# High-temperature Superconducting Cable Technology and Development Trends

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Superconducting cable is expected as one of the solutions for the shortage of transmission capacity in metropolitan areas. Its merits are as follows; (1) large transmission capacity in compact dimension, (2) small transmission loss, (3) no leakage of electro-magnetic field to the outside of the cable, and (4) small impedance. These features are effective for the improvement of reliability and economical competitiveness of electrical networks. Recently, a lot of demonstration projects have started around the world in order to accelerate the application of superconducting cable to the real network systems and its commercialization. In the USA, there are three Superconductivity Partnership Initiative (SPI) projects that are funded by Department of Energy (DOE) and presently under execution. The Albany Project, which is one of these projects and funded also by New York State Energy R & D Association (NYSERDA), is being conducted by SuperPower Inc. (main contractor), Niagara Mohawk (utility company), BOC (cooling system company) and SEI. SEI is in charge of manufacture and installation of 350-m-long superconducting cables, development of terminals and joints, and implementation of the long-term test. The project is planned for 4 years (2002-2006).

## 1. Introduction

Because superconducting cable is compact and can transmit a large amount of electric power, it can utilize more effectively congested underground space where a lot of pipings and other units already exist. Superconducting cable also makes overall construction cost smaller than that of conventional cable.

In the development of Bi-based superconducting wires, a newly developed pressurized sintering method allowed mass production of a low-cost long wire with a high critical current. The critical current of superconducting wire exceeds 130 A per wire (4 mm x 0.2 mm), and it has an increased tensile strength of 140 MPa (at RT), which is an important mechanical property for making the cable practical. Furthermore, uniform characteristics can be obtained for 1 km long wire, even when mass-produced. (1)

Meanwhile, in the development of superconducting cable, SEI has been developing a 3-in-One HTS cable with no electromagnetic field leakage to achieve a compact cable with low transmission loss.

From 2001 to 2002, Sumitomo Electric Industries, Ltd. (SEI) successfully conducted a long-term test of a 66 kV, 1 kA, 114 MVA class superconducting cable in collaboration with Tokyo Electric Power Company (TEPCO) and the Central Research Institute of Electric Power Industry (CRIEPI) at CRIEPI' s Yokosuka Laboratory, to verify its practical performance and to identify problems. (2)

Buoyed by these results, SEI is aiming for the early commercialization of practical superconducting cable, and is participating in a superconducting cable demonstration project (Albany Cable Project) in the United States.

This paper summarizes the advantages of superconducting cables, introduces the results from viability testing conducted with TEPCO, and reports the profile and progress of the Albany Cable Project, which is currently in progress.

## 2. Superconducting Cable Construction

The structure of a superconducting cable is shown in **Fig. 1**. The conductor is formed by laying the Bi-based superconducting wires in a spiral on a former. Polypropylene Laminated Paper (PPLP) is used for the electrical insulation due to its good insulation strength and low dielectric loss at low temperatures, and liquid nitrogen works as a compound insulation in addition to coolant. On the outside of the insulation layer, a superconducting wire of the same conductor material is

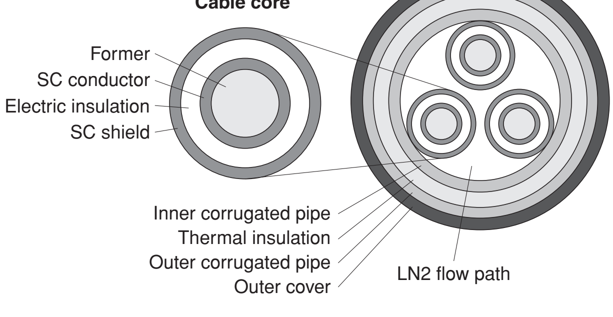



**Fig. 1.** Structure of SC cable

wound in a spiral to form a shield layer. Each shield layer of each core is connected to each other at both end 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 reducing the electromagnetic field leakage outside the cable to zero. Three cores are stranded together, and this is placed inside a double-layered SUS corrugated piping. Thermal insulation is placed between the inner and outer SUS corrugated pipings, where a vacuum state is maintained to improve the thermal insulation performance.

## 3. Advantages of Superconducting Cable

### 3-1 Compactness and High Capacity

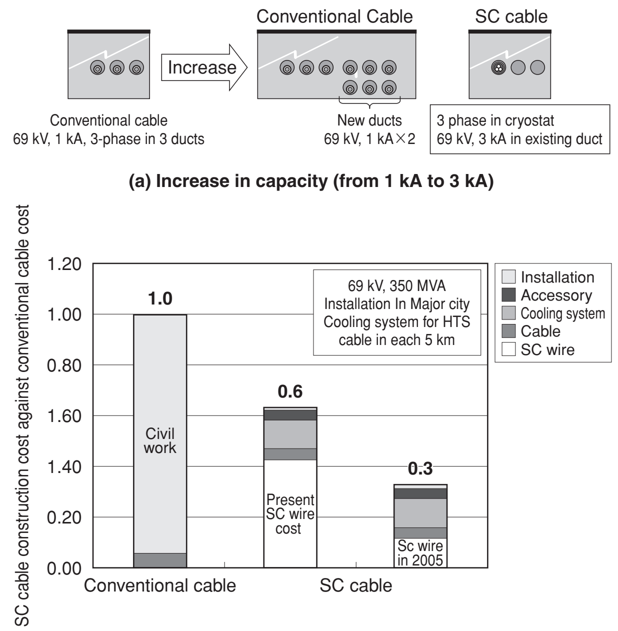
Superconducting cable can transmit electric power at an effective current density of over 100 A/mm$^2$, which is more than 100 times that of copper cable. This allows high-capacity power transmission over the cables with more compact size than conventional cables, which makes it possible to greatly reduce construction costs.

For example, with conventional cable, three conduit lines are normally required to transmit the power for 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 conduit lines must be installed to lay the new cable. Using a 3-core superconducting cable, however, a 200% increase in transmission capacity can be obtained by installing just one superconducting cable without construction of new conduit (**Fig. 2-(a)**). The cost of conduit line construction, especially in a large city like Tokyo or New York, is extremely high. **Figure 2-(b)** shows a comparison of the construction cost between conventional cable and superconducting cable under the above conditions. The superconducting cable line construction cost, calculated assuming that current construction techniques are used and cooling system is in every 5 km, is likely to be much lower than the cost of constructing a new conduit line of a conventional cable. From the above reason, the superconducting cable is expected to be cost competitive.

### 3-2 Low Transmission Loss and Environmental Friendliness

In superconducting cables, the electrical resistance is zero at temperatures below the critical temperature, so its transmission loss is very small. And the superconducting cable developed by SEI has a superconducting shield, so there is no electromagnetic field leakage outside the cable, which also eliminates eddy current loss from the electromagnetic field. **Figure 3** shows a comparison of the transmission loss in a superconducting cable and a conventional cable. The superconducting cable energy losses come from the alternating current (AC) loss that is comparable to the magnetization loss of the superconductor itself, the dielectric loss of the insulation, and the heat invasion through the thermal insulation pipe. To maintain the superconducting cable at a predetermined temperature, coolant from a cooling unit is required to compensate for this heat gain, and the electric power required for the cooling unit, whose efficiency at liquid nitrogen temperature is thought to be approximately 0.1, must be counted as an energy loss.

Comparing 66 kV, 3 kA, 350 MVA class cables, the loss of the superconducting cable is approximately half that of a conventional cable (**Fig. 3**).




**(a) Increase in capacity (from 1 kA to 3 kA)**

**(b)Total installation cost comparison between conventional cable and SC cable**

**Fig. 2.** Total installation cost of SC cable

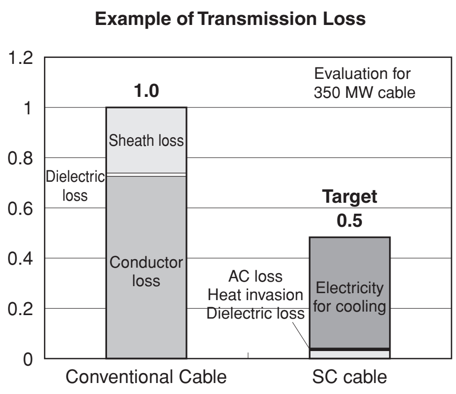



**Fig. 3.** Transmission loss

### 3-3 Low Impedance and Operatability

A superconducting cable that uses a superconducting shield has no electromagnetic field leakage and low reactance. Depending on the shape of the cable, the reactance can be lowered to approximately one-third that of conventional cables. These features allow the cable line capacity to be increased by laying a new line parallel to conventional cables and controlling the current arrangement with a phase regulator (**Fig. 4**). In this

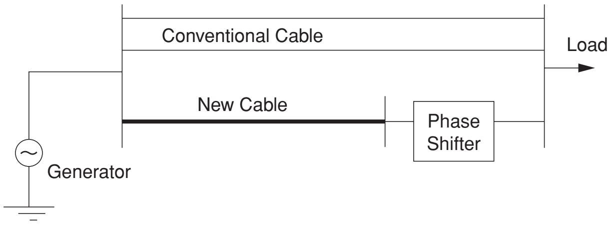



**Fig. 4.** Example of net work with parallel circuit

case, it is thought that the control of the phase regulator can be improved and the reliability of the overall system can be increased by using a superconducting cable in the newly added line rather than a conventional cable.

In addition, one characteristic of superconducting material is that the lower the operating temperature, the greater the amount of current that can flow. **Figure 5** shows the relationship [3] between the superconducting cable temperature and critical current from the SEI-TEPCO verification test. When the operating temperature was lowered from 77 K to 70 K, there was an approximately 30% increase in the current-carrying capacity. It is hoped that this characteristic can be utilized as an emergency measure when there is a problem with another line.

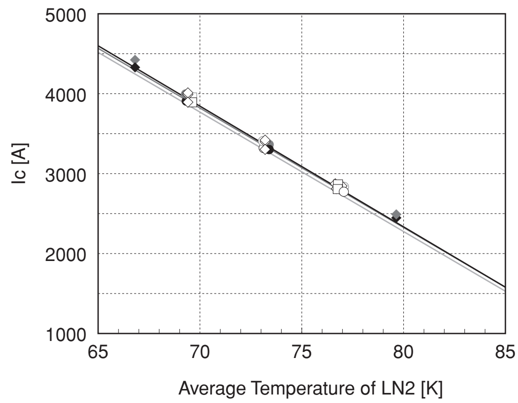



**Fig. 5.** Relationship between cable critical current and temperature in verification tests

## 4. Superconducting Cable Practicality and Achievements Up to the Present

### 4-1 Verification Test in TEPCO project

The joint verification test conducted together with TEPCO and CRIEPI from 2001 to 2002 involved the development of a 100 m, 66 kV, 1 kA class cable, and this test was successfully implemented for a year. The achievements are summarized below. The objectives and issues are set out in **Table 1**.

*Withstand voltage characteristics: The test voltage cleared the 66 kV class voltage and achieved the target.

*Transmission capacity: A 200 MVA (at 2000 A) transmission capacity was calaulated from results of critical current measurement. The current performance at

**Table 1.** Summary of verification test results

| Item | Results | Targets | Further development |
|---|---|---|---|
| Voltage | 66 kV | ← | |
| Current | 2 kA * | 3 kA | Ic 100 A/wire |
| Capacity | 220 MVA* | 350 MVA | |
| Dimension | 150 mm duct | ← | |
| Cable unit length | 500 m** | ← | |
| Distance between cooling stations | 1 km** | 3-5 km | Optimal design of cooling system Decrease of AC loss |

* Estimated from Ic measurement results
** Achievable level

the verification test showed that the critical current of SC wire was nominally in the order of 50 A, but it exceeds 100 A at present. Therefore, the current superconducting cable is expected to cany arround of 350 MVA (3000 A class), the target value of this cable.

*Cable length: A target cable length of 500 m was set, taking into consideration transportability and the distance between manholes. SEI' s development and manufacturing efforts of a 100 m cable confirmed the feasibility of producing a 500 m class cable.

*Distance between cooling systems: The target cooling system installation interval is 3 to 5 km, which is comparable to that of oil supply zones of oil filled (OF) cable. The longer the cooling distance, however, the greater the pressure loss during coolant flow. Thus steps must be taken to reduce this. The pressure loss can be reduced by either reducing the flow volume or by enlarging the flow path, but the latter is not a feasible solution for places that require a compact conduit. To reduce the amount of coolant flow that is required, superconducting wires with lower losses are being developed to decrease the AC loss.

### 4-2 Reliability

(1) Superconductivity

If no external force is applied, or if the cable is designed to withstand external forces, superconducting cables will maintain their characteristics semi-permanently. For example, SEI has confirmed that the current leads and magnets it had manufactured maintain good stability for several years (**Table 2**). [4]

**Table 2.** Durability of high Tc superconductor in current lead and magnet

| | User | Cooling cycle test or vibration test | Result |
|---|---|---|---|
| Current Lead | SR system in SEI (Dec.1993-Sep. 1998) | >200 cycles @ RT to 4.2 K | No degradation |
| Current Lead | Company A | · Linear type: $4\times10^6$cycles with 100 μ deflection @ 77 K | Good durability against mechanical vibration |
| Current Lead | Company A | · Arc type: acceleration test @12 - 38K | Good durability against mechanical vibration |
| Magnet | Company B | 5cycles @ RT to 20K and >100 cycles excitation | No degradation |

Since changes in temperature during operation are very slight in superconducting cables, there are no factors that can lead to deterioration. Consequently, it is expected that stable operation can be achieved. Further, in regard to the thermal expansion and contraction of the cable due to cable cooling and heating, SEI has designed its cable core to be stranded loosely and leave required slack to absorb this expansion and contraction and thereby reduce the stress that is generated. [5] During the verification test, a continuous load test that extended over 2,400 hours was successful [6], and no changes, such as deterioration, were found in the superconducting cable during the verification test.

(2) Electric Insulation Characteristics

PPLP impregnated with liquid nitrogen is used for insulation of the superconducting cable. PPLP is the material that is used for OF cables, and it has been verified that it can maintain stable insulation characteristics at low temperatures, as the insulating oil-soaked material does at room temperature. **Figure 6** shows the result of the V-t characteristics test of PPLP in liquid nitrogen [7]. The result of the evaluation of the lifetime of superconducting cable insulated with PPLP, determined from the result in **Fig. 6**, showed the 66 kV constant stress to be less than 10 kV/mm (actually 7.4 kV/mm), so the cable is estimated to have a life in excess of 30 years ($10^9$ sec). The voltage stress test under an electric field that is not intense enough to generate a partial discharge also showed that PPLP insulated superconducting cable has no tendency to generate a partial discharge even after loading for more than 7,000 hours, which also provides evidence of long life expectancy. These data also suggest that the design stress of electrical insulation can be increased, thus making it possible to reduce the insulation thickness and make the cable even more compact.

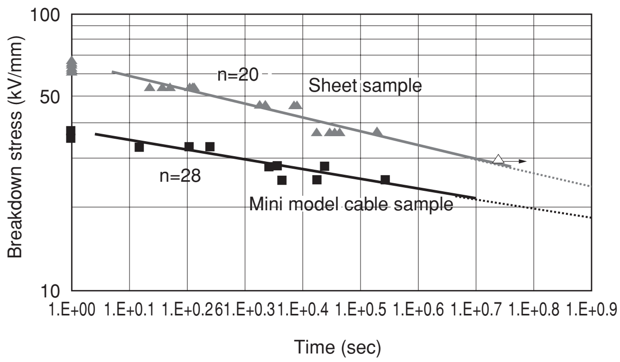



**Fig. 6.** V-t performance of PPLP impregnated with LN2

(3) Cooling System

The cooling system consists of pumps, cooling units, and other devices, so the maintenance technology for these devices must be established.

During the verification test, the cooling system was operated for approximately 6,500 hours, and no problems were found. The manufacturer of the devices used in the cooling system recommends that these devices undergo maintenance once per year. However, ways of making the maintenance interval longer, developing a method for maintenance during operation, and optimizing a backup system need to be studied.

In regard to the above, the verification test examined the impact of cooling system failure on the superconducting cable. The relationship between the coolant temperature and time elapsed after the cooling units were turned off (while the cable continued to operate) is shown in **Fig. 7**. [8] The time elapsed from when the cooling units were turned off to when the cable could no longer be operated was approximately 6 hours. The elapsed time will differ depending on the system configuration and operating conditions, but the result showed that a superconducting cable system provides sufficient time to switch systems when the cooling system fail.

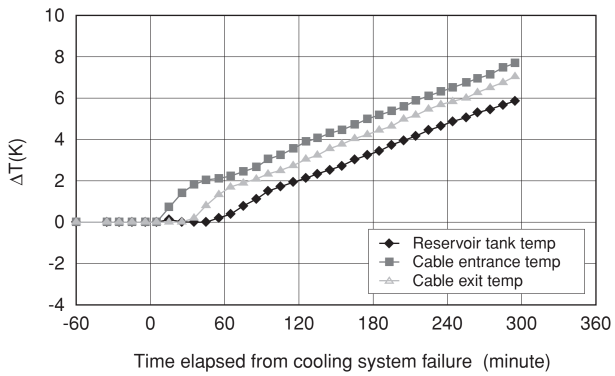



**Fig. 7.** Temperature increase after cooling system failure

## 5. Current Status of Superconducting Cable Development

### 5-1 Status in Japan and Overseas

As was described in Section 3, superconducting cables have several inherent advantages over conventional cables. Consequently, superconducting cable projects are being promoted in Japan and overseas with a view to commercializing this technology as soon as possible.

In the USA, the development of superconducting cables is being promoted in the US Department of Energy (DOE) Superconductivity Partnership Initiative (SPI) Project. The test of 120 m class superconducting cable conducted in Detroit was unsuccessful [9], but Southwire Company' s 30 m class cable has been operating successfully for over 28,000 hours [10].

Three new projects have been started lately, and these are accelerating the development of superconducting cables. The projects are being undertaken as part of the initiative to use superconducting cables to strengthen the US power grid, which showed its vulnerability during the massive blackout of August 2003 in New York. [11]

These three projects are the Albany Cable Project (350 m, 34.5 kV, 800 A), Ohio Cable Project (220 m, 15 kV, 3 kA) [(12)], and Long Island Power Authority (LIPA) Cable Project (600 m, 138 kV, 2.4 kA) [(13)], and these projects are scheduled to begin operation in 2005 to 2006.

In Japan, as part of the Super-GM Project, CRIEPI and Furukawa Electric Co., Ltd. constructed a 500 m, 77 kV class single-core test cable at the CRIEPI laboratory and have begun long-term tests. [(14)]

Thirty meters class superconducting cable is being developed in the "Dream of Advanced Power System by Applied Superconductivity Technologies (DAPAS)" Program in South Korea [(15)]. In China, Yunnan Project is underway with a 30m HTS cable connecting to real grid. [(16)]

Superconducting cable development projects are now being promoted worldwide.

**5-2 Albany Cable Project**

The Albany Cable Project will use a 350 m, 34.5 kV, 800 A, 3-in-One 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 long-term operation. **Figure 8** shows an aerial photograph of the planned construction site. [(17)]

The construction and testing schedule is planned to extend over a 4-year period (2002 to 2006) and will be the first long superconducting cable to be utilized in an actual power line anywhere in the world.

SEI' s role in this project is to connect the cable to the actual line and to verify operation of a practical length of cable under actual loads. In this project, SuperPower Inc. is serving as the main contractor, Niagara Mohawk Power Corporation is supplying the power lines, the BOC Group is supplying the cooling system, and SEI is in charge of manufacturing, installing, and operating the superconducting cable.

The cable system configuration is shown in **Fig. 9**. 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. A circulatory cooling system allows liquid nitrogen to be cooled by a cooling station and then sent to the superconducting cable after passing through a return pipe. The cable will be laid in a newly constructed underground conduit line with an inside diameter of 6 inches (152 mm).

This project will initially employ a cable that uses first-generation Bi-based superconducting wire, which will be subjected to long-term testing. Concurrently, a 30 m cable manufactured using a second-generation thin-film superconducting wire produced by SuperPower Inc. will substitute for the 30 m section of cable in midway of the project.

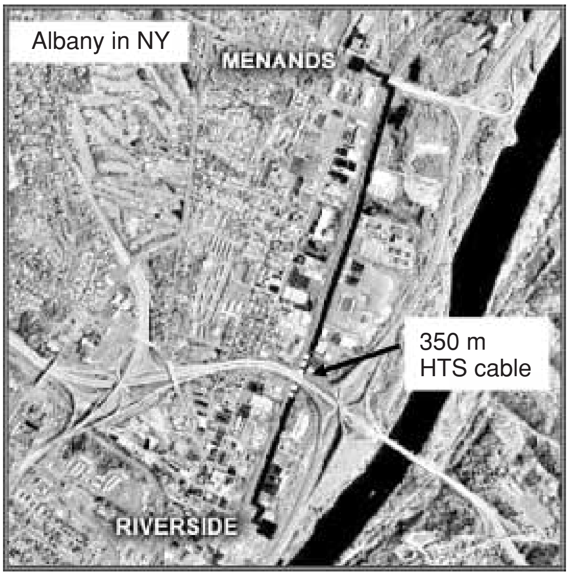



**Fig. 8.** Test site for Albany Project (Albany, NY State)

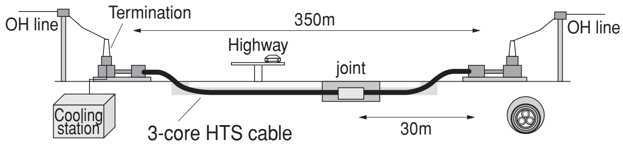



**Fig. 9.** Schematic view of Albany cable system

**Table 3.** Specifications of Albany cable system

| Item | Specifications |
|---|---|
| Voltage, Current | 34.5kV, 800Arms |
| Length | 350m (320m + 30m) |
| Accessory | EB-A<br>Joint in manhole |
| Installation condition | 6-inch duct under ground |

## 6. Conclusions

Early practical application of superconducting cables is a global objective, and the cables have reached the verification stage. SEI will verify its performance in an actual line in the Albany Cable Project and will verify the reliability and practicality of superconducting cable in preparation for full commercialization in the United States and elsewhere.

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