Development of YBCO High-Tc Superconducting Power Cables

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ABSTRACT The high-Tc superconducting cable (HTS cable) is expected to be brought to practical application in the future as a power cable because it can simultaneously realize bulk power transmission, compactness, low loss and low cost. In particular, the coated-conductor of YBCO tape is promising as a superconducting material of the HTS cable thanks to a high critical current and a low cost. Furukawa Electric started developing the YBCO HTS cable in the last NEDO project as Collaborative Research and Development of Fundamental Technologies for Superconductivity Applications under a commission of ISTEC. We investigated the applicability of a coated-conductor to an HTS cable in the project, and we verified that a coated conductor has a good potential for HTS cables. Also, we studied about important technologies related to AC loss reduction, a cable design and a cable joint, and we fabricated and tested a 10 m-class HTS cable.

1. INTRODUCTION

Global warming is one of the most serious environmental issues around the world. Huge ranges of the greenhouse gas, such as CO_2, have been emitted during the history of human development. It is well known that the temperature on the earth have been rising due to the greenhouse gas and that, in particular, amount of the greenhouse gas being emitted into the atmosphere is rapidly increasing recently. If we leave the emission of the greenhouse gas at the same level without taking any countermeasures, we will have to face a critical situation in the future.

Superconductivity is a phenomenon where the resistance of some material becomes zero by cooling it to a cryogenic temperature. The high-Tc superconductor that was found in 1986 obtains a character of superconductivity at the liquid nitrogen temperature of −196°C, even though previous superconductive metals such as NbTi or Nb_3Sn need to be cooled down to the liquid helium temperature of −269°C. The refrigeration cost to cool HTS devices will be much lower than that for metal superconductors. Therefore, the HTS materials are expected to be applied for power devices such as a cable, transformer and fault current limiter, because HTS power devices will additionally bring benefits such as compact, light-weight and energy saving performances compared to conventional power devices using normal-conducting conductors.

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The Furukawa Electric Group has been developing high voltage technologies, low transmission loss technologies and high reliability technologies of transmission lines that are made of copper and aluminum to transmit energy from a power plant to homes and offices, and we supply these products to places all around the world. Furukawa began developing HTS power cable as a next generation power cable based on such technical background. Particularly, an YBCO wire called a coated conductor or 2nd-generation HTS wire is expected to be applied for power cables because it will achieve higher critical currents in high magnetic fields. Also, the price is expected to be low comparable to that of a copper wire when the cost is calculated from wire cost divided by current capacity.

Our study of the technical applicability of YBCO wire to HTS cables, AC loss reducing technology and cable joint, which is an important basic technology, is described in this paper.

2. FUNDAMENTAL TECHNOLOGY TO REDUCE AC LOSS OF THE CABLE

2.1 AC Loss Reducing Technology

When an AC current flows in a superconducting cable, an AC loss is generated in the superconducting wire due to hysteresis behavior since magnetic fluxes try to move by temporally-reversed magnetic field but are trapped by a pinning force that binds the magnetic fluxes in the superconductor. Reducing the AC loss is important from an economic viewpoint because the AC loss becomes the load on refrigerators that are used for cable cooling.

The YBCO wire with a coated conductor structure applied for an HTS cable is shown in Figure 1. An intermediate layer and a superconducting layer are formed on a substrate, and a silver layer is formed to protect the superconducting layer. In addition, a copper tape is laminated on the YBCO tape to prevent burnout from over-current. The conductor of an HTS power cable has a structure in which the HTS wires are wound spirally around a former. In our studies, a large AC loss is generated at the perpendicular magnetic field on the edges of the tape [1]. See Figure 2(a). When an HTS power cable is made with YBCO wires, how to decrease the perpendicular magnetic component applied to the HTS wire is the key point for AC loss reduction. We have found that by winding tapes with a width as narrow as possible around the former with gaps as narrow as possible between the tapes, and by making its shape closer to a cylinder shape as shown in Figure 2 (b), the perpendicular magnetic component can be decreased [1].

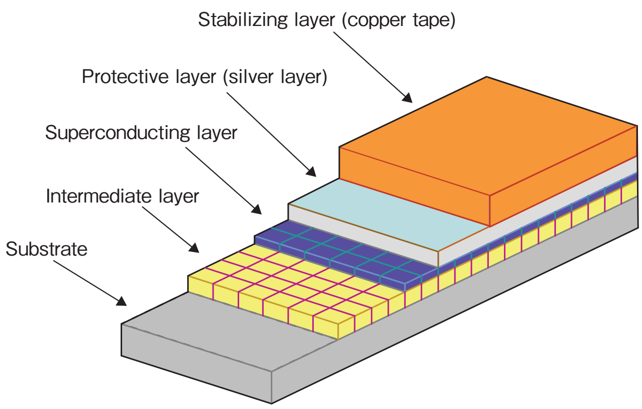

Figure 1 Structure of YBCO tape.

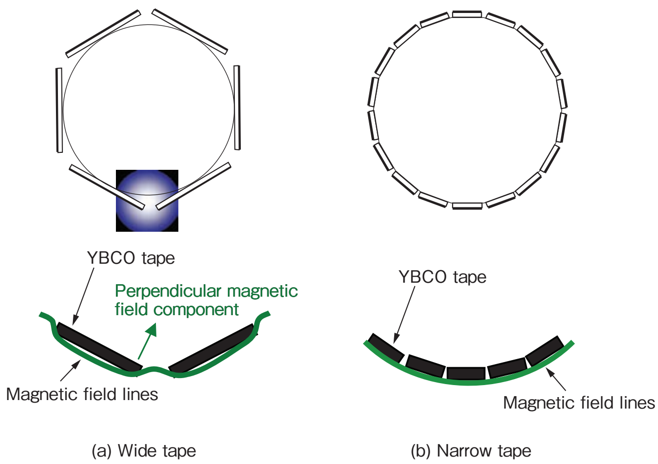

Figure 2 YBCO tape winding form and magnetic field generation.

2.2 Cutting Technology of YBCO Wire

It has been discovered that reducing of AC loss can be achieved by making HTS layer close to a perfect circle using narrow width tapes. A laser cutting method was developed as a measure to cut the HTS tape into a narrow width. The laser cutting is a method in which the concentrated high power laser light is directly irradiated on the tape and a melted part of the tape is blown away by gas. Therefore, the laser can cut the tape with a minimum decrease of critical current because the heat-affected zone is small.

When we actually cut the wire once and measured the critical current before and after cutting, degradation ratio of the critical current was found to be from 2 to 5 %. This indicates that the heat-affected zone was limited. Moreover, the laser cutting also can be applied to the copper laminated YBCO wire because it can cut the YBCO tape and the laminated copper tape simultaneously. All YBCO wires for the HTS cable in our R&D were narrowed by applying this method after combining the YBCO tape and the copper tape.

Figure 3 shows the laser cutting machine and Figure 4 shows the 10 mm-wide tape divided into 5 pieces.

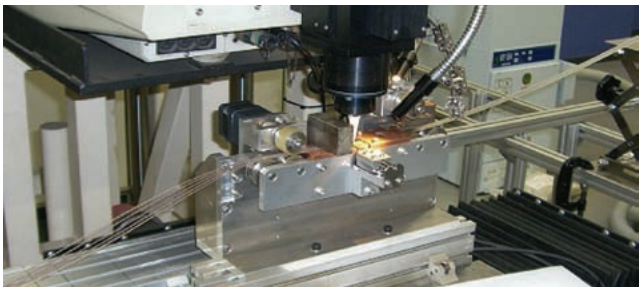

Figure 3 Laser cutting machine for YBCO tape.

Figure 4 YBCO tape divided into 2 mm in width.

2.3 Cu Tape Laminating Technology

If a short circuit accident happens in the real network, a fault current that has about ten times larger value than an operation current flows in a power cable for a few seconds. An ordinary YBCO tape is consisted of a substrate that has high electrical resistance, an intermediate layer of an insulating material, a superconducting layer and a silver layer with thin thickness. If large current over the critical current flows in the YBCO wire, the wire burns out immediately. Copper tape is laminated on the YBCO tape to prevent the burn-out of the tape as shown in Figure 1 and Figure 5. Figure 6 shows the equipment that solders the copper tape of 50 μm to 100 μm in thickness and the YBCO tape together. The equipment can laminate a 500 m-long wire with 200 m/hr of speed, by means of a Pb-free environment-friendly process.

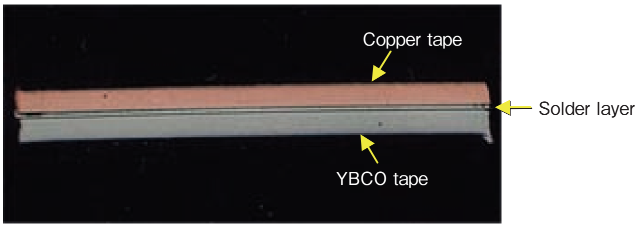

Figure 5 **Copper-composite YBCO tape of 2 mm in width (cross-section).**

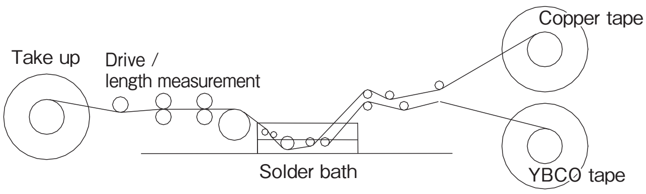

Figure 6 **Laminating machine for copper-composite YBCO tape.**

3. 66/77-KV CLASS TRIPLEX HTS POWER CABLE

3.1 Cable Structure

The structure of a superconducting cable is such that multiple superconducting tapes are spirally wound on the center core called former, which is covered by an electric insulation layer, and then by a superconducting shielding layer and a protection layer which constitute a cable core, and the three cores are accommodated in a thermal insulation pipe in which liquid nitrogen flows as shown in Figure 7. Only one HTS cable is necessary to transmit three-phase ac power. Liquid nitrogen flows in the gap between cores and inside of the thermal insulation pipe. Specifications of the 66/77-kV class triplex HTS cable are described in Table 1. The cable can be installed in a common cable duct of 150 mm in diameter that is used in metropolitan areas of Japan.

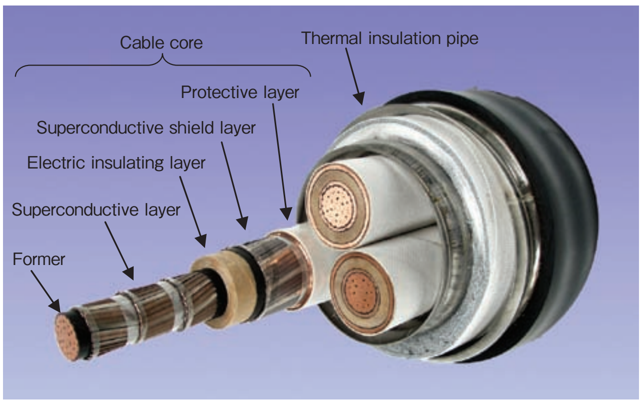

Figure 7 **66/77-kV high-Tc superconducting power cable (triplex type).**

A 66/77-kV class power cable needs to withstand the fault current of 31.5 kA for 2 seconds. A copper stranded conductor with a cross section of 200 mm^2 was used to the former to make large portion of the fault current flow in it. Cable temperature was designed to be suppressed at 140 K immediately after the fault current flowing [2].

Table 1 **Specifications of 66/77-kV YBCO high-Tc superconducting power cable.**

Item	Structure	Outer Diameter
Former	Copper stranded conductor Section area : 200 mm^2	18.3 mm
HTS conductor layer	3 layers Tape width: 2 mm 82 tapes	21.1 mm
Electrical Insulation layer	Liquid nitrogen impregnated multilayer paper insulation	35.5 mm
HTS shield layer	Single layer Tape width: 2 mm 50 tapes	36.2 mm
Protection layer	Cu tape layer + Insulation tape layer	40.0 mm
Thermal insulation pipe	Vacuum thermal insulation pipe made of coaxial corrugated pipe, and multilayer insulation	133 mm

3.2 Development of Cable Joint

HTS power cables will be used as an underground cable in urban areas. We need to develop cable joints that connect several hundred meter cables in a manhole because there is a limitation in cable length due to the transportation to the site using trucks.

We need to avoid that the joint become the weak point in current loading, voltage loading, liquid nitrogen circulation and mechanical property when a cable system with the joints is operated. Therefore, we designed the whole joint and the joint parts using development technologies including low resistance joint method of the HTS tapes, strong joint method of the formers, and no-leak joint method of the thermal insulation pipes. The structure of the joint is shown in Figure 8 and the joint that was fabricated is shown in Figure 9. As shown in Figure 10, two HTS tapes were connected in such a way that a connecting HTS tape 10 mm in width was soldered on the copper laminated layer of the two cable tapes to make a face-to-face contact to reduce the joint resistance.

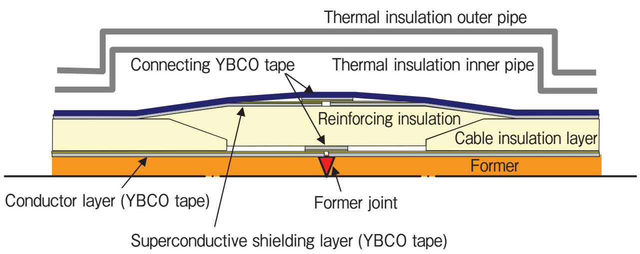

Figure 8 **Schematic cross-section of normal joint for superconducting power cable. Cable cores for other two phases not shown.**

Figure 9 Normal joint for superconducting power cable.

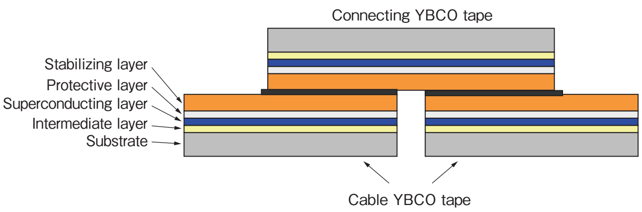

Figure 10 Schematic of YBCO tape jointing for normal cable joint.

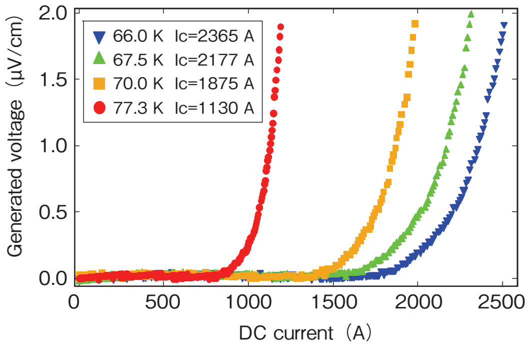

Figure 11 Measurement results of critical current (Ic) of 10-m long YBCO superconductor.

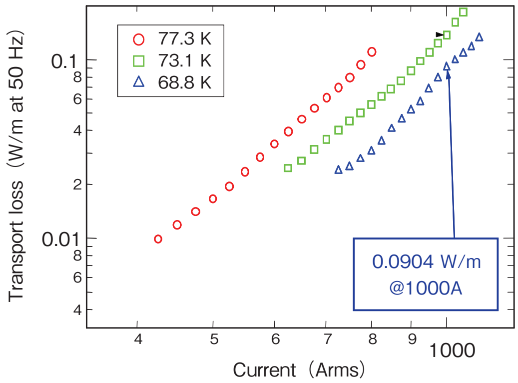

Figure 12 Measurement results of AC loss of 10-m long YBCO superconductor.

4. 10-M HTS CABLE TESTS

4.1 AC Loss Measurement

A 10 m-long HTS cable was fabricated using the YBCO tapes that are laminated with copper tape and cut into 5 pieces by laser, and the critical current and the AC loss were measured. Chubu Electric Power Company had provided two 200-m YBCO tapes named IBAD-MOCVD tapes. The tape was manufactured in such a way that a GZO ($Gd_2Zr_2O_7$) intermediate layer was formed on a hastelloy substrate tape by the IBAD (Ion Beam Assisted Deposition) method, CeO_2 was deposited by the PLD (Pulsed Laser Deposition) method to make an oxide cap layer and a YBCO layer was formed by the MOCVD method [3]. Specifications of the tape and the cable are shown in Table 2.

Critical current of the 10-m conductor was measured at various temperatures. The critical currents are shown in Figure 11 as the V-I curves at different temperatures. AC loss was measured at 68 K and was 0.090 W/m at 1 kA. AC loss measurement results at different temperatures are shown in Figure 12.

Table 2 Specifications of 10-m long YBCO superconductor.

Item	Specification
Former	Type: Cu stranded conductor Cross section: 200 mm^2
Length	10 m
YBCO tape	Supplier: Chubu Electric Power Company Type: IBAD-MOCVD tape Structure: Substrate: Hasteroy 0.1mm/IBAD-GZO/PLD-CeO_2 HTS layer: MOCVD-YBCO Protect layer: Ag, 25 μm in thickness Stabilizing layer: Cu, 0.1 mm in thickness Length: 200 m x 2 tapes Width of original tape: 10 mm Critical current: Ic=100 A/cm
Structure of conductor	Tape width after dividing process: 2 mm Tape number: 82 Layer number : 3 Outer diameter of conductor: ϕ21.1 mm

4.2 Fault Current Test

We demonstrated a 20 m-long HTS cable that was constructed with two 10-m HTS cables with a cable joint. One cable was the 10-m cable mentioned previously and the other was fabricated by Sumitomo Electric Industry. We measured the joint resistance in the cable joint and carried out an over current test in which a fault current of 31.5 kA flowed in the cable for 2 seconds, while the cable was cooled with liquid nitrogen at 77.3 K. DC currents and voltages were measured at voltage taps that were provided 40 cm apart on the outer layer of the conductor in the joint. The voltage-current dependence is shown in Figure 14. Joint resistance was 0.005 $\mu\Omega$ in linear voltage rising area until 600A. The resistance went up gradually with increasing current; however it was extremely low as 0.034 $\mu\Omega$ at a conductor current of 1.2 kA where the generated voltage in the conductor became 1 μV/cm, equivalent to the critical current.

Moreover, the 20-m HTS cable with a cable joint underwent a fault current test in which an over current of 31.5 kA flowed for 2 seconds-- nearly the same as for the fault current in a real network of 66/77-kV transmission voltage--, and although the cable showed the maximum temperature rise of around 80 K almost as designed, virtually no damage such as a critical current decrease was observed. From these results, we confirm that YBCO HTS cable would be used as a power cable instead of XLPE cables in near future. From these results, we confirm that YBCO HTS cable would be used as a power cable instead of XLPE cables in near future.

Figure 13 Fault current test of 20-m long superconducting power cable.

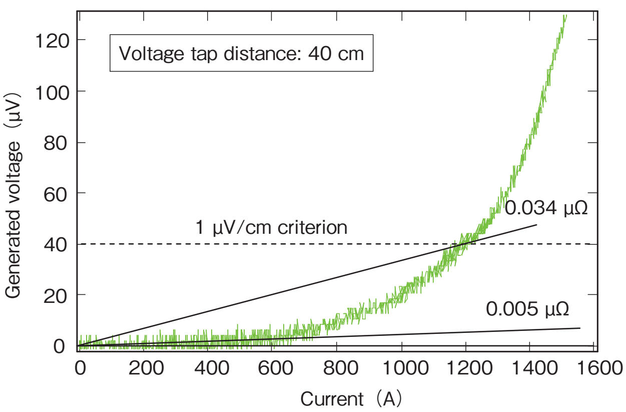

Figure 14 Measurement results of resistance of normal joint.

5. CONCLUSIONS

We have developed a superconducting cable where we used coated conductors of YBCO wires in order to meet the requirement of low loss and low cost for a power cable. In particular, we have been engaged in development of elemental technologies for AC loss reducing, countermeasure against fault current, cable joint design and so on, in addition to proving the possibility of YBCO wires to be applied as an HTS power cable. We can have new knowledge regarding the minimized AC loss of 0.09 W/m at 1 kA, stability against a fault current of 31.5 kA for 2 seconds and a cable joint for a 66/77-kV HTS cable with low electrical resistance.

The development of superconducting cable technology will continue toward the application of HTS power cables to practical fields by further utilizing the superconducting technologies, power cable technologies and material technologies of Furukawa. We are going to take part in the new NEDO project, in which the power application of coated conductors will be further studied, aiming to develop 275-kV class ultra-high voltage HTS power cables in the project [4].

6. ACKNOWLEDGMENT

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