An Extended Thin Approximation Method to Simulate Screening Current in REBCO Coils

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Superconducting magnets wound with second-generation high-temperature superconductors, $REBa_2Cu_3O_{7-x}$ (REBCO, RE = Rare Earth) tapes, are desired to apply high magnetic field NMR, MRI, and accelerators. However, a main problem to practical application is an undesirable irregular magnetic field caused by screening currents induced in REBCO tapes. To investigate the screening current-induced magnetic field, a few simulation methods were developed. One of effective simulation methods employs a finite element method with a thin approximation method. Since the thin approximation method was developed to estimate eddy currents in magnetic steel sheets, it is not applicable to REBCO tapes carrying a transport current. Therefore, the thin approximation method is extended to simulation screening currents in REBCO tapes taking into account carrying a transport current.

***Index Terms*—HTS magnet, REBCO tape, screening current, thin approximation method.**

I. Introduction

RECENTLY, an ultra-high-field NMR magnet wound with REBCO tapes has been developed [1]. A crucial problem to develop such an NMR is an irregular magnetic field caused by screening currents induced in REBCO tapes. A screening current-induced magnetic field was measured in experiments [2], [3], and the behaviors of screening currents were confirmed in simulations [4], [5]. A slight nonuniform current distribution generates an irregular magnetic field of ppm-order, although NMR and MRI systems need magnetic field homogeneity less than a few ppm.

In the simulations [5], a thin approximation method [6], [7] was used, because the REBCO layer was very thin (1 μm). However, the thin approximation method was proposed to compute eddy currents in thin magnetic steel sheets [6]. Then, Hashizume *et al.* applied it to a simulation of shielding currents in high-temperature superconducting bulks [7]. In these simulations, the thin approximation method required three assumptions: (1) simulated materials are very thin, (2) the phenomenon is uniform in the thickness direction, and (3) there is no transport current in the materials.

Recently, the thin approximation method was employed in screening current simulations [5]. However, the assumption of no transport current was not satisfied although the simulation results agreed with measurements. Therefore, we have tried to develop a new thin approximation considering a transport current to simulate screening currents in REBCO tapes.

II. New Thin Approximation Method

To evaluate a screening current-induced magnetic field in detail, a current distribution, including an operating and screening currents, is simulated using 2D FEM with quadrangle mesh coupled with a new thin approximation.

A. Ordinary Thin Approximation

The current density in REBCO tapes is calculated from the following governing equation:

$$\nabla \times (\rho \nabla \times \boldsymbol{T}) = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

where $\boldsymbol{T}$, $\boldsymbol{B}$, and ρ are the current vector potential, the magnetic field, and the electrical resistivity, respectively. A REBCO tape is too thin to make a 3D mesh in the Cartesian (xyz) coordinates, hence the current distribution in the REBCO tape is considered as the 2D phenomenon in the uv space. Applying the thin approximation method for eddy current simulation [6], [7], (1) yields

$$\rho\left(\frac{\partial^2 T}{\partial u^2}+\frac{\partial^2 T}{\partial v^2}\right) -\frac{\mu_0 d}{4\pi}\frac{\partial}{\partial t}\int_S \frac{(\nabla T^{(s)}\times \boldsymbol{i})\times \boldsymbol{R}(x,y,z)}{R(x,y,z)^3}\cdot \boldsymbol{i}\mathrm{d}S = \frac{\partial B_\perp}{\partial t} \tag{2}$$

where T, μ_0, d, $T^{(s)}$, $\boldsymbol{R}(x,y,z)$, $\boldsymbol{i}$, and $B_\perp$ are the current vector potential in the uv system, the permeability of free space, the thickness of REBCO tape, the current vector potential at the source point, the distance vector toward the field point from the source point in the xyz system, the unit vector perpendicular to the REBCO tape surface, and the external magnetic field perpendicular to the REBCO tape surface, as shown in Fig. 1, respectively. The third term in left side of (2) represents the self-field generated by the coil itself. This term is computed from the interlinkage magnetic field perpendicular to the REBCO tape element, contributed from the currents of every element based on the Biot-Savart law.

B. New Thin Approximation Method

In simulation results obtained from the above thin approximation, an operating current flows along the edges of REBCO

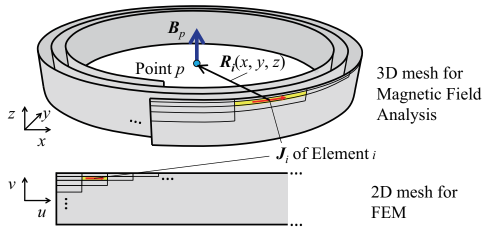

Fig. 1. The 2D quadrangle mesh allocated for magnetic field analysis in the Cartesian (xyz) coordinate (upper), and the 2D quadrangle mesh of the unwound REBCO tape in the local (uv) coordinate (lower).

tape. However, due to the magnetic field parallel to the wide surface of REBCO tape, a slight amount of operating current carries in the middle part of REBCO tape. Therefore, the magnetic field component parallel to the REBCO tape surface must be taken into account.

Here, the u-component of the magnetic field is regarded as 0 because of axisymmetric coil's shape. It is also assumed that the vector potential T linearly varies in the thickness direction:

$$T = \tilde{T} + \triangle T \frac{w}{d} \tag{3}$$

where $\tilde{T}$, $\triangle T$, and w are the current vector potential on one REBCO tape surface, and the difference of the current vector potential between the tape surfaces, and the position in the tape thickness direction.

From the governing equation (1), the following equation is obtained:

$$\rho \frac{\partial^2 T}{\partial v \partial w} = -\frac{\partial B_v}{\partial t}. \tag{4}$$

Here, the u- and v-components of current vector potential are assumed to be constant, because the REBCO layer is very thin. Integrating (4) with respect to the thickness, the following equation is yielded:

$$\rho \frac{\partial \triangle T}{\partial v} = -d \frac{\partial B_v}{\partial t}. \tag{5}$$

Considering the interlinkage magnetic fields of elements each other like the ordinary thin approximation, (5) is extended to

$$\rho \frac{\partial \triangle T}{\partial v} + \frac{\mu_0 d^2}{4\pi} \frac{\partial}{\partial t} \int_S \frac{(\nabla T^{(s)} \times \boldsymbol{i}) \times \boldsymbol{R}(x,y,z)}{R(x,y,z)^3} \cdot \boldsymbol{i}_v \mathrm{d}S$$
$$= -d \frac{\partial B_{ex,v}}{\partial t} \tag{6}$$

where $\boldsymbol{i}_v$ and $B_{ex,v}$ are the v-directional unit vector and the v component of external magnetic field, respectively.

Finally, the above two equations (2) and (6) are discretized by the 2D FEM in the proposed thin approximation method. A transport current is given as a boundary condition.

III. Application

A simulated REBCO magnet consists of 8 single pancake coils, as shown in Fig. 2. The critical current is 91.0 A, and the number of turns of all the REBCO pancake coils is 111. The operating current I linearly increases to 20 A with 10 A/min. The n-power law model, where $n = 23.5$, is taken into account as a non-linear E-J characteristic.

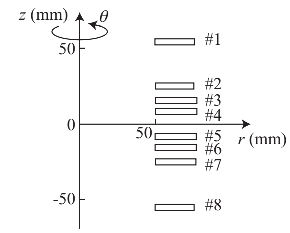

Fig. 2. Simulated magnet consisting of 8 single pancake coils.

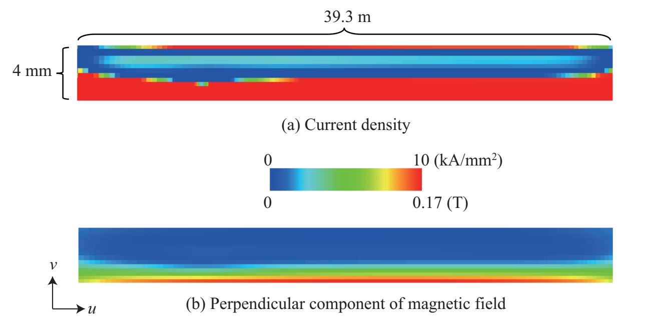

Fig. 3. (a) Current Distribution map, and (b) Perpendicular component of magnetic field of Coil #7, at $I = 20$ A.

Fig. 3 shows the current density distribution and the magnetic field perpendicular to the REBCO tape surface of coil #7 at $I = 20$ A. In Fig. 3, the maps are visualized on the virtually unwound REBCO tape. The most of operating current carry along the bottom edge of REBCO tape due to the screening current effect. However, a small amount of current flows on the upper middle of REBCO tape, although the magnetic field perpendicular to the REBCO tape surface is nearly zero there. From Fig. 3, the validity of the proposed thin approximation method to consider an operating current carrying is confirmed. In the extended paper, we compare the simulation results of the conventional and proposed thin approximation method.

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