Large Current and Low AC Loss High Temperature Superconducting Power Cable Using REBCO Wires

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High temperature superconducting (HTS) products, such as power cables and motors, have higher transmission capabilities and lower AC loss, and are more compact than conventional counterparts. With these advantages, HTS products are expected to contribute to energy saving and global warming prevention. Sumitomo Electric Industries, Ltd. conducted a national joint R&D project from 2008 to 2012 in order to develop HTS coated conductors and build a 15 m long 66 kV/5 kA class "3-in-One" HTS cable system. We first conducted a short cable test to identify the requirements for the HTS cable and developed an appropriate conductor. Then, we produced a total of 6 km of HTS coated conductors, and built a cable system to be installed into the existing underground conduits of 150 mm in inner diameter. The measured AC loss of our new cable was less than one-third that of a conventional cable even after considering cooling system efficiency. The cable system performance was verified to be stable in a long-term operation test.

Keywords: coated conductors, HTS power cable, AC loss

1. Introduction

Superconductivity is a phenomenon of zero electrical resistance. A power cable whose conductors are made of a superconducting material can transmit, at low AC loss, 3 times or more power than possible by a conventional power cable of the same size. If a superconducting material is used in a coil, the produced electromagnet is smaller yet more powerful than conventional electromagnets due to the increased current density. Industrial equipment, such as power cables and motors, incorporating superconductors is capable of achieving large-capacity power transmission and delivering high power despite its compactness, at lower AC loss than that incurred by conventional power cables or industrial equipment. Therefore, such equipment is expected to be useful in measures for energy saving and global warming mitigation. Thin-film REBCO high-temperature superconductors (REBCO conductors) have improved in terms of ease of long-length construction, property, and performances; exhibit high current density and low AC loss features; and enabled large-capacity power transmission in a compact size. Sumitomo Electric Industries, Ltd. conducted research and development of the REBCO conductor and its use in superconducting power cables in the Materials and Power Applications of Coated Conductors (M-PACC) project entrusted by the New Energy and Industrial Technology Development Organization (NEDO)(1).

This paper reports on the results we have achieved in the REBCO project.

2. REBCO Project Overview

In the REBCO project, Sumitomo Electric worked on the development of a 66 kV/5 kA class large-current low AC loss cable and a REBCO conductor used in that cable. In the conductor development, we drove the research and development of practically important constituent technologies for practical use, such as REBCO conductor performance improvement and techniques for the stable manufacture of long-length REBCO conductors, and produced long conductors to fabricate a 15 m long cable required for system verification. In the development of a large-current low AC loss cable, a three-cores-in-one-cryostat type (3-in-One) superconducting cable system capable of passing a 66 kV, 5 kA current was constructed, and its AC loss and durability were verified.

Table 1 shows the large-current, low AC loss cable development targets set in the REBCO project. The transmission capacity target was set to 570 MVA, so as to be equivalent to those of typical 275 kV power cables. The cable's total AC loss target was set to 2.1 W/m-phase at maximum at 5 kA, so as to be less than one-third of that incurred by a conventional power cable, with power dissipation required for cooling taken into account. The cable outside diameter target was set to 150 mm at maximum so as to place the cable in an existing cable conduit for reduced installation cost. Moreover, the specification requirements included resistance to overcurrent that may occur in a power grid accident.

Table 1. Large-current low AC loss cable development targets

Transmission capacity	570 MVA (5 kA, 66 kV)
AC loss	2.1 W/m /phase @ 5 kA max.
Size	Can be placed in ∅150 mm conduit

3. Development and Manufacture of Cable Conductors

3-1 Technology development for long-length high I_c REBCO conductor fabrication

The aim of the REBCO conductor development was to establish techniques for the stable fabrication of REBCO conductors using a textured metal substrate and the PLD method for large-current cable applications. **Figure 1** shows the structure of the REBCO conductor used in the large-current low AC loss cable. **Table 2** shows the specifications for REBCO conductor layers. The REBCO conductor comprises a textured metal substrate, an intermediate layer, a superconducting layer, a stabilizing Ag layer, and a stabilizing Cu layer. The textured metal substrate is a long metal tape whose surface is an aligned crystal layer, on which the intermediate and superconducting layers are formed, preserving their respective crystal alignments. The crystalline alignment of the superconducting layer is important for the properties of the REBCO conductor. As a substrate that provides high mechanical strength and low magnetism required to achieve low AC loss, Sumitomo Electric used a textured metal clad substrate prepared by laminating a Cu film on SUS and plating a Ni layer on the Cu film, where SUS is a high-strength nonmagnetic metal, the Cu film can be textured through heat treatment, and the Ni is intended to prevent oxidation of the Cu film(2). The intermediate layer was provided through RF sputtering, coating three layers of CeO_2, YSZ, and CeO_2 on a 30 mm wide textured metal clad substrate. The superconducting $GdBa_2Cu_3O_y$ layer was coated on the intermediate layer by the pulse laser deposition (PLD) method, followed by the coating of the stabilizing Ag layer by DC sputtering. Subsequently, after oxygen annealing, a conductor of 30 mm in width was cut into six 4 mm wide strips or twelve 2 mm wide strips, and the electroplating method was used to form a 20 µm thick stabilizing Cu layer around them(3).

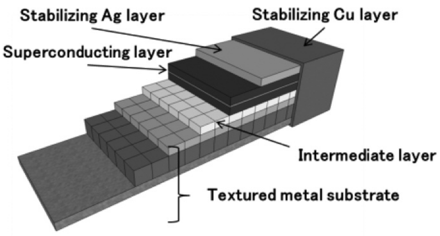

Fig. 1. REBCO conductor structure

Table 2. REBCO conductor specifications

	Material	Film Thickness (µm)	Coating method	Function
Stabilizing Layer	Cu	20	Electroplating	Prevents damage to superconducting layer
	Ag	2–8	DC sputtering	
Superconducting Layer	GdBCO	1–4	PLD method	Power transmission
Intermediate Layer	CeO_2	0.1	RF sputtering	Lattice matching with superconducting layer
	YSZ	0.2–0.4		Dispersion prevention
	CeO_2	0.1–0.2		Seed layer
Textured Metal Substrate	Ni	3	Plating	Oxidation prevention
	Cu	20–50	Rolling and cladding	Textured layer
	SUS	100		Supporting base

First, technology development was carried out to fabricate a high-critical current (I_c)*2 conductor for use in large-current cables. Subsequently, a long-length conductor fabrication process was developed for improved throughput. By combining these accomplishments, a stable process was established to manufacture conductors with high I_c for large-current cables.

When manufacturing long-length REBCO conductors, it is necessary to improve the uniformity of the intermediate layer. Regarding the stabilization of intermediate layer formation conditions, the coating plasma, atmosphere, and temperature were optimized and long-duration coating process stability was improved. Subsequently, an evaluation was conducted on the X-ray diffraction peak intensity ratio I(200)/[I(200) + I(111)] (hereafter referred to as the "alignment rate") that indicates the [100] alignment of the CeO_2 lattice-matching layer coated on 30 mm wide textured clad substrate. The results showed uniform crystalline alignment, with the alignment rate being 95% or higher over the overall length of approximately 170 m of the 30 mm wide conductor as shown in **Fig. 2**.

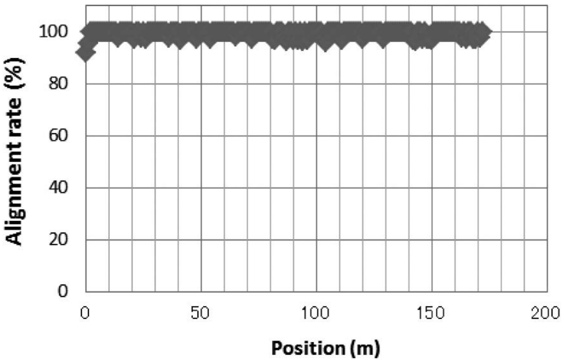

Fig. 2. Longitudinal crystalline alignment rate distribution of intermediate layer CeO_2/YSZ/CeO_2

Regarding superconducting layer formation using the PLD method, the layer properties were rendered uniform in the transverse direction, and improvements were made to the I_c characteristics and the manufacturing capacity. More specifically, the coating conditions (substrate temperature, gas pressure, plume shape, etc.) were optimized to achieve uniform properties and a PLD excimer laser with power 1.5 times higher than the previous one (200 W → 300 W) was introduced to improve I_c characteristics and the manufacturing capacity. The results were I_c values of 200 A/cm-w all over the 30 mm conductor and maximum I_c in the 500 A/cm class at the center of the conductor(4).

Moreover, to ensure long-length uniformity in the superconducting layer formation process, an analysis was conducted to find conditions that would stabilize factors (laser intensity, target surface condition, etc.) involved in coating condition variation. As a result, the wire feed rate was optimized for 150-200 m long coating.

Forming $GdBa_2Cu_3O_x$ on a 170 m long, 30 mm wide intermediate layer, I_c was evaluated in the longitudinal direction. **Figure 3** shows the evaluation results. The I_c value was 400 to 450 A/cm over almost the entire 170 m length, proving the establishment of a long-length REBCO conductor fabrication technology for large-current, low AC loss cables. The knowledge acquired through that prototype was used in the stable manufacture of cable conductors discussed in the following section.

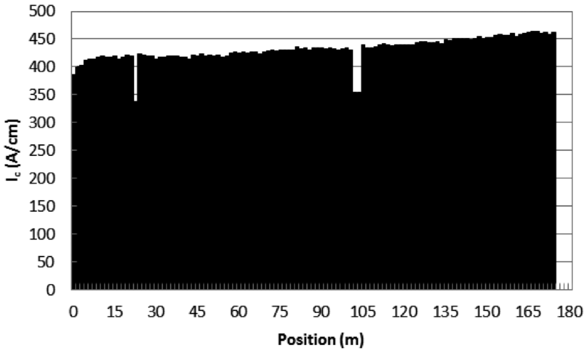

Fig. 3. Longitudinal I_c distribution of 170 m long superconductor

3-2 Stable manufacture of cable conductors

In fiscal 2011 and 2012, REBCO conductors were manufactured for the purposes of cable designing and verification of 66 kV large-current low AC loss cable systems. The conductor specifications included: (1) Constituent layers of cable shall exhibit the I_c shown in **Table 3** at minimum; (2) The **n** value indicating conductor property uniformity shall desirably be 20 or greater, and conductors with an **n** value not greater than 15 shall not be used; (3) When inspecting the I_c of the entire length of a conductor, energization and measurement shall be conducted at 1.5 m intervals; (4) Conductors that present an abnormal appearance (especially at the edges) shall not be used; and (5) Both the front and back stabilizing layers shall be 20 μm in thickness. Furthermore, since it is difficult to detect minute defects through I_c inspection using an energization method, an induction method was also used to measure I_c.

Table 3. Specifications for REBCO conductor for large-current low AC loss cable

Location		Width (mm)	Individual length (m)	Count (for one core)	I_c(A)	I_c(A/cm)
Conductor	Layer 1	4	18	15	132	330
	Layer 2	4	18	15	139	345
	Layer 3	4	19	15	146	365
	Layer 4	2	21	27	74	370
Shield	Layer 1	4	19	24	132	330
	Layer 2	4	19	26	114	285

Conductors used in large-current low AC loss cables are required to exhibit maximum I_c in excess of 370 A/cm. With the aim of efficiently manufacturing high I_c conductors, in-process property inspection was carried out and nonconforming conductors were sorted out. Subsequently, the following shipping inspections (1) to (5) were carried out: (1) Transport I_c measurement (including the **n** value measurement and inspecting the entire length at 1.5 m intervals); (2) Visual inspection (entire length); (3) I_c measurement by the inductive method (inspecting the entire length, especially for small low I_c sections); (4) Width and thickness measurements (inspecting both ends of the conductor); and (5) Stabilizing layer thickness measurement (inspecting one end of the conductor). Conforming conductors ascertained through these inspections in conjunction with the inspection data were supplied to the large-current low AC loss cable manufacturing process.

Figure 4 shows the frequency distributions of I_c exhibited by REBCO conductors 6 km in total length (1 cm width equivalent) fabricated for cable design testing and for large-current cables, and processed up to shipping inspection for both years of manufacture. In fiscal 2011, the first half of the manufacturing period, multiple approaches were concurrently adopted for the manufacture of long-length conductors, including the stabilization of plasma generated by the intermediate layer coating system, the stabilization of laser conditions of the superconducting layer coating system, and the adjustment of slit conditions to reduce appearance defects. As a result, a large proportion of the conductors exhibited I_c values in the range of 200 to 400 A/cm. Low I_c conductors were used principally in prototype cables. In fiscal 2012, the second half of the manufacturing period, improvements were achieved regarding the aforementioned stabilization, and more than 80% of the conductors exhibited I_c values in the range of 300 to 450 A/cm. Better conductors were selected from them, and 1.7 km of 2 mm wide conductor and 5.2 km of 4 mm wide conductor were used to fabricate a large-current low AC loss cable.

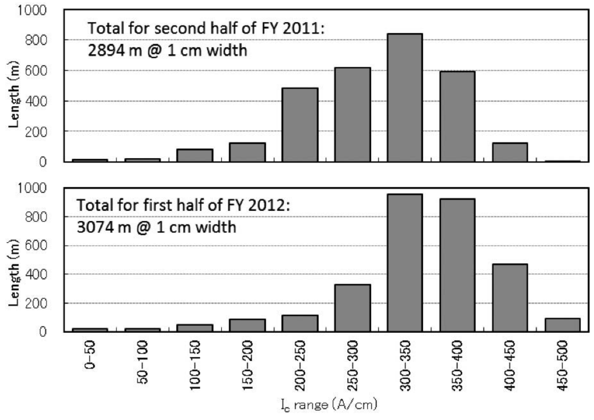

Fig. 4. Frequency distributions of I_c exhibited by model cable conductors, by year of manufacture

4. Key Technology Development for Large-Current Low AC Loss Cables

Figure 5 shows the structure of a large-current low AC loss cable. The cable is the 3-in-One type (three cores [phases] placed in a single cryostat). In comparison with three individual single-core superconducting cables, each core requiring a cryostat, the 3-in-One type reduces installation spaces and heat intruding from the surrounding environment.

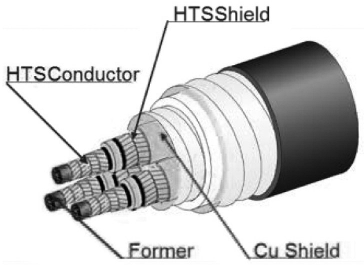

Fig. 5. Structure of large-current cable

The cable core has a structure such that superconducting electrical insulation, a superconducting shield, and copper shield layers are coaxially wound around a copper strand former. In the normal state, electric current passes through the superconducting layer. In this state, approximately the same magnitude of electric current in the opposite phase passes through the superconducting shield layer by virtue of electromagnetic induction, blocking the magnetism otherwise occurring outside the cable. Moreover, the copper former and the copper shield layer protect the superconducting and shield layers from accidental currents.

Structural assessment was conducted first in the development of constituent cable technology to achieve an established cable design for large-current, low AC loss, and compact cables, as a project goal. A cable core structure featuring four superconducting layers and two superconducting shield layers was adopted to achieve both large-current 5 kA operation and compactness, enabling housing in a 150 mm diameter conduit.

Next, using a REBCO conductor, a prototype short cable core was constructed for energization testing. Based on the acquired data, the properties and amount required for constructing a large-current cable conductor were determined. The specifications are shown in **Table 3**. Regarding the conductor I_c of each layer, higher property requirements were set for outer layers in consideration of the effects of inner-layer originating magnetic fields on the conductor I_c. Meanwhile, as shown in **Fig. 6**, it was ascertained that conductor width reduction from 2 mm to 4 mm was effective at reducing AC loss*3(5). Therefore, a 2 mm wide conductor was used for an outermost layer, where the loss becomes large. Individual single-length requirements were determined for each layer, taking into account the winding diameter and pitch of each layer to reduce the amount of required conductors.

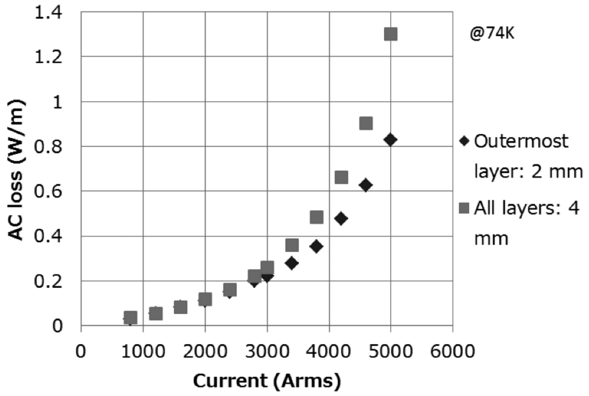

Fig. 6. AC loss characteristics of four-layer conductors with different conductor width

5. Large-Current Low AC Loss Cable System Verification Test

Figure 7 shows the configuration of the 15 m superconducting cable verification system. The superconducting cable was the 3-in-One type, in which three superconducting cores were placed in a single cryostat. The verification test employed a two-core reciprocation energization method in which electric current passed through two of three cores(6). However, a voltage was impressed to all three cores. Termination A is a terminal connection with a bushing and three current leads. Termination B is a container without bushing or current leads, internally connecting the three-phase cores (in liquid nitrogen) to reduce the thermal load on the system.

First, test conditions were assessed to evaluate the practical durability of the 66 kV large-current cable. The items to be tested were determined respectively for sample testing, which examined the integrity of the samples cut out of the ends of the manufactured cable, for 15 m cable system verification testing, and for integrity retention testing, which examined the cable after the verification testing for any property degradation. Key tests verifying the 15 m cable system were: (1) Checks on cable loss (AC loss 2.0 W/m/ph + Induction loss 0.1 W/m/ph) of 2.1 W/m/ph@5 kA, 66 kV;

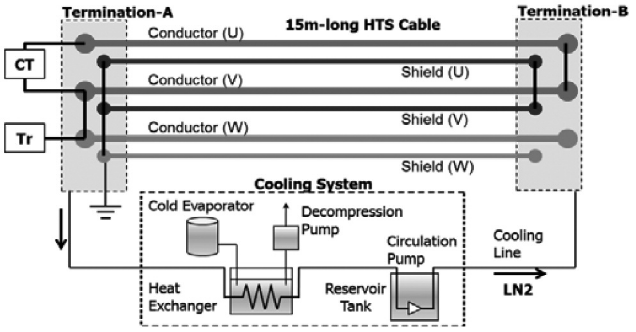

Fig. 7. Configuration of 15 m long superconducting cable verification system

(2) Rated voltage impression characteristic checks; and (3) Voltage impression and energization tests under accelerated test conditions representing 30 years of operation. The verification test results are presented below with a focus on the key tests.

5-1 Sample test

A 19 m long cable was constructed using 1.7 km of 2 mm wide conductor and 5.2 km of 4 mm wide conductor. **Figures 8 and 9** show I_c and AC loss measurement results of a sample cut out of an end section. For both the U and V phases, the measured sample exhibited an I_c 5% to 10% greater than predicted on the basis of the sum of the I_c values of the conductors and the effects of the magnetic field present during energization, proving no deterioration resulting from the cable manufacturing process. Moreover, under 5 kA energization, AC losses were 1.5 W/m/ph for the U phase and 1.8 W/m/ph for the V phase, both lower than the target values.

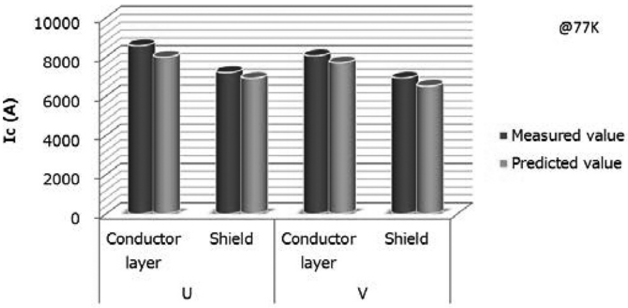

Fig. 8. I_c measurement results for 15 m sample cable

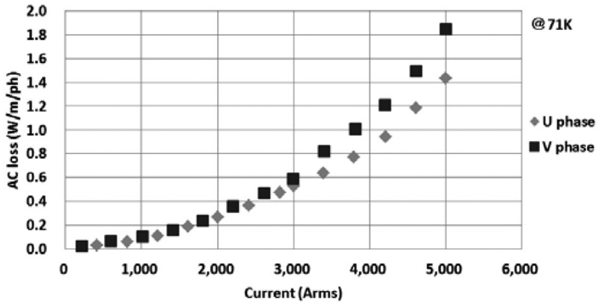

Fig. 9. AC loss measurement results for 15 m sample cable

As the integrity of the cable was verified, a 15 m cable system was constructed at the superconducting cable test field at Sumitomo Electric Fine Polymer, Inc. to test and verify the cable system combined with a cooling system and a measuring and monitoring system. **Photo 1** presents photos of the cable system after construction used in the verification test.

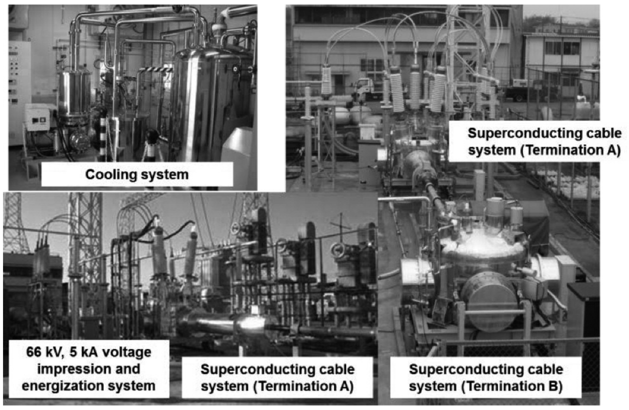

Photo 1. Photos of 15 m long cable system for verification test

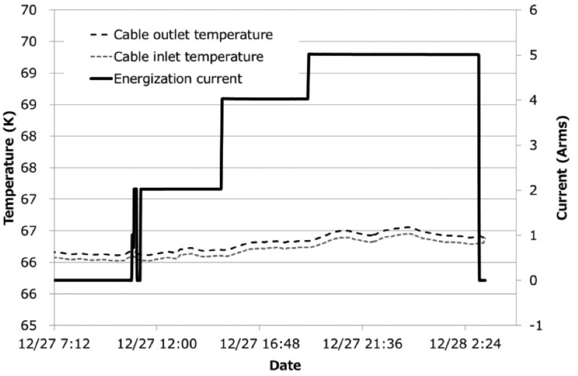

Fig. 10. Current and temperature changes during 5 kA energization

5-2 15 m system verification test

After the initial cooling of the cable system, various tests were conducted.

Figure 10 shows changes in the current and cable inlet and outlet temperatures at 5 kA energization. Using temperature sensors attached at the cable inlet and outlet, liquid nitrogen temperature differences were determined and converted to heat loss by the calorimetric method to determine AC loss. The results showed that the AC loss was 1.8 W/m/ph (at 5 kA energization). Consequently, the heat loss target (2.1 W/m/ph max.), the under voltage impression and energization was achieved even taking induction loss into account, with the sum of the determined AC loss under 5 kA energization and the cable's calculated induction loss of 0.076 W/m/ph not exceeding 1.9 W/m/ph.

An extended voltage impression and energization test was conducted on the superconducting cable system, simulating 30 years of rated voltage impression and energization. The test period was one month. The test voltage was set to 51 kV as an accelerated test condition representing 30 years of operation(7). The system was energized in cycles consisting of 8 ON hours and 16 OFF hours, in consideration of the load variation on actual power lines. The cooling system operating conditions were a liquid nitrogen flow rate of 40 L/min and a pressure of 0.2 to 0.4 MPaG.

Figure 11 shows the results of the 30 day long-term operation test. Before finishing the test, it was confirmed that the peak temperature exhibited no tendency to increase with the passage of test time, with the cable outlet temperature remaining stably at 68 K or below during energization throughout the test period.

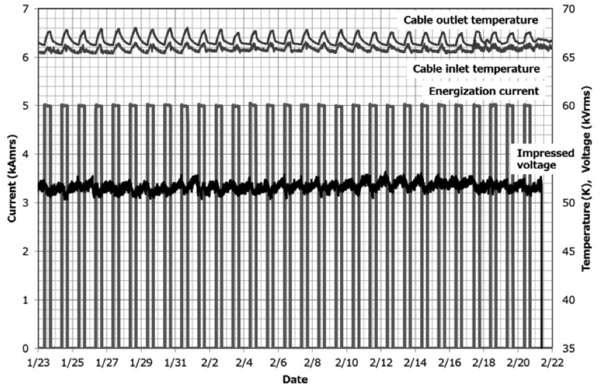

Fig. 11. Status of long-term operation test

5-3 Integrity retention test

Following the system verification test, the cable was disassembled and inspected for any abnormality. Samples cut out of the cable were subjected to a critical current measurement, AC loss measurement, and dielectric test (90 kV AC for 3 h, 100 kV AC for 10 min, and 3 cycles of ±385 kV impulse)(7). The results were favorable, proving that the cable did not degrade in terms of its characteristics through the extended voltage impression and energization test.

Table 4 summarizes the verification tests and test results, including the above-mentioned tests. After undergoing all the tests, the large-current low AC loss superconducting cable system fulfilled the specifications and demonstrated its practical utility.

Table 4. Summary of verification tests and test results

No.	Test	Sample test	15 m verification test	Integrity retention test
1	Extended dielectric test at 60 Hz (90kV, 3h)	–	–	Favorable
2	Dielectric test at 60 Hz (100kV, 10min)	–	–	Favorable
3	Partial discharge test	–	No PD generation (50 PC sensitivity)	No PD generation
4	Lightning impulse dielectric test (±385kV)	–	–	Favorable
5	Extended voltage impression and energization test (1 month)	–	Favorable	–
6	Visual inspection	No abnormality	No abnormality	No abnormality
7	Electrostatic capacitance test	–	As designed (11.8 nF)	As designed (11.7 nF)
8	Tan delta test	–	Favorable (0.059 %)	No change (0.080 %)
9	Insulation resistance test	No abnormality	No abnormality	–
10	Conductor resistance test (former)	As designed (0.14 mΩ /m@20℃)	–	–
11	Structural test	No abnormality	–	No abnormality
12	Ic measurement	As designed (8200 A @77.3K)	As designed (8040 A @77.3K)	No degradation (8090 A @77.3K)
13	Shield current measurement	–	No abnormality (91 %)	No abnormality (91 %)
14	AC loss measurement (at 5kA)	1.5 W/m/ph	1.8 W/m/ph	No change
15	Cryostat heat intrusion measurement	–	1.7 W/m	–
16	Airtightness test	No abnormality	No abnormality	–
17	Vacuum leak test	No leakage	No leakage	–
18	Pressure loss measurement	–	Approx. 2 kPa (@40 L/min)	–
19	Inductance measurement	0.1 μH (As computed)	–	–

6. Conclusion

We worked on processes from the development of REBCO conductors to cable system verification in the REBCO project.

In the development of REBCO conductors, the performance of the REBCO conductors was improved and a relevant manufacturing technology was developed using a low-magnetism textured metal clad substrate and the PLD method. Based on the constituent technologies used to meet the performance and manufacturing rate requirements essential for cable fabrication, a stable manufacturing process was established for high I_c long-length REBCO conductors with longitudinally uniform properties. Using this process, manufacturing was conducted for about one year to yield 1.7 km of 2 mm wide conductor and 5.2 km of 4 mm conductor needed to verify a large-current low AC loss superconducting power cable system. For REBCO conductors to be put to practical use, challenges must be met, such as the elimination of local low I_c sections, the construction of long conductors in excess of 1 km, and the establishment of a low-cost and stable manufacturing technology. On the basis of the present study results, we will strive to solve the above-mentioned challenges and be able to supply REBCO conductors according to market needs.

In the cable development, basic data were collected regarding AC loss and other electrical characteristics and mechanical properties of a cable comprising multilayered superconductors. The data were used to establish a cable design that featured compactness and low loss. Using Sumitomo Electric's REBCO conductors, a 15 m long large-current low AC loss superconducting power cable system was constructed. The transmission loss of the cable was lower than 2.1 W/m/ph at 5 kA, less than one-third of that of conventional power cables, even including the power dissipation required to cool the cable. An extended voltage impression and energization test was conducted to demonstrate the system integrity under accelerated test conditions representing 30 years of operation. For REBCO cables to be put to practical use, it is necessary to verify their long-term reliability and stability in an actual grid. Using the results of preceding studies on bismuth-based superconducting cables, we intend to promote development toward the practical implementation of REBCO cables.

The present study was conducted, entrusted by the New Energy and Industrial Technology Development Organization (NEDO).

Technical Terms

*1 REBCO superconductor: Since it has a thin-film superconducting layer, the REBCO superconductor is also known as a thin-film superconductor. The critical current of other superconducting materials decreases substantially in a magnetic field, while such a decrease in a REBCO superconductor is small. This brings advantages to its application in a magnetic field.

*2 Critical current (I_c): The maximum current that a wire can transmit in a superconducting state. The critical current usually refers to the current value at which 1 μV/cm voltage is generated. Generally, the critical current increases with decreasing superconductor temperatures and decreases in a magnetic field.

*3 AC loss: Energy lost by a superconductor. No energy loss is caused by any direct current or DC field. However, alternating current and AC field cause hysteresis, coupling, and eddy current losses. These energy losses are known collectively as AC loss. The AC loss decreases with decreasing thickness and width of the superconducting layer. Moreover, the AC loss decreases with decreasing ratio of the actual current (Iop) to I_c.

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