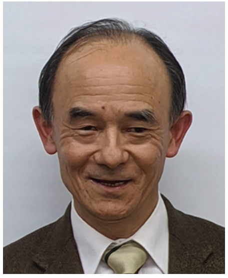
News From Japan



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Development of a 6-kV, 3,000-A Triaxial Superconducting Cable

Dr. H. K. Onnes discovered the zero electric resistance or superconductivity (SC) in mercury (Hg) in 1911, and Dr. J. G. Bednorz and Dr. K. A. Müller discovered high-temperature SC (HTSC) in ceramics in 1986. Although a long time has passed since the discovery of various SC phenomena and materials, their industrial use is still limited. Among various SC phenomena, applications using the generation of a strong magnetic field have been used relatively widely. This column, "News from Japan," has reported the development of HTSC coil windings for a power transformer [1], HTSC magnetic resonance imaging used in medical diagnosis [2], and flywheel energy storage using HTSC magnetic bearings [3], as typical Japanese examples of HTSC applications.

Compared with its use to create strong magnetic fields, the ability to conduct a large electric current seems not to have been used so much, although "News from Japan" has reported the development of a HTSC current lead [4] and a 200-MVA HTSC cable system [5]. A major Japanese cable manufacturer, SWCC Showa Cable Systems Co. Ltd., Kawasaki, mentions that the development of related technologies necessary for the use of a HTSC for large electric current has been promoted in Japan mainly for electric power utility companies to realize high-voltage and large-current in-grid transmission cables. The hurdles for the development of such high-voltage HTSC cables would be high, considering the requirement of very high reliability. The company considers that this could be the main reason for the slow adoption of HTSC to carry large electric currents. The situation seems similar in other countries if we consider that large projects to develop high-voltage HTSC in-grid cables were mainly conducted around 15 years ago [6], [7].

Regarding this, the company anticipates that the introduction of a relatively lower-voltage and large-current HTSC cable system within a small area such as a plant would gain wider popularity because the low voltage needs no substations and the zero electrical resistance can reduce power loss significantly. With this perspective, the company has developed a 6-kV, 3,000-A triaxial HTSC cable and conducted a verification test in cooperation with the New Energy and Industrial Technology Development Organization (NEDO), Kawasaki, and BASF Japan Ltd., Tokyo [8]. This article presents a brief outline of the project.

In a triaxial HTSC cable, conductors for three AC phases are arranged concentrically on a common core inside a common cryogenic envelope, as shown in Figure 1. The electrical insulation between phases must withstand the phase-to-phase voltage rather than the phase-to-ground voltage. The company selected a triaxial HTSC cable because we can expect the following merits. First, as in the case of an ordinary non-SC three-phase cable, we can transmit electricity through three phases of U, V, and W without needing their return paths. With this and taking a triaxial structure, we can reduce the quantity of HTSC conductors and make the cable diameter compact to transmit the same electricity. If we compare the above cable structure with the assembly of three single-phase HTSC cables, approximately two-thirds of HTSC materials is needed because we can reduce the total number of conductors and shields to four from six in the three cables. Third, because we can reduce the total surface area, we can minimize the heat penetration from the outside, which in turn makes it possible to reduce the amount of liquid nitrogen (LN_2) coolant.

The cryostat outer tube shown in Figure 1 is an empty (= vacuum) double tube that serves as thermal insulation. The inside of its inner tube is a passage for liquid nitrogen. In other words, liquid nitrogen circulates, as indicated by the red arrows shown in Figure 1, flowing from the stainless-steel corrugated tube in the center and back to the other side through the space between the cable core and the inner tube of the vacuum isolator. With this structure, liquid nitrogen can cool the HTSC conductors from the inside and outside, eliminating a liquid nitrogen return tube.

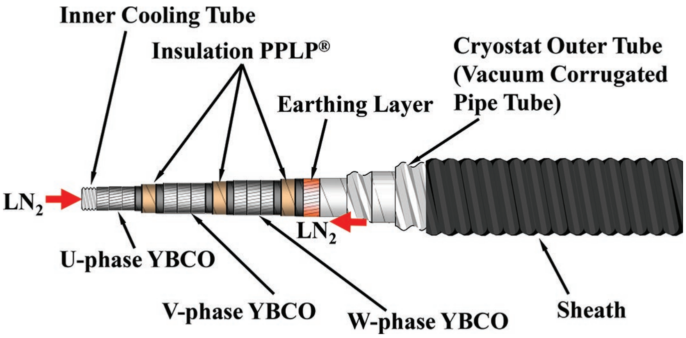

Figure 1. Schematic of the prototype triaxial high-temperature superconductor (HTSC) cable. LN_2 = liquid nitrogen, PPLP = polypropylene laminated paper, and YBCO = HTSC material consisting of yttrium (Y), barium (Ba), copper, and oxygen, with a formula of $Y_xBa_2Cu_3O_{7-x}$ (x = 0.5 to 1.0).

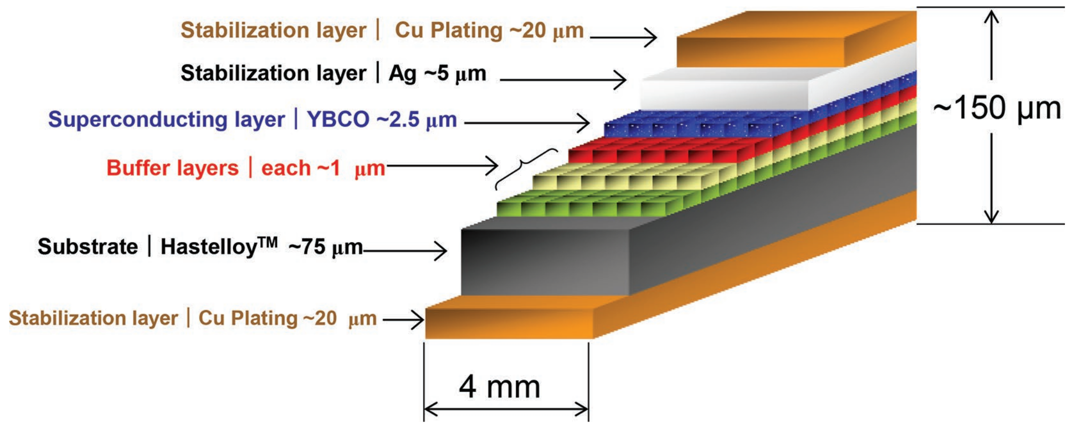

Figure 2. Inner structure of the high-temperature superconducting (HTSC) conductor for the prototype triaxial HTSC cable. Each thickness is not in scale. YBCO = HTSC material consisting of yttrium (Y), barium (Ba), copper, and oxygen, with a formula of $Y_xBa_2Cu_3O_{7-x}$ (x = 0.5 to 1.0), Hastelloy (Haynes International) = a highly corrosion-resistant nickel-chromium-molybdenum alloy.

Figure 2 shows the inner structure of the HTSC conductor used in the cable. The HTSC layer is composed mainly of YBCO deposited on a Hastelloy (Haynes International) substrate. Here, YBCO is a HTSC material consisting of yttrium (Y), barium (Ba), copper, and oxygen, with a formula of $Y_xBa_2Cu_3O_{7-x}$ (x = 0.5 to 1.0) and Hastelloy is a highly corrosion-resistant nickel-chromium-molybdenum alloy. Silver and copper stabilization layers and MgO buffer layers are also important components. The width of the total conductor layer is around 4 mm, and its thickness is around 150 μm, of which 2.5 μm is the YBCO layer, 75 μm is the Hastelloy substrate, and 45 μm is the stabilization layers.

The maximum electric current flowing through each HTSC conductor of the phase U, V, or W was designed to be 3.8 kA. For electrical insulation, the lapping of polypropylene laminated paper (PPLP) with a thickness of 2 mm was adopted. It was confirmed by earlier electric breakdown experiments that the minimum breakdown electric field, E_L, of the PPLP insulation, estimated based on the Weibull statistics, was 36.9 kV/mm for short-time 50/60 Hz AC voltages and 87.4 kV/mm for lightning impulse voltages [9]. Table 1 lists the outer diameters of the prototype HTSC cable and its inner cooling tube, three HTS conductors, and earthing layer. The values of the electric field strength calculated on the surface of these components, which would reach on the application of the commercial-frequency AC and lightning impulse test voltages, are also listed. Table 1 clearly shows that the electric field strength on the surface of each component is well below the corresponding value of E_L for both AC and lightning impulse voltages.

Table 1. Dimensions of the prototype triaxial high-temperature superconductor (HTSC) cable

Item	Diameter (mm)	Electric field (calculated, kV/mm): At 26 kV (AC test voltage)	At 60 kV (lightning impulse test voltage)
Outer diameter	154	—	—
Inner cooling tube	42	—	—
HTSC conductors			
U-phase	46	9.2	21.3
V-phase	52	9.2	21.1
W-phase	58	9.1	21.0
Earthing layer	64	8.3	19.0

The cable company developed an intermediate straight joint to connect two HTSC cables. Figure 3 shows a schematic drawing of the developed joint. The company also developed an outdoor termination. Figure 4 shows its external view. Three current leads to conduct the electric current of each phase outside are arranged coaxially so that we can connect each lead with the conductor of the corresponding phase of the HTSC cable. The electrical insulation is maintained by a stress-cone structure of Kraft paper. A fiberglass-reinforced plastic pipe with excellent thermal insulation performance at cryogenic temperatures was used inside the vacuum thermal isolation tube, with a polymeric hollow tube outside. Solid thermal insulation was also used further outside. With such structures, the termination became compact, as shown in Figure 4. The overall length and height are 4,500 ± 500 mm and 2,000 ± 200 mm, respectively, as shown in Figure 4, whereas the overall width is 500 ± 100 mm.

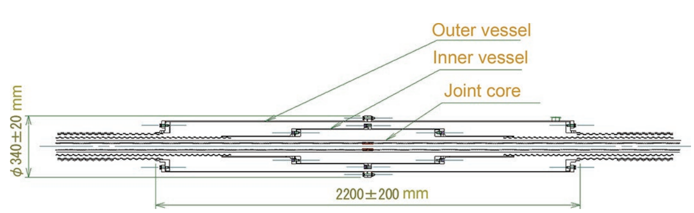

Figure 3. Schematic of the developed straight joint for the prototype triaxial high-temperature superconductor (HTSC) cable.

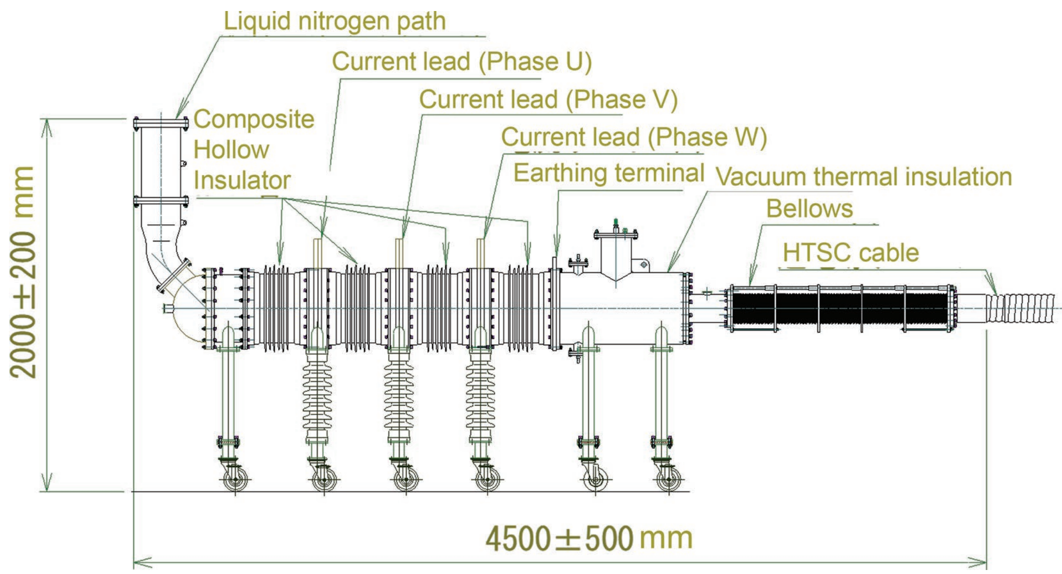

Figure 4. Schematic of the developed outdoor termination for the prototype triaxial high-temperature superconductor (HTSC) cable.

Then, the company conducted a type test according to the procedures given in CIGRE Technical Brochure 538 [10] to confirm the reliability of the developed HTSC cable system. Namely, a 25-m-long 6-kV/3,000-A HTSC cable with one intermediate straight joint and two outdoor end terminations was subjected to the test. During the test, supercooled liquid nitrogen at 68 K was circulated at a flow rate of 20 L/minute. As listed in Table 2, the cable and its joint and terminations passed all the tests.

Next, the company made a similar HTSC cable with a length of 200 m, equipped with two outdoor terminations at each end and two equally-spaced joints. A shunt cable, which was not SC, insulated with cross-linked polyethylene, was also laid, as shown in Figure 5.

The cable system was installed within the distribution network in a chemical plant site of a private company (Totsuka Plant, BASF Japan, Yokohama) for conducting a verification

Table 2. Results of the type test conducted according to the CIGRE TB538 for the prototype triaxial high-temperature superconductor (HTSC) cable with one joint and two end terminations

Test item	Test method	Test result
Bending test	Three 180° turns at a bending diameter below 5.4 m	Passed
Pressure test	No leak at 0.6 MPa for 10 minutes	Passed
Load cycle voltage test	20 cycles of 8-hours-on and 16-hours-off of AC 21 kV	Passed
AC voltage test	26 kV for 30 minutes	Passed
Lightning impulse voltage test	AC 11 kV for 30 minutes, followed by 10 times of imp. ±75 kV. Then, AC 26 kV for 30 minutes	Passed
Partial discharge (PD) test	No PD detection at AC 19 kV	Passed

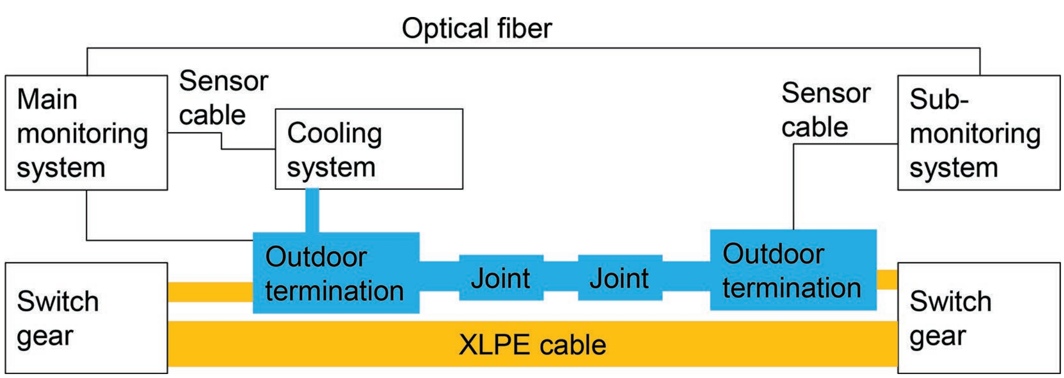

Figure 5. Layout of the arrangement for the verification test on a plant site of the high-temperature superconductor (HTSC) cable with accessories and a shunt cross-linked nonsuperconducting polyethylene cable.

Figure 6. Scene of the verification test, showing the intermediate straight joint.

Figure 7. Scene of the verification test, showing the outdoor end termination.

test for about one year starting the fall of 2020. Figures 6 and 7 are two scenes of the test, showing the intermediate straight joint and outdoor end termination, respectively. During the test, an X-ray inspection was carried out to confirm the presence of the supercooled liquid nitrogen inside the cable mounted 6 m above the ground. In addition, the voltage, current, electric power, temperature, and pressure of the HTSC cable, the flow rate of the liquid nitrogen, and other parameters were recorded on two monitoring systems. As a result, it has become clear that a part of the current flows through the parallel cross-linked polyethylene cable. The reason for this is that the leads outside the two end terminations are not SC. It was confirmed that the current was divided with reasonable ratios, depending on the values of the electrical conductance of the two cable routes. The pressure loss of liquid nitrogen and heat ingress were calculated based on the differences in pressure and temperature between the input and the output ports. As a result, the various parameters experimentally acquired were found to be almost the same as those estimated before the test, proving that the HTSC cable system has high reliability.

The company mentions that the HTSC cable system can reduce power loss by 95% or more compared to conventional cable systems after counting the power required for cooling [8], although it is difficult to go into detail in this short article.

This article was completed in cooperation with Dr. Kazuhisa Adachi of SWCC Showa Cable Systems Co. Ltd.

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