30 m YBCO Cable for the Albany HTS Cable Project

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Abstract. The purpose of the Albany HTS Cable Project is to establish the feasibility of operating a 350 meter long HTS cable system between two substations of the National Grid Power Company, connecting parts of their real commercial grid. This part of the grid has a capacity of 800 A at 34.5 kV, and BSCCO HTS cable began operation on July 20, 2006 in good order. Long-term trouble-free and unattended in-grid operation has continued since then, interrupted just once in early May, 2007 to allow the replacement of the 30 m section of BSCCO cable with new YBCO cable. The YBCO coated conductor for this new HTS cable was prepared by Superpower while a test core was fabricated for testing to confirm the adequacy of its electrical and mechanical properties. This process produced cable with as-designed critical conductor current and shielding, and the results of the fault current test were almost identical to those of BSCCO, with no Ic degradation. Test results thus confirmed the applicability of this YBCO core design. A 30 m YBCO cable was manufactured and shipped to Albany on May, 2007, on schedule. This paper describes the test results for the BSCCO cable and a YBCO sample core, and the manufacture of the 30 m YBCO cable.

1. Introduction
An HTS cable system can achieve large-capacity and low-loss power transmission in a compact facility. This innovative system is expected to present not only economic advantages but also environmental advantages, including conservation of energy and resources and freedom from electromagnetic interference (EMI). These advantages have been driving HTS cable demonstration projects and practical application studies around the world ever since high temperature superconducting material was discovered. In the United States, three HTS cable demonstration projects have been undertaken, funded by the U. S. Department of Energy (DOE). One of these, the Albany cable project, is to confirm the reliability of the 350 meter long HTS cable system (34.5 kV, 800 A) connecting two substations in the National Grid Power Company's network. A 320-meter and a 30-meter cable are installed in a 152 mm (6") underground conduit, joined to each other in a vault [1]. In Phase 1 of this project, this HTS cable system was installed using BSCCO cables and operated in-grid over a long period [2]. In Phase 2, a YBCO cable has been fabricated to replace the 30-meter section of BSCCO cable.
2. HTS cable for the Albany project

The structure of the "3-in-One" HTS cable is shown in Figure 1. The three phase cores are housed in a cable cryostat. This structure has the advantages of more compact size and lower heat invasion from the surroundings compared to three single-core HTS cables. Additionally, the 3 cores are stranded loosely to minimize the stress from longitudinal thermal contraction at the initial cooling-down. In Phase 1, a 320-meter and a 30-meter HTS cable of the “3-in-One” type were manufactured with DI-BSCCO wire that was produced by an innovative CT-OP sintering method [3]. The total length of the wires is approximately 70 km and at 77 K their average critical current (Ic) is 86 A for a 500 m length. The cable core is composed of a 2-layer HTS conductor and a 1-layer HTS shield. Polypropylene laminated paper (PPLP) is used for electrical insulation. To accommodate any fault current, twisted copper wire is used for the former and the Cu wires are wound onto the HTS shield. The cable cryostat is made of co-axial stainless steel corrugated pipes with thermal insulation. The cryostat was evacuated and sealed at the factory after satisfactorily maintaining the required vacuum. A tension member is attached around the outside of the cable cryostat to prevent the loss of core slack due to pulling tension during cable installation. The outer diameter of the cable is designed to be 135 mm in order to allow installation in the 152 mm (6”) underground conduit.

Figure 1. "3-in-One" HTS cable structure

The cable system configuration is shown in Figure 2, and the specifications for the superconducting cable system are shown in Table 1. The 350 m cable is divided into two sections: 320 meters and 30 meters. Both lengths of 3-in-One DI-BSCCO HTS cable were installed sequentially in a 350-meter-long underground conduit with an inner diameter of 6 inches (152 mm). After the installation, both cables were connected by a first-of-its-kind HTS joint box in the vault, and both ends of the cable were connected to overhead power transmission lines by HTS terminations.

Figure 2. Cable system configuration
Table 1. Specifications of HTS cable system

| Item                              | Specification                                      |
|-----------------------------------|---------------------------------------------------|
| Cable configuration               | Three-cores-in-one cryostat (3-in-Ones)            |
| Rated voltage, current            | 34.5 kV, 800 Arms                                 |
| Cable length                      | 350m (320 m + 30 m)                               |
| Accessories                       | Cable termination, Cable joint box, LN2 return pipe (350 m) |
| Laying conditions                 | Underground conduit (inner diameter: 6 inches)    |
| Short-circuit current conditions  | 23 kA, 38 cycles                                  |

3. Test results for 350 m BSCCO cable (Phase 1)

After installation, the cable system was connected to the real network of the National Grid on July 20, 2006. This was the first time that power ever flowed through a long superconducting cable in an actual power grid. Since then, over 9 months of operation time has been logged. On May 1st, 2007, the cable was taken off line, with Phase 1 of the Albany Cable Project successfully completed [4].

Table 2. Main results for Phase 1 BSCCO HTS Cable System

| Test Item                              | Test Results                                      |
|----------------------------------------|---------------------------------------------------|
| Initial cooling                        | Max core tension: approx. 8 kN                    |
|                                        | Vacuum status: good (no leak)                     |
| Critical current                       | 2.3 kA (DC, defined by 1 µV/cm) at 73 K           |
| Heat loss (no-load)                    | HTS cable section: 1.0 kW                         |
|                                        | Entire cable system: 3.1 kW                       |
| Pressure drop                          | 350 m cable section: 0.075 MPa at 50 L/min        |
| DC withstand voltage (based on AEIC code) | 100 kV, 5 minutes, each phase: good             |
| Actual short circuit in grid           | 7 kA, 8 cycles, no system degradation             |
| Total operation time                   | 9 months                                          |

After long-term operation, insulation resistance and Ic tests were conducted to check the soundness of the HTS cable cores. The insulation test showed that the cable maintained good electrical insulation properties. The Ic measurement was carried out for each phase conductor at an average cable temperature of 73 K. The Ic was 2.3 kA (defined as 1 µV/cm) for each of all 3 phases, the same values observed at the commissioning test.

After cable performance was confirmed, the HTS cable system was warmed up to permit replacement of the 30-meter section. The coolant liquid nitrogen was first evacuated into the bulk storage tank of the CRS, and then the system was allowed to warm up naturally. The temperature profile of the warm-up process is shown in Figure 3.

![Figure 3. Temperature profile during the warm-up process](attachment:image_url)
The entire cable system was warmed to ambient temperature over about 3 weeks. In the warm-up process, the vacuum level in each section indicated no leakage and the tension at both terminations returned to the original value of around 2 kN compressive force.

4. YBCO cable verification (Phase 2)

4.1. YBCO Cable specification

In Phase 2, the BSCCO 30-meter section was to be removed and replaced by the YBCO HTS cable. YBCO wire for this cable was manufactured by SuperPower. Table 2 shows the specifications of the YBCO cable and the BSCCO cable. Except for the number of HTS layers, the designs are very similar.

| Item                        | Specifications |
|-----------------------------|----------------|
| Former                      | Twisted copper wires |
| HTS conductor layers        | 3 | 2 |
| Electric insulation         | PPLP (thickness: 4.5 mm) |
| HTS shield layers           | 2 | 1 |
| Copper shield               | Copper tapes |
| 3-cores stranding           | Loosely        |
| Cable outer diameter        | 135 mm         |

4.2. Test cable manufacturing and evaluation

Various experiments have been conducted to verify the design appropriateness and measure the real values of parameters.

4.2.1. Test cable manufacturing and bending test

A 10 m test cable was manufactured to determine its mechanical robustness under the manufacturing process and the bending stress imposed during shipment and installation. The Ic of the YBCO wires was measured in a short sample core cut from the test cable at each stage of manufacture. The Ic retention of the conductor and the shield at each stage are shown in Figure 4 (I), which shows no degradation.

Figure 4. Ic retention of test core during manufacture, bending test
After the test fabrication, a bending test was performed. The bending diameter varied from 1.9 m to 0.5 m, with two 180° bends, and the Ic was also measured after each bending. No degradation was found for a bending diameter above 1.1 m as shown in Figure 4 (II). In these tests, the YBCO stranding cores displayed good mechanical performance, suitable for the proposed manufacturing and installation.

4.2.2. Evaluation of short-circuit current properties

A 1 m sample core with the same structure shown in Table 2 was manufactured to check its short-circuit current properties.

![Figure 5. Temperature rise under various fault conditions (1 cycle = 1/60 sec)](image)

The short-circuit current condition at the Albany site is estimated to be 23 kA in the case of a failure occurring adjacent to the test site. Circuit breakers operate within 8 cycles as the first protection, but if this initial protection fails the second protection will operate within 38 cycles. The influence of the fault current through the cable was checked by experiment, using the 1 m sample core. The experiments were conducted with the LN2 in place. The temperature increase of the conductor and shield were measured under the various sustained cycles shown in Figure 5. In the case of 23 kA at 8 cycles, the maximum temperature increases in the conductor and shield were 7 K and 8 K, respectively. A test was also conducted at 38 cycles, and the maximum temperature increase of the conductor and shield were 30 K and 50 K, respectively. The temperature increase of the YBCO core was nearly the same as that of the BSCCO core. The Ic of the sample was measured after the fault-current tests, and no Ic degradation was observed. A fault-current accident might not produce any damage in the YBCO cable.

5. Fabrication and shipment of 30 m YBCO cable

After the design suitability was verified, a 30 m YBCO cable was manufactured under the same conditions as the YBCO test cable. The total length of wires was 9.7 km, and the Ic of the YBCO wires used in the product cable was about 70 A on average. Table 3 shows the results of the various shipping tests conducted after cable manufacture.

| Test Item                      | Test result                                      |
|-------------------------------|--------------------------------------------------|
| Critical current Ic @ 77 K    | Conductor: 2820 A (Core-1), 2750 A (Core-2), 2660 A (Core-3)  |
|                               | Shield: 2440 A (Core-1), 2500 A (Core-2), 2400 A (Core-3) |
| AC loss @ 800 A_{max}, 60 Hz  | 0.34 W/m/phase                                    |
| Withstand voltage tests       | AC: 69 kV for 10 minutes OK                       |
|                               | Imp: ±200 kV, 10 shots / each OK                  |
|                               | DC: 100 kV for 5 minutes OK                       |
| Bending test (2.4 m = 18D, D = cable outer diameter) | No Ic degradation                                |
|                               | No defect at dismantling inspection               |
The measured Ic values of the conductor and shield were greater than 2600 A and 2400 A, respectively. These Ic values nearly match the estimate made from the Ic values of the YBCO wires. Then the dielectric property of the sample core was inspected. An AC voltage of 69 kV at 60 Hz was applied for 10 minutes. A lightning impulse voltage of 200 kV was applied in 10 shots of both positive and negative polarity. A DC voltage of 100 kV was applied for 5 minutes. The sample core withstood these high voltages. A bending test was also performed on the YBCO sample cable. The Ic was measured, and no degradation was found for a bending diameter of 2.4 m.

These tests confirmed that the cable had good properties as designed, and satisfied the required specifications. Following these favorable results, the YBCO cable was shipped on the drum in Figure 6 to the United States from the Port of Kobe, and arrived at the Albany test site in June 2007.

Figure 6. Albany YBCO HTS cable on shipping drum

6. Conclusion

Phase 1, including the installation of an HTS cable system using DI-BSCCO wire and its 9+ months of in-grid operation, was completed successfully. In parallel, Phase 2 began and a YBCO cable design was confirmed reliable and appropriate by testing the cable properties. Then a 30-meter YBCO cable was manufactured and shipping tests satisfactorily completed, verifying good Ic and AC loss performance, withstand voltage, and durability under bending. The 30-m YBCO cable was shipped to the United States and arrived at the Albany test site in June 2007. The replacement of the 30-meter cable is underway and in-grid operation is scheduled to restart this winter.

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