

SUPERCONDUCTING CABLES FOR POWER TRANSMISSION APPLICATIONS – A REVIEW

F. Schmidt, A. Allais

Nexans – Superconducting Cable System (Hanover – Germany)

Abstract

Superconducting power transmission cables have taken a step towards industrial transfer. The use of high temperature superconductor tapes enables cable operation with a liquid nitrogen cooling system. The interest for such components in an electrical network is undeniable, especially to mitigate the consequences of fault events. The integration of a high voltage cable in a network is always a particular case, and in the field of superconducting cables several designs are already available to fulfill the technical and environmental requirements. The development issues for the project of a high voltage underground cable of 600 m at 138 kV in New York are presented. Previous and ongoing projects of superconducting cables for similar applications are also reviewed.

1. INTRODUCTION

Since the discovery of ceramic-based high temperature superconductors in the late 1980's, the interest in superconducting cables for power transmission and distribution purposes has been renewed. The development of High Temperature Superconducting (HTS) Cables for high capacity power transmission has been started over the last decade to take advantage of the efficiency and operational benefits due to the use of liquid nitrogen for cooling, which represents a cheap and environmental friendly medium. Several prototypes were developed mostly for testing in laboratory setups.

2. CABLE DESIGNS

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. 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. A schematic view is shown in Figure 1. 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' (see Figure 2). 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. (LN₂). Thus LN₂ 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 now either be put into individual or, alternatively, into a single cryogenic envelope.

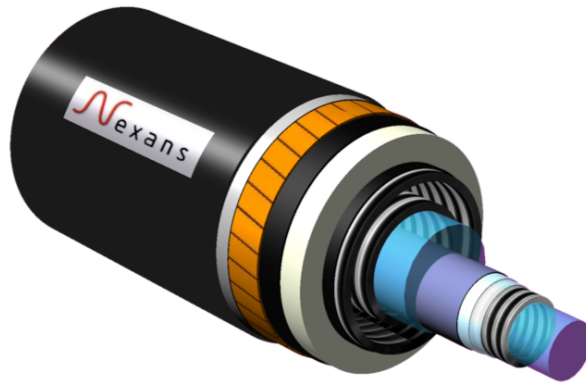


Fig. 1 - Warm dielectric superconducting cable. The dielectric is outside the flexible cryostat tube

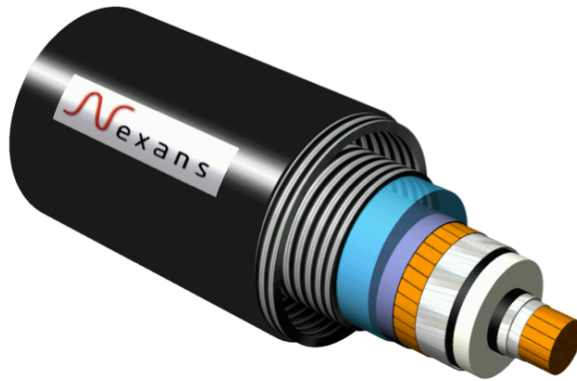


Fig. 2 - Cold dielectric superconducting cable. This is a coaxial cable where the dielectric between core and shield is maintained at cryogenic temperature.

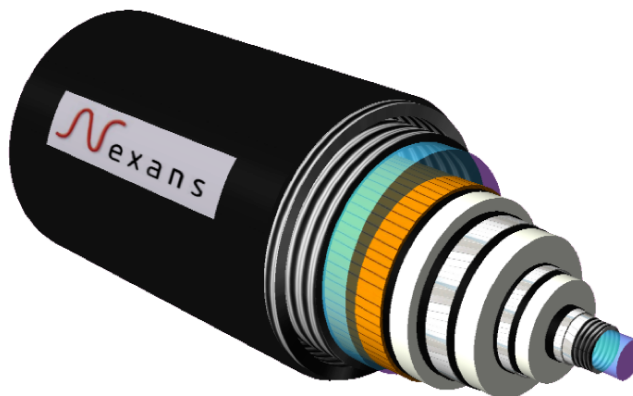


Fig. 3 Triaxial cold dielectric cable design.

A special type of cold dielectric cables is represented by the ‘triaxial design’, shown in Figure 3. In such a design the three phase conductors are concentrically arranged on a single support element divided by wrapped dielectric, which has therefore 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. No such requirements exist for cold dielectric cables, for which Table 1, reproduced from [1], shows a calculation 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.

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	1.4
Overhead Line	0.08	1.26	8.8	0.05

Table 1 Electrical characteristics example of 120 kV class cables

3. DESIGN ISSUES OF A COLD DIELECTRIC TRIPHASE SUPERCONDUCTING CABLE

The following considerations are based on the experience acquired during the first steps of the development of a 600m High Voltage superconducting underground cable in the US electrical network in Long Island – New York (LIPA project). We have pointed out the relations between the system requirements and the cable design.

The main system requirements are the rated current, the voltage, the length, the pipe size and the fault conditions, i.e. fault current and duration. Note that a superconducting cable has very low impedance compared to the other cables in the network, so in case of a fault the current would be naturally driven to it. The pipe size is also of economical interest for retrofitting applications of superconducting cable in existing pipes.

First of all, the number of superconducting tapes to be used depends upon their critical current and the rated current of the cable. The security margin must take into account any possible degradation during manufacturing and handling, as well as the influence of the cable self magnetic field. The judicious choice of the lengths of the conductive layers ensures an adequate current sharing between the different conductor layers.

The dielectric is composed of a wrapped layer of dielectric material impregnated with liquid nitrogen. The thickness of this layer depends on the voltage level.

Any boiling of the liquid nitrogen is prohibited in order to maintain dielectric strength. The consequence in term of mechanical damage due to pressure increase and dielectric breakdown would

be fatal to the cable. In that respect, the requirements are very challenging for the cooling system which has to evacuate the losses along a very long length, insuring that the nitrogen remains in the liquid state at every point. Three parameters govern the cooling system design: the hydraulic diameter, the cable length and the losses. The hydraulic channel is indeed the gap between the cable and the inner diameter of the cryostat. The outer diameter of the cryostat is imposed by the pipe size and the installation conditions. In the case of the LIPA project, three phases have to be installed by pulling through the installation pipe. The vacuum between the two corrugated steel tubes of the cryostat has to be sufficiently large to have low losses (less than 2W/m), so the spacing is fixed early in the design. The inner diameter of the cryostat is a function of the pipe size. The outer diameter of the cable depends upon the thickness of the copper stabilization layers, which have to withstand the fault conditions, and of the high voltage dielectric. Indeed the HTS tapes have little influence on the size of the coaxial cable, however their AC losses, added to the cryostat losses, impose the minimum mass flow of liquid nitrogen needed to achieve an overall temperature gradient in the cable of about 12 K (physical limit of the liquid nitrogen state : 65 K to 77 K). The mass flow, the hydraulic diameter and the length induce a pressure drop. To ensure liquid nitrogen stability the minimum pressure is to be selected according to the dielectric requirements at 77K. The pressure drop therefore is a limiting aspect. The working ranges of pressure and temperature are fixed and impose a compromise between the different cable design parameters (Figure 4).

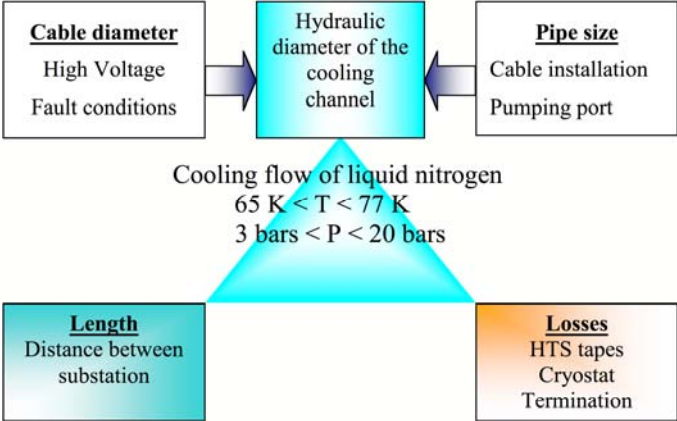


Figure 4 - Cooling system requirements and relevant cable design parameters

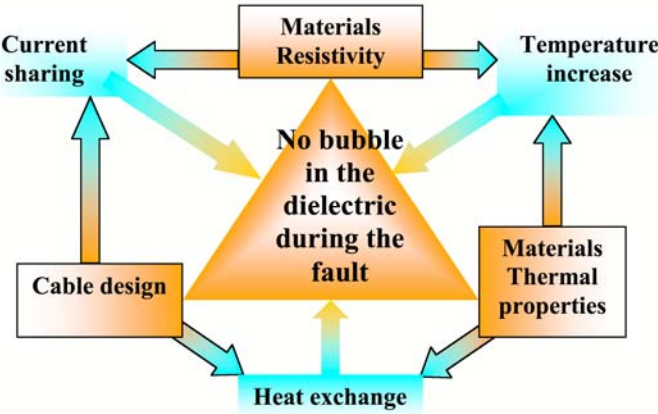


Figure 5 - Fault condition requirements and relevant cable design parameters

The overall goal of the cable design must be to find the appropriate values in the space of design possibilities that fulfill all specifications during normal operation and fault conditions. The fault current specified for such a cable can be huge. In the LIPA project it goes up to 30 times the rated current during a dozen of periods at 60 Hz, i.e. a few hundred milliseconds, which is the time needed to clear the fault by the conventional network security measures. The aim is to avoid the boiling of nitrogen during this time. Three phases can be identified during a fault, i.e. the current sharing, the corresponding Joule effect and the temperature increase in each layer. The current sharing is a consequence of the cable design, i.e. the mutual inductances, and the layers electrical resistances. The heat generation depends on the layers resistance. The temperature increase and the transient heat exchange are driven by the thermal properties of the layered structure of the cable. These coupled effects are summarized in Figure 5.

4. SUPERCONDUCTING CABLE PROJECTS OVERVIEW

Various superconducting cable projects have been started in the past. An overview of the different projects is given in Table 2. 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 e.g. 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.

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

[1] Cryogenic envelope supplied by Nexans. [2] Cryogenic envelope and dielectric supplied by Nexans.

Table 2 Superconducting power cable projects overview

5. CONCLUSIONS

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] J. Howe et al., Very low impedance (VLI) superconductor cables: Concepts, operation implications and financial benefits, white paper, Nov. 2003
- [2] S. Honojo et al., Verification test of a 66 kV High-TC superconducting cable system for practical use, CIGRE 2002, 21-202