Hysteretic Dependence of Magnetic Flux Density on Primary AC Current in Flat-Type Inductive Fault Current Limiter with YBCO Thin Film Discs

Masayuki Harada, Yasunobu Yokomizu and Toshiro Matsumura
Department of Electrical Engineering and Computer Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
E-mail: masayu_h@echo.nuee.nagoya-u.ac.jp

Abstract. This paper focuses on a flat-type inductive superconducting FCL (FIS-FCL) consisting of a pancake coil and a YBCO thin layer disc. AC current injection experiments and magnetic field analysis were carried out for two kinds of FIS-FCL, single-disc model and double-discs model. In the former, the pancake coil was putted on the YBCO disc. In the latter, the pancake coil was sandwiched with two YBCO discs. The double-discs model cancels out the magnetic flux density more effectively than the single-disc model. In the double-discs model, the superconducting state period is longer than in the single-disc model. Thus, it may be concluded that the double-discs model is considered to be suitable for FIS-FCL.

1. Introduction
Recently, by the spread of distributed power supplies, fault current tends to increase, which may cause power system equipment to break. Therefore, the development of fault current limiters (FCL) are expected. We have proposed a flat-type inductive superconducting fault current limiter (FIS-FCL) consisting of a pancake coil with copper wire as the primary winding and a superconducting thin film discs as secondary windings[1]. The small FIS-FCL modules, which were constructed by using discs with yttrium barium copper oxide (YBCO) thin film layer, have been experimentally examined[2]. The FIS-FCL module might be scaled up by piling up for use in practical applications. When a normal load current flows through the primary winding, the magnetic flux generated by primary current is canceled out by that produced by the shielding current induced in the superconducting disc. Thus, the inductance of the FCL is suppressed to be almost zero. On the other hand, when over current such as short circuit current flows through the primary winding, the prospective magnitude of the shielding current induced in the superconducting disc increases more than the critical current level, and then the shielding current has to be limited within critical level. Therefore, the magnetic flux density generated by primary current is no longer canceled out so that the inductance appears in the FCL.

In this paper, in order to understand the periodic behavior of magnetic flux density arising in the FIS-FCL, over current injection experiments were carried out for two different configuration of the FIS-FCL. Furthermore, the magnetic field analysis was performed by using the finite element method to find out the shape of the shielding current induced in the YBCO layer.
2. Experiment

2.1. Experimental condition

Fig. 1 shows schematic arrangements of two different structure of the FIS-FCL and the pick-up coil for measuring magnetic flux density. A pancake coil with copper wire as primary winding is put on the YBCO disc #1 in figure (a) (single-disc model) and sandwiched by two YBCO discs #1 and #2 in figure (b) (double-discs model). The discs #1 and #2 work as secondary windings. In both discs, YBCO thin layer of 185 nm in thickness was coated over sapphire substrate discs of 2 mm in thickness by metal-organic deposition (MOD) method[3].

Fig. 2 shows the experimental circuit. In this paper, AC current of 15 A in peak value was injected into the pancake coil by adjusting the output voltage \( v_s \) to be 30 V in peak value. The electro-motive force \( e \) was induced in the pick-up coil by AC magnetic flux generated in the FCL. The magnetic flux density \( B_z \) at the center of the FCL can be estimated from \( e \) as follows:

\[
B_z = -10.8 \int e \, dt
\] (1)

The coefficient -10.8 was derived by another experiment. In our experiment, waveforms of current \( i \) injected into the primary winding and electromotive force \( e \) induced in the pick-up coil were recorded with a digital oscilloscope.

2.2. Measurement result and magnetic flux density

The over current injection experiments were carried out for two kinds of single-disc model with disc #1 or #2 and double-discs model. The measured waveforms of \( i \), \( e \) and \( B_z \) are illustrated in Fig. 3. In all models, \( e \) hardly appears after the peak point of the injected current. This implies that the change of primary magnetic flux is canceled out by secondary current flowing YBCO layer. The peak value of \( B_z \) in the double-discs model is lower than that in the single-disc model.

Fig. 4 (a) and (b) show the instantaneous magnitude of \( B_z \) against those of \( i \) in both single-disc model and double-discs model. In this figure, the \( B_z-i \) characteristic of a standalone primary winding without the YBCO thin film disc is also plotted for the peak value of \( v_s \) was 30 V. The gradient of this characteristic represents the inductance of the FIS-FCL. In each model (single-disc model with #1 or #2 and double-discs model), the \( B_z-i \) characteristic exhibits hysteresis. The high gradient before current peak is similar to that of the standalone primary winding. Thus, the YBCO layer is considered to be in the resistance-generation state. After
current peak, in contrast, the $B_z$-$i$ characteristic has a very low gradient. This implies that the inductance of FIS-FCL is much smaller than that of standalone primary winding because YBCO layer is superconducting state so that the change of the primary magnetic flux is canceled out by the shielding current induced in YBCO layer. Comparing these low gradients in all models, it is found that the double-discs model has lower gradient than single-disc model. This means that the double-discs model suppress the inductance to small when the YBCO layers are superconducting state. Moreover, in the double-discs model, the period when the YBCO keeps superconducting state is longer than that in single-disc model.

3. Numerical calculation

3.1. Magnetic field analysis

Magnetic field analysis was carried out for a simplified FIS-FCL with a 10-turn pancake coil (Fig. 5). The governing equation is given from Maxwell’s equations and Ohm’s law as follows:

$$\frac{\partial}{\partial z} \left( \frac{1}{\mu} \frac{\partial A_\theta}{\partial z} \right) + \frac{\partial}{\partial r} \left( \frac{1}{\mu r} \frac{\partial (rA_\theta)}{\partial r} \right) + J_0 - \frac{1}{\rho} \frac{\partial A_\theta}{\partial t} = 0,$$

where $J_0$, $\rho$, $\mu$ and $A_\theta$ are the forced current density, resistivity, magnetic permeability and rotation-direction magnitude of vector potential in the element, respectively. In our calculation, $\mu = 1.25 \times 10^{-6} \text{ H/m}$ for all elements, $\rho = 0 \quad \Omega \text{m}$ for the elements corresponding to the primary winding, and $\rho = 1.00 \times 10^{18} \quad \Omega \text{m}$ for the elements corresponding to the spacer and LN$_2$. The resistivity of YBCO layer $\rho_{sc}$ was determined according to the following equation in the $n$-value model[4]:

$$\rho_{sc} = \frac{E_c}{J_c} \left( \frac{|J_{sc}|}{J_c} \right)^{n-1},$$

where $J_{sc}$, $n$ and $J_c$ is the eddy current density induced in the YBCO layer, $n$-value and critical current density of YBCO, respectively. For another YBCO sample, $n$ and $J_c$ were measured.

Figure 3. Measured waveforms in over current carrying experiments.

Figure 4. Hysteresis relationship between the magnetic flux density and injected current.
40.4 and 9.4 kA/mm$^2$, respectively. Then these values of $n$ and $J_c$ were used in this calculation. The vector potential $A_0$ is obtained by solving the governing equation at each element. In this paper, the AC current $i_s = I_m \sin(120\pi t)$ was injected into the primary winding, where peak value $I_m$ was adjusted to 7 A.

3.2. Calculated waveform

Fig. 6 shows the injected current flowing through the primary winding $i$, total shielding current induced in each YBCO layer $i_{sc}$ and magnetic flux density $B_z$, respectively. The magnitude of the critical current in the adopted YBCO layer, $I_c$, is estimated to be 18.8 A, which is the critical current value of the single-disc model. The total critical value of the double-discs model is $2I_c = 37.6$ A. Before current peak, both $i_{sc}$ are limited at the critical current $I_c$ or $2I_c$ and both $B_z$ changes according to $i$.

After current peak, both $i_{sc}$ begin to change against $i$ and the instantaneous absolute value of $i_{sc}$ is under the corresponding critical current. It means that the YBCO layer recovers to the superconducting state. In double-disc model, as shown in Fig. 6 (b), the saturation is reached for a higher applied field than in single-disc model. As seen in Fig. 6 (c), in double-discs model, $B_z$ is limited smaller than in the single-disc model.

**Figure 5.** Simplified FCL model for numerical calculation.

**Figure 6.** Calculated waveforms of injected current $i$, shielding current induced in YBCO layer $i_{sc}$ and magnetic flux density $B_z$.

**Acknowledgements**

We thank the National Institute of Advanced Industrial Science and Technology (AIST) for producing the YBCO thin film disc adopted in experiments.

**References**

[1] Matsumura T, Sugimura M, Yokomizu Y, Shimizu H, Shibuya M, Ichikawa M and Kado H 2005 *IEEE Trans. Appl. Supercond.* 15 2015-18

[2] Higuchi K, Guan Y, Yokomizu Y and Matsumura T 2012 *Physics Procedia* 36 1254-57

[3] Manabe T, Ahn Jun H, Yamaguchi I, Sohma M, Kondo W, Tsukada K, Mizuta S and Kumagai T 2006 *IEICE Trans. Electron.* E89-C 186-90

[4] Ishiyama A, Nakatsugawa J, Noguchi S, Kado H and Ichikawa M 1999 *IEEJ Trans. Power and Energy* 119 1201-09