Thermal Runaway Characteristics of Bi2212 Coil for Conduction-Cooled SMES

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***Abstract*—In this paper, we investigated the thermal runaway characteristics of a conduction-cooled Bi2212 HTS coil with a 4 K-GM cryocooler system under compensating operation for load fluctuations. We measured the temporal evolutions of temperature and voltage distributions of the HTS solenoidal coil for typical current patterns of load fluctuation compensation at different ambient temperatures. On the basis of these experimental results, we constructed a thermal analysis model, and analysed the thermal runaway characteristics during and after the load fluctuation compensation. Based on the results of our experiments and the numerical simulations, we proposed criterion for the monitoring of an HTS SMES system during compensating operation for load fluctuations.**

***Index Terms*—Bi2212, conduction-cooling, SMES, thermal runaway.**

I. Introduction

Superconducting magnetic energy storage (SMES) with high efficiency and response rapidity is expected to play a significant role in highly reliable electric power systems [1]. In the past few decades, a large number of studies have been performed on SMES using LTS materials. More recently, SMES using conduction-cooled HTS materials such as Bi2212 with a GM cryocooler system has been investigated [2]–[6], because of its high current density under high magnetic field environments at temperatures lower than 20 K [7]. However, the conduction-cooled SMES system may cause thermal runaway during its charging and discharging operation. For reliable operation of the conduction-cooled HTS SMES system, the thermal runaway characteristics of Bi2212 coils should be evaluated and further understood.

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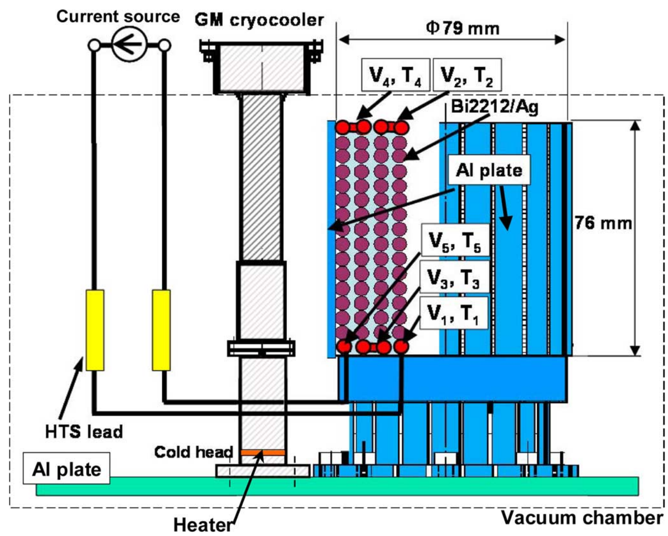

Fig. 1. Arrangement of test coil.

The operating conditions of thermal runaway of HTS SMES coils under a fixed current, or under ac operation applying several hertz, have been discussed [8]. However, under compensating operation for load fluctuations, current, voltage and temperature of a SMES coil always change at the frequency below several hertz. Therefore, in order to protect the SMES coil from the risk of thermal runaway during operation, we have to monitor and detect thermal runway from these time varying parameters.

From the perspective mentioned above, in this paper, we investigated thermal runaway characteristics of a conduction-cooled Bi2212 HTS coil under load fluctuation compensating operation. We measured the temporal evolutions of temperature and voltage in the coil for typical current patterns of load fluctuation compensation. A thermal analysis model was constructed which reproduced the experimental results. From the simulation results using this analytical model, as well as the experimental results, we discovered the upper limit of the operating point where the SMES coil could recover into standby condition without thermal runaway, i.e. criteria for the operating conditions of HTS SMES systems was proposed for load fluctuation compensation.

II. Experimental Setup and Results

Arrangement and specifications of the test coil are shown in Fig. 1 and Table I. The test coil is a 4-layer solenoidal coil composed of Bi2212/Ag wire with 40 turns on each layer [9]. The coil is impregnated with epoxy resin and conduction-cooled by a 4 K-GM cryo-cooler through vertical aluminum plates fixed

TABLE I
SPECIFICATIONS OF TEST COIL

Material	Bi2212
Ag ratio (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 of wire	36 m

on the outermost layer of the coil. Critical current I_c of the test coil at 4.8 K is 178 A.

To measure the 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 Fig. 1. The operating temperature T_0 of the coil can be controlled from 5.6 K to 20 K by the heat balance between the cryocooler and the heater at the cold head.

We injected a typical current pattern for load fluctuation compensation to the test coil, and measured the temporal evolutions of temperature and voltage in the coil. Fig. 2 shows the typical temporal evolutions of voltage and temperature in the test coil for a load fluctuation compensating current pattern. The coil temperature and voltage increased as time passed. Then, at the 5th cycle, the voltage at the innermost layer $(V_1 - V_2)$ rapidly increased, leading to thermal runaway.

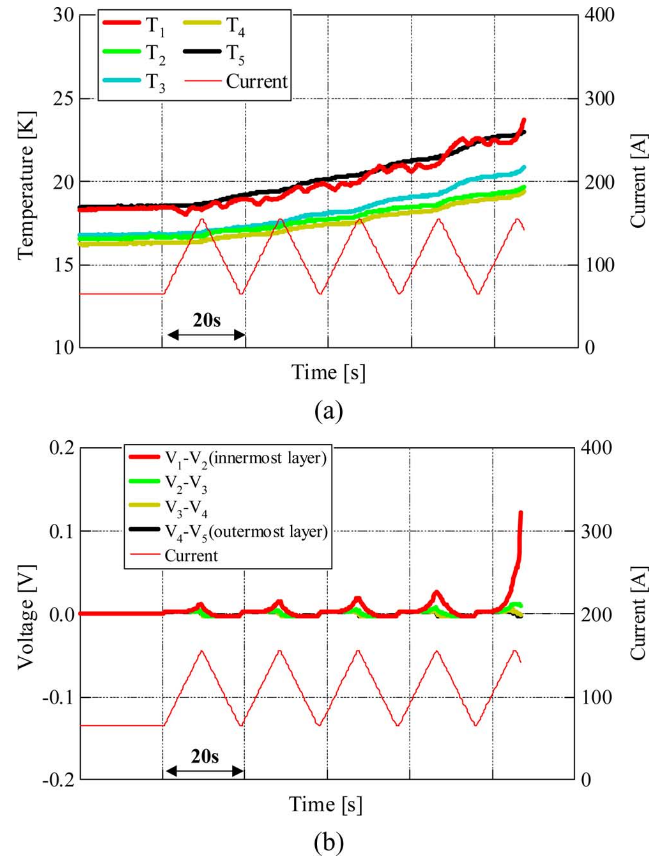

Fig. 2. Experimental results on temporal evolutions of voltage and temperature in test coil sample (standby current $I_0 = 65$ A, operation temperature $T_0 = 17.3$ K). (a) Temporal evolutions of temperature in the coil. (b) Temporal evolutions of voltage in each layer.

III. Thermal Analysis Model

On the basis of experimental results obtained in the previous section, a thermal analysis model considering the axially symmetric cross section of the coil sample was constructed.

The temperature distribution in the Al plate was obtained by

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

where C_{Al} [J/(m$^3 \cdot$ K)], T_{Al} [K] and κ [W/(m $\cdot$ K)] are the specific heat, temperature and thermal conductivity of the Al plate, respectively, q_{cond} [W/m^3] 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 [W] at the HTS segments. Temperature rise in each HTS segment is obtained by

$$C_{\mathrm{sc}} \frac{\partial T_{\mathrm{sc}}}{\partial t} = Q - q, \tag{2}$$

where C_{sc} [J/K] and T_{sc} [K] are the heat capacity and temperature of the Bi2212 in each HTS segment, q [W] is the heat flux between adjacent HTS segments. Heat generation Q at the HTS segments is represented by the following equation,

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

where E [V] is the voltage in the HTS segments, I_{in} [A] is the injected current, I_{c0} [A] is the critical current depending on the temperature and magnetic field. E_{c} [V] is the voltage in the HTS segments with the criterion of 1 μV/cm, and n represents n-value depending on the magnetic field.

Calculation results using this analytical model agreed well with the experimental ones shown in Fig. 2.

IV. Criterion of Thermal Runaway During Load Fluctuation Compensation

A. *Definition of Thermal Runaway During Operation*

During the load fluctuation compensation, current, voltage and temperature of the SMES coil change with time. We assume that the SMES coil has the rated operating values of temperature T_0 and current I_0 in the standby condition. The compensating operation finishes at a certain temperature T_{i} and current I_{i}, and the coil current returns to I_0, as shown in Fig. 3. If the temperature of the SMES coil returns toward T_0, such a response can be regarded as stable recovery. However, if the temperature rises again during the current decay or after reaching I_0, it can be regarded as thermal runaway. Then, as a criterion of thermal runway, we define the upper limit of the operating point $(T_{\mathrm{i}}, I_{\mathrm{i}})$ as the point at which thermal stability can be maintained during the recovery process.

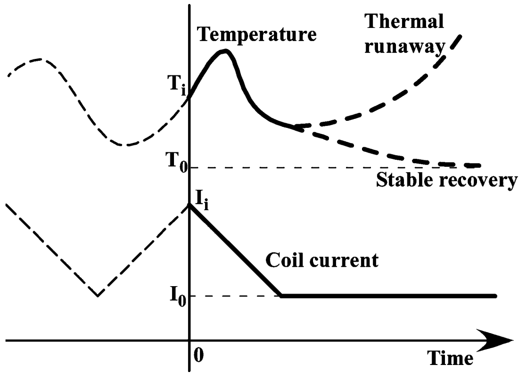

Fig. 3. Calculation patterns of injected current and typical temporal evolutions of coil temperature.

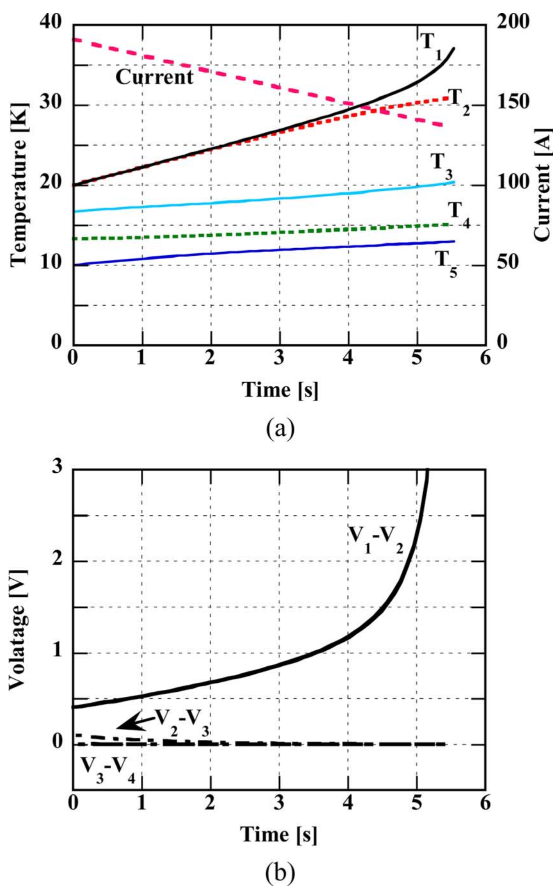

Fig. 4. A typical case of thermal runaway during current decay ($T_0 = 10$ K, $I_0 = 65$ A, $T_\mathrm{i} = 20$ K, and $I_\mathrm{i} = 191$ A). (a) Temporal evolutions of coil temperature and current. (b) Temporal evolutions of resistive voltage.

B. Temporal Evolutions of Coil Temperature and Voltage

The thermal analysis was conducted to find out the criterion of the thermal runaway. Here, $\mathrm{d}I/\mathrm{d}t = -10$ A/s was fixed at $T_0 = 10$ K, critical current I_c was 164 A, and the upper limit of constant current in which the thermal runaway does not occur was 160 A [9].

Fig. 4 shows a typical case of the thermal runaway during the current decay; temporal evolutions of (a) coil temperature and current, and (b) resistive voltage at each layer in the case of $I_0 = 65$ A, $T_\mathrm{i} = 20$ K, and $I_\mathrm{i} = 191$ A. In this case, during the current decay process toward I_0, the innermost temperature T_1 and the voltage $V_1 - V_2$ increased sharply, i.e. thermal runway occurred.

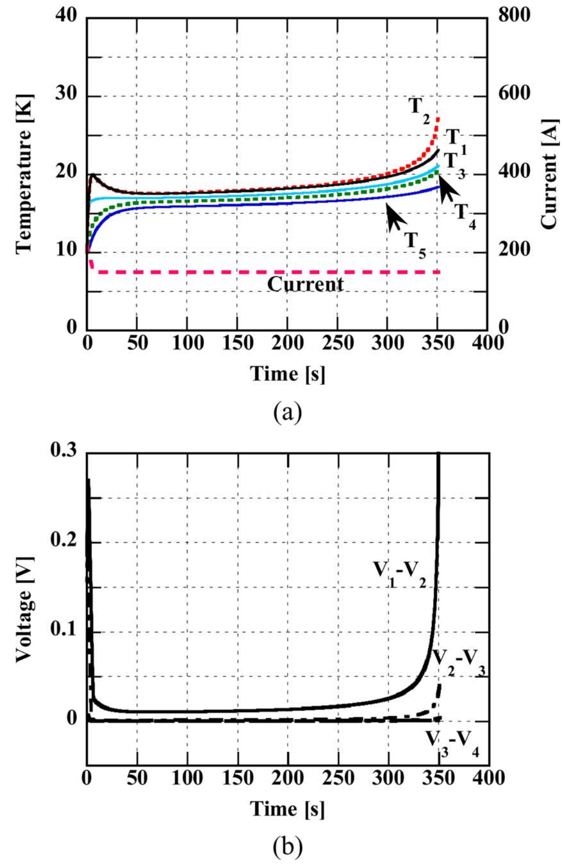

Fig. 5. A typical case of thermal runaway after reaching standby current ($T_0 = 10$ K, $I_0 = 150$ A, $T_\mathrm{i} = 10$ K, and $I_\mathrm{i} = 219$ A). (a) Temporal evolutions of coil temperature and current. (b) Temporal evolutions of resistive voltage.

Fig. 5 shows a typical case of thermal runaway after reaching I_0 at $I_0 = 150$ A, $T_\mathrm{i} = 10$ K, and $I_\mathrm{i} = 219$ A. In this case, at 350 s after reaching I_0, the SMES coil resulted in thermal runaway. Conversely, in Fig. 6 at $I_\mathrm{i} = 218$ A, i.e. 1 A smaller than that in Fig. 5, the SMES coil recovered safely without the thermal runaway.

C. Criterion of Thermal Runaway

From the results of our simulation we determined the criterion of thermal runaway during the load fluctuation compensation, as shown in Fig. 7 for $I_0 = 65$ A and $I_0 = 150$ A at $T_0 = 10$ K. In the compensating operation for load fluctuations, if the coil temperature T_i and the current I_i do not exceed this criterion, the SMES coil will recover to the standby condition without the onset of thermal runaway. That is, the SMES coil can be protected from the thermal runaway by monitoring T_i and I_i.

The criterion, e.g. at $T_\mathrm{i} = T_0 = 10$ K, is $I_\mathrm{i} = 218$ A (see Figs. 5 and 6) and has a current margin of 36% against the upper limit of constant current (160 A). At $T_\mathrm{i} > 15$ K, the criterion for $I_0 = 150$ A is lower than that for $I_0 = 65$ A, because the large coil current as capable of inducing thermal runaway after reaching I_0 as shown in Fig. 5. In the case of $I_0 = 150$ A, the criterion drastically decreases with the increase in T_i. Especially,

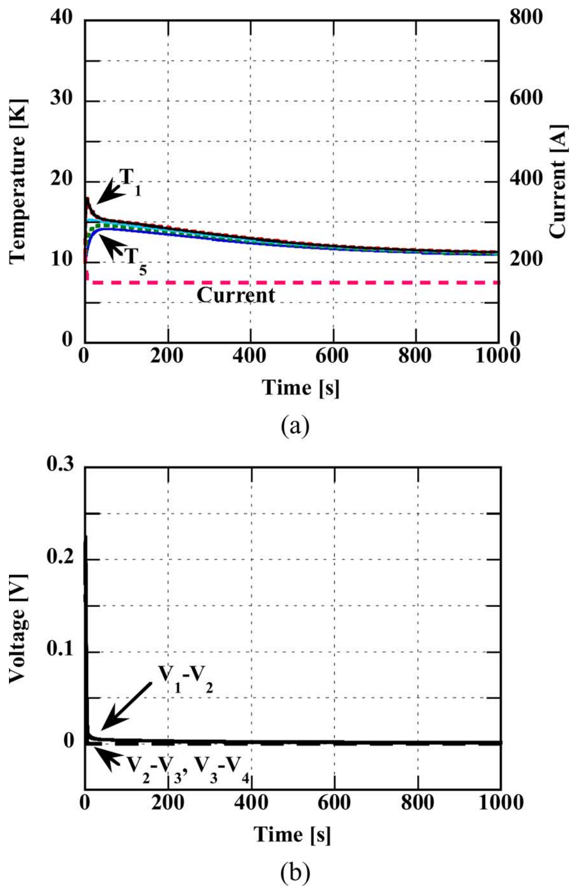

Fig. 6. A typical case of stable recovery ($T_0 = 10\,\mathrm{K}, I_0 = 150\,\mathrm{A}, T_\mathrm{i} = 10\,\mathrm{K}$, and $I_\mathrm{i} = 218\,\mathrm{A}$). (a) Temporal evolutions of coil temperature and current. (b) Temporal evolutions of resistive voltage.

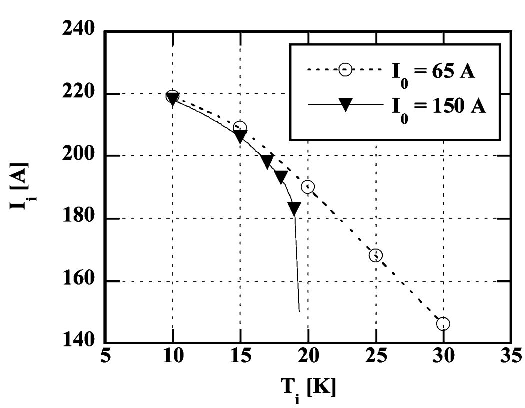

Fig. 7. Criteria of thermal runway during load fluctuation compensating operation ($T_0 = 10\,\mathrm{K}$).

in the case of $T_\mathrm{i} > 20\,\mathrm{K}$, the coil is thermally unstable for all I_i larger than $I_0 = 150\,\mathrm{A}$.

V. Conclusion

In order to protect an HTS SMES coil from thermal runaway during the load fluctuation compensation, we discovered the criterion of the operating condition $(T_\mathrm{i}, I_\mathrm{i})$ below which thermal stability can be maintained in the recovery process and into the standby condition. In addition, the monitoring of the coil temperature and current was suggested to be effective for the diagnosis of the thermal runaway under the compensating operation for load fluctuations. The proposed concept for the preventing thermal runaway, and its monitoring for the HTS SMES coil, is expected to be applied not only to the solenoidal coil in this paper, but also to the pancake coil and actual SMES coils.

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