Japan's First Live Power Transmission Using 3-in-One Superconducting Cable (High-Temperature Superconducting Cable Demonstration Project)

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Japan's first in-grid demonstration of a high-temperature superconducting (HTS) cable system has been started to evaluate its performance, safety and reliability. We developed the cable using the DI-BSCCO HTS wire, and repeated design changes and element testing to meet required specifications. The performance of the cable was confirmed in the preliminary test using a 30-m HTS cable system and it was then successfully installed in Tokyo Electric Power Company's Asahi Substation with associated systems. In October 2012, the cable system was connected to a live power grid and started its operation for a long-term demonstration test.

Keywords: high-temperature superconductors, power cables, in-grid demonstration

1. Introduction

The installation of high-voltage power transmission systems has been actively promoted in Japan for the 40 years since their full-fledged introduction in the 1970s, in concert with large-scale power source development. Although underground power cables are widely used to supply electric power to urban areas, cables installed during the years of steep economic growth have been in service for more than 30 years now, and are suffering functional deterioration due to the degradation of various cable components(1). Enormous civil engineering and construction expenditures are required to replace these aged underground power cables with cross-linked polyethylene insulated vinyl sheath cables (CV cables), and to install new conduit lines or cable tunnels to increase transmission capacity in preparation for future increases in electric power demand. As an economical solution to this problem, high temperature superconducting (HTS) cables are drawing attention since they can carry more power than conventional cables of the same diameter(2). This paper reports on the technological achievements obtained in the High-Temperature Superconducting Cable Demonstration Project, and on the progress of Japan's first in-grid power transmission test using a three-in-one (three-cores-in-one cryostat type) HTS cable.

2. History of Superconducting Cable Development

The history of HTS cable development at Sumitomo Electric Industries, Ltd. is shown in **Fig. 1**. In 1991, Sumitomo Electric launched a study to develop a high-temperature superconducting cable in collaboration with Tokyo Electric Power Company and, about 10 years later, carried out a practicability verification test of a 100 meter-long HTS cable(3). In 2004, Sumitomo Electric introduced a controlled overpressure (CT-OP) sintering technique to dramatically improve HTS wire performance(4). In 2006, Sumitomo Electric successfully installed the world's first in-grid HTS power cable in Albany, U.S.(5),(6).

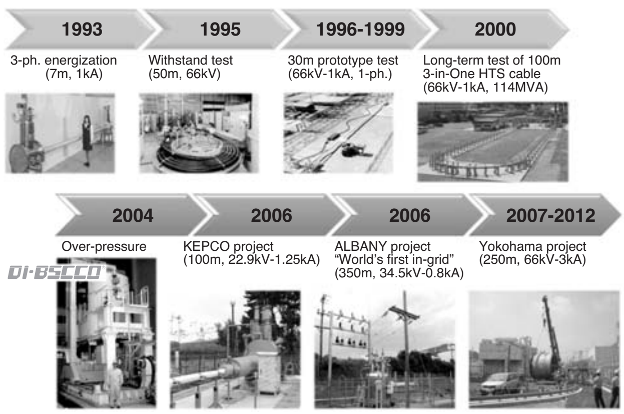

Fig. 1. Sumitomo Electric's History of HTS Cable Development

The HTS power transmission projects currently underway overseas are listed in **Table 1**(7)-(9). The principal objective of these projects is generally to assess the usefulness and performance of HTS cables. Based on the understanding that HTS power transmission technology is currently at a crucial stage for its practical use, the High-Temperature Superconducting Cable Demonstration Project was launched in Japan(10),(11). In this project, electric power companies, HTS cable manufacturers, and cooling system manufacturers have been cooperate in comprehensively evaluating the design, construction, operation and maintenance of the entire cable system including cable cooling systems.

Table 1. Major HTS Power Transmission Projects Abroad

Area	Project	Voltage (kV)	Current (kA)	Length (m)	Note
US	Albany	34.5	0.8	350	Finished
	Ohio	13.2	3	200	In operation
	LIPA	138	2.4	600	In operation
	Hydra	13.8	4	200	Planned
EU	Denmark	30	0.2	30	Finished
	Amsterdam	50	3	6,000	Planned
	Russia	20	1.4	200	Planned
	Essen	10	2.3	1,000	Planned
China	Yunnan	35	2	33.5	In operation
Korea	GENI	22.9	1.25	410	Planned
	Jeju	154	2.25	1,000	Planned

3. Outline of the High-Temperature Superconducting Cable Demonstration Project

In this project, Sumitomo Electric, Tokyo Electric Power Company and Mayekawa Mfg. Co., Ltd. (MYCOM) have been jointly conducting a demonstration test of an HTS cable system connected to a live grid, in order to evaluate the comprehensive performance, safety, reliability and other characteristics of the entire system.

3-1 System layout

The structure of this demonstration system is shown in **Fig. 2**. The power transmission line consists of a 240 m HTS cable with an intermediate joint. Each end of the cable is connected to a cooling system through a termination. The system layout is atypical in that the cable has been bent into a U-shape with a 5 m radius, due to spatial restrictions at the system construction site. The bend is useful for checking its effect on cable performance.

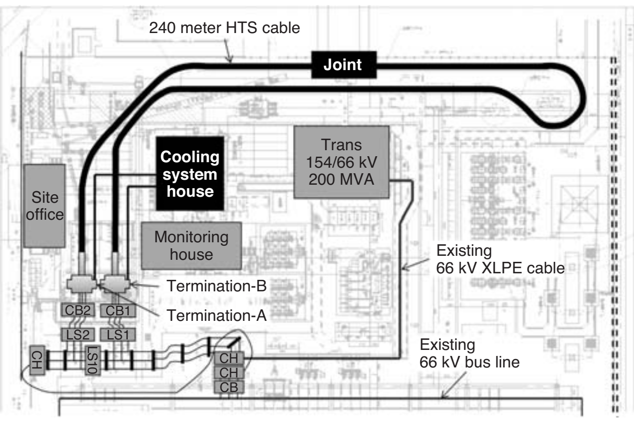

Fig. 2. Demonstration HTS Cable System

3-2 Required specifications

The specifications of the demonstration system are summarized in **Table 2**.

Table 2. Demonstration HTS Cable Specifications

Items	Specifications
Rated capacity	230 MVA (66 kV, 2 kA)
Maximum current	2.75 kA
AC loss	1 W/m/ph @2 kA
Withstand voltage	AC 90 kV for 3 hours, Imp ±385 kV 3 repetitions
Fault current	①No degradation against the F.C. of 31.5 kA, 2 sec. ②The rated capacity can be transmitted immediately after F.C. of 10 kA, 2 sec.

(1) Rated capacity

The rated capacity of the power transmission line is 200 MVA (66 kV, 1.75 kA). Since the maximum overload current reaches 2.63 kA, the HTS cable's rated capacity and continuous current were determined to be 230 MVA (66 kV, 2 kA) and 2.75 kA, respectively.

(2) AC loss characteristic

The AC loss characteristic of the HTS cable is required to be 1 W/m/ph@2kA or less. The final goal of the project is to achieve an AC loss of 1 W/m/ph@3kA or less. This level of AC loss is essential for reducing the HTS cable's transmission loss to 1/2 or less that of conventional cables when the efficiency of the cooling system is taken into account.

(3) Withstand voltage

The withstand voltage was determined in accordance with the Japanese standards for 66 kV class oil-filled (OF) cables (JEC-3401).

(4) Short-circuit withstand current

An analysis using the conventional power transmission system shows that (a) the system should be robust against a maximum load of "20 kA, 2 s" even when the system is not required to continue power transmission after an accident, and (b) the system should continue power transmission even when exposed to a maximum load of "10 kA, 2 s" in the cases where power transmission must be maintained[12]. For item (a), the short-circuit withstand current required of the transmission system was determined to be "31.5 kA, 2 s," which is equal to the maximum current specified for 66 kV class breakers.

3-3 Project schedule

The schedule of the demonstration project is shown in **Table 3**. Although the demonstration test was originally scheduled to commence in 2011 and last for six years, the starting date was postponed for one year because of the Great East Japan Earthquake.

(1) Component development (2007 - 2008)

An HTS cable, an intermediate joint, terminations and other system components were designed and fabricated.

Table 3. Demonstration Project Schedule

	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013
Cable system development	Design & Preliminary tests		Pre-performance test with 30m system				
In-grid demonstration	Analysis of grid condition Decision of test method		Wire and Cable manufacturing Cooling system manufacturing	Pre-performance test of cooling system	Install Construction	Completion test	In-grid operation

Their AC loss, short-circuit withstand current and other basic characteristics were measured; the results met the required specifications[13].

(2) Verification test (2009 - 2011)

The characteristics of a 30 meter-long HTS cable system, which consists of an HTS cable and related devices, were evaluated and verified[13],[14]. The performance of the cable cooling system as an independent unit was also tested[15] and confirmed to be suitable for cooling an live grid.

(3) Demonstration test (2012 - 2013)

An HTS cable system and cooling system were constructed and connected to each other, to measure their basic characteristics. They were then connected to a live grid for a long-term demonstration test, which commenced in October 2012.

4. Major Components of Cable Demonstration System

4-1 Superconducting cable

The structure of the 3-in-One HTS cable is shown in **Photo 1**. The cable core consists of a former made from stranded copper wires, an HTS conducting layer, an insulation layer, an HTS shielding layer, and a copper shielding layer—all of which are coaxially wound around the former. An adiabatic multilayer is provided between two stainless steel double-corrugated cryostats. The adiabatic layer is held at high vacuum to maximize thermal insulation[16].

(1) Increasing capacity and reducing transmission loss

To reduce the AC loss, low-loss DI-BSCCO wires (Type ACT)[17] were used in the 3rd and 4th conducting layers. Type ACT wires contain twisted HTS filaments, reducing AC loss to one third that of standard DI-BSCCO wires (Type HT) which are used in the 1st and 2nd conducting layers and shielding layers. The loading test showed that the AC loss of the designed cable was 0.8 W/m/phase at 2 kA[13], thereby meeting the required specification of 1 W/m/phase or less.

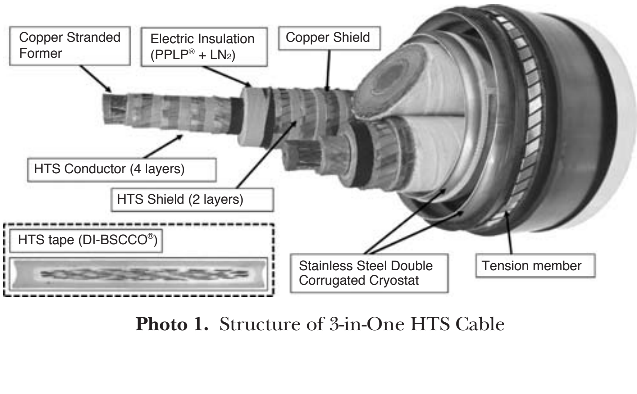

Photo 1. Structure of 3-in-One HTS Cable

(2) Short-circuit withstand current

To suppress temperature increases in the HTS layer, the cable was designed so that any short-circuit current would be diverted into the copper former and copper shield. Numerical simulation determined the minimum required cross-sectional area of copper, a sample of which was tested and met the required specification[13]. In the 30 m cable performance verification test, a test short-circuit current was also applied to the cable to confirm that the current did not affect cable performance[18].

(3) Electrical insulation

The electrical insulation layer is a composite construction of polypropylene laminated paper (PPLP) impregnated with liquid nitrogen. The 30 m cable performance verification test confirmed that a 6 mm-thick electrical insulation layer is sufficient to meet the required specification[19]. In practice, a 7 mm-thick electrical insulation layer was used, to take into account previous long-term load test results.

(4) Stranding three cores

When the three cores are cooled, they shrink 0.3% lengthwise and create a tension of about 3 t. To reduce cable size as much as possible, the terminations were designed to absorb the tension, in lieu of providing a core slackening mechanism in the cable[20]. Reinforcement of the HTS wires with a copper alloy dramatically increased wire mechanical strength[21] and made the above tension-absorbing mechanism practicable. A sample test confirmed that 3-in-One cable performance did not deteriorate even when the cable was cooled with both ends fixed.

(5) Tension member

The three cores and cryostat (corrugated heat-insulating pipes) are mechanically independent from each other. Since the allowable cryostat tension is low, special care must be taken during cable installation. To protect against tension, a tension member constructed of stainless steel tape was fitted to the outer surface of the cryostat[22]. Installation according to the predetermined layout was expected to generate a tension of 2 t, so after taking into account a tension decrease achieved with pushed-in ball rollers, the tension member was designed to bear a maximum tension of 2 t.

4-2 Intermediate joint

A conventional power transmission cable line is usually constructed by connecting the component cables in manholes. **Figure 3** shows the structure of an intermediate joint for a 3-in-One cable that can be used in a standard manhole (about 7 m in length) for a 66 kV class power transmission line. Unlike conventional power transmission cables, HTS cables are easily accommodated in a manhole because they do not require preparation of an offset.

It has been confirmed that the intermediate joint meets the required specifications in **Table 2**(13). It has also been confirmed that the joint would continue to perform as designed even if the cable were subjected to a tension of 4 t, well in excess of the 3 t that will be produced in the cable during cooling, and even if it were subjected to a compressive force of 0.5 t.

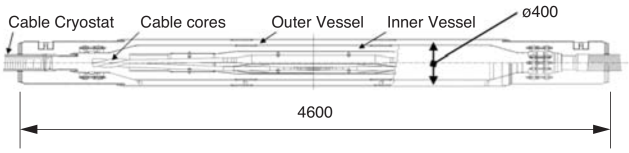

Fig. 3. Structure of 3-in-One Intermediate Joint

4-3 Terminal joint

The structure of one of the terminations for the 3-in-One HTS cable is shown in **Fig. 4**. The cable core is secured to the vessel body through an FRP fixing jig, while the high-voltage portion is brought out to the normal temperature portion through a current lead in the bushing. A B1452 insulator (66 kV class), which has higher electric insulation characteristics than commonly used insulators, was used to protect the joint from brine damage.

It has been confirmed that the terminations meet the required specifications in **Table 2**(13) and also have sufficient mechanical strength to withstand the short-circuit current and electromagnetic force that will be produced in the area outside the cable portion, where there is no shielding layer.

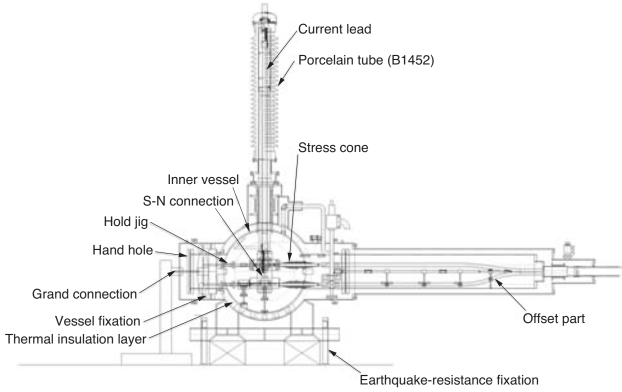

Fig. 4. Structure of Termination for 3-in-One Cable

5. 30 m Cable Verification Test

A performance verification system for the 30 m HTS cable was created by assembling the cable and devices that had been confirmed as meeting the required specifications. The structure of this verification system is shown in **Photo 2**. The verification system included a 90-degree bend with a radius of 5 m, an intermediate joint in the middle of the cable and terminations at each end of the cable. The intermediate joint was assembled in a space that simulated a 7 m long manhole. The cable system was connected to a cooling system (consisting of two 1 kW refrigerators and related equipment). The verification results are shown in **Table 4**(19).

(1) First phase (rated performance confirmation test)

The cable system met all criteria in the critical current (Ic) measurement test, rated current test, withstand voltage

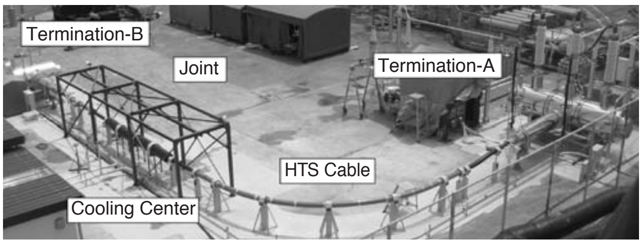

Photo 2. 30 m Cable Verification System

Table 4. Verification Test Results

Test items		Results
Pressurized test		No leakage up to 0.6 MPaG at RT
Current tests	Ic measurement (conductor)	5.4 kA at 77 K, As designed in consideration of magnetic field
	Current loading test	Nominal current of 2 kA for 8 hours, over-current of 2.75 kA for 8 hours, successful
Voltage tests	AC withstand voltage test	AC 76 kV for 10 min, successful
	DC withstand voltage test	DC 152 kV for 10 min, successful
Long term voltage and loading test		At AC 51 kV, and 2kA with 8 hours on and 16 hours off, for 1 month, successful
Thermal cycle test between RT and LN2 temperature		No degradation of Ic, current or voltage performance in 5 repeated thermal cycles
Short-circuit current test		No degradation of Ic after 10 kA for 18 seconds

test and other tests. The system was then subjected to a 30-day long-term current test (at a voltage corresponding to that in an accelerated 30-year service test) and satisfied all criteria(19).

(2) Second phase (thermal cycle test)

After the cable system was heated and cooled cyclically, its electrical, mechanical and thermal characteristics were measured. The results showed that the system characteristics would not change even after exposure to thermal shock.

(3) Third to fifth phases (marginal performance confirmation test)

Over-current testing confirmed that the cable system can steadily carry a current of 2.75 kA. A short-circuit current simulation test has also verified that the system will not fail and that the cooling system will continue working without trouble even if they are exposed to an over-current equivalent to "20 kA, 2 s" or more(18). Under a joint project with the National Institute of Advanced Industrial Science and Technology (AIST), a transient numerical analysis code is developed by reflecting the above test results(23). This analysis code will help simulate the temperature and pressure change in a long HTS cable when subjected to a short-circuit current.

(4) Residual performance test

After completion of all tests, the cable system was disassembled to check system integrity and measure cable critical current and withstand voltage characteristics. The results confirmed that the cable system maintained its functional integrity.

6. Construction of Power Transmission Line

6-1 Manufacturing and shipping inspection of cable

A 270 m demonstration cable was manufactured using DI-BSCCO wires approximately 100 km long. This cable passed all shipping tests (see **Table 5**). The cable was then cut into two segments (78 m and 160 m long) and the cryostats were thoroughly vacuumed and filled with nitrogen gas before shipment(24).

Table 5. Shipping Test Results for Demonstration Cables

Test items	Results	Comments
Critical current measurement at 77 K	Conductor: 6.9 kA Shield: 7.3 kA	As designed
AC loss measurement	0.9 W/m/phase at 2kA, 50Hz	As designed
Cable bending test	No *Ic* degradation with 2.7 mø bending	2.7 m < 18 *D* (*D*: cable dia.)
Withstand voltage tests	No breakdown and no PD signal at AC 90 kV for 3 hours No breakdown at Imp ±385 kV, 3 repetitions	Refer to Japanese standard (JEC 3401, 2006)
Cable pulling and contracting tests	No *Ic* degradation at 5 tons tension and 0.5 tons compressive force	3 tons corresponds to 0.3 % strain

6-2 Laying cables

The two cables were respectively drawn into their conduit pipes on the terminal A and B sides through the intermediate joint space. **Figure 5** shows how the B-side cable's tension fluctuated as it was drawn into its conduit pipe. The B-side cable is longer and requires more bends than the cable on the A side. The maximum measured cable tension was 1.3 t instead of the 2 t estimated in the design stage, verifying that this tension was within the design tolerance of the cable tension members(22).

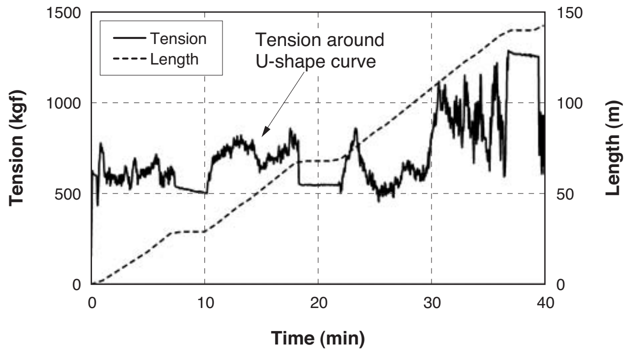

Fig. 5. Cable Tension Fluctuation during Drawing into Conduit Pipe on Terminal B Side

6-3 Connection of intermediate and terminal joints to cable

In the same manner as for conventional power transmission cables, the length of each HTS cable was adjusted (by cutting) and connected to the related devices on the construction site. The vacuum layer of each cryostat was evacuated again during equipment assembly. The assembled joint and terminations are shown in **Photos 3 and 4**, respectively.

6-4 Assembling the cooling system

A schematic diagram of the cooling system is shown in **Fig. 6**, and the installed system is shown in **Photo 5**. The cooling system is composed of six 1 kW Stirling-type refrigerators, two circulating pumps, a reservoir tank and other apparatus. The six refrigerators were arranged in three rows with two units in each, while the circulating pumps were placed in parallel(25). Using this layout, we could evaluate the advantages and disadvantages of serial/parallel

Photo 3. Intermediate Joint

Photo 4. Terminations

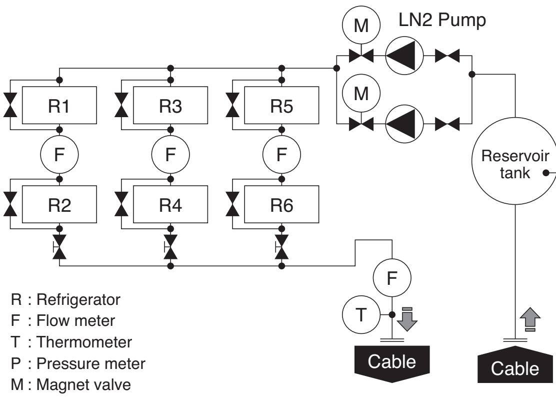

Fig. 6. Schematic Diagram of Cooling System

Photo 5. Cooling System after Installation

arrangement of the refrigerators and circulating pumps, as well as their maintainability and troubleshooting procedures while the cable operation is active. The cooling system was partly assembled in MYCOM's factory in order to verify its performance(15), and it was then disassembled for shipping purposes and reassembled at the Asahi substation.

7. System Qualification Test before Demonstration Operation

After installation of the HTS cable system and cooling system at the demonstration site, but before connecting the demonstration system to a live grid, the system was subjected to a qualification test, whose items are shown in **Table 6**. The qualification test verified that the characteristics and performance of the entire demonstration system met the required specifications.

Table 6. Test Items for Qualification before Demonstrative Operation

Validation item		Description
Validation of system function	Initial cooling character-istics	Validation of initial cooling of cable itself Validation of regenerative cooling starting method
	Cable character-istic	Critical current measurement DC withstand voltage test Heat loss measurement Validation of cyclic cooling
	Cooling system character-istics	Actual measurement of refrigerator's refrigeration capacity Actual measurement of circulating pump characteristics Multiple unit control test
Operation and con-trollability	Temperature and pressure control	Temperature control characteristics test Pressure control characteristics test
	Monitoring	Construction and validation of remote monitoring system
Reliability	Switching opera-tion to spare equipment	Validation of automatic switching from faulty equipment to spare equipment
	Stable operation	Confirmation of prolonged stable operation
Maintain-ability	Maintenance method	Validation of method for maintaining refrigerators, pumps and other apparatus without stopping them

7-1 Initial cooling

(1) Initial cooling method

To minimize the time needed to accomplish initial cooling of the total system, the cable system was cooled separately from the rest of the cooling system in accordance with the following procedures. The change in cable temperature distribution is shown in **Fig. 7**. Only about 3 days were required to carry out the procedures described above, indicating that we had successfully established an effective technique for rapidly and steadily cooling the cable.

(a) Cooling the entire cable system by filling it with nitrogen gas at -100°C and -150°C through terminal A, while monitoring the temperature and pressure of each portion and the cable load at both ends.

(b) Feeding liquid nitrogen into the cable system after the temperature gradient in the system had saturated sufficiently.

(c) Connecting the cable system and cooling system after the respective pressures in both systems had equalized,

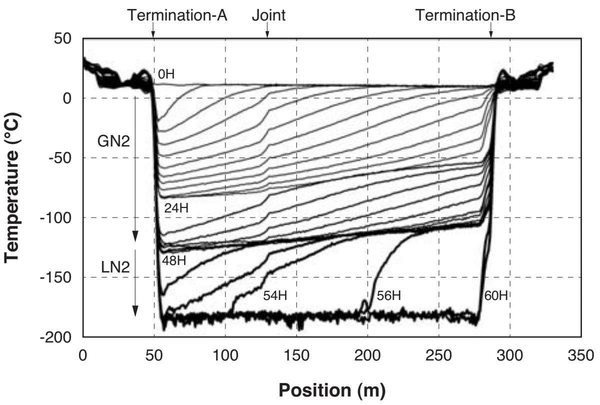

Fig. 7. Cable Temperatures During Initial Cooling, by Time and Position

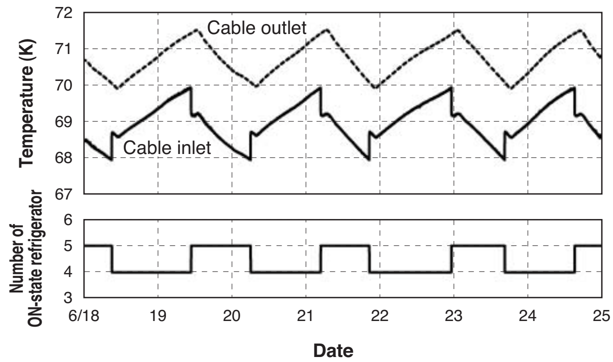

Fig. 8. Temperature Control Test Result

then sequentially starting the circulating pumps and refrigerators in order to shift to the stationary cooling mode.

(2) Load generated by cooling cable system

The load generated in the terminations as a result of cooling the HTS cable system was 3 to 4 t. This was almost equal to the estimated load of 3.5 t (as determined by assuming that the 3-in-One cable and inner cryostat pipe would shrink 0.3% when cooled). In the critical current measurement (described later), the soundness of HTS cable characteristics was also confirmed, verifying the practicability of the method for cooling a non-slackened three-cores-in-one HTS cable with both ends fixed. Through a series of such tests and measurements, we have established a technique for selecting a slackened or non-slackened three-cores-in-one cable according to the use of the cable and the conditions required of the power transmission line.

(3) Checking the impregnation of liquid nitrogen into the insulation layer

In the cable cooling process, electrostatic capacitance C and dielectric loss tangent ($tan\ \delta$) of the cable were measured to observe the status of liquid nitrogen impregnation into the PPLP insulation layer. The electrostatic capacitance decreased to the minimum value as the temperature decreased, finally reaching a constant value of 0.8 μF/km (estimated value: 0.78 μF/km). This verified that liquid nitrogen was impregnated into the PPLP insulation layer. Dielectric loss tangent ($tan\ \delta$) increased to the maximum value as the cable was cooled, finally reaching a constant value of 0.078%.

7-2 Cooling system control test

(1) Temperature control test

In this test, the refrigerators were ON/OFF operated to check if they could control the cable system inlet temperature to 69 ± 1 K. The test results, shown in **Fig. 8**, confirm that the necessary number of refrigerators was used as needed to control the system inlet temperature to within the required range.

(2) Pressure control test

The cooling system is equipped with a spontaneous pressurizer as its main pressurization system. This pressurizer generates pressure by evaporating liquid nitrogen, stored in the reservoir, using intrusion heat. The cooling system is also equipped with a heater-pressurizer as an auxiliary pressurization system, in which the liquid nitrogen is heated by a heater installed in the reservoir. A pressure control test was carried out by artificially reducing the pressure. The results showed that the cooling system automatically recovered the set pressure and subsequently kept the pressure stable.

(3) Maintainability verification

The effectiveness of the method for replacing faulty refrigerators and circulating pumps with spares, without suspending the regenerative cooling process, was checked. Results confirmed that replacement would not affect the pressure and flow rate of liquid nitrogen, and that only a period of about two days was needed to replace the equipment and heat/cool it before/after replacement.

After confirming that the cable system could be cooled continuously and stably without disconnecting the cable system from the cooling system, we carried out various cable characteristics confirmation tests.

7-3 Thermal loss measurement test (no-load test)

Since the cable system was laid with a U-shaped bend and various other bends, it was expected that the lateral pressure attributable to bending the cable and the tension attributable to non-slackened 3-in-One cable construction would facilitate heat intrusion into the cryostat. In most power transmission lines, in which the cables are laid linearly, the increase in the thermal loss is negligible. For this cable demonstration system, however, we checked the increased thermal loss in the cable's curved sections for its effect on the performance of the entire cable system.

The estimated thermal loss of the entire system, as calculated from the correlation between lateral pressure and thermal loss, both of which were determined from a cryostat sample test, was 2.2 kW. This load was almost equal to the actual thermal loss of 2.4 kW, as determined from the temperature difference between system inlet and outlet. Increased thermal loss in the cable's curved sections may pose a problem in future HTS power transmission systems, depending on the routing of the cables.

7-4 Critical current measurement

The critical current (Ic) characteristics were measured to check the soundness of the HTS conductor layer.

(1) Measuring method

When dealing with a long-distance power transmission line, it is difficult to carry electric current by simply connecting a DC power source to both ends of a single cable core. Therefore, in this project we studied a "go-and-return current method" – bearing in mind the practical use of HTS cable systems in the future(26),(27). The HTS conductor layers of two of the three cores (phases W and R in **Fig. 8**) were used to carry current in both directions, as shown in **Fig. 9**.

(2) Estimated waveform

When an electric current is carried on two conductors in different directions, a shielding current (dotted arrow in **Fig. 9**) is induced in the corresponding HTS shield layers which are short-circuited inside both terminations. This shielding current flows in the opposite direction to that of the conductor layer current (solid arrow in **Fig. 9**). Since the induction rate of the shielding current is smaller than it would be when an AC current is carried, a magnetic field leaks from each core. As a result, the measured Ic value becomes smaller than the sum of the Ic values of the HTS wires being used. We carried out a transient electro-magnetic simulation using the Ic values and Ic-B characteristics of the DI-BSCCO wires. The sum of the Ic values of the DI-BSCCO wires was 6.8 kA, while the estimated Ic value of the cable was 6.5 kA. The estimated I-V waveform of the cable is indicated by a dotted line in **Fig. 10**.

(3) Measurement result

Figure 10 also shows the measured I-V waveforms of three phases when the mean cable temperature was 77.3 K. The Ic values of three phases were equal to 6.4 kA. This value was very close to the estimated value, verifying the soundness of the HTS conductor layers. We conducted a total of three cooling tests (with heat cycles), including this measurement test, and confirmed that the cable system was capable of reliably maintaining its performance. As a result of this testing, we have established an Ic measuring technique that can now be used for long-distance HTS cable when it is put to practical use in the future.

7-5 DC Withstand voltage test

A DC withstand voltage test was carried out to check insulating performance over the whole length of the cable. The test condition was set to 151.8 kV (= max. grid voltage of 69 kV × tolerance of 1.1 × 2) for 10 minutes, in accordance with Article 14 of the Interpretation of Technical Standards for Electrical Equipment. This test was carried out during every cooling test; the results were acceptable.

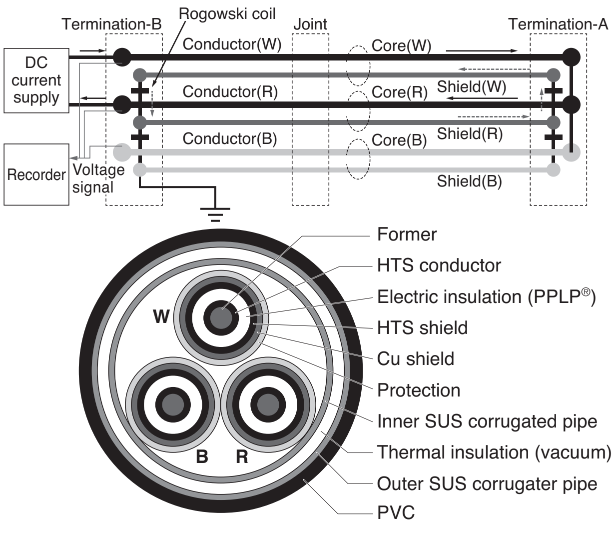

Fig. 9. Critical Current Measuring Circuit

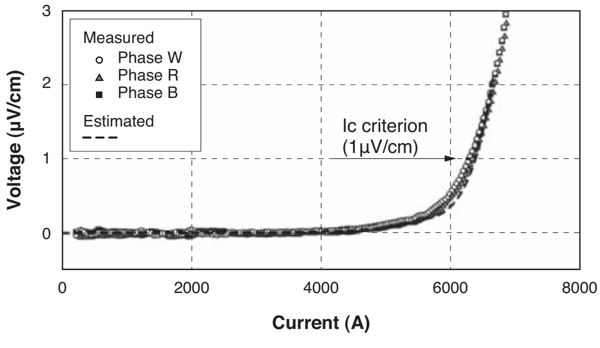

Fig. 10. Critical Current Measurement Result

8. Operational Testing

Cable system performance was tested before commencing operation. The results confirmed that all specification requirements had been met. After successfully completing inspection of the cable system, it was connected to a live power grid at 3:22 p.m. on October 29, 2012, becoming the first of its type in Japan. That was a historical moment, 100 years after the discovery of superconductivity in 1911 and 25 years after the discovery of a bismuth-based high-temperature superconductor in 1988.

System operation has now shifted to the unattended mode and its operation status can be monitored remotely. The one-month operation status of the system is shown in **Fig. 9**, and its daily status can be seen at http://global-sei.com/super/cable_e/ingridj.html. The system will be subjected to a long-term transmission test lasting for at least one year. During this test, the system will be checked for its reliability and stability of operation and optimal main-

Photo 6. Ceremony at the Completion of the Demonstration System (October 29, 2012)

tenance procedures will be established. The test will also clarify problems to be solved before putting HTS cable systems into practical use in the future.

9. Conclusion

HTS cable systems are expected to be useful replacements for existing large-capacity transmission cables that will increase the capacity of conventional transmission systems. The High-Temperature Superconducting Cable Demonstration Project was launched to put HTS technology into practical use while further advancing the technology. To date, we have actively promoted the development of elementary technologies essential for realizing HTS cable systems that will ensure the performance necessary for live grids. In the process, we developed an HTS cable and verified its performance in a 30 m cable system verification test. Following that success, we manufactured the HTS cable for a demonstration project, tested the performance of the cable cooling system as an independent unit, and constructed an HTS power transmission system using these components. After completion inspection of the transmission system on the construction site, the system was connected to a live grid on October 29, 2012 for its demonstration test in a practical grid.

HTS cable components should be further rationalized in terms of performance, size and cost. This demonstration project is of great significance in verifying that HTS cable systems can be used in existing electric power systems and in evaluating the operation/maintenance techniques required for live transmission lines. We will continue working to expedite the practical use of HTS power transmission technology and thereby contribute to realizing an "environment/energy-conscious society."

Part of this work is being promoted jointly with the New Energy and Industrial Technology Development Organization (NEDO) as the "High-Temperature Superconducting Cable Demonstration Project."

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