Performances of Small Fault Current Limiting Breaker Model With High Tc Superconductor

Toshiro Matsumura, Tomohiro Aritake, Yasunobu Yokomizu, Hirotaka Shimizu, and Norimitsu Murayama

***Abstract*—This paper describes the breaking ability of a small model of a fault current limiting circuit breaker (FCLCB), which consists of an air relay unit and a flux flow resistive type of a superconducting FCL unit with a high Tc B2223 bulk. Two Bi2223 elements were connected in series as an elementary FCL unit. Current carrying tests were performed for the elementary FCL unit to find the generating aspects of the flux flow resistance and the contact resistance. Current limiting and breaking performances were measured for the small model of the FCLCB that was constructed by connecting the elementary FCL unit with the relay contactor. It is confirmed that the apparent capability of the breaker unit is elevated by combination with the FCL unit. The FCL unit for the 6.6 kV power distribution systems was also designed.**

***Index Terms*—Bismuth, circuit breakers, fault current limiters, high-temperature superconductors.**

I. Introduction

We have proposed a combination system in which a fault current limiter (FCL) and a circuit breaker (CB) are connected in series [1], [2]. The present study describes the breaking ability of a small model of a fault current limiting circuit breaker (FCLCB), which consists of an air relay unit and a flux flow resistive type of a superconducting FCL unit with a high Tc B2223 bulk.

Although various types of the FCL have been researched and developed [3]–[10], the flux flow resistive type among them is considered to be preferred as an FCL unit to be combined with the circuit breaker. Since the flux flow resistivity is much lower than a normal resistivity [11], a large number of the superconducting elements may be necessary to generate large limiting impedance in the FCL [12]. However, the high limiting impedance is not always needed for the FCLCB because of the coordination between the circuit breaker and the over-current detection system. Furthermore, the flux flow resistive type of the FCL has an advantage of an instant or rapid recovery property [11].

Firstly, two Bi2223 meander-shaped elements were connected in series to make an elementary unit of the flux flow resistive type of the FCL. The generating properties of the flux flow resistance in the elementary FCL unit were measured and compared with the simulated results by means of the empirical expression of the flux flow resistivity as a function of the critical current density, accumulated joule heat and transport current derived from the short stick element [13].

Secondary, the current limiting and breaking performance was investigated for the small model of the FCLCB that was constructed by connecting the elementary FCL unit with the relay contactor. It is confirmed that the FCLCB has higher performance than the switching unit because the FCL unit reduces both the fault current and recovery voltage.

Finally, the FCL unit for the 6.6 kV power distribution systems was designed.

II. Flux Flow Resistive Type of Fault Current Limiter

A flux flow resistance is generated in the superconductor when the transport current exceeds the critical current I_c under the condition that the temperature of the superconductor is below the critical temperature T_c. If the superconductor temperature is maintained below T_c, the flux flow resistance disappears at the moment that the transport current is less than I_c., which decreases with a increase in the temperature. Hence, the SC-FCL using the flux flow resistance may achieve self-recovery to the normal operating mode immediately after the fault clearing by controlling the temperature within the tolerant level.

III. Elementary Unit of Fault Current Limiter

A. Meander-Shaped Bi2223 Bulk

We adopted a Bi2223 bulk as a material for the SC-element in flux flow resistance type FCL. In the case that the bulk element is used, many elements must be connected in series and/or in parallel to apply to actual power system [12]. That is because the resistance of the bulk is relatively small. It is desirable that the points connecting many bulks are as few as possible. To reduce the connecting points, a bulk having long length must be used [8]. Then we used a meander-shaped bulk of which effective length and cross section are 814 mm and 2.25 mm^2, respectively.

Fig. 1 illustrates the SC-element adopted as an elementary unit of the flux flow resistance type of fault current limiter. We connected two bulks (bulk 1 and bulk 2 having same shape described above) with Ag plate of 0.5 mm in thickness by diffusion bonding. The current leads were also joined by same method. All contact areas of connecting points of bulk and Ag plate are

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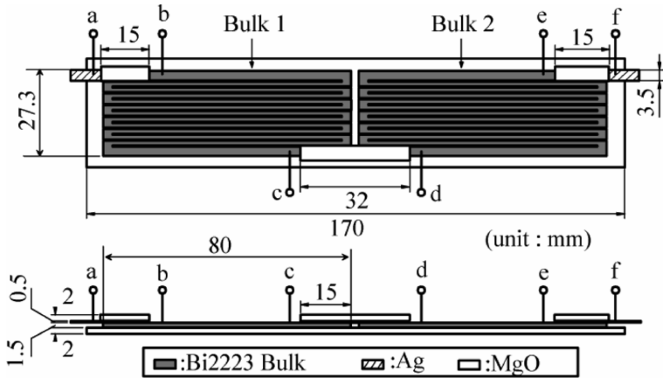

Fig. 1. SC-element consisting of two meander shaped Bi2223 bulks.

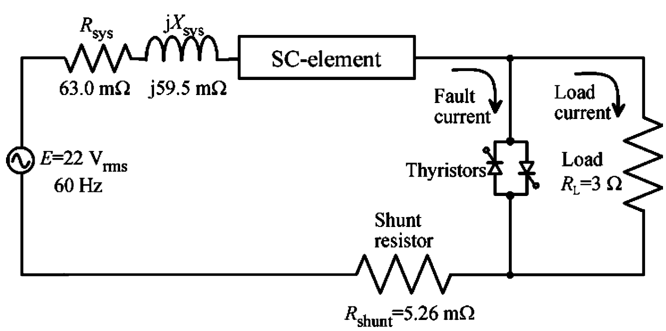

Fig. 2. Set-up for current carrying test.

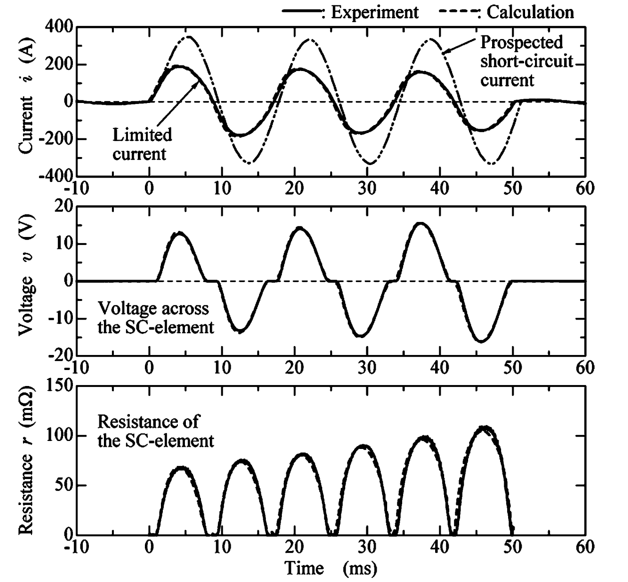

Fig. 3. Example waveforms obtained in current carrying test and simulation.

45 mm^2. The resistance of the adopted SC-element in a superconducting condition, or the contact resistance and the resistance of Ag plate, is measured to be 0.02 $\mathrm{m\Omega}$. Since the SC-element shown in Fig. 1 has four contacts and the contact area between bulk and Ag plate is 45 mm^2 each, the resistivity per unit area of the contact is estimated to be about 0.2 $\mathrm{m\Omega \cdot mm^2}$.

The effective length of the element is 1,628 mm. We also arranged six voltage taps (tap a to f) to measure the voltage generated in the element as shown in Fig. 1. The critical current levels of the bulks used in the SC-element were measured to be 67 A and 60 A under the conditions of 77 K without external magnetic field for bulk 1 and 2, respectively. These magnitudes correspond to the critical current densities of 2,980 $\mathrm{A/cm^2}$ and 2,670 $\mathrm{A/cm^2}$. Hence, the initial current I_{ini} and current density of limiting operation of the SC-element are 60 A and 2,670 $\mathrm{A/cm^2}$.

B. Current Carrying Tests

Fig. 2 shows the experimental set-up. The frequency of the power source is 60 Hz. First, turning off a pair of thyristors, we adjusted the output of the voltage regulator V_{s} to be 22 $\mathrm{V_{rms}}$ to pass the load current of 7.1 $\mathrm{A_{rms}}$ $(= 10\ \mathrm{A_{peak}})$ in the circuit. Secondly, we supplied the overcurrent to the circuit by turning on the thyristors. In the experiments, the overcurrent was carried for 3 cycles. The turn-on phase angle was controlled in order to contain no d.c. transient component. The current through the SC-element was measured with a shunt resistor of 5.26 $\mathrm{m\Omega}$.

Fig. 3 shows the waveforms in the current limiting experiment with solid lines. The horizontal axis indicates the time t from the turn-on of the thyristors. The upper diagram illustrates the prospective short-circuit current and limited one. The voltage v between the taps a and f and the resistance r generated in the SC-element are represented in the middle diagram and lower one of Fig. 3, respectively. The resistance is calculated by division of v by i.

In the upper diagram of Fig. 3, the solid curve indicates the limited current by the SC-element. As shown in the upper and lower diagrams, i exceeds I_{ini} of 60 A and the SC-element begins to generate the resistance at $t = 0.80$ ms. The upper diagram also represents the short-circuit current without the SC-element by a two-dot chain line. In the case without the SC-element, the peak value of the current I_{p} is 339 $\mathrm{A_{peak}}$. On the other hand, first peak value of the current limited by the SC-element is 191 $\mathrm{A_{peak}}$. This magnitude corresponds to 56.4% of that for no SC-element case. The resistance r at the current peak is 70 $\mathrm{m\Omega}$. The SC-element recovers to superconducting state at $t = 7.8$ ms because i is below I_{c}. After that, the similar time variations are repeated. However, the peak value of i decreases gradually. That is because the peak value of r slightly rises by the increase in the temperature of the SC-FCL-element due to the accumulated joule heat.

The magnitude of I_{c} immediate before turn-off of the thyristors was measured to be 24 A. This current level is 40% of I_{ini} but is higher than the peak value of the load current of 10 A. Hence, the load current flows without any resistance of the SC-element. This means that the SC-element recovers to normal operating mode immediate after the fault clearing.

C. Simulation of Resistance Generation

We have developed a simulation code for estimating the generating process of the resistance in the high temperature superconducting element [13]. In our code, the resistivity has to be represented as a function of the current density j flowing through the element and accumulated joule heat W. Fig. 4 shows the generating properties of the resistivity which were obtained through the current carrying tests for a small SC-stick manufactured under a same condition as the meander SC-element in Fig. 1.

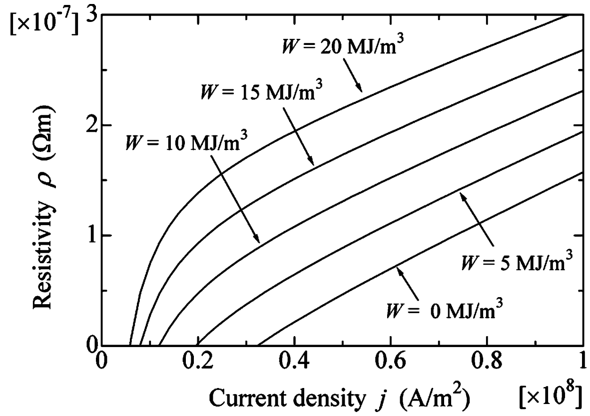

Fig. 4. Resistivity as a function of current density and accumulated joule heat for Bi2223 element adopted in this paper.

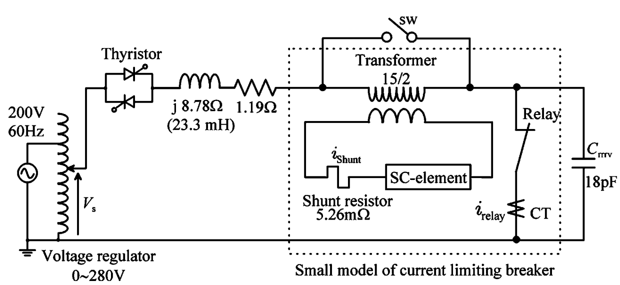

Fig. 5. Set-up for current limiting and breaking experiment.

By using these properties of the resistivity, the current limiting process was simulated for the current test in Fig. 2. The calculated results are illustrated by broken lines in Fig. 3. As shown in this figure, simulated current, voltage and resistance are consistent with the experimentally measured ones.

IV. Current Limiting and Breaking Performance of Small Model of FCLCB

A small model of the fault current limiting beaker was made by assembling the SC-element, relay contactor and transformer as shown in Fig. 5. The relay contactor has the rated current of 1 A and the rated voltage of 220 V. In order to coordinate the FCL unit and the breaking unit in the current rating, the SC-element was connected to the secondary winding of the transformer [14].

In our tests, the source voltage V_s was regulated from 0 to 280 V_{rms} (peak value is 370 V_{peak}). Fig. 6 shows an example of waveforms obtained in the current limiting breaking test with a source voltage of 370 V_{peak}. Fig. 6(a) and (b) corresponds to the case without and with FCL unit, respectively. In case of no FCL unit (switch SW is closed in Fig. 5), as shown in Fig. 6(a), the voltage v_{relay} across the relay begins to appear around $t = 0$, when the contacts of the relay begins to be separated. After that time, the adopted relay can not interrupt the current of 37 A_{peak} although it had two chances to break the current until $t = 20$ ms.

In Fig. 6(b), on the other hand, the relay began to open the contacts at $t = 10$ ms and was able to successfully interrupt the current by combining the FCL unit. At the first half cycle, the FCL unit started to limit the current but its reduction was very small because of the production of little resistance. At the second half cycle, however, it was observed that the resistance of 0.1 mΩ was generated in the SC-element at the secondary side of the transformer. As a result of the resistance generation, the peak value of the current was reduced to 25 A_{peak} and shift the phase angle of the current against the source voltage from 75 to 50 degrees. By this phase shift, the instantaneous value of the source voltage at current zero becomes lower from 357 V to 280 V so that the recovery voltage applied between the contacts of the relay is also reduced.

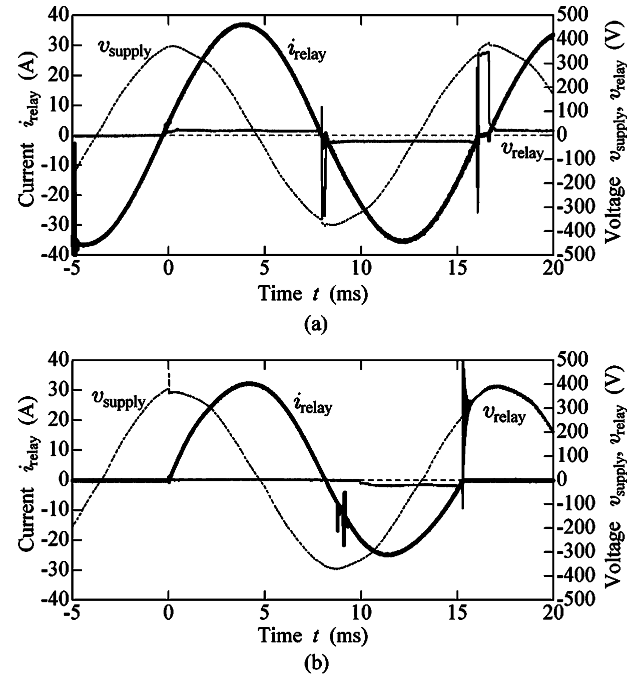

Fig. 6. Waveforms obtained in current limiting and breaking experiment with a source voltage of 370 V_{peak}. (a) Without FCL unit; (b) with FCL unit.

If the recovery voltage causes a breakdown between the separated contacts after current zero, the breaker fails to interrupt the current. So the lower recovery voltage brings about the higher probability of the current interruption of the breaker. Consequently, it is confirmed from the current limiting breaking tests that the successful interruption was brought about not only by the current limitation but also by the suppression of the recovery voltage [1], [2].

V. Design of FCL Unit for 6.6 kV Distribution System

The flux flow resistive type of the superconducting fault current limiter was designed for 6.6 kV_{rms} distribution system having the reactance of 0.38 Ω, where the short circuit fault current was 10 kA_{rms}. The initiation current level of the limiting operation was assumed to be $I_{ini} = 1$ kA_{peak}. It was also supposed that the superconducting element had the generating properties of the resistivity shown in Fig. 4.

For example, the current limiting performance of the FCL unit with the superconducting element of 400 m in length is illustrated in Fig. 7. This FCL unit can reduce the fault current of 14 kA_{peak} to about 4 kA_{peak} as shown in the upper diagram, and produces the resistance over 1 Ω as shown in the lower diagram.

In order to manufacture this FCL unit, for example, 243 SC-elements, whose elementary configuration is shown in Fig. 1, have to be connected in series and 17 sets must be

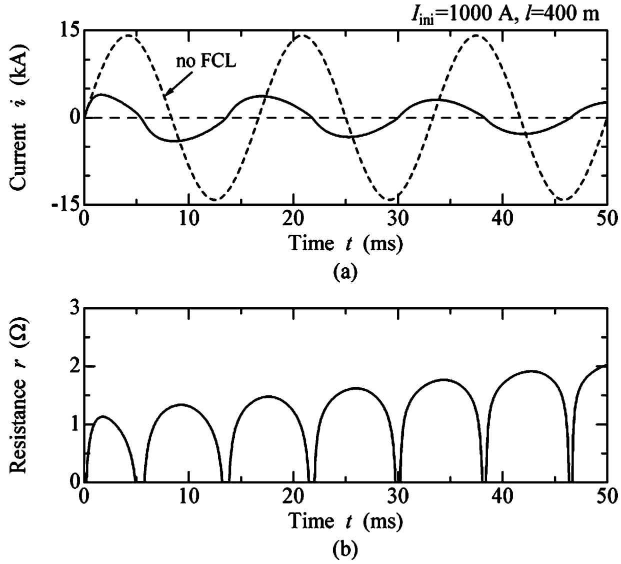

Fig. 7. Current limiting process of the FCL unit for 6.6 kV distribution system. (a) Current; (b) resistance.

connected in parallel. This FCL unit has totally the contact resistance of $0.286\ \mathrm{m}\Omega$. This resistance produces a joule heat loss of 77 W in three-phase for the load current of 300 $\mathrm{A_{rms}}$. This loss is much less than the single feeder transmission capability of 1 MVA. Therefore, it is possible that the contact resistance loss is a grade which does not become a problem practically. It is also confirmed from another investigation that the AC losses are enough small to be neglected in comparison with the contact loss.

VI. Conclusion

The current limiting performance of the flux flow resistive type of the fault current limiter with meander shaped Bi2223 elements and the current breaking performance of the small model of the fault current limiting breaker were experimentally investigated. It is confirmed that the fault current limiter unit can reduce the breaker duty not only by limiting the current but also by suppressing the recovery voltage.

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