Development Trends of Superconducting Cable Technology for Power Transmission Applications

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***Abstract*—The use of Superconducting power transmission cable is expected to take a step towards the solution for the losses in transmission of power in metropolitan areas. High temperature semiconductor tapes, with liquid Nitrogen cooling system, enables cable operation which is to mitigate the consequences of fault in the system. This will lead to the following merits: (1) carrying 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 economic competitiveness of electrical networks. With project demonstrations going on around the world in other to accelerate the application of a better network system, superconducting cable is necessary. High temperature superconductivity (HTS) has the potential for achieving a more fundamental change to electric power technologies than has occurred since the use of electricity. It is with the features listed above that ceramic superconducting alternative with higher capacity while eliminating resistive losses, supplant copper electrical conductors.**

***Index Terms*—Capacity, Copper, Reliability, Superconductor, Technology**

I. Introduction

The discovery of ceramic-based high temperature superconductors in the late 1980´s has raised interest to renew power transmission and distribution cables using superconducting cables. Reasons being that superconducting cable is compact and can transmit a large amount of electric power, it can utilize effectively underground space where a lot of piping's and other congested units exist. With its compact in nature, 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 room temperature (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]. High Temperature Superconducting (HTS) Cables, for high capacity power transmission, has an advantage of efficiency and operational benefits due to the use of liquid nitrogen for cooling, which represents a cheap and environmental friendly medium.

The superconductivity program should focus on its applications, second-generation wire development and strategic research. Several prototypes are developed mostly for testing in laboratory setups.

Meanwhile, in the development of superconducting cable, some companies in the USA have been developing 3-in-1 HTS cable with no electromagnetic field leakage to achieve a compact cable with low transmission loss. Different cable concepts have been developed.

Presently there are in principle two main types of superconducting power cables, distinguished by the type of dielectric used which are warm dielectric design and cold dielectric design [2].

II. SUPERCONDUCTING CABLE DESIGN

The so called 'warm dielectric design' is based on a flexible support with stranded HTS tapes in one or several layers forming the cable conductor. This conductor, cooled by the flow of liquid nitrogen, is surrounded by a cryogenic envelope employing two concentric flexible stainless steel corrugated tubes with vacuum and superinsulation in between [3]. The structure of a superconducting cable is shown in Figure 1.

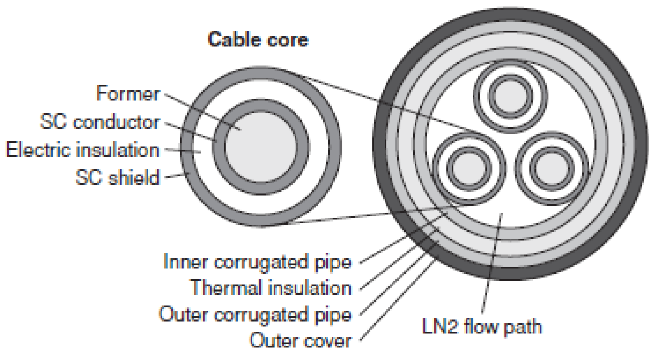

Fig 1. Structure of superconductor cable.

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 wound in a spiral to form a shield layer [3]. Each shield layer of each core is connected

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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 piping's, where a vacuum state is maintained to improve the thermal insulation performance [2]. A schematic view is shown in Figure 2.

Fig 2. Warm dielectric superconducting cable.

With the outer dielectric insulation, the cable screen and the outer cable sheath are at room temperature. Compared to conventional cables, this design offers a high power density using the least amount of HTS-wire for a given level of power transfer. The second type of HTS cable design is the 'cold dielectric' as shown in Figure 3, using the same phase conductor as the warm dielectric, the high voltage insulation now is formed by a tape layered arrangement impregnated with liquid nitrogen. (LN_2).

Fig 3. Cold dielectric superconducting cable

Thus LN_2 is used also as a part of the dielectric system in the cold dielectric cable design. The insulation is surrounded by a screen layer formed with superconducting wires in order to fully shield the cable and to prevent stray electromagnetic field generation. Three of these cable phases can either be put into individual or, into a single cryogenic envelope. A special type of cold dielectric cables is represented by the 'triaxial design', shown in Figure 4.

Fig 4. Triaxial cold dielectric cable.

This design has three phase conductors concentrically arranged on a single support element divided by wrapped dielectric, which has to withstand the phase-to-phase voltage. The differences in superconducting power cable designs have significant implications in terms of efficiency, stray electromagnetic field generation and reactive power characteristics. In the warm dielectric cable design no superconducting shield is present, thus no magnetic shielding effect can be expected during operation. As a consequence, higher electrical losses and higher cable inductance are significant drawbacks relative to the other superconducting cable designs. Additional spacing of the phases is necessary in warm dielectric configuration due to electrical losses influenced by the surrounding magnetic field [2]. No such requirements exist for cold dielectric cables, as shown in Table I, a calculated example compared to conventional cables and overhead lines. On the other hand, the warm dielectric configuration seems easier to achieve as many components and manufacturing processes are well-known from conventional cables. The cold dielectric cable is more ambitious as it involves new developments in the field of dielectric materials and also needs more complicated cable accessories, such as terminations or joints.

TABLE I
ELECTRICAL CHARACTERISTICS EXAMPLE OF120 kV CLASS CABLE

A Comparison of Power Transmission Technologies			
Technology	Resistance (Ω/km)	Inductance (mH/km)	Capacitance (nF/km) (MVAR/km)
Cold Dielectric HTS	0.0001	**0.06**	200/1.08
Conventional XLPE	0.03	0.36	257/1.40
Overhead Line	0.08	1.26	8.8/0.05

III. ADVANTAGES OF SUPERCONDUCTING CABLE

A. 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 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 (Figure 5**)**. The cost of conduit line construction, especially in a large city like Lagos, is extremely high [3]. Figure 6 shows a comparison of the construction cost between conventional cable and superconducting cable under the above conditions.

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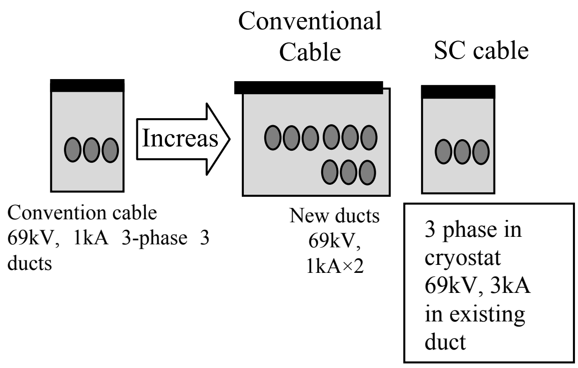

Fig 5. Increase in capacity (from 1kA to 3kA)

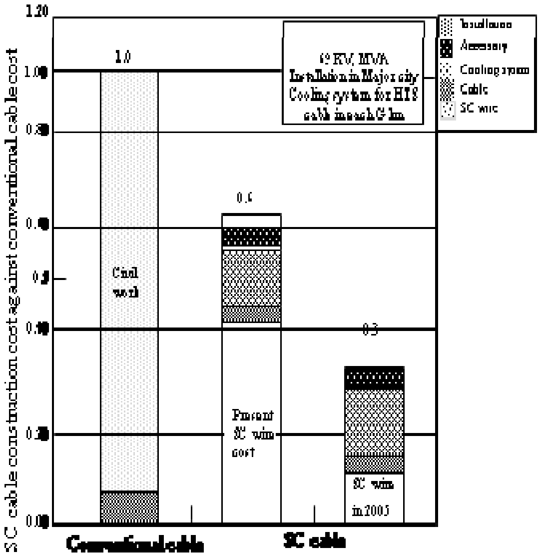

Fig 6. Total Installation cost comparison between conventional cable and SC cable

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.

B. 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. The superconducting cable developed should have a superconducting shield, so that there will be no electromagnetic field leakage outside the cable, which also eliminates eddy current loss from the electromagnetic field. Figure 7 shows a comparison of the transmission loss in a superconducting cable and a conventional cable. Transmitting electricity at high voltage reduces the fraction of energy lost to resistance, which varies depending on the specific conductors, the current flowing, and the length of the transmission line. For example, a 100 mile 765 kV line carrying 1000 MW of power can have losses of 1.1% to 0.5%. A 345 kV line carrying the same load across the same distance has losses of 4.2% [4]. For a given amount of power, a higher voltage reduces the current and thus the resistive losses in the conductor. For example, raising the voltage by a factor of 10 reduces the current by a corresponding factor of 10 and therefore the I^2R losses by a factor of 100, provided the same sized conductors are used in both cases. Even if the conductor size (cross-sectional area) is reduced 10-fold to match the lower current, the I^2R losses are still reduced 10-fold. Long-distance transmission is typically done with overhead lines at voltages of 115 to 1,200 kV. At extremely high voltages, more than 2,000 kV exists between conductor and ground; corona discharge losses are so large that they can offset the lower resistive losses in the line conductors. Measures to reduce corona losses include conductors having larger diameters; often hollow to save weight [5], or bundles of two or more conductors. Transmission and distribution losses in the USA were estimated at 6.6% in 1997 and 6.5% in 2007 [6]. By using underground DC transmission, these losses can be cut in half. Underground cables can be larger diameter because they do not have the constraint of light weight that overhead cables have, being 100 feet in the air. In general, losses are estimated from the discrepancy between power produced (as reported by power plants) and power sold to the end customers; the difference between what is produced and what is consumed constitute transmission and distribution losses [3], assuming no theft of utility occurs.

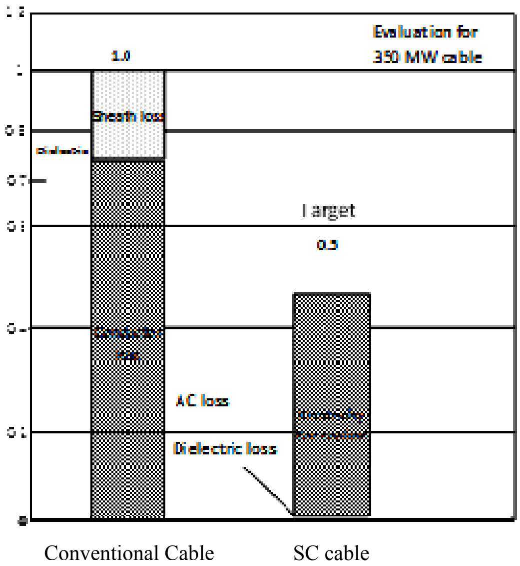

Fig 7. Example of Transmission Loss

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. For maintaining 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 (see Figure 7 above).

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C. *Low Impedance and Operability*

Superconducting cable that uses a superconducting shield has no electromagnetic field leakage and low reactance. This reactance can be lowered, depending on the shape of the cable, 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 (Figure 8).

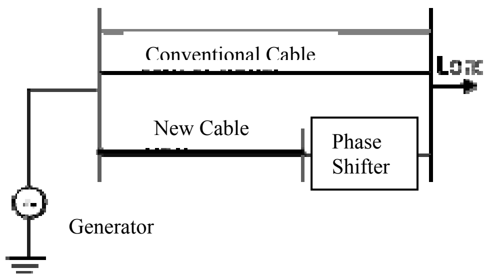

Fig 8. Example of network with parallel circuit

In this 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. Then a verification test conducted when the operating temperature is lowered from 77 K to 70 K, there, 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. HTS-based electric power equipment such as transmission and distribution cable should be developed to carry fault current limiters (FCLs). The superconducting FCLs insert impedance in a conductor when there is a surge of current on utility distribution and transmission networks. Under normal circumstances, they are invisible to the system, having nearly zero resistance to the steady-state current, but when there is an excess of electricity, otherwise known as a fault current, the FCL intervenes and dissipates the surge, thus protecting the other transmission equipment on the line. Fault current limiting superconductor cables can be used to connect existing substations, enabling power sharing between regions. This is a proposition for utilities in that it ensures system redundancy for critical urban infrastructure, increases system reliability, enables load sharing and mitigates power disruptions caused by environmental or human factors.

IV. SUPERCONDUCTING CABLE AND ACHIEVEMENTS

A. *Verification Test*

The verification test conducted from 2001 to 2002 involved the development of a 100 m, 66 kV, 1 kA class cable, and this test was successfully implemented [8]. The achievements are summarized below. The objectives and issues are set out in Table II.

TABLE II.
SUMMARY OF VERIFICATION TEST RESULTS

Item	Results	Targets
Voltage	66kV	←
Current	2kA*	3kA
Capacity	220MVA*	350MVA
Dimension	150mm duct	←
Cable unit length	500m**	←
Distance between cooling stations	1km**	3.5km

Further development
Ic 100 A/wire
Optimal design of cooling system
Decrease of AC loss

*Estimated from Ic measurement results
**Achievable level

- Withstand voltage characteristics: The test voltage cleared the 66 kV class voltages and achieved the target.
- Transmission CAPACITY: A 200 MVA (AT 2000 A) transmission capacity was calculated from results of critical current measurement. The current performance at 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 carry around 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 direct labour. 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 losses 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.

B. *Reliability*

(1) Superconductivity
Superconducting cables will maintain their characteristics semi-permanently if the cable is designed to withstand external forces, or no external force is applied [9]. For example, SEI has confirmed that the current leads and magnets it had manufactured maintain good stability for several years (See Table III).

TABLE III
DURABILITY OF HIGH TEMPERATURE SUPERCONDUCTOR IN CURRENT LEAD AND MAGNET

HTS	User	Cooling cycle test or vibration test	Result
Current Lead	SR system in SEI	>200 cycles @RT to 4.2K	No degradation
	Company A	Linear type: $4x10^6$ cycles with 100μ deflection @ 77K	Good durability against mechanical vibration
		Arc type: acceleration test @ 12K- 38K	
Magnet	Company B	5 cycle @ 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 [8]. During the verification test, a continuous load test that extended over 2,400 hours was successful [10], and no changes, such as deterioration, were found in the superconducting cable during the verification test.

(2) Electric Insulation Characteristics

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 [11].

(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.

Various superconducting cable projects have been started in the past [12]. An overview of the different projects is given in Table IV. Although this table gives a good general view, it does not represent goals and specificities of each individual project. However, it can be seen that the majority of projects make use of the cold dielectric cable configuration, which clearly emerges as the most beneficial. It can also be stated that for the North American and the Japanese markets, retrofitting and cable installation in ducts are respectively the main foreseen applications.

A closer look at some of the projects shows that, among the ongoing ones, the LIPA project will result in a cable at both the highest voltage level and the highest power rating. Compared to example of the Sumitomo/TEPCO project, this cable will also have more than twice the power density. Moreover, LIPA is the only project where a fault current is explicitly specified and, at the same time, it will be the longest superconducting cable ever built.

TABLE IV
SUPERCONDUCTING POWER CABLE PROJECTS OVERVIEW

Location/ Main partner	Utilities	Cable		Use/ Status
		Dielectric type/ Number of phases	Characteristics	
U.S.A./ Pirelli/ASC		Warm/ 1	50m/115kV/2kA	Demonstrator/ Complete
Paris/ Pirelli/ASC	EDF	Cold/ 1	50m/225kV/2.6kA	Demonstrator/ Complete
Tokyo/ SEI	TEPCO	Cold	30m/66kV/1kA	Demonstrator/ Complete
Tokyo/ SEI	TEPCO	Cold/ 3	100m/66kV/1kA	Demonstrator/ Complete
Carrollton (Ga)/ Southwire/IGC	Southern California Edison	Cold/ 3(rigid)	30m/12.5kV/1.25kA	Plant supply/ Complete
Copenhagen/ NKT/NST	Elkraft	Warm/ 3	30m/36kV/2kA	Network/ Complete
Albany (NY)/ SEI/IGC	Niagara Mohawk	Cold/ 3	350m/34.5kV/0.8kA	Network/ Ongoing
Japan/ Furukawa		Cold/ 1	500m/77kV/1kA	Demonstrator/ Ongoing
Columbus (Ohio)/ Southwire	American Electric Power	Cold/ 3	300m/12.5kV/2.5kA	Network/ Ongoing
Kunming (China)/ Innopower/Innova	Yunnan Electric Power	Warm/ 3	30m/35kV/2kA	Network/ Ongoing
Long Island (NY)/ ASC/Nexans	Long Island Power Authority	Cold/ 3	610m/138kV/2.4kA	Network/ Ongoing
Berlin/ Pirelli (ex-Siemens)		Cold/ 1	50m/110kV/2.1kA	Demonstrator/ Stopped
Detroit/ Pirelli/ASC	Detroit Edison	Warm/ 3	120m/24kV/2.4kA	Network/ Failure
Italy/ Pirelli/ASC	ENEL/Edison	Cold/ 1	30m/132kV/3kA	Demonstrator/ ?
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V. CONCLUSION

Practical application of superconducting cables is a global objective, and the cables have reached the verification stage of it reliability and practicality. The development of High Temperature Superconducting power cables has been going on for about ten years and it has resulted in a variety of projects on warm and cold dielectric designs. The first move from laboratory demonstrations to field applications is currently done and represents a necessary step towards the commercialization of this new product. Superconducting cables have significant benefits for power transmission and distribution applications that provide new aspects and possibilities in network planning and operation, and will therefore help to place this technology in the future market.

REFERENCES

[1] K. Yamasaki et. al., "Development of Bi-based Superconducting wires", SEI Technical Review, No. 58, June 2004
[2] F. Schmidt, A. Allais, "Superconducting cable for power transmission application", Nexans – Superconducting Cable System (Hanover – Germany) – A Review.
[3] Takato MASUDA, Hiroyasu YUMURA, Michihiko WATANABE, Hiroshi TAKIGAWA,Yuichi ASHIBE, Chizuru SUZAWA, Takeshi KATO, Keno OKURA, Yuichi YAMADA, Masayuki HIROSE, Ken YATSUKA, Kenichi SATO and Shigeki ISOJIMA, "High temperature Superconducting Cable Technology and Development Trends", Energy review.
[4] Jump up, "American Electric Power, Transmission Facts", page 4:http://www.aep.com/about/transmission/docs/transmission-facts.pdf
[5] Jump up, " Corona and induced currents", California Public Utilities Commission.
[6] Jump up," U.S. Energy Information Administration", November 19, 2009. Retrieved March 29, 2011
[7] T. Masuda et. al, "Verification Test Results of 66kV 3-core High Tc Superconducting Cable (1),(2)", 2003 IEEJ National convention 7-094, 7-095
[8] T. Masuda et. al., "Verification tests of 100m HTS cable system for practical use", 2002 IEEJ Electric Power and Energy Convention
[9] T. Masuda et. al., "Implementation of 2000A Class High-Tc Current Leads for the Superconducting Compact SR Ring "NIJI- Ⅲ"", Advance in Superconductivity Ⅷ, P1235 (1995)
[10] T. Masuda et. al., "The verifications tests on High Tc Superconducting Cable", Journal of the Society of Electrical Materials Engineering, Vol. 12, No.1, PP33-41 (2003)
[11] T. Masuda et. al., "V-t characteristics of PPLP impregnated with liquid nitrogen", 2002 IEEJ National Convention
[12] S. Honojo et al., "Verification test of a 66 kV High-TC superconducting cable system for practical use", CIGRE 2002, 21-202