Analysis of Magnetic Field Application Effect on Fault Current Limiting Characteristics of a Flux-lock Type SFCL

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The magnetic field application effect on resistance of a high-T_C superconducting (HTSC) element comprising a flux-lock type superconducting fault current limiter (SFCL) was investigated. The YBCO thin film, which was etched into a meander line using a lithography, was used as a current limiting element of the flux-lock type SFCL. To increase the magnetic field applied into HTSC element, the capacitor was connected in series with a solenoid-type magnetic field coil installed in the third winding of the flux-lock type SFCL. There was no magnetic field application effect on the resistance of HTSC element despite the application of larger magnetic field into the HTSC element when a fault happened. The resistance of HTSC element, on the contrary, started to decrease at the point of four periods from a fault instant although the amplitude of the applied magnetic field increased.

Keywords : A flux-lock type superconducting fault current limiter (SFCL), Solenoid-type magnetic field coil, Magnetic field application effect

1. INTRODUCTION

Among various types of superconducting fault current limiter (SFCL), a resistive type SFCL has been considered to be the most promising one in commercialization, which most of researches have been focused on. The resistive type SFCL was reported to be simpler and more compact structure as well as fast self-triggering by rapid resistance development when a fault occurred[1-5]. Since there is a limit to increase both the current capacity and the voltage rating of the SFCL due to its fabrication process, the parallel and series connections of the current limiting elements comprising the SFCL are required.

However, in case of series connection of HTSC elements for high voltage application, the power imbalance of HTSC elements due to the slight difference between their critical currents occurs. Especially, HTSC element with lower critical current takes larger power burden, which can result in the destruction of the SFCL[3-6].

Among the various countermeasures to make equal power distribution between HTSC elements during a fault time, the method applying the magnetic field into HTSC element comprising the SFCL has been suggested[7-9]. The flux-lock type SFCL using the third winding has been reported to apply the magnetic field into HTSC element without the additional power supply, which was first suggested in Nagoya university [10-12]. However, the effect of the magnetic field application on the resistance of HTSC element in the flux-lock type SFCL has been not analyzed until now.

In this paper, we investigated the magnetic field application effect on resistance of HTSC element consisting of the flux-lock type SFCL. Through the fault current limiting experiments, it was confirmed that the increase in the resistance of HTSC element was related with the structure of the flux-lock type SFCL, not the application of the magnetic field. In addition, the line current, which was limited by the flux-lock type SFCL, was shown to be affected by the current of the third winding installed for the application of the magnetic field, not by the increase of the HTSC elements' resistance.

2. FLUX-LOCK TYPE SFCL USING SERIES RESONANCE

2.1 Operational principles

The Fig. 1 shows a configuration of the flux-lock type SFCL using the third winding. The SFCL consists of a flux-lock reactor and a magnetic field circuit. The primary and the secondary windings, components of a flux-lock reactor, are wound on the same iron core in parallel into the subtractive polarity or the additive polarity winding direction. YBCO thin film used as HTSC element is connected in series with the secondary winding. The solenoid-type magnetic field coil and the capacitor for the series resonance, which comprised the magnetic field circuit, were installed in the 3rd winding of the SFCL.

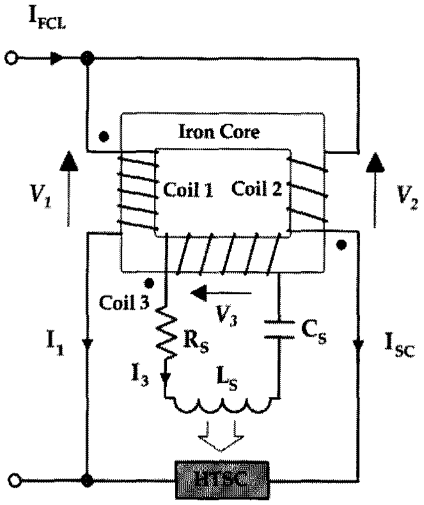

Fig. 1. Diagram of the flux-lock type SFCL using the third winding.

In a normal condition, the magnetic flux linked in each winding does not generate irrespective of two windings' direction because the HTSC element is in superconducting state, which the voltages induced in all three coils are zero.

In case of a short-circuit condition, the HTSC element switches into the normal state from the superconducting state and thus, the resistance of HTSC element generates. As a result, the magnetic flux is linked in each coil and the voltage of each coil is induced immediately after a fault period. Simultaneously, the voltage induced in the third winding makes the current at the magnetic field coil flow, which applies the vertical magnetic field into HTSC element connected with the secondary winding.

2.2 Preparation for experiments

$Y_1Ba_2Cu_3O_{7-X}$ (YBCO) thin film deposited on sapphire substrates was used as material for the HTSC element and a 0.2 μm thick gold layer was coated on it to bypass hot spots. The current limiting element was fabricated by etching the YBCO thin film into 2 mm wide and 420 mm long meander line by a photolithography. The meander line consists of fourteen stripes with different length. Figure 2 shows the fabricated current limiting pattern.

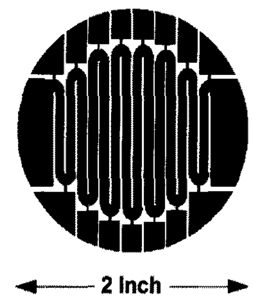

Fig. 2. Pattern of current limiting element.

For the application of magnetic field into HTSC element, the solenoid-type magnetic field coil was designed and fabricated. The magnetic field intensity at the central point of the solenoid-type magnetic field coil was calculated as given by:

$$B_O = Ja\mu_O\beta \ln\left[\frac{\alpha + (\alpha^2+\beta^2)^{\frac{1}{2}}}{1+(1+\beta^2)^{\frac{1}{2}}}\right] \quad (1)$$

where, $\alpha = b/a$, $\beta = l/a$ and J is the average overall current density. a, b and l are the inner radius, the outer radius and a half height of magnetic field coil[11].

The Table 1 shows the designed specification of solenoid-type magnetic field coil.

Table 1. Specification of solenoid-type magnetic field coil.

Solenoid-type magnetic field coil		
Inner Radius (a)	40	mm
Outer Radius (b)	45	mm
Height ($2l$)	320	mm
Number of Turns	2000	Turns
Self Inductance	149	mH

The critical current of HTSC element (I_C) dependent on vertical magnetic field was measured. I_C started to decrease around magnetic field of 20 mT and decreased into about 70 % of the critical current in no magnetic field when the magnetic field of 130 mT was applied.

The schematic diagram of flux-lock type SFCL is shown in Fig. 3. The source resistance of 1 Ω and the load resistance of 50 Ω were connected with the SFCL. The fault current, if the source voltage of 50 V_{rms} was connected with the power system without the SFCL, was expected to be 50 A_{rms}. The fault current limiting characteristics of the flux-lock type SFCL were analyzed according to two windings' direction and the magnetic field effect on the resistance of HTSC element was investigated. The magnetic field generated from the solenoid type magnetic field coil was adjusted by a tap changer installed in the 3rd winding.

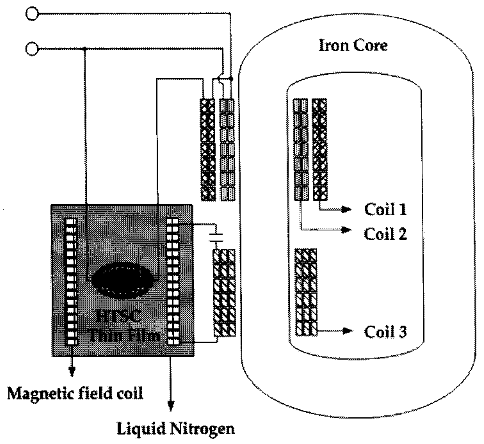

Fig. 3. Schematic diagram of a flux-lock type SFCL.

3. RESULTS AND DISCUSSIONS

The 4 shows the resistance curves generated at the HTSC element according to the number of turns of the 3rd winding. As seen in Fig. 4, it is confirmed that the magnetic field does not make the resistance of the HTSC element get higher in both the subtractive polarity winding and the additive polarity winding. The resistance difference of HTSC elements between two winding directions is resulted from the structure of the flux-lock type SFCL as analyzed previously by us[15].

At the point of 5 cycles from a fault instant, however, the resistance of the HTSC element in case that the number of turns of the third winding is 42 is rather lower than those of other cases. This result can be described as follows: The resistance increase of HTSC element by the application of magnetic field during a fault period causes the decrease of current in the secondary winding or the HTSC element. At the same time, the current of the primary winding increases as the current of the third winding for the generation of magnetic field increases, which leads to the increase of the current in the secondary winding by the magnetic coupling operation between the primary winding and the secondary winding. Therefore, the current of the

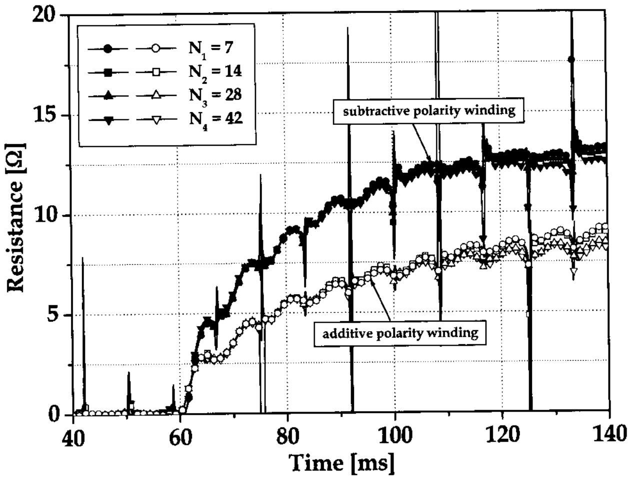

Fig. 4. The resistance curves of HTSC elements dependent on the number of turns of the third winding in both the subtractive polarity and the additive polarity windings.

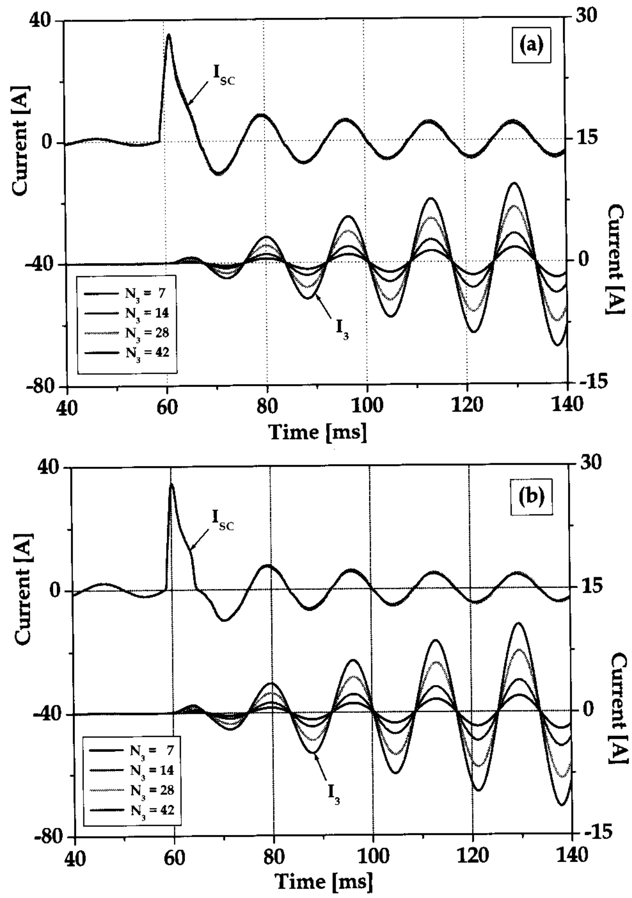

Fig. 5. Current waveforms of the secondary winding (HTSC element) and the third winding dependent on the number of turns of the third winding. (a) subtractive polarity winding. (b) additive polarity winding.

secondary winding is not affected by the current of the third winding, or by the magnetic field application, as seen in Fig. 5 and the resistance of HTSC element does not get higher although the magnetic field is applied as analyzed in Fig. 4. The current of the third winding, on the other hand, affects the line current, which is in proportion to the current of the third winding as shown in Figs. 5 and 6.

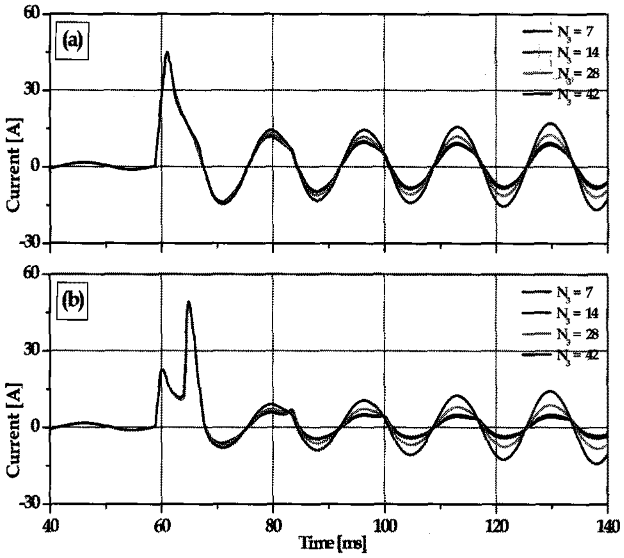

Fig. 6. Line currents dependent on the number of turns of the third winding. (a) subtractive polarity winding. (b) additive polarity winding.

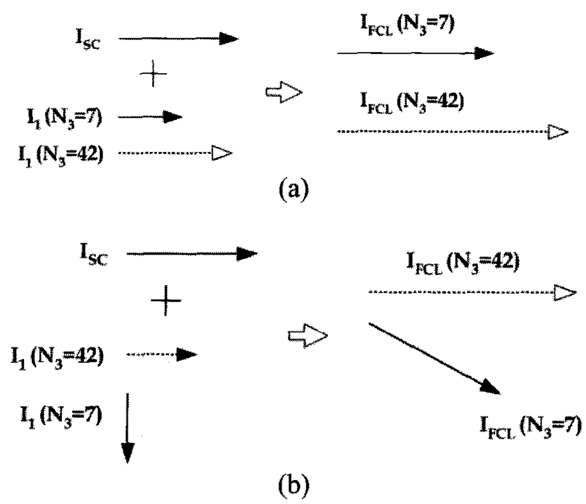

Fig. 7. Phasor diagram for the primary winding and the secondary winding currents and the line current in case that the number of turns of the third winding is 7 or 42. (a) subtractive polarity winding. (b) additive polarity winding.

Figure 7 shows the phasor diagram for the primary winding and the secondary winding currents and the line current in case that the number of turns of the third winding is 7 or 42. From the Fig. 1, the line current (I_{FCL}) can be described to be equal to the sum of the primary winding and the secondary winding currents (I_1, I_{SC}) and thus, as analyzed in Figs. 5 and 6, the amplitude of the line current increases higher as the number of turns of third winding increases, especially, in case of the additive polarity winding.

4. CONCLUSIONS

We analyzed the magnetic field effect of the flux-lock type SFCL using its third winding on resistance of HTSC element according to the number of turns of the third winding. As the current of the third winding for generation of the magnetic field increased, the current of the primary winding increased, which caused to increase the line current. Due to the structure of the flux-lock type SFCL, the application of the vertical magnetic field into HTSC element did not contribute to the increase of HTSC element but the contribute to the increase of the line current.

The research for the flux-lock type SFCL, which the line current could be limited through the increase of the resistance of the HTSC element by the application of the magnetic field, will be made in the future.

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