RECENT DEVELOPMENT OF HIGH-TEMPERATURE SUPERCONDUCTING (HTS) CABLE IN SUMITOMO ELECTRIC INDUSTRIES, LTD.

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INTRODUCTION

Three HTS cable demonstrations in Yokosuka (Japan) by Tokyo Electric Power Company (TEPCO) and Sumitomo Electric Industries, Ltd. (SEI), Copenhagen (Denmark) by NKT and Carrollton (US) by Southwire were successfully implemented. After these successful milestones, the HTS cable development has been entered into the 2nd stage. Three Bi-based cable projects, which are in the real network, have started in US under international collaborations. Also, Asian HTS cable projects are on-going in Japan, Korea and China. SEI is now engaging in the US Albany Project and KEPRI (Korea Electric Power Research Institute) Project adopting Sumitomo's 3-core in one cryostat type (3-in-One^{TM}) HTS cable for distribution network.

HTS CABLE

When compared with conventional power cables, HTS cable has much larger transmission capacity with smaller cable diameter.

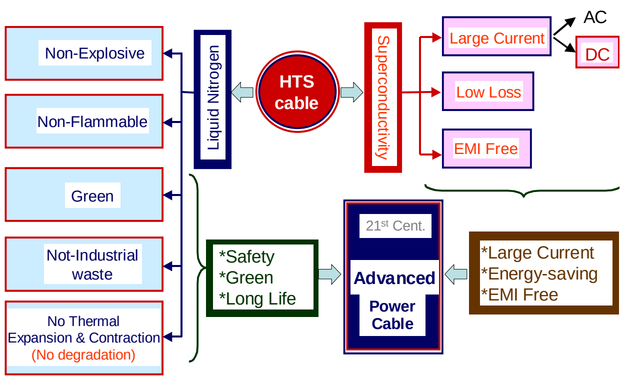


Figure 1: Merits of HTS cable

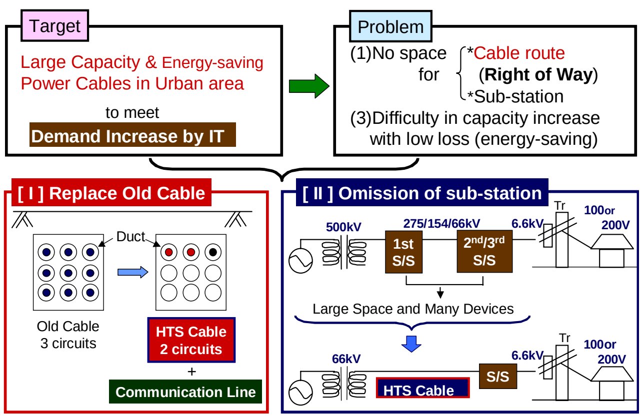
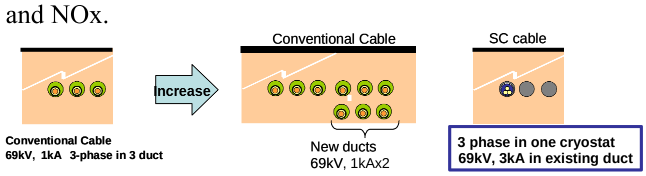


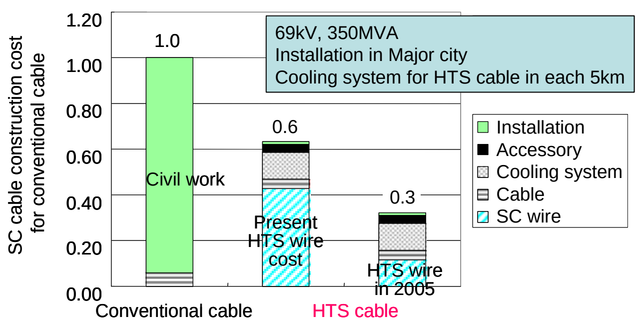
Figure 2: Effective applications for HTS cable

This feature makes it so simple to increase the capacity of power transmission or distribution network, because it can be obtained by only replacing the existing conventional cable by HTS cable instead of constructing a new network. Figure 1 shows the merits of HTS cable and Fig. 2 shows the effective cases of HTS cable application respectively.

For example, with conventional cable, three lines are normally required to transmit the power of one 66 kV, 1 kA circuit. With these lines, if the demand for electric power expands to the extent that a three-fold increase in transmission capacity is required, six new cables must be installed. Using a 3-core HTS cable, however, a 200% increase in transmission capacity can be obtained by installing just one HTS cable, that is, there is no need to construct new conduits (Fig. 3-(a)). The cost of line construction, especially in a large city like Tokyo or New York, is extremely high. Figure 3-(b) shows a comparison of the construction cost between conventional cable and HTS cable under the above conditions. HTS cable line construction cost, calculated assuming that current construction techniques and cooling system in every 5km are used, is likely to be much lower than the cost of constructing a new line of conventional cables. From the above reason, HTS cable is expected to be cost competitive. The feature, that the transmission energy loss of HTS cable is less than half of that of conventional cable, is another important factor to be pointed out (Fig. 4). This feature contributes to reduce greenhouse gas emission such as CO_2 and NOx.



(a) Increasing capacity (1kA→3kA)



(b)Total installation cost comparison of conventional cable and SC cable

Figure 3: Total installation cost of SC cable

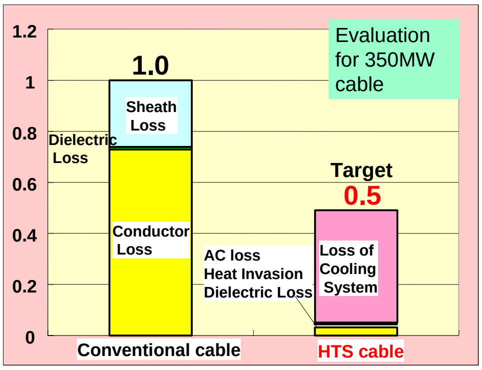


Figure 4: Transmission loss

HTS cable construction

The structure of HTS cable is shown in Fig. 5. The conductor is formed by laying the Bi2223 wires in a spiral onto a former. PolyPropylene Laminated Paper (PPLP®) is used for the electrical insulation due to its good dielectric strength and low dielectric loss at low temperatures, liquid nitrogen works as compound liquid insulation in addition to coolant. On the outside of the insulation layer, Bi2223 wires are wound in a spiral to form a shield layer. Each shield layer of each core is connected to each other at both ends of the cable, so that an electrical current of the same magnitude as that in the conductor is induced in the shield layer in the reverse direction, thus eradicating the electromagnetic field leakage outside the cable. Three cores are stranded together, and are placed inside the double-layered SUS corrugated pipes. Thermal insulation is placed between the inner and outer SUS corrugated pipes, where a vacuum state is maintained to improve the thermal insulation performance.

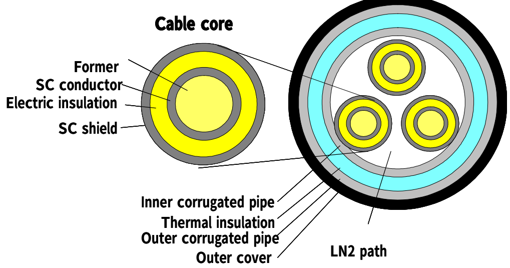


Figure 5: Structure of HTS cable

TEPCO project

The demonstration test jointly conducted with TEPCO and CRIEPI in 2001 through 2002 involved the 100 m, 66 kV, 1 kA class cable, and this test was successfully implemented for a year. The achievements are summarized below.
*Withstand voltage test: Cleared AC 66 kV (Phase to Phase）.
*Transmission capacity: A 200 MVA (at 2000 A) transmission capacity was confirmed. The Ic at that day was 50 A, but it exceeds 100 A at present. This means that the current HTS cable is expected to carry around 350 MVA (3000 A class), the target value of this cable.
*Cable length: Our 100 m long HTS cable confirmed the feasibility of producing a 500 m class cable, the target length taken from transportational restriction and a normal distance between manholes. To extend the cooling distance, the pressure loss must be reduced, and this can be achieved by decreasing AC loss of HTS wire, resulting in less amount of coolant flow. Now, SEI is keenly doing R&D on the reduction of AC loss of HTS wire.
*Distance between Cooling Stations: The target cooling station installation interval is 3 to 5 km, which is comparable to that of oil feeding distance of Oil Filled (OF) cable.
From the achievements, the further improvement of BSCCO 2223 wire is one of the most important factors for the utilization.

DEVELOPMENT OF CT-OP BSCCO WIRE

At present $(Bi,Pb)_2Sr_2Ca_2Cu_3O_X$(Bi2223) HTS wire (Tc :110 K) is a promising candidate among various kinds of HTS wires which can be put into practical use. SEI has proceeded with R&D on Ag-sheathed wires using Bi2223 superconductor and has developed long wires (in kilometer-class) with high Jc that can be semi-mass-produced. Since “not 100% mass density” causes formation of pores and decreases supercurrent between Bi2223 grains grown during sintering, SEI decided to apply the ConTrolled Over Pressure (CT-OP) sintering, which attempts to obtain “100% mass density” by applying gas pressure to Bi2223 wires during the second sintering.

Process of Bi2223 HTS wires

The manufacturing method of Bi2223 wires is called as Powder-In-Tube (PIT) method (Fig. 6). The appearance of wire is tape-shaped as shown in Fig. 8(a), the width is ranging from 4.0 to 4.5 mm and the thickness is from 0.2 to 0.25 mm (Fig. 7). Bi2223 wire consists of multi-filaments (black parts) ensheathed by silver or silver-alloy (white part) [1]-[3]

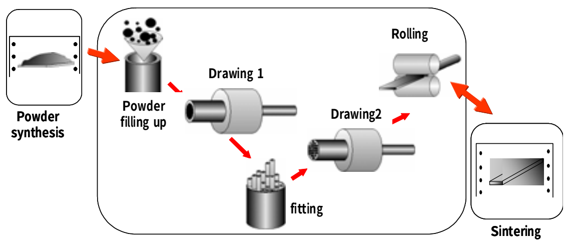


Figure 6: Manufacturing process of Bi2223 wire

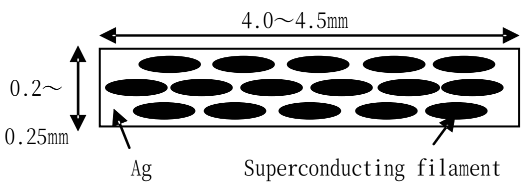


Figure 7: Cross-sectional view of Bi2223 wire

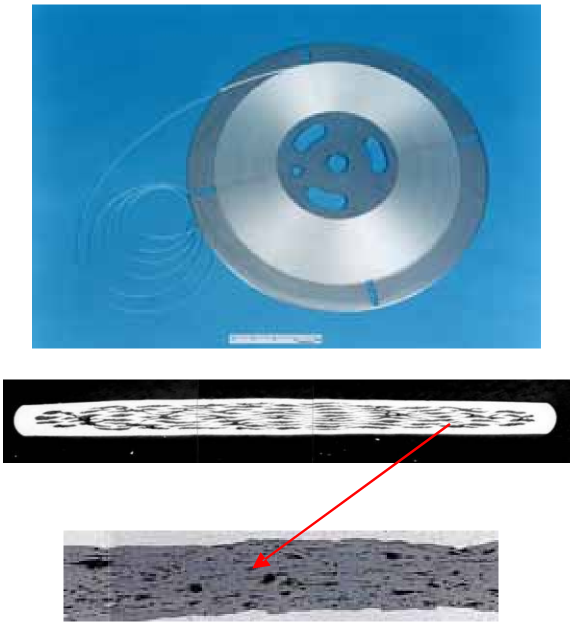


Figure 8: Bi2223 superconducting wires: (a) appearance, (b) cross-sectional view and (c) SEM image.

CT-OP

In order to manufacture high-performance Bi2223 wires, it is necessary to carry out second rolling and second sintering. After the second rolling, Bi2223 grains become little worse (Fig. 9(b)) and cracks appear and such cracks cannot be improved sufficiently by the second sintering. Therefore, SEI decided to apply the CT-OP sintering, in which external isostatic gas pressure (a mixture of oxygen and inert gas) is applied to Bi2223 wire in order to obtain 100% mass density of Bi2223 filaments (Fig. 9(a)).

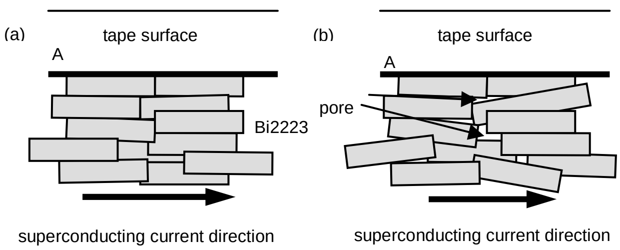


Figure 9: Connectivity between Bi2223 grains. (a)dense and (b) nondense state.

Critical current performance

Table 1 shows the comparison between normal and CT-OP sintering in terms of superconducting current. Ic, Je and Jc are defined as critical current, critical current density per cross-sectional area of wire and critical current density per cross-sectional area of filament, respectively. Jc values of normal sintered sample are 26.0 kA/cm^2 and 32.3 kA/cm^2 and CT-OP sintered sample are 38.9 kA/cm^2 and 40.0 kA/cm^2 in the wires of the silver ratios of 1.5 and 2.2, respectively. Jc becomes 130% or higher by CT-OP sintering. This suggests that CT-OP sintering is an effective method for improving the performance of Bi2223 wires due to 100% mass density of Bi2223 filaments.

Table 1: Ic, Je, Jc of normal and CT-OP sintered samples (1µV/cm, 77 K).

	Silver ratio: 1.5		Silver ratio: 2.2	
	normal	pressure	normal	pressure
Ic (A)	99	131	74	92
Je (kA/cm^2)	10.6	14.3	8.7	10.4
Jc (kA/cm^2)	26.0	38.9	32.3	40.0

Mechanical property

Mechanical property is one of the important factors when Bi2223 wires are applied to practical products. To improve mechanical property, silver-alloy sheath is adopted. Silver ratio also affects mechanical property of Bi2223 wire. Considering that Bi2223 wires consist of filaments and silver or silver alloy, filaments also affect the mechanical property of wires. SEI measured the mechanical property of CT-OP sintered sample, which clearly changed the state of filaments. In a tensile stress tolerance test, Ic was measured at 77 K using stressed samples at room temperature. Figure 10(a) and (b) show results in the silver ratio of 1.5 and 2.2, respectively. Ic0 of vertical axis represents Ic of no stressed sample.

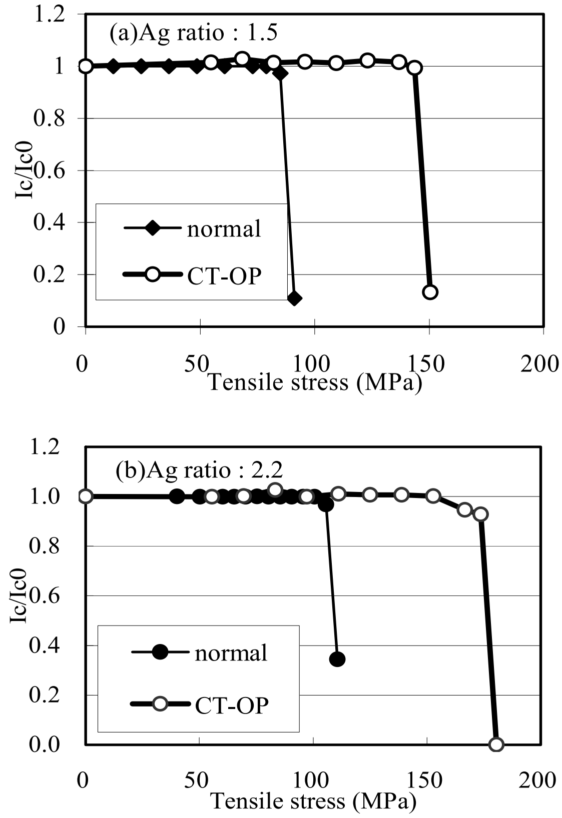


Figure 10: Ic dependence on the tensile stress of the normal sintered wire and CT-OP wire in case of the silver ratio of 1.5 (a) and 2.2(b). I_c and I_{c0} mean critical currents after and before tensile stresses are applied, respectively.

The tensile stress value from which Ic/Ic0 degradation takes place is 85 MPa and 106 MPa on normal sintering and 144 MPa and 167 MPa on CT-OP sintering in the wires of the silver ratio of 1.5 and 2.2, respectively. It is considered that

CT-OP suppresses pores and cracks so that mechanical property of filaments can be improved. Furthermore, considering that tensile stress value in CT-OP samples of silver ratio of 1.5 (144 MPa) is higher than that in normal sintered samples of silver ratio of 2.2(106 MPa), the strength of filaments clearly improves the mechanical property of Bi2223 wires.

Applicability to liquid nitrogen cooling system

Liquid nitrogen cooling system is essential for applications such as power cable and transformer using Bi2223 wire. When cooled in liquid nitrogen and warmed up to room temperature, wires may balloon by vaporization of liquid nitrogen that has entered into filaments through silver sheath. The ballooning will result in the significant degradation in Ic because filament shape is deformed. However, if no pores exist in filaments, wires should never be ballooned. The CT-OP wires with no pore and no crack are not ballooned even without additional hermetic materials, as is confirmed that 1,000m long wires are not ballooned at all after cooled in liquid nitrogen under 1 MPa for 24 hours.

On-going HTS Cable project

In the USA, the US Department of Energy's (DOE) SPI project is promoting the development of HTS cables. The 120 m long HTS cable test line in Detroit was not successful[4], but the Southwire Company's 30 m long cable test has successfully been operating for over 28,000 hours[5].
Three new projects started lately, and these are accelerating the development and application of HTS cables to strengthen the US power grid, which showed its vulnerability during the massive blackout in New York in August 2003[6]. These three projects are the Albany project (350 m, 34.5 kV, 800 A) [7], Ohio project (300 m, 15 kV, 2 kA)[8], and LIPA project (600 m, 138 kV, 2.4 kA)[9], and these projects are scheduled to begin operation over 2005-2006.
Also, Asian HTS cable projects are on-going in Japan, Korea and China.

Albany project

The Albany project will use a 350 m, 34.5 kV, 800 A, 3-core cold dielectric type HTS cable as part of the line between two sub-stations (Menands and Riverside) in Albany, New York, and this cable will be subjected to a long-term operation. Fig. 11 shows a photograph of the planned construction site[10].

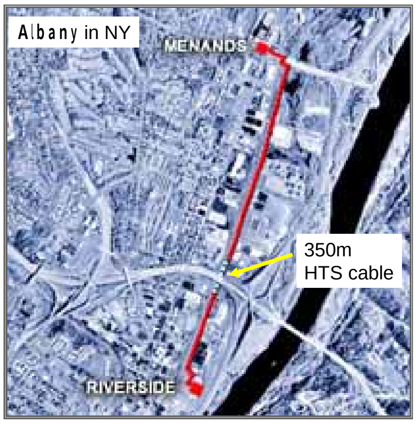
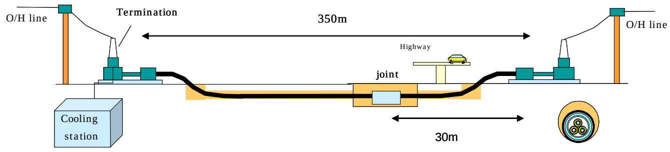


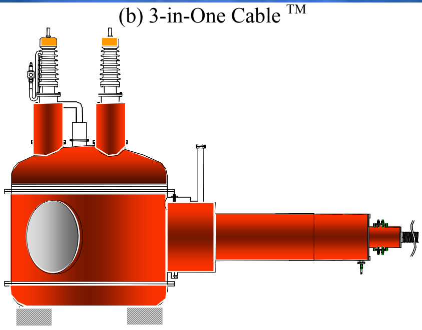
Figure 11: Test site of Albany project (Albany in NY state)

The construction and test is planned to extend over a 4-year period (2002 to 2006) and will be the world first long HTS cable line to be utilized in an actual power grid.
SEI's role in this project is to manufacture, install, construct and connect the cable to the actual line as well as to operate a practical HTS cable line under actual loads. SuperPower Inc. serves as a primal contractor, Niagara Mohawk offers the test-site and supplies a power, The BOC group is in charge of cooling system.

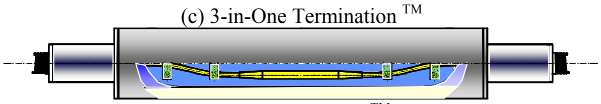


(a) Cable System Overview

(b) 3-in-One Cable TM



(c) 3-in-One Termination TM



(d) 3-in-One Joint TM

Figure 12: Schematic view of Albany cable system

The cable system configuration is shown in Fig. 12. The cable is divided into two sections, one 320 m and the other 30 m in length, and they will be connected by a joint. The

cable will be installed in a newly constructed underground duct with an inside diameter of 6 inches (152 mm).
A 30m portion is planned to be replaced by 2G(YBCO) HTS cable manufactured by SEI, using SuperPower's 2G wires during the latter half of the test period.

KEPRI project

In Korea, it is required to improve the reliability of electric power transmission and distribution network by increasing its capacity to catch up the rapid increase of electric power consumption especially in the urban area. It is very difficult, however, to install a new power transmission or distribution line or sub-stations, due to luck of available space in the underground cable tunnels and cable ducts as well as the difficulty of obtaining the right of way for new cables. Therefore, high power HTS cables are expected to be put into practical use soon.
SEI is awarded the tender for HTS Cable System from Korea Electric Power Research Institute (KEPRI) that is the Central Research Laboratory of Korea Electric Power Corporation (KEPCO).
SEI will supply not only cable and termination but also cooling system as well as implement the installation work at KEPRI's test yard in Kochang, Korea. The principal specification of the system is shown in Table 2 and the schematic view of the system is shown in Fig. 13, respectively.
KEPRI will perform various kinds of tests and experience necessary matters related to the operation and maintenance of HTS cable system. KEPRI will conduct feasibility study of applying HTS cable to real grid from these results. The cable installation is scheduled to start in spring next year and start operation in summer 2005.

Table 2: Principal specification of KEPRI HTS cable system

Length	100 m
Rated Voltage	22.9 kV
Nominal Current	1250 Arms
Cable Type	3-in-One(3 cores in one Cryostat) HTS cold dielectric type cable

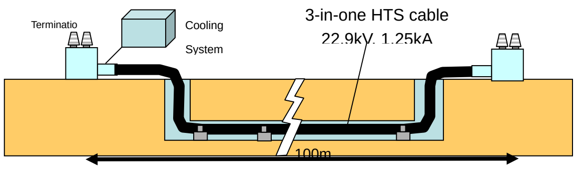


Figure 13: Schematic view of the KEPRI cable system

CONCLUSION

In this 21st century, supported by 3 key matters, "Environment", "Energy", "Natural resources", the importance of HTS technology is increasing more and more to the human society. HTS Cables with Large Transmission Capacity and Low Loss are environmentally friendly, hence indispensable for 21st Century's Power Grid and the innovated Bi-based wire is leading the HTS cable.

REFERENCES

[1] S. Kobayashi, T. Kaneko, N. Ayai, K. Hayashi, H. Takei, and R. Hata, *Physica C*, 357-360, 1115, (2001).
[2] T. Kaneko, S. Kobayashi, K. Hayashi, and K. Sato, 1997, *Advances in Superconductivity IX*, Tokyo: Springer, p907
[3] S. Kobayashi, T. Kaneko, M. Ueyama, T. Hikata, K. Hayashi, K. Sato, 1998, *SEI TECHNICAL REVEIW*, 153, p10
[4] http://www.amsuper.com/press/2002/Detroit_Update.pdf
[5] R. Hawsey, "Overview of U.S. High Temperature Superconductivity Program for Electric Power", *The 2004 International DAPAS workshop*
[6] "Grid 2030, A National Vision For Electricity's Second 100 years", DOE (2003)
[7] T. Masuda, et al., 2004, "Design and Experimental Results for ALBANY HTS Cable", *ASC2004*, 1LT05
[8] J. W. Lue, J.A. Demko et al., 2003, "Tests of 5-m long Triaxial HTS cable", ICEC2003
[9] M Hervey , M. Mccarthy, presented by EPRI Superconductivity Task Force Meeting (Oct. 2003)
[10] C. Weber, presented by EPRI Superconductivity Task Force Meeting (Oct. 2003)
[11] S. Kobayashi, T. Kato, K. Yamazaki, K. Ohkura, K. Fujino, J. Fujikami, E. Ueno, N. Ayai, K. Hayashi, K. Sato, 2004, "Controlled over pressure processing Bi2223 long length wires" *ASC2004*