In-Grid Demonstration of Long-length “3-in-One” HTS Cable (Albany Project)

Hiroyasu YUMURA*, Yuichi ASHIBE, Masayoshi OHYA, Michihiko WATANABE,
Hiroshi TAKIGAWA, Takato MASUDA, Masayuki HIROSE, Ken YATSUKA, Hideki ITOH
and Ryosuke HATA

High-temperature superconducting (HTS) cable, characterized by its high current density and low transmission loss, is a promising compact power cable with large transmission capacity, and has a variety of environmental advantages such as energy saving, resource conservation and EMI-free. Due to these advantages, HTS cable demonstration projects are being promoted around the world. Since the discovery of HTS materials, Sumitomo Electric has been conducting the development of HTS BSCCO wires and three-cores-in-one-cryostat-type HTS cables. Recently, Sumitomo Electric greatly improved the performance of BSCCO wires and developed a new wire named DI-BSCCO. This improvement is accelerating the development of HTS applications, especially HTS cables.
The Albany Project is one of the demonstration projects for HTS cable in the United States funded by the Department of Energy. In Phase I of this project that took place between July 2006 and May 2007, an HTS cable system using the “3-in-One” HTS cable manufactured by Sumitomo Electric operated successful over a practically used underground power grid in unattended conditions for the first time in the world. In Phase II that had started in January 2008, after the world’s first replacement of HTS cable to 2G (YBCO) cable, the HTS cable system was re-energized and restarted operating in a live utility network. In the Albany Project, the HTS cable system demonstrated more than 12 months of reliable operation on a live grid during Phases I and II. This paper describes the details of the in-grid demonstration results of the HTS cable system in the Albany Project.

1. Introduction

High-temperature superconducting (HTS) cables achieve large-capacity, low-loss power transmission in a compact size and are expected to offer not only economical advantages but also environmental advantages like energy conservation, resource conservation, and electromagnetic interference (EMI)-free performance.(1) Due to these advantages, HTS cable demonstration projects and practical application studies are being promoted around the world.

Sumitomo Electric Industries, Ltd. has been pursuing the development of HTS wires since 1986 when HTS materials were first discovered. Since 1991, the Company has been working to develop three cores-in-one cryostat type (commercialized under the trade name “3-in-One ”) HTS cables.(2), (3) It has promoted the development of HTS cables and other HTS applications using its high-performance bismuth-based HTS wire (commercialized under the trade name “DI-BSCCO”) that is manufactured using a proprietarily developed sintering process named the “CT-OP” process.(4), (5) Sumitomo Electric’s “3-in-One” cable has become the first commercial HTS cable to successfully achieve in-grid operation through a practically used underground power grid in the Albany Project, one of the HTS cable demonstration projects conducted by the United States Department of Energy (DOE).

In Phase I of this project, an HTS cable system consisting of two DI-BSCCO cables was energized on July 20, 2006 and began long-term in-grid operation.(6) From that time, a long-term demonstration progressed satisfactorily without human intervention and was completed on May 1, 2007. The HTS cable system achieved a total of nearly 6,800 hours of electricity transmission during Phase I.

In Phase II, a new HTS cable with YBCO coated conductors was manufactured and replaced one of the DI-BSCCO HTS cables. The world’s first HTS cable replacement was completed successfully. The cable system was re-energized and put back in service on January 8, 2008. Then, the in-grid operation progressed satisfactorily and was completed in the end of April 2008. In the Albany Project, during Phases I and II, the HTS cable system demonstrated more than 12 months of reliable operation on the live grid. This paper summarizes the results of the Albany Project’s long-term power transmission demonstration with an HTS cable system.

2. Albany Project overview

In the United States, the vulnerability of power grid has been put as a major problem – for example, it was pointed out as a factor in the massive blackout that occurred in New York in August 2003 – and strengthening the Country’s power grid is considered an urgent issue. In the Energy Policy Act enacted in August 2005, the upgrading of power transmission grid was identified as an issue of vital national importance. One of the solutions for this problem is the “Grid 2030” initiative, to construct a strong nationwide power transmission grid made up of HTS cables by 2030.(7)

As part of this planning, HTS cable demonstration projects have been conducted on the actual power grids, funded by the U.S. DOE. The Albany Project in which Sumitomo Electric participated was one of these projects. The project was conducted on an actual power grid extending approximately 3 kilometers between two substations (Menands and Riverside) in the National Grid electric utility system at Albany, the capital of New York State. In the project, the two HTS cables were applied to a 350-meter section in this power network.(8)

2-1 System specifications/configuration

Table 1 and **Fig. 1** show the specifications and a schematic view of the HTS cable system for the Albany Project. The rated voltage, current and transmission capability of this power network are 34.5 kV, 800 A, and 48 MVA, respectively. The two Sumitomo Electric "3-in-One" HTS cables, each 320 meters and 30 meters, were installed in a 350-meter-long underground conduit having an inner diameter of 6 inches (152 mm). The world's first HTS cable-to-cable joint was placed inside a vault, and both ends of the 350-meter-long cable created by jointing two HTS cables were connected to overhead power transmission lines. The cables, a joint and the terminations were designed in conformance with AEIC standard C55-94, IEEE standard 404 and IEEE standard 48, respectively.

Table 1. HTS Cable System Specifications

Items	Specifications
Cable structure	Three cores-in-one cryostat ("3-in-One")
Voltage and current	34.5 kV, 800 Arms
Cable length	350 m (320 m + 30 m)
Accessories	Cable termination boxes (both ends) Cable-to-cable joint (assembled in a vault) Liquid nitrogen return pipe (350m)
Laying conditions	Underground conduit (inner diameter: 6 inches)
Maximum fault current condition	23 kA, 38 cycles

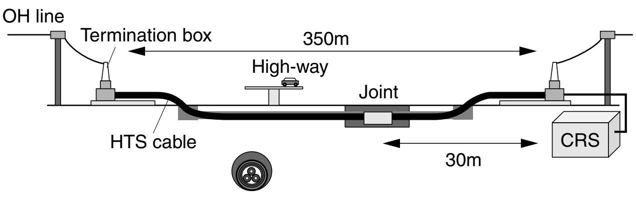


Fig. 1. Schematic View of HTS Cable System

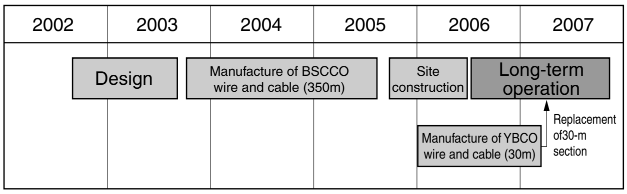
2-2 Project members

SuperPower, Inc. is the prime contractor for the project. National Grid, the Linde Group (formerly the BOC Group) and Sumitomo Electric are participating as partners. As the host utility company, National Grid provided the demonstration network. Linde provided the cooling and monitoring systems. Sumitomo Electric was in charge of design, manufacture, construction and operation of the HTS cable system.

2-3 Project schedule

Table 2 shows the schedule for the project. In Phase I, the HTS cable system consisting of DI-BSCCO cables was installed and conducted long-term operation in the live grid. In Phase II, a 30-meter-long section of the cable system was replaced by a new cable with YBCO coated conductors, and the cable system went back in service. In the project, more than 12 months of long-term operation was planned during Phases I and II.

Table 2. Albany Project Schedule



3. Albany Project - Phase I

3-1 "3-in-One" DI-BSCCO cable (6)

The structure of the "3-in-One" HTS cable applied to this project is shown in **Photo 1**. Three cable cores are housed in a cable cryostat. This structure needs less cable laying space and has lower heat invasion compared to using three single-core HTS cables that require separate cryostat for each core. Moreover, the "3-in-One" cable design can also prevent the thermal contraction of cores that is a problem experienced by HTS cables during the cable cooling process.

Table 3 shows the specifications of the DI-BSCCO cable used in Phase I. A 320-meter cable and a 30-meter cable were manufactured using the DI-BSCCO wires having high levels of critical current, mechanical properties, uniformity over long lengths and anti-ballooning performance.(9) Polypropylene laminated paper (commercialized under the name "PPLP") was used as the electrical insulation material due to its good properties at low temperatures such as high insulation strength and low

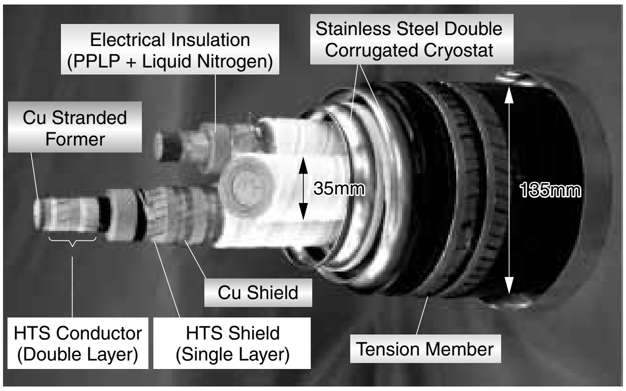


Photo 1. Three Cores-in-One-Cryostat Type HTS Cable Structure

Table 3. DI-BSCCO Cable Specifications

Items	Specifications
Former	Stranded copper wires with insulation
HTS conductor	Double layer of DI-BSCCO wires
Electrical insulation	PPLP (thickness: 4.5 mm)
HTS shield	Single layer of DI-BSCCO wires
Copper shield	Copper tapes
3-core stranding	Loosely-stranded 3-core structure
Thermal insulation layer (cable cryostat)	Co-axial stainless steal corrugated pipes with multi-layered thermal insulation materials
Protective outer sheath covering	Polyethylene/stainless steel tape tension member
Cable outer diameter	135 mm

dielectric loss. PPLP was immersed in liquid nitrogen to provide composite insulation. The DI-BSCCO wires were winded onto the electrical insulation layer of each core to form a shielding layer. The shielding layers of the three cores were shorted at the termination at the both ends in order to induce the shielding current that has almost the same magnitude as the conductor current in the opposite phase. As a result, perfect magnetic shielding can be achieved in each cable core, and the magnetic fields produced by other phases do not affect the HTS wires in each core. Naturally, the outside of the cable is free of EMI. In an AC power system, a fault current may flow for a brief period of time in the event of a short circuit accident.To accommodate fault currents, stranded copper wires were used as the conductor core material (former) and copper tapes were adopted to form a protective layer on the outside of the HTS shield. This design can prevent temperature rise by passing the momentary fault currents separately to the HTS wires and to the stranded copper wires or copper tapes.

The three cores are stranded loosely to create slack. This "loosely-stranded 3-core structure" can absorb a thermal contraction of 0.3 % produced by temperature change during the cool-down from room temperature to liquid nitrogen temperature (approximately -200 degrees Celsius).

To provide thermal insulation between the temperature outside the cable and the liquid nitrogen temperature inside the cable, the cable cryostat is made of a double-wall stainless-steel corrugated pipe with multi-layer thermal insulation, and the space between the two pipe walls is kept in a high vacuum state. This cable cryostat is characterized by high thermal insulation performance (low heat invasion performance). The result obtained from the evaluation of long-term vacuum performance of a 350-meter-class cable cryostat showed that the vacuum level was maintained at a level that heat invasion is small even after more than 100,000 hours since sealing. Therefore, the cable cryostat was evacuated and sealed at a factory while being maintained at an appropriate vacuum state.

The pulling tension on the 320-meter cable section could be estimated to be about 2 tons at a maximum. As this cable has a loosely-stranded 3-core structure, instead of pulling the cores, a tension member made of stainless steel tapes was attached to the outside of the cable cryostat to divide the pulling tension. The outer diameter of the cable is 135 mm and it can be laid into the 6-inches (152 mm) underground conduit.

The cable structure as described above provides the HTS cable with features such as low AC loss and EMI free. And it also accommodates the required current and voltage capacities, fault current condition and pulling tension.(10), (11)

Table 4 shows the results of the various shipping tests conducted after the completion of the DI-BSCCO cable manufacture. As the results of these tests, it was confirmed that the cable has good properties as designed and satisfies the required specifications. After successfully passing the shipping tests, the cable was shipped to the United States.

Table 4. Results of DI-BSCCO Cable Shipping Tests (Sample Tests)

Tests	Test conditions and acceptance values	Test results
Critical current measurement (conductor / shield)	Design value: 1.8 kA (77K, defined by 1 μV/cm criterion)	Same as design value (1.8 kA/each phase)
AC loss measurement	Design value: 0.7 W/m per phase (at 800 A, 60 Hz)	Same as design value (0.7 W/m per phase)
Cable bending test (18D, D = cable outer diameter)	Critical current after bending test Dismantling inspection after bending test	No Ic degradation No defect in HTS tapes and electrical insulation
Withstand voltage test (in accordance to AEIC standard)	AC: 69 kV for 10 minutes Imp.: ±200 kV (10 shots/each) DC: 100 kV for 5 minutes	Good Good Good

3-2 HTS cable system installation at Phase I

The route profile for the HTS cable installation has a 90-degree bend with a radius of 12 meters and the maximum difference in elevation is approximately 5 meters.(6) **Photo 2** shows the installation of the HTS cable. The method applied to install the HTS cable was the same as that commonly used for installing conventional cables. The cable drum was placed on a drum roller and the cable was pulled into the 6 inches (152 mm) underground conduit by a winch. The HTS cable was installed into the con-

Photo 2. HTS Cable Installation

duit very smoothly and the maximum tension was approximately 2 tons, which was almost the same as the tension value calculated in advance with a friction coefficient of 0.25.(6) Furthermore, after the cable installation was completed, it was confirmed that there was no abnormal elongation or external damage to the HTS cable, and there was no degradation in the degree of vacuum level of the cable cryostats. This successful cable installation demonstrated that the HTS cable could be installed using the same method and same equipment as those for conventional cables.

After the HTS cables were installed, the cable-to-cable joint was assembled in a vault (see **Photo 3**) and the HTS terminations were assembled at both ends of the jointed cable (see **Photo 4**).(6) After being assembled, the termination vessels were fixed to the ground.

Photo 3. HTS Cable-to-cable Joint in Underground Vault

Photo 4. HTS Termination

A cooling system and a monitoring system were set up by Linde concurrently with the installation of the HTS cable system. The cooling system has a back-up mode to follow in the event of an equipment failure or a power outage, thus ensuring reliability in actual operation.(12) The operating status of the HTS cable system is monitored 24 hours a day via the network system from the Remote Operation Center (ROC) at Linde. The operating status can also be monitored in real time from anywhere around the world via the Internet, so monitoring from Japan is also possible. In addition to the monitoring of the HTS cable system's operational status, the monitoring system also allows remote fine adjustment of temperature, pressure and other operating conditions of the cooling system. This system enables unattended operation of the HTS cable system.

3-3 Commissioning tests at Phase I (6)

Table 5 describes the commissioning tests and their results for confirming the operational performance of the HTS cable system. After the completion of the installation of the HTS cable system, a withstand pressure test was conducted for the entire cable system including the cooling system. The test was conducted in accordance with the ASME standard for pressure vessels in the United States. The test was conducted under a condition of 0.61 MPaG, which is 1.1 times the pressure setting for the safety valves used in the system (0.55 MPaG). The test results confirmed that the HTS cable system was satisfactory with respect to this test condition.

Table 5. Results for Commissioning Tests of HTS Cable System (Phase I)

Tests	Test Results
System withstand pressure test (in accordance to ASME standard)	0.61 MPaG: good
Initial cooling test	Maximum core tension: approximately 800 kg Vacuum level in each section: good (no leakage) Core behavior inside the joint: within the scope of assumption
Critical current measurement	2.3 kA (at 73 K), 2.8 kA (at 69 K)
Heat loss measurement (under no-load condition)	350-m cable section (including joint): 1.0 kW Entire cable system: 3.1 kW
Pressure drop measurement (flow rate: 50 L/min)	350-m cable section (including joint): 0.075 MPa
DC withstand voltage test (in accordance to AEIC standard)	100 kV, 5 minutes, each phase : good

In the initial cooling process, the maximum tension produced at both terminations was a total of approximately 800 kgf for the three cores. This is much lower than the tension produced when there is no provision for offsetting heat contraction (approximately 5,000 kgf), and the effectiveness of the "loosely stranded 3-core structure" is thereby reconfirmed. In addition, the vacuum level in each section including the cables and the joint was kept at a good level and the core behavior inside the joint was also confirmed to be within the normal range.

Figure 2 shows the results of the critical current (Ic) measurements conducted on the three phases of the HTS conductor at the average cable temperatures of 73 K and 69 K. The Ic values defined by a 1 μV/cm criterion were 2.3 kA at 73 K and 2.8 kA at 69 K for each of all three phases. These Ic values closely match the values estimated from the sample test results of 1.8 kA at 77 K and the critical current vs temperature characteristic of the DI-BSCCO wire as shown in **Fig. 3**. These results confirm that there were neither defects nor deteriorations in the HTS

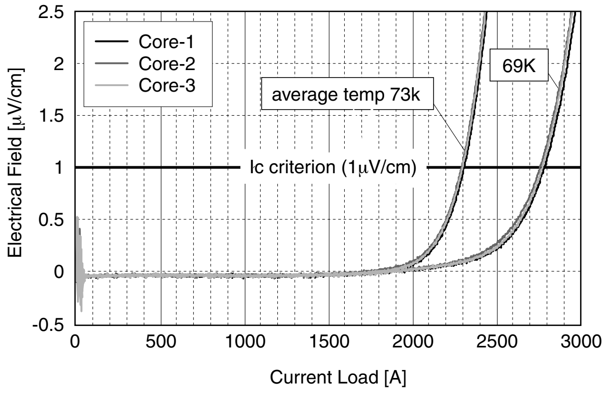


Fig. 2. Critical Current (Ic) Measurement Results for HTS Conductors (in Phase I)

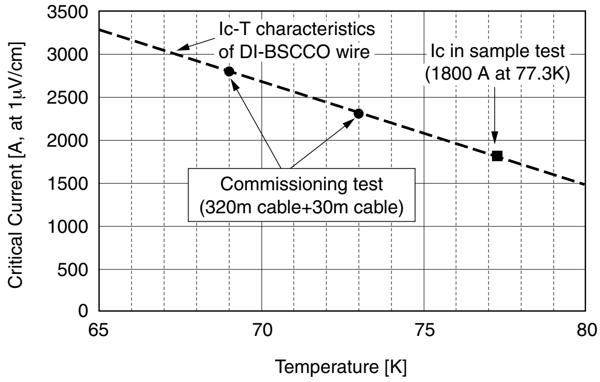


Fig. 3. Comparison between Measured and Calculated Ic Values

conductors throughout the processes of manufacture, transport, installation and cooling of the long HTS cable.

The heat invasion into the cable system in no-load condition was measured. The heat loss in the 350-meter HTS cable section (including the joint) was 1.0 kW and that in the entire HTS cable system including the terminations, the return pipe and the pipes connecting to the cooling system was 3.1 kW. These heat loss values are consistent with design values. The pressure drop in the 350-meter cable section under the condition of a liquid nitrogen flow rate of 50 L/minute was 0.075 MPa. This pressure drop value closely matches the design value of 0.07 MPa calculated using a duct friction coefficient of 0.08.

As the final test before energization, a DC withstand voltage test was conducted in accordance with the AEIC standard. This test is equivalent to the withstand voltage test of a 34.5 kV-class cable after site installation. A DC voltage of 100 kV was applied for 5 minutes to each phase and good results were obtained. With the completion of this test, the cable system successfully passed all of the commissioning tests.

3-4 Cable energization and long-term in-grid operation at Phase I

The good results obtained in the commissioning tests confirmed that the HTS cable system was constructed properly, demonstrated good performance and met the required specifications. In addition, the cooling system allows operation in the back-up mode in the event of a refrigerator failure, liquid nitrogen pump failure or electric power failure, thereby ensuring stability of cable temperature and pressure. In response to these favorable results, the cable system was connected to the actual power grid of National Grid on July 20, 2006. This was a historic moment when power transmission on an actual power grid by long HTS cables started. **Photo 5** shows the HTS cable system connected to the overhead power lines.

The operation of this cable system can be remotely monitored and controlled. Two weeks after the cable system was first energized, the cable system shifted from attended operation to unattended operation and continued to operate on the actual power grid while being remotely monitored. The long-term in-grid operation of the cable system progressed satisfactorily without human intervention since then, and completed on May 1, 2007. The results of the long-term in-grid operation at Phase I are summarized in **Table 6**. The temperature and power transmission values of the cable during the in-grid operation are shown in **Fig. 4**. The shutdown of the in-grid operation had occurred just once, due to the inflow of

Photo 5. HTS Cable System Connected to Overhead Power Lines

Table 6. Results of HTS Cable In-grid Demonstration (Phase I)

Items	Results	Notes
Peak load	> 500 Arms	–
Average load	~ 200 Arms	–
Hours of continuous operation	2,700 hrs	–
Total hours of operation	6,700 hrs	–
Number of outages	1	• Shut down by fault current (7 kA, 8 cycles)
Maintenance	Refrigerator maintenance	• A regularly-scheduled maintenance was performed while the cable is online. • The back-up system was deployed during maintenance.

fault current from a remote and unrelated substation into the HTS cable line via the grid. The waveform of the fault current is shown in **Fig. 5**. The maximum current value was 7 kA and it was cleared in 8 cycles when the first cable line protection system activated. This fault current inflow did not cause any major change in cable temperature. The backup power supply automatically activated during a power outage to keep the cooling system running, and the cable temperatures were thereby maintained. After that, the soundness of the HTS cable system was confirmed, and then the in-grid demonstration was immediately resumed.

During the long-term in-grid operation, the maintenance of the cooling system components such as refrigerators was performed at a regularly scheduled time with cable being online by deploying the back-up mode operation.

Throughout the long-term in-grid demonstration, the temperature and pressure in the cable system were maintained at highly stable levels by the cooling system. The cable system was never removed from service due to problems related to the HTS cables. The long-term in-grid operation was completed successfully on May 1, 2007 and the HTS cable system had completed electricity transmission over a total time of about 6,800 hours. On the average, throughout the long-term in-grid demonstration, the cable system provided 200 A to National Grid customers with a peak load of more than 500 A.

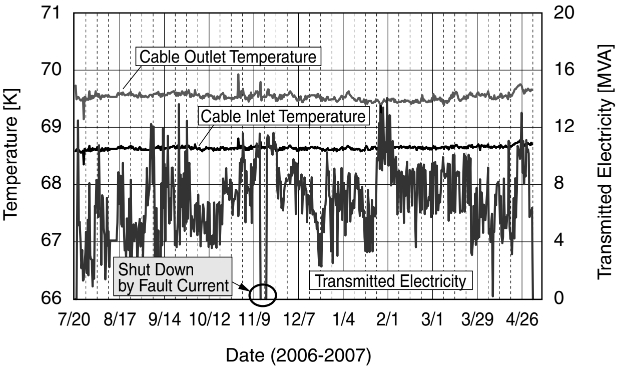


Fig. 4. Status of Long-term In-grid Operation (Phase I)

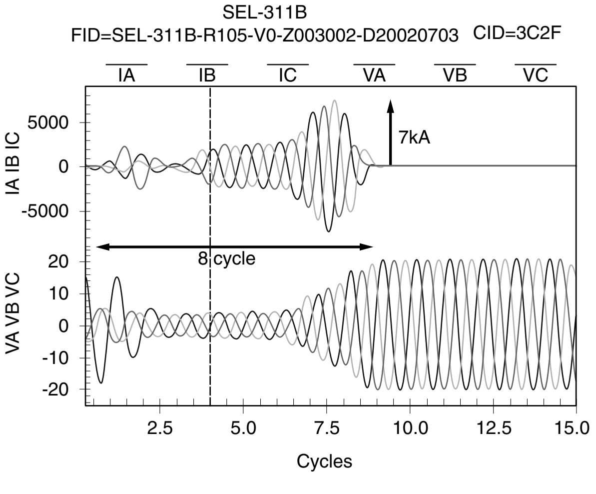


Fig. 5. Fault Current Flow into HTS Cable System

4. Albany Project - Phase II

4-1 30-meter YBCO "3-in-One" cable

(1) Cable structure

For Phase II of the Albany Project, a new 30-meter HTS cable with YBCO coated conductor tapes was manufactured. The structure of the YBCO coated conductor tape developed by SuperPower, Inc. is shown in **Fig. 6**.(13) It is composed of a YBCO HTS layer of approximately 1-μm thickness, a multi-layered intermediate layer and the silver and copper protective stabilizing layers on a Hastelloy substrate. The YBCO coated conductor tape has a dimension of 4 mm width and 0.1 mm thickness. The total amount of the YBCO coated conductor tapes used to manufacture the 30-meter HTS cable is 9.7 km and their average critical current is approximately 70 A.

The YBCO cable structure is shown in **Photo 6**. The YBCO cable has a compact "3-in-One" structure similar to the DI-BSCCO cable. The cable cores are composed of the same copper former as the DI-BSCCO cores, a 3-layer conductor, a PPLP dielectric layer of 4.5 mm thickness, a 2-layer shield and a copper tape layer. The dielectric layer thickness, copper tape layer cross-section area, and core outer diameter of the YBCO cores are the same as those of the DI-BSCCO cores.

(2) Manufacture of YBCO cable and shipping tests

The 30-meter YBCO cable was manufactured under

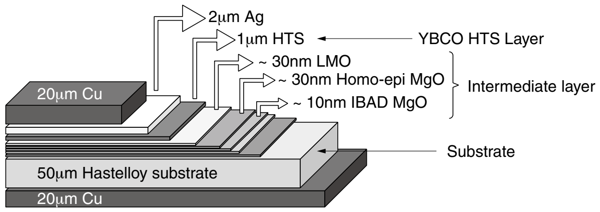


Fig. 6. YBCO Coated Conductor Structure

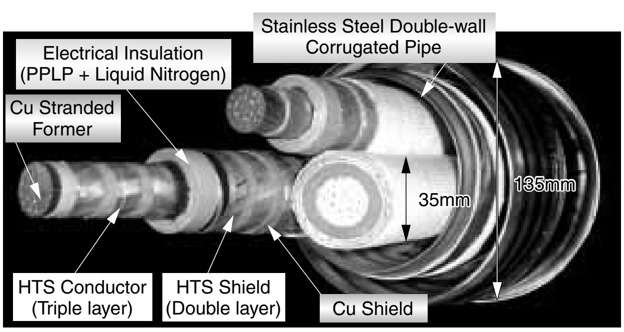


Photo 6. "3-in-One" YBCO Cable Structure

the same conditions to those for the DI-BSCCO cable. The results of the various shipping tests conducted after the completion of cable manufacture are shown in **Table 7**. Because the YBCO coated conductor tapes have lower Ic than the DI-BSCCO ones, the YBCO cores have a 3-layer conductor and a 2-layer shield, whereas the DI-BSCCO cores have a 2-layer conductor and a 1-layer shield. Therefore, the YBCO cores were designed to have higher Ic than the DI-BSCCO cores. The results of these tests confirmed that the YBCO cable demonstrated good properties as designed and satisfied the required specifications. After successfully passing the shipping tests, the cable was shipped to the United States for installation.

Table 7. Results of YBCO Cable Shipping Tests (Sample Tests)

Tests	Test conditions and acceptance values	Test results
Critical current measurement (conductor / shield)	Design: 2.7 ~ 2.8 kA (conductor) : 2.4 ~ 2.5 kA (shield) (77K, defined by 1μV/cm criterion)	Same as design value (Conductor: 2.7 kA, 2.8 kA, 2.7 kA) (Shield: 2.4 kA, 2.4 kA, 2.5 kA)
AC loss measurement	Design (trial test): 0.4 W/m per phase (at 800 A, 60 Hz)	Same as design value (0.34 W/m per phase)
Cable bending test (18D, D = cable outer diameter)	Critical current after bending test Dismantling inspection after bending test	No Ic degradation No defect in HTS tapes and electrical insulation
Withstand voltage test (in accordance to AEIC standard)	AC: 69 kV for 10 minutes Imp.: ±200 kV (10 shots/each) DC: 100 kV for 5 minutes	Good Good Good

4-2 Replacement of 30-meter section with YBCO cable

(1) Cable system warm-up

After the completion of the long-term in-grid demonstration in Phase I, the Megger test and the Ic measurement were conducted in order to check the soundness of the HTS cable cores. The result of these tests showed that the cables maintained good electrical insulation properties and exhibited no change in Ic values. After the soundness of the cables was confirmed, a warm-up of the cable system was conducted in order to replace the 30-meter cable for Phase II. In the warm-up process, liquid nitrogen was collected in the bulk storage tank of the cooling system, and then the cable system was warmed naturally. The entire cable system was warmed to ambient temperature in about three weeks. In the warm-up process, the vacuum level in each section did not indicate any leakage.

(2) HTS cable replacement

After the warm-up of the cable system, the joint and one of the two terminations were dismantled and the 30-meter DI-BSCCO cable was pulled out from the underground conduit. The YBCO cable was placed in the 30-meter section where the 30-meter DI-BSCCO cable was formerly installed. After the replacement of the 30-meter cable, the termination and the joint for connecting the YBCO and DI-BSCCO cores were reassembled.

4-3 Commissioning tests at Phase II

The results of the commissioning tests conducted on the HTS cable system before re-energization are shown in **Table 8**.

Table 8. Results for Commissioning Tests of HTS Cable System (Phase II)

Tests	Test Results
System withstand pressure test (in accordance to ASME standard)	0.61 MPaG: good
Initial cooling test	Maximum core tension: approximately 1,000 kg Vacuum level in each section: good (no leakage) Core behavior inside the joint: within the scope of assumption
Critical current measurement	2.3 kA (at 73 K), 2.8 kA (at 69 K)
Heat loss measurement (under no-load condition)	350-m cable section (including joint): 1.0 kW Entire cable system: 3.4 kW
DC withstand voltage test (in accordance to AEIC standard)	100 kV, 5 minutes, each phase: good

(1) System withstand pressure test

After the replacement of a 30-meter cable section and the reassembling of the cable system were completed, a withstand pressure test was conducted under a condition of 0.61 MPaG as was in Phase I. The test results proved the HTS cable system satisfactory under this test condition.

(2) Initial cooling test

The initial cooling of the HTS cable system was conducted by controlling the temperature in the lengthwise direction of the cable in the same manner as was in Phase I. **Figure 7** shows the temperature profiles obtained by an optical fiber in the cable during the initial cooling process.

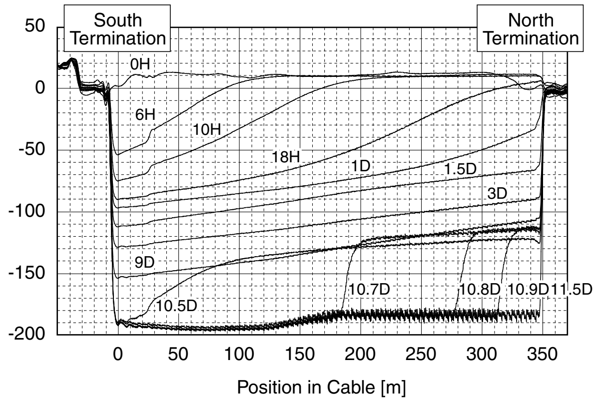


Fig. 7. Temperature Profile along Cable Length in Initial Cooling Process (Phase II)

The cable was cooled gradually for the entire length using nitrogen gas whose temperature was -100 degrees Celsius, and then the temperature of the nitrogen gas being fed into the cable was gradually lowered. When the temperature at the inlet of the cable was -150 degrees Celsius and the temperature gradient for the entire length of the cable had become sufficiently small, liquid nitrogen was then injected into the cable. The entire length of the cable was cooled to the liquid nitrogen temperature in about 12 days that was almost same period of time as that in Phase I. In the initial cooling process, the maximum tension produced at both terminations was a total of approximately 1,000 kgf for three cores. This is much lower than the tension produced when there is no provision for off-setting heat contraction (approximately 5,000 kgf), thus it was confirmed that the HTS cable maintains the "loosely stranded 3-core structure" even after the cable replacement. In addition, the vacuum level in each section showed no deterioration and the core behavior inside the joint was also confirmed to be within the normal range.

(3) Critical current measurement

After the initial cooling process was completed, critical current (Ic) measurement was conducted on each conductor made of the YBCO core and the DI-BSCCO core at the average cable temperatures of 73K and 69K, which are the same temperature condition as that in Phase I. Because the Ic value of the YBCO core is higher than that of the DI-BSCCO core, measured Ic value should be determined by the Ic value of the 320-meter DI-BSCCO cable. The measured Ic value was 2.3 kA at 73K and 2.8 kA at 69K for all three phases as shown in **Fig. 8**. These Ic values are the same as the values measured during Phase I. Therefore, it was confirmed that there was no severe damage on the YBCO cable cores after installation and there was no damage on the DI-BSCCO cores after thermal cycles.

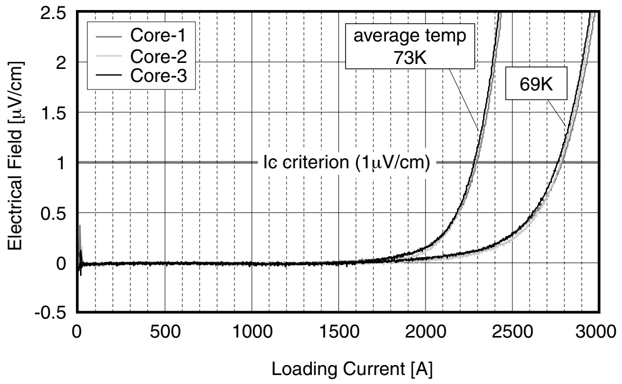


Fig. 8. Results of Critical Current (Ic) Measurement for HTS conductors (Phase II)

(4) Heat loss measurement

Heat invasion into the cable system in a no-load condition was measured. The heat loss in the entire 350-meter HTS cable section was 1.0 kW, which was identical to the value obtained in Phase I. After the cable was manufactured at a factory, the cable cryostats did not require any active vacuum treatment. This result shows that the cable cryostats have kept a good performance without maintenance for a long time approximately three years including thermal cycles. The heat loss of the entire HTS cable system including the terminations, the return pipe and the pipes connecting to the cooling system was 3.4 kW, which was nearly identical to the value obtained in Phase I.

(5) DC withstand voltage test

As the final test before cable re-energization, a DC withstand voltage test was conducted in conformity with the AEIC standard. A DC voltage of 100 kV was applied for 5 minutes for each phase, and good results were obtained. With the completion of this test, the cable system again successfully passed all of the commissioning tests.

4-4 Re-energization and long term in-grid operation at Phase II

The good results obtained in the commissioning tests confirmed that the replacement of the 30-meter DI-BSCCO cable with a 30-meter YBCO cable was completed successfully and demonstrated that the cable system has met the required specifications. In response to these favorable results, the cable system was re-connected to the live power system of National Grid and was back in service on January 8, 2008. The operation of this cable system was able to be monitored and controlled remotely. From that time, a long-term in-grid demonstration progressed satisfactorily without human intervention and was completed successfully at the end of April 2008 as was original scheduled. The cable temperature and transmitted electricity during the in-grid operation at Phase II are shown in **Fig. 9**.

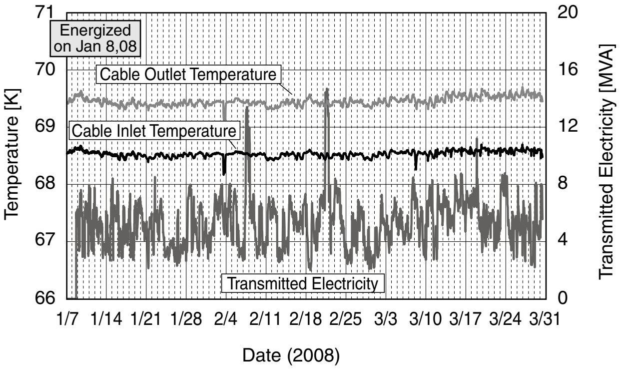


Fig. 9. Long-term In-grid Operation Status (Phase II)

5. Project outline

The verification items and demonstration results of the Albany Project are summarized in **Table 9**.

① The long-length "3-in-One" HTS cables designed to meet the required specifications were manufactured successfully.

② The cables and cable accessories such as joint and terminations were designed to meet the related U.S. standards.

Table 9. Albany Project Summary

Verification Items		Demonstration Results
Cable design	Agreement with requirements for use in actual live grids	• The HTS cable design was verified to satisfy the specifications required in terms of current capacity, voltage, installation condition, fault current, etc.
Cable manufacturing	Long-length cable manufacturing	• Two "3-in-One" HTS cables having a total length of 350 meters that satisfy local standards were manufactured successfully.
Accessories design and manufacturing	Agreement with local standards	• The cables and accessories were designed to meet e related U.S. standards.
Shipping and transportation	Long-distance transportation	• A long-distance transportation by sea and by land from Japan to the U.S was demonstrated.
HTS cable system construction in actual grid	Installation into actual underground conduit	• It was demonstrated that the HTS cable could be installed into the underground conduit with a pulling tension of 2 tons, using the same method and equipment as those for conventional cables.
	Cable-to-cable joint	• The world's first HTS cable-to-cable joint was assembled in the actual underground vault.
	HTS cable system construction	• The construction of the HTS cable system was completed on schedule without any problem or damage in the HTS cables.
	Cable replacement	• The world's first replacement of the HTS cable was completed successfully.
	Commissioning tests	• The HTS cable system passed various tests and was confirmed to meet exacting utility standards. It had garnered approval for connection to the live power grid.
In-grid HTS cable demonstration	In-grid operation	• The HTS cable system was able to operate for more than 12 months without human invention.
	Reliability	• There was no downtime or power outage caused by the trouble of HTS cables and the cooling system. • On the event of fault current, there was neither damage nor significant temperature change in the HTS cables. • There were no change in the critical current values of the HTS conductors during the long-term operation including several thermal-cycles. • It was demonstrated that the cable cryostats had a long life without any active maintenance.
	Maintenance	• A regularly scheduled maintenance for the cooling system components was performed while the cables were in an online state.

③ It was confirmed that there was no damage on the cables and accessories as a result of the long-distance transportation by sea and land from Japan to Albany, NY.

④ The demonstration proved that the HTS cables could be installed into the actual underground conduit using the same method and same equipment as those used for conventional cables.

⑤ The world's first HTS cable-to-cable joint which is essential for constructing a long-length cable network was demonstrated in an underground vault.

⑥ The construction of the HTS cable system in the long-length actual grid was successfully completed on schedule without any problem or damage in the HTS cables.

⑦ The replacement of HTS cable, which would be necessary in the future, was demonstrated in the project for the first time in the world.

⑧ The HTS cable system has passed all of the various commissioning tests and was confirmed to meet the exacting utility standards. The HTS cable system has got certified to be connected with the live grid from the utility company, National Grid.

⑨ The HTS cable system successfully operated unattended in the actual grid for more than 12 months,.

⑩ During the long-term in-grid operation, there was no operational problem with the HTS cable system, and neither the cable nor the cooling system caused downtime or power outage. The HTS cable system demonstrated reliable operation on the live power grid network.

⑪ The HTS cable system was demonstrated under real-world utility conditions including events of significant fault currents. The cable and the cooling system showed no damage, and the cable was maintained at a stable temperature level even in the event of fault current.

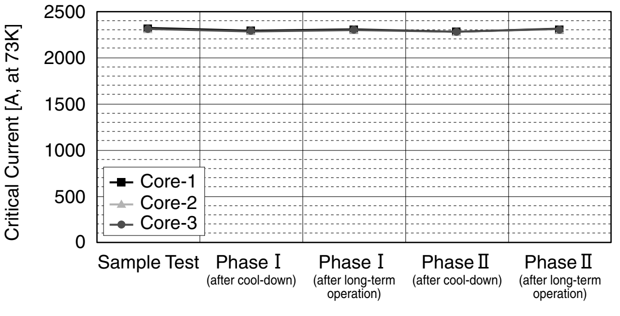


Fig. 10. Critical Current Variation (Phases I and II)

⑫ It was confirmed that the critical current value did not change throughout Phases I and II including thermal cycles, as shown in **Fig. 10**.

⑬ The temperature difference between the outlet and inlet of the cable, indicated by the heat loss of the cable cryostat, was very small and stable throughout Phases I and II including thermal cycles, as shown in **Figs. 11 and 12**. It demonstrated that the cable cryostats did not undergo any major change in heat loss and had long lives without any active maintenance.

⑭ It was demonstrated that regularly-scheduled maintenance for the refrigerator and other components of the cooling system could be performed while the cables are in an online state by deploying the back-up mode operation.

"Of importance to National Grid is that this project has demonstrated the reliability of the technology," said William Flaherty, Energy Solutions Regional Director for National Grid. "We encountered no difficulties in integrating the project into our grid and the entire installation was totally transparent to our customers. The system has stood up to very exacting utility standards and we look forward to further developments in HTS technology."

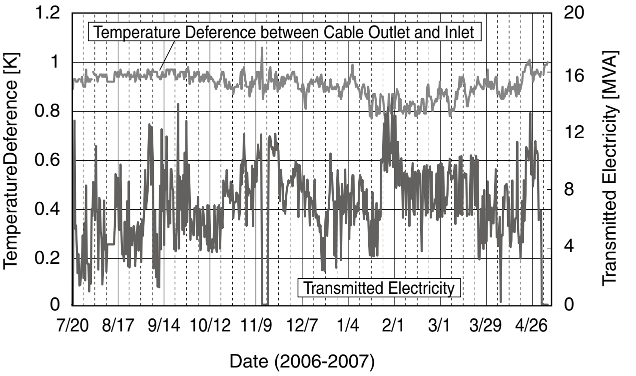


Fig. 11. Temperature Difference and Transmitted Electricity Variations (Phase I)

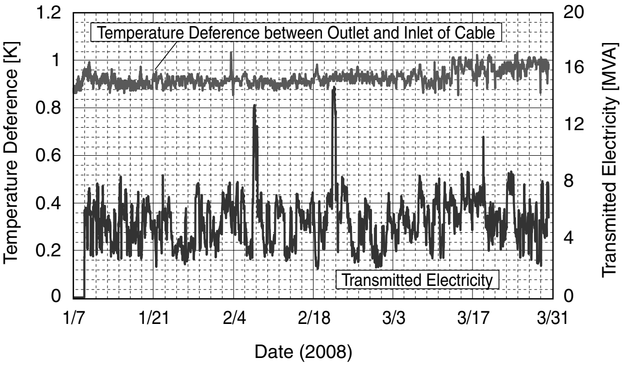


Fig. 12. Temperature Difference and Transmitted Electricity Variations (Phase II)

"Projects such as this one are demonstrating that HTS technologies have the potential to play a critical role in modernizing our electric infrastructure and ensuring the stable and affordable delivery of electricity to our homes and businesses," said Patricia Hoffman, Deputy Assistant Secretary for Electricity Delivery and Energy Reliability at DOE. "The development and deployment of superconductivity and other advanced energy technologies are critical to the Bush Administration's ongoing efforts to increase efficiency and reliability in our nation's energy delivery infrastructure and to enhance our overall national energy security."

The HTS cable system has met all the objectives of the program. The world's first integration of HTS cable into a live power grid and long-term in-gird operation demonstrated the reliabilities of the HTS cable system.

6. Conclusions

In the Albany Project, the HTS cable system demonstrated reliable operation on the live grid for more than 12 months, providing power to about 25,000 homes and businesses. In the United States, followed by this project, the in-grid demonstrations of the HTS cable systems have began in the Ohio Project (started at September 2006) and in the LIPA Project (started at April 2008) . Moreover, an in-grid HTS cable demonstration project has started in Japan from FY2007.(15) Through longstanding and unr-emitting development efforts, HTS technology including HTS cables is steadily going from dream to reality. For full-scale practical application of HTS cables, further performance enhancement and cost reduction are required to HTS wires. Also, further capacity increase and loss property decrease are required to HTS cables, and cable systems need to be constructed in a shorter period. Sumitomo Electric is making further efforts to put HTS cables to commercial use with confidence that HTS technology is an absolute necessity for protection of energy, resource and environment in the 21st Century.

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Contributors (The lead author is indicated by an asterisk (*).)

H. YUMURA*

- Manager, Superconductivity & Energy Technology Department
  He is engaged in the development of HTS cables and their systems.

Y. ASHIBE

- Assistant Manager, Superconductivity & Energy Technology Department

M. OHYA

- Dr. Eng., Superconductivity & Energy Technology Department

M. WATANABE

- Assistant General Manager, Superconductivity & Energy Technology Department

H. TAKIGAWA

- Assistant Manager, Superconductivity & Energy Technology Department

T. MASUDA

- Senior Assistant General Manager, Superconductivity & Energy Technology Department

M. HIROSE

- Senior Assistant General Manager, Superconductivity & Energy Technology Department

K. YATSUKA

- Senior Assistant General Manager, Superconductivity & Energy Technology Department

H. ITOH

- Senior Staff, Power Cable Accessories Division, J-Power Systems Corp.

R. HATA

- Dr. Eng., Chief Engineer, Electric Wire & Cable, Energy Business Unit