Superconducting Power Cables

Technology Watch 2009

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PRODUCT DESCRIPTION

This report is the fourth installment of a Technology Watch series on Superconducting Power Cables that summarize full-scale superconducting cable projects throughout the world. The series provides an overview of technical fundamentals and status updates on ongoing development efforts ranging from full-scale test installations to grid-deployed demonstration projects. This installment of the series covers ongoing full-scale utility installations and proposed demonstration projects worldwide. Information about the capabilities of the high-temperature superconductor (HTS) power cable manufacturers is also presented.

Results and Findings

Superconducting power cable systems are being installed into electric power grids throughout the world. Most of these installations are demonstration projects to validate operational performance and reliability. The United States Department of Energy (DOE) has been a leader of this deployment effort over the past decade by sponsoring three installations in the United States. Recent activities in Europe and Asia have increased international participation in developing the technology into a feasible and reliable product. In addition, Russia is currently developing a superconducting cable system for installation in the Moscow grid. The manufacturers of HTS power cables compose a small, though international, industrial community that provides customized systems based on customer specifications that are unique for a particular application. An EPRI survey completed by several HTS cable manufacturers revealed that several products are currently available.

Challenges and Objectives

- To inform interested individuals within the power industry about the current status of the technology and/or any major developments.
- To provide utility personnel, managers, and supervisors with the appropriate information about superconducting power cable technology so that they can consider all factors when decisions are made about possible use of the technology in their respective power systems.

Applications, Values, and Use

The future power grid will likely incorporate superconducting power equipment for specific applications where physical space and capacity are major issues. Superconducting power cables hold promise to increase transmission capacity and reduce spatial footprint, allowing for retrofit into existing ductwork. In order for this technology to gain acceptance by electric utilities as a commercially viable solution, full-scale testing and utility demonstrations are needed to improve design, develop/refine installation practices, validate performance, demonstrate reliability, and establish proper O&M procedures. This report keeps utility personnel informed by presenting the latest information with regard to these points.

EPRI Perspective

Information regarding superconducting power equipment has been largely confined to academic publications and government-sponsored program reviews not typically attended by utility personnel. Overall, there is relatively little information provided from an electric power utility viewpoint because development has long been pursued by entities within these circles. This report was written with focus on electric utility operations with subjects such as installation, commissioning, and O&M addressed whenever possible. Although additional demonstrations are necessary to develop a more complete picture, lessons have been learned through the course of the projects summarized herein. It is anticipated that upcoming projects will establish a wider sphere of commercial application as well as continue to increase our understanding on the performance of superconducting power cables and ancillary operating equipment.

Approach

Information was gathered though literature search and communication with project managers, equipment manufacturers, and project host utilities. The information gathered was consolidated and presented to keep the reader relatively well informed on the state of the technology without having to access multiple information sources.

Keywords

Cryogenic refrigeration systems
High temperature superconductivity (HTS)
Superconducting power cables
Superconducting power equipment

ACKNOWLEDGMENTS

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CONTENTS

1
INTRODUCTION

Background

Projects to demonstrate superconducting power cable systems in utility power grids have increased internationally as the technology improves and the need to ease issues related to power congestion in densely populated urban centers is realized by power-system operators. Superconducting power cables are a possible solution to these congestion issues because they can provide to three to five times more power capacity than conventional underground cables in the same amount of physical space. One application touted for high-temperature superconductivity (HTS) power cable systems is underground cable retrofits, where the cost of expanding existing tunnels or digging new ones outweighs the initial cost of the superconducting system. Additionally, superconducting power cables may be an effective option where right-of-ways (ROWs) are difficult or impossible to obtain.

The United States currently has two in-grid installations in operation with two more expected to go on-line within the next three years. One project to be installed in the United States is a mile-long superconducting power cable system to be installed in New Orleans, Louisiana. The cable is expected to solve issues with load growth in residential areas, where space limitations make construction of a new substation very costly. It will also be the longest superconducting cable realized to date (the 600 m cable on Long Island currently holds that title). A 5 GW dc HTS cable system has been proposed to connect the three U.S. grids. If installed, the dc cable system will allow significant levels of power to be exchanged among the three grids, which at present are not well connected. Demonstration projects are underway in Korea, China, Japan, and Russia. A list of active superconducting cable installations worldwide is provided in Table 1-1.

Table 1-1
Active Superconducting Cable Deployments (Last Updated in 2009)

Project	Country	Operation	Time Active
Innopower	China	Grid	2004–present
KEPCO/KEPRI	South Korea	Testing Center	2005–present
KERI/LS Cable	South Korea	Testing Center	2006–present
Columbus	USA	Grid	2006–present
Long Island	USA	Grid	2007–present

Demonstration projects allow the manufacturers and the eventual customer (power utilities) to evaluate the feasibility of HTS power cable systems under actual grid conditions. In addition, the demonstrations allow the stakeholders to develop methods for installation, operation, and maintenance of these systems. The demonstration projects offer an avenue of information exchange between the two parties so that the technology can progress further toward commercialization.

Preliminary Materials

This document is one volume of a series of technical updates to inform utility personnel (managers, technical experts, and supervisors) about the operation of superconducting power cables and the status of demonstration projects. Although written on a high level to broaden the potential audience, foundations have been laid for better understanding in previous EPRI reports that address superconductivity, superconducting power cables, and basic cryogenics. It is suggested that readers with little or no experience in superconductivity familiarize themselves with the work summarized in Table 1-2.

Table 1-2
Previously Published EPRI Documents Relevant for Superconducting Power Cables

Title	Document	Description
Superconducting Power Cables, Tech Watch 2006 [1]	1012430	• Provides a comprehensive overview of superconducting cable technology. • Describes three in-grid projects within the USA. • Provides a summary of non-USA projects.
Superconducting Power Cables, Tech Watch 2007 [2]	1013990	• Summarizes operational issues and experienced events for the Albany and Columbus cable project. • Provides further description of the Long Island Power Authority (LIPA) project. • Describes HTS cable projects in Japan, China, and Korea.
Superconducting Power Cables, Tech Watch 2008 [3]	1015988	• Provides a tutorial on cryogenic dielectrics for superconducting power cables. • Tracks the status of worldwide demonstration projects.
Cryogenics, A Utility Primer [4]	1010897	• Introduces cryogenics for superconducting applications. • Provides high-level explanations for understanding at any technical level. • Includes summaries of various superconducting power applications.
EPRI Cryogenic O&M Workshop [5]	1008699	• Summarizes an EPRI workshop held in 2004 concerning issues with cryogenics in superconducting power applications. • Addresses O&M and other issues. • Includes discussions among device manufacturers, the suppliers of cold, and power utilities.

Objective

The purpose of this report is to provide professionals in the power industry an educational tool to increase awareness and understanding of superconducting power cable technologies. It is the intention of the author that interested readers will be able to use this and previous editions in the Technology Watch series (Table 1-2) to acquire a fundamental understanding of the technology both in terms of technical details and the status of development projects.

Methodology

Information collected for publication in this report was obtained from open literature sources as well as direct interaction with developers, electric power utilities, and other technology stakeholders. The acquired information has been presented at a high level and reviewed by the contributing stakeholders to verify that the information is publically available and factually accurate.

2
HTS POWER CABLES: ACTIVITIES IN THE USA

Background

The United States Department of Energy (DOE) has undertaken efforts to improve the performance and reliability of the U.S. power grid by the development of superconducting power equipment for commercial deployment. DOE manages such efforts through its Office of Electricity Delivery and Energy Reliability (OE) that works to ensure that the U.S. electric power infrastructure is secure, resilient, and reliable. The OE works in several areas to improve power delivery, including: R&D of new equipment, security and response, and public policy and permitting issues.

The OE's Superconducting Power Equipment (SPE) program provides a cost share for select development projects that hold promise for future grid deployment. Project teams usually consist of a major developer (usually a vendor), a host utility, a cold supplier, and a National Laboratory. The SPE program typically provides funding for half of each project's budget, while the other half is covered by the project team. This section of the Technology Watch covers three HTS cable demonstration projects that fall under the SPE program (see Table 2-1). In addition, a project sponsored by the U.S. Department of Homeland Security (DHS) and a proposed HTS dc cable system are covered.

Table 2-1
Active HTS Power Cable Demonstration Projects Supported by the U.S. DOE SPE Program

Project	Description	Status	Cumulative Funding in U.S. Millions (as of summer 2008)
Columbus[1]	13.2 kV Triaxial, 200 m long	Energized	\$11.8 (\$5.59 from DOE)
Long Island	138 kV Coaxial, 600 m long	Energized	\$46.90 (\$23.45 from DOE)
New Orleans	13.8 kV Triaxial, > 1 mile long	Deployment in 2011	Not Available

13.2 kV Columbus Cable Begins Third Year of Operation

The American Electric Power Company (AEP) and Southwire have reached an agreement to keep the Columbus HTS cable in service since DOE financial participation with the project ended in 2008. The Columbus cable has operated for more than three years in AEP's Bixby

[1] The DOE contract expired in late 2008. Southwire and the American Electric Power Company reached an agreement to continue operation of the cable on their own terms.

substation located just south of Columbus, Ohio. The 13.2 kV cable provides a link between the secondary of a 138 kV/13.2 kV step-down transformer to the 13.2 kV bus. The cable system is tri-axial (three concentric phases in a single cryostat) with a rated capacity of 69 MVA (3 kA per phase).

The cable system has operated smoothly with minimal interruption since it was commissioned in 2006 [1, 2]. During the hottest days of summer, the cable is often loaded to full capacity with no electrical or thermal issues. Interruptions to operation of the cable system have been mostly confined to routine maintenance, inspections, or issues with the cryogenic cooling system during the infant stages of the demonstration. In fact, the cable system experienced zero downtime from winter 2007 to fall of 2008.

The Columbus cable system was subjected to two major fault events in 2009, where the cable was directly exposed to through-fault current. Both events are believed to be the result of animal intrusion into the 13.2 kV bus located within the substation. In both instances, the fault current flowing into the faulted bus passed directly through the HTS cable. The first event prompted normal breaker operation with auto reclose, so the HTS cable was subjected to multiple hits. During the second reclose operation, the cable experienced its largest fault current (26 kA peak). The HTS remained in service after the fault, requiring zero downtime for re-cooling. The second event prompted lock out of the breaker, so the cable experienced only the initial fault current. No damage was suffered by the cable as a result of either of these fault events. Figure 2-1 shows the waveform capture of the 26 kA event. Notice that the load remained on the HTS cable as the faulted circuit was disconnected.

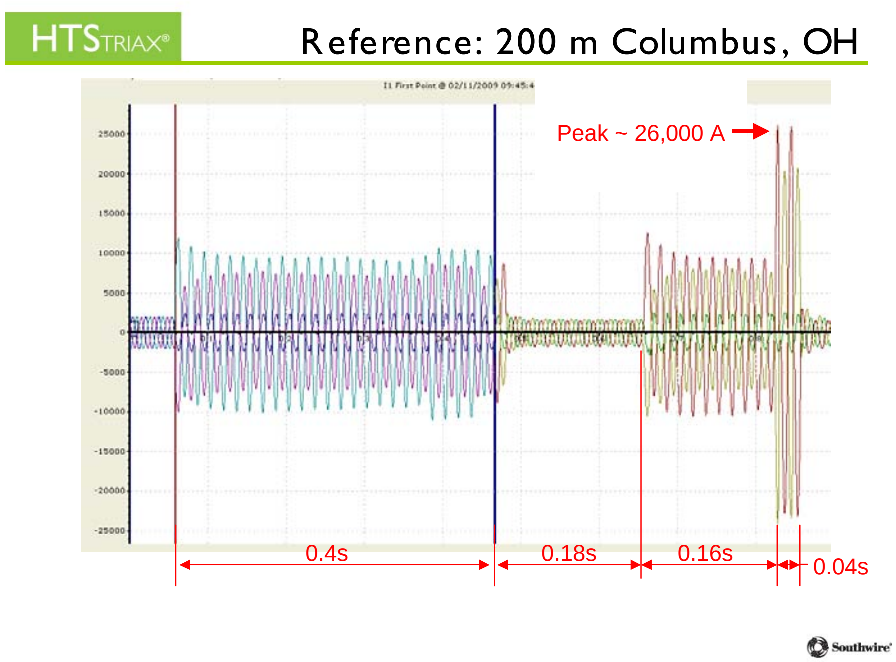

Figure 2-1
Waveform Capture of the 26 kA Fault Event at Bixby Substation in Columbus, Ohio

(Source: Southwire Company)

138 kV HTS Transmission Cable at LIPA

The world's only HTS high-voltage transmission cable continues to operate in the Keyspan/LIPA grid since commissioned in spring of 2008. The 600 m cable system is rated for 138 kV, 574 MVA (2.4 kA/phase) [1, 2], but the conventional interconnecting components in the substation limit the ampacity of the HTS cable system to 200 MVA (~830 A). American Superconductor Corporation (AMSC), manager of the LIPA project, has indicated that the cable system continues to operate smoothly with no degradation over the first year of operation. The cable system is of the coaxial type that consists of an HTS forward-conducting path and a shield within one cryostat. One coaxial HTS cable is necessary to conduct a single electrical phase of current, requiring three coaxial cables to complete the system, as shown in Figure 2-2.

The system experienced a low-level fault over the first year of operation of approximately 6 kA with no damage to the HTS cable system.

Figure 2-2
North Terminations of the 138 kV, 600 m HTS Transmission Cable at Keyspan/LIPA

(Source: Demonstration of a Pre-Commercial Long-Length HTS Cable System Operating in the Power Transmission Network, 2009 DOE Peer Review, August 4, 2009. Alexandria, VA.)

The second phase of the project is now underway, with the replacement of one of the phases with a cable constructed from 2G HTS conductors [3]. The 2G cable will demonstrate a recently developed voltage splice joint designed to accommodate the high voltage level. Modification of the terminations will be performed to accommodate thermal contraction of the 2G cable retrofit. Terminations of the remaining two cables will not be modified.

Initial tests of a field-repairable cryostat developed by Nexans have produced promising results. The repairable cryostat utilizes sectioned vacuum chambers with ports along the length to mitigate heat losses if the vacuum space is breached. Repair methods are also being developed by Nexans to allow repair/replacement of a cryostat section out in the field. Nexans expects that the new cryostat design coupled with appropriate field-repair methods will result in vacuum levels and heat-loss levels to near factory conditions. Current cryostat designs do not allow for adequate repair in the field, and once repaired, the heat-leak levels are typically much higher than those achieved at the factory.

Air Liquide and AMSC continue to develop a modular refrigeration system with increased efficiency and reliability than previous HTS cable refrigeration plants. The concept balances cost and performance by reducing the number of components in the system and optimizing the components to achieve efficiencies required for HTS cable installation. The modularity of the design will allow customers to size their refrigeration requirements according to the length and capacity of their HTS cable systems. The modular concept also provides a component of redundancy in case a module malfunctions or requires maintenance.

The project team is expecting to fabricate the 2G cable in 2010, with installation planned in late 2010 or early 2011. Work on the repairable cryostat and modular refrigeration will continue, with expectations to demonstrate both along with the 2G cable.

13.8 kV HTS Cable Project in New Orleans

The one-mile 13.8 kV, 48 MVA (2 kA) HTS cable system proposed to link together Labarre and Metairie substations has been put on hold by the host utility due to the economic downturn. Entergy, the utility that along with DOE will purchase and install the cable system, cited that stagnated load growth in the area of installation site has delayed the need for the high-capacity cable.

The Entergy project is unique among proposed or existing HTS cable installations because it is a solution to an actual distribution problem rather than a demonstration project. Therefore, Southwire, the manufacturer of the tri-axial cable to be installed, and Entergy have approached the project as an engineering task rather than a R&D project. Detailed information about the Entergy cable is available in the 2008 Technology Watch update [3].

13.8 kV HTS Cable/SFCL in Manhattan (Project HYDRA)

The U.S. Department of Homeland Security (DHS) is sponsoring a project to develop a fault current limiting HTS cable system and to install a prototype of the device into a Manhattan substation. Project HYDRA, described in more detail in [3, 6], was initially slated for installation in 2010, but the recent economic downturn has tentatively postponed the construction of a new substation that will feed one end of the cable.

Development of the cable system continues in anticipation of economic improvements. A full-scale prototype of the fault current limiting cable was tested at the Oak Ridge National Laboratory (ORNL) in early 2009 to validate performance of the device. A 25 m prototype of the fault current limiting HTS cable system was manufactured by Ultera™ and installed at ORNL for design testing in winter of 2008 (see Figure 2-3) [7]. The testing regimen included validation of the critical current, proper operation of the cold dielectric, and characterization of system electrical and heat losses. Tests subjecting the cable to fault currents as high as 60 kA peak fault were also performed to observe the fault current limiting capabilities of the cable. The fault-current tests revealed successful operation of the cable as a fault current limiter (Figure 2-4). The cable was able to limit the magnitude of 60 kA peak fault currents to less than 40 kA peak within the first half cycle.

Figure 2-3
25 m Prototype Test at the Oak Ridge National Laboratory: Terminations (Left), Cable Loop (Right)

(Source: High Temperature Superconducting Cable, 2009 DOE Peer Review, August 4-6, 2009. Alexandria, VA.)

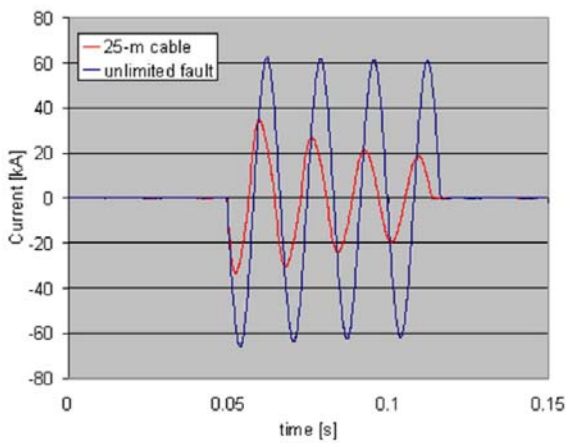

Figure 2-4
Fault Current Limiting Result during 30 m Tests

(Source: High Temperature Superconducting Cable, 2009 DOE Peer Review, August 4-6, 2009. Alexandria, VA.)

The economic downturn has resulted in the stagnation of load growth in the Con Edison power network. As a result, Con Edison has postponed the construction of the new substation that would have accommodated the cable project. Construction of the fault current limiting HTS cable system is expected to continue once economic conditions improve.

HTS DC Cable Super-Substation Project

Tres Amigas, LLC, a startup company based in New Mexico, has proposed a plan to link the three U.S. electrical grids using AC-to-DC converting stations and high-capacity dc superconducting lines. Currently, the three grids (Western Electric Coordinating Council, Eastern Interconnect, and the Electric Reliability Council of Texas) operate asynchronously, making it impossible to move power from one region to another. The separation of the grids presents a major hurdle when it comes to the transport of renewable energy, because it is impossible to move significant power from regions with an abundance of renewable energy to load centers with high electricity demand. Tres Amigas proposes that a common, three-way DC interconnection point between the three grids would allow renewable energies to be used where needed and would stimulate further renewable energy production by providing a path to market.

The key to linking the three grids is the conversion of power from ac to dc and vice versa. The dc power in the interconnection link can be synchronized to any three of the grids using voltage-source converter-based HVDC terminals for this purpose. Tres Amigas proposes that three of these HVDC terminals be linked by three superconducting dc cables, as shown in Figure 2-5.

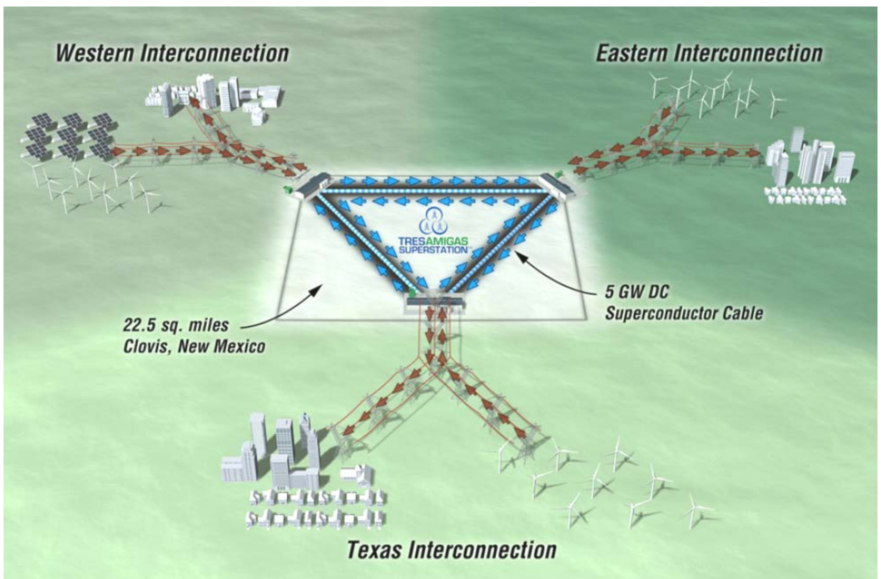

Figure 2-5
Proposed DC Interconnection Point with 5 GW DC HTS Power Cables

(Source: American Superconductor Corporation)

The three cables would form a ring bus configuration, providing an n-1 redundancy measure that would allow the system to maintain operation if one cable is inoperable for any reason. Little technical information about the cable or converter stations was available while compiling this report, although it has been disclosed that the each cable will be capable of transporting 5 GW of power. The proposal by Tres Amigas currently specifies completion of the project by 2014.

3
HTS POWER CABLES: INTERNATIONAL ACTIVITIES

22.9 kV Demonstration in Icheon City, South Korea

The Korean Ministry of Knowledge Economy (MKE) finalized plans in November of 2008 to install a 500 m HTS cable system in the Korea Electric Power Corporation (KEPCO) grid. The demonstration project follows successful testing of two 100 m HTS cable systems at KEPCO's Gochang Testing Center. Key participants of the demonstration project include:

- **KEPCO**

  Korea's sole power utility with majority share owned by the government. KEPCO serves approximately 13 million customers and generates approximately 60 GW.
- **Korea Electric Power Research Institute (KEPRI)**

  A central research institute owned by KEPCO to perform utility-related research.
- **LS Cable, Ltd.**

  Korean-based manufacturer of power cables.

KEPCO will demonstrate an HTS power cable system in a substation located in Icheon City, Korea. The location of the substation is approximately 50 km south of Seoul. The cable will be rated for operation at 22.9 kV, 50 MVA (~1.3 kA). The project will retrofit a three-phase HTS cable system into a space previously occupied by a three-phase 10 MVA conventional underground cable. The HTS cable will provide five times the capacity of the conventional underground cable without the construction cost associated with installing larger ductwork. The HTS cable will be installed between the secondary side of a 152/22.9 kV main transformer and the 22.9 kV substation bus. A schematic of the substation layout is shown in Figure 3-1.

The 500 m HTS cable system design consists of three coaxial HTS cable cores contained in a single cryostat, a configuration identical to the two 100 m cables at Gochang (Figure 3-2). LS Cable will manufacture the cable using 2G tapes manufactured by AMSC to construct the forward and reverse (shield) conducting paths for each phase. Cable manufacturing is already underway, and LS Cable has purchased 80 km of 2G tape from AMSC. The terminations and joint(s) will also be manufactured by LS Cable. The cable will be designed to tolerate faults of up to 25 kA for 5 cycles at 50 Hz without damage.

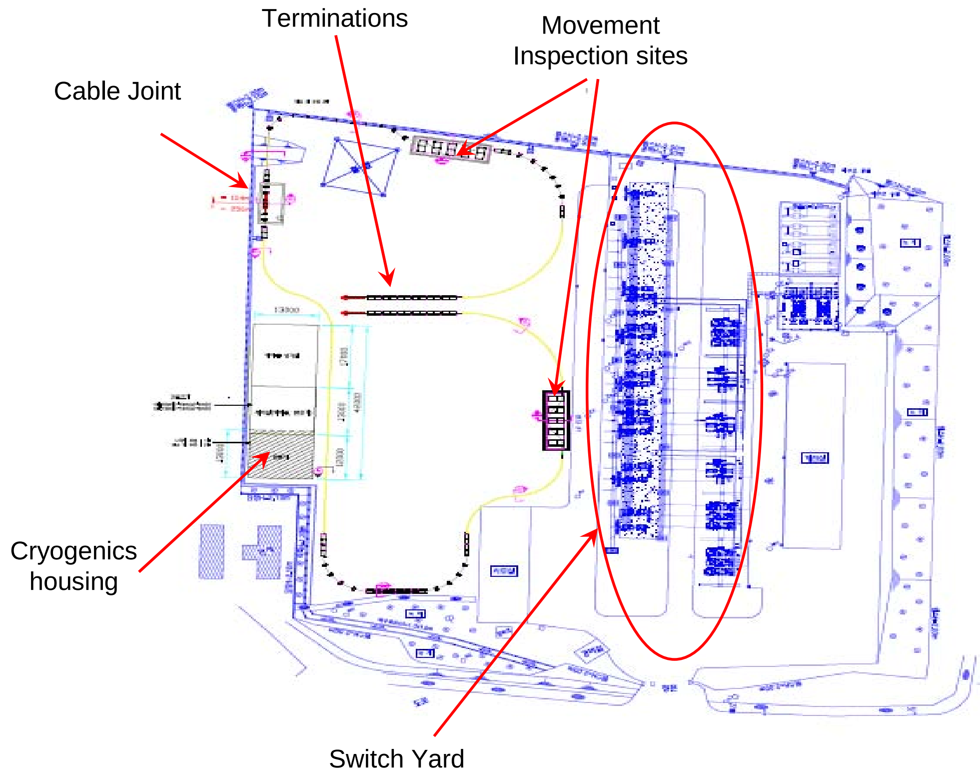

Figure 3-1
22.9 kV HTS Cable Demonstration at Incheon City, Korea (Substation Layout)

(Source: Korea Power Corporation)

Refrigeration of the cable, joints, and terminations will be provided by a closed-loop LN2 system. KEPRI has purchased a Stirling cycle refrigerator from Stirling Netherland. LS Cable will fabricate the complete cooling system and associated controls. The designed capacity of the cooling system is > 8 kW at 77 K.

Fabrication of the HTS cable is expected to begin in late 2009. Installation is slated for late 2010, allowing a year for production and factory testing.

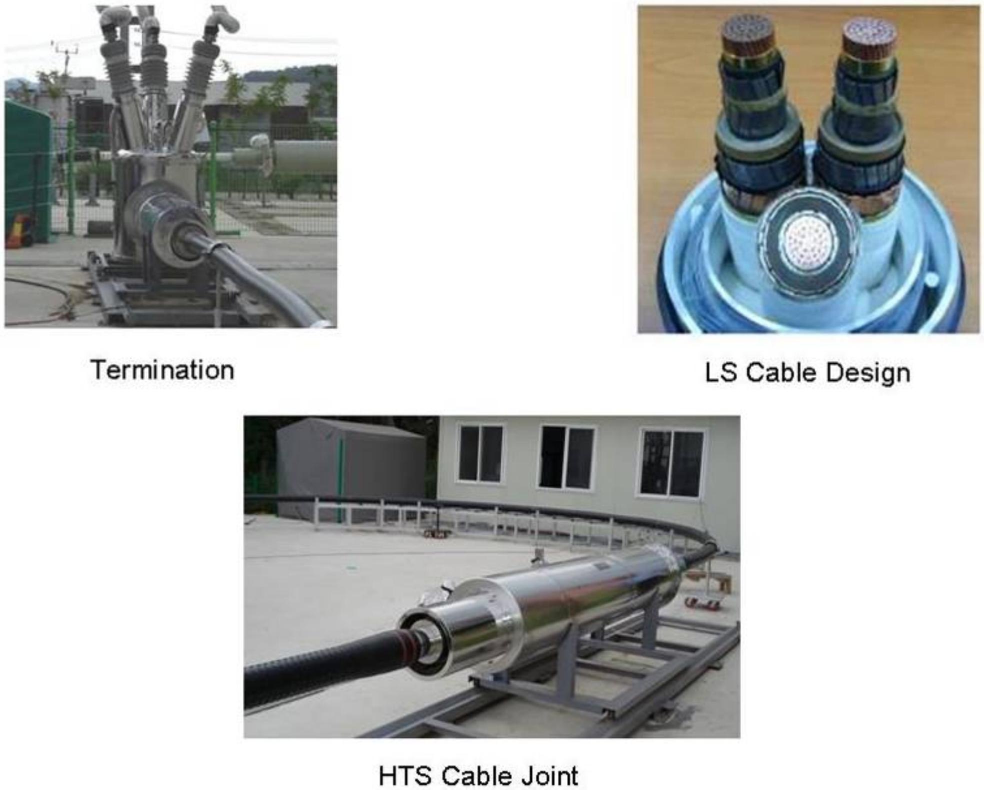

Figure 3-2
22.9 kV LS Cable System Design Prototype During Tests at Gochang

(Source: LS Cable, Ltd.)

In addition to the 22.9 kV HTS cable demonstration, Korea's Development of Advanced Power System using Applied Superconductivity (DAPAS) will develop a transmission-level HTS cable to operate at 154 kV. A prototype is planned for installation at the Gochang testing center in 2010 or 2011 and will have a capacity of 1 GVA (3750 kA per phase). The 100 m demonstration cable will provide a link to a nearby transmission bus that is sourced from a nuclear power plant located a few miles away. To accommodate testing of the 154 kV cable and other transmission-level cables, a new testing facility is being built at the Gochang site. The high-voltage (>100-kV) facility will accommodate the testing of high-voltage power cables and provide the ampacity necessary to quantify the power capacity of such cables.

66kV, 350 MVA Demonstration in Yokohama, Japan

A 66 kV HTS cable system will be installed in a Tokyo Electric Power Company (TEPCO) substation as a demonstration project [8]. The 250 m three-phase HTS cable system will operate at 66 kV/200 MVA (1.75 kA) in the Asahi substation, located approximately 20 km southwest of Tokyo in Yokohama City, Japan. The cable system will link a 154/66 kV step-down transformer to the 66 kV substation bus through a 150 mm conduit. The project team is summarized below:

- **The Ministry of Economy, Trade, and Industry (METI)**

  A Japanese government ministry that facilitates economic activities and policies, including trade and industry. METI provides the project budget to NEDO.

- **New Energy and Industrial Technology Development Organization (NEDO)**

  Originally established by the Japanese government in 1980 to develop new oil-alternative energy technologies, NEDO is responsible for R&D project planning and formation, project management, and post-project technology-evaluation functions. NEDO falls under the organization of METI.

- **Sumitomo Electric Industries (SEI)**

  Global manufacturer of electric wires, cables, and other products. Developer of HTS conductor and power cables.

- **Mayekawa Mfg. Co. Ltd.**

  Development, manufacturing, and engineering of refrigeration devices and processes for industrial applications and commercial use.

- **Tokyo Electric Power Company (TEPCO)**

  Electric power utility serving Tokyo and the greater Tokyo area with the production, transmission, and distribution of electric power to commercial and residential customers.

The one-line diagram presented in Figure 3-3 describes the application of the cable within the Asahi substation as a link between the step-down transformer and 66 kV bus. While the cable will have a manufactured rating of 350 MVA (3 kA), the conventional grid components are rated for only 200 MVA (2 kA). Therefore, the HTS cable will be over-designed for the demonstration, but the higher rating will be necessary for future in-grid applications. The proposed layout of the HTS cable project in the Asahi substation is presented in Figure 3-4. The HTS cable will run out from the transformer about 100 m, make a u-turn and running back toward the 66 kV bus.

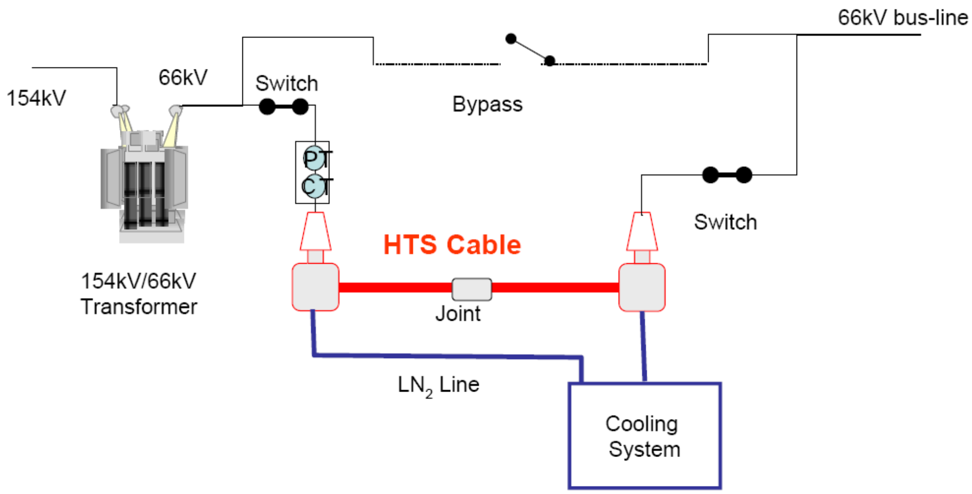

Figure 3-3
One-Line Diagram of Yokohama Cable Installation at Asahi Substation

(Source: Tokyo Electric Power Company)

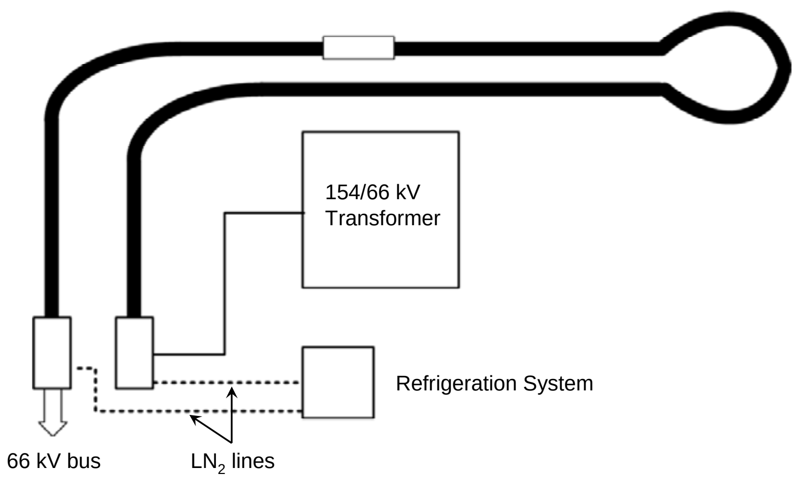

Figure 3-4
Proposed Layout of Yokohama Cable Installation at Asahi Substation

The purpose of the demonstration is to study the feasibility of the technology and gain experience with several operational factors, including:

- Asset management (operation and maintenance)
- System reliability
- System stability under load fluctuation
- Power system protection sequences
- Automation and remote monitoring

The project was initiated in 2007 and is scheduled to continue until 2013. The HTS cable system is scheduled for installation in 2011. Once commissioned, the cable system will operate for one year. Afterwards, the cable system will be de-commissioned and analyzed to determine whether any premature degradation of the cable and ancillary components occurred over the one-year evaluation.

The HTS cable, terminations, and a cable joint will be manufactured by SEI. The cable will be of the Triad geometry, in which three coaxial superconducting cables that make up the three electrical phases share a common cryostat. A single LN2 flow through the cryostat simultaneously cools the three cable cores. The fault-current criterion for the cable design is to withstand a 31.5 kA fault for up to 2 seconds without damage to the HTS tapes or dielectric. Additionally, the cable system should be able to return immediately to service following a 10 kA fault current for durations of up to 2 seconds. A 30 m test was conducted in 2008–2009 to prove the concept. The test resulted in good performance of the HTS conductors and electrical insulation in both the cable and interface components. The tests verified the fault current design goals outlined above and revealed ac loss levels of less than 1 W/m/phase at 2 kA, 50 Hz.

A closed-loop LN2 refrigeration system using several Stirling cryocoolers and circulation pumps will maintain optimal operating temperature for the HTS cable system. Operating temperature for the cable system will range from 67 to 77 K at operating pressures ranging from 0.2 to 0.5 MPaG (mega-Pascal gauge).

From an economical viewpoint, a study performed by SEI indicates that HTS cables require capacities of at least 350 MVA in order to become cost-competitive with conventional cable technologies [9]. The study states that the 350 MVA threshold is where the value of the HTS cable system offsets its high construction costs. For this reason, the development team has targeted the demonstration cable to have a current rating of 3 kA. However, the demonstration cable system will not operate over 1.75 kA (200 MVA) due to limitations of the conventional equipment at the Asahi substation.

Japan is looking for long-term solutions to improve the capacity and reliability of the TEPCO grid. One solution is to construct new underground tunnels that can accommodate 275 kV conventional underground cables. However, limited geographical area for grid expansion makes HTS cables an attractive alternative to the aforementioned solution. HTS cables have high current densities that allow for relatively small cable cross-sections, a characteristic that makes them suitable for retrofitting into already-existing ductwork. Furukawa Electric Co., Ltd., a Japanese manufacturer of power cables, is currently developing a 275 kV cold-dielectric HTS cable to meet this need. Future Technology Watch updates will provide more detailed information about the Furukawa 275 kV cable (limited information was available while compiling this report).

35 kV Demonstration Continues in China

The 33.5 m warm-dielectric HTS power cable manufactured by Innopower Superconductor Cable Co., Ltd., continues to operate at the Puji substation in Kunming, China. The HTS cable provides 40 to 60 MVA to approximately 25,000 homes. The total electricity delivered by the cable has reached 688,000,000 kW hours since it was commissioned in April 2004. The duty load for 2009 was in the range of 600 A to1 kA and continues to increase each year.

The cable was removed from service for approximately 60 days in the July–August 2009 to allow routine maintenance work, including but not limited to:

- Replacement of the bearings in the LN2 pump
- Repairing and recalibrating meters
- Vacuum check
- Enhancement of the thermal insulation parts

Other than the two summer months, the cable has operated normally in the Chinese grid.

A new project in China to develop a cold-dielectric HTS power cable was announced. The Shanghai Electric Cable Research Institute (SECRI) is manufacturing a 30 m cable for testing sometime in 2010. The cable system will be rated at 35 kV/120 MVA (2000 A). More information about this project will be available in future Technology Watch updates.

50 kV, 6 km HTS Cable Proposed in Amsterdam

Dutch distribution system operator Alliander (formerly NUON) and Ultera™ have proposed a project to develop and install a 50 kV, 6 km-long HTS cable system in urban Amsterdam. Participants of the project are summarized below:

- **Alliander**

  A Dutch distribution system operator that provides electric power to 2.9 million customers. Alliander serves among other areas of Amsterdam and the greater Amsterdam area.
- **Ultera™**

  A joint venture between cable manufacturers nkt cables in Europe and Southwire Company in the USA.
- **Delft University of Technology (TU Delft)**

  A major technical university located in the Netherlands. TU Delft will implement research studies and provide a high-voltage laboratory for testing the 50 kV cable.

The proposed HTS cable application is a retrofit solution to a transmission bottleneck that limits power flow into the center of the city. The conventional cable system now in place (*external gas-pressure cables*)[2] was initially designed to provide 100 MVA to center of the city. The design originally provided the N-2 redundancy condition required by Alliander because each one of the three cables alone could provide the 100 MVA capacity required. After the external gas-pressure cables were installed, the power demand of the city's center increased to 200 MVA, and the N-2 redundancy condition was no longer in effect. The proposed project seeks to replace the three 150 kV/100 MVA external gas-pressure cables with two three-phase, 150 kV/200 MVA high-

[2] The cable manufacturer, nkt, calls these cables "external gas-pressure cables" because they are pressurized from the outside using N2 gas. A lead membrane transfers the pressure to the inside of the cable which is oil-paper insulated.

performance XLPE cables (called *City* cables) and one 50 kV/250 MVA tri-axial HTS cable. The retrofit solution would restore N-2 redundancy condition and provide the 200 MVA needed at the center of the city. Figure 3-5 provides a description of the current application and the proposed solution.

The HTS cable will be inherently fault-current limiting to counter the increased magnitudes of fault current expected by the reduced impedance of the superconducting line. Under normal conditions, the HTS line will provide the 200 MVA with the XLPE cables only in operation during a contingency situation.

A significant technical hurdle to the project is the refrigeration system required to cool the 6 km cable span. A feasibility study performed by the project group [10] indicates that two cooling stations, one at each end, will be sufficient if their efficiency is high enough and if the ac losses and heat-leak losses are low. A visual description of the two-station cooling concept is presented in Figure 3-6.

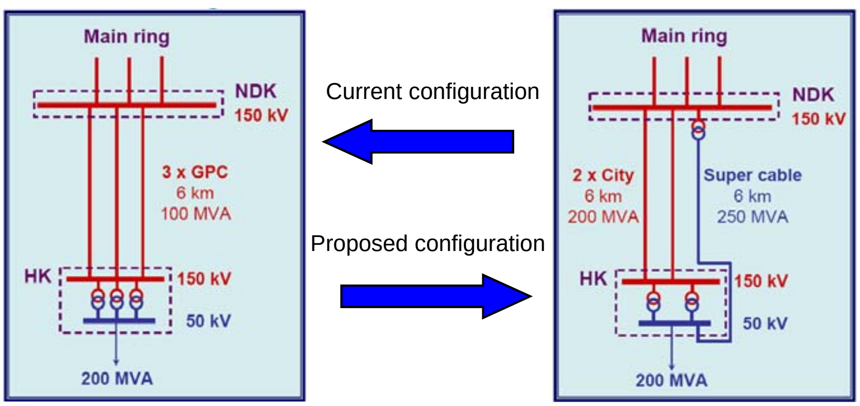

Figure 3-5
Configuration of the Retrofit Cable System Feeding Downtown Amsterdam

(Source: ULTERA)

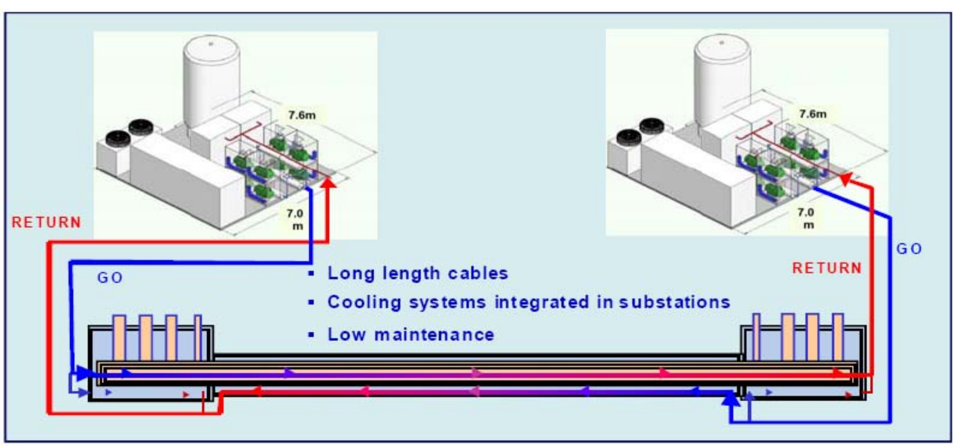

Figure 3-6
Two-Station Cooling Concept for the Proposed 6 km HTS Cable Project in Amsterdam

(Source: ULTERA and Praxair)

The development team has indicated that considerable development work will be needed to reach design specifications for the project. The project group is currently working on a proof of concept that will lead to a prototype cable system for full-scale testing. Installation of the 6 km cable is proposed for the 2014–2015 timeframe.

20 kV HTS Cable System in Development for Moscow, Russia

The Russian Scientific R&D Cable Institute (VNIIKP) together with Krzhizhanovsky Power Engineering Institute (ENIN) and R&D Center for Power Engineering are developing an HTS cable system for installation in a Moscow area substation sometime in 2010. The 200 m cable system will operate at 20 kV with a maximum rated capacity of 70 MVA (2 kA).

The HTS cable is of the coaxial design with forward conducting path and HTS shield contained within a single cryostat. The complete system will utilize three of these coaxial cables to accommodate the three electrical phases. Sumitomo has been selected as the 1G tape supplier for the cable. A conceptual rendering of the cable core design is shown in Figure 3-7.

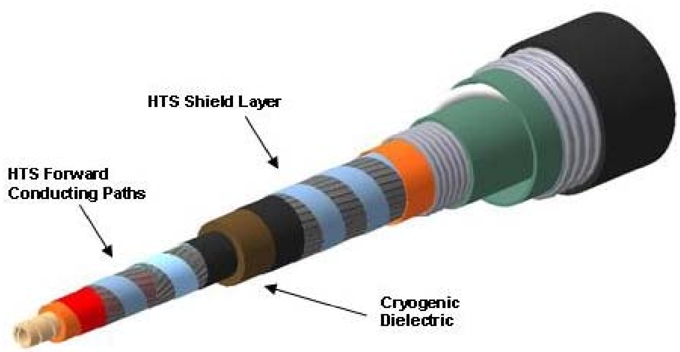

Figure 3-7
20 kV Design Concept of VNIIKP HTS Cable

(Source: Russian Scientific R&D Cable Institute JSC "VNIIKP")

Successful testing of a 30 m HTS cable prototype was completed in 2009 by VNIIKP at the R&D Center for Power Engineering. The HTS tapes were wound onto the 30 m test cable in a VNIIKP workshop, and application of the high-voltage insulation was performed at Kamkabel, a Russian cable manufacturer. Fabrication of the 200 m system was completed in September 2009. The 200 m cable system has been installed at the R&D Center for Power Engineering and will undergo a series of tests before it is installed in the Moscow-area substation.

The R&D Center for Power Engineering, which determines the feasibility and necessity of use for HTS power cables in power grids, has determined that the primary application for HTS cables in Russia is high-capacity underground lines in Moscow and other densely populated areas. An idea proposed by the R&D Center for Power Engineering is to install HTS cables into areas with a high density of customers at relatively low voltages. This application has the potential to reduce or completely eliminate the need for transformer stages because power would flow across low-impedance lines directly to load centers from the generating stations. VNIIKP claims that this solution can provide a considerable cost savings even with the high price of HTS tape because the need for intermediary substations would be eliminated.

Discussions now are taking place to demonstrate >1 km-long cables in the Russian grid, but no plans have been finalized at this point. The status of the 200 m project as well as other activities in Russia will be updated in future editions of the Technology Watch.

4
HTS CABLE MANUFACTURING: VENDOR CAPABILITIES

Overview

The focus of the previous three Technology Watch reports leaned toward the technical details of projects to demonstrate superconducting power cables in commercial power grids. Thus, little information has been provided about the manufacturers themselves and the products that they offer in this technological area. This chapter offers a compilation of information about HTS cable manufacturers and provides some insight into their manufacturing capabilities. The purpose of the information presented in this chapter is to assist prospective end users who are interested in procuring HTS cable systems but do not know where to start. For example, a utility has a need for a high-capacity cable in a densely packed urban center and has decided to investigate procurement of a superconducting power cable as a potential solution. The utility has identified its needs, but how does it know whether there is a product available for its particular application? Who are the suppliers of the HTS power cables? What is the next step? The content presented in this chapter will help to answer some of these questions by providing information about HTS cable manufacturers and their capabilities. Issues will inevitably develop during the procurement process that this chapter does not address, but this chapter will provide an adequate starting point.

Data presented in this chapter was acquired through a survey prepared by EPRI and completed by participating manufacturers of HTS power cables[1]. The purpose of the survey was to gather the most up-to-date information on products available by the various manufacturers. The results of the survey were compiled and used to provide a "look-up guide" for parties interested in procuring a superconducting power cable system.

Description of the Survey

The survey consisted of 15 questions to be answered by each manufacturer, ranging from information about available products to factory testing. Contact information was also requested. The following topics were considered when compiling the summary:

- Electrical classifications (ratings) and geometries
- Manufacturing of ancillary equipment (cryostats, terminations, and splice-joints)
- Specifications required from customer for procurement
- Contact information

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[1] Substantial efforts were made to include all HTS cable manufacturers known to EPRI, with no intention to exclude any. Any omissions are regretted, and EPRI invites corrections for future editions of the Technology Watch. Further, no endorsement by EPRI is implied by inclusion of these suppliers in this report.

Six HTS cable manufacturers responded to the survey questionnaire. They are identified and described in Table 4-1.

Table 4-1
HTS Cable Manufacturers That Participated in the EPRI Survey

Furukawa Electric Co., Ltd.	Furukawa manufactures various types of wire and cable for telecommunications, automotive applications, electronics, and energy applications. Furukawa built the 500 m single-phase HTS cable for the completed Super-ACE project in Yokosuka, Japan. Furukawa is currently developing a 275 kV HTS cable system.
InnoPower Superconductor Cable Co., Ltd.	The first HTS power cable manufacturer in China. InnoPower manufactured a 33.5 m HTS cable system that is currently operating in the Chinese grid at 35 kV. In addition to HTS power cables, InnoPower is also working to develop other superconducting power equipment.
LS Cable, Ltd.	LS Cable manufactures overhead, underground, and submarine power cables for most voltage classifications. In addition to power cables, it also manufactures magnet wire and telecommunication cables. LS Cable completed a 100 m, 22.9 kV HTS cable system that was installed at Gochang testing center in Korea. It is currently manufacturing a 50 m HTS cable system for installation in the Korean grid.
Nexans Deutschland GmbH	Nexans produces both power and telecommunication cable for a variety of industrial customers. HTS efforts at Nexans have resulted in the installation and operation of a 138 kV, 600 m HTS cable on Long Island in the state of New York. The cable system represents the first HTS cable to operate at transmission voltages and also has the distinction of being the longest HTS cable deployed to date.
Sumitomo Electric Industries, Ltd.	Sumitomo manufactures electronics, wire, and cable for industrial uses. In the application of HTS power cables, Sumitomo has long promoted the Triad configuration in which all three coaxial HTS cable cores share a common cryostat. Sumitomo manufactured the 350 m cable system that was installed in Albany, NY. It is currently manufacturing the 66 kV, 250 m cable system for demonstration at Asahi substation in Yokohama, Japan.
Ultera™	Ultera™ is a partnership between nkt cables based in Germany and Southwire Company based in the United States. Ultera™ utilizes the tri-axial geometry (Triax®) in which all three electrical phases are arranged concentrically within a single cryostat. Ultera™ manufactured the 13.2 kV, 200 m HTS cable system that is currently operating in the American Electric Power grid in Columbus, Ohio. Ultera™ has also been chosen to manufacture a 1 km HTS cable system to be installed in New Orleans, a 200 m cable system for project HYDRA, and the 6 km cable system proposed for Amsterdam.

Survey Results

The manufacturers provided valuable feedback concerning their products and capabilities. Basic technical specifications of available products were provided. Most of the participants described key specifications/requirements that they would need from a customer in order to build an HTS cable system. The data gathered from the completed surveys is presented in table format with short summaries for each manufacturer. The data presented in Table 4-2 are technical specifications of the products offered by each manufacturer and include information pertaining to the manufacturing of ancillary components that compose an HTS cable system.

Table 4-3 contains information regarding factory testing and other valuable information to take into account when considering procurement of an HTS cable system. Additional information from the manufacturers that will assist in the specification of an HTS cable system is provided in summaries along with the contact information for each manufacturer. The contact information is presented at the end of this section.

Table 4-2
Technical Specifications of HTS Cable Products Available by the Survey Participants

Vendor		Furukawa	InnoPower	LS Cable	Nexans	Sumitomo	Ultera™
Rating (Class)	Product #1 (P1)	66/77 kV, 350 MVA	110 kV, 180 to 400 MVA	22.9 kV, 50 MVA	138 kV, 765 MVA	34.5 kV, 48 MVA	15-69 kV, • 4000 A
	Product #2 (P2)	275 kV, 1500 MVA[2]	35 kV, 60 to 240 MVA	22.9 kV, 150 MVA	24 kV, 133 MVA	22.9 kV, 50 MVA	
	Product #3 (P3)		10 kV, 30-90 to MVA	154 kV, 1 GVA	10 kV, 50 MVA	66 kV, 343 MVA	
Cable Type	Cold-dielectric	✓		✓	✓	✓	✓
	Warm-dielectric		✓		✓		✓
Cable Geometry	Single-path[1]		✓		✓(P3)[7]		✓
	Coaxial	✓(P2)		✓(P3)	✓(P1,P2, P3)		✓
	Triad	✓(P1)		✓(P1,P2)		✓	
	Tri-axial						✓
HTS Tapes	Gen 1		✓		✓	✓	✓
	Gen 2	✓		✓	✓		✓
HTS Tape Manufacturer	In-house					✓	
	Other	✓[3]	✓[4]	✓[6]	✓[8]		✓[9]
Termination Manufacturer	In house	✓	✓	✓	✓	✓	✓
Cryostat Manufacturer	In-house	✓		✓	✓	✓	✓
	Other		✓[5]				✓[10]
Splice Joint Manufacturer	In-house	✓	✓	✓	✓	✓	✓

[1]HTS forward conducting path only, no HTS shield.

[2]275 kV, 1500 MVA is currently under development.

[3]HTS tapes manufactured by Showa Cable Systems Co., Ltd.

[4]HTS tapes manufactured by Innost or other parties.

[5]Cryostats manufactured by Nexans.

[6]HTS tapes manufactured by American Superconductor.

[7]Nexans constructed the cryogenic envelop and high-voltage insulation for the 35 kV InnoPower Cable system in Kunming.

[8]American Superconductor is primary HTS tape manufacturer, but Nexans also uses other vendors.

[9]Vendor did not specify HTS tape manufacturer.

[10]Vendor indicated in-house and external manufacturing of cryostats but did not identify the external manufacturer.

Table 4-3
Factory Tests and Procurement Information Provided by Survey Participants

Vendor		Furukawa	InnoPower	LS Cable	Nexans	Sumitomo	Ultera™
Turnkey Systems Available		Yes	Yes	Yes	Yes	Yes	Yes
Max Length on Single Spool[1]		500 m	300 m	500 m[6]	600 to 800 m	500 m	~ 1 km
Factory Tests	DC V-I[2]	✓	✓	✓	✓	✓	✓
	AC Loss	✓	✓	✓	✓	✓	✓
	Over-current[3]	✓	✓	✓	✓	✓	✓
	BIL[4]	✓	✓	✓	✓	✓	✓
	AC Withstand	✓	✓	✓	✓	✓	✓
	Partial Discharge	✓	✓	✓	✓	✓	✓
	Other	✓[5]		✓[7]	✓[8]	✓[9]	✓[10]
Installation Assistance		Yes	Yes	Yes	Yes	Yes	Yes

[1]The precise amount of cable that can be wound onto a single spool depends on several criteria including but not limited to: voltage class, type of cable (warm-dielectric or cold-dielectric), and method of shipment (limits spool size).

[2]Voltage response resulting from applied dc current.

[3]Steady-state over-current test.

[4]Basic Insulation level.

[5]Helium leak (vacuum test on cryostat) and pressurizing tests for the cryostat.

[6]Vendor indicated that 2 km is also an option.

[7]Bending test.

[8]Helium leak test (vacuum test on cryostat) and bending test. Tests performed depend on customer and application.

[9]Vendor noted that HTS cable testing at the factory is different from XLPE cables due to the cryogenics involved. The issue of factory testing is now under discussion at CIGRE TF B1.31.

[10]The factory test performed and the specifics of these tests are agreed to with the customer on a per-project basis depending on requirements.

Key Specifications Required by the Customer

The manufacturers were asked to describe key specifications required from the customer for a specific application. This particular question was focused towards obtaining the most basic technical parameters because there are many levels of specifications and other variables to consider (environmental, right-of-way, and so forth) when procuring superconducting power cables. The feedback provided from each survey participant on this topic is presented in Table 4-4.

Table 4-4
Key Specifications Provided by the Customer for HTS Cable Procurement

Manufacturer	Key Specifications	
Furukawa	• Nominal voltage • Maximum current in normal operation • AC-withstand voltage • Impulse-withstand voltage	• Fault current and duration time • Length • Geographic layout of the cable system
InnoPower	• Rated current • Rated voltage	• Fault-current rating • Single-piece length
LS Cable	• No Response[1]	
Nexans	• Voltage • Current • Length • Cable route	• Fault-current requirement • Diameter constraints • Elevation changes • Size limitations in termination area
Sumitomo	• Maximum cable diameter • Fault-current condition • Cable installation layout	• Voltage • Ampacity • Cable length • Vault information
Ultera™	• Voltage • Current • Length	• Load factor • Right-of-way availability • Substation footprint availability

[1] *Survey participant did not provide a list of key specifications but referred to a list of IEC standards.*

Additional Information and Comments from Survey Participants

Survey participants were asked to provide additional information that would be valuable to the survey that was not directly addressed in the questionnaire. The following two entries were included at the end of the survey to fulfill this purpose:

- Describe the key features of your products that are not covered in the survey.
- Include additional information that would be helpful for this survey.

Survey participants provided feedback to one or both of the informational requests. The responses provided are summarized below:

- **Furukawa**

  Places an emphasis on ac loss in its HTS cable systems. It indicated that its products have the lowest ac loss in the world.
- **InnoPower**

  Provided the following statement: "InnoPower's warm dielectric HTS cable is cost-effective and convenient in replacing an existing conventional cable with much higher transmission capacity. It also a good choice for dc power delivery where the cold dielectric HTS cable loses its key merit."
- **LS Cable**

  Indicated that a GIS (gas insulated substation) switch gear connection will be available soon. LS Cable noted that the gas tube could be provided complete with air terminations. The air terminations are the component of the HTS cable termination that interfaces ambient temperature.
- **Nexans**

  Expressed that the survey does not address project-based delivery. Nexans stated that "HTS cables are not yet (and may never be) standard-based products (products with standard properties that are manufactured for stock)."
- **Ultera™**

  Provided the following statement: "Triax cables offer the most compact and high power density HTS cable design option. The Triax design also requires one-half the quantity of HTS wire due to the concentric-phase arrangement. This eliminates the need for superconducting concentric neutral wires for each phase as used with single-phase per cryostat or 3-core per cryostat designs."
- **Sumitomo**

  Suggested that if a survey of the utility industry about the usage of HTS cable systems is conducted, the following ideas and questions would be valuable to the HTS cable industry:

  a) Idea: Involve utility engineers and system designer who design the power generating plant, and who design the electrical circuit between generator and the first transformer which is installed near generator.

  b) Idea*:* Involve utility engineers who are responsible to reduce CO_2 emission from power generating plant.

c) Idea: Involve IPP (Independent Power Provider) company who owns power generating plant and who is responsible to connect their circuits to closest connection point to the grid system.

d) Questions: How much energy is used to run the bus-bar or GIL (gas-insulated line) system between the generator and the first transformer (normally short distance)? And what is the electricity loss that occurs from such bus-bar or GIL system? And what are the annual operating hours of the bus-bar or GIL system?

Observations and Conclusions

EPRI compiled this survey to gather information regarding the manufacturing capabilities of the HTS power cable industry. Six manufacturers participated in the survey. The manufacturers provided information about the products they offer and indicated key specifications required by the customer. Website and contact information for each manufacturer were also provided. The information compiled for the survey is not intended to be a roadmap for obtaining an HTS cable system but will provide a starting point in the procurement process.

Manufacturer Contact Information

Furukawa Electric Co., Ltd

Contact: Shinichi Mukoyama
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Website: www.furukawa.co.jp/english/index.htm

InnoPower Superconductor Cable Co., Ltd.

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Website: www.innopower.com

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5
FUTURE WORK

Future editions of EPRI Technology Watch on Superconducting Power Cables will address the following topics:

- **Track progress of HTS cable projects in the USA** – Report on the status of the HTS demonstrations currently operating and provide updates on the progress of developing projects.
- **Continue to track activities in Europe and Asia on an ongoing basis** – Follow developments in Russia, China, Korea, Japan, and Europe:
    - 20 kV cable installation near Moscow
    - Proposed 6 km HTS cable in Amsterdam, Holland
    - 66 kV HTS cable system in Japan
- **Highlight new developments:**
    - Long-length HTS cable possibilities in Russia
    - 35 kV cold-dielectric cable in China
    - 275 kV Furukawa cable

Superconducting power cable systems continue to be developed and installed throughout the world. Future editions of this report will continue to follow projects in this area and summarize new technical developments.

A
REFERENCES

1. *Superconducting Power Cables, Technology Watch 2006*. EPRI, Palo Alto, CA: 2006. 1012430.
2. *Superconducting Power Cables, Technology Watch 2007*. EPRI, Palo Alto, CA: 2007. 1013990.
3. *Superconducting Power Cables, Technology Watch 2008*. EPRI, Palo Alto, CA: 2008. 1015988.
4. *Cryogenics*. EPRI, Palo Alto, CA: 2006. 1010897.
5. *EPRI Cryogenic O&M Workshop*. EPRI, Palo Alto, CA: 2004. 1008699.
6. *Superconducting Fault Current Limiters, Technology Watch 2009*. EPRI, Palo Alto, CA: 2009. 1017793.
7. *2009 DOE Peer Review. High Temperature Superconducting Cable*. Alexandria, VA, August 4–6, 2009.
8. H. Yumura et al., “HTS Cable Design and Evaluation in Yokohama Project,” Submitted October 2008 for the European Conference on Applied Superconductivity (EUCAS).
9. M. Hirose, Y. Yamada, T. Masuda, K. Sato, and R. Hata, “Study on Commercialization of High-Temperature Superconductor,” SEI Technology Review, vol. 62, 2006.
10. I. Melnik, “Long Length Cable with Integrated FCL Property,” Submitted to the European Conference on Applied Superconductivity, 2009.

B

TABLE OF HTS CABLE PROJECTS WITHIN THE UNITED STATES

Table B-1
HTS Cable Projects In the USA: Overview

Project	Columbus	Albany	Long Island	Long Island 2	New Orleans	HYDRA
Location	Columbus, OH. USA	Albany, NY. USA	Long Island, NY. USA	Long Island, NY. USA	New Orleans, Louisiana	Manhattan, NY. USA
Site	Bixby Substation	Riverside and Menands Substation	Holbrook Substation	Holbrook Substation	Labarre - Metairie Substations	Not available
Status	Installed and Operating	Installed and Operating	Installed and Operating	Fabrication	On hold[4]	On hold[4]
Developer	Ultera™ [1]	SuperPower	AMSC	AMSC	Ultera™ [1]	AMSC
Utility/ Host	American Electric Power	National Grid	LIPA	LIPA	Entergy	ConEd
In-Grid Start Date	September 2006	July 2006	April 2008	2010[2]	2011	2010
End Date	No scheduled termination date	April 2008	LIPA plans to operate system indefinitely.	LIPA plans to operate system indefinitely.	Not Available	No scheduled termination date
Type (AC or DC)	AC	AC	AC	AC[3]	AC	AC[3]
Phases	3	3	3	3	3	3
Geometry	Tri-axial (three concentric phases)	Triad (three phases in a single cryostat)	3-Phase Coaxial (three cores in individual cryostats)	3-Phase Coaxial (three cores in individual cryostats)	Tri-axial (three concentric phases)	Tri-axial (three concentric phases)

Table B-2
HTS Cable Projects in the USA: Design Details

Project	Columbus	Albany	Long Island	Long Island 2	New Orleans	HYDRA
Voltage	13.2 kV	34.5 kV	138 kV	138 kV	13.8 kV	13.8 kV
Rated Current	3000 A_{rms} (69 MVA)	800 A_{rms} (48 MVA)	2400 A_{rms} (Cable will operate @ 800 to 900 A_{rms})	2400 A_{rms} (Cable will operate @ 800 to 900 A_{rms})	2000 A_{rms} (48 MVA)	4000 A_{rms} (96 MVA)
Length	200 m	350 m	600 m	600 m	1.1 miles	200 to 300 m
Fault Current	20 kA_{rms} for 15 cycles (56 kA_{peak} asymmetrical)	23 kA_{rms} for 38 cycles (58 kA_{peak} asymmetrical)	51 kA_{rms} for 12 cycles (~140 kA_{peak} asymmetrical)	51 kA_{rms} for 12 cycles (~140 kA_{peak} asymmetrical)	Not available	40 kA for 4 cycles
Dielectric Design	Cold dielectric	Cold dielectric	Cold dielectric	Cold dielectric	Cold dielectric	Cold dielectric
Dielectric Material	Cryoflex™	Laminated paper polypropylene (LPP)	Laminated paper polypropylene (LPP)	Laminated paper polypropylene (LPP)	Cryoflex™	Cryoflex™
HTS Material	BSCCO w/brass stabilizer	Phase I: BSCCO Phase II: YBCO	BSCCO w/Cu stabilizer	YBCO fault current limiting tape	BSCCO	YBCO fault current limiting tape
HTS Conductor Supplier/ Fabricator	AMSC	Sumitomo (BSCCO) SuperPower (YBCO)	AMSC	AMSC	AMSC	AMSC
AC loss	~ 1.2 W/m/phase @ 60 Hz, 3000 A_{rms}	~0.33 W/m/phase @ 60 Hz, 800 A_{rms}	3.5 W/m/phase @ 60 Hz, 2400 A_{rms}	Not available	Not available	Not available
Cable Fabrication	ULTERA™-1	Sumitomo	Nexans	Nexans	Ultera™-1	Ultera™-1

Table B-3
HTS Cable Projects in the USA: Cryostat and Refrigeration Design Details

Project	Columbus	Albany	Long Island	Long Island 2	New Orleans	HYDRA
Cryostat Type	Flexible, stainless-steel	Flexible, Stainless-steel	Flexible, stainless-steel	Flexible, stainless-steel[7]	Flexible, stainless-steel	Flexible, stainless-steel
Cryostat Supplier	Nexans	Sumitomo	Nexans	Nexans	Not Available	Nexans
Cryostat Loss	1.3 W/m	~1.2 W/m	1.3 W/m (3 cryostats)	Not available	Not available	Not available
Cryogen	LN_2	LN_2	LN_2	LN_2	LN_2	LN_2
Refrigeration Type	Open and closed loop hybrid	Closed-loop, 2 Sterling refrigerators	Closed-loop, reverse-Brayton cycle refrigerator	Closed-loop, reverse-Brayton cycle refrigerator	Not available	Closed-loop, reverse-Brayton cycle refrigerator
Refrigeration Supplier	Praxair	Linde[6]	Air Liquide	Air Liquide	Not available	Air Liquide
Refrigeration System Capacity	Open-loop: 5 kW @ 77 K Pulse tube: 1.5 kW @ 77 K[5]	> 5kW @ 77 K	> 6 kW @ 65 K	> 6 kW @ 65 K	Not Available	10.5 kW @ 72 K[8]

Appendix B Notes

1 ULTERA™ is a partnership between Southwire Co. and NKT cables to design and fabricate HTS cables.

2 Will replace one of the previously installed electrical phases at Long Island.

3 Fault current limiting HTS cable.

4 Project on hold because of stagnated load growth due to the current economic downturn.

5 Two pulse tubes previously removed and replaced with a single, more efficient unit.

6 BOC before the Linde/BOC merger (the consolidated company has assumed the Linde name).

7 Nexans to design a field-repairable cryostat for the project.

8 Expected cooling requirement of the cable system. CRS capacity is presently unknown.

C
TABLE OF HTS CABLE PROJECTS IN KOREA AND JAPAN

Table C-1
HTS Cable Projects in Korea and Japan: Overview

Project	KEPCO/KEPRI	LS Cable/KERI	Icheon	Gochang	Asahi	Super-ACE
Location	Jeonbuk, South Korea	Jeonbuk, South Korea	Icheon City, South Korea	Jeonbuk, South Korea	Yokohama, Japan	Yokosuka, Japan
Site	Gochang Power Testing Center	Gochang Power Testing Center	KEPCO substation	Gochang Power Testing Center	Asahi Substation	CRIEPI[4] Test Facility
Status	Installed and operating	Installation underway	Fabrication	Fabrication	Development	Completed and decommissioned
Developer	KEPRI[1]/KEPCO	LS Cable/KERI[2]	KEPRI[1]/LS Cable	DAPAS[3]	METI/Sumitomo	Super-ACE
Utility/ Host	KEPCO	KEPCO	KEPCO	KEPCO	TEPCO	CRIEPI[4]
Start Date	Summer 2005	Target is winter of 2006.	Target is late 2010.	2010	Target is late 2010.	4/21/2004
End Date	Will operate until at least 2009	Not available	Not available	Not available	Target is early 2012	2/4/2005
Type	AC	AC	AC	AC	AC	AC
Phases	3	3	3	3	3	1
Geometry	Triad (three coaxial phases in a single cryostat)	Triad (three coaxial phases in a single cryostat)	3-Phase Coaxial (independent phases and cryostats)	3-Phase (three cores in individual cryostats)	Triad (three phases in a single cryostat)	Coaxial

Table C-2
HTS Cable Projects in Korea and Japan: Design Details

Project	KEPCO/KEPRI	LS Cable/KERI	Incheon	Gochang	Asahi	Super-ACE
Voltage	22.9 kV	22.9 kV	22.9 kV	154 kV	66 kV	77 kV
Rated Current	1250 A_{rms} (50 MVA)	1260 A_{rms} (50 MVA)	1260 A_{rms} (50 MVA)	3750 A_{rms} (1 GVA)	1750 A_{rms} (200 MVA)	1000 A_{rms} (44 MVA)
Length	100 m	100 m	500 m	100 m	300 m	500 m
Fault Current	25 kA_{rms} for 5 cycles	25 kA_{rms} for 15 cycles (31.5 k_{Apeak} asymmetrical)	25 kA_{rms} for 5 cycles	50 kA for 1.7 s	31.5 k A_{rms} for 2 s	31.5 kA for 0.5 s (90 kA_{peak} including DC offset)
Dielectric Design	Cold dielectric	Cold dielectric	Cold dielectric	Cold dielectric	Cold dielectric	Cold dielectric
Dielectric Material	Laminated paper polypropylene (LPP)	Laminated paper polypropylene (LPP)	Laminated paper polypropylene (LPP)	Laminated paper polypropylene (LPP)	Laminated paper polypropylene (LPP)	Laminated paper polypropylene (LPP)
HTS Material	BSCCO	BSCCO	YBCO	BSCCO	BSCCO	BSCCO
HTS Conductor Supplier/ Fabricator	Sumitomo	AMSC	AMSC	Not available	Sumitomo	Furukawa
AC loss	~1.2 W/m/phase @ 1000 A_{rms}	< 1 W/m/phase	Not available	Not available	Not available	1.3 W/m @1000 A_{rms}, 73 K
Cable Fabrication	Sumitomo	LS Cable	LS Cable	LS Cable	Sumitomo	Furukawa

Table C-3
HTS Cable Projects in Korea and Japan: Cryostat and Refrigeration Design Details

Project	KEPCO/KEPRI	LS Cable/KERI	Incheon	Gochang	Asahi	Super-ACE
Cryostat Type	Flexible, stainless-steel	Flexible, seamless aluminum	Flexible, seamless aluminum	Not available	Flexible, stainless-steel	Flexible, stainless-steel
Cryostat Supplier	Sumitomo	LS Cable	LS Cable	Not available	Sumitomo	Furukawa
Cryostat Loss	~1.2 W/m	1.5 W/m	Not available	Not available	Not available	~1.2 W/m
Cryogen	LN_2	LN_2	LN_2	LN_2	LN_2	LN_2
Refrigeration Type	Open-loop	Closed-loop, Gifford-McMahon + Stirling refrigerators	Closed-loop, Stirling cycle refrigerators	Closed-loop, details not available	Closed-loop, details not available	Closed-loop, 6 Stirling refrigerators
Refrigeration Supplier	Sumitomo	LS Cable	Consortium[5]	Not available	Mayekawa	Furukawa
Refrigeration System Capacity	3 kW (system operates between 66 K & 77 K)	< 2 kW @ 65 K	> 8 kW at 77 K (2 refrigerators at 4 kW each)	Not available	Not available	6 kW @ 80 K

Appendix C Notes

1. Korea Electric Power Research Institute.
2. Korea Electrotechnical Research Institute.
3. Development of Advanced Power System by Applied Superconductivity Technologies.
4. Central Research Institute of Electric Power Industry.
5. Stirling Netherland and LS Cable.

D

TABLE OF HTS CABLE PROJECTS IN EUROPE, CHINA, AND RUSSIA

Table D-1
HTS Cable Projects in Europe, China, and Russia: Overview

Project	Amsterdam	InnoPower	Changtong	Moscow
Location	Amsterdam, Holland	Kunming, China	Lanzou, China	Moscow, Russia
Site	Noord-Hogte Kadijk	Puji Substation	Changtong Cable Factory	Moscow Substation
Status	Development	Installed and operating	Operating	Development
Developer	Ultera™ [1]	Innopower	Institute of EE[3]	VNIIKP
Utility/ Host	Alliander	China Southern Power Grid	Changtong Cable Factory	Not available
Start Date	TBD[2]	4/19/2004	December 2004	Installation scheduled in 2010
End Date	TBD	Will operate until at least 2008	Operation stopped in 2007	Not available
Type	AC	AC	AC	AC
Phases	3	3	3	3
Geometry	Tri-axial (three concentric phases)	3-Phase (three cores in individual cryostats)	3-Phase (three cores in individual cryostats)	3-Phase coaxial (independent phases & cryostats)

Table D-2
HTS Cable Projects in Europe, China, and Russia: Design Details

Project	Amsterdam	InnoPower	Changtong	Moscow
Voltage	50 kV	35 kV	6.6 kV	20 kV
Rated Current	2900 A_{rms} (250 MVA)	2000 A_{rms} (120 MVA)	1500 A_{rms} (17 MVA)[4]	2000 A_{rms} (70 MVA)
Length	6 km	33.5 m	75 m	200 m
Fault Current	20 kA	20 kA_{rms} for 2 s (27 kA_{peak} asymmetrical)	Not available	Not available
Dielectric Design	Cold dielectric	Warm dielectric	Warm dielectric	Cold dielectric
Dielectric Material	Cryoflex™	XLPE	XLPE	Not available
HTS Material	TBD	BSCCO	BSCCO	BSCCO
HTS Conductor Supplier/ Fabricator	TBD	Innova Superconductor Technology. Co, Ltd.	AMSC	Sumitomo
AC loss	TBD	> 1 W/m/phase @ 50 Hz, 1500 A_{rms}, 74 K.	> 0.42 – 0.85 W/m/phase @ 50 Hz, 1500 A_{rms}	Not available
Cable Fabrication	Ultera™ [1]	Shanghai Cable Works	Collaborative group	Not available

Table D-3
HTS Cable Projects in Europe, China, and Russia: Cryostat and Refrigeration Design Details

Project	Amsterdam	InnoPower	Changtong	Moscow
Cryostat Type	Flexible, stainless-steel	Flexible, stainless-steel	Flexible, stainless-steel	Not available
Cryostat Supplier	TBD	Nexans	Heli Cryo Co.	Not available
Cryostat Loss	TBD	~1.2 W/m (3 cryostats)	< 1W/m	Not available
Cryogen	LN_2	LN_2	LN_2	LN_2
Refrigeration Type	TBD	Closed-loop, 7 Gifford-McMahon refrigerators	Open loop	Not available
Refrigeration Supplier	TBD	Cryomech	Technical Institute[5]	Not available
Refrigeration System Capacity	TBD	2 kW @ 77 K	3 kW @ 77 K	Not available

Appendix D Notes

1. ULTERA™ is a partnership between Southwire Co. and NKT cables to design and fabricate HTS cables.
2. "To be decided."
3. Institute of Electrical Engineering, Chinese Academy of Sciences.
4. Designed for 30 MVA (10.5 kV) but operates at 17 MVA (6.6 kV).
5. Technical Institute of Physics & Chemistry, Chinese Academy of Sciences.

E
GLOSSARY OF TERMS

1G	Designation for a "first generation" superconductor made by sintering a ceramic compound (BSCCO) and drawing it into a silver cladding.
2G	Designation for a "second generation" superconductor made by applying thin films of YBCO compound on an underlying metallic substrate
3-Phase Coaxial	A superconducting cable arrangement where the three coaxial cores operate in individual cryostats.
BSCCO	A high-temperature superconductor that has a critical temperature of about 110 K. The two chemical compounds made of these materials that are used for commercial superconducting applications are: $BI_2Sr_2Ca_2Cu_3O_{10}$ (referred to as BSCCO) and $BI_2Sr_2Ca_1Cu_2O_8$ (referred to as Bi-2212).
Closed-Loop System	A cryogenic refrigeration system that uses some form of mechanical refrigeration to cool the liquid nitrogen. Closed-loop systems require less liquid nitrogen deliveries than do open-loop systems.
Cold Dielectric (CD)	A type of superconducting cable in which the dielectric material operates within the cryogenic environment.
Critical Current (I_c)	The current in a superconducting material that results in an electric field of 1 uV/cm. For $I>I_c$ the superconductor operates in a resistive (normal) state.
Critical Current Density (J_c)	The critical current divided by the cross-sectional area of the superconducting material.
Cryocooler	A mechanical cryogenic refrigerator.
Cryoflex™	A dielectric material developed by Southwire Company for use in superconducting power cables.
Cryogenics	The production of low temperatures and the study of low-temperature phenomena.
Cryogen	A term applied to cryogenic fluids.
Cryogenic Refrigeration System (CRS)	A system that provides continuous cooling at cryogenic temperature.
Cryostat	An apparatus designed to contain and thermally insulate a cryogenic environment.
Dielectric	A substance with a high permittivity used for electric insulation.

Efficiency	A term that provides a quantitative description of the effectiveness of a system—generally the ratio formed by dividing the useful output of a system by the total input.
FCL (Fault Current Limiter)	*Fault current limiters* generally refer to devices that provide increased impedance to a network under faulted conditions in order to reduce magnitudes of fault current. Ideally, they provide zero impedance to the network under normal conditions.
High-Temperature Superconductors (HTS)	A class of superconducting materials that achieve the superconducting state at temperatures greater than 20 K (-253ºC). Typically, HTS materials are used in superconducting power applications that can be cooled with liquid nitrogen at 77 K (-196 ºC).
Liquid Nitrogen (LN_2 or LN or LN2)	An inert substance with a boiling temperature of 77 K (-196ºC) at 1 atmosphere. Used to cryogenically cool high-temperature superconducting cables.
Open-Loop System	A type of cryogenic system that consumes liquid nitrogen from a tank to provide cooling. Open-loop cooling systems require frequent liquid nitrogen deliveries to refill the storage tank.
Laminated Paper Polypropylene (LPP)	A dielectric material consisting of a thin film of polypropylene laminated without binder between two layers of Kraft paper and applied in helically wound layers around the conductors to provide adequate electric insulation. Typically used in underground power cables.
SFCL (Superconducting Fault Current Limiter)	Fault current limiters that utilize superconducting materials to perform the limiting action. SFCLs usually utilize the non-linear voltage-current characteristic of superconductors to provide a rapid impedance increase. However, some SFCLs use superconducting DC magnets to saturate an iron core.
Stabilizing Material	A material that provides an alternate current path for over-currents in superconducting power applications. Copper and brass are common stabilizing materials.
Stirling Engine	An engine that converts external heat into mechanical work. The advantage of this type of engine is safer operation because of a lower pressure and a conversion efficiency that is near the Carnot limit. The working fluid cycles between the cold and hot areas causing motion in a mechanical piston.
Stirling Refrigeration Cycle	The Stirling refrigerator or cryocooler operates in a cycle that is the reverse of the Stirling engine. A piston is made to move by an external driver, and the working fluid is forced to remove heat from the cold region. This type of cryocooler is very efficient even in the case of small units that remove less than 1 W at temperatures of 100 K or so.

Superconductor	An electrical conductor that carries an electrical current without a corresponding voltage.
Superinsulation	A type of multilayer insulation used with a vacuum to reduce radiation of heat into a cryogenic environment. Also known as "MLI" (multi-layer insulation).
Terminations	Cryogenic vessels that provide a thermal and electrical interface between an HTS power cable and external power system components.
Triad	A superconducting cable arrangement where three coaxial cable cores are placed in a common cryostat.
Tri-axial	A superconducting cable arrangement that consists of three concentric phases.
Warm Dielectric (WD)	A type of superconducting power cable with which the dielectric operates at ambient temperature and is not subjected to cryogenic conditions.
XLPE (Cross-Linked Polyethylene)	A dielectric material typically used in MV overhead power lines.
YBCO	A high-temperature superconductor composed of yttrium, barium, copper, and oxygen. $YBa_2Cu_3O_7$ is often referred to as a *coated conductor* and is generally made as a tape.

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