Verification of metal layer design for large-capacity superconducting fault current limiting elements using YBCO thin film

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Abstract. A superconducting fault current limiter (FCL) is one of the most attractive solutions to an increase of short-circuit current in electric power networks. The authors have studied resistive type FCLs using YBCO thin film superconductor with the patterning of superconducting and metal layers to increase the capacity of their current and voltage. A new design concept of fault current limiting element has been proposed, which has a meander-shaped gold layer on a wide I-shaped YBCO thin film. Experimental study and comparison between experimental and numerical analysis results verify the validity of the new FCL design concept.

1. Introduction
A superconducting fault current limiter (FCL) [1] is one of the key technologies to the solution of the problem of increasing short-circuit current caused, for example, by the introduction of dispersed power sources into electric power networks. The superconducting FCL is expected to keep or improve the reliability of electric power supply and the flexibility of power network design and operation. The authors have studied resistive type FCLs using YBCO thin film superconductor and developed a numerical analysis tool to study electromagnetic phenomena and current limiting characteristics of this type of FCLs with the influence of inhomogeneous superconducting properties taken into account [2-4].

Design of large-capacity FCLs is also very important issue for practical application of FCLs. Although series and parallel connections of FCL elements are a simple way for getting a large-capacity FCL [5], it is essentially important to design a single large-capacity FCL element [6]. The authors have discussed better design of large-capacity FCL elements using large-size YBCO thin film by a numerical analysis method, and designed an FCL element model whose superconducting layer was deposited on whole area of the substrate but a gold layer was deposited in the shape of meander [4]. The analysis results indicated that the capacity of the element was about twice as large as that of an element without metal layer patterning. By designing such a FCL element without inducing hot spots, the electric field of 50 V/m can be achieved even with an element of some spatial $J_c$ distribution.

Experimental study of a small-scale FCL element based on the above mentioned concept has been also carried out to verify the principle of our proposal and how normal conducting zones propagate in the superconducting film. This paper reports the results of such experiments and the comparison of them with numerical analysis results.
2. FCL element with meander-shaped gold layer

The authors have studied current limiting characteristics of fault current limiting (FCL) elements by a numerical analysis method [2-4]. Three types of FCL elements were compared in the analysis [4]: an FCL element having a wide straight film without patterning, an FCL element having a meander-shaped film covered with gold film, and an FCL element having superconducting film deposited on almost whole area of the substrate and a gold layer deposited in the shape of meander on the superconductor (figure 1). In the analysis, inhomogeneous $J_C$ distribution was taken into account. A current capacity of each element depended on the critical current density $J_C$ of the superconductor, and its voltage capacity was estimated from the maximum sinusoidal voltage which gave the highest local temperature in a film below 400 K during three cycles. Figure 2 shows current flow patterns in the superconducting and normal conducting conditions. When the superconductor becomes normal, a current flow region becomes narrower and longer as shown in figure 2.

The FCL element having a meander-shaped gold layer on simple YBCO thin film superconductor shown in figure 1 suppresses the current more effectively than two other FCL element types. As a result, the voltage capacity of this type of FCL element was over twice as large as that of the other FCL elements, and also its power capacity was the largest. Based on the numerical analysis a fault current limiting element shown in figure 3 was designed [4].

![Figure 1](image1.png)

**Figure 1.** A fault current limiting (FCL) element is composed of a sapphire substrate, YBCO thin film superconductor, gold resistive layer, and silver electrodes. This FCL element has a meander-shaped gold layer.

![Figure 2](image2.png)

**Figure 2.** Change in current flow patterns when the YBCO superconductor becomes normal conducting.

![Figure 3](image3.png)

**Figure 3.** A designed fault current limiting element with a meander-shaped gold layer.
3. Experimental details

A structure of a fault current limiting element used in the experiment is shown in figure 4. It has YBCO thin film superconductor fabricated by the MOD (Metal Organic Deposition) method [7] and the smallest unit of meander-shaped gold layer. The YBCO superconductor is 45 mm wide on the 50 mm wide substrate because of the film formation process. Small circles on the gold layer indicate terminals for voltage measurement, and the voltages between two adjacent terminals were measured. For example, \( V_1 \) indicates a section between first two terminals and also the voltage between the terminals as shown in figure 4. The YBCO film was partly etched on the sides by 4 mm as shown in figure 4. Table 1 summarizes the specifications of the fault current limiting element shown in figure 4.

An electric circuit for FCL experiments is shown in figure 5. A 0.1 \( \Omega \) resistor is connected in parallel to the FCL element for protection. The S-N transition phenomena of YBCO thin film superconductor and the normal-zone propagation were studied from the measured voltage and current waveforms.

The authors have developed a numerical analysis software tool based on the finite element method (FEM) to solve coupled problems of electromagnetic and thermal fields in fault current limiting elements with YBCO thin film superconductor [2-3]. A finite element method for electromagnetic field analysis is based on current vector potentials and the thin-plate approximation. A nonlinear \( E-J \) relation (\( E \): electric field, \( J \): current density) based on the power law was used for modeling electromagnetic property of the superconductor. Figure 9 shows the critical current density (\( J_{C} \)) distribution of the FCL element used in the FEM analysis. The \( J_{C} \) data shown in figure 6, which were based on the \( J_{C} \) distribution measured by an inductive method, were used in the analysis to take into account the influence of inhomogeneity of \( J_{C} \) distribution on current limiting characteristics.

![Figure 4. A fault current limiting element used in the experiment.](image)

![Figure 5. An electric circuit for fault current limiting experiment.](image)

| Table 1. Specifications of the fault current limiting element shown in figure 4. |
|---------------------------------|------------------|
| Width of effective area of the element | 45 mm |
| Length of effective area of the element | 20 mm |
| Thickness of YBCO superconductor | 200 nm |
| Width of gold layer | 2 mm |
| Thickness of gold layer | 100 nm |
| Thickness of sapphire substrate | 550 \( \mu \)m |
| Critical current density of YBCO superconductor | 3.1 MA/cm\(^2\) \( \pm \) 5 \% |
4. Results and discussion

Figure 7 shows experimental results obtained when the voltage amplitude of the AC power source was 26 V. If there were no FCL element in the circuit shown in figure 4, the current would reach about 590 A. Figure 7 (a) shows the waveforms of total current in the circuit and currents flowing in the FCL element and the shunt resistance. From the current waveform of FCL element the occurrence of current limiting process is clearly observed. The peak current is reduced to about 160 A and the amplitude of the current waveform after 10 ms is about 16 A.

Figure 7 (b) shows the time variation of the electric resistance of the FCL element. The electric resistance was calculated from the measured voltage and current of the FCL element, and therefore the calculated values have relatively large error when the current is small. At 60 ms the electric resistance becomes about 1.4 $\Omega$, which is more than ten times higher than the generated resistance of the normal fault current limiting element with a gold protection layer having the same shape (not meander shape but straight-line shape) as the YBCO superconducting layer. These results have demonstrated the validity of the basic concept of the fault current limiting element with a meander shaped gold layer.

Figure 8 shows FEM analysis results obtained under the almost same conditions as the experimental results shown in figure 7. The results in figures 7 and 8 are in fairly good agreement, although there is a little difference in the peak value of the FCL current and the increasing electric resistance of the element. This comparison has verified our FEM analysis method and model for a resistive-type fault current limiting element using YBCO thin film superconductor.

Figure 9 shows measured voltages at the six sections of the meander-shaped gold layer. The S-N transition in the YBCO superconductor occurred first near the section V4, and the normal zone spread from the center area (around the section V4) to both sides (toward V2 (V3) and V5). In the section V1 no voltage was observed until the third cycle, and in the section V6 no voltage was observed even in the third cycle.

Figure 10 shows FEM analysis results of the variation with time of temperature distribution in the FCL element. Temperature rise or the S-N transition occurs around the central area near the V3 and V4 sections, and the normal zone having temperatures higher than the critical temperature ($T_C = 90$ K) of YBCO superconductor spreads upward and downward, which phenomenon qualitatively agrees well with the experimental result shown in figure 9. However, there is a slight difference in the S-N transition around the section V6. The experimental result indicated that the section V6 was still superconductive at 60 ms, but the FEM analysis indicates that the section V6 is normal at 60 ms, as shown in figure 10. It is presumed that such difference may be caused by the errors in the thickness or the resistivity of the actual gold layer [8]. But further studies are necessary to clarify the cause of it.
Figure 7. Variation with time of currents and electric resistance of the FCL element (experimental results).

Figure 8. Variation with time of current and electric resistance of the FCL element (FEM analysis results).

Figure 9. Voltages measured at the six sections of the gold layer (experimental results).
5. Conclusions
Experimental study of current limiting characteristics of the fault current limiting element was performed. The FCL element has YBCO thin film superconductor deposited on the whole sapphire substrate and a meander-shaped gold layer. The experimental results were compared with the FEM analysis results. A sufficiently higher electric resistance was successfully obtained in the current limiting process. The experimental results have verified the basic concept of the new FCL design and the comparison between the experimental and analysis results has verified the validity of the numerical analysis methods and models we have developed.

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