Simulation of Screening Current Induced in YBCO Pancake Coil by 2D FEM with 3D Magnetic Field Analysis

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The effect of screening current in high temperature superconducting (HTS) double-pancake coil on generated magnetic field is investigated by experiments and numerical simulation all over the world. However, an YBCO tape is too thin to make a mesh in 3D space. Therefore, the common 3D FEM is inapplicable to the simulation of screening current. We try to model 2D finite element mesh into an YBCO tape of HTS coil in 3D space. In this paper, the reduction in the central magnetic field due to screening current-induced magnetic field is simulated by 2D finite element method in 3D space.

Index Terms—**HTS magnet, REBCO tape, screening current, superconducting magnet, YBCO-coated conductor.**

I. Introduction

HIGH TEMPERATURE SUPERCONDUCTING (HTS) is used for high field magnets such as MRI and NMR. Recently, a second generation (2G) HTS coated conductor has been attracting attention and expected to be applicable to these applications. In addition, these applications also require an extremely homogenous and temporally stable field below a few ppm. However, it was reported that 2G HTS magnets had a major problem that a screening current induced a spatially and temporally inhomogeneous field [1]-[4].

Since the structure of 2G HTS, e.g., YBCO tape, is very flat like a tape, a large amount of screening current is induced during charging a magnet wound with 2G HTS tape. The screening current, which is inhomogeneously distributed in YBCO tape [5], reduces the central magnetic field and generates the spatially inhomogeneous magnetic field. With a very long elapsed time the screening current is attenuates, and the central magnetic field reaches to the designed strength with designed high homogeneity.

To investigate the problem in detail, it is important to precisely simulate the current density in YBCO tape by finite element method (FEM). However, the YBCO tape is too thin to make a 3D mesh. Then, the current in the thin YBCO tape is assumed to be in 2D phenomenon, but the magnetic field created by the current is taken into account in 3D space. Consequently, we report a simulation method of 2D current density in 3D magnetic field and the simulation results. The simulation results show a reduction of approximately 2% in the central magnetic field compared to a magnet without screening current.

II. Computation Method of Screening Current

A. Current distribution simulation

The current density in an YBCO tape is simulated by 2D FEM. The governing equations are derived as follows:

$$\mathrm{rot}(\rho\,\mathrm{rot}\boldsymbol{T}) = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

where $\boldsymbol{T}$, $\boldsymbol{B}$, and ρ are the current vector potential, the applied magnetic field, and the equivalent electrical resistivity, respectively. The screening current can be simulated as a kind of eddy current. The thickness and width of YBCO layer in a tape is a few µm and a several mm, respectively, and it is too thin. Hence, it is hard that a whole magnet wound with YBCO tape is subdivided into a 3D mesh. Because of the thinness, the current inside YBCO tape is considered as 2D phenomenon, however the magnetic field is three-dimensionally simulated taking into account the 3D configuration of mesh, as shown in Fig. 1.

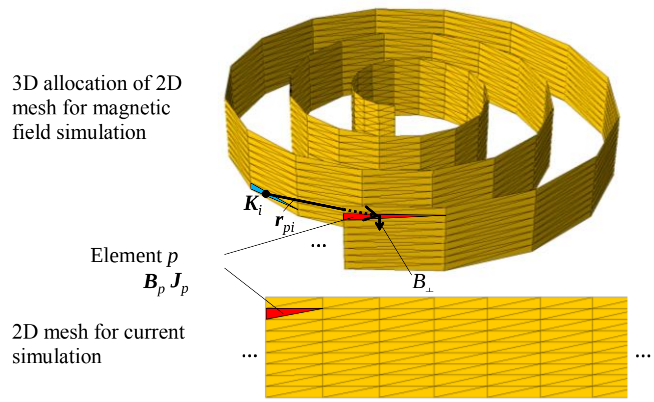

Fig. 1. For magnetic field simulation, 3D mesh is allocated (upper). For current distribution simulation, coil is straightly unwound and subdivided to 2D mesh (lower). Magnetic field $\boldsymbol{B}_p$ is calculated in 3D space superposing current of every element. $B_\perp$ is the perpendicular component of $\boldsymbol{B}_p$ to YBCO tape.

For the current density simulation, the YBCO tape is considered as a straightly unwound shape. Hence, using the applied magnetic field perpendicular to the tape $B_\perp$, (1) yields

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

where d, $T^{(s)}$, $\boldsymbol{R}$, and $\boldsymbol{n}$ are the thickness of YBCO tape, the current vector potential at the source point, the vector toward the field point from the source point, and the vector normal to YBCO tape in 3D space. $B_\perp$ is computed in 3D space by Biot-Savart law. The equivalent electrical resistivity ρ is obtained from the E-J nonlinear characteristics of YBCO tape.

B. Magnetic field computation

All the current density of respective elements are obtained by the 2D simulation mentioned above. To investigate the effect of screening current, the contribution of respective elements to magnetic field is computed based on the Biot-Savart law. The magnetic field $\boldsymbol{B}_p$ generated by the current of all the elements in 3D space is given as

$$\boldsymbol{B}_p = \frac{\mu_0}{4\pi}\sum_{i=1}^{n_e}\int_\theta\int_z \frac{\boldsymbol{K}_i \times (\boldsymbol{r}_p - \boldsymbol{r}_i)}{r_{pi}^{\ 3}} r_{ci} \mathrm{d}z\mathrm{d}\theta \quad (3)$$

where μ_0, $\boldsymbol{K}_i$, $\boldsymbol{r}_p$, $\boldsymbol{r}_i$, r_{pi}, r_{ci}, and n_e are the permeability of free space, the sheet current density of the *i*th element, the position vector of the field point and the *i*th element, the distance between these two points, the radius of the *i*th element, and the number of the elements, respectively. As shown in Fig. 1, the perpendicular component of computed $\boldsymbol{B}_p$ to the YBCO tape is substituted for $B_\perp$ of (2).

III. Screening Current Simulation Results

In this paper, charging of a double-pancake coil wound with YBCO-coated conductor tape is simulated. Tables I and II list the specifications of the YBCO coil and tape. The coil temperature is 4.2 K, and the coil is charged from 0 to 30 A with a current sweep rate of 1.0 A/s.

TABLE I
SPECIFICATIONS OF YBCO DOUBLE-PANCAKE COIL

Outer diameter (mm)	109.0
Inner diameter (mm)	18.0
Length of coil (mm)	8.3
Number of turns	499
Total length of YBCO tape (m)	98.8

TABLE II
SPECIFICATIONS OF YBCO TAPE

Width of YBCO tape (mm)	4.0
Thickness of YBCO tape (mm)	0.1
Thickness of YBCO layer (μm)	1.0

A. Current distribution

Fig. 2 shows the current density distribution in YBCO tape when the transport current is 30 A. It is expected that when a tape wire has high resistance like copper, the current flows homogeneously inside the tape. However, the large amount of screening current is induced in the YBCO tape by self-magnetic field due to almost zero resistivity, in fact, the current density is inhomogeneous, as shown in Fig. 2.

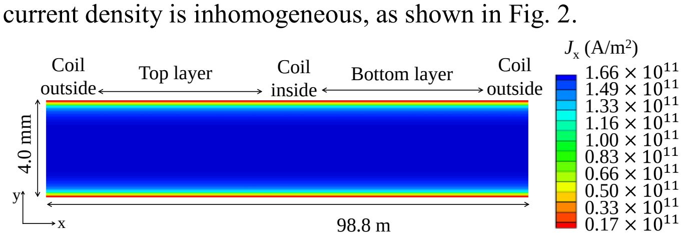

Fig. 2. Current density distribution of YBCO tape at 30 A (not to scale).

B. Central magnetic field

Fig. 3 shows the simulated central magnetic field B_c of YBCO coil. In Fig. 3, B_I shows the central magnetic field when the current homogenously flows inside the tape. B_c is smaller than B_I. This is because the screening current-induced magnetic field reduces the central magnetic field. Fig. 4 shows the difference between B_c and B_I and the relative error. The central magnetic field B_c is approximately 2% small compared with the ideally generated central magnetic field B_I.

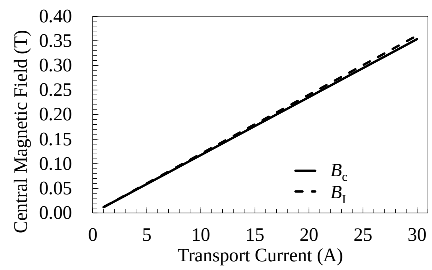

Fig. 3. Simulated central magnetic field of YBCO coil and central magnetic field generated by homogeneous current.

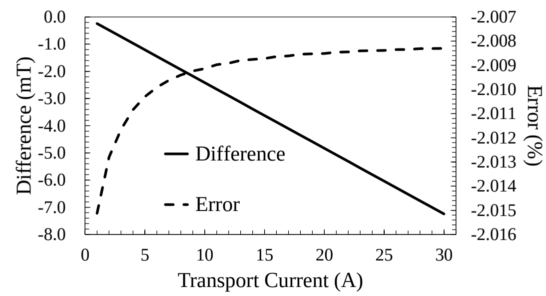

Fig. 4. Difference between B_c and B_I and relative error.

IV. Conclusion

We investigate the effect of screening current of YBCO double-pancake coil on the central magnetic field by using 2D FEM in 3D space. It is confirmed that the screening current-induced magnetic field reduces the central magnetic field.

We will show the more detailed simulation results in the full paper, e.g., the temporal transition of central magnetic field and the magnetic field inhomogeneity around the center.

V. References

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