Flux Flow Resistance in Bi2223 Generated by Pulse Currents

Keita Mutsuura, Hirotaka Shimizu, Yasunobu Yokomizu, and Toshiro Matsumura

***Abstract*—We have proposed a current limiting element using the flux flow resistance in a high temperature superconductor (HTS) for a pulse over-current such as a magnetizing inrush current in a transformer. We experimentally investigated the generation process of flux flow resistance in a Bi2223 bulk with an inrush current. The voltage-current density characteristics and their dependence on the joule heat generated in the Bi2223 bulk were measured. Comparing the results with the characteristics for the ac over-current, we made it clear that the both have almost the same characteristics.**

***Index Terms*—Bi2223 bulk, flux flow resistance, inrush current, voltage-current density characteristics.**

I. Introduction

PULSE current such as magnetizing inrush current in a transformer occasionally generates in an electric power system. The peak value of the inrush current may be several times higher than the normal load current. The inrush current is not interrupted by a circuit breaker because it is not a fault current and it disappears with time. Hence, it has a possibility of giving a large mechanical or thermal stress to the electric power system. If the inrush current can be suppressed by some methods, this problem may be solved.

The application of fault current limiter (FCL) with high temperature superconductor (HTS) is expected as a promising candidate for current limiting technology in electric power systems. In recent years, superconducting FCL's are researched and developed all over the world [1]–[11]. Superconducting/normal (S/N) transition type of FCL is one of the most typical ones. This type of FCL reduces an over-current by a 'normal resistance' generated in the HTS used in the FCL. It is considered that such an FCL to recover to normal operating condition after limiting operation.

To solve the problem of recovery time, we have proposed to use the 'flux flow resistance' of HTS generated in the superconducting FCL instead of 'normal resistance' [2]–[4]. Under the condition that the temperature in HTS is below the critical temperature of the HTS, the flux flow resistance appears in the HTS when the carried current exceeds the critical current and disappears at the moment that the current is less than the critical current. That is, the FCL using the flux flow resistance of HTS (flux flow resistance type of FCL) possibly recovers to normal operating condition without any current interruption immediately. This means that the flux flow resistance type FCL may be effective for the limitation of an inrush current.

It is necessary to understand the generating process of flux flow resistance when the inrush current flows in the HTS to investigate about the possibility of realization of inrush current limiting device. We also need to grasp the dependence of the flux flow resistance generation on the HTS temperature. In this paper, we performed an inrush current limiting test with a HTS. In the experiments, a Bi2223 bulk conductor was used as the sample and the generating process of flux flow resistance was investigated experimentally.

II. Bi2223 Bulk Sample

We adopted a Bi2223 bulk made by sintering [12] as the sample conductor. We took the measurement for two samples (sample 1 and sample 2). Fig. 1 illustrates the configurations of the samples. Copper plates were soldered at both edges of the sample as the electrodes for current terminals. As shown in Fig. 1, voltage taps were connected to measure the voltage generated in the sample.

Table I summarizes the dimensions of the samples. The length of sample 1 is three times as long as that of sample 2. In regard to cross-sectional area, sample 1 is 2.9 times larger than sample 2.

The critical current densities of the samples are also indicated in Table I. The critical current density J_{c0} in sample 1 and sample 2 measured under the conditions of 77 K and 0 T, were $1.35 \times 10^7\ \mathrm{A/m^2}$ and $2.55 \times 10^7\ \mathrm{A/m^2}$, respectively. In our samples, bulk with smaller cross-section trends to have higher critical current density.

III. Experimental Set-Up and Procedure

Fig. 2 illustrates an experimental circuit for inrush current carrying tests. The sample is connected to the primary side of a transformer having its secondary side open. This transformer is usually used as an insulating transformer. The voltage ratio and the rated capacity are 100 V/100 V and 4 kVA. The sample was cooled down by liquid nitrogen $(\mathrm{LN_2})$. An inrush current was supplied to the sample by suddenly applying the voltage to the transformer. The initial phase angle of applied voltage was adjusted to zero. We measured the current and voltage in the sample using a shunt resistor and voltage taps. The impedance of the primary winding and shunt resistor are $0.9 + j8.8\ \Omega$ and 5.26

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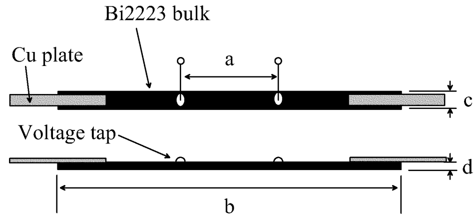

Fig. 1. Configuration of Bi2223 bulk.

TABLE I
DIMENSIONS AND CRITICAL CURRENT DENSITY OF Bi2223 BULK SAMPLES

	Dimension [mm] a	b	c	d	J_{c0} [A/m^2] (77K, 0T)
Sample 1	50.0	141.5	3.75	1.50	1.35×10^7
Sample 2	12.6	52.1	1.50	1.30	2.55×10^7

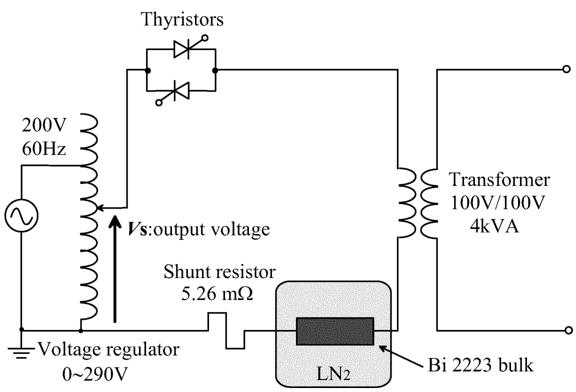

Fig. 2. Experimental circuit for inrush current carrying test.

mΩ, respectively. The other impedance included in the circuit is $34.3 + j108.3$ mΩ.

IV. Typical Measured Waveforms

Fig. 3 shows the example of measured waveforms of the current density j and voltage v per unit length in sample 1 by solid and broken lines, respectively. The maximum value J_p of the current density was 6.6×10^7 A/m^2. During the first half behavior of j in this figure, the voltage starts appearing when j exceeds J_{c0} of 1.35×10^7 A/m^2. After that, v disappears again at the moment that j becomes lower than a certain value. This means that flux flow resistance is present in the sample for this period. The value of j when the voltage disappears is 1.27×10^7 A/m^2 and is lower than J_{c0} because the critical current density is decreased by the temperature rise due to the joule heat in the HTS. Similarly, the voltage at the second and third half behavior in Fig. 3 was generated although the peak value of j is damped as the time passes. On the other hand, during the fourth half behavior of j, the voltage was not generated since the current density is less than the critical current density determined by the temperature of HTS at that time. That is, the state of superconductivity is maintained during the fourth half behavior. This means that a flux flow resistance type of FCL can recover instantly to normal operating state after limiting inrush current.

Fig. 4 shows the time variation in the accumulated joule heat w per unit volume in sample 1, that was obtained by integrating

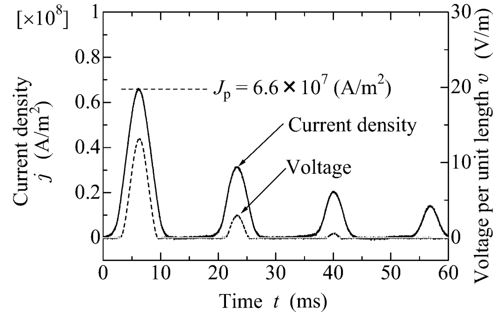

Fig. 3. Waveforms of current density and voltage per unit length in sample 1 when inrush current flows.

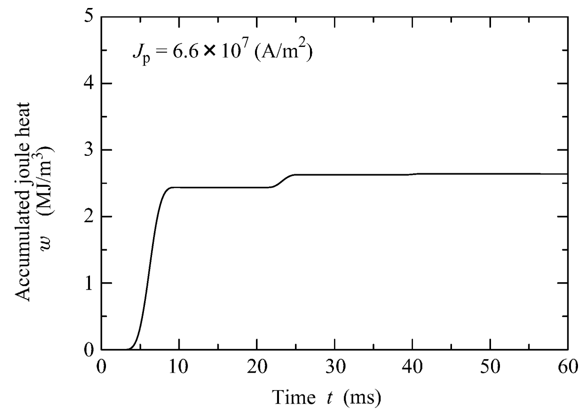

Fig. 4. Waveform of accumulated joule heat in sample 1 when inrush current flows.

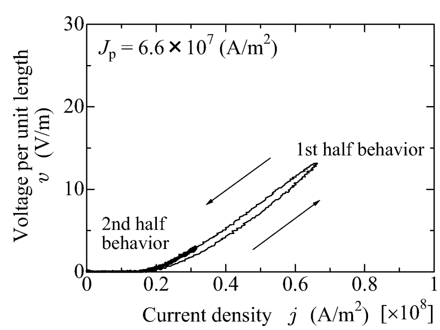

Fig. 5. Voltage per unit length as a function of current density in sample 1 when inrush current flows.

the product of instantaneous values of v and j indicated in Fig. 3. The accumulated joule heat w increases as the time proceeds and the temperature and the resistance of the sample rise. In this figure, the joule heat was not generated much during the second and third half behavior of the inrush current. This means that the joule heat mainly depend on the limiting performance during the first half behavior.

The relationship between the instantaneous values of v and j at the first half behavior and second one in Fig. 3 is shown in Fig. 5 with thin line and thick one, respectively. The voltage v during the first half behavior has different values for same j depending on the current increasing and decreasing period, i.e., v for the current decreasing period is higher than that for the increasing one. The flux flow resistance increases with the HTS temperature. Since the temperature of the HTS for the decreasing period of j gets higher than that for increasing one by

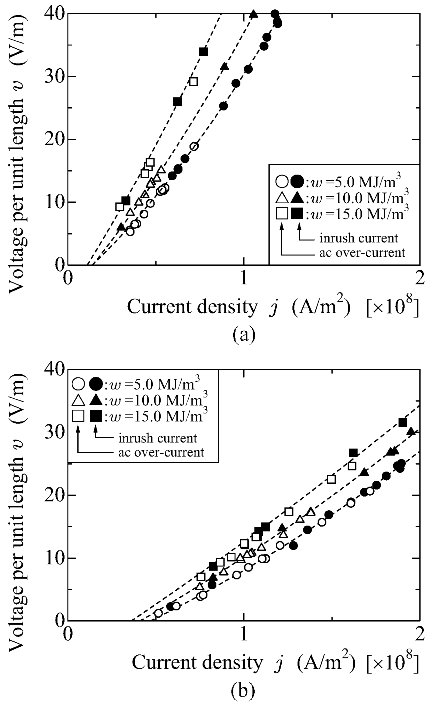

Fig. 6. Voltage-current density characteristics. (a) Sample 1; (b) sample 2.

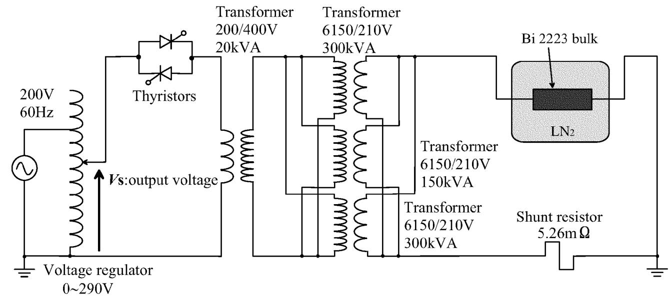

Fig. 7. Experimental circuit for ac over-current carrying test.

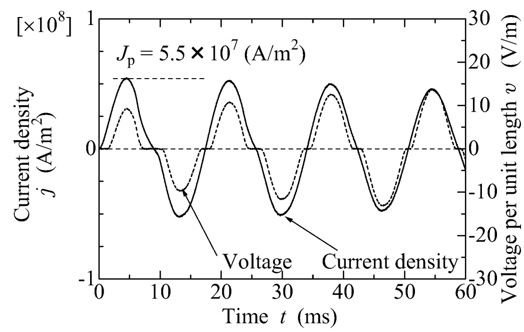

Fig. 8. Waveforms of current density and voltage per unit length in sample 1 when ac over-current flows.

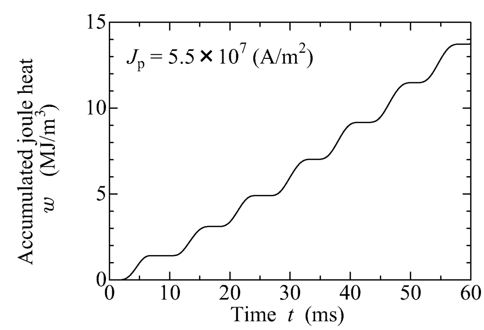

Fig. 9. Waveform of accumulated joule heat in sample 1 when ac over-current flows.

the joule heat, the HTS has the characteristics as shown in Fig. 5. The voltage v during the second half behavior overlaps with that for the decreasing period of the first half behavior. That is because the joule heat is small and then the temperature is hardly increased.

V. Voltage-Current Density Characteristics

As mentioned in the previous chapter, the relation between v and j ($v-j$ characteristics) depends on w. To get $v-j$ characteristics for different values of w [2], [3], various inrush current carrying tests were performed for the sample 1 and 2. In Fig. 6, the measured values of v are plotted with filled marks against the measured current density j at a moment when w is equal to 5.0, 10.0 and 15.0 $\mathrm{MJ/m^3}$. Fig. 6(a) and (b) correspond to the results for sample 1 and sample 2, respectively. Filled circles, triangles and squares indicate the $v-j$ characteristics for $w = 5.0$, 10.0 and 15.0 $\mathrm{MJ/m^3}$ in both figures, respectively. The broken lines in Fig. 6 correspond to the curves approximated as quadratic expression by the method of least squares.

As can be seen in Fig. 6(a), in sample 1, v increases with j as well as in w when the inrush current flows. A similar tendency was also observed in case of sample 2 as illustrated in Fig. 6(b). However, v in sample 1 is larger than that in sample 2. Hence the smaller J_{c0} is, the larger v becomes. This tendency is consistent with the result shown in [3]. Consequently, the magnitude of v depends on j, w and J_c0 in the sample.

VI. Comparison Between Inrush Current and AC Over-Current

The high temperature superconducting element which is installed as an inrush current limiter into the power system can work also as a fault current limiter. In the fault current limiting operation phase, ac over-current flows through HTS. Thus, it is important to clarify $v-j$ characteristics not only for inrush currents but also for ac over-current and to compare them. Fig. 7 illustrates an experimental circuit for ac over-current carrying tests. An ac over-current was suddenly supplied to the sample for 3.5 cycles. For the various peak values of the over-current, current and voltage in the sample were measured and accumulated joule heat generated in the sample was estimated in a similar way described earlier. Fig. 8 shows the example of measured waveforms of j and v in sample 1 by solid and broken lines, respectively. And Fig. 9 shows the accumulated joule heat w per unit volume in sample 1 as a function of time. From Fig. 8 and Fig. 9, the $v-j$ characteristics when the flux flow resistance was generated in the sample 1 and sample 2 for ac over-current were measured by using the same method described above.

The $v-j$ characteristics in case of ac over-current are shown by open marks in Fig. 6. It can be seen in this figure that open circles, triangles and squares are plotted on each broken line obtained from the inrush current carrying tests. In other words, the relationship between the current density and the flux flow resistance for inrush current is found to be nearly the same as that for ac current.

Regardless of the current waveform, ac or pulse, the $v - j$ characteristics for the same w can be expressed by the broken lines in Fig. 6. This means that, as far as the present experimental conditions are concerned, the bulk was almost under the adiabatic state during the current carrying period. In case of inrush current, for every half cycle, there is an interval where the current is small. Therefore, if the time for which the inrush current flows in the bulk becomes long, on the basis of the cooling effect during this interval time, the temperature and resistance rise in case of inrush current may be reduced compared to that of an ac over-current.

VII. Conclusion

We experimentally studied the generation process of the flux flow resistance in a Bi2223 bulk when a pulse over-current as the magnetizing inrush current of a transformer, flows in it. It was confirmed that the sample conductor self-recovered at the moment that the current was below the critical current. The relations among the voltage, current density and joule heat were obtained. Furthermore, it was found that the voltage-current density characteristic for the inrush current was almost the same as that for the ac current under our experimental condition.

References

[1] E. Leung, "Surge protection for power grids," *IEEE Spectrum*, pp. 26–30, 1997.

[2] H. Shimizu, Y. Yokomizu, T. Matsumura, and N. Murayama, "Proposal of flux flow resistance type fault current limiter using high Tc superconducting bulk," *IEEE Trans. Appl. Supercond.*, vol. 12, no. 1, pp. 876–879, 2002.

[3] T. Aritake, T. Noda, H. Shimizu, Y. Yokomizu, T. Matsumura, and N. Murayama, "Relation between critical current density and flux flow resistivity in Bi2223 bulk element for fault current limiter," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 2084–2087, 2003.

[4] H. Shimizu, Y. Yokomizu, M. Goto, T. Matsumura, and N. Murayama, "A study on required volime of superconducting element for flux flow resistance type fault current limiter," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 2052–2055, 2003.

[5] H. Shimizu, K. Kato, Y. Yokomizu, T. Matsumura, and N. Murayama, "Resistance rise in Bi2223 of superconducting bulk after normal transition due to overcurrent," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 1948–1951, 2001.

[6] M. Noe, K.-R. Juengst, F. N. Werfel, S. Elschner, J. Bock, F. Breuer, and R. Kreutz, "Testing bulk HTS modules for resistive superconducting fault current limiters," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1976–1979, 2003.

[7] M. Ichikawa, H. Kado, M. Shibuya, and T. Matsumura, "Inductive type fault current limiter with Bi-2223 thick film on MgO cylinder," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 2004–2007, 2003.

[8] T. Matsumura, A. Kimura, H. Shimizu, Y. Yokomizu, and M. Goto, "Fundamental performance of flux-lock type fault current limiter with two air-core coils," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 2024–2027, 2003.

[9] T. Matsumura, Y. Yokomizu, and T. Uchii, "Development of flux-lock-type fault current limiter with high-Tc superconducting element," *IEEE Trans. Appl. Supercond.*, vol. 7, no. 2, pp. 1001–1004, 1997.

[10] T. Matsumura, H. Shimizu, and Y. Yokomizu, "Design guideline of flux-lock type HTS fault current limiter for power system application," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 1956–1959, 2001.

[11] S.-H. Lim, H.-S. Choi, and B.-S. Han, "Operational characteristics of a flux-lock-type high Tc superconducting fault current limiter with a tap changer," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 1, pp. 82–86, 2004.

[12] N. Murayama and J. B. Vender, "Densification behavior during hot pressing of Bi-Pb-Sr-Ca-Cu-O superconductors," *Physica C*, vol. 256, pp. 156–160, 1996.