Return to Session

SUPERCONDUCTING CABLES – STATUS AND APPLICATIONS

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ABSTRACT

Superconducting cables provide a new way to solve power transmission issues by enhancing the transmitted power through a very high ampacity whereas the classic technology usually relies on a voltage increase. This paper provides an overview of this emerging technology, describing the various types of superconducting cables, reviewing the main projects in the world and highlighting the specific benefits provided by superconducting cable systems.

KEYWORDS

Superconductor, HTS, superconducting wire, superconducting cable

INTRODUCTION

Power utilities are facing increasing challenges to adapt to steadily growing needs, additions of new generators, enhanced reliability requirements and rising constraints to install new equipments, especially at extra-high voltage. There is consequently a rising interest for new technologies which can help to increase electrical grid capacity and flexibility, and superconducting cables constitute a very promising one. Among other benefits, they indeed provide a new way to solve power transmission issues by enhancing the transmitted power through a very high ampacity whereas the classic technology usually relies on a voltage increase when the current exceeds 1,500 A.

OVERVIEW OF SUPERCONDUCTORS

Superconductors are materials which do not exhibit any electrical resistance below a certain temperature called the *critical temperature* (T_c). This phenomenon has been known since 1911 and observed in what are called now the Low Temperature Superconducting (LTS) materials because they are typically cooled with liquid helium at 4 K. LTS compounds are for instance used in Magnetic Resonance Imaging for medical applications, Nuclear Magnetic Resonance for analyses and in fusion reactors such as ITER.

In the late 1980's, a new family of superconductors, the High Temperature Superconducting (HTS) materials, was discovered (figure 1). These compounds differ from the previous ones though a much higher critical temperature allowing them to reach their superconducting properties at 77 K in liquid nitrogen, a cheap, abundant and environmentally benign cooling fluid. All HTS materials are copper oxide-based ceramics.

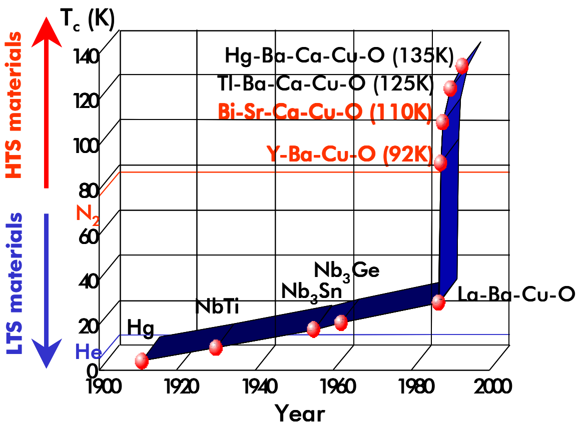


Figure 1: Gradual increase of critical temperature T_c

HTS CABLE SPECIFIC COMPONENTS

HTS WIRES

HTS wires constitute the current carrying elements of superconducting cables in normal operation. Two HTS materials are being used for power cable applications: $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223) and $YBa_2Cu_3O_7$ (Y-123).

The first generation of HTS wires has a multifilament structure. Bi-2223 filaments are embedded in a silver matrix (figure 2).

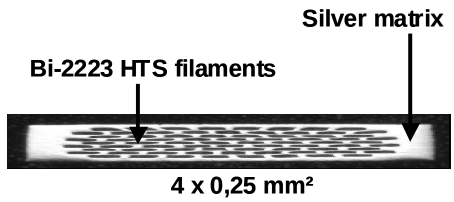


Figure 2: First generation of HTS wire (cross section)

First generation wires are available in kilometric lengths with critical currents exceeding 180 A.

Coated conductors constitute the second generation of HTS wires. They consist of a metallic tape coated with ceramic layers, the top one being made of Y-123 (figure 3).

[Return to Session]

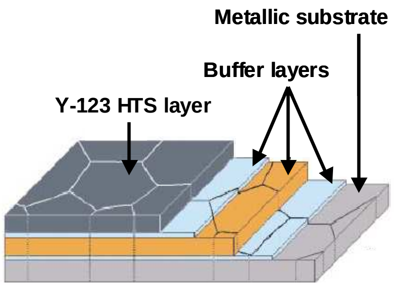


Figure 3: Second generation of HTS wire

This multilayer structure is expected to make these wires significantly cheaper than the multifilament tapes which require a silver matrix. However, coated conductors are only available in short lengths until now with critical currents exceeding 200 A per cm-width.

CRYOGENIC ENVELOPE

The cryogenic envelope provides the thermal insulation which maintains the HTS material below its critical temperature while minimizing the energy consumed by the liquid nitrogen cooling system.

The Nexans CRYOFLEX® flexible, vacuum-insulated cryogenic envelopes (figure 4) consist of two flexible and concentric corrugated stainless steel tubes. The outer part of the inner tube is covered with layers of superinsulation. A spacer with low thermal loss centers the inner tube inside the outer tube and prevents a contact between the two metallic tubes. A molecular sieve guarantees a long-term vacuum. The envelope may be protected with a polyethylene jacket.

1. Corrugated inner tube
2. Spacer
3. Vacuum space
4. Multilayer superinsulation
5. Corrugated outer tube
6. Polyethylene jacket

Figure 4: Nexans CRYOFLEX® cryogenic envelope

The cryogenic envelopes, together with their associated terminations and hardware, are assembled, leak-tested and evacuated at the factory. This enables simple and cost saving installation at customer's site. The flexibility of the envelope enables to handle it like a cable.

CABLE ACCESSORIES

Specific terminations, to connect the HTS cable to the grid, and cable joints are developed to manage the interfaces for both current and liquid nitrogen, and address issues arising from temperature gradients between liquid nitrogen and ambient atmosphere (figure 5).

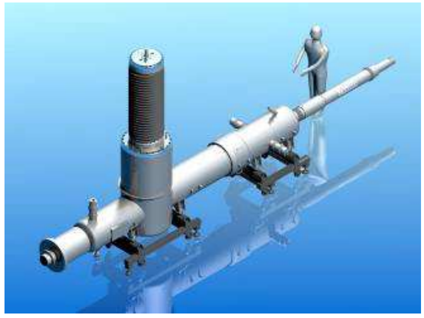


Figure 5: Nexans 138 kV HTS cable termination

HTS CABLE ARCHITECTURES

There are two principal HTS cable types, the warm-dielectric cable and the cold-dielectric cable.

WARM-DIELECTRIC HTS CABLE

HTS wires are stranded around a flexible support and immersed in a flow of liquid nitrogen inside the cryogenic envelope. The dielectric insulation, typically cross-linked polyethylene, is applied on the cryogenic envelope and therefore remains at the ambient temperature (figure 6). It explains that this cable architecture is commonly referred to as a "warm-dielectric" design.

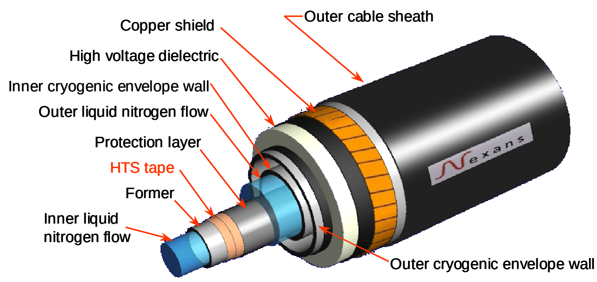


Figure 6: Single-phase warm-dielectric HTS cable

This relatively simple design provides high power density while minimizing the amount of HTS wires for a given transmitted power. Drawbacks compared to cold-dielectric designs are higher electrical losses, translating into additional cooling stations, higher inductance and phase spacing (figure 7) in order to limit the adverse effect, on the current transport capacity of an individual phase, of the stray electromagnetic fields (EMF) generated by the other phases.

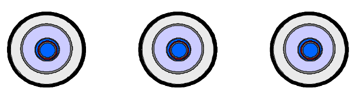


Figure 7: Warm-dielectric HTS cable layout

For these reasons, warm-dielectric designs are more suitable for medium voltage installations.

COLD-DIELECTRIC HTS CABLE

Each phase is composed of a flexible support, which may or may not be hollow, surrounded by a superconducting conductor separated through a lapped dielectric insulation from a superconducting screen (figure 8). Liquid nitrogen flows over and between both layers of HTS wire, providing cooling and contributing to the dielectric insulation between the conductor layers and the HTS shield layer. As the dielectric material, typically polypropylene-laminated paper, remains at about 77 K, this cable architecture is commonly referred to as a "cold-dielectric" design.

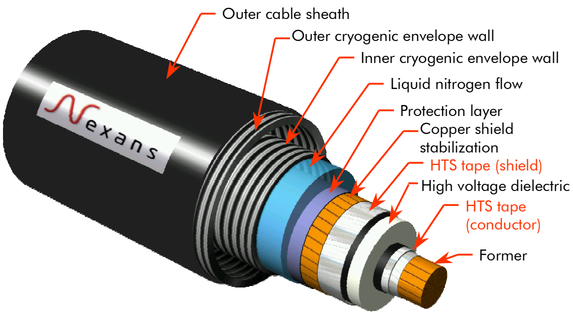
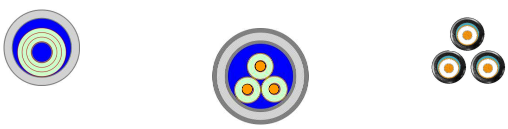


Figure 8: Single-phase cold-dielectric HTS cable

Such a geometry creates a flow of current in the screen which is opposite and equal to the one in the conductor. As a consequence, this design eliminates stray electromagnetic fields outside of the cable assembly. Cable phases can be placed next to each other without any electrical or thermal constraint.

Three cold-dielectric geometries are possible (figure 9). **Concentric phases** offer a very compact design which optimizes the use of HTS tapes and is suitable for medium voltages. Inserting the **three phases in one cryogenic envelope** provides a relatively compact design which allows cable shrinkage and expansion to take place within the cryogenic envelope. Indeed, HTS cable cores shrink when they go into service owing to the temperature decrease from ambient atmosphere to liquid nitrogen, and symmetrically expand in case of warm-up. This layout is suitable for medium voltages and the lower part of high voltages. The geometry with **separate phases** provides the longest unit lengths and is especially suitable for high voltage systems.

Concentric phases **Separate phases**



Three phases in one cryogenic envelope

Figure 9: Cold-dielectric HTS cable layouts

A solid support made of copper wires and the associated copper screen may be used for the transport of faults currents which exceed the HTS wires capacity.

Other advantages of cold-dielectric design are a higher current carrying capacity, reduced AC losses, translating into a wider spacing of cooling stations, and a low inductance owing to the coaxial structure. The inductance of cold-dielectric cables can be up to six times lower than the one of conventional cable and twenty times lower than the one of an overhead line of the same voltage.

As a consequence, cold-dielectric HTS cables differ from conventional cables through a much lower impedance. As impedance determines the power flow division among parallel cables, a coaxial HTS cable will carry more load, other factors (applied voltage and phase angle) being equal, than a conventional cable connected in parallel to the same points of a grid.

MAIN HTS CABLE PROJECTS

CABLE PROJECTS WITH FIRST GENERATION OF HTS WIRE

The three main HTS cable projects in the world using the first generation of HTS wire are located in the United States. They are all based on the cold dielectric concept. Each of them uses the layout the most suitable for the application voltage.

A 200-meter, 3 kA, 13 kV cable with a concentric design has been energized in August 2006 in Columbus (Ohio). A 350-meter, 0.8 kA, 34.5 kV cable with the three phases in one cryogenic envelope was connected to the Albany (New York state) grid in July 2006. But it is in Long Island that the longest and most powerful HTS cable ever manufactured will be deployed in 2007. This 600-meter, 2.4 kA, 138 kV cable will have the transmission power of a 345 kV link (574 MVA).

CABLE PROJECTS WITH SECOND GENERATION OF HTS WIRE

Two projects, one in Europe and one in the United States, aim at manufacturing 30-meter cold-dielectric HTS cables using coated conductors as current carrying elements. The European project aims at developing a one-phase 1 kA, 10 kV phase whereas the American project includes the installation at the Albany site of a three-phase 0.8 kA, 34.5 kV cable replacing a 30-meter cable section with first generation wires.

COLD-DIELECTRIC CABLE BENEFITS

ECONOMIC AND FINANCIAL BENEFITS

Lower voltages

HTS cables are expected to transport ampacities up to 4 to 5 kA which are much higher than the ones of conventional circuits. Utilities may consequently use lower-voltage equipment, avoiding both the electrical losses (I^2R) typical of high-current operation and the capital costs of step-up and step-down transformers (as well as the no-load losses within the transformers themselves). For instance, high-current HTS cables at 115 kV or even 69 kV may solve problems that would ordinarily require a 230 kV or 345 kV conventional solution.

Greater controllability

Owing to their very low impedance, HTS cables allow to control power flows with conventional phase angle regulators, providing benefits which are usually supplied by flexible AC transmission systems or DC transmission.

Reduced electrical losses and improved asset utilization

As the power flow in a cable is inversely proportional to its impedance, cold-dielectric HTS cables, owing to their very low impedance, attract current flow. They consequently reduce electrical losses by favoring a transmission path with minimized losses. They may also draw the current flow away from overtaxed circuits, preventing them from deteriorating due to heat and therefore extending their lifetime. Inserting HTS cables in strategic locations can therefore take the heat off urban power delivery grids.

Expanded generator siting options

By reducing voltage drop, cold-dielectric HTS cables allow to locate new generators farther from urban centers.

Use of existing infrastructure and pathways

Cold-dielectric HTS cables require a smaller right-of-way than conventional circuits. They might be routed through existing corridors or, in the ideal case, through existing ducts, shortening the time to have a new link permitted and installed and consequently resolving faster grid congestion problems.

ENVIRONMENTAL BENEFITS

Cold-dielectric HTS cables yield several environmental advantages over conventional circuits:

- an underground installation eliminating visual impact,
- reduced losses in HTS cables but also in adjacent conventional circuits that are offloaded owing to the very low impedance of HTS cables,
- a dielectric fluid, liquid nitrogen, which is cheap, abundant and environmentally compatible,
- elimination of stray EMF thanks to the HTS shield,
- enhanced generator dispatch, relaxing the constraints on generating units located in urbanized areas.

CONCLUSION

HTS cables, through the wide range of economic and environmental benefits they generate, constitute a new tool for power utilities to resolve grid congestion problems and extend the lifetime of their existing systems. The ongoing demonstration projects, especially the ones in the United States, are key to demonstrate the feasibility and the reliability of this new technology.

Although HTS cables are more expensive than conventional cables, HTS cable systems can be economically viable in locations were associated savings (in permitting, right-of-way, civil works, substation equipment,…) compensate for the higher HTS cable price. Applications were HTS cables are economically competitive are expected to increase when the second generation of HTS wires, the cheaper coated conductors, becomes available on an industrial scale.

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GLOSSARY

AC: Alternating Current
DC: Direct Current
EMF: Electromagnetic Field
HTS: High Temperature Superconducting
LTS: Low Temperature Superconducting