# Successful Field Tests of the World's Longest 500-m High-Tc Superconducting Power Cable

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**ABSTRACT** Furukawa Electric has completed, in cooperation with CRIEPI (Central Research Institute of Electric Power Industry) and Super-GM (Engineering Research Association for Superconductive Generation Equipment and Materials), all pre-determined items in the field test of the world's longest 500-m high-Tc superconducting (HTS) cable, thereby succeeding in establishing basic technologies for practical application of the HTS cable in the future. This test project has been carried out as a part of Super ACE (Research and Development of Fundamental Technologies for Superconducting AC Power Equipment) project of METI (the Ministry of Economy, Trade and Industry), being commissioned by NEDO (the New Energy and Industrial Technology Development Organization) to Super-GM.

In practical application of the HTS cable, it is required to cool the cable several km in length using liquid nitrogen, making it necessary to study the details of basic operation characteristics and the issue of long distance circulation of liquid nitrogen. We have laid a 500-m HTS cable manufactured by Furukawa Electric in the premises of the Yokosuka Research Laboratory of Electric Power Engineering Research Laboratory, CRIEPI, and have been conducting since April 2004 various tests including those for basic characteristics, rated loading characteristics, load fluctuation characteristics, and limiting and overloading performance. Recently, the tests have been completed successfully, and the results will be briefly reported in this paper.

## 1. INTRODUCTION

The HTS power cable, which enables high-capacity power transmission with its compact size, is expected to bring about significant advantageous effects in future, because it is capable of responding to the needs of power systems including suppression of $CO_2$ emission, improvement in environmental harmonization, enhanced system stability, and cost reduction.

Realization of the HTS cable systems requires that long-distance HTS cables should be cooled using liquid nitrogen, so that system problems such as cooling characteristics of the HTS cable and long-distance circulation behavior of liquid nitrogen have to be appropriately solved. With regard to the cooling section of the HTS cable, given the fact that the cooling sections for existing normal-conducting power cables are several km in length, it was assumed that the existing cooling equipment would be replaced with refrigerators for the HTS cable and that practical HTS cable systems would have cooling sections equivalent to the existing ones in length. Accordingly, it was decided to adopt a cable section length of 5 km for the HTS cable to be developed here and a cable length of 500 m which is the minimum length to enable accurate simulation of the cooling and thermo-mechanical characteristics. This cable length of 500 m is thought to correspond to a suitable jointing distance, i.e. manhole distance, for cable laying whereby cable units of this length are jointed to constitute a 5-km cable section. Thus, behavior confirmation using the 500-m cable will obviously permit scale expansion into an integrated HTS cable system.

A 500-m HTS cable was manufactured and laid by Furukawa Electric, and tested jointly by CRIEPI and Furukawa Electric at the premises of the Yokosuka Research Laboratory of Electric Power Engineering Research Laboratory, CRIEPI.

## 2. STRUCTURE OF HTS CABLE

Figure 1 shows the structure of the HTS cable and Table 1 its specifications. It is a 77-kV, 1-kA power cable consisting of single-core, cold electric insulation and superconducting shield layer, and has an outer diameter of 133 mm to be accommodated in a cable duct 150 mm in diameter. The core former consists of a stainless steel

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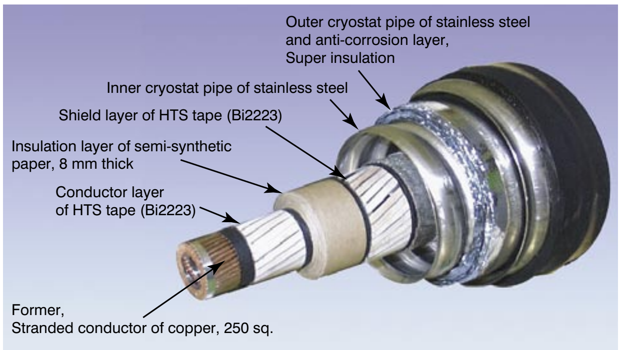



**Figure 1 Structure of HTC cable [1).]**

**Table 1 Specifications of the HTS cable.**

| Item | Structure | | Outer diameter (mm) |
|---|---|---|---|
| Conductor layer | Former | SUS spiral pipe | 28 |
| | | Stranded conductor of hollow copper wire (250 mm²) | |
| | HTS conductor layer | Bi2223 tape | 30 |
| Insulation layer | Insulator (8 mmt) | Semi-synthetic paper | 48 |
| Shielding layer | HTS shield layer | Bi2223 tape | 58 |
| Cryostat pipe | Inner cryostat pipe | SUS corrugated pipe | 92 |
| | Vacuum insulation layer | Super insulation (SI) | |
| | Outer cryostat pipe | SUS corrugated pipe | 124 |
| | Anti-corrosion layer | PVC | 133 |

spiral pipe and copper strands, on the surface of which a conductor layer comprised of Bi2223 tape is positioned. Around the core former, intervened by an electric insulation layer 8 mm in thickness, a shield layer of Bi2223 tape is provided. This is surrounded by a protective layer on which an optical fiber for measuring temperature distribution over the cable length is wound together with a heater wire for calibrating the cable AC loss. The cryostat pipe has a structure of vacuum thermal insulation whereby super insulation (SI) is multilayered between double corrugated pipes of SUS, aimed at a heat invasion rate of 1 W/m or less. With its outermost layer of PVC protective layer, the cable weighs 14 kg/m, lighter than conventional cables.

In addition, the cable incorporated foil electrodes for partial discharge measurement and Pb indicators for cable behavior identification.

## 3. MANUFACTURE OF HTS CABLE

### 3.1 Manufacture of HTS Core

Because of its small thickness of 0.2 mm and its brittle property, Bi2223 HTS tape is subject to degradation in critical current $I_c$ if excessive tension or bending is applied. Therefore, in the forming process of multiple conductor tapes around the core former, winding tension on each tape was optimally controlled individually, thereby minimizing the strain on the tape. The electric insulation layer was created by winding multiple layers of semi-synthetic paper (PPL paper) using the conventional paper winding machine for OF cables. The HTS shield layer was also formed by winding Bi2223 HTS tape on the electric insulation layer while controlling the winding tension. During its manufacturing process, the HTS cable was wound on drums a number of times to be transferred to the next process, undergoing bending strains each time. Thus it was necessary to confirm whether there was a cable degradation caused by strains such as those during the HTS tape winding or drum winding, and accordingly, critical current $I_c$ was measured with the test pieces cut from the cable end, using those 1-m long after every major process and 20-m long after the final process. Figure 2 shows the changes in $I_c$ of the HTS conductor and shield layers at each process, taking the summation of original $I_c$ of all HTS tapes as 100 %. As the result, it was confirmed that there was virtually no degradation and that manufacturing of the 500-m HTS cable was successfully completed.

### 3.2 Manufacture of Cryostat Pipe

Stainless steel corrugated pipes for the cryostat pipe were manufactured by welding stainless steel sheet into a pipe, which was subsequently corrugated. With regard to the super insulation to be provided as a thermal insulation layer between the inner and outer cryostat pipes, research and development study was carried out beforehand aimed at realizing a low heat invasion rate of 1 W/m, and the pipe system was implemented under the optimum conditions thus obtained. Simultaneously, a factory-based manufacturing technology [1)] was newly established that enabled producing the optimum conditions over the entire length of 500 m. What is more, the thermal insulation layer has to maintain a high degree of vacuum so as to realize high performance in thermal insulation. In the formation process of the thermal insulation layer, therefore, proper care should be taken including cleaning the surface of the cryostat pipe by washing, dehumidification by humidity control, and elimination of cracks and pinholes at the welded seam, making it essential to establish such technologies as the pinhole-free welding technology

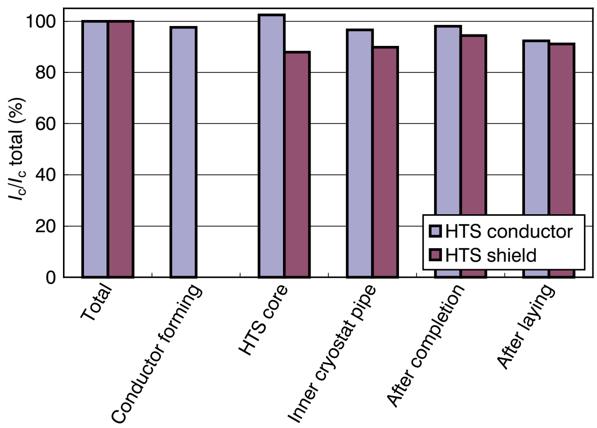



**Figure 2 Critical current $I_c$ of test pieces after each manufacturing process [1).]**

for cryostat pipes and the in-process pinhole detection technology. Furukawa Electric had already established a manufacturing technology of long-length stainless steel corrugated pipes for sheathing the stainless steel sheathed cables currently in use, so that it was possible for the Company to manufacture high-reliability cryostat pipes by expanding the above mentioned technologies and by establishing the eddy current flaw detection technology that allows in-process detection of pinholes at the welded seam. Moreover, a helium leak test was conducted after pipe manufacturing with a sensitivity higher than $10^{-9}$ Pa·m$^3$/s confirming no leaks, and, in addition, a pressure test was carried out with a pressure that is 1.5 times the design pressure (1.1 MPa) validating air tightness. Figure 3 shows the appearance of the manufactured HTS cable, which looks like an ordinary cable due to its PVC sheath.

**Figure 3 Appearance of the 500-m HTS cable.**

## 4. TRANSPORTATION OF HTS CABLE

The manufactured HTS cable had to be transported, for the purpose of field test, from the Furukawa's plant in Ichihara, Chiba Prefecture to the CRIEPI's laboratory in Yokosuka, Kanagawa Prefecture. It was anticipated that, during transportation, the cable core would vibrate in large amplitudes due to the different diameters of the cable core and cryostat pipe, and this could result in any damage in the cable core. Accordingly, a vibration test using test pieces was carried out beforehand in order to investigate the effects of vibration during transportation on the cable, in which, assuming all-land transportation, vibration with 3 G and 7 Hz was continuously applied for 3 hr, and the change in $I_c$ before and after the test was measured. Although no decrease in $I_c$ was found denying troubles from land transportation, it was decided to adopt sea transportation to be on the safe side. Thus the cable was transported by ship for approximately 50 km from Ichihara wharf to Yokosuka port, then from there by a semi-truck for 10 km. See Figure 4. The vertical and horizontal accelerations during the transportation were measured using accelerometers mounted on the cable drum, and the results showed that horizontal acceleration was virtually 0 G, vertical acceleration during sea transportation was 0.2 G or less, vertical acceleration during land transportation was 1.0 G or less, and a maximum acceleration of 1.5 G occurred only once in the premises of the CRIEPI Laboratory, indicating that the transportation exerted virtually no effect on the cable in view of the results of the vibration test.

**Figure 4 Transportation of the 500-m HTS cable.**

## 5. ASSEMBLY OF TERMINATION

A termination, which had been developed jointly by Furukawa Electric and Chubu Electric Power Co., was used in this test. Its structure is shown in Figure 5 and appearance in Figure 6. The termination has a three-segment structure comprising a thermal gradient tank, a former tank and an outer-core tank, and it is movable on rails preventing excessive strains due to thermal contraction.

The HTS cable and the termination are so configured as to have partitioned vacuum sections, and the cable was evacuated for its thermal insulation layer during the period of termination assembly. The assembly work comprised provision of foil electrodes for partial discharge detection, optical connectors for optical fiber and hermetic sealing of various wires for measurement.

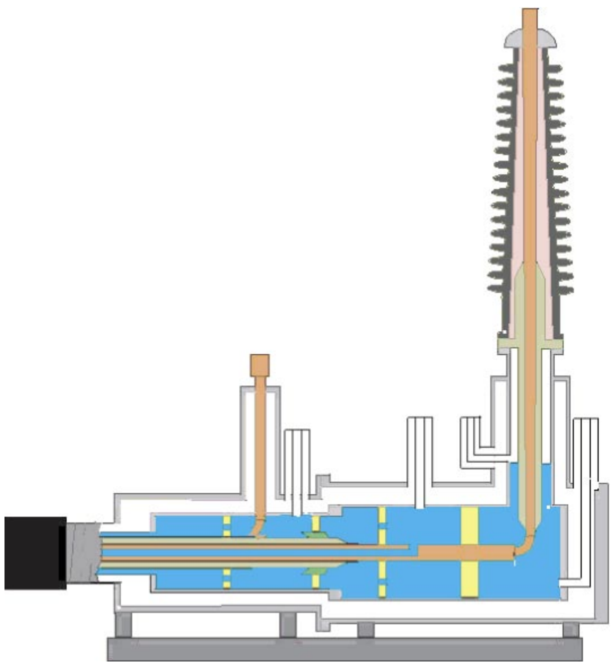


**Figure 5 Structure of termination [2].**

Figure 6 Appearance of termination.

Figure 8 Test line of the 500-m HTS cable photographed from the U bend section (1).

## 6. TEST LINE AND COOLING SYSTEM

Figure 7 shows the test line layout [2]. The test line configured on a race track consisted of a 10m-high rising and falling section simulating river-crossing bridges, an offset section aimed at relaxation of thermal contraction, and an underground section simulating conduit-based laying, and the terminations were installed on rails rendering it movable along with thermal contraction.

Figures 8 and 9 show the views of the test line.

The cooling system for the HTS cable circulates liquid nitrogen for cooling the cable, and the coolant also serves as an impregnant for the electric insulation layer, i.e. paper insulation layer impregnated with liquid nitrogen. To prevent gasification of liquid nitrogen which can initiate dielectric breakdown of cryogenic electric insulation, the coolant is pressurized to circulate in the state of single-phase flow, i.e. subcooled state, thereby cooling the cable taking advantage of its thermal capacity.

The cooling system for the 500-m HTS cable employed six Stirling refrigerators with a cooling capacity of 1 kW at 77 K, allocating four for the cable and two for the termination cooling. A storage tank was used to pressurize liquid nitrogen to a subcooled state, and two circulation pumps were utilized to circulate liquid nitrogen to the HTS cable and the termination respectively. This configuration of two partitioned cooling systems each equipped with circulation pumps and a refrigerator is advantageous since it

Figure 9 Test line of the 500-m HTS cable photographed from the termination.

allowed, at the initial stage of cooling, prevention of heat invasion from the termination and the cable individually, thereby shortening the initial cooling time. Moreover, by pressuring the storage tank to maintain a subcooled state all over the system, it is possible to reduce the outlet pressure of circulation pumps thus improving the cooling efficiency thanks to the decreased pumping loads. It becomes also possible, in case of accidents such as pump malfunction, to continue operation for a specified time without damaging the cable.

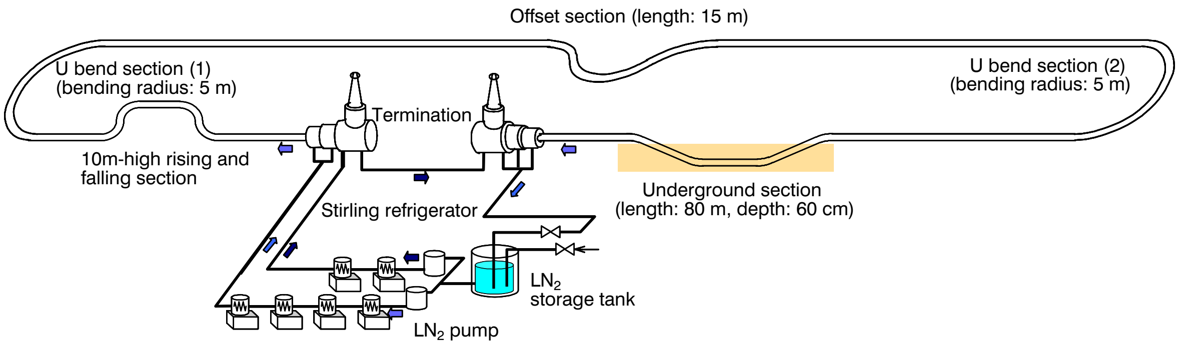



Figure 7 Test line layout with cooling system [2].

## 7. RESULTS OF FIELD TEST

The field test was carried out at the CRIEPI Laboratory according to the schedule shown below. Laying test of the HTS cable was conducted in November 2003, basic characteristics test from March through June 2004, rated loading test from September through December, load fluctuation test and limiting and overloading test from January through February 2005, and cable removal and residual performance test from February through March 2005.

Test results will be presented in outline in terms of laying efficiency, basic characteristics, rated loading characteristics, load fluctuation characteristics, and limiting and overloading performance.

### 7.1 Cable Installation Test

In the cable installation test, the cable was investigated whether it could be laid in duct just like conventional cables.

In the cable laying, a pulling eye that had been preliminarily mounted at the cable end was used to lay the cable in the duct for approximately 170 m including the underground and 5-m radius U bend sections, and subsequently, the whole 500-m length was laid using a hauling machine and ball rollers. While the front end of the cable was subjected to a tension of 16 kN corresponding to 90 % of the allowable tension at the beginning of laying, it was found that, as a result of a critical current measurement for the specimens taken from the front end of the cable that underwent laying, there was no degradation in characteristics between before and after cable transportation and laying. Furthermore, it was confirmed that the cable pressurization conducted at the time of manufacturing using dry air maintained a positive pressure even after cable laying, and being supported by the result of argon leak test that was carried out later, it was verified that there was no leak whatever in the cryostat pipe.

### 7.2 Basic Characteristics Test

The basic characteristics test was conducted focusing on confirming the thermal behavior at cooling and temperature rise, cooling characteristics or amount of heat invasion, electric characteristics including initial withstand voltage, critical current, and AC loss.

#### 7.2.1. Cooling and Temperature Rise Test

To cool the HTS cable from room temperature down to the liquid nitrogen temperature of −196°C, nitrogen gas of low temperature was used first for gradual cooling and then liquid nitrogen in turn in the latter half period of cooling. Temperature distribution was measured by means of an optical fiber wound around the HTS cable core.

The time required for cooling was 117 hr for gradual cooling using nitrogen gas in addition to 21 hr for liquid nitrogen cooling, totaling 138 hr, i.e. about six days.

Temperature rising was effected by releasing liquid nitrogen through the bleeder valve provided at the return line of liquid nitrogen. Because the underground section was located lower in elevation than the bleeder valve, this section was slower in temperature rising due to the residual liquid nitrogen. The whole cable sections took 211 hr, i.e. about nine days, to reach room temperature. This temperature rise time considerably depended on ambient temperature and sunshine, so that in case of low ambient temperature and weak sunshine, it took a longer time due to a significant reduction of heat inflow from the termination.

#### 7.2.2. Measurement of Thermal Loss

Heat invasion into the cryostat pipe was determined based on the measurements of temperature and pressure differences between the upstream and downstream points, i.e. 0 m and 500 m from the origin, while circulating liquid nitrogen at a constant flow rate. The results showed that the thermal loss including viscosity loss of the 500-m HTS cable was 1.23 W/m, and the thermal loss due to heat invasion from outside the cryostat pipe was 1.21 W/m.

At the U bend section, heat invasion was seen to be four to six times larger than that in straight sections. This is due to the fact that the cable core is pressed against the inner cryostat pipe because of the thermal contraction of the core, reducing the thickness of the thermal insulation layer thus decreasing its thermal performance. Figure 10 shows the X-ray photographs of the U bend and straight sections of the HTS cable taken perpendicularly. At the bent section, the thermal insulation layer is seen to be pressed tight due to thermal contraction, indicating mechanical lateral pressure and increase in heat invasion. At the straight section, on the other hand, it has been confirmed that the HTS cable developed here possesses thermal insulation performance equivalent to 1 W/m or less, achieving the initial target.

#### 7.2.3. On Pressurization of Cooling

During the circulation of liquid nitrogen, an X-ray photograph taken at the 10m-high rising and falling section showed a shadow image which was attributed to a gas phase. See Figure 11. In this cooling system, the storage tank is pressurized with gas in order to maintain, even in case of pump malfunction, the inner pressure thus preventing occurrence of dielectric breakdown. At the beginning, helium gas having a boiling temperature lower than liquid nitrogen was used as a pressurizing gas, but it was found that, since helium gas dissolves into liquid nitrogen, the dissolved helium gas gasified as the temperature of liquid nitrogen rose in low pressure, producing a mass of

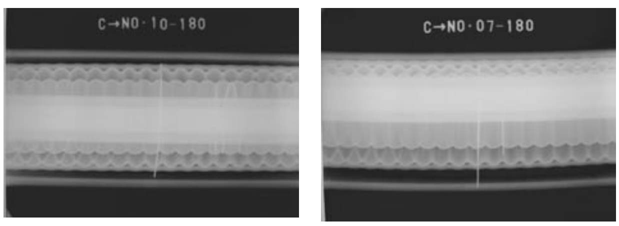



**Figure 10 X-ray photograph of cable sections during $LN_2$ cooling. (Left: straight section, Right: U bend section)**

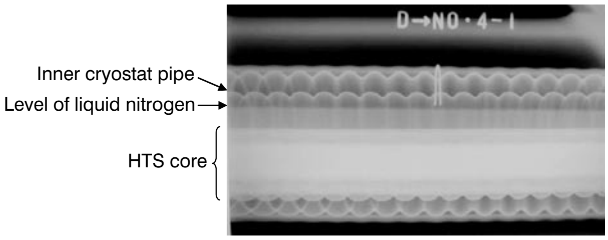



**Figure 11 X-ray photograph taken at the 10m-high rising and falling section.**

gas [1]. Existence of this helium gas mass raised concerns about significant reduction in the electric insulation performance of the cable core. Accordingly, a method was devised in which nitrogen gas was efficiently used as a pressurizing gas in place of helium gas, and it was confirmed that stable circulation of liquid nitrogen was achieved.

7.2.4. Thermo-Mechanical Behavior

When cooled from ambient temperature to liquid nitrogen temperature, the cable core that constitutes the conductor contracts by about 0.3 % due to thermal contraction [5]. Stress would be generated unless this contraction was smoothly effected, so that a serpentine offset was provided in the cable line aiming at relaxing stresses due to thermal contraction. Figure 12 shows the structure of the offset.

The movement was checked using X-ray over the whole 500-m length, and it was confirmed that the cable moved sufficiently according to cooling and temperature rise and that the offset absorbed a contraction length of about 690 mm between before and after cooling. This length was in good agreement with the predicted value which was calculated assuming that the offset took care of almost all the thermal contraction of the 200-m long straight section, and it was confirmed that the mechanical stress relaxation

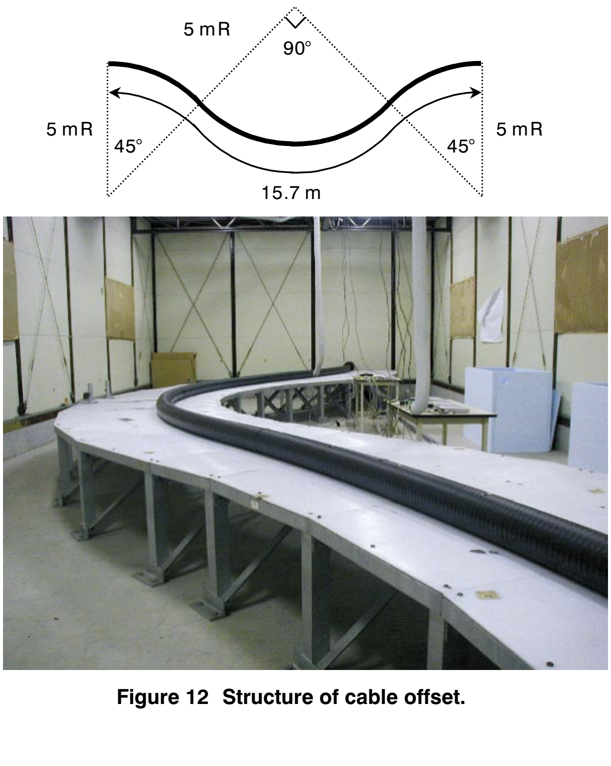



**Figure 12 Structure of cable offset.**

functioned satisfactorily. At the time of temperature rise, in the meantime, the final returning length of the cable remained at a value of 490 mm. This may be attributed to the fact that the cable was moved mostly to the underground section where the temperature rising was slow at the time of temperature rise [3].

7.2.5. Electric Characteristics Test for Withstand Voltage and Superconducting Characteristics

The HTS cable developed here can be evaluated for its performance only when impregnated with liquid nitrogen. Thus it was during the field test that the cable was confirmed as to whether it could exhibit the withstand voltage and superconducting characteristics as designed.

(1) Withstand Voltage Test

Conditions for withstand voltage were set out as 95 kVrms for 10 min, in consideration of a time factor of conversion for 30 years. Test voltages were applied in 5 kVrms/min steps until 95 kVrms. And in the mean time, in order to survey the soundness of the electric insulation layer, partial discharge measurement by tuning method was carried out using the foil electrodes installed on the termination under the condition of a noise level of 100 pC.

As a result of a voltage application of 95 kVrms for 10 min, any partial discharge exceeding 100 pC was not detected, and this confirmed the validity of the design methodology [5] for the electric insulation of the present HTS cable.

(2) Superconducting Characteristics

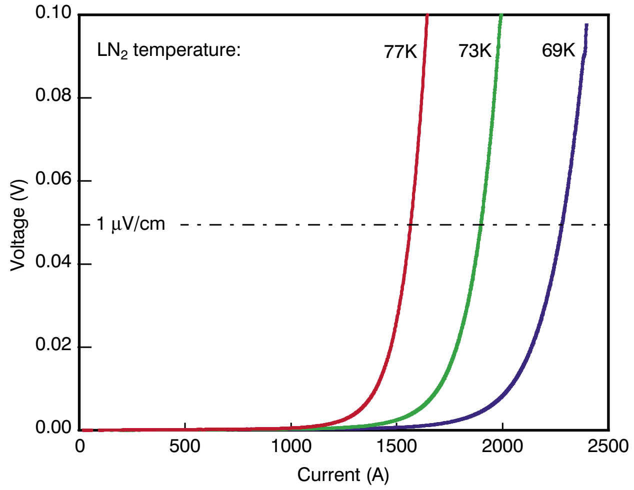
Figure 13 shows the superconducting characteristics with its left part of the graphs indicating that no voltage is induced, i.e. zero electric resistance even at a conduction current of 1000 A.

Critical current is used to evaluate the state of superconductivity, and it is defined as a current that induces a voltage generation of 1 μV/cm. Because the present cable is 500 m long, the point of 50 mV corresponds to the critical current. The critical currents at an average liquid nitrogen temperature of 73 K for the conductor core and shield layers were 1910 A and 1620 A, respectively [3], and it was demonstrated that the cable satisfied the initial specification for critical current of 1000 A or more. Table 2 shows critical current data for various temperatures, and it can be seen that the lower the temperature the higher the critical current for superconductivity.

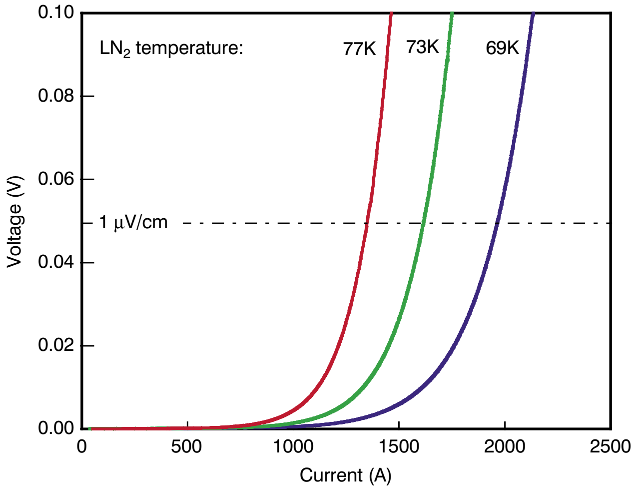
Meanwhile, when a HTS cable is used with an alternating current, alternating-current (AC) loss is generated due to the alternating magnetic fields. The AC loss for the present cable was 1.3 W/m under the conditions of 73 K in averaged liquid nitrogen temperature and 1000 Arms in conduction current, showing a rapid AC loss increase when the current exceeded 900 A [3]. Thus it was shown that the AC loss at 1000 A of the HTS cable manufactured here is equivalent to the amount of heat invasion through the cryostat pipe.

### 7.3 Results of Rated Loading Test [3]

To confirm the operation characteristics of cooling system and the electric insulation characteristics, a conduc-




(a) Conductor




(b) Shield

**Figure 13** $I$-$V$ **characteristics of the 500-m HTS cable.**

**Table 2 Critical current of the 500-m HTS cable at different positions and temperatures.**

| Position | 69 K (–204°C) | 73 K (–200°C) | 77 K (–196°C) |
|---|---|---|---|
| HTS conductor | 2290 A | 1910 A | 1570 A |
| HTS shield | 1965 A | 1620 A | 1350 A |

tion current of 1000 A was continuously imposed for one month at a voltage to ground of 70 kVrms under the conditions of averaged liquid nitrogen temperature: 73 K, liquid nitrogen flow rate: 30 ℓ/min, and pressure: 0.3 MPa(abs). These conditions were determined assuming insulation degradation in 30 years.

The present HTS cable has a superconducting shield layer in which, taking advantage of perfect diamagnetism specific to superconductivity, a shield current having a phase opposite to that of the conduction current flows thus shielding the magnetic field from leaking to the outside. As shown in Figure 14, the shield current was 980 A at a conduction current of 1000 A in the conductor layer, confirming also the performance of a cable which is low in magnetic field leakage.

After the one-month loading test, a withstand voltage

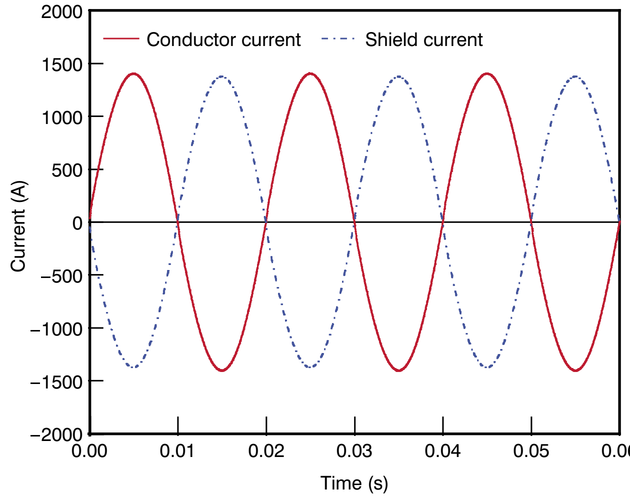



**Figure 14 Current waveforms of the 500-m HTS cable.**

test at 95 kVrms was carried out, confirming no occurrence of partial discharge. Thus, it was confirmed that there was no degradation in terms of electric insulation performance.

### 7.4 Results of Load Fluctuation Test [3)]

In this test, the current was made to fluctuate simulating daily load fluctuations in an actual electric power system, and the tracking behavior of the cooling system was investigated. Although certain amount of overshoot was observed, the system stabilized in about 3 hr.

### 7.5 Results of Limiting and Overloading Test [3)]

In this test, in order to evaluate the time limitation of continuous loading test, refrigerators were stopped in simulation of refrigerator malfunction, while continuing the rated loading test. The test was conducted while monitoring such system indicators as temperature, pressure and occurrence of partial discharge, and it was found that the pressure reached its limitation in 3 hr 30 min under the conditions of 73 K for the averaged liquid nitrogen temperature at the initial stage and 30 ℓ/min for the liquid nitrogen flow rate. This is satisfactory from the standpoint of system operation because a refrigerator malfunction can be settled with no hassles after interrupting power transmission over the cable.

In addition, additional tests were conducted including refrigerator stop test assuming refrigerator malfunction, cooling system stop test assuming refrigerator and pump malfunction, overcurrent test whereby a 130-% $I_c$ was applied for 1 hr, and overvolatage test assuming an abnormal voltage of 150 kV.

Critical current was measured after each test, and no degradation was found.

### 7.6 Cable Removal and Residual Performance Test

Cable specimens 6 m long were taken from the offset section, U bend section, 10m-high rising and falling section, underground section, and cable end section that underwent bending, and the specimens were subjected, in addition to six comparison specimens each 6 m in length taken from the straight section, to critical current measurement and visual inspection. As a result, virtually no degradation in the critical current was found for the HTS conductor, while local degradations were seen in the HTS shield. Although the degree of degradation was within a practically allowable range of about 5 %, this is something that awaits further investigation. Results of disassembly investigation confirmed that there was no damage in the HTS tapes.

## 8. CONCLUSION

The HTS cable withstood all the items of this field test without being damaged. As the result, it has been confirmed that the cable is sound over its entire length and that owing to its high reliability the cable has withstood various tests including the one for limiting and overloading performance. Furthermore, important achievements have been accomplished through this series of tests, which obviously contribute to practical applications of the HTS cable in terms of design, testing, laying, and operation.

Development of the HTS cable is underway in U.S., Korea, China, etc. It is thought to be of great significance that, ahead of these development programs, we were able to obtain various data intended for practical applications of the HTS cable.

Incidentally, unprecedented numbers of typhoons landed on Japan during the period of this test including three big ones that directly hit the test premises. Although the HTS cable was exposed to strong wind and rain at that time, the cable survived the typhoons allowing us to continue the test. This is thought to be a proof of the robustness of the cable.

## ACKNOWLEDGEMENT

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