Fault Current Limiting Characteristics of Flux-lock Type SFCL with Several Secondary Windings

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We investigated fault current limiting characteristics of the flux-lock type superconducting fault current limiter (SFCL), which consisted of a primary winding and several secondary windings connected in series between high-T_C superconducting (HTSC) thin films. Each YBCO thin film has a 2 mm wide and 42 cm long meander line with 14 stripes of different length. The power imbalance due to the slight difference of I_C between YBCO current limiting elements causes the significant power burden on YBCO element with lower I_C. We confirmed from our experiments that the mutual coupling between the primary winding and secondary windings of the flux-lock type SFCL reduced the power imbalance between YBCO current limiting elements compared with the resistive type SFCL connected in series.

Keywords : Fault current limiting characteristics, Flux-lock type superconducting fault current limiter, Power burden, Mutual coupling

1. INTRODUCTION

As capacities of power transmission for growing electric power demand increase, fault currents of the related machinery in the grid have increased more and more. The ratings of circuit breakers have reached their limits by these fault currents so that the power system has been threatened by them all the time. As one of counter measures for unannounced fault accidents, superconducting fault current limiters (SFCLs) have been developed[1-3]. Among the developed SFCLs, the flux-lock type SFCL can be classified into resistive type SFCL because fault current can be limited by quench occurrence of superconducting element.

For the application of SFCLs into power system, voltage and current ratings of SFCLs is required to increase. Especially, in order to increase the voltage ratings of SFCLs, superconducting elements consisting of SFCL should be connected in series. However, the imbalanced power dissipation of superconducting elements happens due to slight difference in critical current density between them[4-6]. Some solutions for it have been suggested[7-9].

In this paper, we investigated that the flux-lock type SFCL using several secondary windings connected in series between superconducting elements could perform the operation for the balanced power dissipation between them. The flux-lock type SFCL using YBCO thin films, which has been developed by us[10,11], was fabricated and its fault current limiting characteristics were investigated.

2. PRINCIPLE AND DESIGN OF FLUX-LOCK TYPE SFCL

Figure 1 shows electrical circuit of the flux-lock type SFCL with several secondary windings connected in

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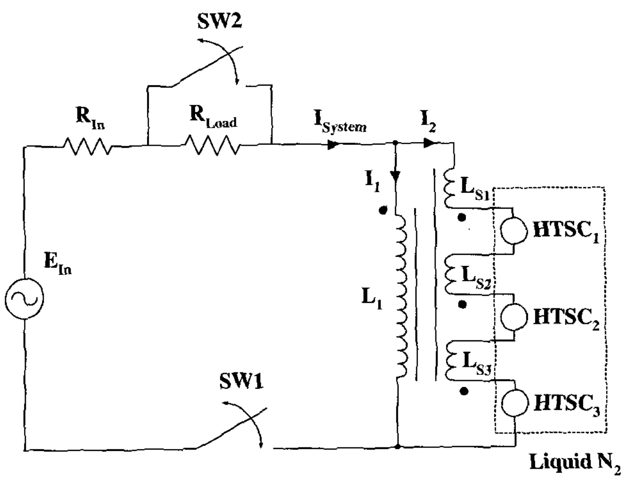

Fig. 1. Experimental circuit of flux-lock type SFCL with several secondary windings connected in series with HTSC elements.

series through each superconducting element. The primary winding of this flux-lock type SFCL is connected in parallel with several secondary windings, which can help the balanced power dissipation between superconducting elements after a fault occurs. Under the normal condition where the current passing through HTSC elements does not exceed the critical current of them, the resistances of HTSC elements are zero. In this case, The magnetic flux generated from the primary winding can be cancelled out by the ones generated from several secondary windings. Therefore, voltages across the primary and the secondary windings are zeros, which leads the impedance of the flux-lock type SFCL to be zero. Under the fault condition, the over-current passing through HTSC elements exceeds the critical currents of them so that the resistances of HTSC elements generate. The generation of these resistances in HTSC elements allows the magnetic flux between the primary winding and the several secondary windings and the voltage in each winding induces. Thus, the fault current of system can be limited by the limiting impedance of this SFCL. In addition, the mutual coupling between the primary winding and the secondary windings of this SFCL can be contributed to the balanced power burden between HTSC elements after a fault occurs.

To estimate the fault current limiting characteristics of the flux-lock type SFCL with several secondary windings, the current limiting element and the flux-lock reactor were designed. Current limiting elements were fabricated using 300-nm-thick $YBa_2Cu_3O_7$ (YBCO) thin films grown on Al_2O_3 substrates with 2 inch diameter. A 0.2 μm thick gold layer was coated in situ on the YBCO thin film for dispersion of the joule heat generated at hot spots, which inhomogeneous parts of YBCO thin film may act as inevitably when a fault current flows in the thin film. The current limiting elements were fabricated by etching the YBCO thin films covered with gold layer into 2 mm wide and 420 mm long meander line using photolithography technique which consisted of fourteen stripes with different length, respectively[11]. The flux-lock reactor, which consists of one primary winding and three secondary windings, was fabricated. Table 1 shows the design specifications for the flux-lock reactor. In the experimental circuit as shown in Fig. 1, E_{In} is a source voltage, and I_{System}, I_1 and I_2 are the current flowing in the power source, the primary and the secondary windings, respectively. R_{In} is the resistance of power source, which is 1 Ω for easy calculation of fault current in case of no SFCL and R_{Load} is the resistance of load, which is 30 Ω. For the normal state operation, the switch SW_1 was closed and then, the switch SW_2 was closed for the fault state operation. The data from experiments were taken using a multi-channel digitizer through current transformer (CT) and potential transformer (PT).

Table 1. Design specifications for the flux-lock reactor.

Iron Core	Size	Unit
Outer Horizontal Length (l_{OY})	171	mm
Outer Vertical Length (l_{OX})	106	mm
Inner Horizontal Length (l_{IY})	106	mm
Inner Vertical Length (l_{IX})	41	mm
Thickness	85	mm
Primary winding	**Value**	**Unit**
Self inductance (L_P)	87.5	mH
Secondary windings	**Value**	**Unit**
Self Inductance (L_{S1})	2.5 or 6	mH
Self Inductance (L_{S2})	2.5 or 6	mH
Self Inductance (L_{S3})	2.5 or 6	mH

3. EXPERIMENTAL RESULTS AND DISCUSSION

Three superconducting elements were used for the experiments to investigate the balanced power dissipation between them, which were connected in series with each secondary winding of the flux-lock type SFCL shown in Fig. 1. The critical currents of HTSC1, HTSC2 and HTSC3 based on 1 mV/cm line were 15.3, 15.7 and 15.5 A, respectively. Figure 2 shows the current and voltage curves of the flux-lock type SFCL with several secondary windings connected in series through each HTSC element in case that the inductances of the primary and the secondary windings were 87.5 mH and 2.5 mH, respectively. The initial power imbalance reduces gradually as a fault time passes. The flux linkage between the primary and the secondary windings

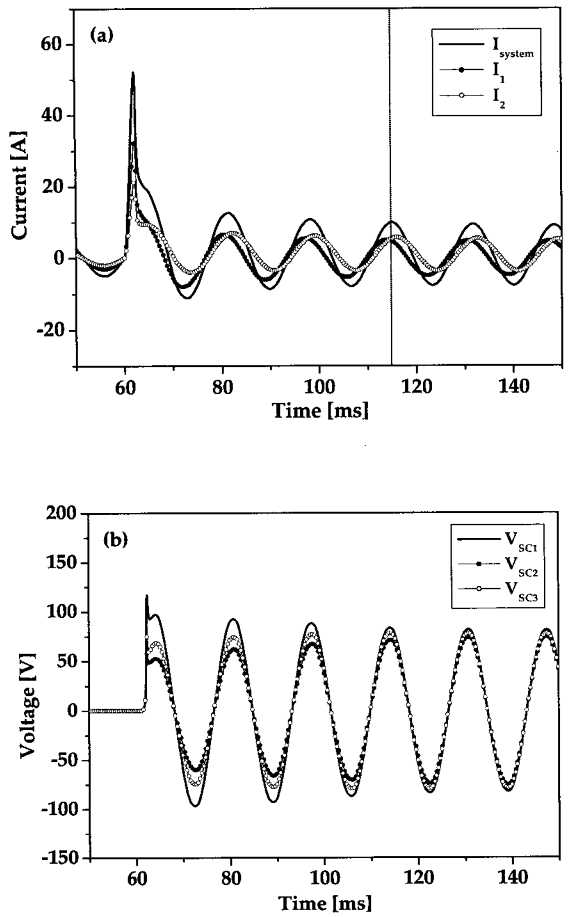

Fig. 2. Electrical properties of HTSC elements in the flux-lock type SFCL with several secondary windings connected with each HTSC element in series (L_P= 87.5 mH, L_{S1}=L_{S2}=L_{S3}= 2.5 mH). (a) Current curves of three HTSC elements and (b) Voltage curves of three HTSC elements.

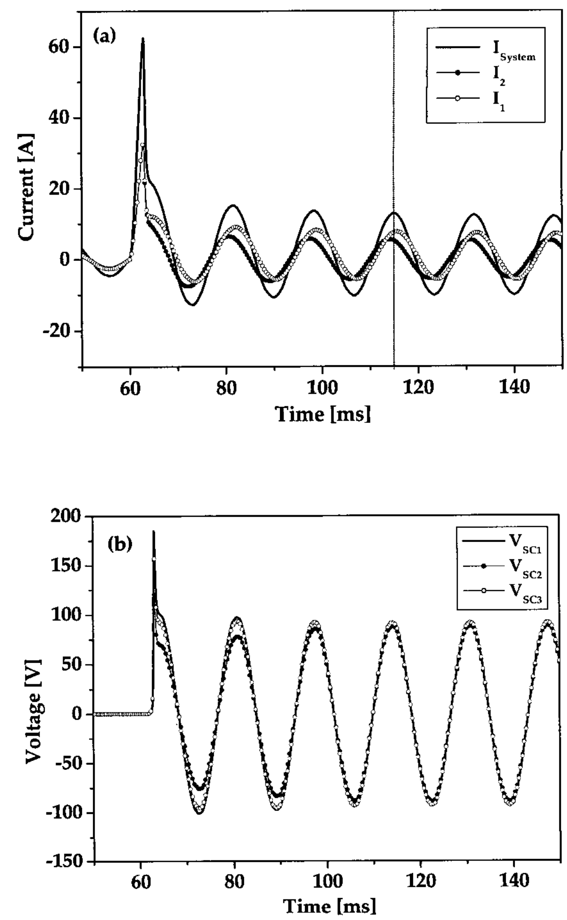

Fig. 3. Electrical properties of HTSC elements in the flux-lock type SFCL with several secondary windings connected with each HTSC element in series (L_P= 87.5 mH, L_{S1}=L_{S2}=L_{S3}= 6 mH). (a) Current curves of three HTSC elements and (b) Voltage curves of three HTSC elements.

through one iron core induced the balanced quench of HTSC elements and lead to the balanced power burden between HTSC elements. Figure 3 represents the quench properties of HTSC elements in case that the inductances of the secondary windings of the flux-lock type SFCL increase into 6 mH. Power imbalance was reduced more than the case where the inductances of secondary windings were 2.5 mH. The resistances of HTSC elements at points marked with a vertical dotted line in Fig. 3(a) were 17 Ω, 16.9 Ω, and 16.4 Ω respectively. The difference between resistances of HTSC elements was decreased compared with the case that the resistances of HTSC elements at the same points shown in Fig. 2(a) was 14.2 Ω, 15.6 Ω, and 16.5 Ω respectively. We confirmed from above experiments that the several secondary windings of the flux-lock type SFCL, connected in series through each HTSC element, could be acted as power balancer for HTSC elements with different critical currents.

The quench behaviours near the quench starting point, as shown in Fig. 4, were compared for two cases of Figs. 2 and 3. The rising rate of current passing through HTSC elements after a fault happened was immediately decreased from 15661 A/s to 11477.6 A/s as the inductance of secondary winding increased from 2.5 mH to 6 mH, which was calculated by the amplitude of the current variation per passing time until the current was limited by the generation of resistances. Voltages at each HTSC elements, which appeared almost simultaneously, increased rapidly to different peak points with different

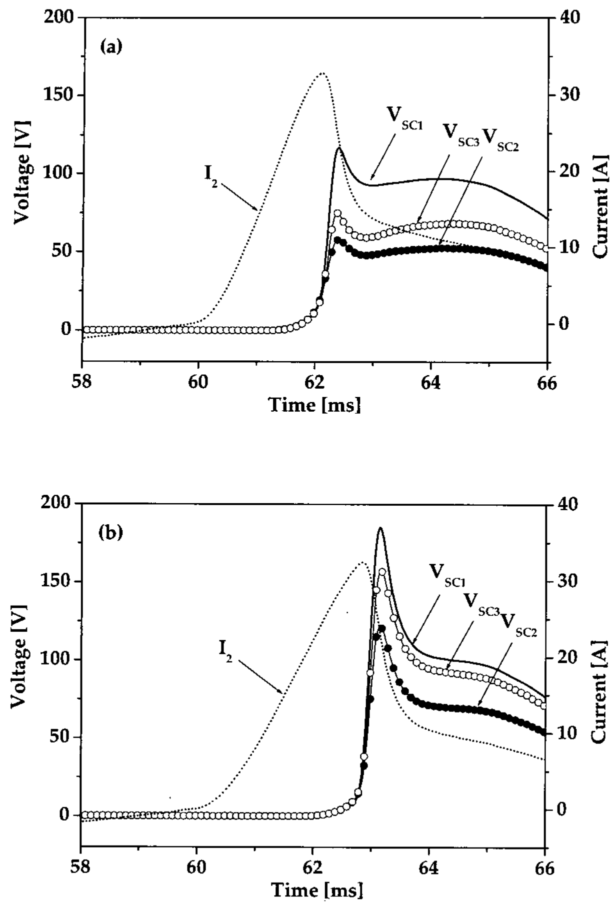

Fig. 4. Quench properties of HTSC element consisting of the flux-lock type SFCL (L_P= 87.5 mH). (a) L_{S1}=L_{S2}=L_{S3}= 2.5 mH and (b) L_{S1}=L_{S2}=L_{S3}= 6 mH.

rising rates. This was caused by different critical currents between HTSC elements as estimated from the comparison of the critical currents for HTSC elements. It was confirmed that the higher critical current of HTSC element, the lower peak point at the voltage of HTSC element after quench generation appeared. As the first peak points where the voltages of HTSC elements reached after a fault happened increased, it was also observed that voltage difference between HTSC elements decreased more. In other words, the flux-lock type SFCL with several secondary windings could be operated as the balancer for uneven power dissipation between HTSC elements connected in series and the imbalance of power dissipation was reduced more by increasing the inductance of the secondary windings, which could be performed by the mutual coupling between the primary winding and the several secondary windings.

4. CONCLUSION

In this paper, we investigated that the imbalance of power dissipation of HTSC elements, which has been a problem in case of series connection of HTSC elements with different I_C, could be reduced in the flux-lock type SFCL with the several secondary windings. It was analyzed from the experiments that the flux linkage between the primary winding and the secondary windings lead the balanced power dissipation between HTSC elements.

We will research topologies using the magnetic coupling such as the flux-lock type and the hybrid type SFCLs for the decrease of the unbalanced power dissipation between HTSC elements.

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