Low-cost and high-power-density resistive fault-current limiting elements using YBCO thin films and Au-Ag alloy shunt layers

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Abstract. We propose a new design for the high-temperature superconducting thin-film fault-current limiter (FCL), which uses high-resistivity Au-Ag alloy shunt layers instead of the pure gold (or silver) shunt layers conventionally used. An FCL element (5 mm wide and 40 mm long) with a YBCO thin film (THEVA) and a parallel inductively-wound shunt resistor successfully withstood very high electric field (> 44 V peak/cm) for 5 cycles (0.1 sec) after switching, and achieved a very high switching power density, ~2.0 kVA/cm². We confirmed similar maximum tolerable electric field (> 40 V peak/cm, limited by power supply) in a larger sample (1 cm × 6 cm). The composition of our FCL element is very simple, and the achieved power density is more than five times higher than conventional devices, which leads to a dramatic reduction in the amount of expensive superconducting thin films. We made a conceptual design and cost estimation of our FCL elements used in a typical 6.6 kV FCL.

1. Introduction
Due to the general trend towards deregulation in Japan and in Europe, a lot of distributed generators of Independent Power Producers (IPPs) have been connected to the existing power grid, which sometimes causes a significant increase in short-circuit currents. One of the most attractive solutions to the increased short-circuit currents is the introduction of a fault-current limiter (FCL). Among many FCLs the resistive superconducting FCL using high-temperature superconducting thin films is most promising due to its compactness and self-triggered, rapid switching operation [1–3]. Its major drawback has been its high cost due to the high cost of large-area superconducting thin films. The cost reduction of the superconducting thin-film FCL is strongly desired.

We recently reported the result of switching experiments for a resistive superconducting thin-film FCL element that uses high-resistivity Au-Ag alloy shunt layers instead of the pure gold (or silver) shunt layers conventionally used [4]. Such shunt layers are used to solve the “hot-spots” problem, that is, burnout of the weakest part of the film at the initial stage of the fault. The FCL has to withstand high voltages during the current-limiting operation, and the maximum tolerable electric field $E_{\text{max}}$ (maximum tolerable voltage per unit length, $V_{\text{max}}/L$) should be as high as possible to reduce the total length of FCL elements. Because the power dissipation during the fault can be calculated as $V_{\text{max}}^2/R$ ($R$: resistance of the FCL element), the increase of $R$ enables to increase $V_{\text{max}}$ without increasing power dissipation. However, the “hot-spots” problem prevents to use very high $R$, as in non-shunted, bare YBCO films. So far, a common technique to prevent “hot-spots” is to cover the YBCO film with a
gold shunt layer [1–3], but this causes significant decrease in $R$, resulting in relatively low $E_{\text{max}} \leq 10$ V/cm [1, 2]. Our new approach of using high-resistivity alloy shunt layers has solved the “hot-spots” problem without the serious decrease of $R$ and enabled a high $E_{\text{max}} > 38$ V/cm, which leads to a cost reduction through the reduction in the total length of FCL elements [4]. In this study, we report on new results of switching experiments with using larger capacity power supplies and on a conceptual design and cost estimation of our FCL elements used for a typical FCL, a three-phase 6.6 kV/400 A FCL.

2. A new design for high power-density thin-film FCL elements

We used 300-nm-thick YBa$_2$Cu$_3$O$_7$ (YBCO) films that were grown epitaxially by thermal co-evaporation on 1 cm × 12 cm × 1.0 mm sapphire substrates buffered with CeO$_2$ layers (purchased from THEVA Ltd.). The critical current density $J_c$ distribution measured by an inductive method was very homogeneous, typically, $J_c = 3.05\pm0.05$ MA/cm$^2$. The YBCO films are cut into smaller pieces of 5.0 mm × 60 mm ($I_c \approx 45$ A), and both ends (5 mm × 10 mm) were covered by gold layers and used as electrodes (Fig. 1). A 50-nm-thick Au-Ag alloy shunt layer was deposited on the center part (5.0 mm × 40 mm) of the film by RF sputtering using a Au-Ag alloy target with an appropriate composition. After the deposition the room-temperature resistance of the film decreased from 62.0 $\Omega$ to 16.7 $\Omega$. To further mitigate the “hot-spots” problem, an additional shunt resistor with sufficiently low resistance ($2.9 \Omega$), made of a noninductively-wound Manganin wire, was connected in parallel with the Au-Ag/YBCO/sapphire film (Fig. 1).

![Figure 1: Schematic of the YBCO thin-film fault-current limiting element with a Au-Ag alloy shunt layer and a noninductively-wound shunt resistor.](image)

A switching experiment was performed with a controllable ac power supply (8 kVA rms/66 A rms). It was operated in a constant-current mode, and the supply current was increased from 30 A$_{\text{peak}}$ to 80 A$_{\text{peak}}$ at a fault angle of 0°. Figure 2a shows the voltage across the Au-Ag shunt layer and the total supply current that flowed through the Au-Ag/YBCO film and the parallel resistor. The voltage emerged rapidly when the current exceeded ~68 A, and the Au-Ag/YBCO film successfully withstood 169–178 V$_{\text{peak}}$ for five cycles (0.1 sec) without any damage, and the same result was obtained in repeated experiments. In this experiment the resistance of the film was measured (not shown here), and the temperature of the film was estimated. The temperature increased to over 200 K within one cycle after the fault and finally reached about 400 K, and the details will be reported elsewhere [5]. Because the rated current in normal operation is $I_{\text{rate}} = I_c/\sqrt{2} \approx 31.8$ A rms [4] and the $E_{\text{max}}$ is greater than 44 V$_{\text{peak}}$/cm = 31.1 V$_{\text{rms}}$/cm, very high switching power density, $P_{\text{sw}}/WL = (I_{\text{rate}}/W)E_{\text{max}} \approx 2.0$ kVA/cm$^2$ was achieved ($W$: width of the YBCO film).
It is important to demonstrate that this high power density can be realized in larger films such as used in practical FCLs. We thus performed a switching experiment in a larger film (1 cm × 8 cm) having an effective fault-current limiting length of 6 cm. The YBCO/CeO$_2$/sapphire film was cut from the 1 cm × 12 cm films in the same batch, and a 50-nm-thick Au-Ag alloy shunt layer was deposited on the center part (1 cm × 6 cm) similarly. The room-temperature resistance of the film decreased from ~47 Ω to 11.8 Ω with the shunt layer, and a noninductively-wound shunt resistor (2.0 Ω) was connected in parallel with the Au-Ag/YBCO/sapphire film. The result of a switching experiment with using a larger controllable ac power supply (180 V$_{rms}$/1 kA$_{rms}$) is shown in Fig. 2b. When the supply current was increased from ~58 A$_{peak}$ to ~144 A$_{peak}$ at a fault angle of 0°, the film current increased immediately up to ~115 A, then decreased rapidly. The voltage emerged rapidly, and the Au-Ag/YBCO film successfully withstood 215–242 V$_{peak}$ for five cycles (0.1 sec) without any damage, and the same result was obtained in a repeated experiment. It is demonstrated that very high $E_{max} > 40$ V$_{peak}$/cm can be realized up to an effective FCL length of 6 cm, if the film withstand the first cycle. The emerged voltages within the first half cycle after the fault were substantially lower than those for later cycles, probably because of slower response of this power supply. We thus performed another switching experiment in a similar 1-cm-wide film but with a shorter effective fault-current limiting length of 4 cm. We confirmed that the film successfully withstood ~182 V$_{peak}$ just after the fault ($E_{max} > 45$ V$_{peak}$/cm).

3. Conceptual design of a FCL and its cost estimation
The composition of our FCL element is very simple, and the achieved power density (2.0 kVA/cm$^2$) is about five times higher than conventional devices that used pure gold shunt layers [1–3]. This leads to a dramatic reduction in the amount of expensive superconducting films. We made a conceptual design of a typical FCL that is used in a distributed generator site, a three-phase 6.6 kV$_{rms}$/400 A$_{rms}$ FCL (4.57 MVA), and estimated the cost of YBCO films needed. We note that other materials that are necessary to produce our FCL elements, such as, a Au-Ag target, FRP plates, Manganin wires, etc. are much cheaper than YBCO thin films. Here we assume that high $E_{max} ≥ 30$ V$_{rms}$/cm = 3 kV$_{rms}$/m (= 4.24 kV$_{peak}$/m) can be used in the conceptual design. The switching experiments shown in Fig.2 were made on YBCO/CeO$_2$/sapphire films with 1-mm-thick sapphire substrates, but through further optimization we expect that the $E_{max} ≥ 3$ kV$_{rms}$/m design will be possible also for YBCO films with 0.5-mm-thick sapphire substrates, because we observed slightly lower $E_{max}$ values in YBCO films with 0.53-mm-thick sapphire substrates.
If we use YBCO films ($J_c = 3$ MA/cm$^2$ and thickness = 300 nm) of 1.6 cm × 12 cm (effective FCL length of 10 cm), the rated current and the rated voltage of one FCL element can be 102 A$_{rms}$ and 0.3 kV$_{rms}$, respectively. Since the line to ground voltage of the three-phase 6.6 kV line is 3.81 kV$_{rms}$, fourteen-series connection of the elements has enough $V_{max} > 4.2$ kV$_{rms} > 3.81$ kV$_{rms}$. For the rated current of 400 A$_{rms}$, four-parallel connection of the elements is necessary. We will make a module that consists of four elements (two parallel and two series) on an FRP plate of 16 cm × 28 cm (Fig. 3). Then, two-parallel and seven-series connection of the modules results in one phase of the 6.6 kV/400 A FCL, and totally 42 modules (168 pieces of films) are necessary for the three phases (Fig. 3). The series connection to increase the voltage rating was investigated by Hyun et al [6], and parallel connection of equal shunt resistors to each FCL element successfully produced simultaneous quenches, which leads to linear increase of voltage rating with the series numbers [3, 6]. We note that such equal shunt resistors are naturally incorporated in our new design (Fig. 1).

THEVA Ltd. can fabricate 15 pieces of 1.6 cm × 12 cm YBCO/CeO$_2$/sapphire films in one batch (9 inches area), and the production of 42 FCL modules (168 pieces) needs 12 batches. Present price of the YBCO/CeO$_2$ deposition is 0.3 million¥/batch (if ordered in ≥20 batches), and further reduction of 30–40% is expected if ordered in very large amount [7]. Then the 12 batches cost 3.6 million¥. The price of 1.6 cm × 12 cm sapphire substrates is ~4,300¥/piece (0.5-mm-thick) or ~5,500¥/piece (1.0-mm-thick), if we buy large amount (~5,000 pieces) [8]. Then, 168 pieces of the sapphire substrates cost 0.72 million¥ (or 0.92 million¥). The total cost of YBCO films is ~4.3 (4.5) million¥. It must be further reduced but not so far from an acceptable range, if the desired price of FCLs for distributed generators is 1,000–2,000 yen/kVA [9] and the price of a 3-phase 6.6 kV/400 A FCL is ≤9.2 million¥.

Figure 3: Conceptual design of a module that contains four FCL elements, and fourteen modules that consist one phase of a 6.6 kV/400 A FCL.

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