Resistance Rise in Bi2223 Superconducting Bulk after Normal Transition due to Overcurrent

H. Shimizu, K. Kato ,Y. Yokomizu, T. Matsumura and N. Murayama

Abstract— **The resistance and joule heat generating in a Bi2223 bulk for overcurrent carrying period were measured. We suddenly supplied the overcurrent having the peak value which is about ten times as high as the critical current of the sample conductor. The resistance slightly increased immediately after the current exceeded the critical current level. When the accumulative joule heat generated in the sample reached 32 MJ/m^3, the quench occurred. The resistance rise in the sample proceeds adiabatically and the magnitude of the resistance may be estimated only by the joule heat generated in the sample.**

Index Terms— **Bi2223 bulk, joule heat, overcurrent, resistance**

I. Introduction

As a promising candidate for current limiting technology in electric power system, the introduction of fault current limiter is expected. Recently, many researches and developments of the superconducting fault current limiter (SC-FCL) using the superconducting/normal transition of high T_c superconductor have been carried out[1]-[7].

The superconducting element in the SC-FCL is required to generate the resistance before the first peak of the fault current. Furthermore, the generating properties of the resistance in the superconducting element for the period of limiting operation strongly influence the current limiting factor, terminal voltage induced in SC-FCL, recovery time to superconducting state and so on[8]. Hence, for practical design of the SC-FCL, it is important to understand the characteristics of the resistance generated in the superconducting element when the overcurrent flows.

In this paper, the resistance generated in a high T_c superconducting bulk supplied with overcurrent was experimentally investigated. A Bi2223 bulk made by sintering was adopted as the sample conductor. By using a condenser type of high current source, we supplied overcurrent having the peak value of up to 920 A which is about ten times as high as the critical current of the Bi2223 sample. The time and the input energy required to cause the quench were measured. Furthermore, the relationship between the sample resistance and input energy was estimated.

II. Experimental Set-up and Procedure

We adopted a Bi2223 bulk as the sample conductor[9]. The Bi2223 bulk was made by sintering under the conditions of 850 °C and 300 kg/cm^2 for 20 hours in air. Fig. 1 illustrates the shape of the Bi2223 sample. The cross section and length are 3.4 mm^2 (3.4 mm×1.0 mm) and 70 mm, respectively. Silver plates were connected at both edges of the sample at 830 °C under 40 kg/cm^2 pressure for 10 hours in air. The contact area between the sample and silver plate at each side is 34 mm^2 (3.4 mm×10.0 mm). Voltage taps were attached in the middle part of the sample at an interval of 35 mm to measure the voltage generated in the sample.

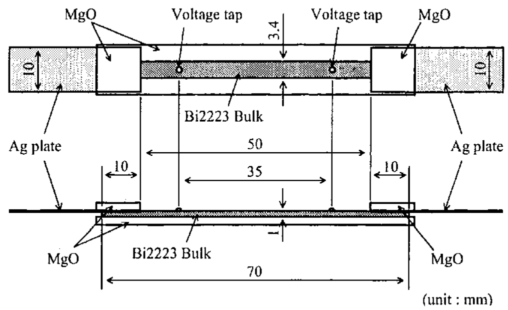

Fig. 1. Shape of Bi2223 bulk sample adopted.

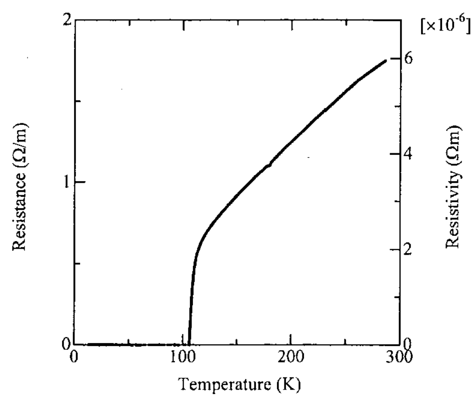

Fig. 2. Temperature dependence of resistance of sample conductor.

The temperature dependence of the resistance of the sample conductor was measured by fall-of-potential method. In the measurement, we set the sample current to be 10 mA and changed the temperature within the range of 14 K to 286 K. Fig. 2 shows the sample resistance per unit length as a function of the temperature. The right vertical axis in this figure indicates the resistivity of the sample. As seen from Fig. 2, the critical

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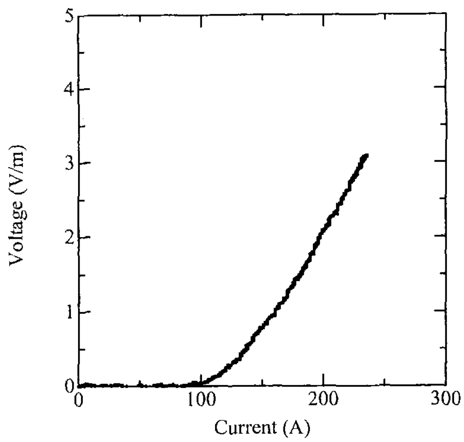

Fig. 3. Voltage-current characteristics of Bi2223 sample.

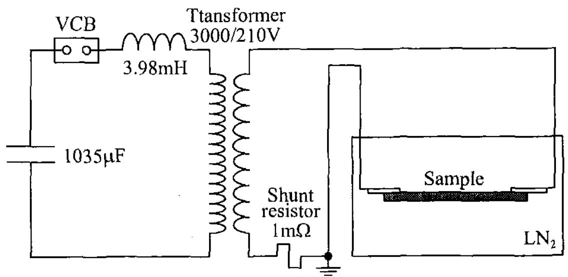

Fig. 4. Circuit for overcurrent carrying test.

temperature of the sample is 106 K. For the temperature range of more than 150 K, the resistance varies in proportion to the temperature. The magnitude of the resistance at 273 K is 1.69 Ω/m.

Fig. 3 shows the voltage-current characteristics of the sample. In this figure, the voltage is indicated in the magnitude per unit length of the sample. The critical current of the sample was measured to 90 A (defined by the criterion of 0.1 mV/cm). This current level corresponds to the critical current density of 2 650 A/cm^2.

Fig. 4 illustrates a circuit for overcurrent carrying test. After charging a capacitor with capacitance of 1 035 μF to a certain voltage, we suddenly supplied a overcurrent through a 3.98 mH reactor and a step-down transformer by closing a vacuum circuit breaker (VCB). In the case that no resistance is generated in the sample, the current is the damping sinusoidal one with the frequency of 50 Hz. The peak value of the sample current I_p changes with the charging voltage. In the experiments, adjusting the charging voltage within 320 to 370 V, we varied I_p with range of 775 to 920 $\mathrm{A_{peak}}$.

III. Measured Waveforms

Fig. 5 shows typical examples of waveform measured for I_p = 920 $\mathrm{A_{peak}}$. The horizontal axis of this figure indicates the elapsed time t from the beginning of the current supply.

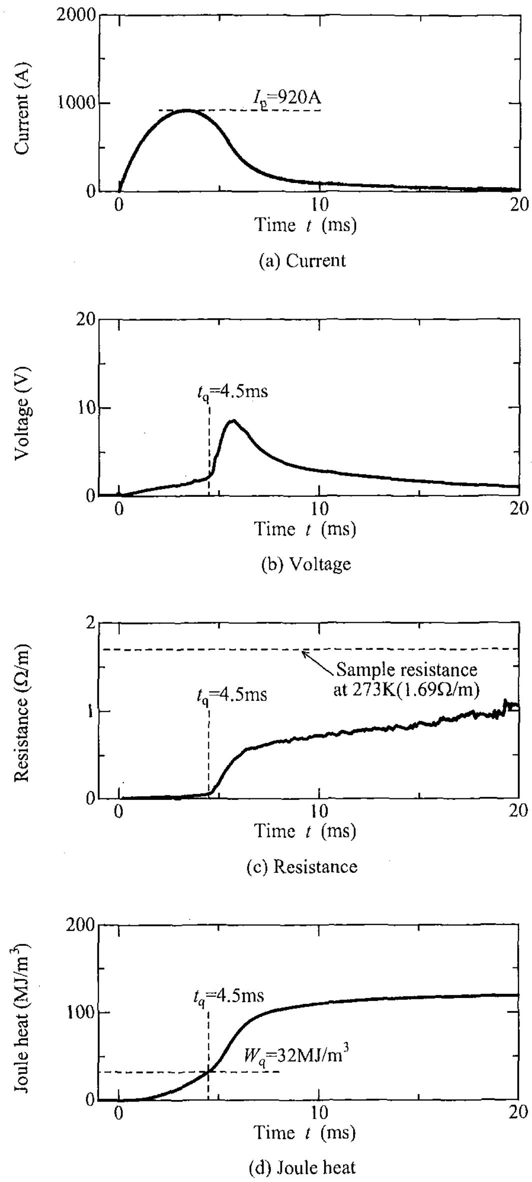

Fig. 5. Measured waveforms of current, voltage, resistance and joule heat.

Fig. 5 (a) and (b) correspond to the waveforms of the sample current and voltage, respectively. The sample starts to generate the voltage and the sample current simultaneously exceeds the critical current of 90 A because the sample begins to produce the resistance. For t < 4.5 ms, the voltage slightly increases with t. At t = 4.5 ms, there is a rapid rise of the voltage. This means that the sample resistance increases suddenly, i.e., the quench occurs at this point. In this paper, the time where the quench is caused is defined as t_q.

Fig. 5 (c) and (d) show the time variation in the resistance and accumulative joule heat generated in the sample. We obtained the sample resistance by dividing the instantaneous value of the voltage by that of the current. The resistance is indicated in the magnitude per unit length of the sample. The accumulative joule heat was estimated by integrating the product of the voltage and current. In Fig. 5 (d), the joule heat is shown in the magnitude per unit volume of the sample.

For $t < t_q$, since the resistance is less than 0.05 Ω/m, the sample may be regarded as being in flux flow state. The sample temperature ascend by the joule heat generated in the flux flow resistance. The resistance begins to sharply increase at $t = t_q$ because of the quench of the sample. This means that the sample temperature attained to the critical temperature. As seen from Fig. 5 (d), the joule heat W_q required for the quench of the sample is 32 MJ/m^3. At $t = 6.5$ ms, the magnitude of the resistance attains to about ten times of that at $t = t_q$. After that, the sample resistance continues to increase. At $t = 20$ ms, the joule heat was 120 MJ/m^3 and the resistance reaches 1 Ω/m. This magnitude of the sample resistance corresponds to about 60 % of that at 273 K.

IV. Time and Energy Required for Quench

Fig.6 shows the time t_q and joule heat W_q required for the quench of the sample as a function of I_p. The joule heat W_q is the energy necessary to cause the quench in the sample. The time t_q decreases with an increase in I_p because the joule heat generated per unit time goes up with I_p. On the other hand, W_q is independent of I_p and the magnitude of W_q is 32 MJ/m^3. This means the temperature of the sample adiabatically rises until the quench occurs in the sample.

In the case of Fig. 5, the quench of the sample occurs after the first peak of the current. However, in the actual application of the SC-FCL, it may be required that the quench of the superconducting element occurs before the first peak of the fault current. If the Bi2223 bulk adopted in this paper is used for the SC-FCL, we must design the dimension of the bulk to generate the joule heat of 32 MJ/m^3 within the desired period. For example, to bring about the quench within 2 ms after the fault occurrence, the joule heat of 16 GW/m^3 must be generated in the flux flow resistance of the Bi2223 bulk.

V. Relation between Resistance and Joule Heat

We now discussed the relation between the resistance and joule heat generated in the sample. Fig. 7 shows the sample resistance as a function of the joule heat for $I_p = 920\mathrm{A}_{peak}$. This figure was obtained from the instantaneous values of the resistance and joule heat indicated in Fig. 5 (c) and (d). In Fig. 7, the results for $I_p = 775\ \mathrm{A}_{peak}$ and 815 A_{peak} are also indicated. The relations between the sample resistance and joule heat for $I_p = 775$ and 815 A_{peak} agree with a part of the characteristics for $I_p = 920\mathrm{A}_{peak}$ although the joule heat generated per unit time differ according to I_p. From this result, it is found that the sample temperature rise adiabatically and the sample resistance may be determined only by the joule heat.

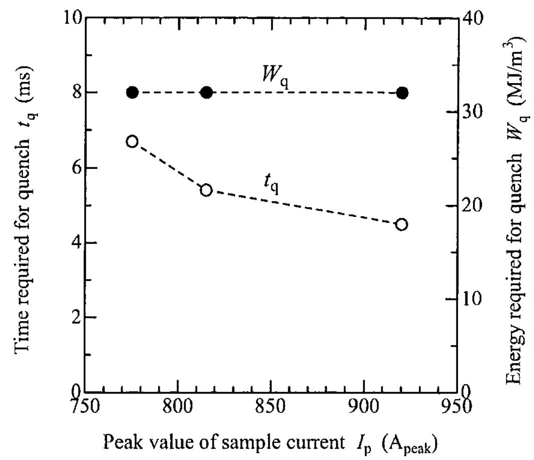

Fig. 6. Time and energy required for quench.

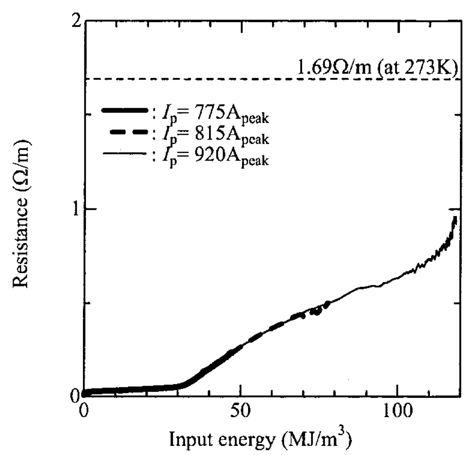

Fig. 7. Resistance as a function of joule heat.

VI. Simulation of Resistance Rise Process of Superconducting Element in SC-FCL

In the design and practical use of SC-FCL for electric power system, it is important to grasp the transient behavior of the fault current and the voltage across the SC-FCL terminal during the limiting operation. To estimate such current and voltage, we must perform the transient fault analysis in the electric power system with the SC-FCL taking account of the dynamic change of the resistance in superconducting element. By using the data obtained in the experiments, we may simulate the process of the resistance rise in the superconducting element as follows. First, the resistance of the superconducting element is estimated immediately after the current passing through the element exceeds the critical current from Fig. 3. Secondly, the joule heat in the element is calculated from the resistance obtained in preceding step and the element current. Thirdly, from the joule heat, the resistance increased is derived using characteristics shown in Fig. 7. Repeating these calculation, we can calculate the time variation in the element resistance.

VII. Conclusions

The resistance change in the Bi2223 bulk supplied the overcurrent was experimentally investigated. The increase in the resistance proceeds adiabatically for the period of about 20 ms which is considered in this paper. The quench of the sample was caused by the generation of the joule heat of 32 MJ/m^3. The magnitude of the resistance can be estimated by the joule heat generated in the sample. From this reason, it is pointed out that the process of the resistance rise may be simulate using the relation between the resistance and joule heat.

In future, we will design and manufacture the superconducting element with the Bi2223 bulk used as the measuring object in this paper for SC-FCL on an experimental basis from the results currently obtained.

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