Study on Commercialization of High-Temperature Superconductor

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By using the Controlled Over Pressure (CT-OP) process, Sumitomo Electric Industries, Ltd. (SEI) has developed a world's-longest, commercial-level $Bi_2Sr_2Ca_2Cu_3O$ (BSCCO) high-temperature superconducting (HTS) wire and named it "Dynamically Innovative BSCCO (DI-BSCCO)". Because the DI-BSCCO wire has the high critical current, high strength, high production yield and anti-ballooning properties and it is far superior to conventional BSCCO wires, SEI is pursuing the use of the DI-BSCCO wire for HTS applications. This paper summarizes the result of the study on HTS cable system. The authors studied the reliability from the perspectives of lifespan and failure, economic efficiency from transmission loss reduction and energy saving performance, and environmental performance from EMI and LCA evaluation, and concluded that HTS cables have reached the stage of actual utilization. It is expected that after HTS cables are evaluated on actual grids in the near future, practical utilization will be accelerated. SEI is aimed to penetrate the global HTS market with its DI-BSCCO wire by further improving the performances and promoting the practical application of the wire.

1. Introduction

1-1 First mile technology

20 years have passed since high-temperature superconducor was discovered. From the very beginning of the discovery of high-temperature superconductor, Sumitomo Electric Industries, Ltd. has proceeded with research and development, ranging from material research to applied product development. Recently Sumitomo Electric has succeeded in achieving significant improvements in the performance of bismuth-based ($Bi_2Sr_2Ca_2Cu_3O_x$) superconducting wire, referred to as first generation high-temperature superconducting wire, using the Controlled Over Pressure (CT-OP) sintering technique and facilities proprietarily developed by Sumitomo Electric. Nowadays, Sumitomo Electric is reaching a phase where it can supply the world's longest level high-temperature superconducting wires on a commercial basis (1). Bismuth-based superconducting wire manufactured by the CT-OP process is an innovative superconducting wire that has outstripped conventional bismuth-based superconducting wires in almost all characteristics such as high critical current, high mechanical strength, high yield, and anti-ballooning property, going beyond the conventional concept of first generation BSCCO wires. Sumitomo Electric has named this innovative bismuth-based superconducting wire DI-BSCCO, meaning "dynamically-innovative BSCCO", and is striving to develop products for practical use. This paper presents Sumitomo Electric's activities in this area, including research and development endeavors and technological challenges to be overcome, focusing on the case examples of superconducting cable systems.

2. Development of superconducting wire

2-1 Price reduction of superconducting wire

Superconductivity is a state in which electricity flows with zero resistivity. This means that a low-voltage, large-current power can be transmitted without power loss, which in turn allows conductors to be made more compact, Application of superconductivity technology can therefore bring about power transmission/distribution cables with lower losses, as well as strong electromagnets. However, for high-temperature superconductor, which usually takes place at liquid nitrogen temperatures (approximately -200 deg. C), such factors as economic evaluation including cooling efficiency achievement of higher performance of superconducting wires, and price reduction will become critical challenges. **Figure 1** shows a part of the road map of the development of DI-BSCCO (2). At this point in time, a price of \$100/kAm at 77K, which is about 2,000 yen per meter of wire at a critical current of Ic = 200 A, has already become feasible, and it is likely that higher performance and lower price will be achieved in the future, reaching to \$20/kAm at 77K. Because \$20/kAm is almost the same as the price of a standard copper wire, there are

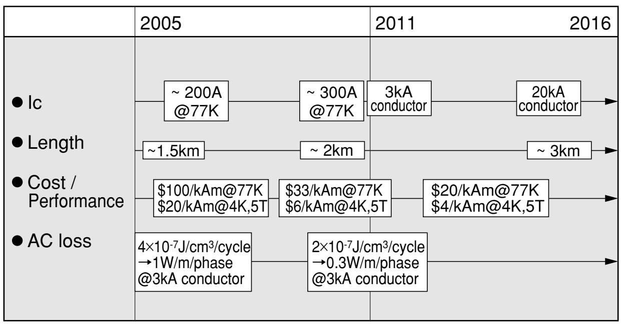


Fig. 1. Road map for bismuth-based superconducting wire (DI-BSCCO)

high expectations for the application of DI-BSCCO to superconducting equipment.

2-2 Superconducting wires with higher performance and reliability

Sumitomo Electric has engaged in the development of bismuth-based superconducting wires for nearly 20 years, and those wires have been employed in superconducting equipment since the early 1990s, offering satisfactory results. Degradation factors of superconducting wires include cooling cycle, repeated distortion and stress, long-term electrical conduction, repeated excitation and demagnetization, and changes in chemical composition (such as oxygen). **Table 1** shows the survey results of Sumitomo Electric's wire materials in long-term use, summarized according to the above mentioned degradation factors. The table shows that these superconducting wires in long-term use in the past show no degradation. Furthermore, considering the fact that the superconducting wires used in the components listed in **Table 1** are those produced before the CT-OP process was adopted and that the present DI-BSCCO has far improved mechanical properties, DI-BSCCO is obviously superior to conventional materials in terms of compactification and improvement in reliability. Tensile strain properties used in designing DI-BSCCO are shown in **Fig. 2**. It shows that in the case of high strength type wire, no degradation of critical current occurs at up to about 0.3 percent strain. In DI-BSCCO produced by the CT-OP process, the density of superconductor thereof is 100 percent. This enables DI-BSCCO to have high strength while preventing penetration of liquid nitrogen into superconductor and ballooning due to a sudden temperature rise from occurring. In terms of quality assurance, the full-length critical current characteristics test is conducted in the shipping inspection of DI-BSCCO, assuring reliability over the entire product length.

Table 1. BSCCO superconducting wires in long-term use

	Cooling /Vibration Tests	Excitation or Current loading	Results
Current Leads	More than 200 cycles at between RT and 4.2K	More than several times the number of heat cycles	No degradation
	Linear type: 100μ deflection $4x10^6$ cycles at 77K	Overload : 1,000A (Ic=750A) in Liq. Nitrogen	Anti-vibration durability confirmed
	Arc type: Acceleration test at 12 to 38K	1,000A after acceleration test	
Magnets (1998.10-2000.12)	5 cycles at between RT and 20K	1 to 2 times/week; Total of several hundred times	No degradation
Coils for Motors	50 cycles at between RT and 77K	Excited in every 10 heat cycles	No degradation
Cables (2001.06-2002.06)	4 cycles at between RT and 77K	Total 2,400 hours at 1,000 to 1,500 A	No degradation

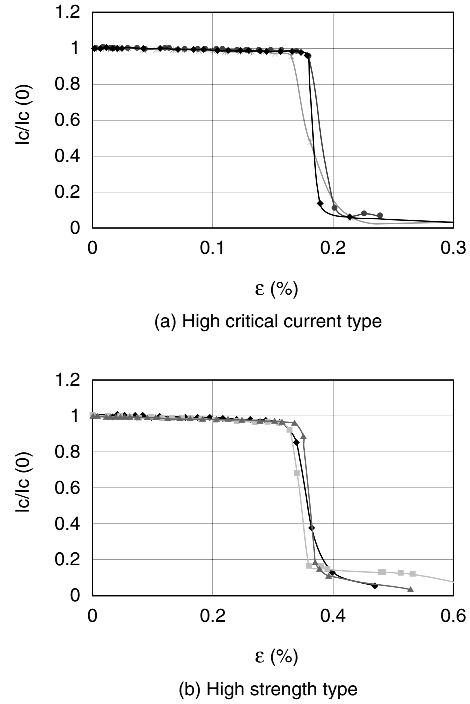


Fig. 2. Critical current vs. tensile strain properties of CT-OP wire (Data provided by Osamura, Kyoto Univ.)

3. Application of DI-BSCCO to HTS cable

Figure 3 summarizes the relationship between the advantages and applicable uses of HTS cable. For HTS cable system, it is extremely important to conduct evaluation on reliability and economical efficiency. There are two typical cases of economical efficiency. One is when HTS cable itself is more inexpensive than existing cable, and the other is when HTS cable system as a total cable system is inexpensive than other systems. In the former case, cable will be selected by taking into consideration the target performance per cost of the HTS cable. However, in order to meet growing environmental requirements such as CO_2 reduction and EMI-free, use of HTS cable are indispensable and therefore will inevitably be adopted.

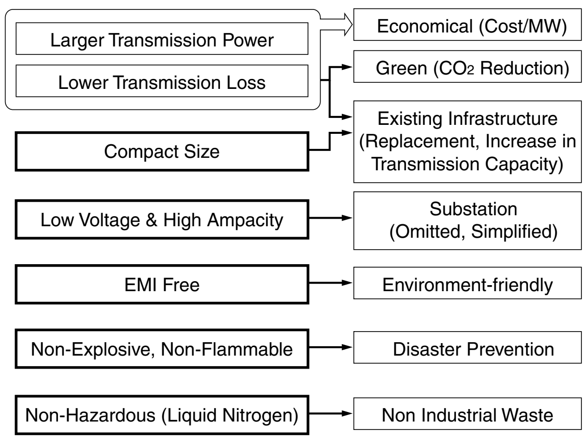


Fig. 3. Advantages and applicable uses of HTS cable

4. Reliability evaluation of HTS cable

4-1 Evaluation in practicability verification test

Figure 4 shows the basic structure of Sumitomo Electric's cold dielectric, three-core in one cryostat type HTS cable. The overview of the test line, its outline and the test results are given in **Fig. 5**, **Table 2** and **Table 3**, respectively.

The core of the three-core in one cryostat type HTS cable is formed in the following process; (i) BSCCO wire is spirally wound on the core-former consisting of a copper twisted wire, (ii) PPLP (Polypropylene Laminated Paper) is applied on it, (iii) a return circuit of BSCCO wire is formed outside the PPLP, (iv) a protective layer is applied on the outside thereof, and (v) these three cores are twisted. Thereafter, double corrugated stainless steel pipes are applied, the inside of which are evacuated, hence forming a cryostat.

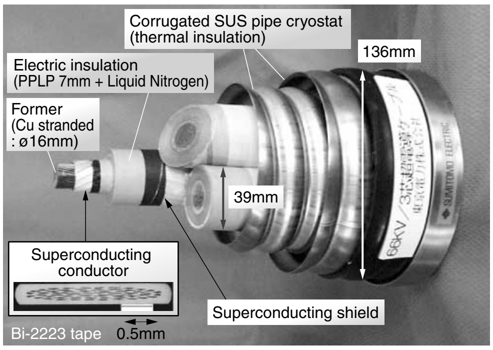


Fig. 4. Basic structure of HTS cable

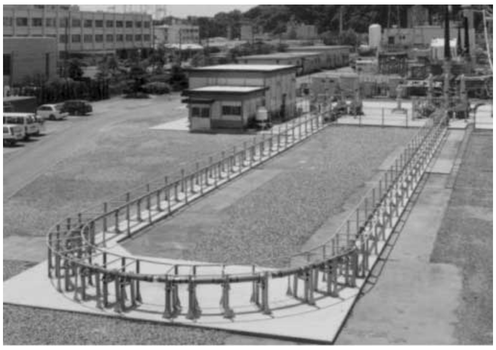


Fig. 5. Verification test line

Table 2. Outlines of verification test

Rated Voltage		66kVrms
Nominal Current		1kArms
Nominal Capacity		114MVA
HTS cable	Shape	3 core in one Cryostat
	Length	100m
	Electrical Insulation	PPLP (Poly-Propylene Laminated Paper) impregnated with LN_2
	Splitter Box	2
	Termination	6 (End Box in Air)
Laying		On the ground (partially installed in the 150mm duct)
Cooling System		Circulation of sub cooled LN_2

Table 3. Results of verification test

Items		Results, Measurement	Remarks
Electrical Properties	Voltage test	AC 130kV for 3H	Based on Japanese standard for 66kV OF cable with 5m sample
		Imp-385kV x 3 shots	350kV (66kV BIL)x1.1
	Capacitance, tan δ	0.24μF/km, 0.08% at 77K	
	V-t characteristics	n-value > 20 for PD occurence	PPLP sheet tests
	Critical current	Ic>2700A(DC)	for 100m cable
Mechanical Properties	Bending test	No degradation with bending diameter of 1.9m	Base on Japanese standard
Thermal Properties	AC loss (3 Phase)	2.0W/m at 1kA	for 100m cable
	Thermal Invasion	2.5W/m	for 100m cable
	Long duration	>2400H at OP, >6500H at cooling	for 100m cable
System Performance	Load fluctuation	1000A 16H + 200A 8H for 1 month	for 100m cable
	Over current	AC 1500A	1.5 times of nominal current
	Cooling cycle	No degradation for 4 times	for 100m cable

A long term demonstration test of this HTS cable was conducted from 2001 to 2002 under joint research by Sumitomo Electric and Tokyo Electric Power Company [3]. Superconducting equipment undergoes thermal contraction (0.3% of distortion) due to temperature change of approximately 220 deg. C between room temperature (300K) and LN_2 temperature (77K). In order to absorb such a big contraction, the "loosely-stranded three core" structure was devised.

Throughout the long-term test, HTS cable was subjected to four cooling and warming cycles. It was verified that the performance was electrically and mechanically stable and good properties were observed, showing that this HTS cable system has completely reached the level of commercial application. Nowadays, as shown in **Fig. 2**, it has become possible to obtain higher reliability and mechanical toughness through the CT-OP process.

4-2 Life cycle assessment of HTS cable

Major causes of deterioration of existing cables are heat generation by power transmission and expansion-contraction cycles due to temperature change between day and night. In contrast, HTS cable are not subject to these temperature changes, because temperature within a cryostat is maintained constant during operation.

Performance of HTS cable itself is verified by an initial test and a long-term test. However, as HTS cable system requires a cooling system comprised of pumps and a cryocooler, maintenance technologies for these equipments must be established and verified.

① Long-term life cycle characteristics of insulation performance

Although "thermal degradation" is not generated in HTS cable, because its operating temperature is as low as approximately -200 deg. C, it is still necessary to evaluate long-term insulation characteristics (ie., V-t characteristics) in the same way as is the case of existing extra-high voltage cables. HTS cable is a member of the OF cable family, forming composite structure of "insulating tape and liquid impregnated insulation". Since liquid nitrogen is similar to synthetic oil used in OF cable, it is expected that HTS cable will show similar insulating properties as OF cable. Results of many electrical tests such as AC breakdown test and impulse dielectric breakdown test have been reported so far (4). **Figure 6** shows the results of V-t test under accelerated voltage (5). AC breakdown did not occur even after 7000 hours of voltage application. However, when it is assumed that AC breakdown has occurred at this point in time, the value n (the gradient of V-t curve) becomes more than 20, which is equivalent to the V-t characteristics of PPLP-OF cable.

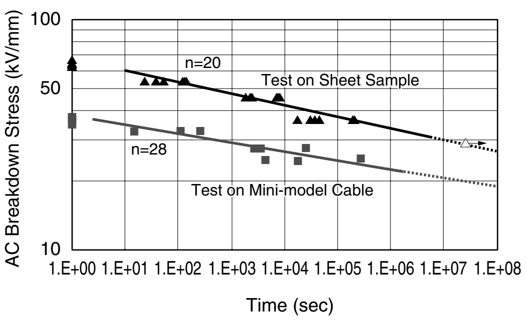


Fig. 6. V-t characteristics of liquid nitrogen-impregnated PPLP

② Mechanical degradation

HTS cable undergoes no temperature change during operation. For that reason, the only phenomenon that need be taken into account in preventing degradation is thermomechanical hysteresis that is exhibited when cooled from room temperature to -200 degrees C or when heated. Strain hysteresis of each component/material is approximately 0.3 percent on the assumption that no absorption measures are taken. The high-strength type DI-BSCCO wire shown in **Fig. 2** does not undergo degradation at a 0.3 percent distortion. Additionally, when cable is designed to absorb the thermal contraction, DI-BSCCO is free from mechanical degradation arising from thermal contraction. Moreover, for cryostat consisting of stainless steel tubes, the number of cyclic bending showing ruptures at 0.3 percent distortion is approximately 10^5 times according to the S-N curve (6) shown in **Fig. 7**, which proves that it is completely satisfactory in the use conditions of the cable.

4-3 Fault current (short-circuit current) design

When an accident occurs in AC power system, high current flows in HTS cable even for a short time. Accordingly, AC power apparatus needs to accept such a short-time high current. However, if a full accidental current should flow only through HTS wires, a HTS conductor should become enormous, hence noneconomical. Consequently, it is necessary to implement the design which allows a slight temperature rise in superconducting wire without damaging them, while heeding dielectric breakdown.

Solutions to this challenge are as follows; (i) stranded copper conductor is applied to the core-former, which works as the conductor, as a measure against short-time accidental high current flowing in a conductor; (ii) an additional copper shield layer is applied to the outer side of the superconducting shield layer in order to shunt short-time accidental high current from the superconducting wire into the copper wire; and (iii) heat capacity is increased in order to restrain short-time temperature rise. **Table 4** is a case example employing these solutions, which shows the design of the HTS cable for the DOE-Albany Project in the USA that is scheduled to be completed in 2006. The temperature rise at each component during short-circuit test is shown in **Fig. 8** (7).

Table 4. Structure of the HTS cable for Albany Project

Items	Specifications
Former	Copper stranded conductor
HTS Conductor	2 layer with Bi-2223 tape
Electrical Insulation	PPLP with 4.5 mm thickness
HTS Shield	1 layer with Bi-2223 tape
Protection Layer	Copper tape
3-core Stranding	Loosely stranded
Thermal Insulation	Double stainless steel corrugated pipe
Protection Layer	PE+SUS tension members

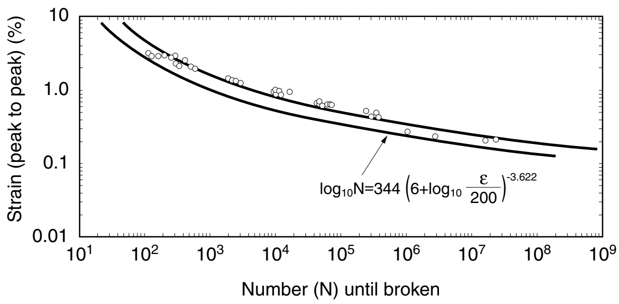


Fig. 7. S-N curve of stainless steel sheath (at RT)

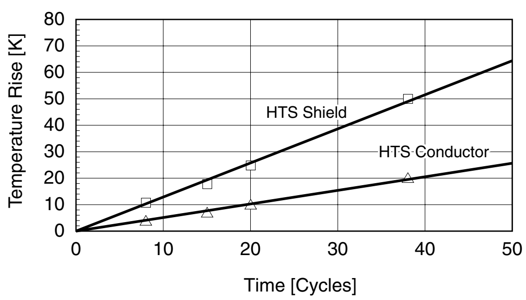


Fig. 8. Cable temperature rise when short-circuited

In the Albany Project, the maximum short-circuit current is specified as 23 kA, and the circuits is equipped with the first protection system for blocking the current after 8 cycles, and the second (backup) protection system for blocking after 38 cycles. Assuming that the short-circuit current intruded into a cable under these conditions, a 23-kA short-circuit test was implemented using short-circuit time as a parameter, and the temperature rises in cable conductor and shield wire were measured.

The maximum temperature rise after 38-cycle blocking is 20 K at the conductor, and 50 K at the shield. Furthermore, at the time point of 38 cycles at which the current is blocked, the transient temperature rise is 14 K in the conductor and 24 K in the shield. Through visual inspection and critical temperature test implemented after dismantling the tested cable, it was verified that there were no effects upon the superconducting characteristics by such a rise in temperature, and that cable performance was not degraded. The sizes of the core-former and copper shields need be determined by taking into account the operating temperature, pressure requirements and overloading conditions.

4-4 Reliability of cooling system

(1) Basic configuration of cooling system

As shown in **Fig. 9**, the cooling system for HTS cable is comprised of a cryocooler, a circulation pump, and a reservoir tank. Capacity of reservoir tank is determined depending on such factors as predicted temperature change during the operation of HTS cable and cooling maintenance time when cooling equipment is suspended.

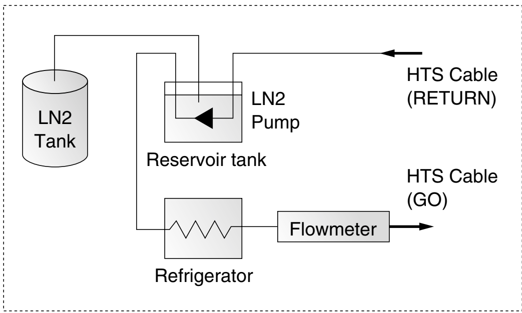


Fig. 9. Configuration of cooling system for HTS cable

(2) Service life of cooling system (Maintenance policy)

The cooling system of HTS cable requires maintenance such as periodic inspections and consumable part replacements since a pump and a cryocooler are rotating machines. Although there have been as yet only a small number of case examples of long-term continuous operation of HTS cable cooling system, some cases have achieved more than a few thousand-hour operation in total without causing problems. Taking into consideration the investigation results of such operations, continuous operation time for about one year is conceivable enough.

In order to enhance the reliability of the cooling system, it is preferable to prepare a standby unit from the beginning, and to implement a switching run between the two cooling units. In the case that the HTS cable system including the cooling system becomes large scale, it will be necessary to conduct the study on various factors such as low-pricing, high efficiency, and high reliability, in addition to the size of cryocooler, or series/parallel operation of small-sized equipments.

4-5 Sustainment of power transmission of HTS cable at the time of emergency shut-down of cooling system

It is a critical question how long HTS cables can continuously be operated when a cooling system is forced to shut down under an emergency situation. If the operations of the HTS cable system can be maintained until the start-up of the standby cooling unit, or the completion of switchover of transmission/distribution circuits, the reliability of the HTS cable system will rise accordingly.

It is assumed that there are, in practice, two scenarios, in which cooling system is shut down; (i) cryocooler is shut off, but circulating pump is still running, and (ii) both cryocooler and circulating pump are shut off. Two tests were implemented on the verification test line shown in Section 4-1. The results are summarized in **Table 5** and **Fig. 10**, which prove that power transmission can be maintained for approximately five hours. However such operation time depends upon each transmission system's conditions, therefore careful study will be necessary. Of all factors, decreasing "AC loss of HTS cable", which is the main cause of a rise in cable temperature, is the most important factor, in order to extend the allowable power transmission operable time when the cooling system is shut down. In this light, DC HTS cable, which generates no transmission loss unlike AC cable, can enjoy an overwhelming advantage in respect of the sustainment of power transmission time in case of accident.

Table 5. Test results of cooling system failures

Case	Results
Cryocooler shut down and pump operated	Temperature of the cable rose at 1.4 K/h. Nominal current 1,000 A could be loaded for 5 hours.
Cryocooler and pump failed	Liquid nitrogen was stopped and local temperature rose near the termination. Nominal current 1,000 A could be loaded for 5.5 hours.

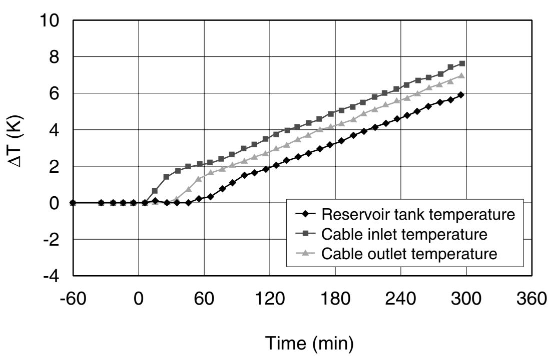


Fig. 10. Simulation test results of cooling system failure

4-6 Study of improvement in reliability of HTS cable system

Ic of superconducting wires depends on temperature. **Figure 11** shows the temperature dependency of critical current of the HTS cable described in Section 4-1 [9].

When the HTS cable with the critical current of 2,700 A at 77.3 K is cooled down to 69.5 K, critical current can be increased by approximately 1.5 times to 4,000 A. As liquid nitrogen remains in liquid state at temperatures as low as 65 K, it is theoretically possible to utilize a temperature margin of 12 K (between 77 and 65 K) as cooling temperature.

Figure 12 shows HTS cable systems and their emergency operations by making use of the improved Ic of HTS wires when overcooled [10]. In Japan, conventional cable systems employ the “three and two” system, which is shown in **Fig. 12**. A three and two system is provided with one spare line to prepare for accidents. In other words, whereas two lines are enough for rated power transmission, three lines are provided. Thus, if one line is shut down, rated capacity power transmission can be maintained by operating the other two circuits at 100 percent.

In the case of HTS cable system, on the other hand, a transmission line is normally composed of two or three lines that meet the rated capacity. When one line is shut down in an accident, the other line that is operating can continuously carry rated current by following the process as follows; (i) the cooling system for a shut-down line is assigned to the other line; (ii) the cooling capacity of the working line is increased so that its cooling temperature is decreased; and, (iii) the decreased temperature increases the critical current (Ic) and enhances current-carrying capacity per line. In this way, use of HTS cable requires less cable redundancy in comparison with the conventional cable systems, leading to the improvement in economic efficiency as well as the attainment of reliability. In view of the above, when comparing the economical efficiency between conventional cables and HTS cable, it is important to compare them as total systems by taking into account their cable redundancy.

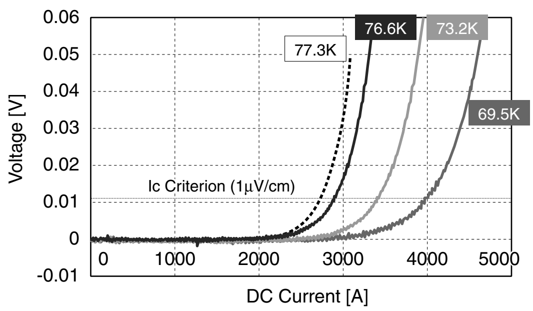


Fig. 11. Change in critical current characteristics caused by temperature change

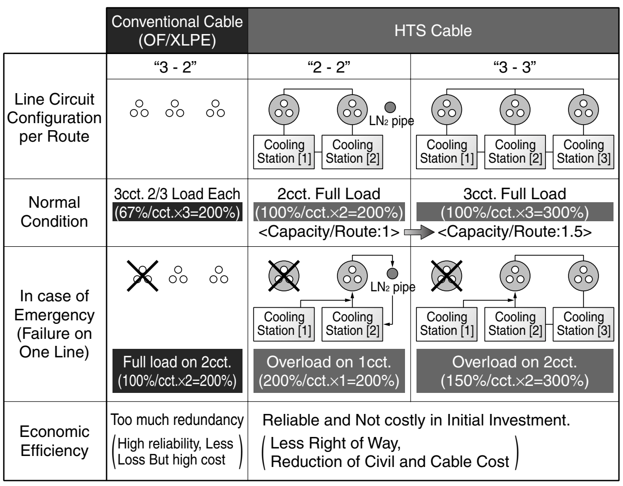


Fig. 12. HTS cable system and its emergency operation in comparison with conventional cable system

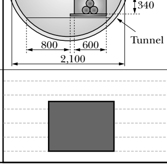
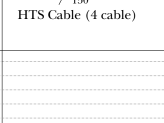
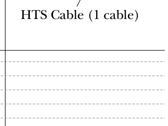
5. Economic efficiency of HTS cable system

5-1 Streamlining of cable route

The biggest expected target of HTS cable application is large power transmission. In many cases, conventional cables are placed into utility tunnels, because transmission capacity is significantly decreased due to soil thermal resistance in duct installation. Considering the extremely high construction costs of the utility tunnel, it is advantageous to use HTS cable which can transmit the same power as conventional cables even when installed in the duct because it is not influenced by soil thermal resistance. Moreover, HTS cable can simply replace existing cables in ducts and there is no need to install new ducts. **Table 6** shows a comparison between the conventional cables (in tunnel installation) and HTS cable (in duct installation), assuming a 1,500 MVA power transmission in urban area. The table shows that significantly greater economic efficiency is produced by streamlining the cable route from the utility tunnel to duct [11].

Moreover, HTS cables allow the use of low voltage-high current because unlike conventional extra-high voltage power cables, they are free from the constraints of charging current that is proportional to transmission voltage. This advantage enables long-distance power distribution, and some proposals have been presented in which intermediate substations at satellite towns that transform voltage can be either omitted or streamlined to a switching station [12]. It is seen that economical effectiveness in this case will become greater.

Table 6. Effectiveness of HTS cable (cable route is streamlined)

[Evaluation Model] Capacity: 1500MVA	AC		DC
	Conventional Cable (275kV Single Core XLPE)	HTS Cable (66kV 3-core in One Cryostat type)	HTS Cable (130kV 3-core in One Cryostat type)
Laying Style			
Consturction Cost X100 M$			

5-2 Economic evaluation of HTS cable

Table 7 shows the comparison between the existing AC cables, HTS AC cables, and HTS DC cables in terms of such factors as loss, energy-saving and economic efficiency, taking 1,500 MVA power transmission route as an example. Fundamental figures used in this evaluation are Ic (critical current at 77 K) = 200 A, and wire price of $20/m.

① In loss assessment with taking into account cooling efficiency, compared with existing normal-temperature cables, the amount of loss can be reduced to approximately one-forth in AC HTS cable, and to approximately one-fortieth in DC HTS cable. The reduced loss of AC HTS cable is the calculated "future target value", but that of DC HTS cable is the value that is immediately feasible.

② Energy-saving effects produced by HTS cable are unquestionably large. When these effects are either converted into a discounted present value (DPV) on an assumption of a 5 percent annual interest rate throughout a 30-year operation period, or evaluated as an emission trading value (assuming that the market price of CO_2 emission trading will be ¥5,000/t-C by around 2010, and that the price may potentially rise to ¥10,000/t-C in the distant future), it is observed that the economical merit of HTS cable is large in either case. In addition, it has been proved that whereas AC HTS cable provides economic efficiency only when AC-loss reduction effects are taken into account, DC HTS cable whose loss is limited only to heat invasion can exhibit more economic efficiency by itself as it now stands.

Figure 13 shows the summarized research results of economic effects with the load factor and loss factor taken into consideration. The load factor is defined as "percentage of average maximum power during a given period", and the loss factor is defined as "percentage of actual loss to the loss at a 1.0 load factor". Generally, to obtain the loss factor from the load factor, the following formulae is used;

Loss factor = 0.3 x (Load factor) + 0.7 x (Load factor)^2

The loss factors generally employed in the JCS No. 168 standard (for permissible electrical current of power cable) prescribed by the Japanese Cable Makers' Association (JCMA) are 0.6 to 0.8 for the general power-transmission/distribution lines, and 1.0 for the special transmission lines (out-going power cables from thermal power, etc.).

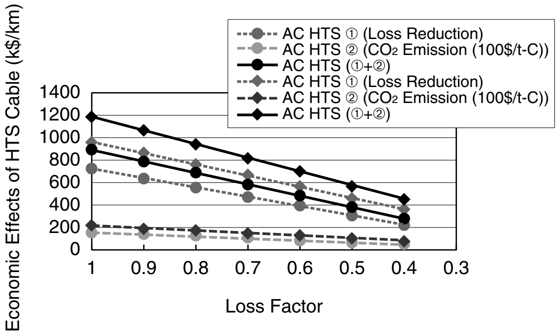


Fig. 13. Economic evaluation of HTS cable to conventional AC cable

In the model cables analyzed here, economic efficiency decreases to approximately two-thirds at a loss factor of 0.6, and to almost a half at a 0.4 loss factor. Still, the effectiveness brought about by applying HTS cables is outstanding, although it is necessary to implement individual economic evaluation in actual applications.

Table 7. Effectiveness of HTS cable (economic evaluation of HTS cable)

Cable System		AC		DC
		Conventional Cable	HTS Cable	HTS Cable
Transmission Capacity		1500MVA (500MVA x 3cct)	ditto (375MVA x 2cct x 2Route)	ditto (1500MVA x 1cct)
Transmission Voltage		275kVrms	66kVrms	130kV
Transmission Current		1kArms/phase	3.3kA/phase	12kA/phase
Cable Type		Single phase XLPE Cable	3-in-One HTS Cable	3-in-One HTS Cable
Cable Size		Approx. 140mm	Approx. 135mm	Approx. 135mm
Number of Cables		9	1/2 ▷ 4	1/4 ▷ 1
Transmission Loss		740kW/km	1/4 ▷ 200kW/km	1/10 ▷ 20kW/km
CO_2 Emission*1 (CO_2 Reduction)		778ton-C/km/year (–)	210ton-C/km/year (568ton-C/km/year)	21ton-C/km/year (757ton-C/km/year)
Transmission Loss Cost*2 (Cost Reduction)		648,000/km/year (–)	175,000$/km/year (473,000$/km/year)	18,000$/km/year (630,000$/km/year)
NPV for Loss (30years, int. 5%)		(–)	+7.28M$/km (473x15.4)	+9.7M$/km (630x15.4)
Dealing in Emissions (30years)	50$/-C	(–)	+0.852M$/km (50¥568¥30)	+1.136M$/km (50¥757¥30)
	100$/-C	(–)	+1.7M$/km (100¥56¥30)	+2.27M$/km (100¥757¥30)

6. Environmental merits of HTS cable system

6-1 No leakage of magnetic field (EMI-free)

HTS cable uses HTS wires for both its conductors and shields as shown in **Fig. 4**. When HTS wires are used in its shield, the HTS cable can induce the current to flow into the shield in opposite phase in the conductor at almost the same intensity as conductor current, thereby forming a perfect magnetic shield. Thus, significant reduction of eddy current loss or conductor AC loss becomes possible. HTS cable is also an electro-magnetic interference (EMI) -free cable that does not leak electromagnetic field to outside. **Figure 14** shows the waveforms of the current flowing into superconducting conductor and shield, obtained through the verification test mentioned in Section 4-1. It is confirmed that the two currents have opposite phases and nearly the same intensity. It is also confirmed that there is no magnetic field leakage to the periphery of the cable through the actual measurements [9].

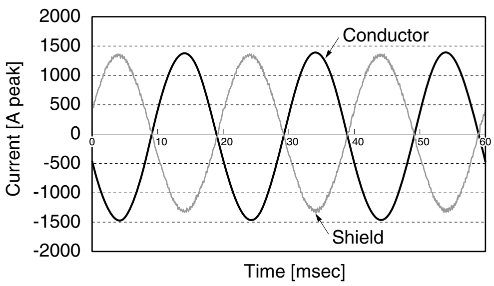


Fig. 14. Conductor and shield current

HTS cable has a composite insulation of liquid nitrogen and PPLP, instead of synthetic insulating oil and PPLP used in the existing oil-filled (OF) cables. Because HTS cable uses oil instead of liquid nitrogen, it is a non-flammable, nonexplosive cable. Liquid nitrogen is not hazardous when leaked or disposed of. Therefore, it may safely be said that HTS cable is "clean" and "green".

6-2 Life cycle assessment (LCA) of HTS cable

Currently, LCA is being broadly used as an assessment method of effective use of resources of the earth as well as impact (load) exerted upon environment. Generally, LCA evaluates the total carbon-dioxide emissions generated during the lifetime of a product which includes the whole process of procurement of raw materials, production, distribution, use, and disposal. Superconducting equipment, which is advantageous for energy saving, natural resources saving, and environmental reasons, must prove its effectiveness through LCA. The LCA assessment for the HTS cable have been implemented, the outlines of which are shown below.

(1) Analysis models

· A 66-kV, 3-kA (350-MVA) AC HTS cable was used. Three conventional 275-kV 1x1,000 mm^2 OF cables (duct installed) having the same capacity as that of the HTS cable were selected as the comparative counterpart.

· The AC cable structure employed in the HTS cable was that already developed and verified in the past. Critical current (Ic) of superconducting wires used for this assessment was set at 100 A, 150 A, and 200 A, respectively. In addition, a DC HTS cable, from which more low-loss effects can be expected, was also evaluated.

· Heat invasion into HTS cable was set at 1.5 W/m, and AC loss was set in three cases at 4, 3 and 2 W/m (at 3kA). Cooling efficiency was set as COP = 0.1.

· For operation period, the lifespan was set at 30 years under the condition that the load factor is 1.0

(2) LCA assessment up to manufacture and installation

Table 8 shows the estimated results of amounts of CO_2 emission at each point of manufacture and operation of conventional OF cables and HTS cables. Because the basic structures of HTS cables and OF cables have many similarities, it is seen that no big differences exist in these similarities. On the other hand, larger amount of CO_2 is generated in the manufacture of HTS cables than in the manufacture of OF cables. The greater CO_2 emissions is assumed to come from the manufacture of HTS wires, which is a HTS cable-specific property, and is the only difference from the OF cables. It is important in light of LCA to reduce the amount of the HTS wires used in cables, that is, to improve Ic of HTS wire.

Table 8. LCA estimated results (converted into CO_2 emission amount)

	OFcable (275kV 1× 1000mm²) 3 cables/km	3-core in One cryostat HTS cable (AC66 kV·3kA) 1cable/km		Single core in One Cryostat HTS cable (DC100 kV·3.5kA) Mono pole·1cable/km	
Production	32t	Ic=100A	~600t	Ic=100A	~170t
		Ic=150A	~410t	Ic=150A	~120t
		Ic=200A	~310t	Ic=200A	~100t
Running (30years)	9100t	AC loss=4W/m	7100t	1900t	
		AC loss=3W/m	5800t		
		AC loss=2W/m	4500t		
Total	9132t	4810~7700t		2000~2070t	
		▲4322~▲1432t		▲7132~▲7062t	

Meanwhile, compared to CO_2 emissions during manufacturing, both types of cables emit significantly large amounts of CO_2 during their operation. For this reason, abatement of transmission loss by HTS cable provides significant advantage in the LCA assessment. For AC power transmission, efficacy of HTS cable will become more outstanding in the LCA assessment when the AC HTS cable producing less loss is attained. Thus, the reduction of AC loss will become more important.

Compared to the AC HTS cable, DC HTS cable requires less number of superconducting wires, and has no transmission loss such as the AC loss for AC HTS cable except for a slight heat loss due to heat invasion. This means that DC HTS cable is likely to acquire great CO_2 reduction effects in the LCA assessment.

However, because many of the raw materials used in superconducting wires are special materials, it will become necessary to conduct acquisition of related data, quantitative evaluations for various applications and such for more accurate LCA assessment.

7. Future challenges

This paper has verified the reliability and economic efficiency of HTS cables. To apply these cables to actual grids in future, it will become necessary to individually implement evaluations for each line according to each evaluation item described herein. In addition, it is critical to improve reliability and economic efficiency by enhancing performance and reducing price.

Currently, Sumitomo Electric is implementing a world's first practicability demonstration test project for HTS AC cable extending 350 m (including joint) in a real grid in Albany, New York State in the US, jointly with SuperPower Inc, the BOC Group, and National Grid (formerly Niagara Mohawk), and funded by the US Department of Energy and New York State. This is the world's first long-term test of HTS cable in real grid. Sumitomo Electric is firmly convinced that experiences and achievements to be obtained through this test will make a great contribution to the commercial viability of HTS cables.

Although this paper was prepared focusing on HTS cable systems, Sumitomo Electric will endeavor to do its best effort to achieve early commercialization of other superconductivity-applied products (coils, motors, etc.) by implementing evaluations in the same way as those explained herein.

8. Conclusion

Almost a century has passed since the superconductivity phenomenon was discovered in 1911. Although metallic low-temperature superconducting (LTS) wires such as niobium titanium and niobium tin wires are currently commercially utilized, their applications are limited. It is certain that commercialization of superconductor will great progress when superconducting equipments fabricated from HTS wires, rather than from LTS wires, come into practical use. The DI-BSCCO bismuth-based superconducting wire of Sumitomo Electric is dynamically innovative in terms that it has a potential to initiate broader commercialization of superconductors. Sumitomo Electric will thus take the lead in the world superconductor market based on the firm belief that the 21st century is the century of superconductivity technologies, while proceeding with performance improvement, application development, and applicability verification of DI-BSCCO.

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