Phase II of the Albany HTS Cable Project

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***Abstract*— High-temperature superconducting (HTS) cable systems are expected to be a solution for improvement of the power grid and three demonstration projects in the real grid are underway in the United States. One of these is the Albany, NY HTS Cable Project, involving the installation and operation of a 350 meter HTS cable system with a capacity of 34.5kV, 800A, installed between two substations in National Grid's electric utility system. A 320 meter and a 30 meter cable are installed in an underground conduit and connected together by a joint, or splice in a vault. In Phase I of this project, the cables were fabricated with DI-BSCCO wire in a 3-core-in-one cryostat structure. After the installation of the HTS cable system, the in-grid operation began on July 20, 2006 and operated successfully in unattended condition through May 1, 2007. In Phase II, the 30 meter section was replaced by a 2G (YBCO) cable. The 2G cable was fabricated with SuperPower's YBCO coated conductors in a 3-core-in-one cryostat. After replacement of the 30 meter section, the joint and one termination were reassembled and the commissioning tests that included initial cooling, critical current measurement and DC withstand voltage test were completed successfully. After the commissioning tests, the HTS cable system with a 30 meter YBCO cable and a 320 meter DI-BSCCO cable was re-energized on January 8, 2008 and started again to operate in a live utility network. This paper describes the latest status of the Albany HTS cable project.**

***Index Terms* — High-temperature superconductors, Superconducting cables, Superconducting transmission lines, Power cable installation, Power cable joints, Power cable testing**

I. INTRODUCTION

HIGH Temperature Superconducting (HTS) cables achieve large-capacity, low-loss power transmission in a compact size and are expected to offer not only economic advantages but also environmental advantages including 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. In the United States, three HTS cable demonstration projects, funded by the U.S. Department of Energy, have been conducted on actual power grids. One of these programs, conducted in Albany, NY, involves installing and operating a 350 meter long HTS cable system with a capacity of 34.5 kilovolts (kV), 800 amps (A), connected between two substations in the National Grid electric utility system. A 320 meter and a 30 meter cable are installed into 152mm (6") underground conduit and joined to each other in an underground vault [2]. In Phase I of this project, the HTS cable system with DI-BSCCO cables was installed and energized on July 20, 2006 [3]. From that time, a long term in-grid operation progressed satisfactorily without human intervention and was completed on May 1, 2007. The HTS cable system accumulated nearly 7000 hours of electricity transmission [4].

In Phase II, the 30 meter cable section was replaced by a new cable with YBCO coated conductors developed by SuperPower.

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II. 30-METER YBCO CABLE

For the Phase II of this project, a new 30 meter cable with YBCO coated conductors was fabricated [5]. Fig. 1 shows the cable structure. The YBCO cable has a 3-cores-in-1 cryostat structure similar to the DI-BSCCO cable. The specification of the YBCO cable core is shown in Table I. The cable core is made of SuperPower's YBCO tapes which have surround copper stabilization with 4 mm width and 0.1 mm thickness. The total length of the wire is 9.7 km and their average critical current is approximately 70 A. The cable core is composed of the same Cu former as DI-BSCCO cable, 3-layer conductor, PPLP dielectric of 4.5 mm thickness, 2-layer shield and Cu tape layer. The outer diameter is approximately 35 mm which is almost the same as the DI-BSCCO core.

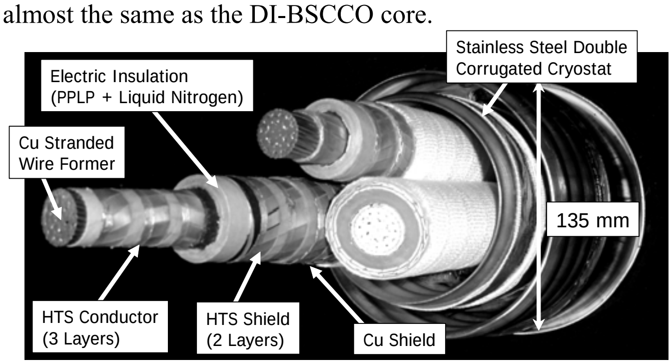

Fig. 1. Three cores - in - one cryostat type YBCO cable structure

The 30 meter YBCO cable was manufactured with almost the same conditions as DI-BSCCO cable at Sumitomo Electric Osaka works in Japan. The results of the various shipping tests conducted after the completion of cable manufacture are shown in Table II. The results of these tests confirmed that the cable had good properties as designed and satisfied the required specifications. After the success of shipping tests, the cable was shipped to Albany, NY for installation.

TABLE I SPECIFICATION OF YBCO CABLE CORE

Items	Specifications	
	DI-BSCCO Cable (manufactured in 2005)	**YBCO Cable (manufactured in 2007)**
Former	Cu stranded with surface insulation	
HTS Conductor	DI-BSCCO tape / 2 layers (Total : 23 pcs)	YBCO tape / 3 layers (Total : 35 pcs)
Dielectric	PPLP / 4.5mm of thickness	
HTS Shield	DI-BSCCO tape / 1 layer (Total 19 pcs)	YBCO tape /2 layers (Total : 38 pcs)
Protection	Cu tape layers / Kraft paper	
Core O.D.	Approx. 35 mm	

TABLE II SHIPPING TEST RESULTS FOR YBCO CABLE

Test Items	DI-BSCCO Cable (fabricated in 2005)	YBCO Cable (fabricated in 2007)
Ic (77K) Conductor :	1.8kA / each phase	2.7kA, 2.8kA, 2.7kA
Shield :	1.8kA / each phase	2.4kA, 2.4kA, 2.5kA
AC loss (0.8kA,60Hz)	0.70 W/m/ph	0.34 W/m/ph
Voltage Test (based on AEIC)	AC: 69kV for 10minutes, Good Imp: ±200kV 10shots/each, Good DC: 100kV for 5 minutes, Good	
Bending test (2.4m= 18x Cable O.D.)	No Ic degradation No defect at dismantling inspection	

III. REPLACEMENT OF 30-METER SECTION WITH YBCO CABLE

A. Warm-up of the Cable System

After the completion of a long term in-grid operation in Phase I, the Megger test and I_c measurement were conducted in order to check the soundness of the HTS cable cores. The result of these tests showed that the cable maintained good electrical insulation properties and had no change in I_c values.

After the confirmation of the soundness of the cable, the cable system was warmed up in order to replace the 30-meter section in Phase II. At the warm-up process, liquid nitrogen was pushed out into the bulk storage tank of the CRS initially and then the cable system was warmed up 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 didn't indicate any leakage.

B. HTS Cable Replacement

After the warm-up process of the cable, the joint and one termination were dismantled and the 30-meter DI-BSCCO cable was pulled out from the underground conduit. The YBCO cable was pulled into the 30-meter cryostat section that formerly held the 30-meter DI-BSCCO cable. After replacement of the 30-meter cable (see Fig. 2), the joint which had the connections of YBCO and DI-BSCCO cores and one termination were reassembled.

C. Commissioning Test at Phase II

The results of commissioning test conducted before re-energization of the HTS cable system are shown in Table III. After the installation of HTS cable system was completed, a

Fig. 2. 30-meter YBCO Cable installation

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 setting pressure of the safety valves used in the system (0.55 MPaG). The test results confirmed that the HTS cable system is satisfactory with respect to this test condition.

Initial cooling for the HTS cable system was conducted by controlling the temperature in the lengthwise direction of the cable in the same manner as Phase I. Fig. 3 shows the temperature profiles measured by the optical fiber system along the cable during initial cooling process. The cable was cooled down gradually for the entire length using nitrogen gases at a temperature of -100 degrees Celsius and then the temperature of the nitrogen gas flowing 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 turned sufficiently small, liquid nitrogen was then injected into the cable. The entire length of the cable was cooled to the liquid nitrogen temperature. In the initial cooling process, the maximum tension produced at both terminations was a total of approximately 1,000 kg for the three cores. This is much lower than the tension produced when there is no allowance for absorption of heat-shrinkage (approximately 5,000 kg) and the effectiveness of the "loosely stranded 3-core structure" is reconfirmed. In addition, the vacuum level in each section, including the cable and the joint showed no deterioration and the core behavior inside the joint was also confirmed to be within the normal range.

The critical current (I_c) measurements were made on each of the YBCO/DI-BSCCO cores at an average cable temperature of 73K and also at 69K. The I_c values were 2.3 kA at 73K and 2.8kA at 69K respectively for each of the three phases as shown in Fig. 4. These are same I_c as the values measured during Phase I, because the YBCO core has larger I_c than DI-BSCCO core and measured I_c should be 320-meter DI-BSCCO one. These I_c values closely matches the value estimated from the DI-BSCCO sample test result of 1.8 kA at 77 K and I_c -T characteristics of DI-BSCCO wire as shown in Fig. 5.

Next, the heat invasion into the cable system in no-load condition was measured. The heat loss in the 350-meter HTS cable section and the entire HTS cable system including the terminations, the return pipe and the pipes connecting to the cooling system are 1.0 kW and 3.4kW, respectively. They were nearly identical to the values in Phase I.

As the final test before re-energization, a DC withstand voltage test was conducted in conformity 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 a period of 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.

TABLE III SUMMARY OF COMMISSIONG TESTS FOR PHASE II

Item	Test Conditions and Results
System withstand pressure test based on ASME code	0.61MPaG: Good
Initial cooling test	Maximum core tension: approx. 1000kg Vacuum level in each part: no leakage
Ic (DC, defined at 1μV/cm)	2.3kA (at 73K)、2.8kA (at 69K)
Heat loss in no-load condition	350 m cable section: 1.0 kW Total for cable system: 3.4 kW
DC withstand voltage test based on AEIC	100 kV, 5 minutes, each phase: Good

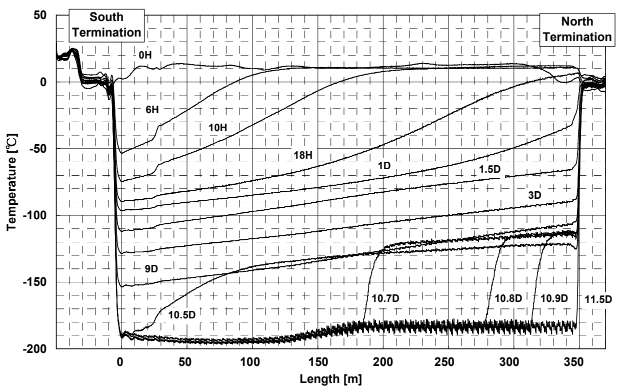

Fig. 3. Temperature profiles along the cable during initial cooling process

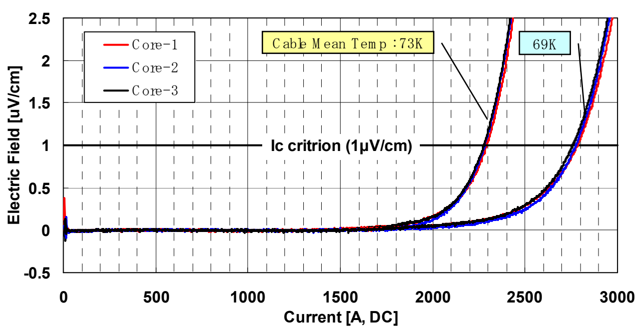

Fig. 4. I-E characteristics measured by the critical current tests

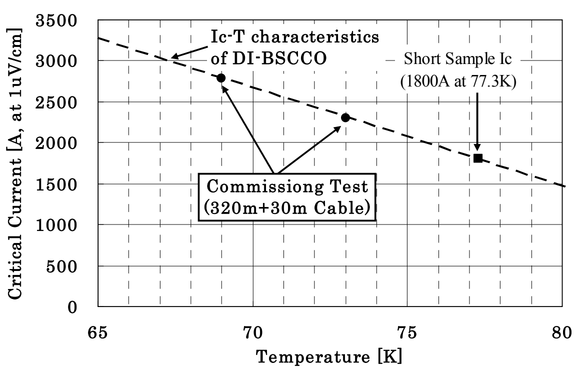

Fig. 5. Comparison the measured Ic with calculations

IV. RE-ENERGIZATION AND LONG TERM IN-GRID OPERATION

The good results obtained in the commissioning tests confirmed that the replacement of the 30-meter section with YBCO cable had been completed successfully and demonstrated that it 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 at the site can be monitored and controlled remotely. From that time, a long term in-grid operation progressed satisfactorily without human intervention and was completed successfully at the end of April 2008. The cable temperatures and transmitted electricity during the in-grid operation in Phase II are shown in Fig. 6.

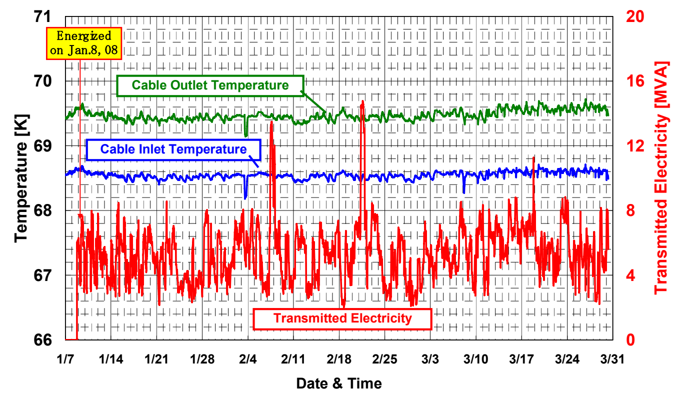

Fig. 6. Stats of the long term in-grid operation in Phase II

V. SUMMARY OF CABLE PROPERTIES IN PHASES I & II

A. Variation of Critical Current

After the completion of a long term in-grid operation in Phase II, the critical current measurements are conducted. The variation of critical current from Phase I through Phase II is shown in Fig. 7. The critical current of the long cable are a very good match with expected values from short sample testing at 77K. The critical current values had no change throughout Phase I and Phase II including heat-cycles.

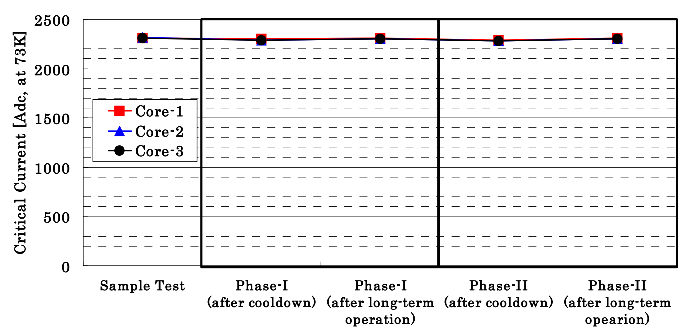

Fig. 7. Variation of critical current from phase I through phase II

B. Variation of temperature difference on the cable

The temperature deference on the cable and transmitted electricity at a long term operation during Phases I and II are shown in Figs. 8 and 9, respectively. The temperature deference between outlet and inlet of the HTS cable was very stable during the long term in-grid operation in the range of 0.9 +/- 0.1 K. This shows that the cryogenic refrigeration system maintained excellent stability and the cable didn't see any large change in heat loss during the long term in-grid operation.

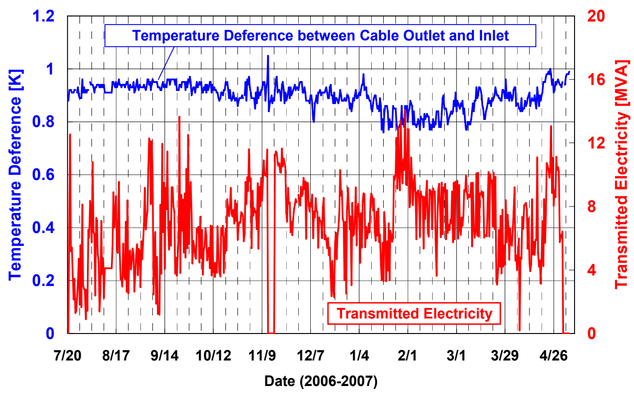

Fig. 8. Variation of temperature deference and transmitted electricity in Phase I

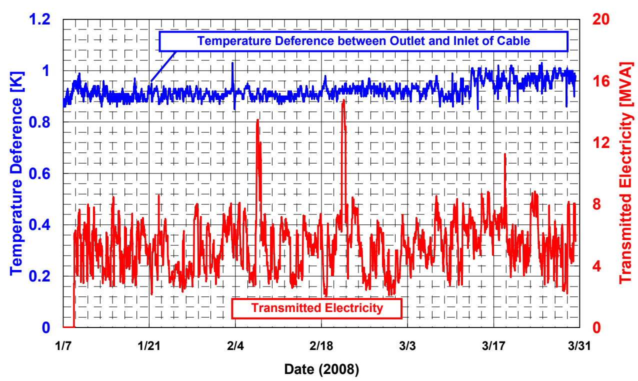

Fig. 9. Variation of temperature deference & transmitted electricity in Phase II

VI. Conclusion

In Phase II of the Albany HTS Cable project, the replacement of the 30-meter cable section with a new YBCO cable and pre-commissioning testing of the YBCO/DI-BSCCO cable were completed successfully. The cable system was re-energized and put back in service on January 8, 2008. A long term in-grid operation progressed satisfactorily without human intervention and was completed successfully at the end of April 2008.

In the Albany HTS Cable project, the HTS cable system demonstrated more than 12 months of reliable operation on the live grid during Phases I and II. The cable system was subjected to real-world utility conditions, including a fault current event in phase I. There were no operational issues with the HTS cable and zero downtime or outages were caused by the cable or cryogenic system during either phase of the project.

The HTS cable maintained its mechanical and electrical properties, such as critical current and heat losses, during Phases I and II, including several thermal cycles.

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