Development of Flux-Lock-Type Fault Current Limiter with High-T_C Superconducting Element

T.Matsumura, T.Uchii, Y.Yokomizu
Dept. of Electrical Engineering, Nagoya University, NAGOYA 464-01, JAPAN

Abstract **— The present paper proposes a new type fault current limiter (FCL), which consists of a high T_C superconducting (HTS) element, three coils wound on the same core, and a magnetic field coil covering the HTS element. In this FCL, the initial limiting current level can be controlled by adjusting the inductances of the coils. Furthermore, an external a.c. magnetic field is applied to the HTS element to get higher resistance in the current-limiting phase. A current-limiting experiment by a model FCL was carried out, and the limiting performance of the FCL was observed. Both the initial limiting current level and the limiting impedance could be increased in this FCL compared with the corresponding values of the HTS element itself.**

I. Introduction

As electric power transmission systems grow to supply the increasing electric power demand, short-circuit currents tend to increase and impose a severe burden on circuit-breakers. Thus, a fault current limiter (FCL) is expected to be introduced into the power systems and to reduce the short-circuit current.

It is well known that a superconductor transits from a superconducting mode to a normal resistive one when the current passing through it exceeds a critical level. An application of superconductors to an FCL utilizing this characteristic has been investigated recently [1]. Especially, an FCL with high T_C superconductor (HTS) which operates at 77 K in liquid nitrogen is strongly expected to be developed because of its low refrigeration costs [2] and high insulation abilities. Although many papers on high T_C superconducting FCL are published [3]-[7], it has not yet come to a practical scale at the present time. Increase of both the current capacity and the limiting impedance is necessary.

The present paper proposes a new type FCL, which consists of a flux-lock reactor with an HTS element and a magnetic field coil. This FCL could increase both the initial limiting current level and the limiting impedance simultaneously by a transformer action and magnetic field application. Firstly, fundamentals of the FCL are described. Secondly, the normal resistance of the HTS element is measured to be increased by an external a.c. magnetic field application. Lastly, a scaled-down model of the FCL is constructed and its current-limiting performance is experimentally tested.

Manuscript received August 25, 1996.

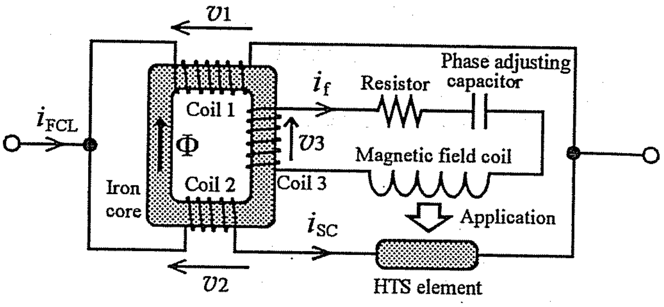

Fig. 1. Fundamental configuration of the FCL.

II. Flux-Lock-Type Fault Current Limiter

A. Structure of the FCL

Fig.1 shows a fundamental configuration of a new type FCL with a high T_C superconductor. The FCL consists of a flux-lock reactor and magnetic field coil circuit. The former is composed of coil 1 and coil 2 which are connected in parallel with each other through an HTS element. The latter is constructed by coil 3, a magnetic field coil, a series resistor and phase adjusting capacitor. Coil 1, 2 and 3 are densely wound on the same core to reduce the leakage flux. The two coils of the flux-lock reactor are wound to counteract each other's flux.

B. Principle

1) Normal condition: In Fig.1, the voltages across the coil 1, 2 and 3 are given by:

$$v_1 = n_1 \frac{d\Phi}{dt}, \quad v_2 = -n_2 \frac{d\Phi}{dt}, \quad v_3 = n_3 \frac{d\Phi}{dt} \tag{1}$$

where, n_1, n_2 and n_3 are numbers of turns of the coils and Φ is the magnetic flux through the iron core i.e. the flux linkaged commonly in the three coils. Under normal condition when load current passes through the FCL, the HTS element is in superconducting state, so that the voltage across the element is zero. Then, coil 1 and 2 are directly connected in parallel, thus,

$$v_1 = v_2 . \tag{2}$$

From (1), we get

$$\left(n_1 + n_2\right)\frac{d\Phi}{dt} = 0 . \tag{3}$$

1051-8223/97$10.00 © 1997 IEEE

Since $n_1 + n_2 \neq 0$, it follows that

$$\frac{d\Phi}{dt} = 0 \cdot \tag{4}$$

Equation (4) implies that the linkage flux is locked in a d.c. mode, so that the voltages across the three coils must be zero. In other words, a negligible low impedance is realized in the FCL for a normal load current.

Furthermore, the field current i_f does not flow in this case, and the HTS element is not exposed to magnetic field. Thus, no deterioration of the critical current by external magnetic field is brought about in a superconducting state of the HTS element.

2) Fault condition: When the HTS element loses its superconductivity and has somewhat resistance due to an overcurrent, (2) and (3) are no longer established. Thus, Φ varies with time and the voltages across the coils are induced. In consequence, limiting impedance appears in the FCL, so that the overcurrent can be reduced.

Simultaneously, i_f flows in the magnetic field coil and then the external a.c. magnetic field is applied to the HTS element. This operation causes the resistance of the element to get higher effectively. This FCL has a self-triggering mechanism and no additional external power source for applying magnetic field.

C. Limiting Impedance and Branch Currents

In Fig.1, supposing that no leakage flux exists and the normal resistance of the HTS element R_{SC} is constant, the limiting impedance Z_{limit}, the branch current I_{SC} passing through the HTS element and the field current I_f are expressed as follows:

$$Z_{limit} = [\omega L_1 R R_{SC} + j\omega L_1(\omega L_f - 1/\omega C) R_{SC}] / \chi \tag{5}$$

$$I_{SC} = [\{\omega(L_1+M_{12})R + j\omega(L_1+M_{12})(\omega L_f - 1/\omega C)\} / \chi] I_{FCL} \tag{6}$$

$$I_f = [\omega M_{13} R_{SC} / \chi] I_{FCL} \tag{7}$$

$$\begin{aligned}\chi = [&\omega(L_1+2M_{12}+L_2)R + \{\omega L_3 + (\omega L_f - 1/\omega C)\} R_{SC}] \\ &+ j[\omega(L_1+2M_{12}+L_2)(\omega L_f - 1/\omega C) - R R_{SC}]\end{aligned} \tag{8}$$

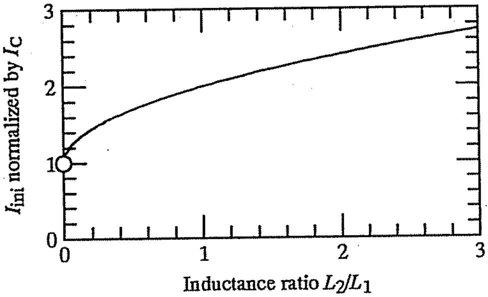

Fig. 2. Increase in the initial limiting current level normalized by the critical current (I_{ini}/I_C) as a function of the inductance ratio of coil 2 to coil 1 (L_2/L_1).

where, L_1, L_2, L_3, M_{12} and M_{13} are the self-inductances and mutual-inductances of the coils. C, R and L_f are the phase adjusting capacitance, the series resistance and self-inductance of the magnetic field coil circuit, respectively, ω is angular frequency, and I_{FCL} is the current passing through the whole FCL.

In (5), $Z_{limit} = 0$ at $R_{SC} = 0$, which implies that the FCL has zero impedance in a superconducting state. In the above equations, L_f can be removed by series resonance between L_f and C i.e. $\omega L_f - 1/\omega C = 0$. Thus, a magnetic field coil having high magnetomotive force can be connected to apply the large magnetic field to the HTS element.

D. Initial Limiting Current Level

The initial limiting current level I_{ini} is given as I_{FCL} when I_{SC} reaches the critical current of the HTS element I_C. Hence, inserting R_{SC}=0 and I_{SC}=I_C in (6), I_{ini} is given by:

$$I_{ini} = \left(1 + \sqrt{L_2 / L_1}\right) I_C \cdot \tag{9}$$

This equation indicates that I_{ini} is always higher than I_C and can be arranged to be a specified magnitude by adjusting the inductance ratio L_2/L_1. Dependence of I_{ini}/I_C on L_2/L_1 is shown in Fig.2.

III. EFFECT OF A.C. MAGNETIC FIELD APPLICATION

In our FCL, we expect that the a.c. magnetic field produces the high normal resistance of the HTS element. In this section, the resistive characteristics of the HTS element are measured under an external a.c. magnetic field. We used an $YBa_2Cu_3O_{7-\delta}$ high T_C superconducting element rod-shaped with 6 mm in diameter and 95 mm in length. The critical current was measured to be 12 A.

An a.c. current with a frequency of 60 Hz was supplied to the element in the longitudinal direction and an external a.c. magnetic field with a frequency of 60 Hz was applied perpendicularly to the current direction.

Fig.3 shows the waveforms of the current, magnetic flux density and normal resistance when the over current with a peak value of 20 A and magnetic flux density with a peak value of 8.5 mT are applied. Figure (a) and (b) indicate the case of the current and the magnetic field being in-phase and with a phase difference of 90°, respectively. In both (a) and (b), upper figures show the waveforms of the current and the applied magnetic flux density together. Lower ones indicate the corresponding waveform of the induced resistance and the resistance in the absence of the applied magnetic field.

It is found from figures (a) and (b) that the external a.c. magnetic field increases the resistance of the element. Especially, in the case (a), the resistance is kept to be three times as high as without the magnetic field during the current above 3 A, but in the case (b), the resistance reaches the peak value at relatively low current level.

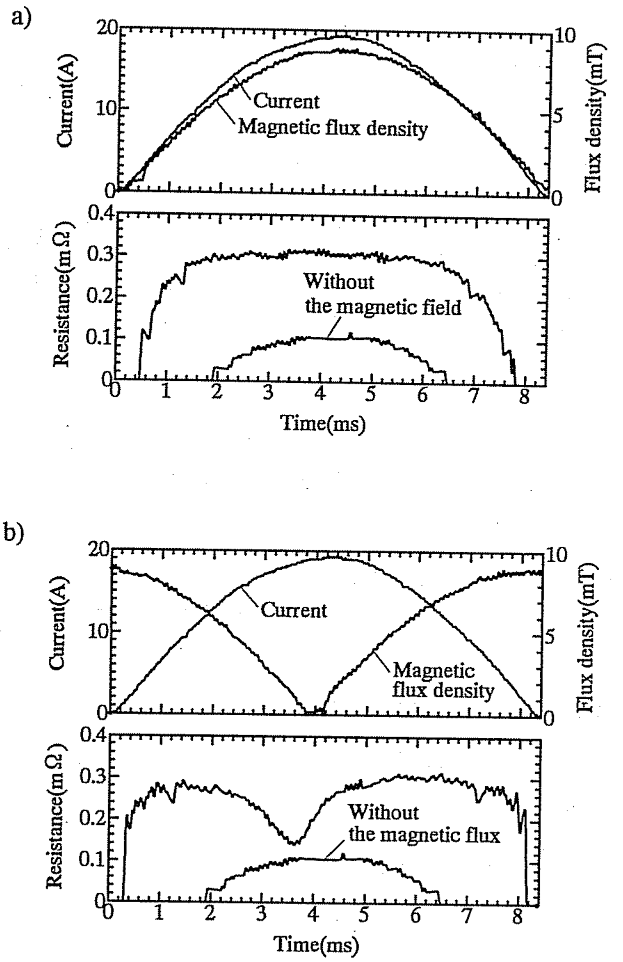

Fig. 3. Waveforms of the induced resistance by a.c. current with a peak value of 19 A and external a.c. magnetic flux density with a peak value of 8.5-9.0 mT. (a): in-phase, (b): phase difference of 90°.

From the viewpoint of the FCL, the case (a) is the more effective than the case (b), because the purpose of the FCL is to reduce the peak value of the overcurrent. From (6) and (7), I_{SC} and I_f can be made to be in-phase to each other by setting $\omega L_f - 1/\omega C = 0$.

IV. CURRENT-LIMITING EXPERIMENT

A. Model of Flux-Lock-Type SCFCL

The schematic diagram of a scaled-down FCL is shown in Fig.4. L_1, L_2 and L_3 are adjusted to be 11.3 mH, 1.1 mH and 8.0 mH, respectively. Three coils are made of copper wire with 1.5 mm×4.5 mm in cross section. The HTS element adopted for the FCL has the zigzag-shape with 310 mm in length and 1.5 mm×1 mm in cross section. Eleven elements are connected in series in the FCL, which has the critical current of 2.2 A and the flux flow resistance of 2.6 V/A as a whole. Specifications of the magnetic field coil are shown in Table.1. The phase adjusting capacitance is fixed at 42 μF for series resonance with L_f. The HTS elements are placed in the space of the magnetic field coil to be perpendicular to the field. The HTS elements and the magnetic field coil are soaked in liquid nitrogen.

From (9), the initial limiting current level of this FCL should be 1.3 times as high as the critical current of the HTS element.

The test circuit is shown in Fig.5. The magnitude of an a.c. voltage source is 10 V_{rms}. The FCL is connected in series to resistors corresponding to the system resistance and the load. The load current is 2.0 A_{peak}. The thyristor switch closes to simulate a short-circuit fault when the phase angle of the source is zero. The prospective value of the short-circuit current without the FCL is 17.7 A_{peak}.

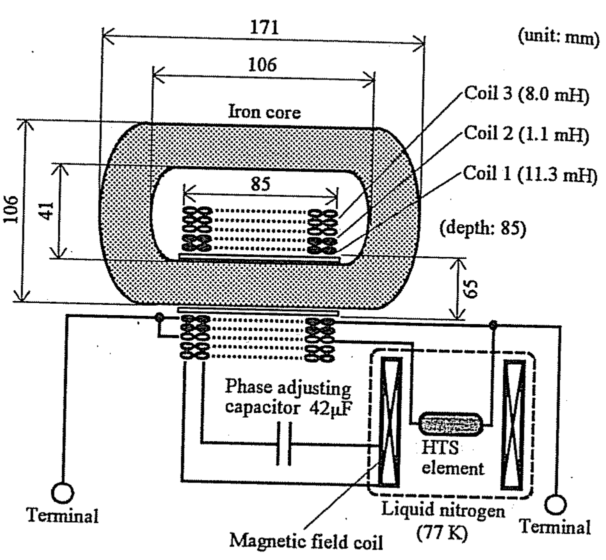

Fig. 4. Schematic diagram of a model flux-lock-type SCFCL.

TABLE I
SPECIFICATIONS OF THE MAGNETIC FIELD COIL

Contents	Value
Magnetomotive force	0.006 T/A
Self-inductance	163 mH
Resistance	3 Ω (at 77 K)
Diameter	114 mm
Height	636 mm

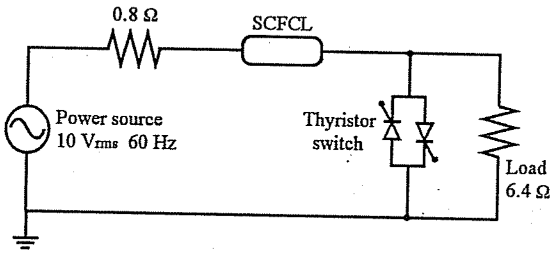

Fig. 5. Circuit diagram of the current-limiting experiment.

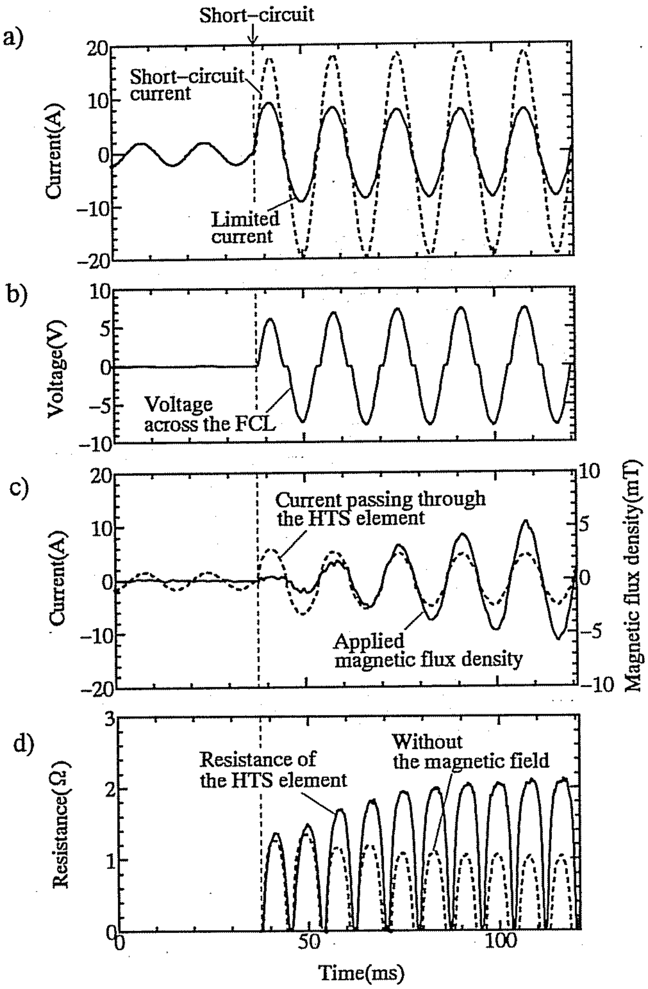

Fig. 6. Current-limiting performance. (a): limited current by the FCL and the prospective short-circuit current without the FCL, (b): the voltage across the FCL, (c): applied magnetic flux density and the current passing through the HTS element, (d): the resistance of the HTS element and the prospective resistance without the applied magnetic field density.

B. Current-Limiting Performance

The waveforms measured in the current-limiting experiment are shown in Fig.6. In figure (a), the solid curve indicates the limited current by the FCL, and the broken curve represents the prospective short-circuit current without the FCL. Figure (b) shows the voltage across the FCL. The voltage is not measured in the load current phase when the HTS element is in the superconducting state, but as soon as short-circuit occurs a large voltage appears. The fault current is suppressed down to 51 % (9.1/17.7). From the waveforms, the initial limiting current level of the FCL is 2.7 A, which is close to the value of 2.6 A calculated by (9).

Figure (c) shows the applied magnetic field density and the current passing through the HTS element, together. The magnetic field appears in-phase immediately after the short-circuit somewhat with a time delay. Figure (d) indicates the resistance of the HTS element together with the prospective resistance without the applied magnetic field. The resistance of the HTS element is increased by the application of the magnetic field. In the FCL, the resistance almost reaches saturation at the third cycle, and then the resistance is about twice as high as without the magnetic field.

V. CONCLUSIONS

We have studied the fundamental performance of flux-lock-type SCFCL theoretically and experimentally. In the FCL, the initial limiting current level can be increased by adjusting the inductance combination of the coils. Furthermore, an external a.c. magnetic field is applied to the HTS element to get higher resistance only in a current-limiting phase. When the phase difference between the magnetic field and the current passing through the HTS element is zero, the limiting performance becomes the most effective, which can be realized in the FCL by setting the phase adjusting capacitance appropriately. Consequently, both the initial limiting current level and the limiting impedance could be increased in the FCL compared with the zero-field value of the HTS element.

REFERENCES

[1] V.D.Pham, Y.Laumond, T.Verhaege, A.Fevrier, M.Gollet, and M.Bekhaled, "Towards the Superconducting Fault Current Limiter," *IEEE Trans. Power Delivery*, vol. 6, no. 2, 1991, pp. 801-808.

[2] R.F.Giese and M.Runde, "Assessment Study of Superconducting Fault-Current Limiters Operating at 77 K," *IEEE Trans. Power Delivery*, vol. 8, no. 3, 1993, pp. 1138-1147.

[3] L.S.Fleishman, Yu.A.Bashkirov, V.A.Aresteanu, Y.Brissette, and J.R.Cave, "Design Considerations for an Inductive High T_C Superconducting Fault Current Limiter," *IEEE Trans. Appl. Supercond.* , vol. 3, no. 1, 1993, pp. 570-573.

[4] Y.Yokomizu, T.Matsumura, H.Okubo, and Y.Kito, "Current-Limiting Performance of a $YBa_2Cu_3O_{7-x}$ Superconductor by the Transition from Superconducting to Normal-Conducting State," ETEP vol. 5, no. 2, 1995, pp. 99-105.

[5] V.Meerovich, V.Sokolovsky, G.Jung, and S.Goren, "High-T_C Superconducting Inductive Current Limiter for 1kV/25A Performance," *IEEE Trans. Appl. Supercond.* , vol. 5, no. 2, 1995, pp. 1044 -1046.

[6] W.Paul, Th.Baumann, J.Rhyner, and F. Platter, "Tests of 100 kW High-T_C Superconducting Fault Current Limiter," *IEEE Trans. Appl. Supercond.* , vol. 5, no. 2, 1995, pp. 1059-1062.

[7] M.Ichikawa and M.Okazaki, "A Magnetic Shielding Type Superconducting Fault Current Limiter using a Bi2212 Thick Film Cylinder," *IEEE Trans. Appl. Supercond.* , vol. 5, no. 2, 1995, pp. 1067-1070.