

Electrical and thermal characteristics of Bi2212/Ag HTS coils for conduction-cooled SMES

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Abstract. In this paper, we investigated the electrical and thermal performance of conduction-cooled Bi2212/Ag HTS coils with 4K-GM cryocooler system. First, we measured the critical current I_c for different ambient temperatures T_0 at 4.2 K - 40 K. Experimental results revealed that I_c increased with the decrease in T_0 and was saturated at $T_0 < 10$ K. We carried out thermal analysis considering heat generation, conduction and transfer under conduction-cooling condition, and reproduced the electrical and thermal characteristics of the conduction-cooled HTS coil, taking account of temperature dependence of specific heat and thermal conductivity of the materials. We also measured the temperature rise of Bi2212/Ag HTS coil for different continuous current levels at $T_0 = 4.8$ K. Experimental results revealed the criterion of thermal runaway, which was discussed in terms of heat generation and propagation in the test coil.

1. Introduction

Superconducting magnetic energy storage (SMES) with high efficiency and response rapidity is expected to play a significant role in the highly reliable electric power system [1]. In the past few decades, a large number of studies have been made on SMES using LTS [2]. In recent years, SMES using conduction-cooled HTS such as Bi2212/Ag with GM cryocooler system has also been investigated, because of its high current density under high magnetic field environment at the temperature lower than 20 K [3]. However, the optimum operating condition of HTS SMES has not so far been discussed. Especially, thermal runaway characteristics in conduction-cooled HTS coils are important to discuss the operating condition of SMES.

From the viewpoint mentioned above, in this paper, we investigated the electrical and thermal performance of conduction-cooled Bi2212/Ag HTS coils with 4K-GM cryocooler system. We measured the critical current at 4.2 K - 40 K, and verified by thermal analysis under conduction-cooling condition. We also measured the temperature rise of Bi2212/Ag HTS coils for different continuous current levels, and discussed thermal runaway criterion of conduction-cooled Bi2212/Ag HTS coils.

2. Test Coil and conduction-cooling system

Specifications of the test coil sample are shown in table 1. The sample is 4-layer solenoidal coil composed of Bi2212/Ag wire with 40 turns on each layer[4]. The coil is impregnated with epoxy resin and conduction-cooled by 4K-GM cryocooler through vertical aluminium plates fixed on the outermost layer of the coil.

Arrangement of the coil is shown in figure 1. To measure temperature and voltage distributions of the coil, 5 thermocouples (t_1 - t_5) and 5 voltage taps (v_1 - v_5) are arranged as indicated in figure 1. The initial temperature T_0 of the coil was controlled from 4.2 K to 40 K by the heater at the cold head.

Table 1. Specifications of test coil sample.

Material	Bi2212/Ag
Ag rate (Ag/Bi2212)	3.0
Diameter of wire	1.02 mm
Coil inner diameter	64 mm
Coil outer diameter	79 mm
Coil height	76 mm
Number of layers	4
Number of turns	40 turns/layer
Inductance	1.12 mH
Total length	36.0 m

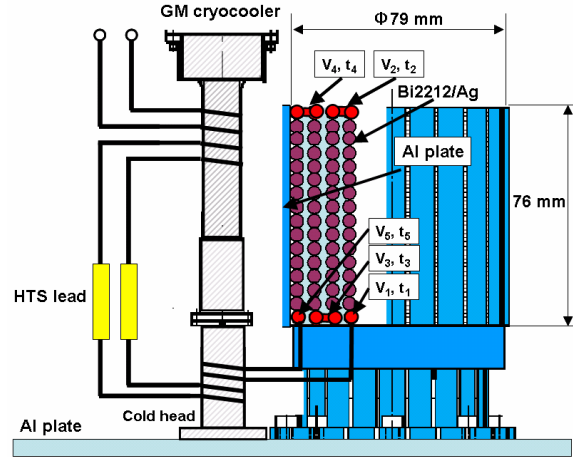


Figure 1. Arrangement of test coil sample.

3. Critical current characteristics

3.1 Experimental results

We injected dc current to the coil with the increment of 20 A/s, and obtained the temporal evolution of coil voltage in each layer. On the increase in the injected dc current, critical current I_c was obtained with the criterion of $1 \mu\text{V}/\text{cm}$.

Figure 2 shows the temporal evolution of current and coil voltage in each layer at initial temperature $T_0 = 4.9 \text{ K}$. The voltage in the innermost layer increased rapidly as the current increased. Figure 3 shows the T_0 dependence of I_c . I_c increased with the decrease in T_0 at $T_0 > 10 \text{ K}$, and was saturated at $T_0 < 10 \text{ K}$. In addition, compared with I_c in terms of the whole coil, I_c of the innermost layer was smaller by approximately 10 %, which may be attributed to the higher magnetic field strength as well as the less effective conduction-cooling in the innermost layer.

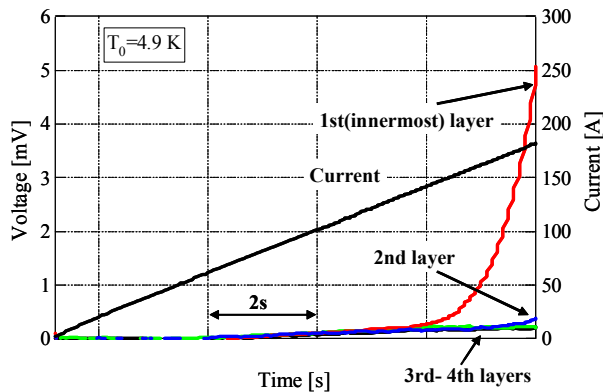


Figure 2. Temporal evolution of current and coil voltage in each layer at $T_0 = 4.9 \text{ K}$.

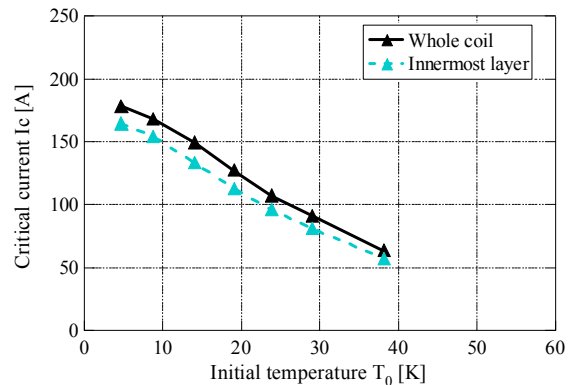


Figure 3. Critical current I_c as a function of initial temperature T_0 .

3.2 Thermal analysis

In order to discuss the experimental results on $I_c - T_0$ characteristics, thermal analysis considering the axially symmetric cross section of the test coil sample was carried out.

3.2.1 *Calculation model.* The temperature distribution in the Al plate is obtained by equation (1),

$$C_{Al} \frac{\partial T_{Al}}{\partial t} = \frac{\partial}{\partial x} \left(\kappa \frac{\partial T_{Al}}{\partial x} \right) + q_{cond}(x) \quad (1)$$

where C_{Al} , T_{Al} and κ are the specific heat, temperature and thermal conductivity of the Al plate, respectively, q_{cond} is the heat flux from the HTS conductor on the outermost layer to the Al plate. Two-dimensional temperature distribution in the HTS coil area can be calculated by considering heat generation Q at small HTS segments, each dimension of which is 1.8 mm (width) x 14.4 mm (height). Temperature rise in each HTS segment is obtained by equation (2),

$$C_{sc} \frac{\partial T_{sc}}{\partial t} = Q - q \quad (2)$$

where C_{sc} and T_{sc} are the specific heat and temperature of the Bi2212/Ag, q is the heat flux between adjacent HTS segments. Heat generation Q at HTS segments is represented by following equation,

$$Q = E \cdot I_{in} = E_c \left(\frac{I_{in}}{I_{c0}(B, T)} \right)^{n(B)} \cdot I_{in} \quad (3)$$

where E is the voltage in HTS segments, I_{in} is the injected current, I_{c0} is the intrinsic critical current depending on the temperature and magnetic field in case of better cooling condition such as in GHe. E_c is the voltage in HTS segments with the criterion of 1 μ V/cm, and n represents n-value depending on magnetic field. Then, we increased I_{in} with the increment of 20 A/s at the initial temperature T_0 , and calculated the voltage and temperature evolutions in the test coil sample.

3.2.2 *Calculation results and discussion.* Figure 4 shows experimental and calculation results on temporal evolution of coil voltage in each layer at $T_0 = 4.9$ K. Calculation results agreed well with the experimental ones, including the concentration of voltage in the innermost layer. Figure 5 shows the $I_c - T_0$ characteristics in experiment and calculation. Calculation results could reproduce the experimental $I_c - T_0$ characteristics with the saturation tendency at $T_0 < 10$ K.

Saturation of I_c in conduction-cooling condition can be interpreted by the temperature dependence of specific heat and thermal conductivity of the materials[4]. The specific heat of Bi2212/Ag and aluminum at the cryogenic temperature decreases with the temperature decrease. On the other hand, thermal conductivity of aluminum has maximum value at about 30 K, i.e. decreases with the temperature decrease at $T < 30$ K. Thus, especially at $T < 30$ K, the temperature of HTS conductor can easily heat up, in other words, conduction-cooling performance may become poor.

4. Thermal runaway characteristics

In this section, we measured thermal runaway characteristics of conduction-cooled Bi2212/Ag coil at $T_0 = 4.8$ K. We injected constant current lower than $I_c = 178$ A at $T_0 = 4.8$ K in figure 3. Figure 6 shows the temporal evolutions of average coil temperature, which is the average of 5- thermocouples outputs, for different current level I . In case of $I > 145$ A, the average coil temperature increased rapidly within the time range of 600 s, and the coil fell into the thermal runaway.

The thermal runaway of the coil can be discussed in terms of the temporal evolution of temperature and voltage in each coil layer as shown in figure 7. At $t < 400$ s, the temperature difference existed in each coil layer, which would be caused by heat invasion from current leads, because T_1 and T_5 of innermost and outermost layers were higher than the others. The voltage V_{12} at the innermost layer started to increase, due to the higher magnetic field strength as well as the less effective conduction-cooling. This could induce the further temperature rise of the innermost layer, and propagated in the whole coil, which can be confirmed by that the temperature in each layer

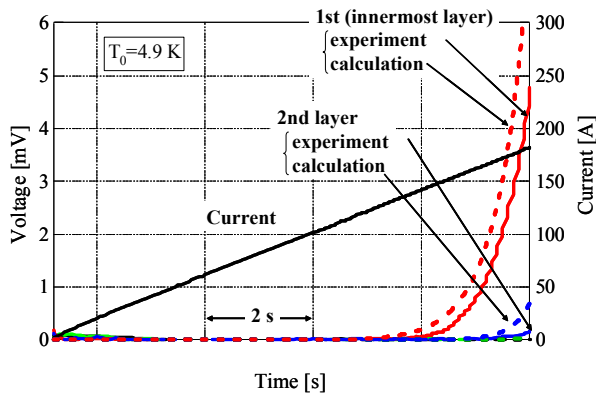


Figure 4. Experimental and calculation results on temporal evolution of coil voltage in each layer at $T_0 = 4.9$ K.

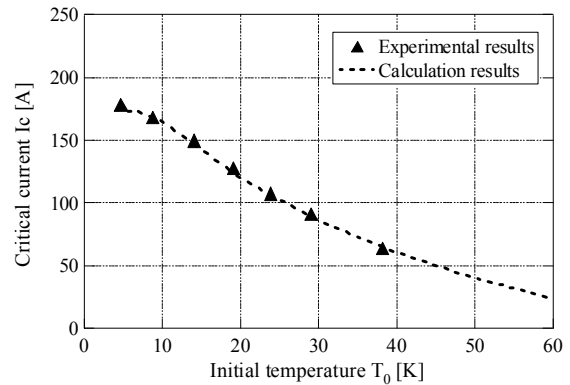


Figure 5. Experimental and calculation results on I_c as a function of T_0 .

became homogeneous at $t > 600$ s. Thus, the heat generation in the innermost layer became dominant in the temporal evolution of temperature in the whole coil, and resulted in thermal runaway. In this case at $T_0 = 4.8$ K, the criterion of thermal runaway was $I = 145$ A, which corresponded to about 80 % of I_c .

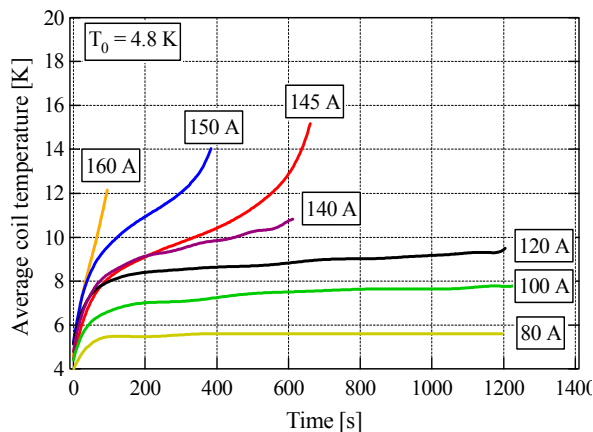


Figure 6. Temporal evolutions of average coil temperature for different current.

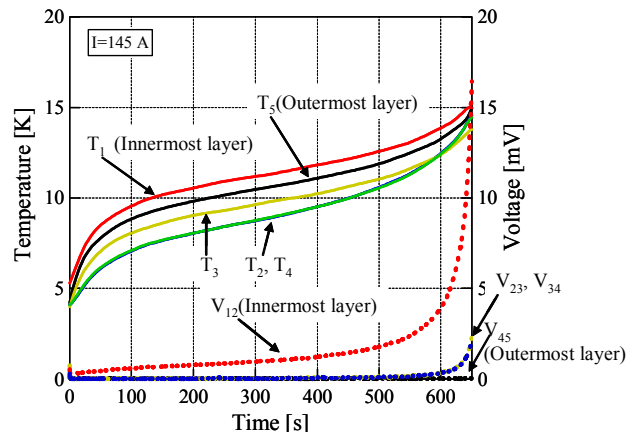


Figure 7. Temporal evolution of temperature and voltage in each layer.

5. Conclusion

We investigated electrical and thermal characteristics of the conduction-cooled Bi2212/Ag HTS coil for SMES application. First, we obtained critical current I_c at 4.2K-40K by experiment and thermal analysis. Due to the temperature dependence of thermal conductivity and specific heat of materials, I_c increased and was saturated with the decrease in the ambient temperature lower than 10 K. Secondly, we obtained thermal runaway characteristics at the initial temperature of 4.8 K, and then discussed the criterion of thermal runaway in terms of the heat generation and propagation in the test coil.

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