Fundamental Performance of Flux-Lock Type Fault Current Limiter With Two Air-Core Coils

T. Matsumura, A. Kimura, H. Shimizu, Y. Yokomizu, and M. Goto

***Abstract*—This paper proposes a superconducting fault current limiter (FCL) which is a modified version of the flux-lock type fault current limiter developed by us. This FCL consists of a high T_c superconductor (HTS) and two coaxial air-core coils. One coil is connected in parallel with another one through the HTS. The HTS is arranged inside the coils. Under fault condition, the HTS generates resistance by a overcurrent. The limiting impedance appears in the FCL so that the overcurrent can be reduced. Furthermore, the resistance of the HTS increases because the HTS is exposed the magnetic field of the coils. As a result, we can get larger limiting impedance in the current limiting phase. We concretely designed a 200 V class FCL with Bi2223 bulk and estimated the transient behavior in current limiting operation. It is confirmed that the magnitude of fault current was suppressed significantly by this type of FCL with Bi2223 bulk and that the limiting effect was slightly improved by the application of the magnetic field induced by two air-core coils.**

***Index Terms*—Bi2223 bulk, fault current limiter, flux-lock, magnetic field.**

I. Introduction

AS ELECTRIC power transmission systems grow to supply the increasing electric power demand, short circuit currents tend to increase so that a severe burden is imposed on circuit-breakers. To reduce the short circuit current, superconducting fault current limiter (SC-FCL) is expected to be developed and introduced into power systems [1]. Especially, efforts have been continuously put into the development of an SC-FCL with high T_c superconductor (HTS) which operates in liquid nitrogen temperature of 77 K because of its low refrigeration costs and high dielectric strength [2]–[5].

In superconducting/normal transition (S/N) type of the SC-FCL, the superconducting element must generate the enough resistance to get the sufficient current limiting effect. To improve the current limiting performance of the SC-FCL with the HTS, we have proposed flux-lock type fault current limiter (FL-FCL) which consists of HTS, iron core, three coils and a magnetic field coil covering the HTS [6]. The basal performances of the FL-FCL was estimated by experiments and computer simulations [6]. The design guideline of the FL-FCL for the case of introducing to electric distribution system was indicated [7].

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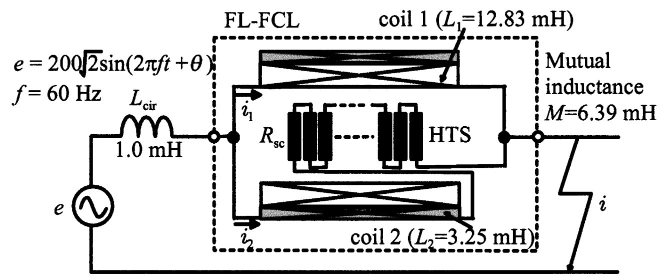

Fig. 1. FL-FCL configuration and simulation circuit.

In this paper, we propose modified version of the FL-FCL which consists of only HTS and two air-core coils. A 200 V class FL-FCL with two coaxial air-core coils is designed specifically and its current limiting performance is evaluated by a numerical simulation to understand the current limiting process of the air-core type of the FL-FCL.

II. Principle of FL-FCL With Two Air-Core Coils

Fig. 1 illustrates a configuration of the FL-FCL with two air-core coils. This FL-FCL is composed of coaxial air-core coils (coil 1 and coil 2) and HTS. Coil 1 is connected in parallel with coil 2 through the HTS. The HTS is arranged inside the coaxial coils as shown in Fig. 1. The revised FL-FCL has simpler configuration compared with the old version.

Under the normal condition where the magnitude of the current i passing through the HTS is below the critical current I_c of the HTS, the resistance of the HTS is zero because the HTS is in superconducting state. In this case, two coaxial coils are connected directly in parallel. When two coils with complete magnetic coupling are connected directly in parallel, in general, the magnetic flux induced by each coil cancels out each other so that no voltage across two coils appears. Consequently, the impedance of the FL-FCL is almost zero. In this case, no magnetic flux is applied to the HTS. Hence, the degradation of I_c and increase in an ac loss do not occur.

Under fault condition, the HTS generates resistance because the overcurrent exceeds I_c. The balance of magnetic flux is upset. The limiting impedance Z_{limit} appears in the FCL so that the overcurrent can be reduced. Furthermore, since the HTS is exposed to the magnetic flux only during the current limiting phase, larger limiting impedance Z_{limit} may be obtained.

III. Design of FL-FCL With Two Air-Core Coils

We concretely designed a 200 V class FL-FCL with two air-core coils to estimate the current limiting performance of the FL-FCL.

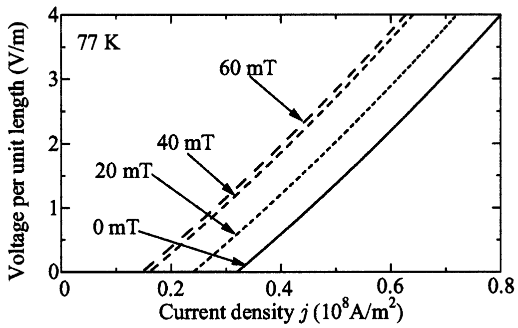

Fig. 2. Voltage-current density characteristics.

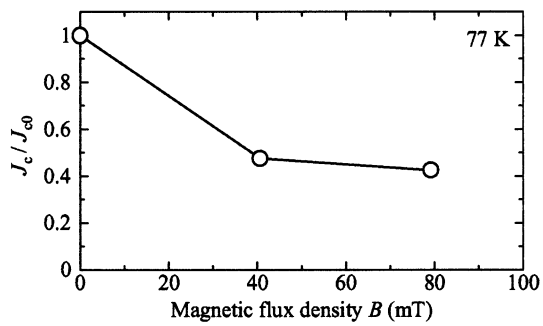

Fig. 3. Dependence of critical current density on magnetic flux density.

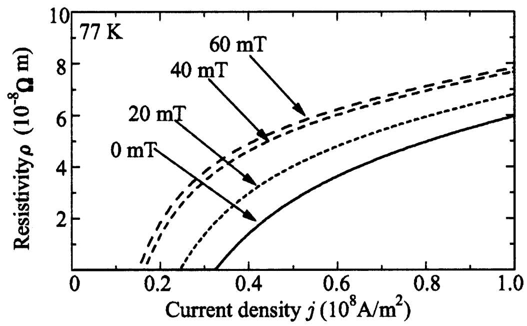

Fig. 4. Resistivity-current density characteristics.

TABLE I
SPECIFICATIONS OF COILS FOR FL-FCL

coil 1	
turn number	332
layer number	4
thickness	1 mm
self inductance L_1	12.83 mH
coil 2	
turn number	166
layer number	2
thickness	0.5 mm
self inductance L_2	3.25 mH
mutual inductance M	6.39 mH
(coupling coefficient k)	(0.99)

A. High T_c Superconductor

It was assumed that a Bi2223 bulk made by sintering [8] was adopted as the HTS. We designed the FL-FCL on the basis of the generating characteristic of a flux flow resistance in the Bi2223 bulk. At 77 K and in the absence of magnetic flux density (0 mT), the voltage per unit length v_0 [V/m] generating in the Bi2223 bulk has been derived from our experiments as a function of current density j [A/m^2] as follows [9]:

$$v_0 = \begin{cases} 0 & (j \leq J_{c0}) \\ -2.06 + 5.69 \times 10^{-8} j & \\ +2.35 \times 10^{-16} j^2 & (j > J_{c0}) \end{cases} \quad (1)$$

where J_{c0} is the critical current density (3.2×10^7 A/m^2) at 77 K and 0 mT.

The voltage versus current density characteristic at 77 K and 0 mT ($v_0 - j$ characteristics) is shown with solid line in Fig. 2. The critical current density J_{c0} corresponds to the intersection of the solid line and the axis of abscissa.

When magnetic flux density B is applied to our Bi2223 bulk, J_{c0} decreases to $J_c(B)$. Fig. 3 shows the dependence of J_c on B for the case that B is applied vertically to the current passing through the Bi2223 bulk [10]. We supposed that the relationships between the voltage and the current density ($v - j$ characteristics) in the magnetic flux application phase were represented by making a parallel translation of the $v_0 - j$ curve for no magnetic flux. On the basis of the reduction in J_c shown in Fig. 3, we got $v - j$ characteristics for the cases of $B = 20$ mT, 40 mT and 60 mT as shown by dotted lines in Fig. 2.

We can obtain the resistivity ρ of the Bi2223 bulk by dividing v with j. Fig. 4 indicates the dependences of ρ on j ($\rho - j$ characteristics). The higher ρ is caused by the larger j and B. For simplicity, we assumed that the Bi2223 bulk was cooled enough so that the temperature rise induced by joule heat generating in the Bi2223 bulk was neglected. In the design of the FL-FCL described below, we use rod-shaped Bi2223 bulk of 1 mm^2 in cross section. In this case, the critical current I_{c0} in the absence of magnetic flux density is 32 A.

B. Design of FL-FCL With Two Air-Core Coils

Fig. 1 and Table I show the dimensions of FL-FCL and the design specifications of coils for FL-FCL, respectively. We can actually make rod-shaped Bi2223 bulk of about 140 mm in length. Thus, inside diameter of coils was set to be 216 mm so that the rod-shaped bulk could be arranged vertically to the central axis of coils. The length of coils is 300 mm. The superconducting tape wire of 3.6 mm $\times$ 0.25 mm in cross section is supposed to be used as the coaxial coil wire. The number of turns of coil 1 and coil 2 are 332 and 166, respectively. In this case, self inductances of coil 1 and coil 2 (L_1 and L_2) are estimated to be 12.83 mH and 3.25 mH. A mutual inductance M between two coils is evaluated to be 6.39 mH. Hence, the coupling coefficient $k\ (= M/\sqrt{L_1 L_2})$ is calculated to be 0.99. This means that good magnetic coupling is realized in this FL-FCL.

In the case of FL-FCL, when $k \simeq 1$, the initiation current I_{ini} of the limiting process is given by next expression [6]

$$I_{ini} = \left(1 + \sqrt{\frac{L_2}{L_1}}\right) I_{c0}. \quad (2)$$

As inductance ratio L_2/L_1 is almost 1/4 in our design, I_{ini} is about 1.5 times as high as the critical current I_{c0} of Bi2223 bulk. Since I_{c0} is 32 A as described in previous section, I_{ini} of the FL-FCL is 48 A.

It is assumed that two coils are wound so that the magnetic flux generated by the coils will compensate each other when coil currents I_1 and I_2 flow from the source side to load one as shown in Fig. 1. This configuration allows our FL-FCL to have very small impedance and magnetic flux density in the normal operating state. The impedance of the FL-FCL in normal state is calculated to be 0.011 Ω (60 Hz). The flux density inside the coils is estimated to be 0.1 mT, which hardly brings degradation of the critical current in the HTS as seen from Fig. 3.

C. Simulation Condition

The current limiting performance of the FL-FCL designed in the previous section was simulated for the circuit in Fig. 1. The magnitude and frequency of the source voltage are 200 V and 60 Hz, respectively. We supposed that the circuit impedance composed of only reactance component whose inductance L_{cir} was 1.0 mH. From Fig. 1, the following differential equations with the winding currents i_1 and i_2 can be obtained:

$$L_{cir}\frac{d(i_1+i_2)}{dt}+L_1\frac{di_1}{dt}-M\frac{di_2}{dt} = \sqrt{2}E\sin(2\pi ft+\theta) \quad (3)$$

$$L_{cir}\frac{d(i_1+i_2)}{dt}+L_2\frac{di_2}{dt}-M\frac{di_1}{dt}+\rho\frac{l_{sc}}{A_{sc}}i_2 = \sqrt{2}E\sin(2\pi ft+\theta) \quad (4)$$

where t is the elapsed time from the fault occurrence, θ is a phase angle of the source voltage at $t=0$, l_{sc} and A_{sc} are the total length and cross section of Bi2223 bulk. Equations (3) and (4) we solved under the initial condition that i_1 and i_2 were zero at $t=0$. In this paper, we supposed $l_{sc}=100$ m and $A_{sc}=1$ mm^2, respectively. In this case, many bulks are connected in series inside the coils as shown in Fig. 1. The resistivity ρ of the Bi2223 bulk can be expressed as a function of j and B as indicated in Fig. 4. It was assumed that uniform magnetic flux density was applied to the whole part of the bulk.

IV. Simulation Results of Limiting Performance

A. Typical Waveforms

Typical waveforms for the case of $\theta=0°$ are illustrated in Fig. 5 to discuss the current limiting performance of the air-core type FL-FCL. Fig. 5(a)–(c) show i_1 passing through coil 1, i_2 passing through coil 2 and the fault current i. In these figures, the "prospective" currents, which flow through each branch if the HTS keeps to be in superconducting state, are also plotted with broken lines. Fig. 5(d) indicates the magnetic flux density B applied to the Bi2223 bulk and i_2. Fig. 5(e) shows the resistance of the Bi2223 bulk.

It is found from the broken line in Fig. 5(a)–(c) that the maximum dc component is included in each prospective current without S/N transition of HTS. The maximum values of the prospective currents for i_1, i_2, and i are 483 A, 963 A and 1446 A, respectively.

For this serious fault condition, it is pointed out that the FL-FCL designed by us can greatly reduce winding currents

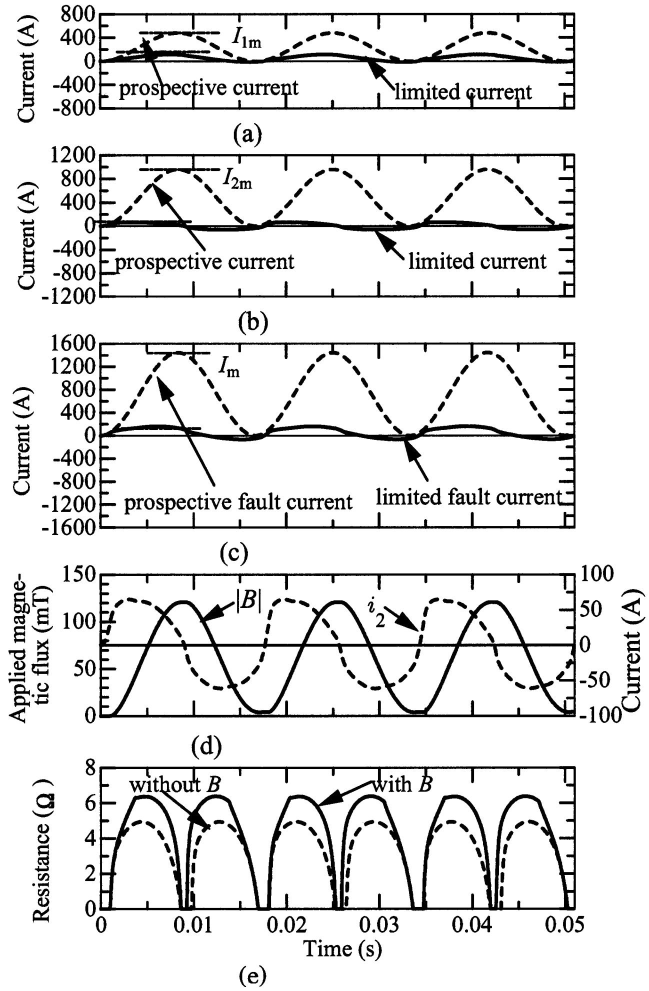

Fig. 5. Typical waveforms for the case of $\theta=0°$. (a) Current i_1, (b) current i_2, (c) fault current i, (d) magnetic flux density $|B|$, (e) resistance R_{sc}.

i_1, i_2, and fault current i. The dc component in i_2 is reduced to zero by the resistance of the HTS although that in i_1 remains. The maximum value of each current I_{1m}, I_{2m}, and I_m are 118.3 A, 64.7 A and 162 A and are suppressed down to 24.5% (118.3/483), 6.7% (64.7/963) and 11.2% (162/1446), respectively. As shown with the broken lines in Fig. 5(a) and (b), the winding current i_1 is in-phase with i_2 and the magnitude of i_1 is almost half of that of i_2 when the HTS does not transit from the superconducting state to the normal state. Since the turn number ratio of two coils is N_1: N_2 = 1: 2, magnetomotive force of the coil 1 N_1i_1 is almost equal to that of the coil 2, N_2i_2, so that the magnetic flux density inside the coils is almost zero.

On the other hand, when the HTS transits to the normal state by the overcurrent, there is a phase difference of about 90° between i_2 and B as shown in Fig. 5(d). As the Bi2223 bulk generates resistance R_{sc} when the overcurrent flows through FL-FCL, the balance of N_1i_1 and N_2i_2 collapses and then B is induced inside the coils. At the same time, the phase of i_2 leads largely than i_1 by the resistance of the HTS, so that there is large phase difference between i_2 and B.

In the case of $\theta=0°$, in spite of phase difference of almost 90° between i_2 and B, the relatively large magnetic flux density

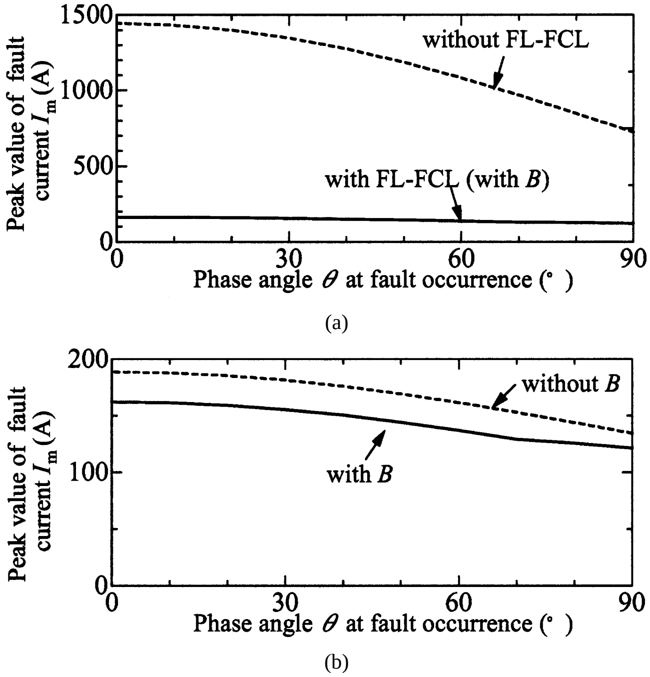

Fig. 6. Dependence of maximum value of fault current on phase angle at fault occurrence. (a) Without FL-FCL and with FL-FCL (with B). (b) Without B and with B.

of 60 mT imposed on the HTS because of the significant transient dc component in B. Fig. 5(e) indicates that the resistance of Bi2223 bulk is enlarged from 4.95 Ω to 6.38 Ω by the application of B.

B. Dependence of Current Limiting Performance on Phase Angle of Voltage Source at Fault Occurrence

Fig. 6(a) shows the dependences of the peak values I_m of prospective fault current and limited fault current on θ. In the case of no FL-FCL, I_m becomes greatly small with an increase in θ because the dc component decreases. On the other hand, since the FL-FCL strongly reduce the dc component, the limited current has little dependence on θ. If we discuss the current limiting effect from the standpoint of the ratio of the limited current to the prospective one, I_m is suppressed down to 11.2% for $\theta = 0°$ and 16.8% for $\theta = 90°$. In other words, when the phase at the fault occurrence is zero, the best current limiting ratio is seemingly derived while the peak value of the limited current is largest.

Fig. 6(b) is enlarged figure of Fig. 6(a) in vertical axis to show more details. In this figure, the limited current in the case that HTS is arranged outside of coil, i.e., magnetic field is not applied to the Bi2223 bulk, is also plotted by the broken line. It is found that I_m is more suppressed by the application of B. The smaller θ brings slightly larger difference of I_m. The peak value of current I_m is suppressed down to 86% on $\theta = 0°$, 91% on $\theta = 90°$ by the presence of B.

As described in previous section, there is a phase difference of about 90° between i_2 and B independently of θ. When θ is large, little dc component remains in B. Thus, when i_2 reaches the peak value, B is not applied to the Bi2223 bulk effectively, so that little current limiting effect is realized by the application of B. On the other hand, in the case of small θ, the relatively large dc component is included. Therefore, when i_2 reaches the peak value, the relative large B is applied, so that the large current limiting effect is realized by the application of B.

V. Conclusion

In this paper, we evaluated the current limiting performance of the modified FL-FCL with two air-core coils considering the $v - j$ characteristics of Bi2223 bulk. As a result, it is pointed out that even if the air-core coils are used instead of iron core, the fault current can be suppressed sufficiently. It is also found that the current limiting performance is improved slightly by the application of magnetic field.

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