Demonstration of a 500 m HTS Power Cable in the Super-ACE Project

M. Yagi, S. Mukoyama
The Furukawa Electric Co., LTD., JAPAN

M. Ichikawa, T. Takahashi, H. Suzuki
Central Research Institute of Electric Power Industry (CRIEPI), JAPAN

A. Kimura
Engineering Research Association for Superconductive Generation Equipment and Materials (Super-GM), JAPAN

Abstract. A demonstration of a 500 m single-core high-Tc superconducting (HTS) cable has been carried out by Furukawa, CRIEPI and Super-GM at the CRIEPI site in Yokosuka, Japan. The cable was a cryogenic dielectric type rated at 77kV/1kA. In the test, critical currents (Ic) of HTS conductor and HTS shield at 73 K were 1910 A and 1620 A respectively, with heat invasion of 1.21 W/m, and a pressure drop of 100 Pa/m at an LN2 flow rate of 50 L/min. Rated loading tests corresponding to degradation of the insulation over 30 years were carried out, and there was no degradation in the cable. Moreover, overload and limiting tests were performed under the adverse conditions of over-voltage, over-current and stopping of refrigerators and pumps. After these events, the cable was removed and studied, revealing almost no damage.

1. Introduction
To make HTS cable a practical reality it is essential to understand the cooling characteristics of long-length superconducting cables and the circulation of liquid nitrogen. Therefore, field testing of a 500 m HTS cable, the longest in the world, was planned as part of the Super-ACE project. HTS cable manufactured by Furukawa Electric was installed at the Yokosuka Laboratory of CRIEPI and various tests were carried out from March 2004 to March 2005.

2. Structure of HTS Cable
Figure 1 shows the structure of the HTS cable [1]. It was designed for a nominal voltage of 77 kV and a current capacity of 1 kA. It has a single-core structure with an HTS shielding layer and a cold type dielectric that provides an 8 mm thick layer of electrical insulation. Its overall outer diameter of 133 mm allows its installation in an underground duct with an inner diameter of 150 mm.

3. Cooling Characteristics
3.1. Testing Line and Cooling System
Figure 2 shows the layout of the 500 m HTS cable system. The three-dimensional layout has several noteworthy features, such as an underground section to simulate an actual underground cable
installation, a 10-m-high section simulating a bridge over a river, and an offset section for absorbing the thermal contraction and expansion of the cable during cooling and warming periods.

Table 1 shows the specifications of the cooling equipment. The cooling system for the HTS cable had six Stirling refrigerators; four for the cable and two for the terminations. A storage tank was used for pressurized liquid nitrogen (LN$_2$) in a sub-cooled state, and two LN$_2$ pumps circulated LN$_2$ to the cable and terminations [2].

**Table 1 Specifications of the cooling system**

| 500 m cooling system | Specification                           |
|----------------------|----------------------------------------|
| LN$_2$ tank capacity | 1,000 L                                |
| LN$_2$ capacity for HTS cable | 2,000 L                              |
| LN$_2$ pump power    | 10L/min-50L/min differential pressure $<$0.50 Pa |
| A Stirling cooler power | 1 kW at 77 K, 0.8 kW at 65 K          |
| Coolant temperature | 65 – 77 K                              |
| Maximum Pressure     | 1 MPa                                  |

3.2. Heat Invasion

Heat invasion of the cable was calculated from temperature and pressure differences between the upstream (0 m, the origin) and downstream (500 m from the origin) circulating LN$_2$. Heat invasion in the 500-m HTS cable was 1.21 W/m and a flow resistance loss was 0.02 W/m calculated from the temperature difference of 0.75K, the pressure difference of 16kPa and the average temperature of 73K,
the flowing rate of 30 L/min. It was confirmed by the calibration [3] using the heat load whose heater line was wound around the HTS conductor in advance.

3.3. Pressure Drop
Subcooled LN$_2$ was circulated in the 500 m cable, and the pressure drop was measured. The pressure drop was 100 Pa/m at a flow rate of 50 L/min. This was not dependent on LN$_2$ temperature over the range from 69 K to 77 K, which is why changes in LN$_2$ density are small at these temperatures.

3.4. Results of Limiting test
A limiting test was carried out while monitoring the temperature, the pressure and the occurrence of PD (partial discharge) at a voltage of 45 kVrms, a current of 1 kArms, and an average LN$_2$ temperature of 73 K, flowing at 30 L/min and a tank pressure of 0.4 MPa-abs.

When refrigerators were stopped to simulate their malfunction, the pressure reached its limit in 3.5 hours and no PD was found (noise level, 250 pC).

When the LN$_2$ pumps were stopped for an hour, no PD was found and the increases in temperature and pressure were smooth.

4. Electrical Properties

4.1. Withstand Voltage Test and Rated Loading Test
A withstand voltage test was carried out at 95 kVrms for 10 min. Test voltages were applied in 5 kVrms/min steps up to 95 kVrms. During voltage application, PD measurement was carried out by the tuning method using foil electrodes installed on the termination (noise level, 100 pC). No PD was detected [4].

To confirm the operating characteristics of the cooling system and the electrical insulation, a current of 1 kArms was continuously imposed for one month at a voltage to ground of 70 kVrms, with an average temperature of 73 K, an LN$_2$ flow rate of 30 L/min and a pressure of 0.4 MPa-abs in the LN$_2$ tank. These conditions were assumed to be those prevailing after 30 years.

The shielding current, with a phase opposite to that in the conductor, was 980 Arms, making the ratio of magnetic shielding 98 %.

After the one-month loading test, a withstand voltage test at 95 kVrms was carried out for 10 min, and there was no indication of PD. Thus, it was confirmed that there was no degradation of electrical insulation performance.

4.2. Over-voltage test
An over-voltage test was carried out at zero current using a voltage that increased in steps of 5 kVrms per 5 min from 45 kVrms to 150 kVrms, with an average LN$_2$ temperature of 73 K, flowing at 30 L/min and a tank pressure of 0.4 MPa-abs.

When the voltage reached 150 kVrms, no PD was found (noise level, 250 pC).

5. Superconducting Characteristics

5.1. Measurement of Critical Current and AC loss
The terminal section had a voltage tap to determine the critical current (Ic) by the four-terminal method. The critical currents of the HTS conductor and the HTS shield at an average temperature of 73 K were 1910 A and 1620 A respectively.

When an HTS cable is used with an alternating-current (AC) of 50 Hz, an AC loss is generated due to the alternating magnetic fields. The AC loss of this HTS cable when carrying 1000 Arms was 1.34 W/m at an average 73 K LN$_2$ temperature. When the current exceeded 900 Arms, the AC loss increased rapidly.
5.2. Over-current test
An over-current test was carried out with current increasing in steps of 50 Arms per hour starting from 1 kArms and with monitoring of temperature and pressure, input electric power for CT and any occurrence of PD under test conditions of 45 kVrms, an LN₂ flow rate of 30 L/min, tank pressure of 0.4 MPa-abs and average LN₂ temperatures of 73 K and 77 K.

When the current reached 1450 Arms and was kept for 45 min at 73 K, the input electric power increased by 10% and the test was stopped. In the 77 K case, the test was stopped due to the electric power increasing at 30 min and 1250 Arms.

During these tests, no PD was found (noise level, 250 pC). After each test, Ic was measured and no degradation was found.

6. Residual test
After all tests, a 500 m HTS cable was removed and cable specimens 6 m long were taken from various sections (see figure 3) and examined. No Ic degradation was found in the HTS conductor, but local degradation was seen in the HTS shield at the U-bend sections (point 7, 11), the offset section (point 9) and the underground section (point 12). These degradations might have arisen during the over-current test but were within the allowable range of about 5%. They were so small and their area was so limited that no degradation could be found by examining the 500 m length as a whole.

Figure 3 Positions of the samples for the residual test

7. Conclusions
Demonstration tests of a 500 m long HTS cable have revealed essential information about its characteristics that will determine the design criteria for HTS cable installations. These include the characteristics of items of practical importance such as its cooling system, LN₂ flow, electrical insulation and current flow.

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