Operational Characteristics of Flux-lock Type SFCL using Series Resonance

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We analyzed the fault current limiting characteristics of a flux-lock type high-T_C superconducting fault current limiter (HTSC-FCL) using series resonance between capacitor for series resonance and magnetic field coil which was installed in coil 3. The capacitor for the series resonance in the flux-lock type HTSC-FCL was inserted in series with the magnetic field coil to apply enough magnetic field into HTSC element, which resulted in higher resistance of HTSC element. However, the impedance of the flux lock type HTSC-FCL has started to decrease since the current of coil 3 exceeded one of coil 2 after a fault accident. The decrease in the impedance of the FCL causes the line current to increase and, if continues, the capacitor for the series resonance to be destructed. To avoid this operation, the flux-lock type HTSC-FCL requires an additional device such as fault current interrupter or control circuit for magnetic field. From the experimental results, we investigated the parameter range where the operation as mentioned above for the designed flux-lock type HTSC-FCL using series resonance occurred.

Keywords : Flux-lock type high-T_C superconducting fault current limiter, Magnetic field coil, Series resonance

1. INTRODUCTION

The increase in capacities of power transmission and in fault current of the related machinery in the grid has resulted in the development of various types of superconducting fault current limiters (SFCLs)[1-9]. Especially, the flux-lock type high-T_C superconducting fault current limiter (HTSC-FCL) has been expected to be more advantageous than any other HTSC-FCL because of larger current capacity and higher normal resistance[10-12]. To increase the normal resistance of HTSC element, the flux-lock type HTSC-FCL imposed the magnetic field into HTSC element using magnetic field coil surrounding it immediately after a short circuit occurred. Furthermore, the magnetic field generated from the magnetic field coil could be increased effectively by using series resonance between magnetic field coil and capacitor for series resonance. However, in case of the application of series resonance, the continuous increase in the amplitude of the current of coil 3 after a fault happened has caused continuous decrease in the impedance of the flux-lock type HTSC-FCL, which resulted in inefficient fault current limiting operation. In this paper, we investigated the parameter range where the decrease in the impedance of the flux-lock type HTSC-FCL using series resonance appeared after a fault happened.

2. DESIGN OF FLUX-LOCK TYPE SFCL

The fundamental configuration of the flux-lock type

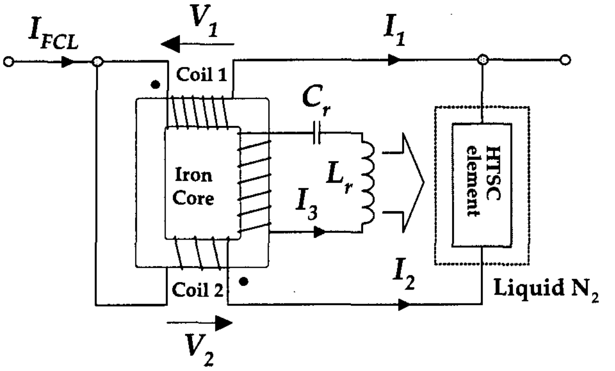

Fig. 1. Fundamental configuration of the flux-lock type HTSC-FCL using series resonance.

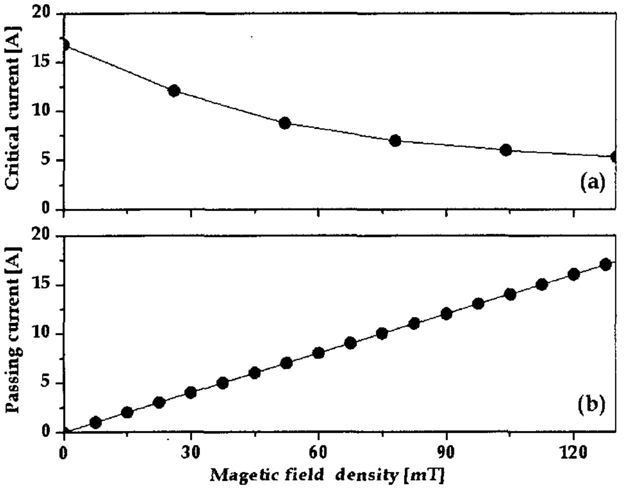

Fig. 2. Dependence on the external magnetic field of critical current for HTSC element and the magnetic field generated from the magnetic field coil proportional to the current passing coil 3.

HTSC-FCL using series resonance was shown Fig. 1. I_1 and I_3 represent the currents of coil 1 and 3. I_2 and I_{FCL} are the current flowing into the HTSC element and the line current of the system, respectively. $YBa_2Cu_3O_{7-x}$(YBCO) thin film was used as HTSC element consisting of the flux-lock type HTSC-FCL. YBCO thin film with 0.3 μm thickness was grown on sapphire substrate with 2 inch diameter and covered with a 0.2 μm thick gold layer for bypass around hot spots. Current limiting element was made by etching the YBCO thin film into 2 mm wide and 420 mm long meander line by a photolithography. The meander line consisted of fourteen stripes with different length.

The dependence of the fabricated current limiting element on the external magnetic field of the critical current was shown in Fig. 2(a). The magnetic field produced from the magnetic field coil of coil 3, which was proportional to the current passing the magnetic field coil, was also displayed in Fig. 2(b). The critical current, which decreased from 16.5 A at 0 mT to 12 A at 25 mT, decreased more as the external magnetic field increased. The basic operational principle for the flux-lock type HTSC-FCL was described in reference[10] in detail. To apply effective magnetic field into HTSC element, the capacitor for series resonance was connected in series with magnetic field coil of coil 3.

The design parameters for the experiment were shown

Table 1. Parameters for the experiment.

Iron Core	Size	Unit
OuterHorizontal 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
Coil 1, 2 and 3	Value	Unit
Turns in Coil 1	42	Turns
Turns in Coil 2	14	Turns
Turns in Coil 3	7, 14, 28, 42	Turns
Solenoid Magnet Field Coil	Size	Unit
Inner Radius	40	mm
Outer Radius	45	mm
Height	340	mm
Number of Turns	1200	Turns
Self Inductance (L_r)	149	mH
Capacitor for Series Resonance	Value	Unit
(C_r)	50	μF
HTSC Thin Film (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	mm
Gold layer thickness	0.2	mm

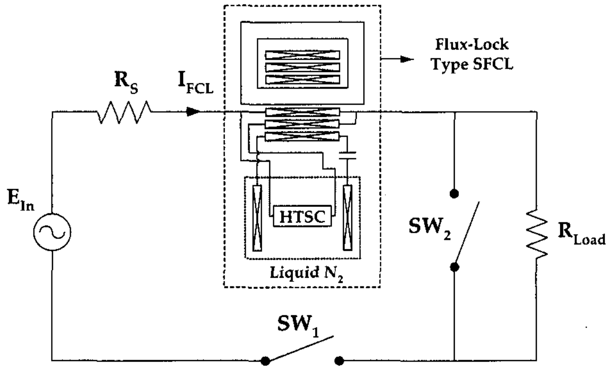

Fig. 3. Circuit diagram for fault current limiting experiment.

in Table 1. The experimental circuit was shown in Fig. 3. The source voltage(E_{In}) was 50 V_{rms}. The source resistance (R_S) and the load resistance (R_{Load}) were 1 Ω and 50 Ω, respectively. The fault accidents from the experimental circuit were simulated by closing SW_2 after SW_1 was closed.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 and 5 show the experimental current waveforms of the flux-lock type HTSC-FCL using series resonance in case that the number of turns in coil 3 is 42 and 28, respectively. From the observation for current waveforms flowing in each coil, the continuous increase in current of coil 3, namely, current in the magnetic field coil, after a fault happened, caused the line current to increase. In case that the number of turns in coil 3 was 42 as shown Fig. 4, the line current started to increase after the 3rd peak of the line current appeared. On the other hand, in case that the number of turns in coil 3 was 28, as shown in Fig. 5, the line current started to increase after the 4th peak of the line current appeared.

It was confirmed from the Fig. 6 that the trend of the line current after a fault happened was dependent on the number of turns in coil 3. As did not appear in Fig. 6, in case that the number of turns in coil 3 was 14 and 7 respectively, the line current was expected to increase some time after a few peaks of the line current appeared due to the characteristic of series resonance between the capacitor for series resonance and the magnetic field coil. The resistance of HTSC element with the number of turns of coil 3 did not show large difference as shown in Fig. 7, which resulted from the fast quench of HTSC thin film. However, the resistance of HTSC element consisting of the flux-lock type HTSC-FCL increased higher than the case of the independent operation of HTSC element.

From above results, the flux-lock type HTSC-FCL using series resonance is expected to need the additional device such as the fault current interrupter or the control circuit for the magnetic field coil in order to keep the current of coil 3 from increasing continuously after a fault occurs.

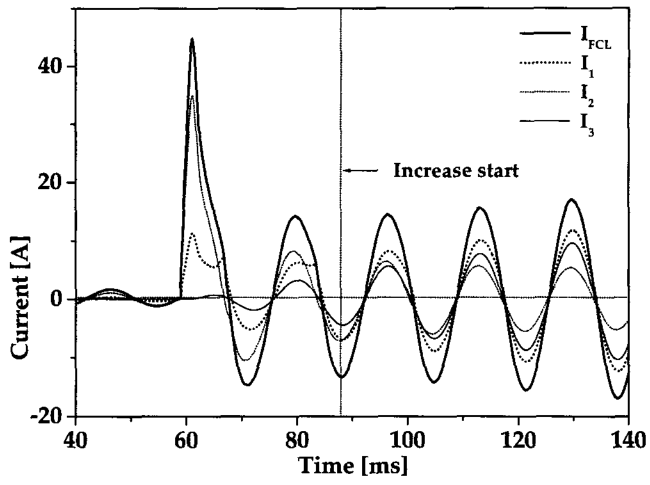

Fig. 4. Experimental current waveforms of the flux-lock type HTSC-FCL using series resonance in case that the number of turns in coil 3 is 42 ($C_r = 50uF$).

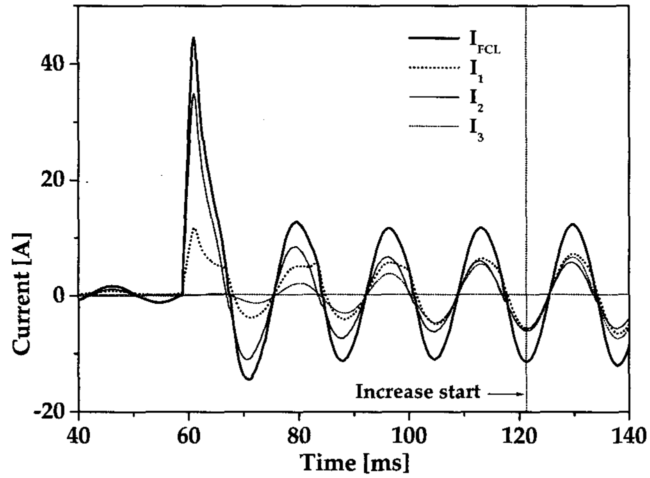

Fig. 5. Experimental current waveforms of the flux-lock type HTSC-FCL using series resonance in case that the number of turns in coil 3 is 28 ($C_r = 50uF$).

The condition for the line current to increase after a fault happened was investigated through Fig. 4 and 5. Since the current of coil 3 exceeded the current of coil 2 as pointed a dotted line in Fig. 4 and Fig. 5, the line current has started to increase. The equivalent circuit of the flux-lock type HTSC-FCL was derived for the analysis of current in each coil as shown in Fig. 8. In Fig. 8, L_1, L_2 and L_3 are the self inductances of each coil and M_{12}, M_{23} and M_{13} represent mutual inductances between two coils and R_{SC} is the normal resistance of HTSC element, which is influenced by ac magnetic field and R_3 is the resistance which includes both the resistance of the magnetic field coil and the additional resistance of coil 3. Assuming the coupling coefficient was 1, the equation for the current of coil 2 and coil 3 with regard to the line current from Fig. 8 could be drawn as the equation (1) and (2). From the equation (1) and (2), the condition that the line current started to increase could be derived as expressed in equation (3).

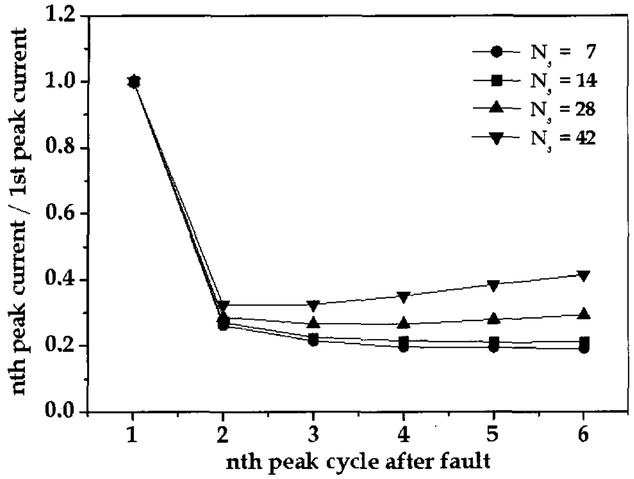

Fig. 6. Peak variance of line currents after short-circuit accidents with the number of turns in coil 3 in case that the capacitor for series resonance is 50 μF.

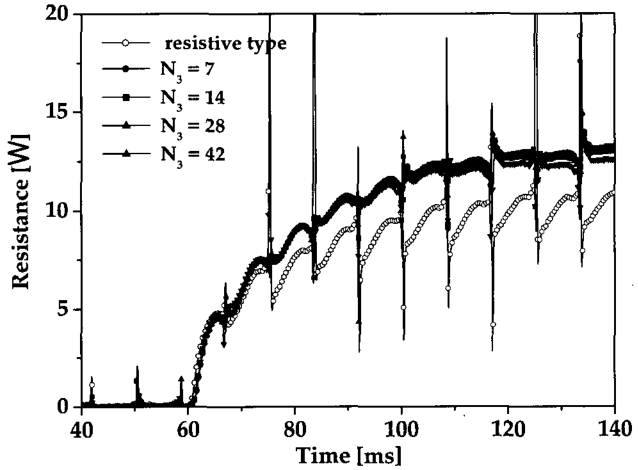

Fig. 7. Resistance curves of HTSC element with the number of turns in coil 3 in case that the capacitor for series resonance is 50 μF.

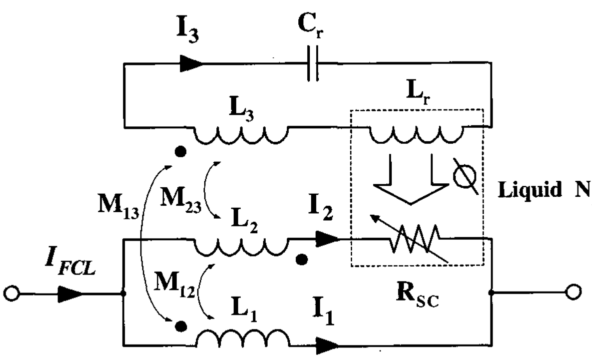

Fig. 8. Equivalent circuit of the flux-lock type HTSC-FCL using series resonance.

$$I_2 = \frac{jw\sqrt{L_1}X \cdot I_{FCL}}{R_{SC} + j\left\{wX^2 + \frac{wL_3}{R_3}R_{SC}\right\}} \qquad (1)$$

$$I_3 = \frac{j\frac{w\sqrt{L_1L_3}}{R_3}R_{SC}I_{FCL}}{R_{SC} + j\left\{wX^2 + \frac{wL_3}{R_3}R_{SC}\right\}} \qquad (2)$$

$$R_{SC} \ge \frac{R_3}{\sqrt{L_3}}X \qquad (3)$$

Where X is equal to $\sqrt{L_1} \pm \sqrt{L_2}$. The sign of "-" or "+" is determined by whether the coil 1 and the coil 2 are wound to increase or decrease the magnetic field generated by each coil.

From the equation (3), the time for the line current to start to increase after the occurrence of a fault is expected to be shorter as either the number of turns of coil 3 increases or the additional resistance of coil 3 including the resistance of the magnetic field coil decreases. Therefore, by adjusting the number of turns of coil 3 or the additional resistance of coil 3, the continuous increase of the line current is expected to be suppressed after a fault happens.

4. CONCLUSION

We analyzed the fault current characteristics of the flux-lock type HTSC-FCL using series resonance between the capacitor for series resonance and the magnetic field coil to apply the magnetic field into HTSC element effectively. From the experimental results, the condition that the line current started to increase after a fault happened was investigated. The countermeasures to prevent the line current from increasing after a fault happens will be proposed and confirm through the experiments in the future.

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