Proposal of Flux Flow Resistance Type Fault Current Limiter Using Bi2223 High T_C Superconducting Bulk

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

Abstract—A flux flow resistance type fault current limiter (FCL) suppressing an overcurrent only by the flux flow resistance of a high temperature superconductor (HTS) was proposed. This type of FCL may recover to superconducting state so that a load current is passed immediately after the fault clearing because the flux flow resistance disappears at the moment that the current becomes lower than the critical current. That is an infinitely short recovery may be achieved. In this paper, we carry out a feasibility study on the flow resistive FCL using Bi2223 bulk installed at the outgoing feeder in a 6.6 kV distribution substation. It is pointed out the flux flow resistance type FCL may be realized by using the bulk of about 10^{-2} to 10^{-1} m^3.

Index Terms—Bi2223 bulk, fault current limiter, flux flow resistance, joule heat.

I. INTRODUCTION

FAULT current limiter (FCL) with high temperature superconductor (HTS) is expected as a promising candidate to suppress overcurrent due to a short-circuit fault in power system [1]–[4]. A typical superconducting FCL is a resistive type which reduces the fault current by the resistance generated by overcurrent flowing in the superconducting element. The FCL is required to recover to normal operating state after the fault clearing as soon as possible for the rapid reclosing in the power system. In the case of superconducting FCL, when the temperature of the HTS exceeds the critical value by the joule heat produced for the limiting operation, it takes some time to recover because the HTS must be cooled for the recovery to superconducting state.

As the superconducting FCL without the recovery time we propose a flux flow resistance type of FCL suppressing the fault current only by the flux flow resistance of HTS. The flux flow resistance appears in HTS when the transport current exceeds the critical current under the condition that the temperature of the HTS is below the critical temperature. Since the flux flow resistance disappears at the moment that the current decreases to lower level than the critical current, the load current may be passed through the HTS without any resistance immediately after the fault clearing. This may realize an infinitely short recovery time. The critical current of HTS degrades with an increase in the temperature of the superconductor due to the joule heat generated in the flux flow resistance. If the critical current is

lower than the load current flowing after the reclosing, the infinitely short recovery time is not achieved. Hence, it is important to clarify the thermal conditions where the flux flow resistance is used as the limiting resistance.

We consider a Bi2223 bulk as the superconducting material. First, we measured the dependence of the critical current density and the flux flow resistance on the joule heat generated in the bulk for the overcurrent carrying period to obtain the fundamental properties. Supposing that the flux flow resistance type FCL with the Bi2223 bulk is installed into a 6.6 kV distribution system, we carried out the simulation of the limiting performance of the FCL taking account of the dependence of the critical current density and flux flow resistance on the temperature measured for the bulk. To demonstrate the feasibility of this type FCL using Bi2223 bulk, the volume of the bulk required to realize the infinitely short recovery time was evaluated.

II. FUNDAMENTAL PROPERTIES OF Bi2223 BULK

A Bi2223 bulk made by sintering [5]–[7] was considered as the material of HTS element for the fault current limiter. The critical temperature T_{c0} of the bulk under no current condition is 106 K. The critical current density J_{c0} for 77 K was measured to be 2.65×10^7 A/m^3 (defined by the criterion of 0.1 mV/cm). We ignore the existence of external magnetic field applied to the bulk throughout this paper.

A. Dependence of Critical Current Density on Joule Heat

When the density j of the current flowing in HTS exceeds the critical current density J_{c0} at the temperature of 77 K, the flux flow resistance begins to appear. The temperature T of the HTS goes up by the joule heat produced in the flux flow resistance so that the critical current density J_c is reduced. If T reaches to T_c depending on j, the normal transition of the superconductor occurs, i.e., J_c becomes zero. On the other hand, in the case that T is less than the critical temperature T_c, the flux flow state is kept and the superconductor simultaneously recovers to the state with no resistance immediately after j becomes lower than J_c.

In the case of ac current, the bulk repeats the appearance and disappearance of the flux flow resistance decreasing J_c under the condition of $T < T_c$. By the measurement of the current density at the moment that the resistance appears or disappears together with the accumulated joule heat W generated by that time, the relation between J_c and joule heat is obtained as shown in Fig. 1. The joule heat in Fig. 1 is indicated by the magnitude per unit volume of the bulk. In this experiment, the ac (60 Hz) overcurrent was supplied to the bulk for the period of 167 ms (10 cycles). Changing the peak value of the overcurrent, we

Fig. 1. Critical current density as a function of joule heat per unit volume.

Fig. 3. Dependence of resistivity on current density.

We assumed that v was expressed as functions of j and W as in the next equation.

$$v(j, W) = a_0(W) + a_1(W)j + a_2(W)j^2 \qquad (2)$$

where $a_0(W)$, $a_1(W)$ and $a_2(W)$ are a function only of W. We obtained the equation of $a_0(W)$, $a_1(W)$ and $a_2(W)$ for each W by the least squared method. Furthermore, it is found that $a_0(W)$, $a_1(W)$ and $a_2(W)$ are written as a function of W as follows.

$$a_0(W) = -2.06 + 8.08 \times 10^{-8}W \qquad (3)$$
$$a_1(W) = 5.69 \times 10^{-8} + 2.54 \times 10^{-15}W \qquad (4)$$
$$a_2(W) = 2.35 \times 10^{-16} - 1.34 \times 10^{-26}W. \qquad (5)$$

The approximated curves expressed by (2) are also shown in Fig. 2. As seen in this figure, close agreement between the approximated curves and the measured results is obtained.

C. Dependence of Resistivity on Current Density

From (2), the resistivity ρ for $j > J_c$ is

$$\rho(j, W) = \frac{v(j, W)}{j} = \frac{a_0(W)}{j} + a_1(W) + a_2(W)j. \qquad (6)$$

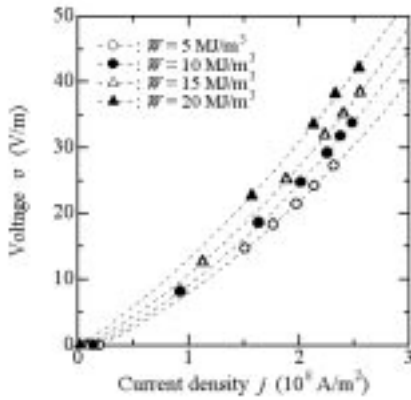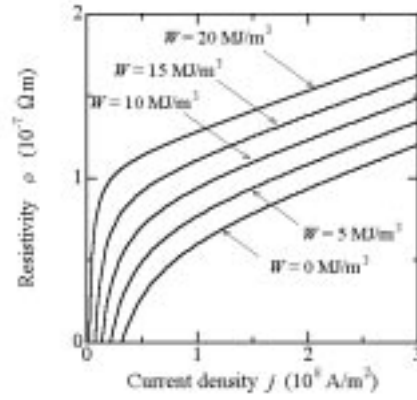In Fig. 3, (6) is graphed. It is confirmed that the resistivity ρ increases with j and W.

Fig. 2. Voltage–current density characteristics.

performed the current carrying tests several times. The critical current density J_c linearly decreases with an increase in W. By the method of least squares, we obtained the equation of J_c as a function of W as follows.

$$J_c(W) = -1.21W + 2.65 \times 10^7. \qquad (1)$$

The line corresponding to this equation is also indicated by the broken line in Fig. 1. Since all J_cs measured for the currents having different peak value agree with the line of (1), it is found that the bulk was under the adiabatic condition for the current carrying period. This means that W was used only for temperature rise of bulk.

B. Voltage–Current Density Characteristics

The voltage–current density characteristics, namely the relation between the current density j and the voltage v in the bulk also depend on W. In several overcurrent carrying tests for the bulk, we also measured instantaneous values of v and j at the moment of $W = 5$, 10, 15 and 20 MJ/m^3. Fig. 2 shows measured v–j characteristics with some kinds of dots.

III. Limiting Performance of Flux Flow Resistance Type Fault Current Limiter in Distribution System

A. Calculation Conditions

We assumed that the flux flow resistance type fault current limiter with the Bi2223 bulk mentioned above is installed at the outgoing feeder in a distribution substation. We considered the situation that a three-phase short-circuit fault occurs near the substation. Fig. 4 illustrates the single-phase equivalent circuit. The system voltage and frequency are 6.6 kV and 60 Hz, respectively. The system impedance is j0.38 Ω (1.01 mH). In this case,
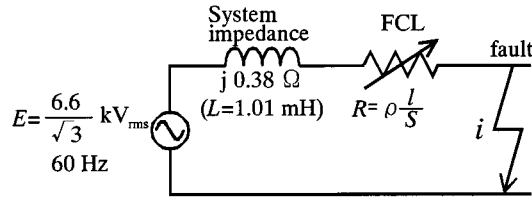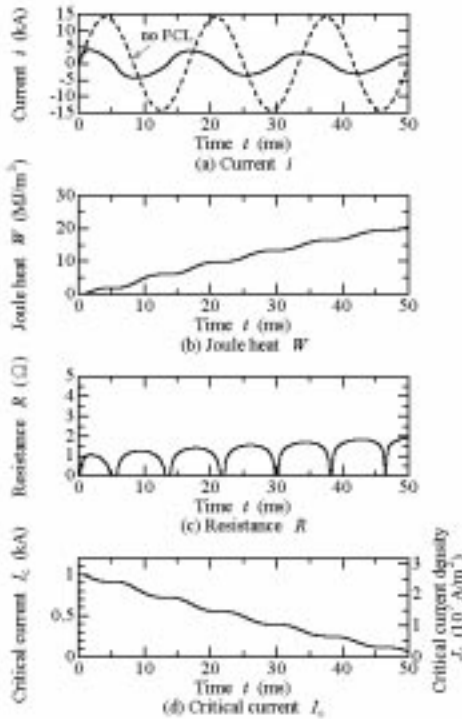
Fig. 4.   Model of 6.6 kV class distribution system.

Fig. 5.   Calculated waveforms ($I_{ini} = 1000\,\mathrm{A}, l = 600\,\mathrm{m}, V = 2.26 \times 10^{-2}$ m^3).

the short-circuit current for no fault current limiter is 10 kA$_{rms}$. From Fig. 4, following equation is written.

$$L \frac{di}{dt} + \rho \frac{l}{S} i = \sqrt{2}\, E \sin \omega t \qquad (7)$$

where I is the instantaneous value of fault current, L is the inductance of the system, ρ is resistivity generated in the superconducting bulk, l and S are the length and cross section of the bulk, E is the root mean square value of phase voltage, ω is the angular frequency. It is assumed that the bulk is under the adiabatic condition and ρ follows (6). The fault occurs when the phase angle of E is $\pi/2$. Calculating (7) numerically, we can obtain i. In the case of a resistive type fault current limiter, the limiting resistance starts to be generated at the moment that I attains to I_{c0}. Hence, the initial current of limiting action I_{ini} is equal to the critical current at 77 K I_{c0}. In this paper, we assumed that I_{ini} is 1000 A. In this case, the cross section of the bulk element is 3.78×10^{-5} m^2 because J_{c0} is 2.65×10^{7} A/m^2.
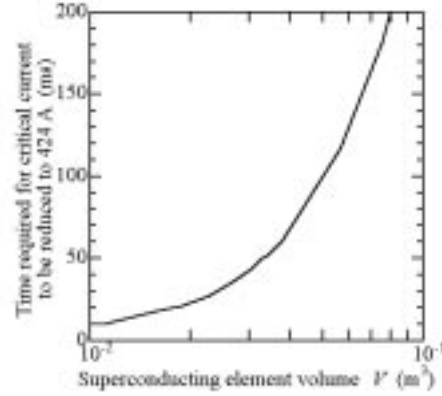

Fig. 6.   Time required for critical current to be reduced to 424 A as a function of superconducting element volume.

B. Calculated Waveforms

Changing the length of the bulk element l, we calculated the time variations of Ii, W, the limiting resistance R $(=\rho(l/S))$ and the critical current I_c $(=J_c S)$. Fig. 5 shows the example of typical waveforms. This figure obtained for l of 600 m. In this case, the volume of the bulk element V $(=Sl)$ is 2.26×10^{-2} m^3. Fig. 5(a)–(d) indicate i, W, R and I_c, respectively. We computed W integrating $i^2 R$. The critical current I_c was obtained by substitution W into (1). In Fig. 5(a), the waveform of the current without the fault current limiter is also shown with broken line. As shown in the first half cycle of Fig. 5(a) and (c), i exceeds I_{ini} of 1000 A and the fault current limiter begins to generate the limiting resistance at $t = 0.24$ ms. The maximum value of the fault current I_m is 4.31 kA which is 30.5% of that in no fault current limiter case. The limiting resistance R recovers to zero at $t = 4.9$ ms because i is below I_c being shown in Fig. 5(d). After that, the similar time variations are repeated. The peak value of i however reduces slightly. That is because the peak value of R gradually rises by the increase in W.

We now suppose that the load current of a distribution feeder is 300 A$_{rms}$ (424 A$_{peak}$). From Fig. 5(d), I_c declines to 424 A at $t = t_{424\,A} = 27.0$ ms. If the fault current is interrupted before $t = t_{424\,A}$, the FCL can pass the load current of 424 A$_{peak}$ without any resistance immediately after the current interruption.

IV. CURRENT INTERRUPTING TIME FOR INFINITELY SHORT RECOVERY

Fig. 6 shows the relation between $t_{424\,A}$ and V. This result is calculated for $I_{ini} = 1000$ A. Since the calculation is performed under the condition of constant cross section of 3.78×10^{-5} m^2, large V means the long l. The fault current is suppressed to the lower level using the bulk with the larger volume because we can get large limiting resistance by long bulk. Furthermore, the joule heat generated in the bulk per unit volume decreases with an increase in V. As a result, the time $t_{424\,A}$ increases with V as shown in Fig. 6. In the case of the current interrupting time of 50 ms (3 cycles at 60 Hz), the volume $V_{50\,ms}$ required for the infinitely short recovery time is 3.29×10^{-2} m^3 (870
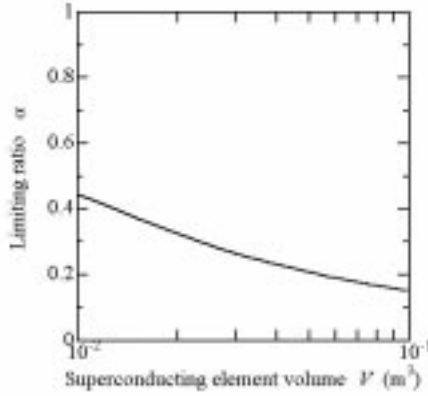
Fig. 7. Limiting ratio α as a function of superconducting element volume.

m in length). The gross size of the superconducting element including the cooling channel in the FCL is almost the same as that of a several ten kVA class pole transformer.

V. LIMITING EFFECT ON PEAK VALUE OF FAULT CURRENT

The limiting effect of peak value of fault current is considered as the performance of the flux flow resistance type FCL. To estimate the effect quantitatively, we defined the limiting ratio α as follows.

$$\alpha = \frac{I_m}{I_{m0}} \tag{8}$$

where I_{0m} is the peak value of fault current in the case of no fault current limiter. In this calculation, I_{0m} is 14.1 kA_{peak}. The small α means that the FCL has high limiting effect.

Fig. 7 shows α as a function of V. This figure is also obtained for $I_{ini} = 1000$ A. The fault current lessens with an increase in V because R increases. Hence α reduced as V goes up. From Fig. 7, α is 0.25 for $V = V_{50\,\mathrm{ms}} = 3.29 \times 10^{-2}$ m^3 which is required to recover immediately after 50 ms from the fault

occurrence as pointed out in preceding chapter. We can maintain I_c more than 424 A at $t = 50$ ms by specifying α less than 0.25. This means that α must be less than a certain value in order to realize the infinitely short recovery time. In other words, to realize larger α, we must use not flux flow resistance type FCL but the normal resistance type one which has a finite recovery time.

VI. CONCLUSION

A FCL using the flux flow resistance of HTS was proposed. This type of FCL may recover to the normal operating state without any delay time after the fault clearing. Supposing that the flux flow resistance type FCL using Bi2223 bulk is introduced into a 6.6 kV distribution system, we discussed the possibility of realization of the infinitely short recovery. It is pointed out that the infinitely short recovery time can be realized by the flux flow resistance type FCL using a large but realistic volume of bulk material.

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