Short circuit experiment on an FCL coil wound with YBCO tape with a high-resistance stabilizing layer

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Abstract. One of the programs in the Ministry of Economy, Trade and Industry regarding R&D for developing YBCO conductors is to evaluate the suitability of the conductors in several applications. This paper focuses on one of the expected power applications, namely, a fault current limiter (FCL). YBCO tape conductors with ion beam assisted deposition (IBAD) substrates are used in this work. In order to increase the resistivity of the conductor, which is preferable for FCL applications, the thickness of a protective layer made of silver was decreased as much as possible. After obtaining the required current limiting performance in short sample experiments, a model coil was developed aiming at 6.6 kV-class FCLs. Short circuit experiments were conducted with a short-circuit generator. The coil successfully suppressed a short-circuit current of over 1.4 kA to about 500 A under an applied voltage of 3.8 kV, which is the nominal phase-to-ground voltage. The coil also suppressed a short-circuit current of 17 kA down to 700 A. The experimental results are as expected and show promise toward FCL applications.

1. Introduction
Superconducting fault current limiters (FCL) using various superconducting materials have been investigated by various organizations for a number of years [1][2]. Second-generation superconducting wires made from yttrium barium copper oxide (YBCO) is a new approach in FCL development, and their practical realization is expected. One advantage of YBCO tapes is their ability to obtain high resistivity, which is preferable in super-to-normal transition type FCLs. The high resistivity of the conductor decreases the length of conductor necessary to obtain the resistance required for the fault current limitation, which reduces the cost of the FCL.

One of the programs currently underway in the Ministry of Economy, Trade and Industry (METI) involves investigating fundamentals of FCLs. In particular, the program addresses evaluation of the fault current limiting performance of a resistive FCL using YBCO tapes.

This paper describes the present status of the study, beginning with a short sample experiment on YBCO tapes with a high-resistance layer, followed by a short circuit experiment on model coils designed based on the results of the short sample experiment.

2. YBCO tape with high-resistance layer
In the development of these YBCO tapes with ion beam assisted deposition (IBAD) substrates, two processes were used to increase the resistance. The configurations of the conductors in these two processes are schematically shown in Fig. 1(a) and (b). In the first process shown in Fig. 1(a), for the
protective layer made of silver, which dominates the resistance, thicknesses of 10 μm and 5 μm were used instead of the normal thickness of 20 μm. The conductor had no additional stabilized layer on the silver layer. On the other hand, in the second process shown in Fig. 1 (b), a high-resistance metal layer was attached on the silver layer as a stabilizer. A nickel-chromium alloy, which has a high resistivity of about 9x10^{-6} ohm-m at 300 K, is non-magnetic, and can be easily processed, was selected as the stabilizing metal. Only the configuration shown in Fig. 1 (a) is sufficient to obtain high resistivity, because the high-resistance metal layer shown in (b) decreases the resistivity. However the configuration in (b) is considered to possess the following two advantages. The first is ease of handling when fabricating a coil lest the conductor be damaged chemically or mechanically due to careless handling. The second is improved stability. The high-resistance layer avoids local voltage increases because of its thermal capacity.

In this paper, we focus on experiments on the conductor shown in Fig. 1 (a). Experiments regarding the conductor shown in Fig. 1 (b) will be reported in another paper [3].

Fig. 1 Configurations of the conductors.

3. Short sample experiment
Tests on short sample conductors were conducted using the following procedure [4]. YBCO samples with lengths of 10 to 100 cm were electrically connected to two power sources via a selector switch. One power source was an induction voltage regulator (IVR), which applied an excess current to the sample to simulate a short circuit failure mode. The excess current was three cycles at a frequency of 50 Hz. The other was a direct current source, which was used to evaluate the voltage-current characteristics before and after applying the excess current. The applied voltage was gradually increased until the sample showed degradation in the voltage-current characteristics.

The generated resistance as a function of the applied voltage from the IVR is shown in Fig. 2,

Fig. 2 Generated resistance versus applied voltage.

and the generated temperature versus applied voltage is shown in Fig. 3.

Fig. 3 Generated temperature versus applied voltage.
where the silver layer thickness is the parameter. The generated resistance was calculated by dividing the voltage by the current of the final peak of the waves (the sixth peak in the 3-cycle wave). Prior to the experiments, the temperature dependence of the resistance of the samples was measured so that the generated resistance could be converted to temperature. The temperature reached as a function of the applied voltage is shown in Fig. 3. In each sample, a stable current limiting effect was obtained. In addition, each sample showed no degradation in superconducting performance up to a temperature of 500 K after applying the excess current.

4. Model coil experiment

4.1. Model coil
A model coil was wound with the conductor without the high-resistance metal stabilizer (Fig. 1(a)). The thickness of the silver layer was selected as 10 mm to obtain long, stable conductors. The specifications of the coil are shown in Table 1. The critical current of the YBCO tape used was about 50 A. A single tape was wound along grooves machined on four-layer bobbins made of fiber-reinforced plastic (FRP). The four layers, having different diameters, were located concentrically and electrically connected in series. The whole coil was designed to reduce self-inductance by arranging for the current in the first and fourth layers to be in the opposite direction to that in the second and third layers. A photograph of the coil is shown in Fig. 4.

Table 1 Specifications of the coil.

| Item                  | Value          |
|-----------------------|----------------|
| HTS conductor         | Hastelloy/YBCO/Ag10μm |
| Voltage               | 6.6 kV         |
| Current               | 50 A           |
| Impedance             | 100 μH         |
| Number of layers      | 4              |
| No. parallel tapes    | 1              |
| Length of winding     | 80 m           |
| Inner radius          | 0.15 m         |
| Outer radius          | 0.24 m         |
| Height                | 0.35 m         |

4.2. Short circuit experiment

4.2.1. Experimental set-up To verify the coil operation, a short circuit experiment was carried out. The coil was connected to a short circuit generator with a dummy load and a line inductance. The dummy load governed the nominal current in the non-fault condition and was connected with a short-circuit switch that triggered a short circuit upon closing. The line inductance was set to regulate the short-circuit current value. The regulated values were 1 kA and 12.5 kA. A nominal current was flowing with the short-circuit switch open, followed by closing the switch to bring about the fault condition.

The current value was measured with a current transformer (CT). The voltage values of each layer were measured by voltage dividers using resistances and capacitors. The generated resistance of the coil was calculated from the voltage and current values. The temperature reached by the conductor after the fault event was estimated from the relation between the resistance and the temperature, where uniform voltage generation along the longitudinal direction of the conductor was assumed. This assumption might not be valid. However, the estimated temperature is the representative value characterizing the current limiting coil.
4.2.2. Experimental result  The short circuit experiments were carried out under various experimental conditions. A voltage from 0.5 kVrms up to 3.8 kVrms was applied with various phases and durations. Experiments without the coil were also carried out. Fig. 5 shows one typical result with an applied voltage of 3.8 kVrms, which corresponds to the voltage between the lines and the ground for a 6.6 kV line system. The short-circuit current without the FCL was obtained in advance and is superimposed in the figure. Comparing with the wave without the FCL, the fault current of 1.4 kA was successfully suppressed to below 500 A, which shows a good current limiting effect. A noteworthy point here is that the fault current was limited before the first wave peak (5 ms). The coil limited the fault current 2 ms after the fault. Almost the same result was obtained for the case of the short circuit of 12.5 kA. The fault current of 17 kA was successfully suppressed to below 700 A. The resistance growth is shown in Fig. 6. It indicates that the resistance was generated quickly after the fault. The temperature reached was estimated to be about 370 K, which was slightly high for safe design without degradation. However, we also found that the experimental results were in good agreement with numerical results based on analysis using the Electro-Magnetic Transients Program (EMTP), which will be discussed in another paper. Therefore, it should be possible to refine the conductor or coil configuration to obtain a more appropriate fault-current-limiting effect [2].

![Fig. 5 Typical experimental result with applied voltage of 3.8 kVrms.](image1)

![Fig. 6 Resistance growth.](image2)

5. Summary and conclusion
This work focused on evaluation of the fault current limiting performance of a resistive FCL using YBCO tapes with an IBAD substrate. The resistivity of the conductor was decreased by reducing the thickness of the silver protecting layer. In a short-circuit experiment with an applied voltage of 3.8 kV, the model coil wound with the conductor successfully suppressed a short circuit current of 17 kA to below 700 A in a quick response time of 2 ms. The results are as expected and show promise toward FCL applications. Results for a conductor with a high-resistance metal layer will be reported in another paper.

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