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DEVELOPMENT AND DEMONSTRATION OF A LONG LENGTH TRANSMISSION VOLTAGE COLD DIELECTRIC SUPERCONDUCTING CABLE TO OPERATE IN THE LONG ISLAND POWER AUTHORITY GRID

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ABSTRACT

The US Department of Energy is funding the world's first cold dielectric superconducting power cable demonstration project at transmission level voltage, to be installed at the Long Island Power Authority (LIPA) grid in 2007. The cable is designed to carry 574 MVA at a voltage of 138 kV. It will remain installed as a permanent part of the LIPA grid. The project team is comprised of American Superconductor, Nexans, Air Liquide and LIPA. This paper will give an overview of the technical goals of this project as well as the project status. It will describe the cable design and development process, the refrigeration system and the site installation status. An overview will be given about some system-specific operational characteristics influencing the cable system design such as fault currents.

KEYWORDS

Superconducting cable, Superconductor, high voltage

INTRODUCTION

High-capacity, underground HTS power cable has long been considered an enabling technology for power transmission. Power cables using HTS wires have been developed to increase the power capacity in utility power networks while maintaining a relatively small footprint. Over the past decade, several HTS cable designs have been developed and demonstrated [1]-[4]. All HTS cables have a much higher power density than copper-based cables. Moreover, because they are actively cooled and thermally independent of the surrounding environment, they can fit to much more compact installations than conventional copper cables, without concern for spacing or special thermal backfill materials to assure dissipation of heat. The Lipa HTS cable project is funded by the US Department of Energy. The project goal is to design, develop and demonstrate the first long length, transmission level voltage, cold dielectric, high temperature superconducting power cable. The cable is designed for permanent installation in the Long Island Power Authority (LIPA) grid and will be able to carry 574 MVA at a voltage of 138 KV. This paper gives a project overview and discusses aspects of the cable design, refrigeration system and site design.

PROJECT DESCRIPTION

The project is a Superconductivity Partnership Initiative (SPI) between the United States Department of Energy (DOE) and industry to develop a long length transmission voltage high temperature superconductor power cable. American Superconductor Corporation is the prime contractor as well as the manufacturer of the high temperature superconducting wires. Nexans is providing the design, the development and manufacturing of the cable, terminations and cryostat and Air Liquide is providing the cryogenic refrigeration expertise. The host utility, LIPA, is providing the site, civil work, controls and protection, transmission planning and the operation of the HTS cable. The cable system will be integrated into the LIPA grid and ready for energization in 2007.

CABLE SYSTEM DESIGN

Specification

The cable system to be installed in the Long Island Power Authority grid is the worlds first to operate at the transmission level voltage of 138 kV. This cable is designed to carry 2400 A rated current resulting in 574 MVA of total power carrying capacity. The 600 meter long system is able to withstand 51 kA rms fault currents for 12 line cycles. In addition to that the system is designed to withstand lower level through faults while staying in operation.
The system will be installed in the Holbrook Substation area of the LIPA grid heading north for a distance of 600 meters where a new switching station is installed. This new station will house the cryogenic refrigerator, the HTS cable terminations, liquid nitrogen storage and the necessary controls for operation and control of the cable system, The power for this line will be taken from an existing 138 KV overhead circuit which will remain in parallel as a backup.

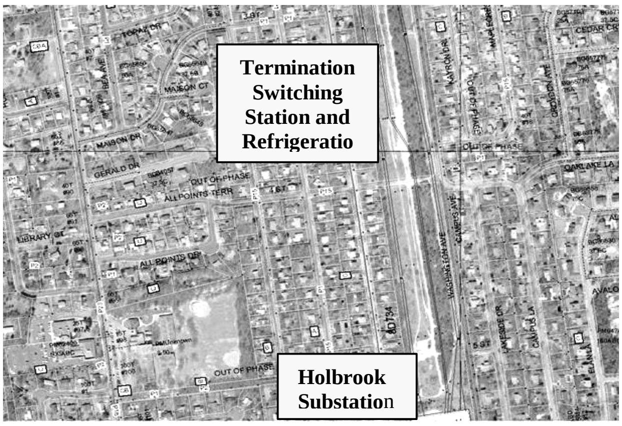

Fig. 1. Aerial view of the cable route

Cable general description

The cable used in the LIPA project is a cold dielectric design. The cable system contains three individual HTS cables and six terminations. The cable configuration consists of a copper former, two HTS conductor layers, an high voltage insulation layer, an HTS screen layer, a copper screen stabilizer and a cryogenic envelope. Fig.1 shows a schematic of cable cross section. During the normal operation, the cable core is maintained at operating temperature by circulating sub-cooled liquid nitrogen.

Fig. 2. Structure of superconducting cable phase

Each cable phase is pulled into a HDPE conduit on site and linked to an outdoor termination at both ends located in the substation areas that will connect the cable to the LIPA grid. The terminations provide both a connection to the cable and interface to the cable cooling system.
In order to enable the appropriate opposite current flow in the superconducting shield layers the screens of the individual cable phases are connected at both cable ends. This is done through a cryogenic jumper cable located and connected at the cable terminations. The termination also contains a bursting disc to protect against transient overpressure generation inside the cable system and particularly inside the termination. A termination sketch can be seen in Fig. 3.

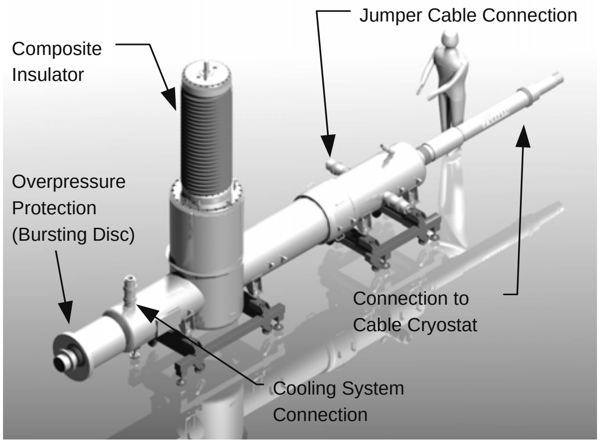

Fig. 3. Superconducting cable termination

The BSCCO 2223 superconducting wires used as current carrying elements are available in different qualities with regard to

- o Critical current (Ic)
- o Mechanical stress tolerance
- o Hermeticity against LN_2

The cable design for this project is based on the use of hermetic wires with a critical current of 135A per wire at a width of 4.3 mm for the conductor layers and 105 amps for the shield layers. The HTS wire Ic directly impacts the cable conductor design, the tolerance against mechanical stress is an important aspect that determines cable manufacturing and handling requirements.
Based on experience with superconducting BSCCO-wires, hermeticity against LN_2 is identified as an absolute requirement to prevent ballooning of HTS-wires during any thermal cycles the cable may see [6].
The LIPA cable required the production and supply of approximately 155,000 meters of superconducting wire plus several kilometers of additional wire for qualification of the manufacturing processes for the cable.

Cable Operating Parameters

The selection of the cable operating parameters is driven by coolant properties, Ic characteristics of the wire, the cable core characteristics and the fault conditions of the installation site [5]. The selection process usually takes a few iterations due to coupling of various parameters. The fault current carrying capability of the cable is one of the strongest drivers for the cable design in both, hydraulic layout as well as geometry through the required cross section of the copper former and screen layers. Since nitrogen is used as coolant, the minimum operating temperature of approximately 65 K is selected, which is close to the solidification point. With the different constraints mentioned the maximum operating temperature, the maximum operating pressure and the diameter of the cable cryostat are determined. As a result of this design process, the operating pressure of 18 bar, LN_2 flow rate of 0.375 kg/s, the cryostat diameter of 84 mm and maximum operating temperature of 72 K are selected. The cryostat losses of 1.3 W/m/phase and a total pressure drop over the entire cable of 2 bar are expected. Fig 4 illustrates a final system thermal budget with various operating conditions.

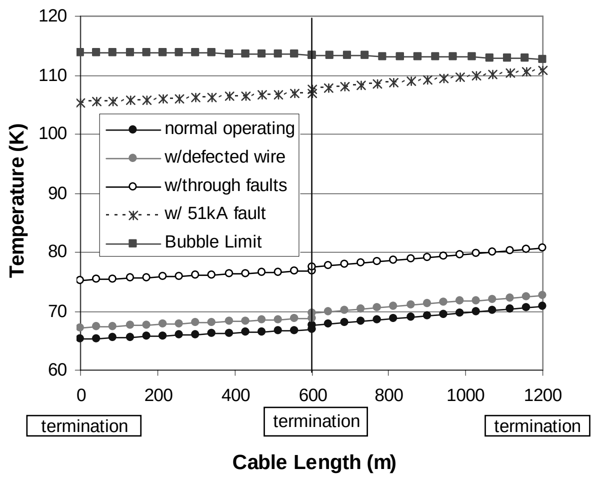

Fig. 4. Lipa cable thermal budget

The main loss components in this superconducting cable are identified as:

- Cryostat thermal losses
- AC-losses of conductor and shield
- Eddy current and resistive losses in the former and copper shield
- Dielectric losses in the insulation
- Hydraulic losses through the liquid nitrogen (LN2) flow
- Thermal and resistive losses in the termination

Each of these loss mechanisms have been studied analytically and to the largest extent possible tested and verified during the course of the project. The following table shows the calculated value of the electrical loss mechanisms at three different loadings on the cable, no load, 200 MVA and full load of 574 MVA.

Table 1
Electrical losses of the cable at different ratings

	Electrical Losses (W/m)		
	0 MVA	200 MVA	574 MVA
Former	0	0,04	0,24
HTS core	0	0,19	2,73
HTS shield	0	0,04	0,61
Outer Stabilizer + Cryostat	0	0,03	0,20
Dielectric	0,50	0,50	0,50
Total	0,50	0,79	4,28

To fully qualify the cabling process, a prototype 30 meter cable and two full scale terminations have been fabricated and tested. Sub-cooled LN_2 was used as coolant during entire test. Beside High voltage tests and Ic- measurement tests regarding the thermal losses and hydraulic behaviour have been performed as well as load cycle tests and AC-loss measurement .and have verified the calculation results.

Fig. 5. Test setup of 30m prototype cable

Fault Management

As with conventional cable, HTS cables must be safe and reliable when abnormal conditions, such as local and through faults, occur in the power grid. Typically, the through faults are those that are generated at other locations but affect the power flow on the superconductor cable, while the local faults are those which happen directly on superconductor cable or related peripherals and in general require repairs, maintenance or replacement of equipment by utility operating personnel. After a through fault it may or may not be required to take the cable out of service depending on the amount of energy dissipated in the system, the fault history, the cable thermal behaviour and layout and the cooling system capabilities.
During a local fault, a large current many times greater than the rated current of the cable is created for a brief period of time until the circuit breakers can be opened. As a result, a tremendous amount of energy is dissipated into the cable core in a relatively short time. This dissipated energy drives not only cable system design but also cooling system design.
To provide proper system protection, it is necessary to have a general fault protection scheme that can be used to handle both local faults and through faults. Such a scheme has been developed during the course of this project and implemented in the Lipa grid protection environment.

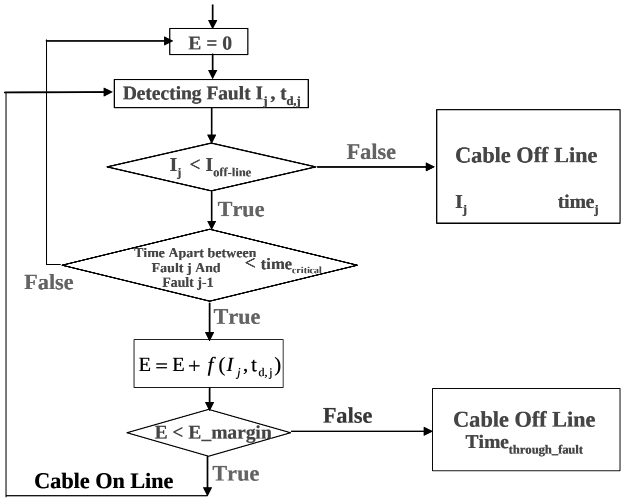

Fig. 6. Fault management scheme

The protection scheme for the current cable project is illustrated in Fig.6, where E is the energy stored in HTS cable core due to faults; I_j is the fault current of fault j; $t_{d,j}$ is the time duration of fault j; $f(I_j,t_{d,j})$ is the function to calculate energy dissipated into HTS cable core due to fault j; I_{off_line} is the single off-line current at which the cable must be taken off line; $time_{critical}$ is the time period during which the effect of the previous fault is entirely diminished and E_{margin} is the pre-determined threshold at which the cable must be taken off line. The Cable Off Line table shows how long the cable must be taken off line for a specific fault current I_j when the fault current is larger than single off-line current I_{off_line}. The off-line time is a function of refrigeration power and coolant flow rate. Even though, the scheme is designed for the current cable project, it could be used for the other cold dielectric cable design

REFRIGERATION SYSTEM DESIGN

General description

The refrigeration system used in the LIPA project is a turbo-Brayton Helium refrigerator that circulates subcooled 65K LN2 through the cable cryostat. A 100% capacity backup system comprised of two vacuum bath LN2 subcoolers and

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Fig. 7. 13,000 Gallon LN2 Bulk Storage tank

13000 gallon bulk storage tank supports the reliability of the system. The refrigeration capacity of the system in Primary mode is 5.65 kW and backup is 6.77 kW. If required both the primary and backup can be run together to augment the refrigeration capacity.
The 65K LN2 is supplied to the cable cryostat via a distribution valve cold box and vacuum insulated piping. The cooling down of the cable is performed via a specialized mixing skid that allows the cable cryostat to be cooled in a controlled manor.

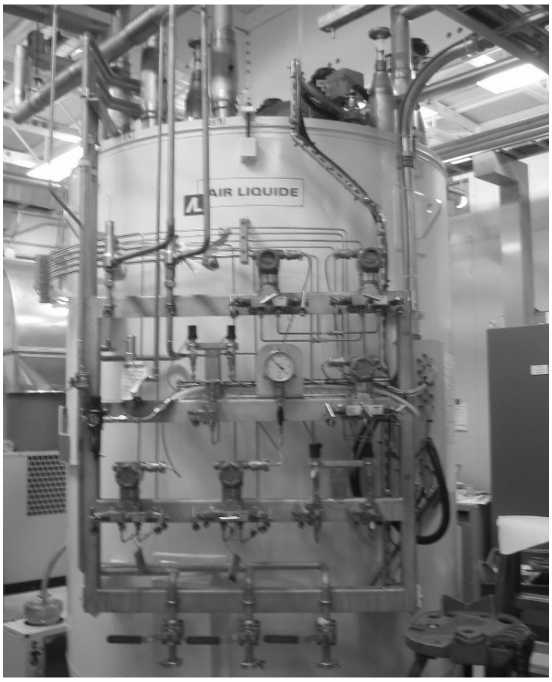

Fig. 8. Distribution Cold Box

To ensure a sufficient cool down the cold gas supply temperature for cable cool down is automatically controlled based on measurement of temperature gradients in the cable system that have been selected and verified during the cable system development and prototype testing phase.

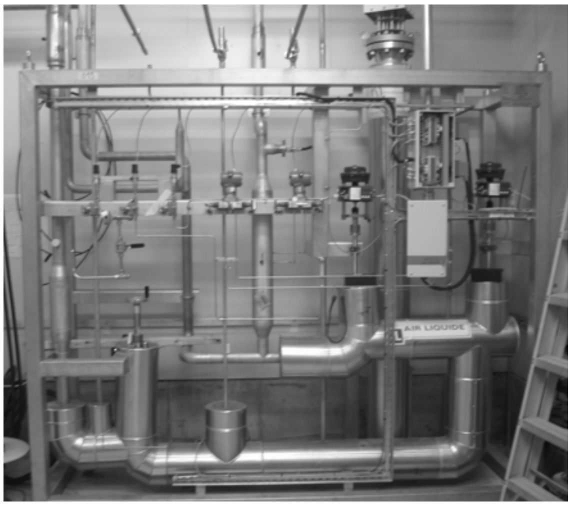

Fig. 9. Cool Down Skid

INSTALLATION STATUS

Cable

The superconducting cable phases have been manufactured based on the established manufacturing processes developed during this project. Conventional machines have been used slightly modified to strand the superconducting wire and to manufacture the high voltage dielectric.
The cable dielectric is designed to meet the demands on bending properties as well as high voltage insulation in the cold environment superconducting cables are used.. The cable cryostat was manufactured around the cable core using a longitudinal tube welding process. Initial vacuuming of the cryostat is done in the factory and the cryostat afterwards sealed for life.
After cryostat manufacturing and vacuuming the cable drums are shipped to the Long Island site for cable pulling end of May 2007.

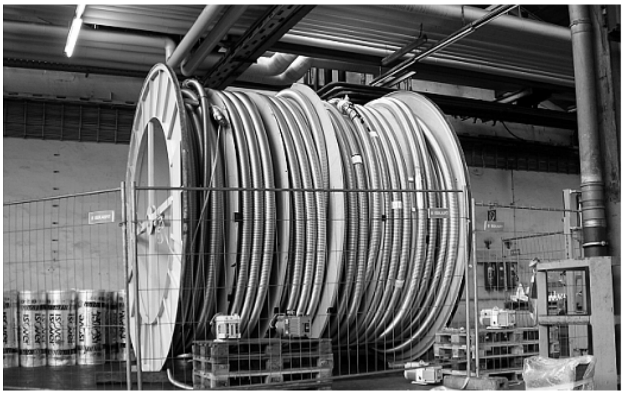

Fig. 10. Cable drum ready to be shipped

Terminations

Every high voltage components and related consumables and tools for the project terminations have been shipped to the Long Islang site.
Among these components, each bushing unit, based on a specific design adapted to high voltage and cryogenic constraints combination, has been routine tested and validated before shipment.
The cryostat, with its 7 m long and 4 m height design, is

another key component for the termination (Fig 11). It allows to manage the transition between ambient temperature and cryogenic temperature and to withstand the high voltage constraints in the same time. At this stage of the project, 2 units have been already shipped to the installation site. 2 additional units are ready to be shipped and the last pair of cryostat will be shipped before end of May.

Fig. 11. Termination cryostat

Refrigerator system

The refrigeration system installation was completed the end of January 2007. Startup and pre commissioning activities were performed through to mid March with many successful starts and stops and switchovers between primary and backup.

Fig. 12. Helium compressor

Final commissioning and performance testing is scheduled to be completed by the end of May, with all performance aspects of the refrigeration system critical to cable operation characterized and validated against design values, i.e. refrigeration power, LN2 flow rate at design pressure drop, LN2 temperature, overall system effects on change of operation. Adjustments, if required, to the operating logic of the refrigeration system will be done at this time.

Site preparation

The preparation of the cable installation site has been started in 2006. HDPE conduits have been buried for pulling the cable. The terminations for the individual phases will be placed on a concrete pad that includes gravel pits to receive liquid nitrogen in case of the cable system overpressure protection being activated. The concrete pad shown in Fig. 13 is ready to receive the terminations. Auxiliary switchgear such as circuit breakers have been installed as necessary to connect the system to the grid.

Fig. 13. Termination concrete pad

CONCLUSION

A 138 kV, 3 phase transmission cable system has been developed and manufactured and is now ready to be integrated into the grid on Long Island NY. It will be the first demonstration of an HTS cable at transmission voltage on the grid. It is being designed to operate reliably and to withstand fault currents up to 51,000 amps RMS. The cable will be completed and put into service in the LIPA grid in 2007.

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GLOSSARY

LN_2	Liquid Nitrogen
HTS	High Temperature Superconductor
Ic	Critical Current