}\nabla \times \mathbf{B} + \sigma \frac{\partial A}{\partial t} = \mathbf{J} \tag{1}$$

with

$$\mathbf{E} = -\frac{\partial A}{\partial t} + \nabla V, \ \ \mathbf{B} = \nabla \times \mathbf{A} \tag{2}$$

where μ_0 is the magnetic permeability of vacuum, $\mathbf{A}$ is the magnetic vector potential along the φ-axis, $\mathbf{J}$ is the current density, and V represents the potential difference per unit length of tape along the z-direction, which is uniform across the tape cross section.

The properties of the superconducting zone have been defined according to nonlinear E–J relation [28]

$$E = E_c \left(\frac{J}{J_c}\right)^n \tag{3}$$

where E is the electrical field parallel to the current density (J), E_c is the threshold value for the electrical field (1×10^{-4} V/m), J is the current density, J_c is the critical current density, and n is the numerical constant related to flux creep, e.g., $n = 5$ (strong flux creep). However, $n > 20$ is usually a good approximation for the Bean model for HTS tapes [29]. Equation 3 is used for defining the conductivity of the superconducting region. Conductivity expression for the superconducting region is given as follows:

$$\sigma = J_c \frac{(|E/E_c| + \Delta)^{1/n}}{(E + \Delta)} \tag{4}$$

Using this expression, for every winding of the superconducting coil, a numerical value for Δ is estimated to be around 10^{-5}. Equal current in each winding of the SC coil is applied as integral constraint. A transport current I_t is taken

Table 2 Parameters for the copper stabilizer

Quantity (unit)	Explanation	Value
ρ_0 (Ω/m)	Resistivity	1.72×10^{-8}
α (1/K)	Temperature coefficient of resistivity	3.9×10^{-3}
T_0 (K)	Reference temperature	273.15
T (K)	Operation temperature	77

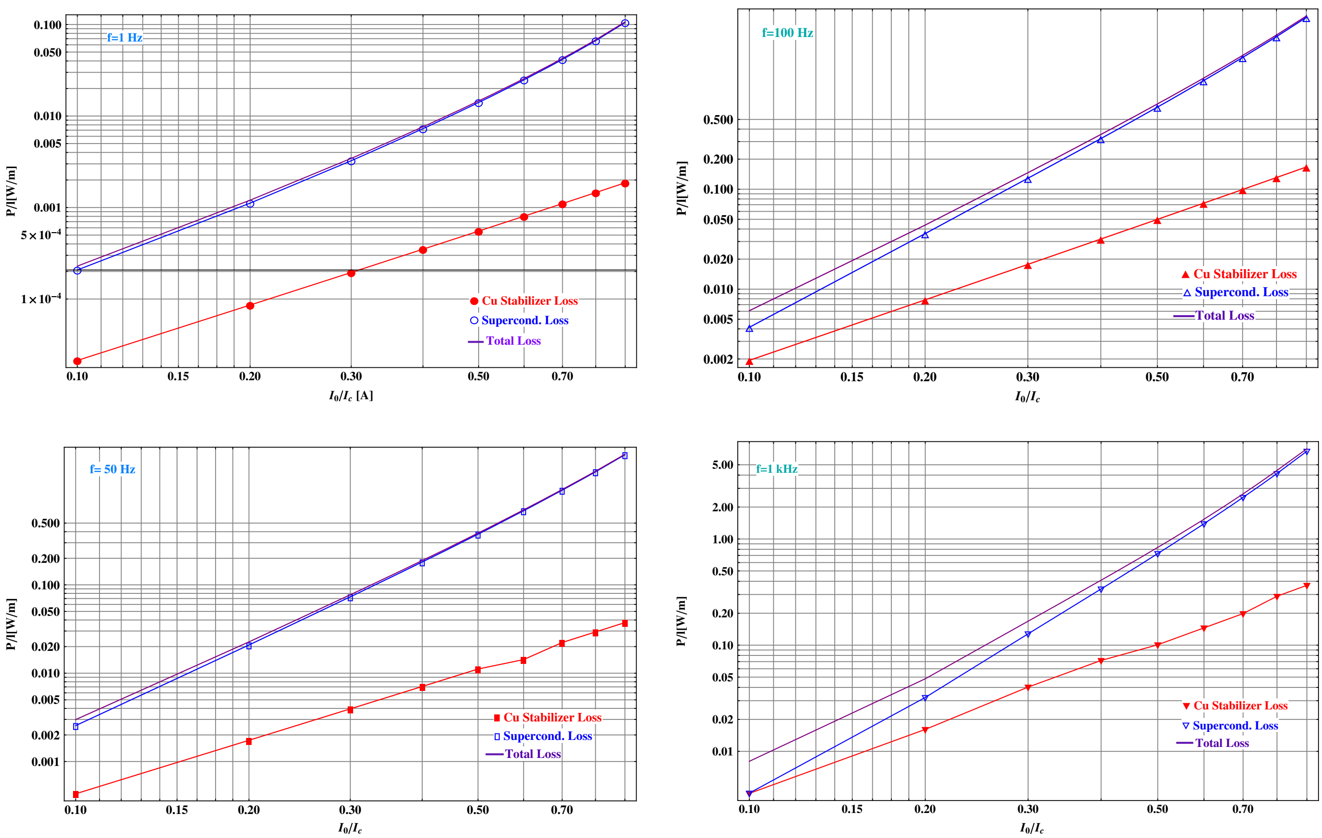

Fig. 2 Comparison of the current losses at different current frequencies at coils made of YBCO-coated conductors with the Cu stabilizers. At low frequencies, eddy current losses at the Cu stabilizers are very low compared to superconducting losses at high frequencies

as the surface integral of **J** over the cross section of the SC layer as follows:

$$I_t = \int \mathbf{J} \cdot d\mathbf{a} \tag{5}$$

where **a** is a surface element vector of the cross section over the superconducting tape. We have developed a new method based on the $A - V$ formulation for solving (1)–(4) using I_t.

Eddy currents are induced by the time variance of the magnetic fields produced by the current flowing through superconducting layers. The loss due to the eddy currents in the copper layer is ignored at low frequencies in the literature [22, 23, 26], whereas it becomes significant at high frequencies, since the penetration depth of the eddy currents in the copper layer decreases with the frequency via

$$\delta = \sqrt{\frac{2}{\sigma \mu f}} \tag{6}$$

where σ is conductivity, μ is relative permeability multiplied by the permittivity of vacuum, and f is the frequency of the applied current. We have exploited the field-dependent critical current density expression [30]:

$$j_c = \frac{J_c(T)}{\left(1 + \frac{\sqrt{k_a^2 B_{||}^2 + B_\perp^2}}{B_0}\right)^\beta} \tag{7}$$

where J_{c0}, B_0, and β are the parameters specifying the superconducting materials; k_a is the anisotropy parameter, taken as unity; and $B_{||}$ and $B_\perp$ are the parallel and perpendicular components of the magnetic flux density to the wide surface of the tapes, respectively. The temperature dependence of the critical current density is employed $J_c(T) = J_{c0}/(1 - T/T_c)^2$, where J_{c0} is the zero Kelvin critical current density. The parameters used in the calculation are given in Table 1.

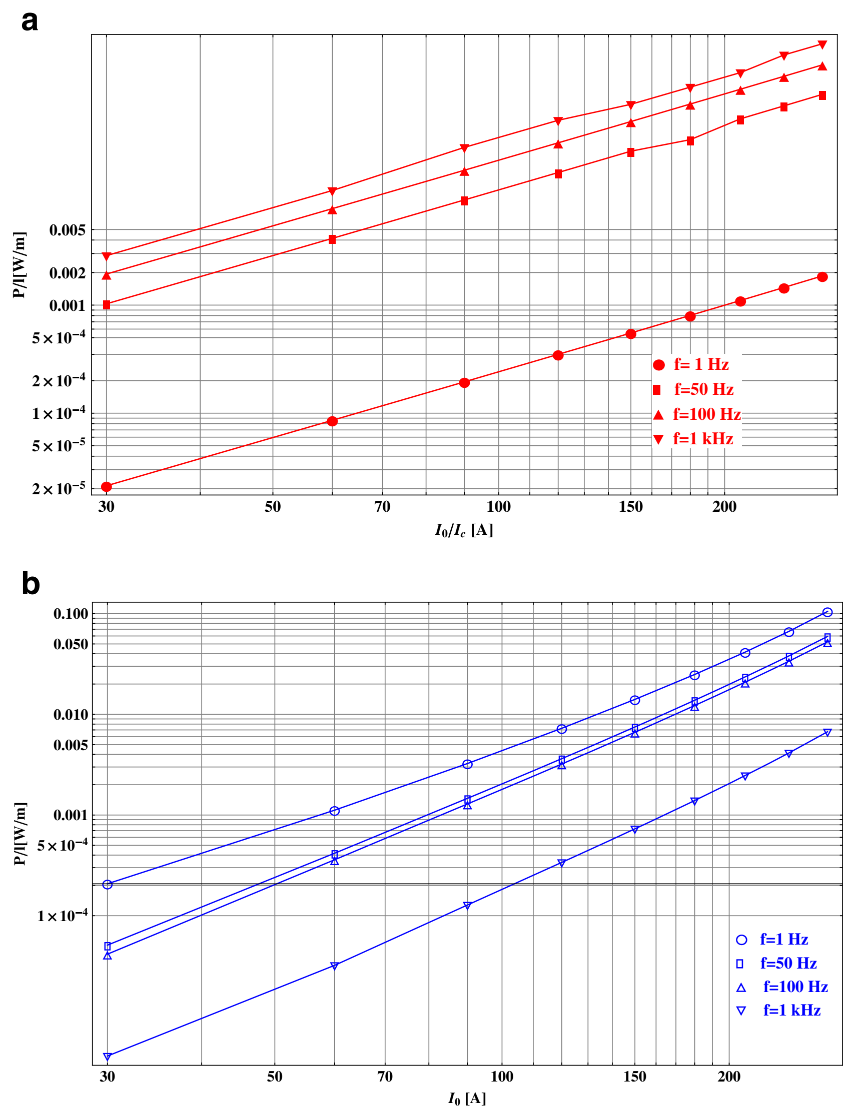

Fig. 3 The losses per cycle for the **a** Cu stabilizers and **b** superconducting tape for four frequencies

Specifications of the superconductors in the coils have been determined with (4). In pursuance of the equal amount of current flowing at each winding, the potential gradient in (2) has been set as a state variable. The linear conductivity of the copper stabilizer is given by

$$\sigma(T) = \frac{1}{\rho_0 \left(1 + \alpha \left(T - T_0\right)\right)} \tag{8}$$

where T_0 is the reference temperature, ρ_0 is the resistivity at the reference temperature, α is the temperature coefficient of resistivity, and T is the temperature at which the conductor operates. All the parameters chosen for the conductivity of the copper stabilizers are listed in Table 2.

3 Results and Discussion

The losses for superconductors at four frequencies and the eddy current losses for Cu stabilizers are compared in Fig. 2. The frequencies at which the losses are calculated are $f = 1$, 50, 100, and 1000 Hz. The time-averaged loss at the copper stabilizer is calculated using

$$P_{\mathrm{Cu}} = \frac{1}{S} \iint \frac{J^2}{2\sigma} dS \tag{9}$$

Since the critical current has a sinusoidal time dependence, its period average brings 1/2. The total eddy current loss is the sum of all the contributions of $2N$ copper windings

$$P_g = \sum_{i=1}^{2N} (P_{Cu})_i \tag{10}$$

As displayed in Fig. 2, altering the frequency has made significant changes on AC loss both for the Cu stabilizer and the superconducting layer. Loss is quite low at low frequencies for the stabilizers; however, it increases with the frequency. This is because the amplitude of the induced current is proportional to the frequency of the applied current [22]. Consider the frequency of $f = 50$ Hz, at which most of the high current transformers with the copper stabilizers perform. At low current amplitudes around $I_c/10$, the loss at the superconductor is almost 2.5 times higher than that of the Cu stabilizer. However, the situation totally changes for the current values around $I_0 \approx 0.8 I_c$, leading the P_s/P_{Cu} ratio to approach 33. This leads to the following conclusions: if a copper stabilizer is forced to work under low current amplitudes, heating process due to eddy currents must be taken into account for a new optimization. Contrarily, for the high current case, SC loss becomes dominant. For such structures, the losses at the copper stabilizers are high but negligible compared to losses due to the superconductors.

Considering the frequency of $f = 1000$ Hz, at low current amplitudes around $I_c/10$, the losses due to the superconductors and Cu stabilizers are comparable, whereas when $I_0 \approx 0.8 I_c$, the P_s/P_{Cu} ratio approaches 40. When superconducting coils are used, this phenomenon may play an important role for reducing AC loss in high-frequency induction furnaces.

There appears to be another important aspect regarding the losses in superconducting zones when $P_{sc} \propto I_0^3$. The total loss at Cu layers is proportional to I_0^2. This is reasonable since the currents induced at the Cu stabilizers face time-stable linear ohmic resistance resulting in ohmic heat. This is the main reason for amplitude dependence of the loss.

In Fig. 3, the period-averaged loss per cycle, which is the power per unit length divided by the frequency, is shown for both superconducting and Cu layers for four frequencies.

Figure 3a gives the calculated rates as functions of transport current amplitude for the Cu stabilizers. Note that the rate increases very steeply as frequency increases. The penetration of the induced eddy current decreases as frequency increases as given by (6). Since a high amount of current is forced to flow in a very confined area, at high frequencies, the resistance causes an increase in the loss. At very low frequencies, eddy currents fully penetrate the stabilizer. In this limit, the loss rates in the superconductor do not change since the copper stabilizers do not affect the magnetic field distribution at all.

Figure 3b shows the calculated rates as a function of transport current amplitude for the superconductors. This rate attenuates linearly due to a decrease in the current penetration with increasing frequency. On the other hand, the loss power per unit length, which is equal to the frequency times this rate, increases.

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