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Performance improvement of a high-temperature superconducting coil by separating and grading the coil edge

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ABSTRACT

In this paper, we establish a model to analyze the transport current performance of a high-temperature superconducting (HTS) coil, considering the dependencies of critical current and *n*-value of an HTS tape on magnetic field and magnetic field angles. This analysis shows that relatively large electric fields appear at the coil's edges, preventing improvement in the transport current performance of the coil. To solve this problem, in this paper, we propose a graded coil in which several coil edges of different heights are separated and graded. Analysis of its performance shows that the coil's critical current increases, thus confirming that there exists an optimum coil cross section at which the stored energy and central magnetic field improve 2.1 times and 45%, respectively, compared with a typical rectangular coil that employs the same total length of the HTS tape. It is recommended that these results of the coil should be applied to SMES.

1. Introduction

Recent studies have investigated the benefits of high-temperature superconductors (HTS). These superconductors have lower refrigeration costs, but components such as HTS tapes are expensive. In this study, we propose a new HTS coil that can be manufactured at lower costs, maintaining its good performance.

The critical current and *n*-value of Bi-2223/Ag tapes generally depend on the applied magnetic field and magnetic field angles at a constant temperature [1,2]. The critical current and *n*-value were measured at various magnetic fields and magnetic field angles at 77 K. As a result, we obtained fitting equations for the magnetic field and magnetic field angle parameters. Employing these equations, we have calculated the coil's critical currents. This process revealed that relatively large electric fields occur at the edges of the coil [3], because large magnetic fields and magnetic field angles appear in the HTS tapes at the coil edges. If the magnitude of these electric fields is reduced, the transport current performance of the coil will improve, and other important coil characteristics, such as central magnetic field and stored energy, will also increase.

To pursue these improvements, we studied an HTS coil with several separated coils at the edges [4]. Based on the concept of this separation, the present paper reports further improvements by varying the heights of the separated coils while maintaining the total HTS tape length constant. This graded separation results in much larger improvements than the use of separated coils of constant height. The stored energy improves by 2.1 times and the central magnetic field increases by 45% compared with a coil of rectangular cross section wound with the same length of the HTS tape. Since the graded coil is based on the fundamental and general properties of critical current and *n*-value of an HTS tape, i.e., anistropic properties, and even though the scale of it is varied, performances of the coils will be displayed. In particular, the coil is suitable to SMES.

2. Fitting equations of an HTS tape

First, we must be able to analyze the transport current performance of an HTS coil. For this purpose, it is necessary to obtain the critical current and *n*-value equations for the HTS tape, which have magnetic field and magnetic field angle parameters. Thus, we measured the critical currents and *n*-values of a Bi-2223/Ag tape with various magnetic fields and magnetic field angles at 77 K. The width of the tape is 4.0 mm, the thickness 0.2 mm and the silver ratio 1.3. From the measured data, fitting equations with parameters of magnetic field and magnetic field angle are derived as follows.

$$I_c(B,\theta) = 63.9\exp\{-f(\theta)\times B\} \quad (1)$$

$$f(\theta) = 1.8 + 6.4\times10^{-3}\theta + 8.2\times10^{-3}\theta^2 - 2.4\times10^{-4}\theta^3 + 3.16\times10^{-6}\theta^4 - 1.47\times10^{-8}\theta^5 \quad (2)$$

$$n(B,\theta) = 17.2\exp\{-g(\theta)\times B\} \quad (3)$$

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$$g(\theta) = -1.81 \times 10^{-9} \times \theta^5 + 5.10 \times 10^{-7} \times \theta^4 - 4.87 \times 10^{-5} \times \theta^3 + 1.29 \times 10^{-3} \times \theta^2 + 0.06 \times \theta + 0.97 \quad (4)$$

where I_c (A) is the critical current, n the n value, B (T) the magnetic field and θ (°) the magnetic field angle to the tape, respectively.

3. Analysis of transport current performance of an HTS coil

Employing the equations presented in Section 2, we can analyze the transport current performance of an HTS coil as follows.

(1) Analyze the magnetic field distribution within the coil cross section to obtain the magnitude of the magnetic field and magnetic field angles in each tape.
(2) Calculate the voltage in each tape using Eqs. (1)–(4).
(3) Sum the voltages within the entire cross section of the coil.

By following the above procedure, we obtained each coil's voltage in terms of its current. Table 1 shows the specifications of the HTS coil, which is the original coil produced from the Fabry factor constant curve [5]. Graded coils will be designed from this coil.

Fig. 1 shows the current–voltage characteristics of the HTS coil presented in Table 1. The critical current of this coil is 13.8 A. Figs. 2 and 3 present the distribution of magnetic fields and the flux lines, respectively, at the above critical current. As shown in these figures, edges of this coil are subjected to strong magnetic fields and magnetic field angles; that is, the critical currents of the tape in these portions are particularly low. Therefore, as shown in Fig. 4, relatively large electric fields are generated at the coil edges.

4. Graded coil

As discussed in the previous section, we must reduce the magnetic field angles at the edges of the coil to obtain large coil critical current. In our previous study, we fabricated an HTS coil with several separated coils at the edge [4]. A schematic of the coil and cross section are shown in Fig. 5a and b respectively. This coil has a smaller magnetic field angle and a higher critical current than a typical rectangular coil. Thus, the central magnetic field and stored energy improved by 13% and 43%, respectively, at the optimum number of separated coils (eight) [4].

To further improve the HTS coil, in this paper, we propose a graded coil, i.e., assign different heights to each separated coil

Table 1
Specifications of an original HTS coil.

Number of turns	6548
Inner diameter (mm)	50
Outer diameter (mm)	160
Height (mm)	100
Inductance (H)	2.1

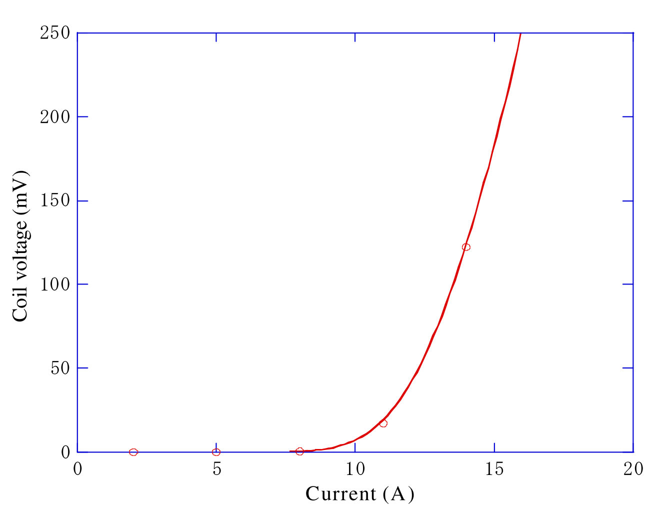

Fig. 1. Current–voltage characteristics of HTS coil (a voltage in definition is 110 mV).

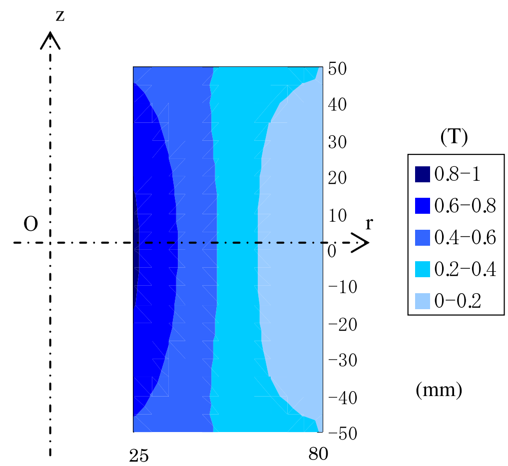

Fig. 2. Magnetic field distribution at critical current.

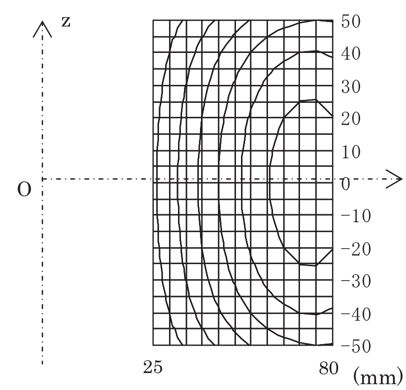

Fig. 3. Flux lines at critical current.

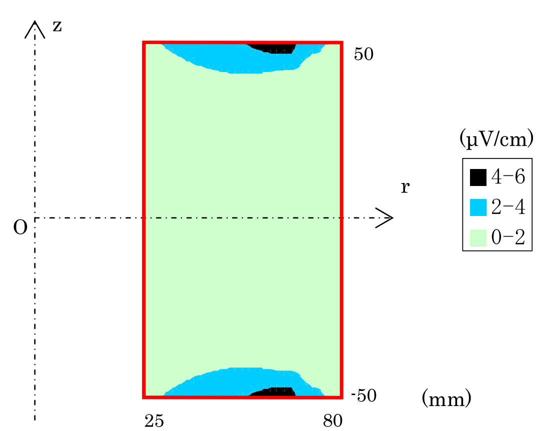

Fig. 4. Electric field distribution.