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# New HTS Cable Project in Japan: Basic Study on Ground Fault Characteristics of 66 kV Class Cables

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***Abstract*— In July 2014, a new high-temperature superconducting (HTS) cable project supported by the New Energy and Industrial Technology Development Organization (NEDO) began in Japan. The aim of this project is to verify and improve the safety and reliability of HTS cable systems. The main verification targets are system safety in the event of the following accidents: (1) ground fault, (2) short-circuit current, (3) cryostat failure. We are also developing technologies such as (4) a low heat loss cryostat and (5) a high efficiency cooling system.**

**If a ground fault occurs, it is a matter of concern that the pressure in the cryostat increases due to the arc energy. It is an additional concern if the arc penetrates the cryostat so that the liquid nitrogen leaks out of the cable. It is important to know the amount of energy in the arc in order to numerically predict the outcomes of a ground fault. We performed basic ground fault tests using sheet samples immersed in liquid nitrogen while measuring the arc energy and also examining the structure of a protection layer that can prevent arc penetration to the outside of the cable core.**

***Index Terms*—High-temperature superconductors, power cables, dielectric breakdown.**

## I. INTRODUCTION

THE stability and reliability of high temperature superconducting (HTS) cable systems in normal operation has been verified by real grid interconnection tests like NEDO's "High-temperature superconducting cable demonstration project" [1, 2]. However, general practical use of HTS cable systems requires the verification of their stability not only in normal operation, but also their safety and reliability in the event of various accidents (ground fault, short-circuit current, liquid nitrogen leakage, etc.) and understanding these phenomena and their impact [3]. This inspired the new NEDO project "Empirical studies on the safety and reliability of the next-generation power transmission system", which has since 2014 been conducting safety verifications dealing with accidents that might occur when an HTS cable system is operated in the real grid. This paper presents a summary of the project and reports the results of the 66 kV class ground fault test on sheet samples.

## II. OUTLINE OF THE PROJECT

### *A. Goal and Organization*

The goal of the project is to verify and improve the safety and reliability of HTS cable systems. The main concern is system safety in the event of the following accidents: (1) ground fault, (2) short-circuit current, (3) cryostat failure. We are also developing technologies such as (4) a low heat loss cryostat and (5) a high efficiency cooling system. The Tokyo Electric Power Company is studying the specified accidents and their evaluation. Sumitomo Electric Industries, Ltd. (SEI) is conducting safety and reliability tests of 22 kV and 66 kV cable systems and evaluating trials of a cryostat damage accident. Furukawa Electric Co., Ltd. and Fujikura Ltd. are conducting these tests on a 275 kV cable system [4]. Mayekawa Mfg. Co., Ltd. is working on improving the performance of the cooling system [5].

### *B. Cable Evaluation*

The structures of the three cables are shown in Fig.1, and the specifications and grid conditions of each cable are shown in Table I. The maximum ground fault and short-circuit current depends on the voltage class and grid conditions. It was decided to set the ground fault current of the 66 kV system (resistance neutral grounding) as high as 1.5 kA. For the 275 kV system (solid neutral grounding), the maximum ground fault current selected was 31.5 kA for urban underground lines (45 kA for particular lines) and 63 kA for overhead lines. For the short-circuit current, maxima of 31.5 kA and 63 kA were set for the 66 kV and 275 kV systems, respectively. The ground fault tests were to be performed with cable samples of several meters, and the short-circuit current tests with dozens of meters of cable. The behavior of a long cable system of several km will be discussed using numerical simulation.

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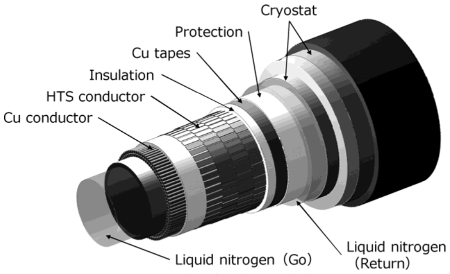
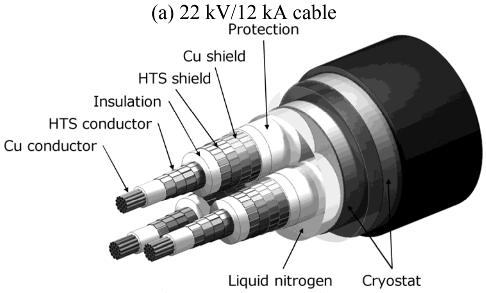
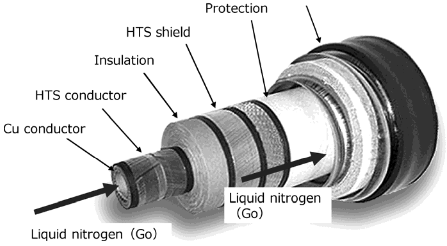


(a) 22 kV/12 kA cable



(b) 66 kV/2 kA cable



(c) 275 kV/3 kA cable

Fig. 1. Structures of the three type HTS cable.

TABLE I
CABLE SPECIFICATIONS AND GRID CONDITIONS

| Items | 22 kV/12 kA | 66 kV/2 kA | 275 kV/3 kA |
|---|---|---|---|
| Structure | Single | 3-in-One | Single |
| Made by | SEI | SEI | Furukawa, Fujikura |
| Application | Feeder line of generator | Urban underground | Urban underground |
| Neutral grounding | Resistance | Resistance | Solid |
| Ground fault | about 100 A | ~ 1.5 kA | ~ 31.5 kA(underground)<br>~ 63 kA(overhead) |
| Short circuit | ~ 63 kA | ~ 31.5 kA | ~ 63 kA |

## III. GROUND FAULT CURRENT TESTS (66 KV)

If a ground fault occurs in an HTS cable, there is a concern that the pressure in the cryostat may increase due to the superposition of a pressure shock wave and liquid nitrogen vaporization due to the arc energy. It is also a concern that the arc may perforate the cryostat so that the liquid nitrogen leaks out of the cable. Furthermore, for the 3-in-One type HTS cable shown in Fig. 1(b), if the arc damages the electrical insulation layer of another phase, there is a possibility of progression to a two-phase or three-phase short-circuit fault accident. Since the resistance grounding method is employed in 66 kV lines in Japan, the ground fault current is comparatively small, as shown in Table 1. However, if a short-circuit accident occurs, a very large fault current flows and the damage from the accident will be serious. It is vital to avoid the progression to a short-circuit accident.

First, it is important to confirm the amount of arc energy generated by a ground fault in order to numerically predict the phenomena that may occur and to provide suitable protection for the HTS cable. We therefore conducted the basic ground fault tests using sheet samples as the first step in the evaluation of ground fault characteristics. In this test, we measured the arc energy and also examined the structure of the protection layer that can prevent arc penetration to the outside of the cable core (the protection layer is the outermost layer of the cable core, as shown in Fig. 1(b)).

### A. *Test Equipment*

An overview of the test equipment and sample is shown in Fig. 2. A laminated sheet sample 180 mm in diameter is placed in the SUS open vessel (500 mmφ × 600 mm high), and it is cooled by liquid nitrogen. The ground fault current is applied for 2 seconds using a short-circuit generator between a copper bar electrode (35 mmφ) that corresponds to the conductor layer and a copper plate (1.2 mm thick) that corresponds to the shield layer. A solder wire (1 mmφ) is set in a pre-drilled hole in the laminated insulation papers (PPLP, 7 mm thick). The wire forms a conducting path between the electrode and the copper plate before the energization, but it evaporates within a few cycles after the energization, so that an arc is generated in the insulation layer [6]. The SUS plate (0.8 mm thick) that corresponds to the cryostat (inner pipe) is connected to the terminal of the short-circuit generator, as is the copper plate, so we can detect the arc penetration to the SUS plate by the current shunting to the SUS plate. The arc energy is obtained by integrating the product of the ground fault current and the terminal voltage between the electrode and the copper plate.

### B. *Results of Test I*

First, in order to examine the effect of the protection layer

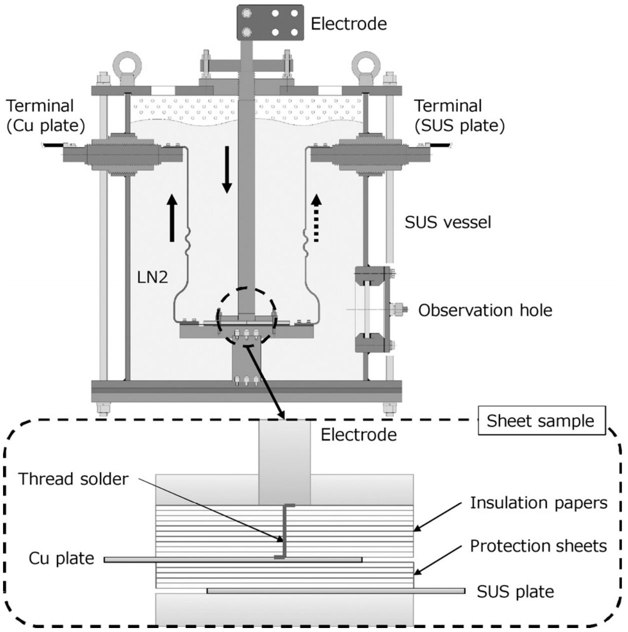
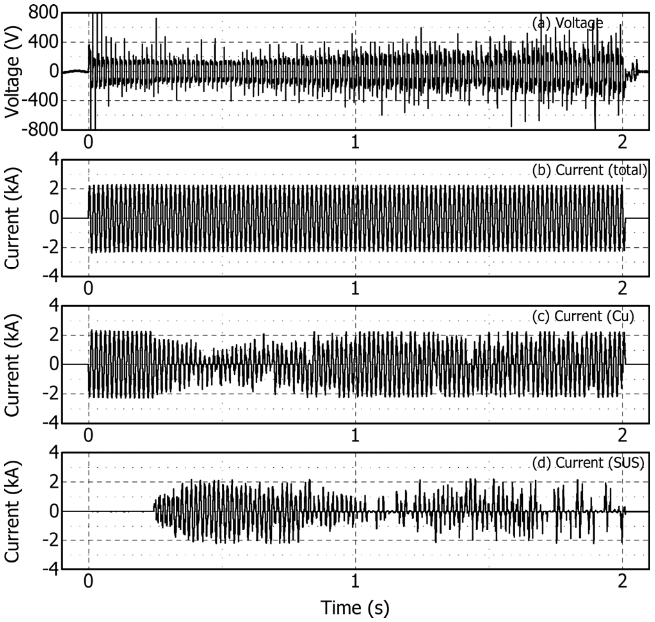


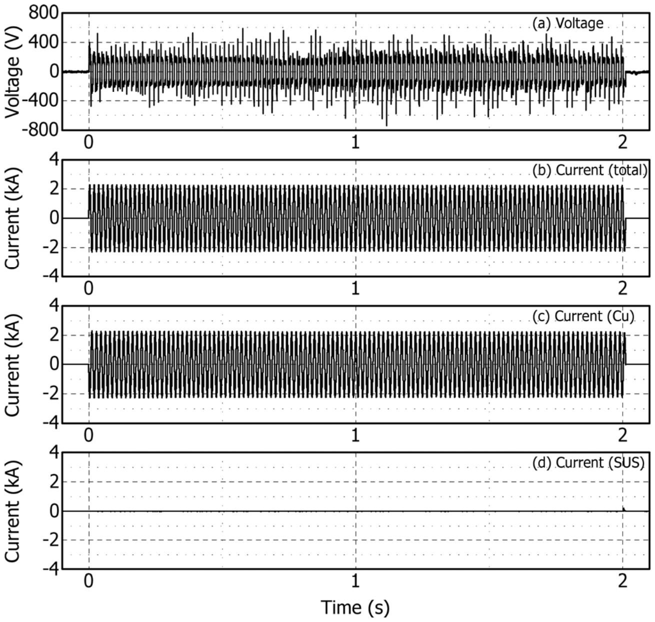
Fig. 2. Schematic view of the test apparatus

TABLE II
Specifications of the test samples and test conditions.

| Items | Sample 1 | Sample 2 |
|---|---|---|
| Insulation layer | PPLP (7 $\text{mm}^t$) | |
| Shield layer | Cu plate (1.2 $\text{mm}^t$) | |
| Protection layer | PPLP,<br>Fiber sheets A<br>(0.6+3.0 $\text{mm}^t$) | PPLP,<br>Fiber sheets A<br>(0.6+5.5 $\text{mm}^t$) |
| Cryostat (Inner pipe) | SUS plate (0.8 $\text{mm}^t$) | |
| Fault current | 1589 A | 1587 A |
| Duration | 2.01 s | 2.01 s |



(a) Sample 1



(b) Sample 2

Fig. 3. Waveforms of the voltage and current.

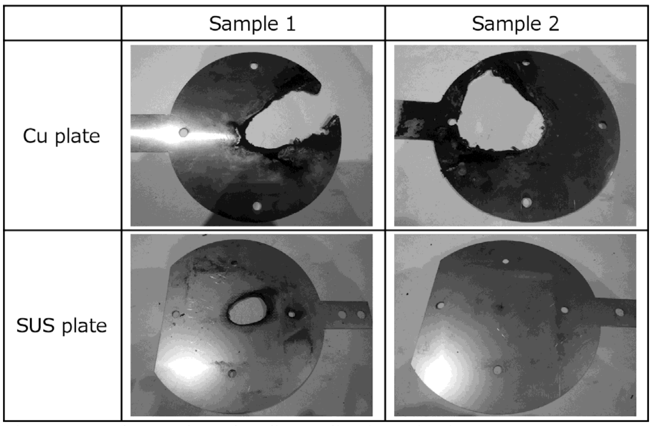


Fig. 4. Cu and SUS plate after dismantling investigation.

thickness on the arc penetration to the SUS plate, we tested two samples with different protection layers. The specifications of the samples and test conditions are shown in Table II. The graund fault current was 1500 A, and the energizing duration 2 s. The measured waveforms of the terminal voltage and the total current and each layer current are shown in Fig. 3.

*Sample 1*

As shown in Fig. 3(a), the current shunts to the SUS plate 15 cycles after energization. The arc penetrates the 3.0 mm protection layer and arrives at the SUS plate. We dismantled the sample after the test, and confirmed that there was a hole in the SUS plate (see Fig. 4).

*Sample 2*

As shown in Fig. 3(b), the current does not shunt to the SUS plate. This indicates that the arc cannot penetrate the protection layer and thus cannot reach the SUS plate. The dismantling investigation showed no damage to the SUS plate (see Fig. 4).

This verified that arc penetration to the SUS plate (cryostat) can be prevented with an appropriate protection layer. The generated arc voltage gradient was about 200 V/cm for both samples 1 and 2 (measured between 1.8 and 2.0 seconds after energization), which is almost equivalent to the arc voltage of 150 V/cm that occurs in an oil-immersed PPLP layer [7]. The generated arc energy was 420 kJ and 450 kJ for samples 1 and 2, respectively.

### *C. Results of Test II*

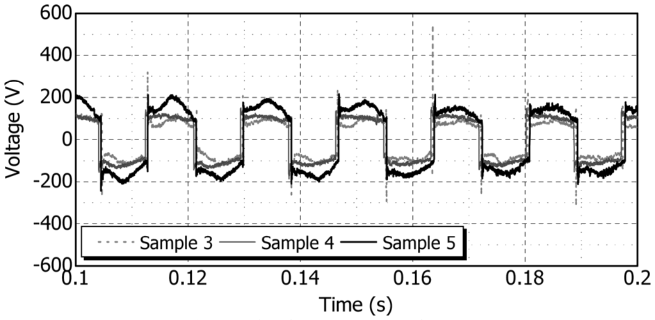
Next, in order to examine the influence of the ground fault current on the arc energy, we tested the three samples under different current conditions. Specifications of the samples and test conditions are shown in Table III. The ground fault currents were about 500 A, 1500 A and 3000 A, and the energizing duration was 2 s.

The measured waveforms of the terminal voltage are shown in Fig. 5. The peak value of the voltage waveforms, which were approximately square waves, were slightly dependent on the current value; the voltage increased with increasing current. This tendency became noteworthy as test duration increased. In addition, the phase of the voltage slipped off over time, but this depended on the load characteristics of the short-circuit generator. The dismantling investigation showed no damage to the SUS plate in any sample.

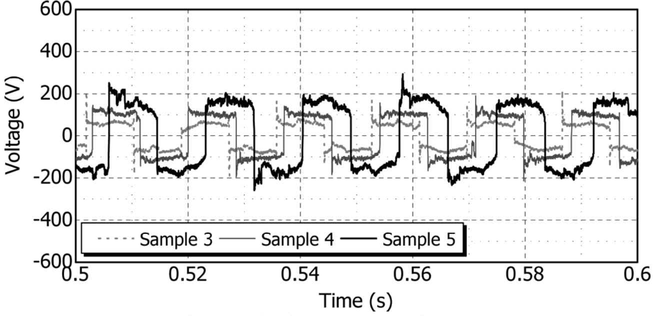
Fig. 6 shows the measured arc energy for samples 3, 4 and 5.

TABLE III
SPECIFICATIONS OF THE TEST SAMPLES AND TEST CONDITIONS

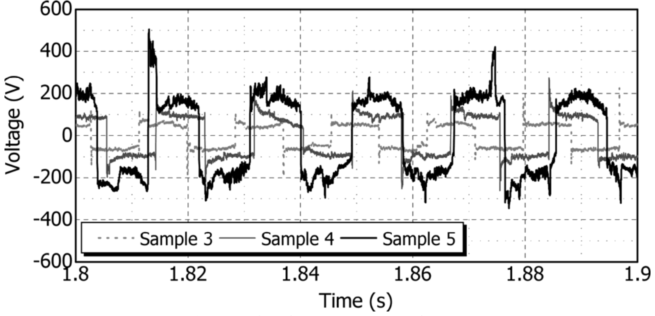
| Items | Sample 3 | Sample 4 | Sample 5 |
|---|---|---|---|
| Insulation layer | PPLP (7 mm$^t$) | | |
| Shield layer | Cu plate (1.2 mm$^t$) | | |
| Protection layer | PPLP,<br>Fiber sheets B<br>(0.6+6.5 mm$^t$) | PPLP,<br>Fiber sheets B<br>(0.6+6.5 mm$^t$) | PPLP,<br>Fiber sheets B<br>(0.6+13.0 mm$^t$) |
| Cryostat (Inner pipe) | SUS plate (0.8 mm$^t$) | | |
| Fault current | 519 A | 1582 A | 3013 A |
| Duration | 2.01 s | 2.00 s | 2.01 s |



(a) Duration between 0.1 and 0.2 s.



(b) Duration between 0.5 and 0.6 s.



(c) Duration between 1.8 and 1.9 s.

Fig. 5. Waveforms of the voltage.

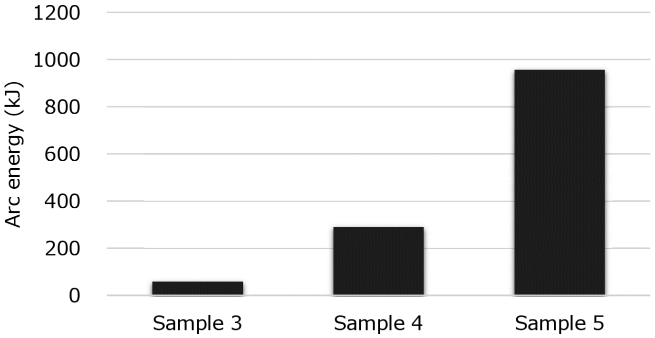


Fig. 6. Dependence of the arc energy on the ground fault current.

The arc energy for sample 4 was 300 kJ. This value was slightly smaller than those of samples 1 and 2, which may have been due to a difference in the fiber sheet material used in the protection layer. The arc energy for sample 3 (500 A) was 60 kJ, which is one-fifth that of sample 4 (1500 A). The arc energy for sample 5 (3000 A) was 960 kJ, or three times that of sample 4 (1500 A). Our group is the first to obtain data about the arc energy generated in a liquid-nitrogen-immersed PPLP electric insulation layer, and its dependence on the ground fault current. In the future, we will perform ground fault tests on samples more representative of those in actual HTS cables, and also perform numerical simulations of the pressure rise and dynamic pressure tests of the cryostat using the measured arc energy value.

## IV. CONCLUSIONS

The new HTS cable project "Empirical studies on the safety and reliability of the next-generation power transmission system" has been launched. We selected certain accident cases to examine by conducting safety verification tests: ground fault, short-circuit current and broken cryostat accidents.

To elucidate the ground fault phenomenon that occurs in 66 kV class HTS cable, we performed ground fault tests of sheet-shaped samples of the material used, and clarified the following:

(1) The perforation of the cryostat by the arc can be avoided by appropriate design of the cable core protection layer.
(2) The arc voltage in the liquid-nitrogen-immersed PPLP is about 150 ~ 200 V/cm for a ground fault current of 1500 A, which is almost the same as that in the oil-immersed PPLP.
(3) The arc energy is 300 ~ 450 kJ for a ground fault current of 1500 A.

As the next step, we will perform ground fault tests of cable samples, and also numerically simulate the pressure rise in the cryostat using measured arc energy values. These results will then inform future HTS cable designs.

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