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論 文
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Hysteresis Characteristics of Flux-Lock Type Superconducting Fault Current Limiter

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Abstract - For the design to prevent the saturation of the iron core and the effective fault current limitation, the analysis for the operation of the flux-lock type superconducting fault current limiter (SFCL) with consideration for the hysteresis characteristics of the iron core is required. In this paper, the hysteresis characteristics of the flux-lock reactor, which is an essential component of the flux-lock type SFCL, were investigated. Under normal condition, the hysteresis loss of the iron core in the flux-lock type SFCL does not happen due to its winding structure. From the equivalent circuit for the flux-lock type SFCL and the fault current limiting experiments, the hysteresis curves could be drawn. From the analysis for both the hysteresis curves and the fault current limiting characteristics due to the number of turns for the 1st and 2nd windings, the increase of the number of turns in the 2nd winding of the flux-lock type SFCL had a role to prevent the iron core from saturation.

Key Words : flux-lock type superconducting fault current limiter, fault current limiting characteristics, hysteresis characteristics, saturation of an iron core.

1. INTRODUCTION

With the increase in the capacity for power transmission and the demand for electric power, the fault current levels have risen to exceed available cut-off ratings of existing circuit breakers [1-2]. With continuous efforts to suppress the increase of fault currents, various types of superconducting fault current limiters (SFCLs) have been developed in many countries, incorporating many merits that other devices could not have[3-8]. Among these SFCLs, the flux-lock type SFCL can be classified into resistive type SFCL because the fault current can be limited by the quench occurrence of the superconducting material. The merit of the flux-lock type SFCL is that the normal resistance of the high-TC superconducting (HTSC) element can be increased by the application of the magnetic field from the magnetic field circuit and that the limiting current capacity can be increased [9-10].However, in spite of the generation of the higher resistance of the HTSC element, its fault current limiting characteristics can be debased due to the saturation of the iron core, which was an essential component of the flux-lock type SFCL. Therefore, the analysis for the operation of the flux-lock type SFCL with consideration for the hysteresis characteristics of the iron core is required to prevent its saturation immediately following a fault accident.

In this work, the hysteresis characteristics of the iron core of the flux-lock type SFCL were analyzed through the equivalent circuit of a saturable transformer including the nonlinear magnetizing characteristic of the iron core. It was observed from the experiments that the increase of the number of turns of the 2nd winding could prevent the iron core of the flux-lock type SFCL from the saturation.

2. Analysis of Equivalent Circuit for Flux-Lock Type SFCL

2.1 Principle of Flux-Lock Type SFCL

Fig. 1 shows a configuration of the flux-lock type SFCL. i_1, i_2 and i_{FCL} are the primary, the secondary and the system currents, respectively. The primary and the secondary windings, which are connected in parallel through the HTSC element such as bulk or thin film, are wound to counteract each other's flux on the same iron core. Under normal condition, the flux generated from the primary winding is canceled out by one from the secondary winding because the resistance of the HTSC element is zero. In the fault condition when the current in the secondary winding exceeds the critical current of the HTSC element, the appearance of the resistance of the HTSC element allows the linkage flux within the iron

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core and the impedance of the SFCL, thus limiting the fault current.

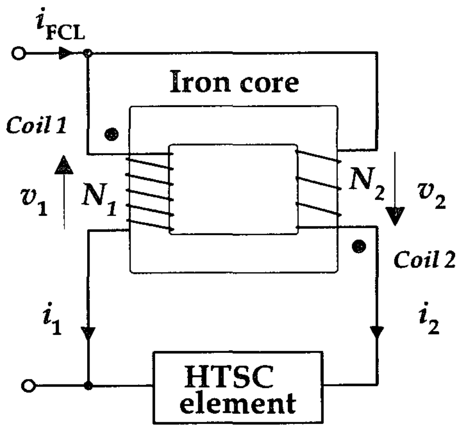

Fig. 1 Configuration of the flux-lock type SFCL with the third winding.

2.2. Equivalent Circuit of Flux-Lock Type SFCL

The equivalent circuit reflecting the nonlinear magnetizing characteristic of the saturable transformer is shown in Fig. 2. R_{l1} and R_{l2} represent the resistances of each winding, respectively and L_{l1} and L_{l2} represent the leakage inductances of each winding, respectively. N_1 and N_2 are the numbers of turns of each winding. L_m and R_C, which consist of the exciting branch, express the magnetization inductance and the resistance of the iron loss for the iron core.

The limiting impedance of the flux-lock type SFCL (ZFCL), based on the assumption that the leakage inductances, the resistances of each winding and the iron loss can be negligible, can be expressed as follows:

$$Z_{FCL} = \frac{1}{\frac{1}{\frac{V_1}{I_1'}} + \frac{1}{\omega L_m} + \frac{1}{\left(-\frac{V_2}{I_2} + R_{SC}\right)}} \quad (1)$$

where R_{SC} is the resistance of the HTSC element, w is angular frequency and I_1' is the current, which is expressed in phasor form, viewed from the primary winding for the currents flowing at the secondary winding. I_1' is equal to $(N_2/N_1)I_2$. V_1, V_2 and I_2, which are expressed in phasor form, are the voltages of the primary and the secondary windings, and the current flowing at the secondary winding, respectively.

2.3. Hysteresis Characteristic of Iron Core

From Fig. 2, the exciting current (i_e) and the voltage across the exciting branch can be expressed as Equations (2) and (3).

$$i_e(t) = i_1(t) - i_1'(t) \quad (2)$$

$$\frac{d\lambda(t)}{dt} \approx v_1(t) \quad (3)$$

where v_1 is the voltage induced in the primary winding and is the linkage flux of the iron core. Equations (2) and (3) can be used irrespective of the saturation of the iron core. Assuming that each winding is wound closely and that the resistance of each winding is small, the leakage inductances (L_{l1}, L_{l2}) and the resistances of each winding (R_{l1}, R_{l2}) can be negligible. Therefore, the linkage flux of the iron core can be obtained by integrating the voltage induced in the primary winding from t_0 to t.

The hysteresis loops of the iron core of the flux-lock type SFCL at each fault period can be obtained with Equations (2) and (3) from the measured currents for each winding and the voltage across the primary winding.

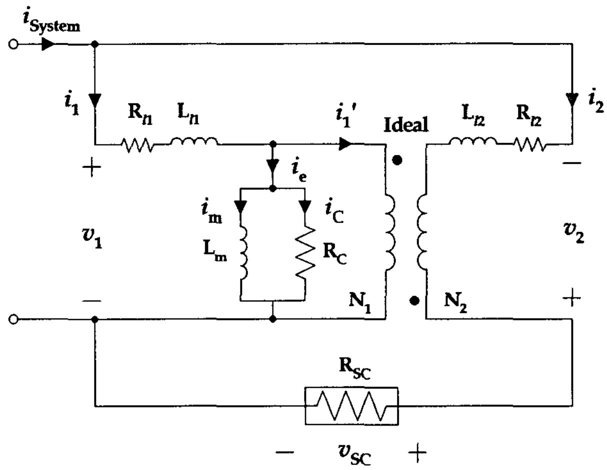

Fig. 2 Equivalent circuit of the flux-lock type SFCL considering the hysteresis characteristics of the flux-lock reactor.

3. EXPERIMENTS AND RESULTS

3.1 Preparation of Experiment

Two windings comprising the flux-lock type SFCL were stacked on the same core to minimize the leakage inductance. The designed specifications of the flux-lock type SFCL are shown in Table 1. The current limiting element, which was connected with the secondary winding of the flux-lock type SFCL, was fabricated using 300-nm-thick $Y_1Ba_2Cu_3O_{7-x}$ (YBCO) thin films grown on 2 inch diameter Al_2O_3 substrates. A 0.2 m thick gold layer was coated on the YBCO thin film, which disperses the joule heat generated at hot spots after quench happens and protects the YBCO thin film against moisture. The line for the current limiting element was patterned by etching the YBCO thin film covered with a gold layer into a 2 mm wide and 420 mm long meander line using photolithography. The meander line consists of fourteen stripes with different lengths, respectively.

TABLE 1 The detailed design parameters for the flux-lock type SFCL

Iron Core (Laminated Si)	Value	Unit
Outer Horizontal Length (l_{OX})	106	mm
Outer Vertical Length (l_{OY})	171	mm
Inner Horizontal Length (l_{IX})	41	mm
Inner Vertical Length (l_{IY})	106	mm
Thickness	85	mm
COIL 1 AND 2	**Value**	**Unit**
Turns in Coil 1	42	Turns
Turns in Coil 2	14, 28	Turns
HTSC Thin Film	**Value**	**Unit**
Material	YBCO	
Critical Temperature	87	K
Critical Current	16.5	A
Total Meander Line Length	420.	mm
Line Width	2	mm
Thin Film Thickness	0.3	μm
Gold Layer Thickness	0.2	μm

The schematic diagram for the experimental circuit, which is composed of a 60-Hz ac power supply, a line resistance of 1 , a resistive load of 50 , a flux-lock reactor and $Y_1Ba_2Cu_3O_{7-X}$ (YBCO) thin film for the current limiting element, is shown in Fig. 3. The fault accidents from the experimental circuit were simulated by closing S2 at 0 °angle of source voltage after S1was closed. The data were obtained and analyzed from the data acquisition system (DL750 Scope Corder, YOKOGAWA).

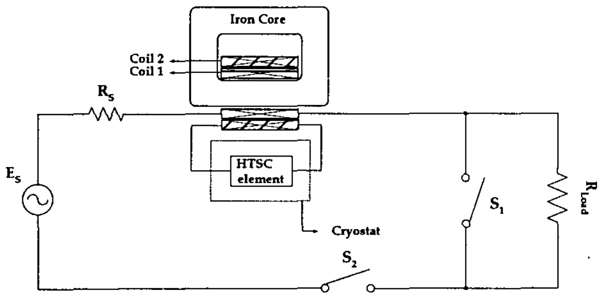

Fig. 3 Schematic diagram for the experimental circuit of the flux-lock type SFCL.

3.2 Experimental Results

To investigate the effect of the number of turns of the secondary winding of the flux-lock type SFCL with the fixed number of the primary windings on the operational characteristics of a fault current limiter with a saturable iron core, the fault current limiting characteristics were experimented. Fig. 4 shows current waveforms and resistance of the HTSC element in case that the number of turns of the secondary winding for the fixed number of the primary winding is 14 and 28, respectively. After a fault happened, the second peak of the current in the primary winding in case that the number of turns of the secondary winding is 14 (Fig. 4(a)) could be observed and the current waveform of the primary winding was distorted due to the increased exciting current (i_e), which was related with the saturation of the iron core. However, the distortion of the current in the primary winding reduced gradually as the resistance of the HTSC element increased. On the other hand, the second peak of the current in the primary winding in case that the number of turns of the secondary winding is 28 did not almost appear as shown in Fig. 4(b), which resulted from the decreased exciting current (i_e).

The resistance of the HTSC element in the case that the number of turns of the secondary winding was 28 increased a little higher than that in the case that the number of turns of the secondary winding was 14.

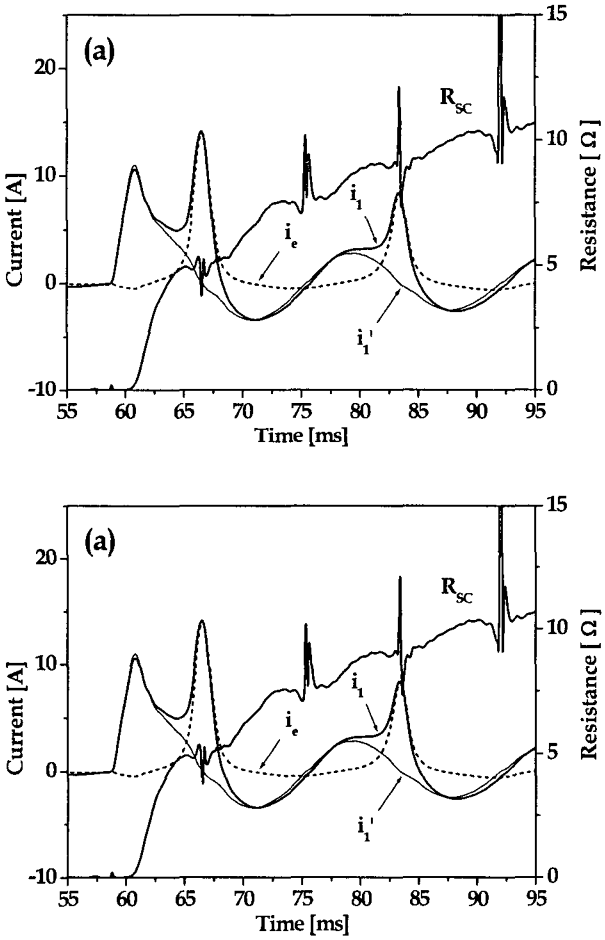

Fig. 4 Current waveforms and resistance of HTSC element. (a) N_1 = 42, N_2 = 14 (b) N_1 = 42, N_2 = 28

Fig. 5 shows the hysteresis loops of the iron core of the flux-lock type SFCL, which were obtained using Equations (2) and (3) from the measured currents and voltages. It was observed from Fig. 5 that the iron core of the flux-lock type SFCL with 14 turns in the secondary winding showed the larger loop with nonlinear form than that of the flux-lock type SFCL with 28 turns in the secondary winding. Larger difference of hysteresis loop for two cases during the initial fault period, however, decreased as the fault period increased, which resulted from the resistance increase of the HTSC element.

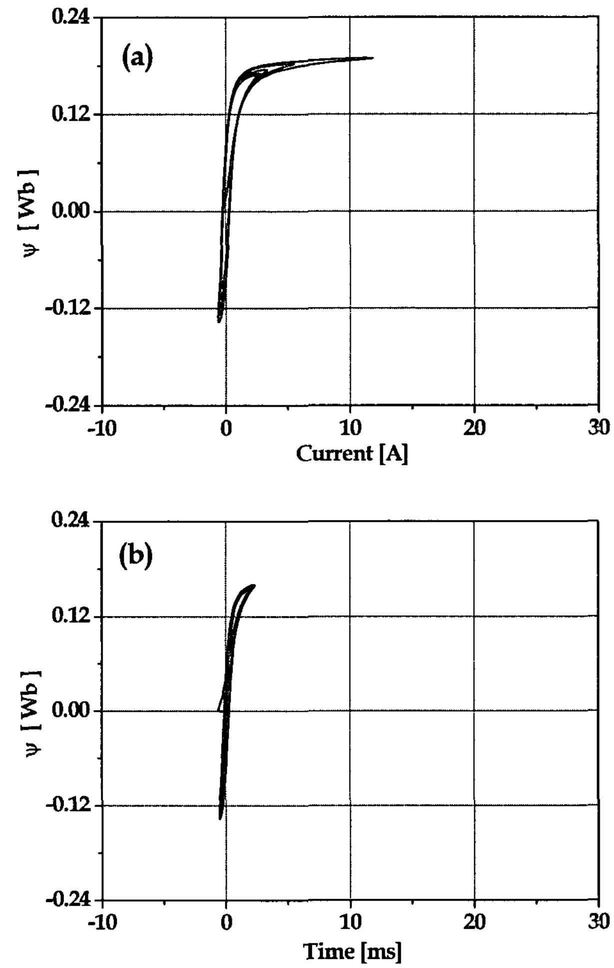

Fig. 5 Hysteresis curve obtained from the measured current and voltage of flux-lock type SFCL.
(a) N_1 = 42, N_2 = 14 (b) N_1 = 42, N_2 = 28

Fig. 6 shows the line current waveforms due to the number of turns of the secondary winding of the flux-lock type SFCL with the same number of turns of the primary winding. As seen in Fig. 6, the amplitude of the line current in case that the number of turns of the secondary winding was 28 was undistorted and, on the other hand, larger than that of the line current in case that the number of turns of the secondary winding was 14.

4. conclusions

The flux-lock type SFCL, like other SFCLs using an iron core, indicates the saturation of the iron core as the voltage ratings of the SFCL increased. To analyze and overcome it, the hysteresis characteristics of an iron core of the flux-lock type SFCL were investigated from the measured currents and voltages based on the equivalent circuit of a saturable transformer reflecting the nonlinear magnetizing characteristic. From the analysis for the variation of the number of turns of the secondary winding of the flux-lock type SFCL with the same number of turns of the primary winding, the larger number of turns of the secondary winding prevented the saturation of the iron core comprising the flux-lock type SFCL. Conversely, the amplitude of the limited line current increased further as the number of turns of the secondary winding increased.

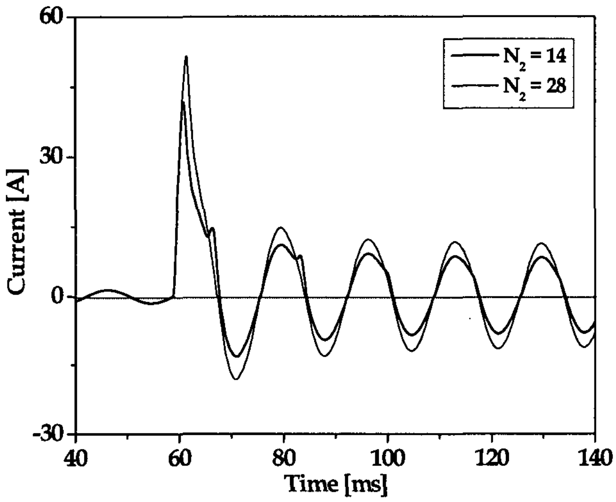

Fig. 6 Line current waveforms in case that the number of turns of the secondary winding of the flux-lock type SFCL with the same number of turns of the primarywinding was 14 and 28, respectively.

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REFERENCES

[1] E. Thuries, V. D. Pham, Y. Laumond, T. Verhaege, A. Fevrier, M. Collet, and M. Bekhaled, "Towards the superconducting fault current limiter," IEEE Trans. on Power Delivery, vol. 6, no. 2, pp. 801-808, April 1991.

[2] E. Leung, "Surge protection for power grids," IEEE Spectrum, vol. 34, no. 7, pp. 26-30, July 1997.
[3] L. Salasoo, A. F. Imece, R. W. Delmerico, and R. D. Wyatt, "Comparison of superconducting fault limiter concepts in electric utility applications," IEEE Trans. on Appl. Supercond., vol. 5, no. 2, pp. 1079-1082, June 1995.
[4] J. X. Jin, S. X. Dou, H. K. Liu, C. Grantham, Z. J. Zeng, Z. Y. Liu, T. R. Blackburn, X. Y. Li, H. L. Liu, and J. Y. Liu, "Electrical application of high Tc superconducting saturable magnetic core fault current limiter," IEEE Trans. on Appl. Supercond., vol. 7, no. 2, pp. 1009-1012, June 1997.
[5] H. Kado, and M. Ichikawa, "Performance of a high-Tc superconducting fault current limiter-design of a 6.6 kV magnetic shielding type superconducting fault current limiter," IEEE Trans. on Appl. Supercond., vol. 7, no. 2, pp. 993-996, June 1997.
[6] B. Gromoll, G. Ries, W. Schmidt, H.-P. Kraemer, B. Seebacher, B. Utz, R. Nies, H.-W. Newmuller, E. Baltzer, and S. Fischer, "Resistive fault current limiters with YBCO films 100kVA functional model," IEEE Trans. on Appl. Supercond., vol. 9, no. 2, pp. 656-659, June 1999.
[7] M. Yamaguchi, S. Fukui, T. Satoh, Y. Kaburaki, T. Horikawa, and T. Honjo, "Performance of DC reactor type fault current limiter using high temperature superconducting coil," IEEE Trans. on Appl. Supercond., vol. 9, no. 2, pp. 940-943, June 1999.
[8] T. Hoshino, K. M. Salim, M. Nishikawa, I. Muta, and T. Nakamura, "Proposal of saturated DC reactor type superconducting fault current limiter (SFCL)," Cryogenics, vol. 41, no. 7, pp. 469-474, July 2001.
[9] T. Matsumura, T. Uchii, and Y. Yokomizu, "Development of flux-lock type fault current limiter with high-TC superconducting element," IEEE Trans. on Appl. Supercond., vol. 7, no. 2, pp. 1001-1004, June 1997.
[10] S. H. Lim, H. S. Choi, and B. S. Han, "The fault current limiting characteristics of a flux-lock type high-Tc superconducting fault current limiter using series resonance," Cryogenics, vol. 44, no. 4, pp. 249-254, April 2004.

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