Superconducting Power Equipment

Technology Watch 2011

1021890

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Technical Update, December 2011

EPRI Project Manager

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ACKNOWLEDGMENTS

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Superconducting Power Equipment: Technology Watch 2011. EPRI, Palo Alto, CA: 2011. 1021890.

ABSTRACT

The 2010 Electric Power Research Institute (EPRI) Technology Watch (Techwatch) report on superconducting power applications (EPRI report 1019995, *Superconducting Power Equipment: Technology Watch 2010*) introduced coverage about superconducting magnetic energy storage systems and superconducting transformers. The 2011 report contains additional information about superconducting power equipment, including progress to demonstrations in some projects. The 2011 report also includes a section on superconducting substations with a description of the substation that was commissioned in Baiyin, China, in February 2011.

Many demonstration cable and superconductor fault current limiter projects have operated successfully for several years, and this report provides updates on European and U.S. projects. The updates are organized by system manufacturer rather than by national initiative. As projects mature, the demonstration scale is increasing with many cable and superconductor fault current limiter initiatives moving to transmission level applications, spurred by innovations in design and improvements in refrigeration systems. This report contains details about cable projects in Asia that were absent from *Techwatch 2010*.

Worldwide, the demand to transport large quantities of renewable energy from wind, solar, or hydro projects in remote locations to population load centers is increasing. Improved efficiency and greater power capacity that superconducting cables provide in this application continue to attract interest. In Asia, the first commercial superconducting dc cable demonstration was commissioned in China, where significant hydro and wind-generated power in the west is required to be transported thousands of miles to consumers in the east. In the United States, the Tres Amigas interconnect project, which will use superconductors, is, in part, motivated by the need to transport wind power from west to east.

Keywords
Superconducting fault current limiters
Superconducting magnetic energy storage
Superconducting power cables
Superconducting transformers
Superconducting substation
Superconductors

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INTRODUCTION

General Comments

This report is a supplement to the 2010 Techwatch, (EPRI report 1019995). This issue provides updates on projects reported in 2010 as well as descriptions and details about emerging superconducting power equipment technologies.

Three important superconductor characteristics provide benefits to electric power transmission and distribution systems. First, the extremely high current density available in superconducting materials allows devices to be smaller and lighter than conventional equivalents. Second, zero resistivity that is characteristic of superconductors lowers the losses in most devices so that they can be more efficient than conventional systems. Third, superconductors undergo an abrupt phase change from superconducting to the normal state, which can be used to produce dramatic changes in impedance in a fraction of a second. These characteristics continue to attract attention from government and industry research initiatives, manufacturers, and utilities.

The focus in superconducting developments towards cable and fault current limitation reflects lower technological barriers to commercialization in these applications. This report provides extensive coverage about the continued evolution from demonstration to commercial applications in the superconducting cable and fault current limiter fields.

Worldwide interest in superconducting technologies mirrors overall electric power industry trends towards increased efficiency, responsiveness and compactness in applications. Greater population growth in urban areas and increased demand for electricity motivate research into superconducting transformers that can occupy a smaller space and operate more safely than oil insulated conventional equivalents. A section in this report focuses on emerging superconducting power equipment technologies beyond cable and fault current limiters. Although combining superconducting equipment (cables, fault current limiters, transformers, etc.) has not been widely advocated in the west, the Chinese commissioned the first superconducting substation in 2011 and will likely continue to research ways to improve efficient power delivery for their rapidly growing economy. The Chinese superconducting substation is covered in detail in this update.

Significant investment worldwide in renewable electricity generation reflects environmental and price concerns among consumers. This investment has produced a consequent interest in transporting large power quantities over long distances from remote locations with wind, solar and hydro generation to the load consuming centers. Superconducting cable technologies (particularly DC cables) offer efficiency and size advantages in these large power transfer systems. The first commercial application of a superconducting DC cable is covered here as well as the proposed superconducting DC interconnects between the three US interconnects. An initiative in Europe is also covered. The integration of renewable power that is often variable in nature has spurred investment in storage technologies. Large-scale variable generation has to be carefully integrated into the grid in order to maintain system frequency. Increased contingency reserve is needed to respond to sudden changes in supply when wind or solar power fluctuates.

The role that storage can play in regulation is increasingly valuable – meaning that superconducting magnetic energy storage (SMES) systems have increased future potential. The SMES coverage in the 2010 report is supplemented here by a discussion positioning SMES among alternative storage technologies and a spotlight on responses from SMES projects to a recent Department of Energy (DOE) ARPA-E sponsored RFP.

Superconductor cable and superconductor fault current limiter demonstration projects commenced twelve years ago in the laboratory, progressed to field tests, and are being scaled up from distribution to the transmission level. A key group of manufacturers is involved in many projects. The first report section in the 2011 report is an update on the demonstration projects covered in detail in 2010. This report also provides more extensive and detailed coverage about cable systems in China, Korea and Japan. Extensive tables in the appendices detail cable projects worldwide.

The 2010 Techwatch, [EPRI report 1019995] included an extensive Bibliography divided into sections on the various technologies. In this edition new references are listed as footnotes and where applicable, as references appended to the various sections. The reader is advised that all of the previous Techwatches are in the public domain and available from EPRI at no cost. A list of previous EPRI reports on superconductivity is provided in Appendix F.

2011 is the centennial of the discovery of superconductivity. For a variety of reasons, superconducting power applications have not achieved measurable penetration into electric power systems. However, new stresses being placed on conventional technologies and new demands for increased efficiency and performance continue to encourage investment in improving superconducting technologies and extending their reach into new power equipment applications.

Superconductor Wire Manufacture

Since the 2010 Techwatch [EPRI report 1019995] Furukawa Electric Company Limited has acquired leading US second generation (2G) HTS wire developer and manufacturer SuperPower Inc. Furukawa's business involves the manufacture and sale of electric wire and cable, including superconducting products, and related non-metal products. Furukawa's goal is to develop new 2G HTS-based products for the power grid and electric power infrastructure as part of a future global business expansion plan. Furukawa intends to invest in SuperPower with the aim of generating sales of $100 million within the next five years[1]. SuperPower was previously a division of the Dutch company Royal Philips Electronics N.V.

Superconducting Fault Current Limiters

Superconducting fault current limiters and fault current controllers with the capability of rapidly increasing their impedance on demand, and thus limiting high fault currents continue to be developed. They have the promise of controlling fault currents to levels where conventional protection equipment can operate safely. A significant advantage of proposed superconductor

[1] Superconductor Week, Vol. 25, No. 17 October 21, 2011

fault current limiter technologies is the ability to remain virtually invisible to the grid under nominal operation, introducing negligible impedance in the power system until a fault event occurs. Ideally, once the limiting action is no longer needed, a superconducting fault current limiter quickly returns to its nominal low impedance state.

Superconducting Cables

Superconducting power cables are under development by many institutions around the world. They come in a variety of forms and are expected to fill a variety of niches in the power grid. The same companies that produce conventional underground transmission cable typically manufacture these cables. Several companies worldwide now offer superconducting cables, in commercial prototype designs. The current effort to commercialize these cables is often supported by government programs, but some of the companies carry out significant research of their own with the goal of establishing a viable market for these cables in the near future.

Superconducting Transformers

Superconducting transformers are under development in several industries, laboratories, and universities around the world. However, considerable research will be required before commercialization. Perhaps the biggest challenge is developing systems that can be competitive with conventional transformers, which are effective, highly developed, and are continuously being improved. Superconducting transformers can be designed to have two special characteristics that will accelerate their use in some niche applications. One is their possible fault current limiting capability, and the other is the ability to operate under overload conditions with no consequent reduction in life.

Superconducting Magnetic Energy Storage

Over the past 40 or so years, superconducting magnetic energy storage designs have been developed for many different applications. The ability to charge a storage device from the grid and discharge to power on demand is increasingly valuable. New stresses on the grid from renewable power generation as well as the retirement of legacy coal plants that traditionally played a big role in providing reserve power mean that SMES will be an important future technology.

Enabling Technologies

Several technologies are critical to ensure the performance and competitiveness of superconducting power applications. These include cryogenics, low temperature dielectrics, and power converters. A number of developments in cryogenic technology are described in this Techwatch edition.

Report Organization

This report consists of four chapters and six appendices. The Introduction (this chapter) provides a high-level overview and essential background for understanding the rest of the report contents. Chapter Two presents an update on superconducting cable and superconductor fault current limiter demonstrations covered in previous Techwatches. Chapter Three presents new developments in superconducting power technologies. Chapter Four provides conclusions from this update.

The first three appendices provide a detailed inventory regarding superconductor cable projects and demonstrations in progress worldwide today. Presented in table form the projects are listed in a comparative way that will allow interested readers to quickly find appropriate examples they may wish to research further. The tables also contain references to additional source material. Appendix D provides a similar inventory of superconductor fault current limiter projects. Appendix E is a Glossary of Terms and Appendix F is a list of current EPRI reports on superconductivity.

2
UPDATES ON SUPERCONDUCTING POWER PROJECTS DESCRIBED IN TECHWATCH 2010

Several superconducting power equipment demonstrations have been completed and dismantled in the last two years. Most of these projects were described in Techwatch 2010 (EPRI report 1019995). In this section we address those projects that were described in Techwatch 2010 and are either under development or are installed and in operation at this time.

Superconducting Power Cables

LIPA AMSC

The world's first transmission-class HTS cable system was energized in early 2008 and continues operation in central Long Island within the Keyspan / Long Island Power Authority (LIPA) power system. The 138 kV HTS cable system is a demonstration project funded under the Department of Energy (DOE) Superconducting Power Equipment (SPE) program. Project partners include DOE, AMSC[2], Nexans, Air Liquide, and LIPA. The 600 m underground cable system is the longest in-grid HTS cable to date, linking the Holbrook Substation to overhead lines that travel north to Port Jefferson. The LIPA cable system has a rated power capacity of 574 MVA (2.4 kA/phase), however conventional interconnecting components (overhead line and substation bus equipment) limit the operating capacity at the site to 200 MVA (~830 A/phase). The north terminations of the cable system are shown in Figure 2-1.

Operation

The cable has operated at capacities approaching 100 MVA (< 400 A) that is less than 20 percent of the cable's manufactured rated capacity and approximately half the Holbrook substation's capacity limit. Initial planning called for the HTS cable system to be installed at the East Garden Substation where full capacity (2400 A) was needed; however, the installation site was moved to the Holbrook substation where maximum current requirement is approximately 800 A.

[2] Formerly named American Superconductor Corporation (name was changed in 2011).

Figure 2-1
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 cable has operated smoothly for more than three years with no degradation of electrical characteristics (see Table 2-1). There have been cable downtimes due to false trips related to over-estimation of protection parameters and unexpected issues with the cryogenic refrigeration system. Most of these events occurred during the first year of operation, which is not unexpected for a prototype system. As the project team's experience increased, the cable system performed almost flawlessly—achieving 95 percent availability during the second year of operation.

Table 2-1
LIPA 1 operational performance after two years

		2009			2010		
Operating Parameter		**Case 1**	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**
Load	MVA	0	16	82	0	17	87
Average Current	A	0	75	350	0	76	368
Line Voltage	kV	138	138	138	138	138	138
Total Thermal Load	W	3672	4301	4615	3958	4464	4922
Cable Cryostat Loss	W/m/phase	1.3	1.3	1.3	1.35	1.35	1.35
Cable Electric Loss	W/m/phase	0	0.3	0.4	0	0.35	0.42

Phase-2 of the LIPA Project

Phase 2 of the LIPA project will demonstrate enhanced commercial viability of HTS cable systems through technical improvements (see Table 2-2).

Table 2-2
LIPA Phase 2 design improvements

Improvement	Enhanced Commercial Viability
Cable constructed from 2G HTS tapes	Projected to cost less to produce than 1G tapes when commercially mature Provides fault current limiting capabilities
Cable splice joint	Allows HTS cables to be joined for added length or section repair/replacement at specified voltage and temperature requirements
Field repairable cryostat	Cryostat can be repaired in the field if invaded/breached Reparability allows an HTS cable to continue operation (after repair) at a thermal state manageable by the refrigeration system
Advanced refrigeration system	Reduced number of components increases reliability and simplifies maintenance Achieves efficiencies required for HTS cable operation (approximately 20% Carnot at 20kW)

One of the three HTS cables at the Holbrook site will be replaced with a 600 m cable using second generation (2G) HTS tape. The 2G cable retrofit was initially proposed to be inherently fault-current limiting. However, concerns about potential electrical imbalance associated with a single fault current limiting phase led the project team to decide instead to use fault tolerant cable (capable of surviving fault current for several cycles), which matches the three phases already installed. That part of the project, i.e., a separate 600 m fault current limiting cable, is to be developed and tested, but will not be deployed at the Holbrook site. Several new design aspects are incorporated into the 2G cable retrofit at Holbrook. It will use field reparable cryostats and be able to accommodate a portion of the thermal contraction associated with cool-down.
The terminations will continue to provide some contraction compensation for thermal contraction. The project team anticipates that the cumulative compensation provided by both the terminations and internally, will accommodate commercial cable systems with lengths much greater than 600 m.

A splice joint designed to accommodate the high voltage levels and cryogenic conditions of the 138 kV HTS cable system will be demonstrated during Phase 2 at the Holbrook site. The splice will connect two sections of the 600 m 2G HTS cable and will be performed in the field. A conceptual drawing of the splice installation is shown in Figure 2-2.

Figure 2-2
Conceptual drawing of the splice joint installed at the Holbrook Site
Source: Demonstration of a Pre-Commercial Long-Length HTS Cable Operation in the Power Transmission Network, DOE Peer Review Update, June 2010, Arlington, VA

The field repairable cryostat utilizes sectioned vacuum chambers with ports along its length to mitigate heat losses if the vacuum space is breached. Coupled with in-situ repair methods developed by Nexans, the new cryostat design allows field repair/replacement of cryostat sections. HTS cable cryostats previously required complete replacement if breached or damaged. Initial test results have revealed post-repair cryostat conditions with heat in-leak levels acceptable for continued cable operation, although they are 2–3 times higher than original factory levels. The heat in-leak to the cryostat is after a repair, and only a part of the length of the cable is affected. Thus, since the sections are about 100 m long and there are three phases, if one of the segments of one phase needed to be repaired, the total heat leak associated with the cryostats would only increase by 3/18 or 15 percent and the total heat leak might increase by 10 percent or so. Nexans has also indicated that the field repairable cryostat has passed qualification tests.

Air Liquide and AMSC continue to develop a modular refrigeration system with both efficiency and reliability increased over previous HTS cable cryogenic refrigeration systems (see Figure 2-3). The concept balances cost and performance by reducing the number of components in the system and optimizing them to achieve efficiencies required for HTS cable installation. The design modularity will allow customers to size their refrigeration requirements according to their HTS cable systems length and capacity. The modular concept also provides redundancy in case a module malfunctions or requires maintenance.

LIPA Phase 2 currently has an in-service date of 2012.

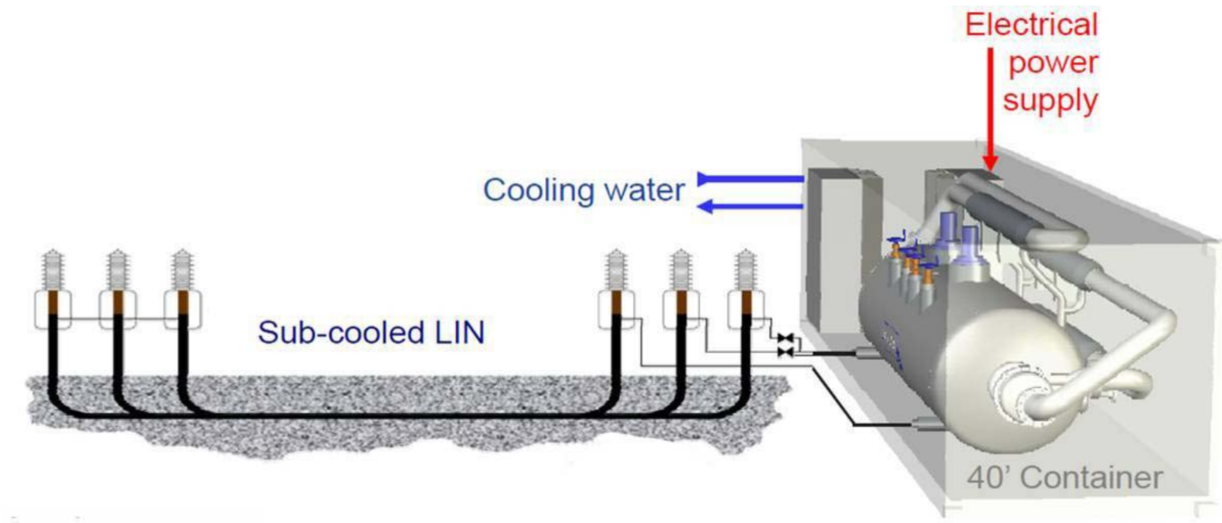

Figure 2-3
Conceptual drawing of the LIPA cable system and improved refrigeration system
Source: Demonstration of a Pre-Commercial Long-Length HTS Cable Operation in the Power Transmission Network, DOE Peer Review Update, June 2010, Arlington, VA

AEP Southwire

Project Overview

The 200-m long, 13.2 kV, 69 MVA Columbus HTS Triax® cable system maintains the longest operational record of any HTS cable system within the United States and continues to deliver power at load currents approaching the rated value of 3 kA. Commissioned in August 2006, the Columbus cable has operated for more than five years in American Electric Power's (AEP) Bixby substation located in Columbus, Ohio. The HTS Triax® cable system provides an internal substation link between the secondary of a 138 kV/13.2 kV step-down transformer and the 13.2 kV substation bus, and carries the full substation load for all customers served from the Bixby substation. The cable system, (see Figure 2-4) includes the HTS Triax® cable, terminations, and a splice. The cooling system (see Figure 2-5) employs an open-cycle process in which liquid nitrogen is pumped and exhausted to the atmosphere in order to reach the 70 K operating temperature. The cooling system also included facilities to allow development and run time of prototype pulse-tube cryocoolers, which accumulated 10 months of operation at the site. Detailed descriptions of the Columbus HTS Triax cable project including system design has been presented previously (Techwatch 2006-2010, EPRI reports 1012430, 1013990, 1015988, 1017792 and 1019995).

Figure 2-4
HTS Triax® cable (left), termination (center) and splice (right)
Used with permission from Southwire Company

Figure 2-5
Open cycle cooling system showing storage tank, vaporizer, cold box and control building
Used with permission from Southwire Company

HTS Triax® Operation Update

The Columbus HTS cable has accumulated over 33,000 operating hours with full substation electrical load. Average cable load while in operation is $1343A_{rms,}$ with peak loads reaching $2700A_{rms}$ in the summer months. In the four-year time period from December 2006 through December 2010, the cable was maintained at operating temperature and pressure for a documented 33,821 hours (96.3 percent uptime). AEP energized the system for a documented 30,662 hours (87.3 percent uptime). Between winter 2007 and fall 2008 the cable remained online for eight months without interruption. From August 2006 through July 2010 the cable system experienced significant over-currents from at least 111 through faults greater than $5000A_{peak}$ giving valuable experience regarding reaction to over-currents. Over 5 years, the cable has been thermally cycled three times for service purposes and has shown no associated performance degradation.

Heat Loads

The oscillations in heat load coincide with seasonal substation loading (see Figure 2-6) but also show increased peak summer heat loads with time. The gradual increase from year to year seen in the figure is believed to result from reduced vacuum quality in the vacuum-jacketed enclosures, but this is still being investigated. Scatter in the data is an artifact of the heat load calculations where temperature data depend on the flow-through time of the cooling medium. Maximum peak loads are typically 3,500 W in the summer months. Typical cable electrical load profiles have been presented previously in (Techwatch 2007, 2008, 2010, EPRI reports 1013990, 1015988 and 1019995).

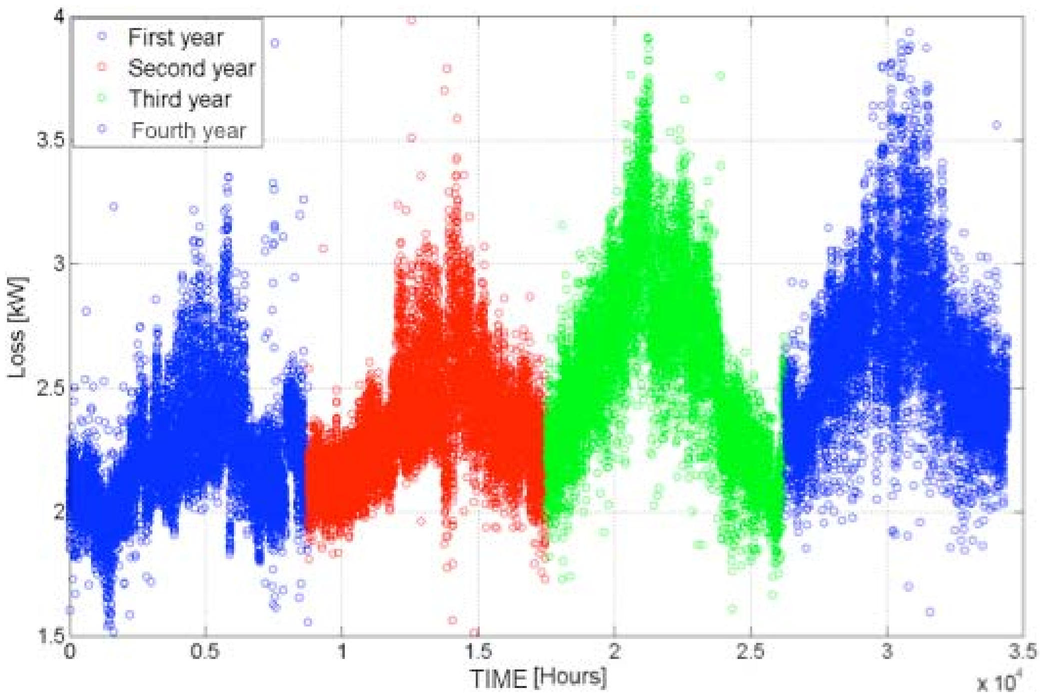

Figure 2-6
Cable and termination heat loads (October 2006–May 2011)
Used with permission from Southwire Company

Interruptions

The HTS Triax® cable, terminations, and splice have experienced numerous through fault events without associated adverse effects, power interruptions, or necessary outages. The HTS Triax® cable technology itself has proven highly reliable. Problems with the auxiliary systems (cooling hardware, sensors, valves, and control system components) have accounted for an average six system interruptions per year. Together with planned outings for R&D and service, this has resulted in 80 percent in-grid service time over the life of the system. This corresponds approximately to the documented system availability. While this is a low availability statistic for utilities, the majority of interruptions have been related to balance of system problems that are not untypical for prototypes.

Typical service interruption or outage causes are:

- Planned outages – for example, for the integration of pulse tube hardware or control system modifications.
- Malfunctioning auxiliary hardware or sensors – can cause longer off-line periods because of repair time or lead time on parts.
- Loss of power to the cooling skid – usually very short interruptions, after which time the cable system is quickly put back on line.
- Transient events on the substation bus – such as voltage fluctuations or fault current events that have impacted sensors and the control system.

It is evident that while the auxiliary systems are critical to the cable system operation, they prove to be the weakest component with respect to reliability.

Columbus HTS Triax® Cable Future

After completing 5 years of operation, a new research phase is planned for the Columbus HTS Triax® cable site. Co-funded by the DOE and Southwire/Ultera, the work includes replacing the existing open-cycle cooling system with an optimized closed-cycle cooling system that does not consume liquid nitrogen. The project team includes Southwire/Ultera, AEP (the host utility), Oak Ridge National Lab, and a yet to be determined cooling system supplier. In conjunction with this upgrade, the operating experience will be leveraged to optimize all aspects of the cable auxiliary systems, including the cooling technology, control systems, sensors, and operating contingencies. The project has the following goals:

- Improved cooling system reliability that will enable 99.9% HTS cable system availability.
- Improved cooling and cable system efficiency and performance.
- Smaller cooling system footprint.
- Simple cooling system design to enable simple operating and maintenance procedures.
- Cooling system maintenance intervals of greater than 1 year.
- Lower capital and operating cost over what is available today.

The primary program goal is to commercially enable HTS cable technology by developing cost effecting cooling systems that are acceptable for utility electric grid integration. It is anticipated that the new closed-cycle cooling system will be commissioned by first quarter 2013.

Tres Amigas

Tres Amigas, LLC, a startup, merchant-transmission company based in New Mexico, is leading a project to link the three U.S. electrical grids using AC-to-DC converting stations and high-capacity DC superconducting power lines. Currently, the three grids (Western Electric Coordinating Council, Eastern Interconnect, and the Electric Reliability Council of Texas) operate asynchronously, making it difficult to move large amounts of power from one region to another. The separation of the grids presents a major hurdle to the transport of renewable energy, because it is difficult 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. Tres Amigas proposes that three HVDC terminals be linked by superconducting DC cables (see Figure 2-7)][3]. The present design is a modification of the original design in which the DC cables formed a ring that allowed power to flow into or out of each converter as demand required. The present design is a more compact system, with tighter interconnections and shorter distances between the converters.

The Tres Amigas proposal currently specifies project completion by 2014. Tres Amigas has leased land for the supersubstation in Clovis NM, and LS Cable and Nexans have been announced as HTS cable subcontractors[4]. ALSTOM has been announced as a supplier for a 750MW/kV converter system[5]. The project has currently secured \$3 million and is attempting to raise a further \$15 million in equity. The overall cost has been estimated at between \$1 billion and \$1.5 billion. Construction on the facility could begin in the first quarter of 2012[6].

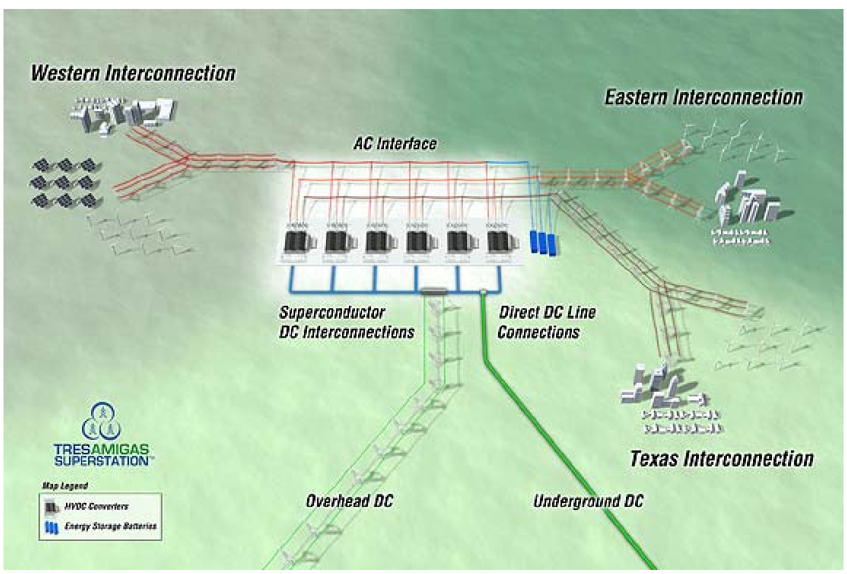

Figure 2-7
Tres amigas proposed DC HTS cable interconnection
Used with permission from Tres Amigas LLC

3 Superconductor Week Vol. 24, No. 22 December 16, 2010

4 Superconductor Week Vol. 25 No. 8 May 31, 2011

5 Superconductor Week Vol. 25 No. 10 June 28, 2011

6 Superconductor Week Vol. 25 No. 20 November 23, 2011

AMSC/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 demonstration cable connecting two substations in the New York City area. The effort is referred to as project HYDRA and has been described in considerable detail in earlier EPRI Techwatch publications (Cable Techwatch 2008 EPRI report 1015988, FCL Techwatch 2009, EPRI report 1017792). A significant issue with the cable installation at Con Edison is the economic need for such a large cable (4000 A rms current – greater than any other AC superconducting cable). The economic downturn caused load growth throughout the Con Edison power network to stagnate. Con Edison consequently postponed constructing a new substation originally planned to accommodate one end of the Hydra cable.

However, development of the unique fault current limiting cable continued. A full-scale prototype was tested at Oak Ridge National Laboratory (ORNL) in 2009 (see Figure 2-8). The initial results proved promising, but, since time was available, several engineering improvements were made to the cable design and to the manufacturing processes. A second full-scale 25 m long cable was manufactured. In December 2011, ORNL completed the qualification tests required for in-grid operation. The Test Plan developed by the project team includes the following tests, which were being performed at ORNL:

- Fault Current Limiting Test
- Thermal Stability Test
- Verification of Manufacturability
- Verification of System Operating Parameters
- Operating Capacity Test
- Dielectric Performance Test
- Verification of Cryogenic Requirements

In addition to the required tests, ORNL is evaluating the heat generated in the cable resulting from AC current and field variation in the cable. In most cases, this measurement would be rather straightforward. However, the heat flow into the cryogenic system from the 4000 A power leads is considerably greater than the total heat generated in the cable itself. The challenge is therefore to separate out a small heat signal from the cable given the background noise signals from the power leads.

Test results were to be presented to the Department of Homeland Security (DHS) near the end of calendar 2011. AMSC, the project developer, has already indicated that the fault current limiting tests have produced promising results with exceptionally good agreement between model predictions and measured performance at ORNL (see Figure 2-9).

While discussions related to the planned in-grid cable demonstration in the vicinity of New York City are continuing, no official announcement has yet been made.

Figure 2-8
25 m prototype test at the ORNL: terminations (left), cable loop (right)
Source: High Temperature Superconducting Cable, 2009 DOE Peer Review, August 4–6, 2009. Alexandria, VA

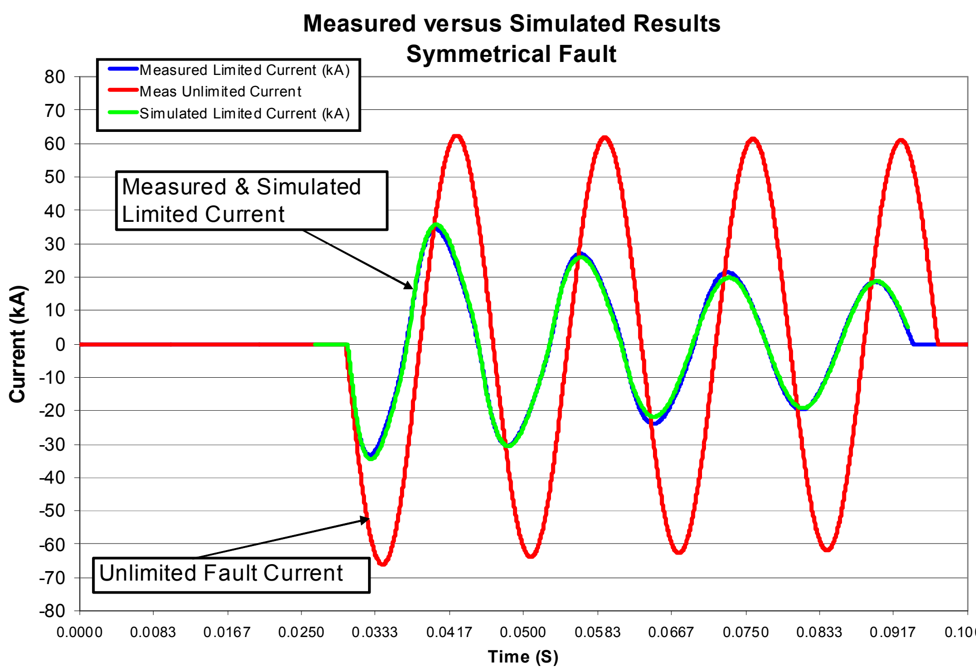

Figure 2-9
Comparison of simulated data to measured FCL performance during the 25 m tests at ORNL
Used with permission from American Superconductor Corporation

Yokohama

Installation of a 3 phase 66 kV (200 MVA) HTS power cable system has resumed at Tokyo Electric Power Company's (TEPCO) Asahi substation in Yokohama, Japan following a temporary halt on construction after the massive earthquake and subsequent tsunami in March 2011. The 250-m HTS cable consists of three single-phase coaxial cables in a single cryostat. When installed, the system will link a 154/66 kV transformer to the Asahi substation sub-transmission bus. Successful testing of a 30m prototype was completed in 2009 and the 250 m long HTS cable was fabricated in 2010. The cryogenic refrigeration system was installed in February 2011 just prior to the earthquake. Installation of the cable was supposed to begin in March 2011, but was postponed following the earthquake. Cable installation has since started and is expected to be completed in 2012 (see Figure 2-10). Post-earthquake verification tests conducted on the cryogenic refrigeration system confirmed that no damage was sustained. The cable system expects to be energized in 2012.

Figure 2-10
Installation of 66 kV (200 MVA) HTS cable system in Yokohama, Japan
Used with permission from TEPCO

The Yokohama demonstration project is sponsored by Japan's Ministry for Economy, Trade, and Industry (METI) through the New Energy and Industrial Technology Development Organization (NEDO), an organization responsible the development of new energy and conservation technologies for the national government (see Table 2-3). The goal of the project is to execute a long-term cable system evaluation in a commercial power system environment. Japan is looking for retrofit solutions to expand its electric transmission and distribution networks in existing underground tunnels and trenches. HTS cables have the potential to provide increased electrical capacity while utilizing the same spatial footprint as conventional underground power cables. More detailed information on the Yokohama cable project is presented in previous Techwatch editions (2008, 2009 and 2010 EPRI reports 1015988, 1017792 and 1019995).

Table 2-3
Project team for HTS cable demonstration in Yokohama, Japan

Entity	Role
Ministry of Economy, Trade, and Industry (METI)	Project Funding and Management
Tokyo Electric Power Company (TEPCO)	Host utility
Sumitomo Electric Industries (SEI)	Design, manufacturing, and installation of HTS cable and terminations
Mayekawa MFG Company	Design, manufacturing, and installation of cryogenic refrigeration system

Chubu

Chubu University in Nagoya, Japan has developed DC superconducting power cable systems technology since 2000[7]. In 2006, the Center for Applied Superconductivity and Sustainable Energy Research (CASER) was initiated at Chubu University to focus R&D efforts on ultra-long distance DC superconducting power transmission systems. The mission of CASER is to develop high efficient (low loss) energy transmission systems for long distance renewable energy transfer.

A 20m DC HTS cable system was developed at CASER. Prototype system testing began in 2006 and continues today. In 2010, the test facility was expanded to accommodate a 200m prototype superconducting cable DC system. The cable system was designed to operate at ±10kV with a 2 kA rating (20 MW). A cryogenic refrigeration system was also constructed to supply 1 kW of cooling to the cable at 77 K using a Stirling refrigeration cycle. Testing of the 200 m cable system was started in early 2010 and has continued into 2011. Key milestones of the test protocol include:

- Evaluation of thermal expansion and contraction (during thermal cycling)
- Measurement and reduction of heat in-leak at the terminations and along the cryostat
- Characterization of system pressure drops for liquid nitrogen circulation

Researchers at CASER used data acquired from these tests to improve the cable system design and to support analysis for potential system scale-up from 200 m to 2 km and 20 km lengths. The analysis concluded that a 2 km system is possible using the present conductor design and existing refrigeration components (maximum rating of refrigeration unit is 15 kW). However, a 20 km system would require redesign of the cable system (for example, larger diameter to improve pressure drops) and expanding the refrigeration system capacity. CASER researchers have also evaluated liquid helium as a potential substitute for nitrogen for long distance cable systems. The use of liquid helium (gas is also possible) is suggested because it has a lower friction coefficient than liquid nitrogen and has potential to reduce pressure drops along the cable

[7] Yamaguchi et al, CEC ICMC 2011 "The Experiments of 200 Meter Superconducting DC power Cable in Chubu University and the Estimation for Longer Cable Cooling."

length. Additionally, the current capacity of the HTS tape dramatically increases at the lower temperatures of liquid helium. CASER researchers continue to investigate these cooling possibilities and seek methods to improve heat in-leak losses in the cryostat and terminations. The next step at Chubu University and CASER is to initiate discussions of industrial and utility applications with several parties.

Russia

The Russian Scientific Research and Development Cable Institute (VNIIKP) continues leading a project to manufacture and install a 200m HTS cable system in the Moscow area Dinamo substation. Factory acceptance tests were completed in 2009 followed by more extensive cable system testing with an improved cryogenic refrigeration system at the Research and Development Center for Power Engineering in Russia. Installation is currently scheduled for late 2012 to accommodate additional testing and site preparation by the power utility.

The HTS cable system was designed and built by VNIIKP and a collaboration of other Russian Institutes. The cable system is rated for operation at 20 kV and 1.5 kA with a 70 MVA maximum rated capacity (at 2 kA). The design is coaxial, such that each electrical phase contains an HTS forward conducting path and an HTS shield. The HTS paths were constructed from first generation (BSCCO) HTS tapes manufactured by Sumitomo Electric Industries. Total funding for the project is estimated to be approximately $10 million U.S. with half dedicated to cable development/production and the rest to cryogenic system development and other research and development. This cable project has been reported in earlier Techwatch editions (Techwatch 2008, EPRI report 1015988 and 2009 EPRI report 1017792).

A recent VNIIKP prototype hybrid hydrogen and DC superconducting cable test is reported in Chapter 3 of this update.

Superconducting Fault Current Limiters

Zenergy at AEP Ohio and CE Electric Scunthorpe (UK)

During 2011, Zenergy Power Inc. went through several administrative crises. The Board of Directors was changed twice, and, in September, a decision was made to end their program to develop superconducting fault current limiters. During the first three quarters of the year, however, Zenergy continued work on two major superconducting fault current limiter projects, a 3-phase 138 kV installation at the American Electric Power (AEP) Tidd substation in Ohio and a 11 kV FCL for CE Electric in Scunthorpe, United Kingdom. Both projects were reported in some detail in last year's Techwatch (EPRI report 1019995). The following is a brief update on 2011 progress prior to the program cancellation.

The major 2011 goal for the AEP fault current limiter project was to fabricate and test one phase of the fault current limiter at the KEMA test facility in Pennsylvania. The unit was to have two superconducting coils and two conventional coils around an iron core. The conventional part is designed like a conventional transformer with oil insulation for the coils and core. That part was to be fabricated by Pennsylvania Transformer Technology Incorporated (PTT) in Canon, Pennsylvania. After much of the detailed design was completed, and some of the fabrication started, the effort at PTT was terminated in September.

The German arm of Zenergy in Rheinbach, Germany fabricated the superconducting coils. At least one was tested successfully. The schedule was for the two coils to be shipped to the US in time for the November test at KEMA. According to a September press release most if not all of the activities of the German company have been terminated.

The superconductor fault current limiter prepared for CE Electric was completed early in 2011. The test sequence was high-voltage tests, fault current limiting tests, and then an additional set of high voltage tests. Some arcing was observed during the second high-voltage tests. A device inspection showed that some interconnections had been damaged by motion during the fault current tests. Since that time, the repair was completed and the unit passed tests with the same protocols as in the original test.

In October the fault current limiter was shipped to the system integrator, ASL in Great Britain.

Nexans at Boxburg

The superconductor fault current limiter installed at Boxburg Germany (described in detail in the 2010 Techwatch, EPRI report 1019995) was decommissioned in early 2011. The outer shell has been used for a superconductor fault current limiter of a different design that uses YBCO tape in place of the resistive elements that have been used in all previous Nexans fault current limiters. The retrofit device was tested for short circuit performance in September 2011 at a test laboratory in Berlin and was then delivered to Boxburg. The YBCO tapes are co-wound with a stainless steel shunt, which carries most of the current when a fault occurs. The total length of tape and the relative size of the shunt are determined by the operating voltage and current and the prospective fault current. Figure 2-11 shows a typical tape element.

Several of these elements are stacked vertically to provide fault current limiting for a single phase. The dimension and shape of the elements are such that three of the single phase systems can be placed in the cryostat that was originally used at Boxburg. A stainless steel shunt is wound in parallel with the YBCO tape and carries most of the current during a fault (see Figure 2-12).

Figure 2-11
The Nexans YBCO tape element for the Boxburg
Courtesy of Electric Power Research Institute

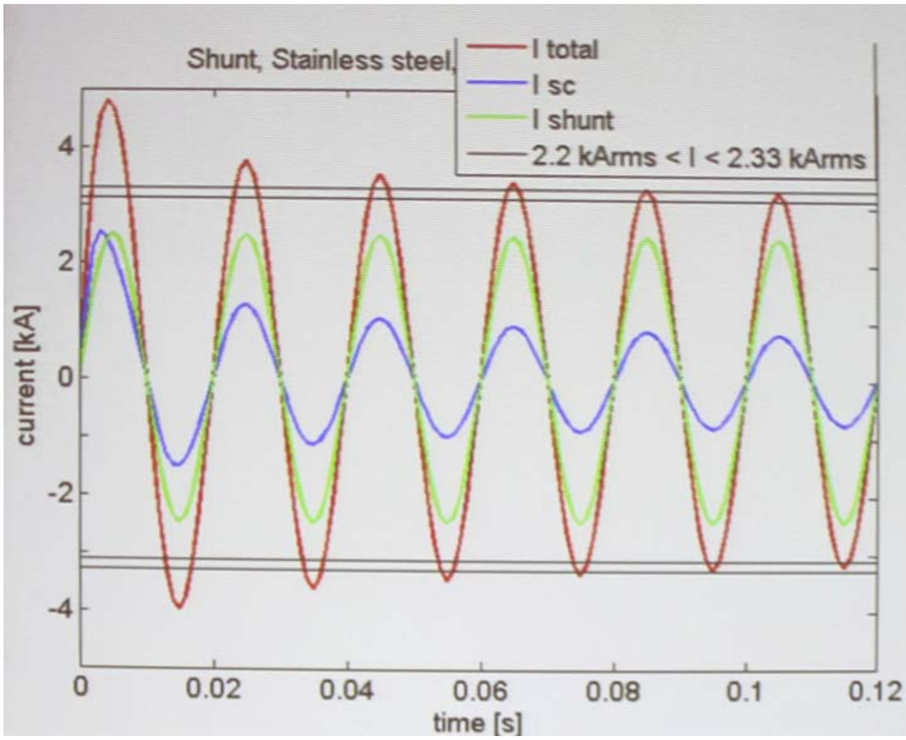

Figure 2-12
Expected performance of a YBCO tape based superconductor fault current limiter
Courtesy of Electric Power Research Institute

Nexans has compared their resistive and tape-based superconductor fault current limiters (see Table 2-4).The tape-based systems can operate at a higher temperature, provides a greater reduction in fault current, and have lower losses than the resistive devices.

In addition to the Boxburg installation, Nexans has several other superconductor fault current limiter systems that will be installed in Europe. They are continuing to operate and evaluate a unit that was installed in the United Kingdom last year, and are in the process of preparing a tape-based system for a separate installation. Also, as part of a program referred to as EccoFlow, Nexans is building a superconductor fault current limiter rated at 24 kV 1000 A. The unit will be installed on the island of Majorca in the summer of 2012. It will operate in the utility there for some months and will then be decommissioned and moved to a site in Slovenia in 2013.

Table 2-4
Comparison between Nexens resistive (BSCCO2212) and tape based (YBCOCC) superconductor fault current limiters

	BSCCO2212	YBCOCC
Operating Temperature [K]	65 (in general)	77
Voltage at Limitation [Vrms/m]	35 150 (future?)	50
AC - losses at Ip = Ic [W/kAm]	20 (Monofilar, 65 K) 6 (Bifilar, 65 K)	0.4
First Limited Peak	20 * Ic @ 77 K 10 * Ic @ 65 K	5 * Ic
Recovery Time [s]	~ 60	~ 10
Volume, weight	Comparable	
Overcurrent, Ip (1s)	2 * Ic	1.1 * Ic
Shunt	Integrated	Additional
HV - Insulation	Monofilar Bifilar	Bifilar Pancake
Inductivity (µH)	36 (Monofilar)	4.5
Costs (SC)	Today	Tomorrow (?)

138 kV Superconductor Fault Current Limiter Demonstration Project at Southern California Edison

The Department of Energy (DOE) sponsored the initial development of a 138 kV-class superconductor fault current limiter "SuperLimiter^{TM}" for use at the Devers substation near Riverside, California, on the Southern California Edison (SCE) power network. The goals of the project are to build a single-phase prototype for laboratory testing in 2009-2010, followed by a three-phase unit slated for grid installation in 2011. The project team is outlined in Table 2-5.

The SuperLimiter^{TM} is a hybrid resistive superconductor fault current limiter that utilizes modular superconductor elements, which can be assembled to rather precise current limiting specifications. The hybrid design depends on the superconductor to limit the fault initially and then uses a fast operating switch to remove the superconductor from the circuit after it has quenched. When the switch opens, a conventional air-core reactor that is in parallel with the superconducting element then carries the current. The superconducting module allows for fast reduction of the fault current (< 1 cycle), while the switch and air-core reactor provide long-duration limiting. This method reduces the amount of heating in the superconductor module, which speeds up the re-cooling process after a fault, thereby reducing the time required to return to normal operation after a limiting action.

Table 2-5
SuperLimiter™ superconductor fault current limiter project team summary

Collaborator	Company/Organization Description	Contributions
American Superconductor Corp. (AMSC)	Developer and supplier of HTS conductor and applications.	Prime contractor System designer HTS tape
Siemens	Siemens AG (Berlin and Munich) is a global manufacturer in electronics and electrical engineering, operating in the industry, energy, and healthcare sectors.	Design and fabrication of the superconducting elements that compose the SuperLimiter™ System modeling
Southern California Edison (SCE)	A large U.S. power utility that provides service to approximately 13 million people, 5,000 large businesses, and 280,000 small businesses throughout central and southern California.	Host utility System integration Provides grid requirements and specifications
Nexans	A global manufacturer of communications and power cables. Based in Europe, Nexans is developing HTS power technologies.	Designer/supplier of transmission-class terminations High-voltage design of the SuperLimiter™
Los Alamos National Laboratory (LANL)	A DOE-operated laboratory dedicated to national security and fundamental research.	AC loss measurements
Texas Center for Superconductivity at the University of Houston (TcSUH)	The largest multidisciplinary university superconductivity and advanced materials research effort in the United States, with over 200 faculty, postdoctoral fellows, graduate, and undergraduate students.	Wire characterization

As of last year, the part of the program to fabricate and install a complete, three-phase system at SCE was put on hold. Based on the lack of sufficient funds to continue, that phase of the program has now been canceled. However, a single-phase prototype has been tested successfully.

The single-phase prototype is approximately 8 m long and 2 m in diameter. It is designed to operate as one phase of a three phase, 138 kV superconductor fault current limiter. It includes superconducting tapes arranged in parallel and series to accommodate the voltage and current. The design is flexible in that multiple currents and voltages can be accommodated in the system by arranging the superconducting components in the cryostat and by adjusting the fast acting switch and the normal inductive element.

A refrigerator and cryostat maintain the superconducting element at an operating temperature of 71 to 72 K. Prior to energization of the prototype, the heat leak into the cryostat was measured to be about 900 W. This is to be compared to a calculated heat leak closer to 600W at the design vacuum level of 1×10^{-4} Torr. However, the lowest vacuum level attained during the test was about 4×10^{-3}, or a factor of 40 more than planned. Temperature monitors within the cryostat allowed the team to determine that the poor vacuum was caused by the assembly procedure and could be corrected.

Tests of the prototype were carried out to determine the range of reduction of the prospective fault current. Facilities in North America for power equipment tests are strained by the requirements of superconductor fault current limiters that can operate over 68 kV or so. As a result, the maximum power and current during prototype tests were limited. In general the fault current was limited to 34 percent of prospective value. The recovery time for 9.3 kA peak fault current was about 17.5 seconds. However, recovery time depended on level of limited fault current.

Lightning impulse tests at 650 kV and switching impulse tests at 540 kV (according to IEEE specification, C57.16) were successfully carried out.

After all tests were completed, the DC critical current of the system was measured. A voltage developed across the superconductor that corresponded to that expected if a few centimeters of conductor were normal. The system was disassembled and no damage was obvious. The various elements will be tested to find the cause of the resistance and to plan on ways to avoid this problem in the future.

3 NEW DEVELOPMENTS IN SUPERCONDUCTING POWER TECHNOLOGIES

Over the years there have been many suggestions of superconducting power equipment put forward, but after some excitement they have not been pursued. Here we describe existing projects that are underway at a level that suggests some at least will actually reach a demonstration stage.

Superconducting Fault Current Limiters

Bruker Energy and Supercon Technologies

For several years Bruker, a German company that manufactures both low-temperature and high temperature superconductors has been developing a shielded core type superconductor fault current limiter (Techwatch 2010, EPRI report 1019995, Appendix B for superconductor fault current limiter descriptions). The Bruker superconductor fault current limiter design is based on an HTS tape wrapped around an iron core. The basic element of the fault current limiter is a superconducting ring made from several independent superconducting tapes that form shorted turns (see Figure 3-1). The ring is bathed in liquid nitrogen and the ring arrangement and orientation is such that each tape is well ventilated. The design enables them to be cooled to nitrogen temperature very rapidly. This is particularly important after a fault when the system needs to recover before another fault occurs. Both the number of tapes in each ring and the number of rings used in an FCL depend on the installation.

There are several advantages to the Bruker design compared to other superconductor fault current limiters. The system response is passive, that is, there is no need to trigger the limiting action. After a fault, while the superconductor is cooling down, a separate coil introduces impedance into the circuit. If this impedance were in the circuit for a long period it would affect system operation and overall efficiency. The design is such that as the rings become superconducting the external impedance is reduced, again in a passive manner, so that under normal operation the fault current limiter is transparent to grid operation.

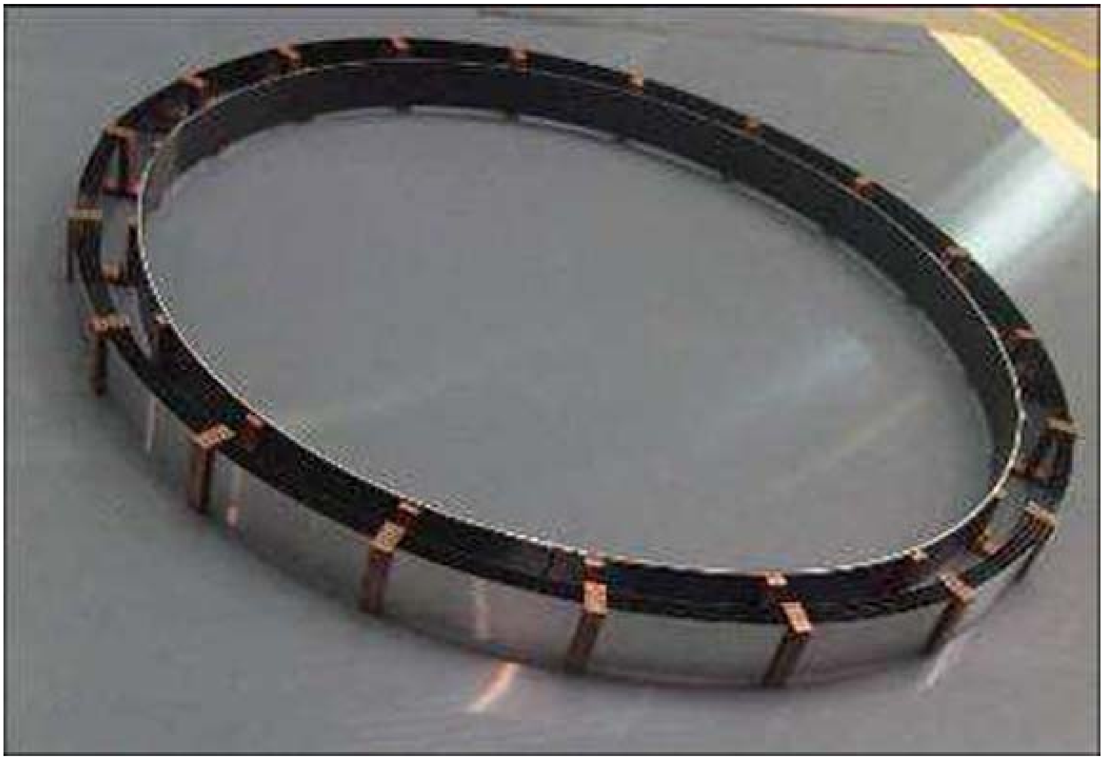

Figure 3-1
Bruker superconducting fault current limiter ring
Used with permission from Bruker Energy and Superconducting Technology

Bruker has recently teamed with Schneider Electric, a major international electronic power equipment manufacturer to produce and market a commercial superconductor fault current limiter system. The first device will be installed in Augsburg, Bavaria, Germany. It will be placed on the local utility, Stadtwerke Augsburg, which is a large municipal electricity, gas, and community heating supplier.

The three phase superconductor fault current limiter will be installed on a 10.6 kV section of the grid that is fed from a 40 MVA 10/110 kV transformer. The system is protected by an existing circuit breaker. The superconductor fault current limiter purpose is to ensure that operation continues seamlessly as the fault current on the system increases with load. It will limit a prospective fault of 25 kA to about 5 kA. Response time is about 1 ms. The cryogenic capabilities and element heating will allow the system to limit the current for about 500 ms. The superconductor fault current limiter specifications are as follows:

- Operating voltage 10 kV
- Power rating 15 MVA
- Operating current (rms) 817 A
- Fault current parameters:
  - Limited maximum aperiodic short-circuit current (1st peak) <5 kA
  - Limited steady state fault current 2 kA
  - Maximum a periodic short-circuit current (1st peak) 25.1 kA

- Initial symmetrical short circuit current 10.25 kA
- Tripping time ~1 ms
- Fault duration max. 500 ms

- Number of conductors in a ring = 8
- Number of rings in the fault current limiter = 12

Varian Power Systems

Varian Power Systems, a division of Applied Materials, Inc. has completed initial KEMA testing for it's newly developed superconducting fault current limiter (see Figure 3-2). It is a superconductor technology, modular, and compact platform for distribution and transmission use. These devices insert no significant impedance during normal operations but in fault condition the system responds instantly by adding sufficient impedance on the line to reduce the first peak and subsequent fault currents by 20–80 percent (as specified by customers). The device was successfully tested at KEMA in the following test conditions:

- Test Parameters
  - System voltages from 10 kV to 125 kV
  - Prospective fault currents up to 56 kA
  - Subjected to 50 high energy faults
  - Tested to the limit of KEMA (U.S.) capability.

- Test Results
  - Demonstrated <1ms response for first peak reduction
  - Demonstrated > 60% fault reduction at 13.8 kV
  - Fault reduction at 125 kV
  - No functional degradation after more than 50 faults
  - Passed 220 kV single-phase to ground (Satisfying IEC and IEEE standards for transmission line systems up to 200kV)

- Fault Current Limiter Operation
- Normal operation
  - Load current flows through superconducting unit
  - Superconductor fault current limiter introduces no significant impedance and zero voltage drop

- Fault condition
  - Superconductor inherently senses fault current, quenches, inserts high resistance
  - Current transfers to shunt and limits fault current

- Recovery
  - Superconducting unit recovers superconducting state quickly in seconds

- KEMA Short Circuit Test Capability
  - Voltage – single phase up to 72 kV (125 kV Line-to-line)
  - 3 circuits from transformer at 22 KV, 44 kV and 72 KV
  - Directly connected to generator – up to 12.5 kV single phase (21.65 kV line-to-line)
  - Short circuit current – 8 kA at 72 kV to 63 kA at 10 kV

- High Voltage Test Capability
  - AC high voltage tester – up to 220 kV (single phase)

Figure 3-2
Varian superconducting fault current limiter under fault testing at KEMA, Chalfont, PA
Used with permission from Varian Power Systems

Varian Power Systems is a wholly owned division of Applied Materials Inc., that manufactures power systems solutions for the utility market in Gloucester MA.

Superconducting Power Cables

China: IEECAS DC Cable

The Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS) is demonstrating a DC HTS cable in a commercial environment. The 360 m HTS cable system was energized in the first half of 2011 and feeds an aluminum electrolysis plant. Technical cable system specifications are provided (see Table 3-1).

Table 3-1
IEECAS DC cable specifications

Characteristic	Description
Rated voltage	1.3 kV
Rated Capacity	~10 kA (13 MW)
Length	360 m
Dielectric Type	Warm dielectric
Refrigeration Type	Stirling Cycle
Refrigeration Capacity	4 kW @ 77 K
Cable Coolant	Liquid Nitrogen

DC HTS power cables development in China is driven by the need to transport energy from renewable sources (hydro and wind) located mainly in relatively unpopulated western China to load centers along the heavily populated eastern coastline. China already has several HVDC transmission lines that accomplish this mission for power generated in the Three Gorges Hydro project. As China increases power production from hydro, coal, and nuclear, several more transmission corridors will have to be opened up over the next two decades. The smaller right of way requirement for HTS DC power cables is a major factor in the Chinese decision to use superconducting cable.

South Korea: LS Cable and System I'cheon Substation

A 500-m long 22.9 kV HTS power cable system was installed and energized in the 154/22.9kV Korea Electric Power Company (KEPCO) I'cheon substation located near Seoul, South Korea. The cable is rated for operation at 22.9 kV, 50 MVA (1.3 kA) and is installed between the secondary side of a 152/22.9 kV main transformer and the 22.9 kV substation bus (see Figure-3-3). The project is the longest HTS cable in the world to be energized in the grid utilizing 2G-superconductor wire and is also currently the longest distribution voltage superconductor power cable in operation.

The 500 m HTS cable system design consists of three coaxial HTS cable cores contained in a single cryostat and manufactured using 2G HTS tapes manufactured by AMSC. The cable was installed in the first half of 2011 and commissioned in early October 2011. A conceptual drawing of the HTS cable terminations is shown in Figure 3-4.

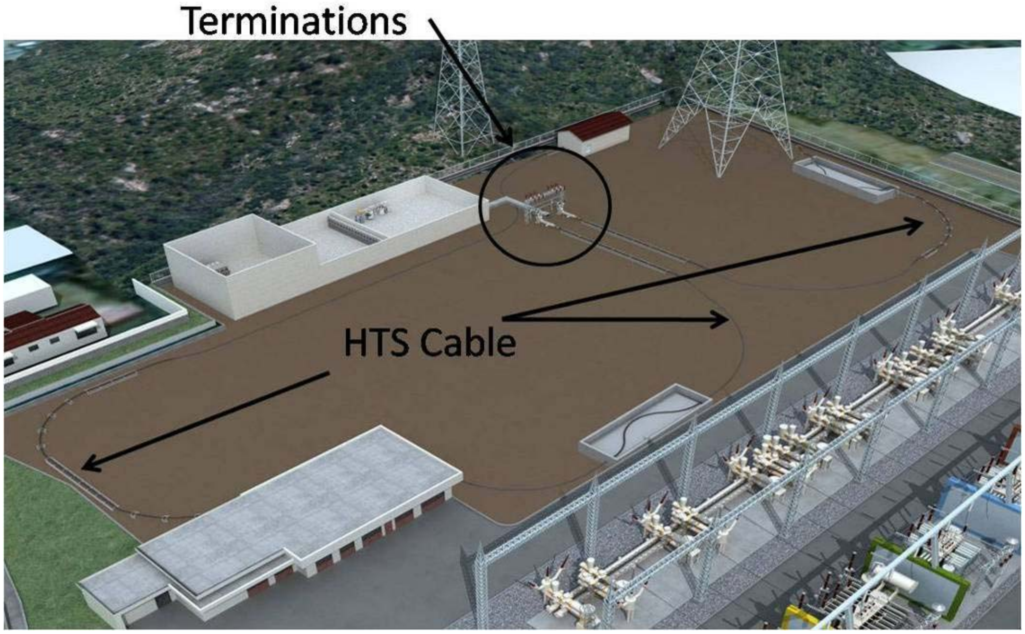

Figure-3-3
Conceptual drawing of the 500 m HTS cable installation in I'cheon City, Korea
Source: KEPRI-EPRI Joint Superconductivity Conference, November 16–18, 2009, Daejon, South Korea

Figure 3-4
Conceptual drawing of the 22.9kV HTS cable terminations in I'cheon City, Korea
Source: KEPRI-EPRI Joint Superconductivity Conference, November 16–18, 2009, Daejon, South Korea

South Korea: LS Cable and System, Gochang Power Test Center

LS Cable has also developed a transmission-level HTS cable to operate at 154 kV. A prototype is planned for installation at the Gochang testing center in 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.

South Korea: LS Cable and System Future Potential Projects

The Korea Electric Power Research Institute (KEPRI), Korea Electric Power Company (KEPCO), and LS Cable have developed plans to demonstrate full-scale grid deployments of an AC transmission class HTS cable and an 80kV class DC HTS cable (see Table 3-2)[8]. In addition, plans have also been proposed to deploy a long length 22.9kV class HTS power cable in I'cheon City (in addition to the 500 m demonstration system currently in operation). AMSC and LS Cable have formed a collaborative partnership focused on deploying 50 miles of HTS power cables in commercial power grids over a five-year period[9]. LS Cable will provide cable manufacturing and AMSC will supply LS Cable with its 2G (Amperium™) HTS tape.

Table 3-2
Proposed LS Cable HTS cable deployments in South Korea

Class	Project Description
22.9 kV, 50 MVA	3km HTS cable to connect 154 kV/22.9 kV substation to distribution center located in the heart of I'cheon City. Expected completion date is 2013. 6km HTS cable that will connect two substations in Anyang. Expected completion date is 2016.
154 kV, 500 MVA	1 km connection at Hanlim test bed on Jeju Island. Expected completion date is 2014. 4 km HTS cable. Site and completion date to be determined.
80 kV DC, 60 MW	1 km HTS DC cable to be installed in the Jeju Island smart grid demonstration in 2013 where HVDC lines between substations will be connected.

[8] Presentation to EPRI Superconductivity Conference October 2011, Tallahassee, FL

[9] Superconductor Week, 10/31/2010

Japan: Furukawa

Furukawa Electric Co., Ltd., in Japan has developed a 275 kV class HTS power cable with a rated capacity of 1 kA (three-phase power is 500 MVA). Prototypes of the cable and termination designs were fabricated for voltage and current load tests (see Figure 3-5). The voltage tests (that is, AC voltage test, impulse test, and partial discharge test) were conducted in 2010 and 2011 on a single termination and a 5 m section of the HTS cable prototype. The cable design is a cold-dielectric coaxial type. The superconducting layers constructed from second generation HTS tapes. The project team reported that the tests were conducted successfully with satisfactory results.

Much of the electric transmission backbone in Japan operates at 275 kV. A three-phase system with the Furukawa design would be capable of 3 kA (1,500 MVA), or roughly the capacity of the average thermal power generator or nuclear power generator, and provide additional capacity for the transmission system where retrofit cable solutions are necessary.

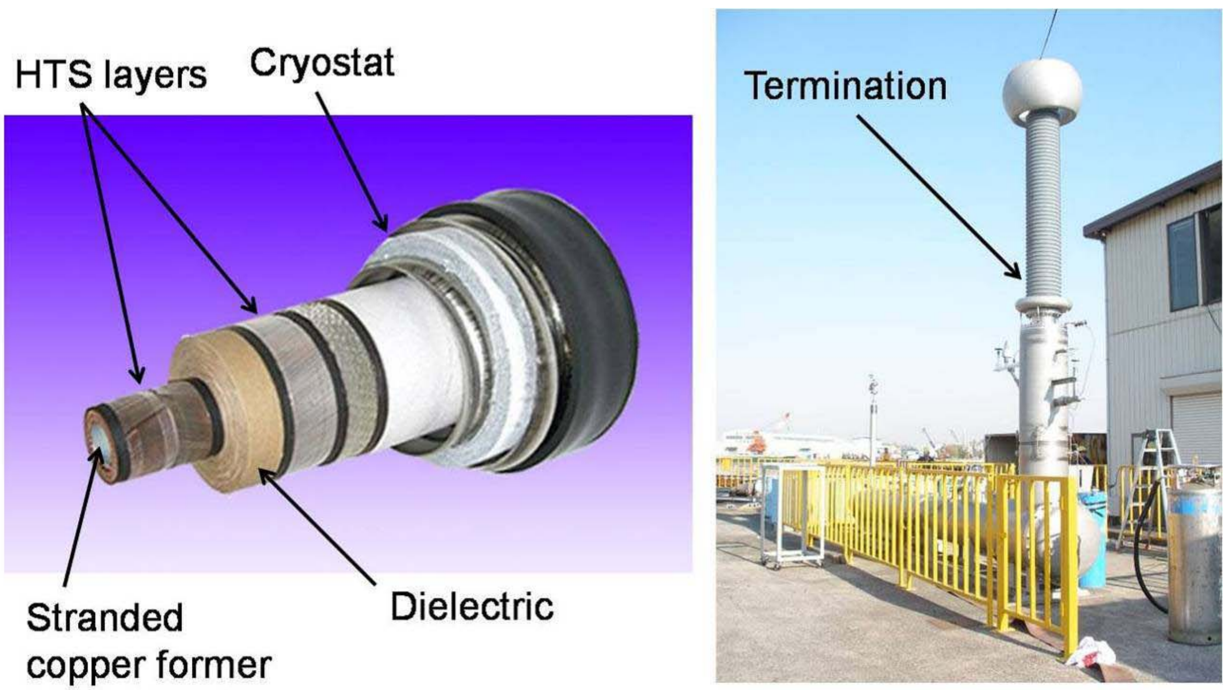

Figure 3-5
Furukawa 275 kV HTS cable geometry (left) and cable termination (right)
Used with permission from Furukawa Electric Company, Ltd

New Energy and Industrial Technology Development Organization (NEDO) sponsors the development of the Furukawa cable system. A NEDO program was initiated in 2009 to develop electric power devices including SMES devices, power transformers, and HTS power cables. Furukawa was selected by NEDO to develop a 275 kV HTS cable system. The project team has indicated that they plan to demonstrate a full-scale HTS cable system (30 m, 275 kV) within the next two years.

Netherlands: nkt Cables

A 6 km HTS cable system proposed for installation in Amsterdam remains in the design phase as the system undergoes type testing. The Dutch development project is an independent (privately sponsored) effort between the potential customer (Alliandar), a University (Technical University of Delft), and a vendor (nkt cables) to jointly develop a product. This development project mimics how vendors, like nkt cables develop most of their conventional cable products; through collaboration with a potential customer using private funds. While details of the agreement between the project team and Alliandar are not publically available, realization of a full-scale 6km HTS cable system is contingent on several factors including progress with technical development, cost of the equipment, economic factors, and the utility's need for expanding system capacity. Details relating to project scope, application scenarios, and technical details of the cable system are provided in the 2009 Techwatch edition (EPRI report 1017792).

Russia: Hydrogen Superconducting Cable

A Russian team from three research institutes [10] has developed and tested a first prototype hybrid hydrogen and superconducting cable system. The team includes Russian Academy of Science (RAS – general management), Russian Scientific R&D Cable Institute (VNIIKP – MgB2 cable development) and Moscow Aviation Institute – Technical University (MAI – hydrogen cryogenic system development). The work is based on development presented at IASS to replace standard High Voltage DC (HVDC) lines with DC Superconducting line using HTS MgB_2 superconductors[11].

The hybrid system has a hydrogen transfer cryostat with 12 m length fed by current leads with rated current up to 3-4kA. The cryostat inner diameter is 40 mm and the outer diameter is 80 mm with vacuum super insulation between the walls. No liquid nitrogen pre cooling is used in the cryostat.

The power cable was developed using MgB_2 superconducting wire from Columbus superconductor, Genoa, Italy. The wire is 3.65 mm × 0.65 mm size with 12 MgB_2 filaments and a Cu central stabilizer in Ni matrix[12]. Five tapes are used in the cable design, twisted around copper bunch superconductor protected against fault. The copper bunch is placed around a central stainless steel spiral with an inner diameter of 12 mm. The outer cable diameter is 28 mm.

The transport system was test filled with liquid hydrogen from a storage tank. The hydrogen flow rate was from 2 to 7 g/sec under pressure ranging from 0.15 to 0.45 MPa. Temperatures varied from 20 to 26 K during the test. The voltage current characteristics of the cable were measured at different temperatures and critical currents by 1 μV/cm. At 20 K the critical current of the cable was more than 2600 A and at 26 K the critical current was more than 2000 A. This confirms that the superconducting properties of MgB_2 can be used for high current power cables.

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[10] V. S. Vysotsky, A. A. Nosov, S. S. Fetisov, G. G. Svalov at the Russian Scientific R&D Cable Institute; V. V. Kostyuk; E. V. Blagov at the Russian Academy of Science and I. V. Antyukhov, V. P. Firsov at the Moscow Aviation Institute – Technical University.

[11] C. Rubbia, "The future of large power electric transmission," available at: http://www.iass-potsdam.de/fileadmin/user_upload/Rubbia_presentation.pdf

[12] Columbus Superconductor SpA, available at: http://www.columbussuperconductors.com/mgb2.htm

These results are the first experimental demonstration of the feasibility of high power energy transport systems where energy is transferred by both liquid hydrogen and electricity.

Institute for Advanced Sustainability Studies Workshop, Potsdam, May 2011

Over 40 international experts from academia, research institutions and industry met in Potsdam during May 2011 for an International Brainstorming Workshop[13] at the Institute for Advanced Sustainability Studies (IASS) to discuss current and future prospects for long-distance electricity transport through superconducting cables.

The speakers included Alex Müller, who received the Nobel Prize for Physics (with Georg Bednorz) for the discovery of high-temperature superconductors in 1986. Representatives from research institutes, including CERN, DESY and Fermilab, made presentations. Topics covered included scientific and technical advances in superconductors and the advantages of HVDC superconducting cables using HTS.

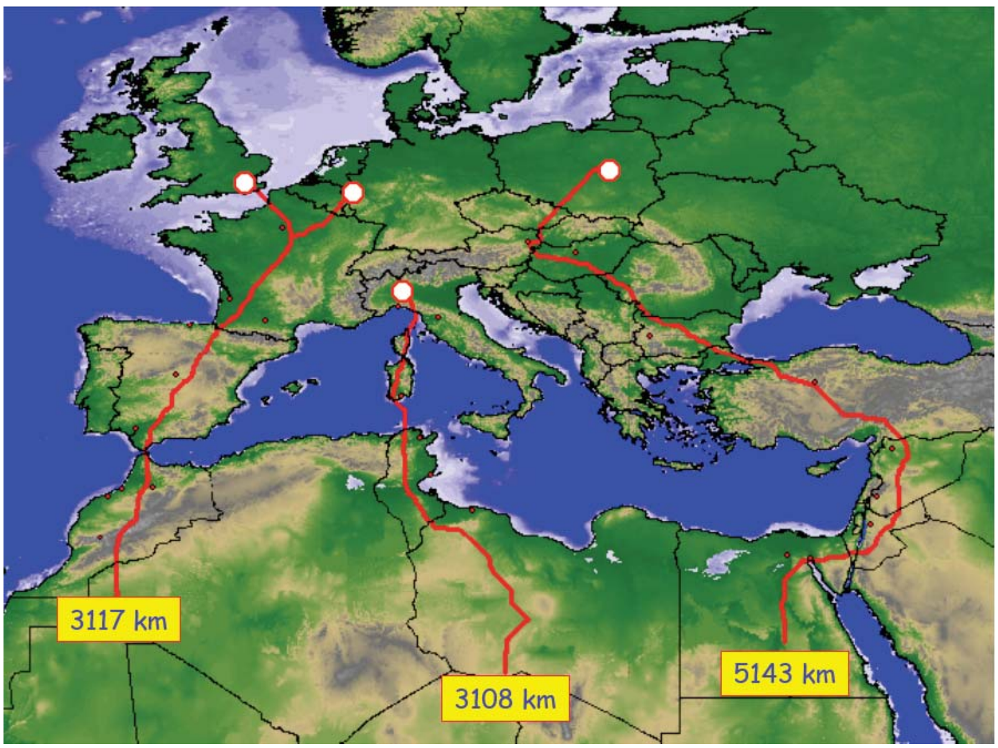

Figure 3-6
Proposed paths for superconducting HVDC cables in the EUMENA project
Used with permission from IASS and Deutsches Zentrum Für Luft-und Raumfahrt e.V. (DLR)

Renewable energy resources, such as solar, wind, geothermal and tidal power, are being developed in many parts of the world in response to environmental concerns. Renewable energy sources are typically located far from population centers meaning that the generated energy has to be transported over long distances, up to several thousand kilometers. The need to transport large quantities of electricity over long distances is driving interest in superconducting cable initiatives in China and Europe as reported elsewhere in Tech Watch 2011. One major advantage to using DC superconducting technology over high voltage AC or DC overhead lines for long distance transmission is that DC cables can be buried underground. Underground cables are less intrusive on the landscape and are protected from the elements.

One such initiative, mentioned in the introductory presentation from Nobel Laureate Carlo Rubbia, Scientific Director at IASS, is the EUMENA project (see Figure 3-6). The project objective is to transport electricity generated from abundant solar power in the Middle East and North Africa (MENA) to population centers in Central and Western Europe using underground HVDC superconducting cables.

The workshop included discussion and presentations on high voltage DC (HVDC) and DC superconductor technology worldwide. The IASS is looking to develop innovative projects and create a platform for the world’s leading superconductivity researchers.

Presenters reported results from laboratory-scale prototype superconducting cable systems in Japan, China and the United States. Other alternatives, such as gas-insulated lines (GIL) and applications of conventional long-distance high-voltage DC submarine cables were also presented.

Superconducting Transformers

Waukesha SuperPower Transformer

In 2009 the Department of Energy (DOE) initiated a Smart Grid effort to develop a variety of new technologies for the power grid. One winning proposal under this program was a Waukesha Electric Systems Inc. (WES) design for a superconducting transformer with a fault current limiting capability. The team developing the transformer is WES, SuperPower, Southern California Edison (SCE), and ORNL. The original program goal was to design, construct and install a device at SCE’s MacArthur Substation in Irvine, California by December 2012.

The technical program goal is to develop a 28 MVA three-phase fault current limiting medium-power utility transformer (69 kV/12.47 kV class). The nameplate current rating is 132 A for the high-voltage winding and 1296 A for the low voltage winding. The transformer is expected to have the current carrying capacity to operate at 45 percent overload. Another design goal is to reduce the prospective peak current during a fault by a factor of two.

The design (see Figure 3-7) is based on a conventional oil insulated transformer with liquid nitrogen replacing the oil. The three superconducting coil sets are immersed in liquid nitrogen, which acts as the transformer dielectric. Several cryocoolers cool a liquid nitrogen tank directly below them that circulates the coolant around the coils. The operating temperature is about 70 K and the liquid nitrogen bath is maintained at 2 atmospheres absolute pressure. As in other HTS power systems, pressure is used to reduce the chance of bubbles forming in the liquid. The temperature has to rise above about 84 K for bubbles to form. Like most conventional large power transformers, the steel core is air cooled by a blower system.

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[13] http://www.iass-potsdam.de/index.php?id=153

When there is a power overload that generates greater heat then the cryocoolers can absorb, the onboard liquid nitrogen tank can satisfy the increased heat load for short periods. For continuous overload operation, the transformer requires additional nitrogen, which would be trucked to the site.

The original schedule was to have a three-phase transformer installed at the MacArthur Substation during 2013. That date has been extended because the final contract with DOE did not get signed until the December 2010. The delay in initial funding postponed work on the engineering details. A new schedule will be forthcoming when the program gets underway in earnest.

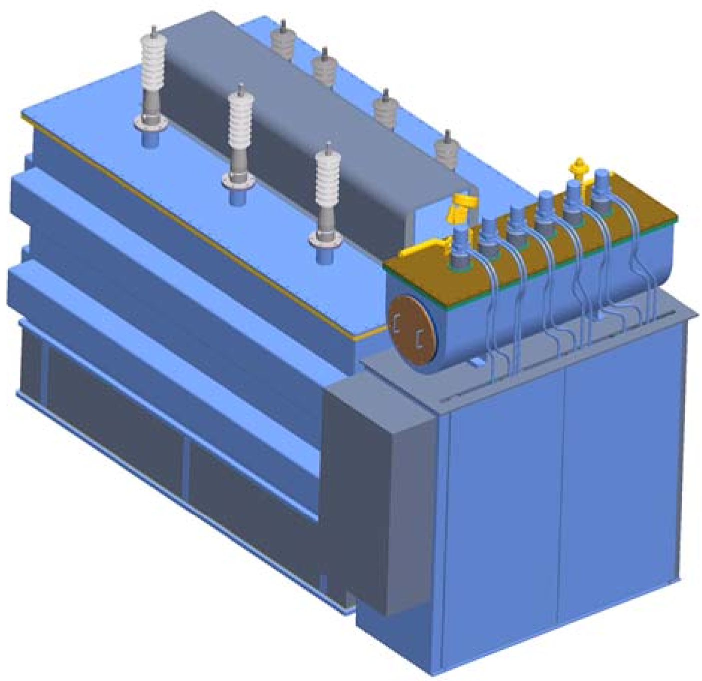

Figure 3-7
Artist's impression of Waukesha HTS FCL transformer
Used with permission from Waukesha

Fault Current Limiting Transformers

Japan

Several programs on fault current limiting transformers are underway around the world. Japan has two programs, the first, which is by far the largest program on superconducting transformers to date, is by a team including Nagoya University, Chubu Electric Power, and the Karlsruhe Institute of Technology. The program began in 2000 and went through several development stages that led to several fault current limiting transformers being tested successfully. The earliest transformers used BSCCO conductor and in 2007 they completed and successfully tested a 100 kVA transformer using YBCO coated conductor. In 2009 this effort was extended by successfully testing a 2 MVA class, 22 kV/6.6 kV transformer. The coil components are immersed in liquid nitrogen and tabs for connection to the outside and between the various layers of primary and secondary coil layers are located at the top and bottom of the coil structure (see Figure 3-8).

Figure 3-8
One phase of Nagoya 2 MVA superconducting fault current limiter transformer
Courtesy of the Electric Power Research Institute

Further program details and progress reports regarding the fault current limiting transformer may be obtained from descriptions published by IEEE and EUCAS[14].

A second Japanese superconducting transformer program team includes Kyushu University, Kyushu Electric Power, Fujikuru Electric and ISTEC[15]. The team has built and tested a single-phase 400 V/400 V, approximately 30 A, model transformer. The transformer operating current was designed to be no more than 100 A maximum due to ancillary equipment limitations. Expected and observed current limitation during a fault is approximately a factor of two.

Hungary

Several small current limiting transformers have been built and tested by a Hungarian group. The most recent transformer (the fifth in a progression of larger devices) is 2 MVA, which has only been tested in single-phase to date. This 22 kV/6.6 kV device, which seems to be modeled after the Nagoya transformer but does not have the current limiting feature, uses YBCO tape and is nitrogen bath cooled. Plans are to build a three-phase system and install it on a Hungarian utility or city system. Janos Kosa described the program at EUCAS 2011.

Superconducting Substations

Introduction

Superconducting devices benefit electric power systems for the following reasons:

- Extremely high current density in superconducting materials allows most devices to be smaller and lighter than conventional equivalents
- Zero resistivity that is characteristic of superconductors lowers the losses in most devices so that they can be more efficient than conventional systems

Superconductors undergo an abrupt phase change from superconducting to the normal state, which can be used to produce dramatic changes in impedance in a fraction of a second.

When multiple superconducting devices are combined, two additional system benefits accrue. The first is that a combined system with a larger refrigerator will be more efficient than two smaller independent systems. The second is that significant heat loss in most superconducting applications is associated with the leads that take the power from ambient to cryogenic temperatures. With two devices combined one or more lead sets are removed and the total losses decrease.

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[14] N.Hayakawa, H.Kagawa, and H.Okubom, N.Kashima, and S.Nagaya, "A System Study on Superconducting Fault Current Limiting Transformer (SFCLT) with the Functions of Fault Current Suppression and System Stability Improvement" , IEEE Transactions On Applied Superconductivity, Vol. 11 , No, I , March 2001 pp 1936-1939.
C. Kurupakorn, H. Kojima, N. Hayakawa, M. Goto, N. Kashima, S. Nagaya, M. Noe, K.-P. Juengst, and H. Okubo, "Recovery Characteristics After Current Limitation of High Temperature Superconducting Fault Current Limiting Transformer (HTc-SFCLT)," IEEE Transactions on Applied Superconductivity, Vol. 15 , No. 2 , June 2005 pp. 1859-1863. H. Okubo, C. Kurupakorn, S. Ito, H. Kojima, N. Hayakawa, F. Endo, and M. Noe, 'High-Tc Superconducting Fault Current Limiting Transformer (HTc-SFCLT) With 2G Coated Conductors," IEEE Transactions on Applied Superconductivity, Vol. 17 , No. 2 , June 2007 pp. 1768-1771.

[15] M Kotari, H Kojima, N Hayakawa, F Endo, H Okubo, "Development of 2 MVA Class Superconducting Fault Current Limiting Transformer (SFCLT) with YBCO Coated Conductors', EUCAS 2009, 2010 J. Phys.: Conf. Ser. 234 032070, EUCAS 2011 paper 2LA P6, "Development of REBCO superconducting transformers with current limiting function" - to be published.

Combining multiple superconducting power devices such as an SMES device and a cable to form an integrated system was proposed in the early 1970s. Those technologies used low temperature superconductors and they never became practical for power applications. In 1999 EPRI began exploring the possibility of a superconducting substation, described in EPRI Report 1000915, *The All Superconducting Substation: A Comparison with a Conventional Substation*.

The Baiyin 10.5 kV Superconducting Substation

In 2002 several Chinese institutions centered within the Institute of Electrical Engineering (IEE) of the Chinese Academy of Science (CAS) were working separately on various HTS power applications. They chose to specify the overall substation characteristics and then adapt individual device designs to fit. Work progressed on various substation components for the next 8 years. These applications have now been brought together into the Baiyin substation, which is considered to be Phase One of a larger program to develop more substations using material and other technology improvements developed here.

Each substation device had been operated independently before moving to the site. In 2010 the components were installed at the Baiyin substation, which feeds power to several industrial businesses in the surrounding area (see Figure 3-9 and Figure 3-10). The station was commissioned on February 16, 2011. Various superconducting devices at the site include a cable; a transformer, a fault current limiter and magnetic energy storage were operated elsewhere prior to their installation at Baiyin (see Table 3-3). Each device will be discussed in more detail in the subsections that follow.

Figure 3-9
Artist's impression of the Baiyin substation
Used with permission from the Institute of Electrical Engineering of the Chinese Academy of Sciences

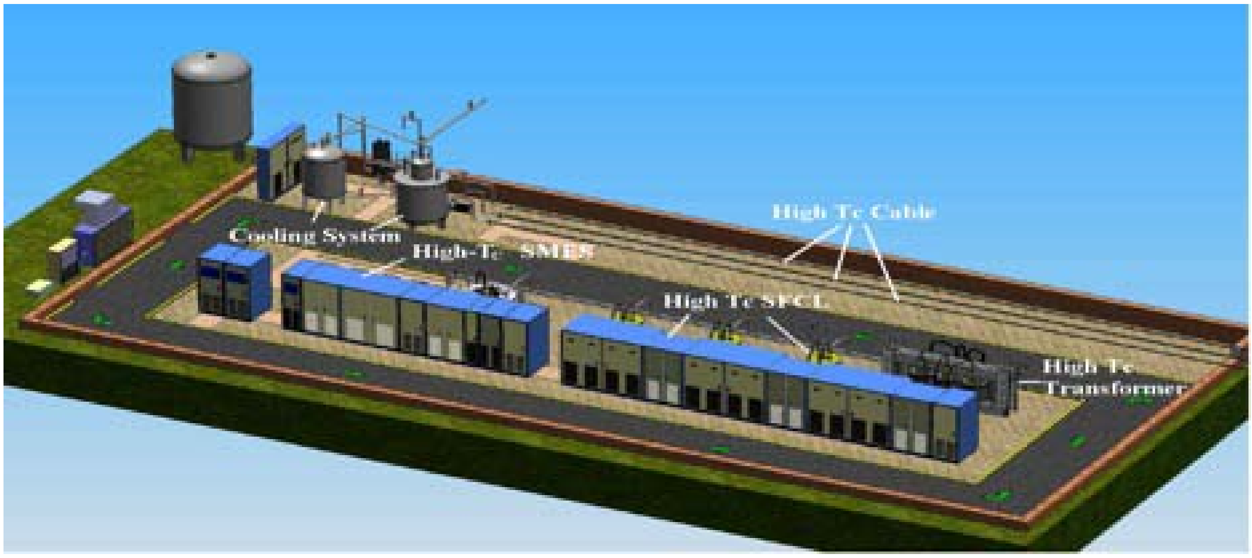


Figure 3-10
Cutaway showing components at the Baiyin superconducting substation
Used with permission from the Institute of Electrical Engineering of the Chinese Academy of Sciences

Table 3-3
Substation components at Baiyin

Component	Characteristics	Initial Location	On Grid
Substation	10.5 kV 750 kVA	N/A	Feb 2011
Cable	3-phase 75 m long 10.5 kV/1.5 kA	Changtong Cable factory	2004
Transformer	630 kVA 10.5kV/0.4 kV 30A/909A	TBEA Cable Plant, City of Changji, Xinjiang Province, Northern China	2005
SFCL	2 10.5 kV/1.5 kA	Hunan Province	2005
SMES	E_{max}=1MJ P_{max}=0.5 MW	Beijing	2007

Superconducting Power Cable

The 75 m long power cable in the substation operated successfully at the Changtong Power Cable Company for over 7000 hours in 2004. It consists of three independent, single-phase, cold-dielectric cables rated at 6.6 kV. Each phase has two layers of superconductor, the outer layer acting as a return path to reduce the external magnetic field. Overall rating of the 3 phase system is 10.5 kV/1.5 kA.

At the Changtong factory the three single-phase cables were placed vertically in a snakelike shape, (shown in Techwatch 2008, EPRI report 1015988). At the Baiyin substation they are placed in a linear form.

Superconducting Magnetic Energy Storage

The SMES device at the Baiyin substation [see Figure 3-11] uses BSCCO-2223 multifilament tape supplied by AMSC and operates in boiling helium at 4.2 K. It stores 1 MJ and has a peak field of 5.72 T[16]. Coil parameters are shown in Table 3-4.

Superconducting Transformer

The superconducting transformer[17] consists of three primary/secondary coils coupled by an amorphous alloy core (see Figure 3-12 and Figure 3-13). The transformer is optimized for 50 Hz, the standard frequency for the Chinese grid. Losses at peak operating current are about 1.7 percent, exclusive of the cryogenic power. Transformer specifications are shown in Table 3-5 and the winding specifications are given in Table 3-6.

Table 3-4
SMES device characteristics at Baiyin substation

SMES characteristics	Specification
Coil structure	Pancake Wound
Number of pancakes	44 double
Conductor Type	AMSC BSCCO 2223
Conductor length (km)	16.4
Operating current (A)	564
Operating temperature	4.2 K
Coil Height (mm)	645
Coil ID (mm)	400
Coil OD (mm)	568
Inductance (H)	6.28

[16] See Shaotao Dai, Liye Xiao, Zikai Wang et al, "Design of a 1 MJ/0.5 MVA, HTS Magnet for SMES," IEEE Transactions on Applied Superconductivity, Vol. 17, No. 2, pp. 1977–1980, June 2007 for design details.

[17] Yinshun Wang, Xiang Zhao, Junjie Han et al, "Development of a 630 kVA Three-Phase HTS Transformer with Amorphous Alloy Cores," IEEE Transactions on Applied Superconductivity, Vol. 17, No. 2, pp. 2051–2054, June 2007.

Figure 3-11
SMES design at Baiyin substation
Used with permission from the Institute of Electrical Engineering of the Chinese Academy of Sciences

Table 3-5
Baiyin superconducting transformer specifications

Transformer characteristic	Specification
Voltage primary/secondary (kV)	10.4/0.4
Current primary/secondary (A)	35/909
Iron core (one per coil set)	Amorphous alloy steel
Iron core diameter (mm)	396
Iron core height (mm)	870
Flux density (T)	1.275
Cryostat (one per coil set)	Epoxy fiberglass
Cryostat ID/OD (mm)	410/760
Operating temperature	77 K
Impedance (%)	2.45

Table 3-6
Baiyin superconducting transformer winding specifications

Primary Winding Component	Specification
Coil structure	Solenoid
Number of layers	8
Conductor Type	AMSC BSCCO 2223 stainless steel reinforced
Coil Height (mm)	342
Coil ID/OD (mm)	488/504
Secondary winding	
Coil structure	Pancake
Number of pancakes	23 double
Conductor Type	AMSC BSCCO 2223 stainless steel reinforced
Coil Height (mm)	355
Coil ID/OD (mm)	581/608
Operating temperature	77 K

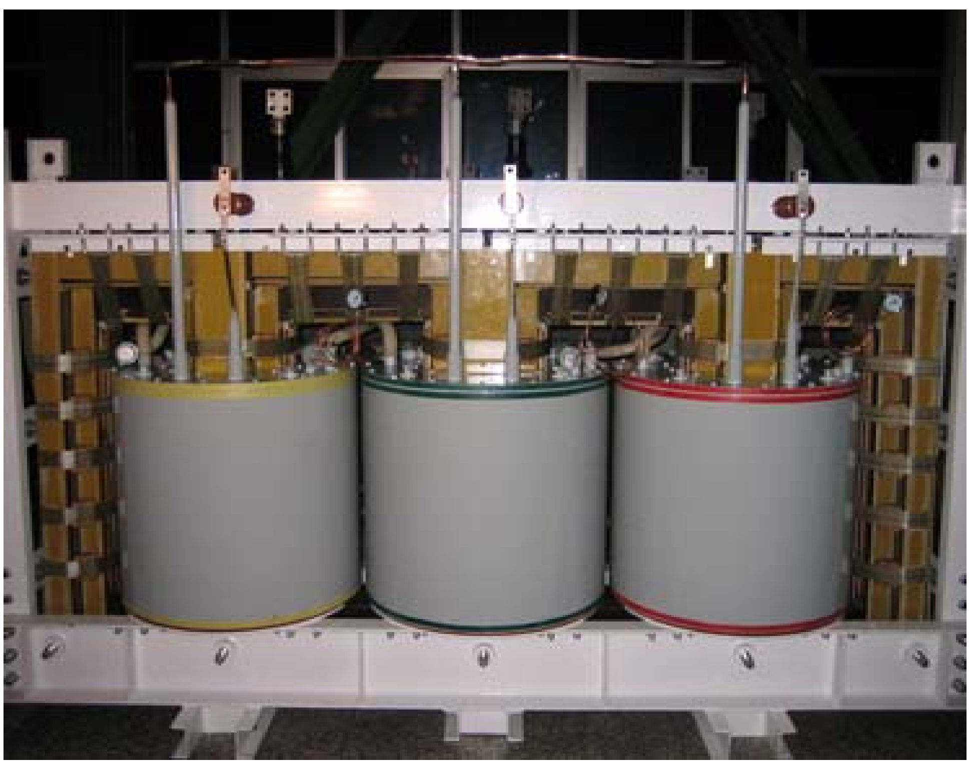


Figure 3-12
Baiyin superconducting substation transformer
Used with permission from the Institute of Electrical Engineering of the Chinese Academy of Sciences

Figure 3-13
Baiyin superconducting substation transformer winding
Used with permission from the Institute of Electrical Engineering of the Chinese Academy of Sciences

Superconducting Fault Current Limiter

The Baiyin superconductor fault current limiter is a bridge type using IGBTs to switch power flow to an external resistor when the current exceeds a critical value. Since the design uses active controls it is called a fault current controller because the allowable current can be preset. In this case, a prospective fault current of 3.5 kA is reduced to 645 A. Each phase has a superconducting coil (see Figure 3-14). The superconductor fault current limiter was installed and operated for a year in 2004 at Gaoxi substation in Hunan province.

Figure 3-14
Baiyin superconducting substation fault current limiter
Used with permission from the Institute of Electrical Engineering of the Chinese Academy of Sciences

Cryogenic System

The main refrigerator for the Baiyin substation is a Stirling cryocooler, which operates at 77 K. Liquid nitrogen is piped from the refrigerator to the 4 superconducting components of the substation. In addition to the liquid nitrogen shield on the SMES coil, 4 small GM cryocoolers are attached directly to the cryostat to lower the coil temperature to 4.2 K. The power leads for the SMES are modified HTS leads that reduce the heat flow into the 4.2 K region.

The central cooling system consists of a liquid nitrogen tank (which is outside the main building), a cold box, and a Stirling cryocooler. The liquid nitrogen tank contains make-up nitrogen and it supplements the refrigerator during cool down. The central cooling system and the HTS devices are connected via underground and aboveground liquid nitrogen pipes, some of which are vacuum insulated to decrease liquid nitrogen consumption and to avoid cold piping within the building. A liquid nitrogen pump is used to force the nitrogen through the system.

Superconducting Magnetic Energy Storage Systems

Introduction

The 2010 EPRI Techwatch (EPRI report 1019995) provided considerable background information for Superconducting Magnetic Energy Storage (SMES) systems. The technology facilitates energy storage without chemicals and moving parts -the energy is contained in a magnetic field. The device is charged and discharged by increasing and decreasing the current in a superconducting wire. As with mechanical energy storage systems (for example, flywheels and compressed air), stored forces need to be contained. The material used for containment in flywheels is typically steel or carbon fiber and in compressed air systems the cavern walls. There is a linear relationship between the total stored energy and the integrated stress in the container supports. This relationship holds for SMES devices as well, so that in addition to the superconductor a structural constraint is required to contain the stored energy.

SMES devices operate at low temperatures so there are inherent losses from operating the refrigeration system continuously to maintain operating temperature. The energy required for the refrigeration system during a storage cycle can represent a significant portion of the total energy stored. SMES system efficiency is governed by refrigeration operation and power losses in the converter. Early SMES systems used more energy to maintain the stored energy than was available for discharge. This might be acceptable in special situations but devices for large-scale storage and system stability applications should have efficiencies greater than 75 percent.

When reviewing stored energy devices, it is important to establish perspective between short-term devices such as batteries, flywheels and SMES and bulk energy storage devices such as pumped hydro. For short-term devices such as batteries, flywheels and SMES, the stored energy is usually quoted in megajoules (MJ). The megawatt-hour (MWh) is the unit more often used for large energy storage systems such as pumped hydro and compressed air. There are 3,600 MJ in a MWh. Approximate values for a AAA battery (0.004 MJ), energy stored in a large flywheel (100 MJ) and a large pumped hydro plant (2000 MWh) indicate the difference in energy storage capacity. Table 3-7 shows energy stored in various systems and devices. Note that the jelly donut and gasoline require oxygen to produce the energy listed. All values are approximate, that is, have one significant decimal.

Department of Energy ARPA-E program

Under the 2009 DOE ARPA-E program initiative that encouraged large-scale energy storage, two SMES based systems were proposed. Of the two, one was selected for development at Brookhaven National Laboratory and the other, from MIT was not selected. Both designs are reviewed here.

Table 3-7
Comparative energy stored in small and large energy storage devices

Device	Energy (MJ)	Energy (MWh)
AAA battery	0.004	1x E-6
SLI lead acid automotive battery	1	3x E-4
Jelly donut	1	3x E-4
Kinetic Energy of a car at 100 km/h	1	3x E-4
Liter of gasoline	30	1x E-2
Energy stored in a large flywheel	100	3x E-2
Energy stored in a pumped hydro plant	5x E+7	2x E+4

SuperPower, ABB, Brookhaven National Laboratory SMES

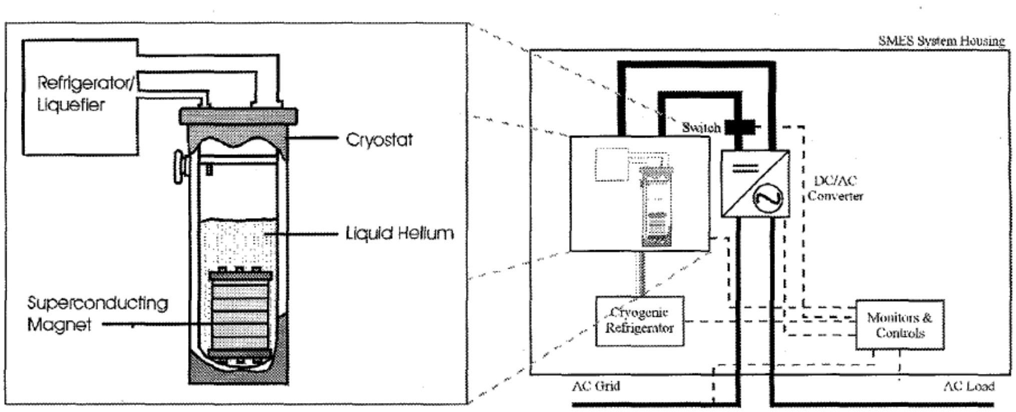
ARPA-E is providing Superpower, ABB and Brookhaven laboratory $4.2M for a SMES development program expected to cost $5.6M. The immediate goal is to produce a compact SMES system using 2G superconductors operating in liquid helium at a very high magnetic field (over 25 T). The magnetic structure design is several small solenoidal coils arranged in a toroidal configuration. This configuration is effective in controlling the external field, but requires about 3 times more (expensive) superconductor material than a solenoidal coil.

During the program, Brookhaven National Laboratory will construct a 3.2 MJ coil using SuperPower's 2G HTS conductor and ABB will provide a 20 kW AC-DC-AC converter. This device is considered as the prototype for a larger 100 MJ SMES that could be suitable for utility scale applications such as frequency regulation.

The challenge for the program is to deliver a system that is no more expensive than an equivalent flywheel system.

MIT SMES proposal to ARPA

The MIT plasma and fusion laboratory unsuccessfully proposed a significantly larger SMES device than Brookhaven for the ARPA-E program. The SMES system includes a superconducting magnet, a power conversion system, a refrigerator, and a monitoring and control component [see Figure 3-15]. The proposed MIT device would store 72 MJ in a solenoidal coil (versus Brookhaven's 3.2 MJ in a toroidal coil). The proposal design used LTS material in the initial device rather than 2G HTS conductors. Another significant difference was the use of existing cryostat (perhaps slightly modified), refrigeration facilities, and a 5 MW AC-DC-AC converter. The total proposed system budget to store 20 times the energy with a power rating 250 times greater was $9.6M.



a) Cutaway of Cryostat & Coil **b) SMES System**

Figure 3-15
MIT proposed 72 MJ SMES design
Used with permission from William Hassenzahl

Military and Space Applications

There is considerable interest is using SMES for various military and space applications. The rationale is based on the possibility for very high specific power (MW/kg) and significant specific energy storage capability (MJ/kg). The U.S. Air Force has issued an RFP for an airborne system to be used on military aircraft both for reserve/emergency power and as an energy source for a directed energy weapon (details on the latter are classified). The device is required to operate at a temperature about 70 K, store several MJ, and possess a power capacity in the 10s of MWs.

The French government also has a program with the same general goals.

On occasion NASA has explored SMES applications for satellite use. In general their conclusion has been that flywheels have a greater specific energy (MJ/kg), and that specific power is not important for NASA applications.

4 CONCLUSIONS

This report is a supplement to the 2010 Techwatch, (EPRI report 1019995). This issue provides updates on projects reported in 2010 as well as descriptions and details about emerging superconducting power equipment technologies.

Three important superconductor characteristics provide benefits to electric power transmission and distribution systems. Extremely high current density in superconducting materials allows devices to be smaller and lighter than conventional equivalents. Zero resistance makes them ideal for transmitting electricity in power cables, while the ability to shift from the superconducting state to the normal state can be used as an effective element in limiting fault currents. These characteristics continue to attract attention from government and industry research initiatives, manufacturers, and utilities.

Superconductor cable and fault current limiter demonstration projects commenced twelve years ago in the laboratory have now progressed to the field and are being scaled up from distribution to the transmission level. A key group of manufacturers is involved in many projects. This report contains an update on the demonstration projects covered in detail in 2010. The report also provides more extensive and detailed coverage about cable systems in China, Korea and Japan. Extensive tables in the appendices detail cable projects worldwide.

Worldwide interest in superconducting technologies mirrors overall electric power industry trends towards increased efficiency, responsiveness and compactness in applications. Greater population growth in urban areas and increased demand for electricity motivate research into superconducting transformers that can occupy a smaller space and operate more safely than oil insulated conventional equivalents. A section in this report focuses on emerging superconducting power equipment technologies beyond cable and fault current limiters. Although combining superconducting equipment (cables, fault current limiters, transformers etc) has not been widely advocated in the west, the Chinese commissioned the first superconducting substation in 2011 and will likely continue to research ways to improve efficient power delivery for their rapidly growing economy. The Chinese superconducting substation is covered in detail in this update.

Significant investment worldwide in renewable electricity generation reflects environmental and price concerns among consumers. This investment has produced a consequent interest in transporting large power quantities over long distances from remote locations with wind, solar and hydro generation to the load consuming centers. Superconducting cable technologies (whether AC or DC) offer efficiency and size advantages in these large power transfer systems. The first commercial application of a superconducting DC cable is covered here as well as the proposed superconducting DC interconnects between the three U.S. interconnects. The integration of renewable power that is often variable in nature has spurred investment in storage technologies. Large-scale variable generation has to be carefully integrated into the grid in order to maintain system frequency. Increased contingency reserve is needed to respond to sudden changes in supply when wind or solar power fluctuates. The role that storage can play in regulation is increasingly valuable – meaning that SMES systems have increased future potential. The SMES coverage in the 2010 report is supplemented here by a discussion positioning SMES among alternative storage technologies and a spotlight on responses from SMES projects to a recent Department of Energy (DOE) ARPA-E sponsored RFP.

2011 is the centennial of the discovery of superconductivity. For a variety of reasons, superconducting power applications have not achieved measurable penetration into commercial electric power systems. However, new stresses being placed on conventional technologies and new demands for increased efficiency and performance continue to encourage investment in improving superconducting technologies and extending their reach into new power equipment applications.

A
HTS CABLE PROJECTS IN THE UNITED STATES

Table A-1
HTS cable projects in the United States: 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	Decommissioned	Installed and Operating	Cable to be installed in 2012[2]	Cancelled[4]	Qualification Testing Completed
Developer	Ultera[TM-1]	SuperPower	AMSC	AMSC	Ultera[TM-1]	AMSC
Utility/ Host	American Electric Power	National Grid	LIPA	LIPA	Entergy	ConEd
In-Grid Start Date	September 2006	July 2006	April 2008	2012	N/A	Postponed
End Date	No scheduled termination date	April 2008	LIPA plans to operate system indefinitely.	LIPA plans to operate system indefinitely.	N/A	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 A-2
HTS cable projects in the United States: 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	1700 meters	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^{TM-1}	Sumitomo	Nexans	Nexans	Ultera^{TM-1}	Ultera^{TM-1}

Table A-3
HTS cable projects in the United States: 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	DH Industries
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 A 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 tolerant HTS cable.
4. Project cancelled 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.

B

HTS CABLE PROJECTS IN EUROPE CHINA AND RUSSIA

Table B-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	Dinamo Substation
Status	Development	Installed and operating	Operating[6]	Development
Developer	Ultera[TM-1]	Innopower	Institute of EE[3]	VNIIKP
Utility/ Host	Alliander (dgo)	China Southern Power Grid	Changtong Cable Factory	Not available
Start Date	TBD[2]	4/19/2004	December 2004	Installation scheduled in 2012
End Date	TBD	Not Available	Not Available	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 and cryostats)

Table B-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^{TM}	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^{TM-1}	Shanghai Cable Works	Collaborative group	VNIIKP

Table B-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	Openloop	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 B 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 and Chemistry, Chinese Academy of Sciences.
6. Cable decommissioned in 2007, but re-energized in 2011 as part of the HTS substation project in China.

C
HTS CABLE PROJECTS IN KOREA AND JAPAN

Table C-1
HTS cable projects in Korea and Japan: overview

Project	KEPCO/KEPRI	LS Cable/KERI	I'cheon	Gochang	Asahi	Super-ACE
Location	Jeonbuk, South Korea	Jeonbuk, South Korea	I'cheon 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	Installed and operating	Fabrication	Fabrication	Installation underway	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	Winter 2006.	September 2011	Not Available	Target is 2012.	4/21/2004
End Date	Will operate until at least 2009	Not available	Not available	Not available	Not Available	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	I'cheon	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	I'cheon	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 and 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

SUPERCONDUCTING FAULT CURRENT LIMITING PROJECTS

Table D-1
Superconducting fault current limiter projects worldwide: overview

Project	England	Germany	A2A	Puji	Korea	Nagoya
Location	Lancashire, UK	Boxburg, Germany	North Italy	Kunming, China	Gochang, Junbuk Province	Nagoya, Japan
Site	Bamber Bridge	Local Power Plant	San Dionigi Substation (MI)	Puji Substation	Gochang Power Testing Center	Nagoya University
Status	Operating	Decommissioned For Retrofit	Fabrication of first prototype	Operating	Operation tests	Development[4]
Developer	Nexans	Nexans	ERSE Spa	Innopower	Consortium[2]	Nagoya University
Utility/ Host	Consortium[1]	Vattenfall Europe Generation AG	A2A Reti Elettriche Spa Group	Yunnan Electric Power Grid	KEPCO	TBD
In-Grid Start Date	Fall 2009	Fall 2009 Retrofit 2011	Early 2010	December 2007	TBD[3]	TBD
End Date	Mid 2010	TBD	End of 2011	TBD	TBD	TBD
Type	Resistive	Resistive	Resistive	Saturable Core	Hybrid Resistive	HTS Transformer
Phases	3	3	3	3	3	3

[1] CE Electric UK, Electricity Northwest, and Scottish Power Energy Networks.

[2] DAPAS (funding, program management), KEPCO and LSIS (Developers).

[3] To be decided.

[4] Development prototype; currently no plans for grid deployment.

Table D-2
Superconducting fault current limiter projects worldwide: design details

Project	England	Germany	A2A	Puji	Korea	Japan
Voltage	12 kV	12 kV	9 kV	35 kV	22.9 kV	22 kV/ 6.6 kV, wye-wye
Rated Current	100 A (2 MVA)	800 (16 MVA)	250 A (4 MVA)[1]	1.5 kA (90 MVA)	630 A (2 MVA)[5]	52.5 / 175A; 2 MVA
Expected Max Fault Current	55 kA_{PEAK}	63 kA_{PEAK}	I_{sc} = 30 kA_{PEAK} (first peak)[3]	41 kA	25 kA_{RMS} asymmetric	Unavailable
Current-Limiting Capability	55 kA → 7 kA	63 kA → 30 kA	$2 < I_{sc} / I_{Lim} < 2.2$	~56% (23 kA)	12.5 kA_{RMS} → ~5.6 kA_{RMS}	Unavailable
Max Limiting Duration	0.12 s	0.12 s	300 to 400 ms	>200 ms @ 10 kA_{RMS} [4]	1.5 seconds	5 cycles (50-60 Hz)
Peak Max Voltage Drop	U_o	1.6 x U_o	<10 V @ $I_{nominal}$	<1%	Unavailable	Unavailable
Let-Through Current	1.8 kA	6.6-7 kA	I_{Lim} <16 kA_{PEAK} (first peak) I_{Lim} =6 kA_{RMS} (steady-state)	Unavailable	630 A to 1.5 kA_{PEAK}	Unavailable
Recovery Time	Minutes	Minutes	>10 s (full recovery)	<800 ms	~ 100 ms	Instant-recovery under specified load conditions
HTS Material	BSSCO-2212 bulk tubes	BSSCO-2212 bulk tubes Retrofit YBCO	BSCCO 1G	BSCCO-2223	YBCO	HV: BSCCO LV: YBCO
HTS Conductor Supplier/Fabricator	Nexans	Nexans	SEI	INNOST and AMSC	Unavailable	Unavailable
Size (h ,w, l)	Diameter 1.2 m height 2.5 m	2.5 m, 1 m, 13 m	3.5 m, 2 m, 4 m[2]	Diameter 4 m, height 4.2 m	2.5 m, 1.2 m, 2.4 m	Diameter 690 mm, height 1,000 mm
Weight	2 tons	2.5 tons	3.8 tons[3]	27 tons	Less than 1 ton	425 kg

[1] 1-kA (15-MVA) unit in development.

[2] I_{sc} = 30 kA_{PEAK} (first peak), I_{sc} = 12 kA_{rms} (steady-state)

[3] Entire system: includes HTS, cryostat, refrigeration system, etc.

[4] Puji: Experimental result. Design value is 23 kA.

[5] 3-kA (120-MVA) unit in development.

Table D-3
Superconducting fault current limiter projects worldwide: cryostat and refrigeration design details

Project	England	Germany	A2A	Puji	Korea	Japan
Cryogen	LN2	LN2	LN2	LN2	LN2	LN2
Refrigeration Type	Closed-loop	Open-loop	Closed-loop Stirling cycle	Open-loop	Closed-loop	Unavailable
Refrigeration Supplier	Cryomech	Nexans	Stirling BV (NL)	Unavailable	Unavailable	Unavailable
Refrigeration System Capacity	300 W @ 77 K	3 kW @ 65 K	1 kW @ 77 K	200 W @ 77 K	220 W @ 80 K	Unavailable
Nominal Operating Temperature	73 K	65 K Retrofit 77	65 K	77 K	71 K	77 K

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 μV/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	Superconducting cable arrangements 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. YBa2Cu3O7 is often referred to as a coated conductor and is generally made as a tape.

F
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EPRI Superconductivity Conferences—Proceedings

Tenth EPRI Superconductivity Conference, Tallahassee, Florida

http://www.cvent.com/d/ydqbpk/2K

2009 Conference, Taejon, Republic of Korea

Report Number 1020603

http://my.epri.com/portal/server.pt?Product_id=000000000001020603

2008 Conference, Oak Ridge, TN USA

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2002 – 2007: CD of Proceedings available on request to: seckroad@epri.com

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