Generating Performance of Limiting Impedance in Flat Type of Fault Current Limiter With High Tc Superconducting Plate

Toshiro Matsumura, Mitsuhiro Sugimura, Yasunobu Yokomizu, Hirotaka Shimizu, Masatoyo Shibuya, Michiharu Ichikawa, and Hiroyuki Kado

***Abstract*—We have proposed a flat type of the superconducting fault current limiter (FCL) which is a modified version of a magnetic shielding type of the fault current limiter. The new FCL basically consists of a doughnut-like form high Tc superconductor (HTS) plate and spiral coil, each of which works as a secondary one-turn winding and a primary winding, respectively. The FCL modules can be easily built up to make a large scale FCL. This simple construction may enable us to reduce the manufacturing costs. We made two small modules of the flat type FCL with Bi2223 bulk plate and YBCO thin film plate and investigated the generation of the limiting impedance due to an excess current. Higher ratio of the limiting impedance to normal one was produced by the YBCO thin film plate than by the Bi2223 bulk plate.**

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

I. Introduction

FAULT current limiter (FCL) is expected as a reduction technology of a short-circuit current in an electric power system so that various types of the superconducting FCL have been researched and developed [1]–[16]. We have proposed a flat type of the superconducting fault current limiter [17], which is a modified version of a magnetic shielding type FCL [4], [7]. The flat type FCL has a simple construction and basically consists of a doughnut-like form high Tc superconductor (HTS) plate and spiral coil, each of which works as a secondary one-turn winding and a primary winding, respectively. The FCL modules can be easily built up to make a large scale FCL for a practical use. This simple construction may enable us to reduce the manufacturing costs because it is easy to make the HTS plates.

Two small modules of the flat type FCL with Bi2223 bulk plate and YBCO thin film plate were made. The generating performance of the limiting impedance in current limiting operation was investigated.

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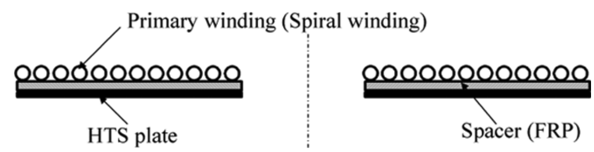

Fig. 1. Configuration of flat type of FCL.

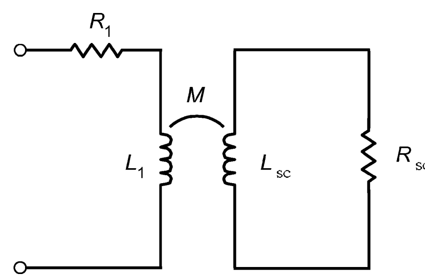

Fig. 2. Equivalent circuit of flat type fault current limiter.

II. Flat Type Fault Current Limiter

Fig. 1 shows a configuration of the flat type FCL which consists of a spiral winding (primary winding) and a HTS plate in doughnut shape. The spacer is inserted between the spiral winding and the HTS plate for an electrical and thermal insulation. The spiral winding is connected to an electrical power system in series and the current I_1 (load current or fault one) in the power system flows in it. The shielding current I_2 is induced in the HTS plate by the time variation in the magnetic flux ϕ_1 due to I_1.

The principle of this type of FCL is essentially same as that of a magnetic shielding type FCL [4], [7]. Under the normal condition of the FCL, the magnitude of I_1 is the load current level and I_2 is less than the critical current I_c of the HTS. If the HTS and spiral winding are arranged properly so that the magnetic coupling between them is strong, ϕ_1 is almost completely cancelled by the magnetic flux ϕ_2 due to I_2 and the impedance Z_0 of the FCL is realized to be almost zero. When a short-circuit fault occurs, I_2 exceeds I_c and a resistance appears in the HTS. As the result, the FCL generates a certain limiting impedance Z_{FCL} and reduces the overcurrent.

Fig. 2 shows the equivalent circuit of the FCL. In this figure, R_1 and L_1 are the resistance and self inductance of the primary winding whereas R_{sc} and L_{sc} are the resistance and self inductance of the HTS plate and M is the mutual inductance between

TABLE I
SPECIFICATION OF FLAT TYPE OF FCL ADOPTED

	parameter	Bi2223	YBCO
Primary winding	Turn	14	
	Wire diameter (mm)	1.6	
	Resistance R_1 (77K, mΩ)	2.92	
	Self inductance L_1 (μH)	201	213
	Mutual inductance M (μH)	14.2	15.3
	Magnetic coupling coefficient k	0.994	
HTS plate	Inside diameter (mm)	25.4	
	Outside diameter (mm)	76.2	
	Thickness of HTS part (μm)	500	0.3
	Thickness of plate with substrate (μm)	3,500	500
	Self inductance L_{sc} (μH)	1.02	1.11
Spacer	Thickness (FRP, mm)	1	
FCL	Impedance at normal operation Z_0 (mΩ)	10	7.1
	Limiting impedance Z_{FCL} (mΩ)	48	49
	Impedance ratio Z_{FCL}/Z_0	4.8	6.9

the spiral winding and the HTS plate. Under the normal condition, R_{sc} is zero. Assuming that L_{sc} is constant, we obtain the FCL impedance Z_0 at the normal condition as follows.

$$Z_0 = \sqrt{R_1^2 + \omega^2\left(L_1 - \frac{M^2}{L_{sc}}\right)^2} = \sqrt{R_1^2 + \omega^2(1-k^2)^2 L_1^2} \quad (1)$$

where ω is the angular frequency of the power system and k is the magnetic coupling coefficient. The FCL impedance Z_{FCL} at the current limiting operation changes with the instantaneous value of the current because R_{sc} varies depending on the current. For sufficiently large R_{sc}, however, the magnitude of Z_{FCL} reaches to

$$Z_{FCL} = \sqrt{R_1^2 + \omega^2 L_1^2} \quad (R_{sc} = \infty) \quad (2)$$

In the conventional magnetic shielding type of FCL, the HTS in cylindrical shape is used in place of the HTS plate. Since it is much easier to make the HTS plate than cylinder, the FCL proposed by us can be manufactured at lower cost. Furthermore, the FCL with HTS plate can also be easily built up to make a large scale FCL.

III. SMALL MODULES OF FLAT TYPE FCL

We made two small modules of the flat type of FCL to perform current carrying tests. The specifications of the modules are summarized in Table I and their configurations are illustrated in Fig. 3. We used copper wire of 1.6 mm in diameter as the primary winding. The turn number of the primary winding is 14 for both modules. The resistance R_1 at 77 K was measured to be 2.92 mΩ. The Bi2223 bulk and YBCO film were adopted as the HTS plate. Fig. 3(c) shows a photograph of the Bi2223 plate. The outside and inside diameters of the HTS plate are 76.2 mm and 25.4 mm, respectively. The 500 μm thick Bi2223 bulk plate was produced on the MgO substrate with the thickness of 3 mm, while the 0.3 μm thin YBCO film was formed on the 0.5 mm thick sapphire plate. The FRP (Fiberglass Reinforced Plastic) plate of 1 mm thickness was used for the spacer.

We used iron cores to improve the magnetic coupling and enlarge the self inductance of the winding. The primary winding

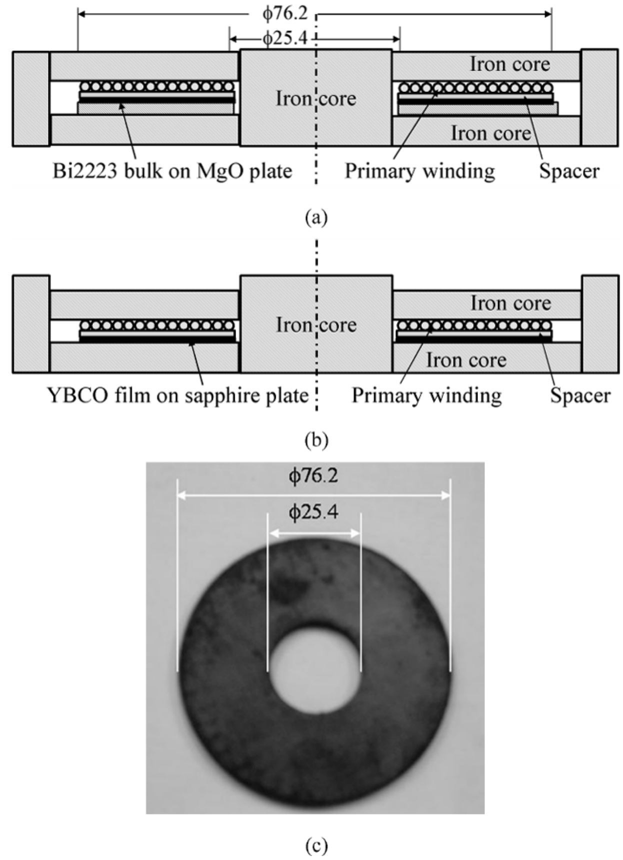

Fig. 3. Small models of flat type fault current limiter with HTS plate and iron core. (a) Small module of flat type FCL with Bi2223 bulk plate; (b) small module of flat type FCL with YBCO film plate; (c) Bi2223 bulk plate adopted.

and HTS plate were sandwiched with two iron plates and enclosed with the iron bar and cylinder as shown in Fig. 3.

The self-inductance of the primary winding was measured to be 201 μH and 213 μH for the Bi2223 version and the YBCO one, respectively. Supposing the current flows uniformly in the HTS plate, L_{sc} and M are calculated to be 1.02 μH and 14.2 μH for Bi2223 version, while to be 1.11 μH and 15.3 μH for YBCO one. These differences in the inductance between Bi2223 version and YBCO one are induced by the difference in the magnetic path due to the thickness of the HTS plate including the substrate.

IV. CURRENT CARRYING TEST

We supplied a.c. current of 60 Hz to the FCL and measured the current and the voltage across the FCL. The whole module of the FCL with the iron core was cooled by liquid nitrogen. Figs. 4 and 5 show the examples of the waveforms measured for Bi2223 version and YBCO one, respectively.

Fig. 4(a) is the result in the case that the peak value I_p of the current is 8.85 A, in which the Bi2223 plate is recognized to be under the superconducting condition. In this paper, we define the quotient of the peak value V_p of the FCL voltage divided by I_p as an impedance of the FCL. Since V_p is measured to be 89 mV in Fig. 4(a), the FCL impedance Z_0 of the Bi2223 version under the superconducting condition is estimated to be around 10 mΩ. Fig. 4(b) indicates the waveforms measured for

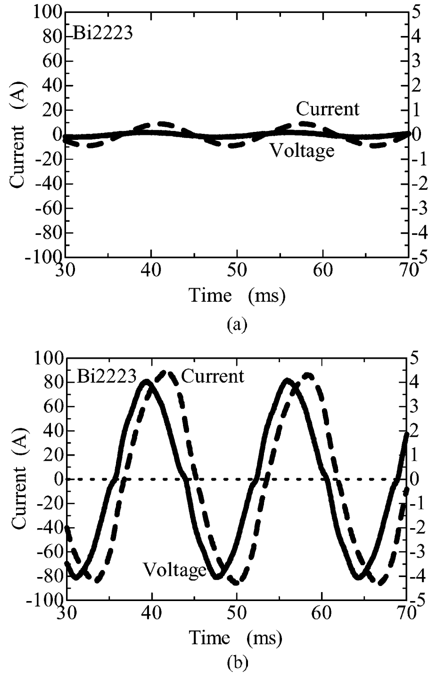

Fig. 4. Typical waveforms of current and voltage for Bi2223 version. (a) $I_\mathrm{p} = 8.85\ \mathrm{A_{peak}}$; (b) $I_\mathrm{p} = 84.7\ \mathrm{A_{peak}}$.

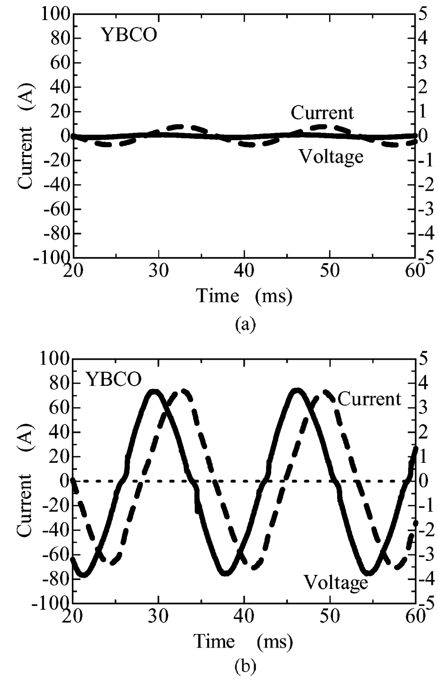

Fig. 5. Typical waveforms of current and voltage for YBCO version. (a) $I_\mathrm{p} = 7.45\ \mathrm{A_{peak}}$; (b) $I_\mathrm{p} = 71.5\ \mathrm{A_{peak}}$.

$I_\mathrm{p} = 84.7$ A. From this figure, the FCL impedance Z_FCL of the Bi2223 version at the limiting operation is evaluated to be 47.3 $\mathrm{m\Omega}$. This magnitude is about 4.7 times of that for $I_\mathrm{p} = 8.85$ A.

On the other hand, in case of the YBCO version, the FCL impedance Z_0 under the superconducting condition is estimated to be 7.45 $\mathrm{m\Omega}$ for the peak current of 7.45 A because V_p is measured to be 55.4 mV in Fig. 5(a). Fig. 5(b) indicates the waveforms obtained for $I_\mathrm{p} = 71.5$ A. From this figure, the FCL impedance Z_FCL of the YBCO version at the limiting operation is estimated to be 52.1 $\mathrm{m\Omega}$, which is about 7 times of that for $I_\mathrm{p} = 7.45$ A.

In Figs. (4b) and (5b), a phase of the voltage is ahead of that of the current by 43 and 60 degrees, respectively. This means that the flat FCL works almost as a reactive type of FCL.

V. Impedance of Flat Type of FCL

Fig. 6 illustrates the dependence of the impedance of FCL Z_0 and Z_FCL on the peak value of the primary current I_P obtained by current carrying tests for the Bi2223 version and YBCO one. Since the magnitudes of the critical current of the Bi2223 bulk and YBCO film differ from each other, the current at an abscissa is normalized by each magnitude (20 A for Bi2223, 12 A for YBCO) corresponding to the critical current.

As the current through the primary winding increases, the impedance of the Bi2223 version of the FCL increases monotonically from $Z_0 = 10\ \mathrm{m\Omega}$ and has a saturation tendency to $Z_\mathrm{FCL} = 48\ \mathrm{m\Omega}$. On the other hand, in case of the YBCO version, the impedance increases from $Z_0 = 7\ \mathrm{m\Omega}$ to $57\ \mathrm{m\Omega}$ with an increase and then gradually decreases to $Z_\mathrm{FCL} = 49\ \mathrm{m\Omega}$ as the current increases. From Fig. 6, the impedance ratio Z_FCL/Z_0 was derived to be about five and seven for the Bi2223 version and the YBCO one. These results on the impedance are summarized at the bottom rows in Table I.

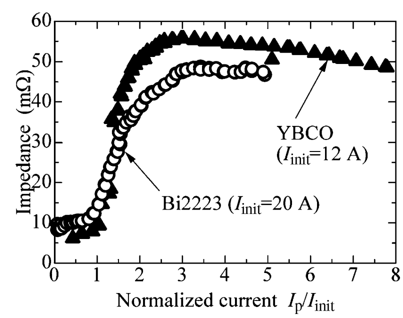

Fig. 6. Impedance of flat type FCL as a function of current.

VI. Discussion

In this paper, the iron core adopted in the experiments consisted of four pieces so that there were small air gaps in the magnetic circuit. Furthermore, the saturation of the magnetic flux was observed in the experiments. Both small air gaps and magnetic saturation inhibit the increase in the impedance of the FCL under the current limiting condition.

We may improve the impedance ratio using the primary winding made from the HTS wire. That is because the winding resistance R_1, which dominated Z_0 in the trial module, can be reduced to almost zero by using the HTS wire. Furthermore, Z_FCL may be enlarged by enclosing the FCL with the highly permeable iron core without any air gaps, because the use of the ferromagnetic material strengthens the magnetic coupling between the primary winding and the HTS plate, and it increases the magnitude of the inductance.

VII. Conclusion

We investigated the generating performance of the impedance for the flat type of the fault current limiter. Two small modules were made from Bi2223 bulk plate and YBCO film plate. Higher ratio of the limiting impedance to the normal one was produced by the YBCO thin film plate than by the Bi2223 bulk plate.

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