Study on Improvement of Recovery Characteristics of GdBCO Non-inductive coil for resistive SFCL

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Abstract. Using the practical application of the resistance SFCLs (Superconducting Fault Current Limiter), it is required to quickly return to the superconducting state after interruption of the fault current. The quick recovery needs to improve the cooling property of a superconducting tape. It is confirmed that the recovery characteristics of a superconducting tape can be improved by the PTFE (PolyTetraFluroEthylene) coating or applying pressure. In this paper, we used GdBCO tapes for the resistive SFCL and investigated the effect of the PTFE coating or applying pressure for improvement of its recovery characteristics of non-inductive coil. Besides, we observed the boiling phenomena on the surface of the part of GdBCO tapes between under pressurized conditions and ambient pressure by a high-speed video camera.

1. Introduction
Sustainable energies such as solar power generations or wind power generations have recently increased. Therefore, electric systems are becoming more and more complicated and large-scaled. Fault current will become larger and the capacity of circuit breakers will increase because of the increase of distributed generation plants. SFCL is expected as a way to suppress the fault current and reduce the burden of circuit breakers [1], [2].

In this paper, we focused on the resistive SFCL. The resistive SFCL keeps a superconducting state and the no energies are lost under normal operating conditions. When the fault occurs and the fault current reaches the critical current of superconducting tapes, the resistive SFCL turns to a normal conducting state. By turning to a normal conducting state, the impedance becomes large and it suppresses the fault current. After limiting operation, the resistive SFCL has to return to a superconducting state within an allowance period for the next operation.

Under the limiting operation, the impedance of the resistive SFCL generates Joule heat and it delays the recovery time for the resistive SFCL to a superconducting state. To use the resistive SFCL in an actual electric system, the recovery time is an important factor and is affected by the boiling phenomena on the surface of the superconducting tape of the resistive SFCL [3], [4]. The Joule heat generated by limiting operation rises the temperature of the superconducting tapes and forms the vapor film on the surface of the superconducting tapes. The vapor film which has low conductivity delays the recovery time.

It is reported that the recovery time can be shortened by coating PTFE on the surface of the superconducting tape and applying pressure to liquid nitrogen which is a cryogen [5], [6], [7]. It was confirmed that the recovery time was reduced by preventing from forming a stable vapor film of nitrogen on the tape surface [8], [9], [10]. Under a pressurized condition, it is expected that the recovery
characteristics will be improved due to an increase in heat transfer efficiency [11], [12], [13]. We examined the effect of coating PTFE and applying pressure by using non-inductive coil SFCL. Besides, we tried to shorten the recovery time by various ways of coating on the surface of the superconducting tape.

2. Experiment

2.1. Experimental Apparatus

We used a pressure-proof LN$_2$ cryostat and it is shown in Fig. 1. It has an LN$_2$ tank whose inner-diameter is 335 mm and the height is 1000 mm and can be used at most 0.60 MPa in absolute pressure. The cryostat is a double structure and has a vacuum layer for thermal insulation. It has two windows whose diameters are 130.8 mm for observation of the boiling phenomena. A high-speed video camera (NAC image technology) was used to observe the boiling phenomena. Photographs were taken with the video camera 500 times in a second through the window. To observe the boiling phenomena clearly, test samples were brightened by an LED lump.

![Cryostat and High-speed video camera](image)

Fig. 1 Experimental setup

2.2. Test sample

GdBCO tapes were used as test samples. Its composition is shown in Table 1. The length, width and thickness of the tape is 2560 mm, 4 mm and 0.2 mm respectively. The critical current, n-value and resistance per length of the tape is 178 A ~ 184 A, 25.7 ~ 29.6 and 276.8 m$\Omega$/m. The tapes are set in non-inductive coil SFCL. This element sample is designed to cancel a magnetic field by winding tape spirally from outside to inside and returning with counter direction from inside to outside. Considering the practical use as the resistive SFCL, some element samples can be stacked according to a voltage level of electric systems.

The bobbin, which is made of FRP, has rectangular slits for fitting the tape with a depth of 5 mm and width of 1 mm as shown in Fig. 2. After setting the tape, the top of the bobbin was covered with the same bobbin as a lid. Both ends (30 mm length) of the tape were fixed to the copper terminals. The lengths between the voltage taps are about 2500 mm. Tap to tap resistance at room temperature is 655 m$\Omega$ ~ 692 m$\Omega$. 
Table 1: Composition of GdBCO tapes

| Composition          | Layer  | Thickness (μm) |
|----------------------|--------|---------------|
| Protective layer     | Ag     | 1.5 ~ 2.0     |
| Superconducting layer| GdBCO  | 7 ~ 9         |
| Middle layer         | Y₂O₃   | 0.12 ~ 0.15   |
| Clad substrate       | Ni     | 2             |
|                      | Cu     | 17            |
|                      | SUS    | 100           |

2.3. Surface coating

We prepared 5 types of the sample in which different superconducting tapes were set respectively. The sample No.1 is the Bare sample which has the tape without any coating. The sample No.2 is PTFE coated sample which has the tape coated on both sides by PTFE. It is reported that the thickness of the layer of PTFE is about 5 μm [14]. The sample No.3, No.4, and No.5 were made to shorten the recovery time. The sample No.3 is PTFE 15 mm interval coated sample which has the tape coated on both sides by PTFE at 15 mm intervals. Half of the surface of the tape is bare and the other is coated by PTFE. The sample No.4 is PTFE 5mm interval coated sample and is the same as the No.3 with 5 mm intervals. The sample No.5 is Fluorosurf (Fluoro Technology Co. Ltd.) coated sample which has the tape coated on both sides by fluorosurf, which is the coating material which has low heat conductivity. Although fluorosurf is similar to PTFE, the thickness of the layer of fluorosurf is about 10 nm ~ 30 nm and is much thinner than the layer of PTFE.

2.4. Experimental method

Test samples were immersed in LN₂ with the axial direction vertical. The test circuit, which has the interlock switch (switch 1 and switch 2 are ON/OFF reciprocally), is shown in Fig. 3. At the beginning, the switch 1 is turned OFF and the switch 2 is ON. The switch 1 was turned ON for 100 ms, the AC fault current flows through the test sample and the switch 2 is OFF. For comparing the recovery characteristics of the samples, the AC power source voltage was determined so that the resistance of the sample reached about 600 mΩ for 100 ms. After then, the switch 1 was turned OFF and the switch 2 was turned ON. The current source of 100 mA was applied to measure the sample resistance during the recovery process.
In this study, experiments were conducted under 0.10 MPa, 0.20 MPa, 0.30 MPa, 0.35 MPa, 0.40 MPa, 0.45 MPa, 0.50 MPa. In each case, the temperature of LN$_2$ was kept 77.3 K ~ 77.8 K (subcooled condition).

3. Results and Discussion

3.1. Limiting operation

One example of the experimental result of the current limiting operation by the test sample is shown in Fig. 4. The switch 1 was closed for 100 ms to simulate a fault. The large AC flowed through the superconducting tape. The tape immediately turned to the normal conducting state and begun to limit the current by the resistance. The resistance of the tape was increasing with time according to the temperature of the tape was rising. When the resistance reached 600 mΩ, the switch 1 was open and the switch 2 was closed to conduct 100 mA DC to measure the resistance of the tape in the cooling stage.

It was confirmed that the sample limited the peak current from 860 A to 470 A in Fig. 4. The resistance during a fault was calculated by dividing the voltage at the sample by the current through the current.
3.2. Temporal change of resistance

3.2.1. Bare sample. The results of the temporal change of resistance of the bare sample under 0.10 MPa to 0.50 MPa are shown in Fig. 5. Recovery time got shorter when pressure was applying from 0.10 MPa to 0.40 MPa. Recovery time under 0.45 MPa and 0.50 MPa does not get shorter than the recovery time since the saturated temperature of $LN_2$ under 0.45 MPa and 0.50 MPa was rising to the vicinity of the critical temperature of the superconducting tape and nucleate boiling on the surface of the tape finished before the tape returned to the superconducting state.

At the beginning of the recovery, the recovery rate was slow since the surface of the tape was covered with vapor film which inhibited heat exchange (phase 1). At some point, the condition of the surface of the tape changed generally from film boiling to nucleate boiling and the recovery rate was getting sharp (phase 2). As above, the recovery rate of the bare sample consisted of two phases.

3.2.2. PTFE coated sample. The results of the temporal change of resistance of PTFE coated sample under 0.10 MPa to 0.50 MPa are shown in Fig. 6. Although recovery time got shorter when pressure was applying from 0.10 MPa to 0.50 MPa, the effect of applying pressure got smaller according to applying pressure like the bare sample.

It was reported that PTFE coating quickened the transition from film boiling to nucleate boiling since the PTFE coating prevented from forming a stable vapor film and made the minimum heat flux smaller [7]. Therefore, PTFE coated samples were expected to shorten the recovery time due to the above effects. Under the same pressure, the recovery rate of PTFE coated sample was linear to time unlike bare sample and was better than the bare sample, but the recovery time of the PTFE coated sample was almost the same as the recovery time of the bare sample since the recovery rate got worse just before the superconducting tape returned to the superconducting state. As expected, the recovery rate of this sample during film boiling got better than the bare sample due to the effect of the PTFE coating mentioned (phase 1). The PTFE coating unstabilized the vapor film and quicken the cooling of the tape. Under the higher pressurized conditions, the effect of PTFE coating was increasing and the resistance of this sample was rapidly reduced. The recovery rate of this sample during nucleate boiling and natural convection got worse by PTFE coating (phase 2). In terms of the temporal change of the resistance, the transition from film boiling to nucleate boiling was not confirmed. As pressure was increased, however, the saturated temperature of $LN_2$ reached near the critical temperature of the GdBCO tape (92 K) and exceeded it. This leads to that the recovery time was delayed since the heat transfer from the PTFE
coated surface migrate from boiling to natural convection just before the superconducting tape returned to the superconducting state.

Fig. 6 Temporal change of resistance of PTFE coated sample

3.2.3. *PTFE 15 mm interval coated sample*. The results of the temporal change of resistance of PTFE 15 mm interval coated sample under 0.10 MPa to 0.50 MPa are shown in Fig. 7. Alike to the bare sample and the PTFE sample, the recovery time got shorter when pressure was applying from 0.10 MPa to 0.50 MPa and the effect of applying pressure got smaller as pressure was increased.

This sample was made to improve the recovery characteristics of the PTFE coated sample just before returning to the superconducting state. This sample has both the bare surface and the PTFE coated surface. The PTFE coated surface of this sample cooled the superconducting tape during film boiling mainly and the bare surface of this sample cooled the tape during nucleate boiling and natural convection mainly. Besides, it would be difficult to form a uniform and stable vapor film on the surface of the tape since the bare and the PTFE coated surface, on which the boiling phenomena were different from each other, existed alternately. Therefore, the combination of the bare and the PTFE coated surface was expected to shorten the recovery time. The recovery rate of this sample would be between that of the bare sample and that of the PTFE coated sample. Although the recovery rate of this sample was improved just before returning to superconducting state comparing to the PTFE coated sample (phase 2), the effect of the PTFE coating on the recovery rate of this sample during film boiling was smaller than the PTFE coated sample (phase 1). Therefore, the recovery time of this sample was longer than that of the PTFE coated sample.

The effect of PTFE coating on the recovery rate of this sample during film boiling was smaller than expected since the area of the PTFE coated surface of this sample was half of the PTFE coated sample. On the other hand, the heat conducted from the PTFE coated surface to the bare surface and the recovery characteristics was improved just before returning to a superconducting state since this sample has the bare surface, unlike the PTFE coated sample. Additionally, an unstable vapor film, especially on the boundary between the bare surface and the PTFE coated surface, was observed by a high-speed video camera since the cooling process of the bare surface and the PTFE coated surface were different from each other.
3.2.4. **PTFE 5 mm interval coated sample.** The results of the temporal change of resistance of the PTFE 5 mm interval coated sample under 0.10 MPa to 0.50 MPa are shown in Fig. 8. Alike to the other samples, recovery time got shorter when pressure was applying from 0.10 MPa to 0.50 MPa and the effect of applying pressure got smaller as pressure was increased.

The superconducting tape of this sample had the narrower intervals between the bare surface and the PTFE coated surface than the PTFE 15 mm interval coated sample. The tape of this sample had a lot of the boundary between the bare surface and the PTFE coated surface and it was expected that the boundary prevented from forming a stable vapor film. Alike to the PTFE 15 mm interval coated sample, the recovery rate of this sample would be between that of bare sample and that of PTFE coated sample, but the recovery rate of this sample was better than that of the PTFE 15 mm interval coated sample. The area of the PTFE coated surface of this sample was equal to that of the PTFE 15 mm interval coated sample. However, the intervals of this sample between the bare surface and the PTFE coated surface were narrower than that of the PTFE 15 mm interval coated sample. Therefore, the recovery rate of this sample was better than that of the PTFE 15 mm interval coated sample, since it became more difficult to form a stable vapor film on the surface of this sample than that of the PTFE 15 mm interval coated sample. This resulted in that it was confirmed that the recovery characteristics of the sample were improved by shortening the intervals between the bare surface and the PTFE coated surface.

Fig. 7  Temporal change of resistance of PTFE 15 mm interval coated sample
3.2.5. Fluorosurf coated sample. The results of the temporal change of resistance of the fluorosurf coated sample under 0.10 MPa to 0.50 MPa are shown in Fig. 9. Alike to the other samples, recovery time got shorter when pressure was applying from 0.10 MPa to 0.50 MPa and the effect of applying pressure got smaller as pressure was increased.

Like the above two samples, this sample was made to improve the recovery characteristics of the PTFE coated sample just before returning to superconducting state. The fluorosurf coating, which was thinner than the PTFE coating, was used not to prevent the sample from cooling during nucleate boiling and natural convection better than the PTFE coating. It was confirmed that the recovery rate of this sample just before returning to superconducting state was improved by replacing the PTFE coating with the fluorosurf coating. On the other hand, the recovery rate of this sample was a little smaller than the PTFE coated sample during film boiling. As a result, the recovery time of this sample was shorter than the PTFE coated sample. The recovery rate of this sample during nucleate boiling and natural convection was improved since it became easy for the tape to transfer heat from the tape to LN$_2$ as the thickness of coating was thinner. During film boiling, however, the effect of unstabilizing vapor film by coating was smaller and the recovery characteristics were worse as the thickness of the coating was thin. It is considered that the balance of the above two effects determined the recovery time.
4. Conclusion

The recovery characteristics and time of resistive SFCL to superconducting state is an important factor for the practical use. In this study, the effect of applying pressure of LN$_2$ and surface coating on the recovery characteristics was examined in the non-inductive coil SFCL. It was confirmed that the recovery time of the sample got shorter by applying pressure. As pressure was increased, the effect of applying pressure became smaller. PTFE coating improved the recovery characteristics during film and nucleate boiling, but the recovery characteristics during natural convection got worse. The samples, which have the bare surface and the PTFE coated surface, has better recovery characteristics than the bare sample, but have the worse recovery characteristics than PTFE coated sample. Fluorosurf coated sample has as good the recovery characteristics as PTFE coated sample and the recovery time is the shortest of all samples.

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