Superconductivity
INTERNATIONAL ENERGY AGENCY

High Temperature Superconductivity Application Readiness Map

Energy Delivery – Transmission, Substation and Distribution Applications

July 2021

Contents

1. Introduction

We depend on the electric power system more than ever to supply our residential, commercial and industrial sectors. To this end, new technologies and tools are being developed to provide a reliable, flexible, resilient and secure generation, transmission, and distribution system. High temperature superconductivity (HTS) is one of the technologies that has the potential to do this.

1.1. Technology Overview

Superconductivity is a phenomenon that causes certain materials, at low temperatures, to lose essentially all resistance to the flow of electricity. The lack of resistance enables a range of innovative technology applications. The temperature at which resistance ceases is referred to as the "transition temperature", or critical temperature (Tc). Tc is usually measured in kelvin (K)—0 K being absolute zero. HTS gets its name originally because it has a higher transition temperature (77 K, which can be achieved when using liquid nitrogen) than low temperature superconductivity (LTS) (around 4.2 K, which can be achieved using liquid helium).

Devices based on LTS have been available in certain specific markets for decades. Superconducting magnets, in particular, are well-established in many applications that require very high magnetic fields; for example: powerful electromagnets, including high-energy-physics particle accelerators and magnetic resonance and imaging (MRI) systems.

Starting from the discovery of HTS materials in late 80's, more than thirty years of research and development have brought new equipment incorporating HTS to the threshold of greatly improving the electric infrastructure. Laboratory scale tests have transitioned to large scale HTS-based projects that serve utility customers. HTS projects are being considered as permanent infrastructure to solve real-world electric grid problems. HTS materials have been employed or proposed for use in a variety of applications and sectors, including the energy, transportation, industrial, medical and defense sectors. HTS wire is the key enabler of making devices for the electric power system that are more efficient and compact, and offer greater resiliency, than conventional solutions.

Several examples of well-recognized types of superconducting materials include:

- BSCCO (Bismuth - Strontium - Calcium - Copper – Oxide), known as HTS first generation (1G)
- REBCO (Rare earth - Barium - Copper Oxide), known as HTS second generation (2G). REBCO may also be referred to as YBCO or GdBCO since they are the most commonly used rare earths in the manufacturing process
- MgB_2 (Magnesium diboride) with critical temperature around 35 K
- Nb_3Sn (Niobium-Tin) and Nb-Ti (Niobium-Titanium) used in LTS applications

One of the most critical components of a superconductive device is the cryogenic (refrigeration) system for achieving operating temperatures. Because Liquid Nitrogen (LN) is relatively ubiquitous and less expensive than liquid helium, HTS technologies offer greater potential to develop cost-effective solutions for the electric power sector.

1.2. HTS Benefits

New power system applications, utilizing HTS wire, are targeted to provide a more reliable, resilient, sustainable and efficient electric grid. HTS power grid applications are creating unique opportunities for promising commercial components that can enable the needed evolution of the energy system; such components include high-capacity power cables, fault current limiters, high-efficiency generators for offshore wind turbines, energy storage, and innovative transformers. Not only do superconductor-based devices provide improvements over conventional electric grid technologies, but they also offer unique alternatives to system challenges that cannot be addressed utilizing conventional solutions.

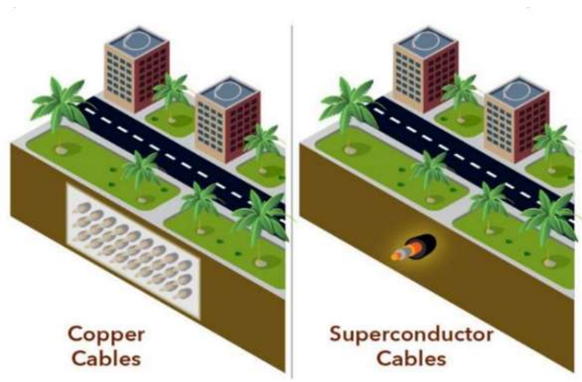

Figure 1 Superconducting cables can replace many conventional copper cables and transfer transmission power at distribution voltages.

HTS cables can carry much larger levels of power than conventional cables for the same underground cross-section and right-of-way. As fiber optics revolutionized the telecommunications grid, HTS enabled cables offer advantages versus conventional copper solutions. They can provide the same level power, but at a much lower voltage. In addition, many of the world's utilities are coping with increasing fault (short-circuit) currents, possibly requiring new substation circuit breakers. An HTS fault current limiter (FCL) can help manage increasing fault currents more cost-effectively and reduce losses by at least 50% in solid-state FCLs and at least 90% in fault-current-limiting reactors. Energy storage can increase the utilization of renewable resources and improve power quality. Superconducting Magnetic Energy Storage (SMES) has several advantages over other storage technologies, including rapid response times, nearly infinite charge/discharge cycles without degradation, and very high round trip efficiency.

2. Scope

This document is an energy delivery application readiness map for HTS. We define the readiness map as a way to illustrate the Technology Readiness Levels (TRL) over time of HTS applications in various sectors. Definitions of the TRL levels are found in Figure 2. Examples of sectors in which HTS is, or can be, used include energy delivery, energy supply, transportation, medicine, and industrial processes. The sector this document focuses on is energy delivery, whose applications can be further broken down into transmission, substation and distribution.

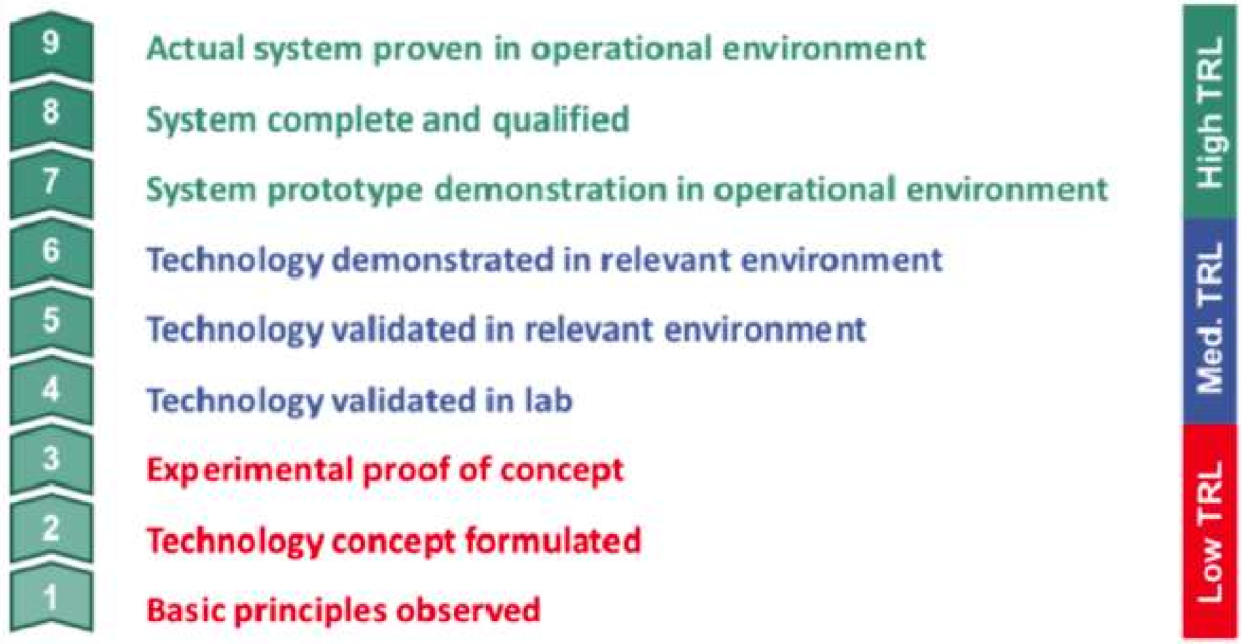

Figure 2. Technology Readiness Levels[1]

3. Energy Delivery Sector

Figure 3 below shows the TRL levels of various transmission, substation and distribution applications in the energy delivery sector. For each of the applications, the TRL for today and future were determined by using the input of industry experts. Factors influencing technology readiness include:

- Underlying scientific/engineering maturity (e.g., HTS wire design; cabling technology)
- Potential for ongoing R&D of component technologies (e.g., existing or planned research activities; institutional support; etc.)
- Maturity of component subsystems common to other applications (e.g., cryogenic systems)
- Specific application readiness (e.g., maturity of HTS AC cable design; user need for non-conventional solutions)
- Education of developers as to customer needs

The rationale for the TRL levels for each application is described in the following sections. Instead of using a specific TRL number 1-9 for each of the applications, they are categorized into low, medium and high TRL levels. Specific TRL levels are less meaningful when looking at future years.

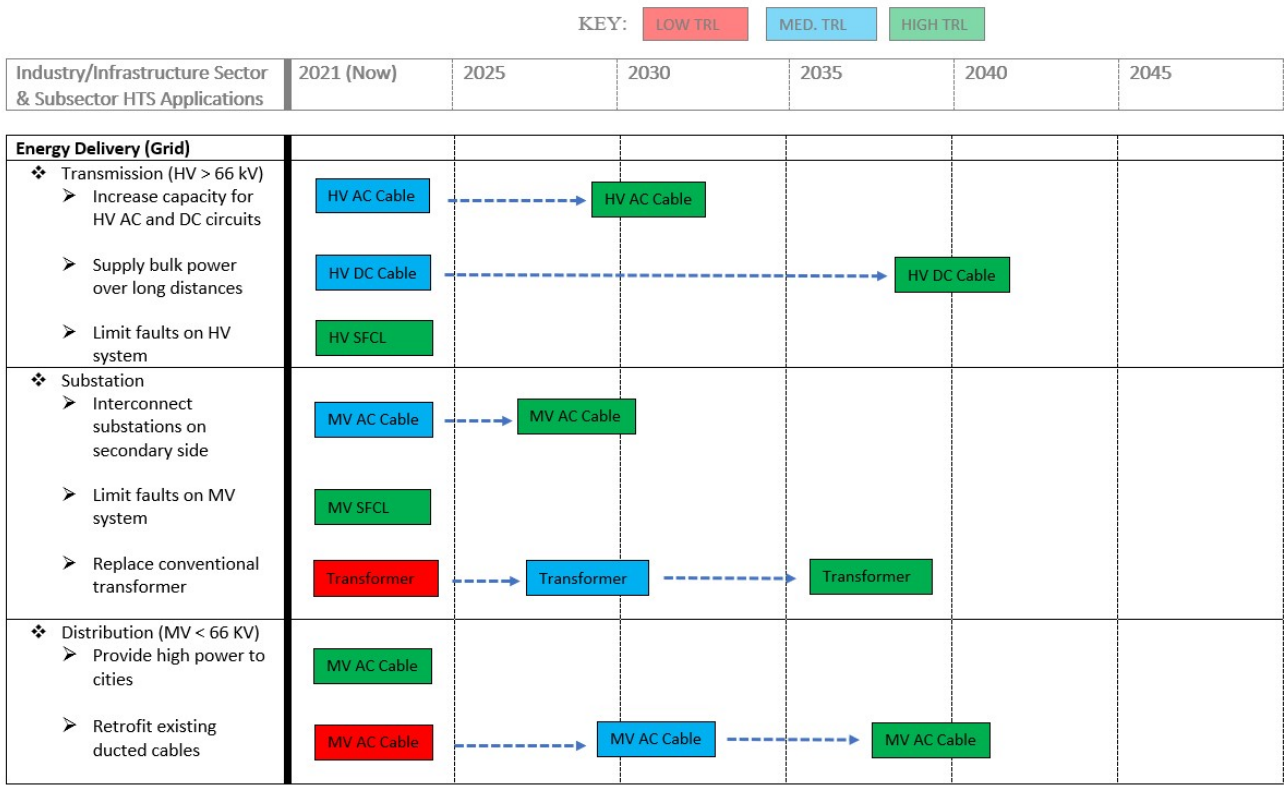

Figure 3. Technology Readiness Levels for HTS Applications

3.1. Transmission

Transmission applications include increasing capacity of AC and DC circuits, and limiting faults on the high voltage system.

3.1.1. Increase capacity for HV AC circuits – HV AC Cable

The location of power generating plants is often far from the end users. The high-power requirements of modern urban and suburban regions necessitates the use of high voltage transmission lines from power plants to load serving substations. High voltages require substantial insulation between conductors, and the least expensive way to achieve that is with air. Hence, most transmission lines are overhead allowing wide separation between conductors. There are situations, however, where overhead lines are not possible, chiefly in some suburban areas and dense urban centers. As well, there are regions where overhead lines are opposed, for health and/or aesthetic reasons. In these situations, a high voltage underground cable may be the only option to bring electric power from outside the area. Underground cables have a near century-long record of use and a high degree of design sophistication.

Underground cables offer greater immunity from adverse environments and greater public acceptance. However, an underground cable is 4 to 14 times more expensive than an overhead line due to greater design complexity for electrical insulation and significant installation costs (about 40 percent of the total).[2] In addition, because of the inherent capacitance of an AC cable, there is a limit to its length (DC cables are not as prone to distance limitations). Both types exhibit ohmic losses. With a lower capacitance than conventional cables, an HTS AC cable can be considerably longer. Also, HTS cables generate no heat due to ohmic losses in the conductors and thus do not require specially designed and constructed thermal backfill for the rejection of heat to the atmosphere. Providing for heat rejection is a significant cost component for installation and maintenance of conventional cables.

High voltage transmission lines or cables must be terminated in high voltage substations, which are often located directly within dense urban centers in order to serve the substantial load there. These substations require a large space for air insulation of above-ground conductors and/or exposed terminals. High voltage transformers are large and contain significant quantities of flammable and environmentally corrosive oil. Urban substations are often located inside buildings in commercial districts in which high voltage clearances are difficult to obtain leading to elevated safety concerns. In confined spaces accidents such as transformer bushing failures or fires can have far more serious consequences than for "open air" substations in suburban locations.[3] In such situations, a lower voltage HTS AC cable capable of carrying present and/or future loads may replace an existing or proposed high-voltage overhead line or underground cable. While the concept is straightforward, it must be noted that there are complex tradeoffs involving efficiency, reliability, availability, cost, etc. that will impact the feasibility of a specific project.

In view of the above considerations a typical application for HV AC HTS is to send transmission level power to or within urban load centers where narrow right-of-way (ROW), construction constraints and environmental considerations severely limit or forbid the use of conventional approaches. Such applications typically involve distances greater than a few kilometers. All of the HTS cable projects to date have been approximately 1-km or shorter so there are not examples of moving transmission level power over longer distances. However, there are some projects that are exploring the use of HTS cables in longer applications.

An AC HTS cable project called SuperLink is being proposed in the Munich, Germany electric grid. This project would construct a 12-kilometer, high voltage link between the main transformer stations in Mening and the Lunch South load center.[4] A declaration of intent has been signed, resulting in a development application to the German Federal Ministry of Economy. This project would be the longest project in the world. The cable would have a power rating of 500 MW and a voltage level of 110 kV. It is planned to be installed in existing ducts to minimize the construction work and deliver a large amount of power through a narrow corridor in the middle of Munich.[5] Partners in the project include NKT, Linde plc, THEVA, the South Westphalia University of Applied Sciences (FH-SWF), Stadtwerke München Infrastruktur, the Karlsruhe Institute of Technology (KIT) and Stadtwerke München.

In 2018, TenneT investigated the possibility of installing a 3.4km-long section of an AC HTS cable in the city of Enschede in the Netherlands. TenneT manages the high-voltage grid in the Netherlands and large parts of Germany. At that time, the investment differences between a conventional cable and HTS cable were found to be too excessive and the project did not move forward. The superconductor for this specific project would cost approximately four times more than a conventional cable. A major investment such as the superconductor is regarded as a non-regular expansion investment and because TenneT's investments are publicly funded the additional costs of this innovative project would not be recovered by utility ratepayers. Therefore, there are limits to how much TenneT could invest. As costs come down, TenneT is considering the option of using superconductivity for future grid upgrade projects.

In 2016, Korea Electric Power Company (KEPCO) completed a demonstration test of a 1 km, 154 kV, 600 MVA three-phase HTS AC cable in the Jeju smart-grid demonstration center. The cable was inserted into an operational electric grid between the HanLim and Gumak substations on Jeju Island.[6] In 2021, KEPCO has proposed a new commercial project, the Onsu Project. This will be a 1.6 kilometer 154 kV, 400 MVA 3-phase HTS AC cable interconnecting two substations. The HTS cable will be used instead of the original plan to use conventional XLPE, resulting in reduced civil work costs and ability to use existing tunnel.[7]

Analysis: While there have been successful demonstrations of AC cables, as described above, there are no systems that are as complete and qualified as conventional cables serving the same objectives. Technical success has been achieved for relevant use cases and short-length projects, but there remain significant design and operational barriers to achieving commercially viable deployments. Therefore, today's TRL level is ranked at "medium".

Barriers to advance TRL level: There are several major barriers for advancing TRL levels.

Factory Testing: Underground cable is shipped from the manufacturing plant on large reels. The capacity of a shipping reel is limited to between 0.5 and 1 km, typically, depending on cable design and transportation methods. Factory acceptance testing for voltage integrity of electrical insulation is necessary for 100% of all reels shipped to the project site. Otherwise, a reel with potential insulation defects may produce failure in the field when first energized. Location of the failed section, removal, reinstallation and recommissioning is a costly and time-consuming process. Projects involving more than a very few reels of untested cable have a statistically high probability of encountering a faulty reel due to the inherent variability in any manufacturing process. Acceptance testing is therefore a standardized step in the manufacture of conventional cable. However, at present, there is no means to do the same for an HTS cable because the insulation of present day HTS cables requires wetting paper tapes with a liquid cryogen. Factory testing would require immersing an entire shipping reel (weighing tens of tons) in the liquid cryogen – a clear impracticality. There are potentially two approaches to overcome the acceptance testing barrier. The preferred approach would be to develop and test a solid dielectric similar to conventional cables (i.e., extrudable), capable of performing at cryogenic temperatures but not requiring the reduced temperatures for its electrical insulating properties. The resulting cable could be factory tested with essentially the same methods as conventional cable. There is research in the U.S. underway to develop such a dielectric. Alternatively, it may be possible to develop standardized surrogate tests on cable samples from each reel, the results for which can be shown to apply to all of the cable on the reel with more than reasonable certainty.

Cryogenic and Vacuum Systems: The need for optimized and field-proven cryogenic systems for HTS cable installations presents another barrier to higher TRLs. Cryogenic refrigeration is a well-established industry for many applications, but there are not available systems designed specifically for HTS cables. Economic studies suggest that the efficiencies of commercially available refrigerators is inadequate for utility applications. Available refrigerator sizes also are not optimal. Space limitations within the substation for refrigeration equipment, particularly in the dense urban locations most attractive for this application, may require innovative approaches, yet to be determined. These situations lead to uncertainties regarding system design and performance, operational characteristics, and maintenance procedures. Additionally, there is little or no precedent for mechanical equipment installed inside utility substations nor for the presence of non-utility maintenance personnel. Electric utilities are generally very conservative and risk-averse, preferring equipment that is well-proven for the application and operations that are entirely under their control. Thus, achieving a higher TRL requires cryogenic systems that have been optimized and fully tested for longer-length underground HTS cable systems, as well as having operation and maintenance practices that are consistent with current electric utility industry standards.

Cable Splices: Cable splices between installed sections are a necessary fact for all underground cable systems. Cable splices are by far the weakest link in the cable system and are prone to failure if not properly constructed. Splicing must occur in the field, whether in permanent underground vaults or in temporary field facilities for later direct burial. Splicing is as much an art as it is a science. It requires ultra clean conditions and a high degree of training. HTS cable splices have greater complexity and greater consequences from failure. Additionally, splicing HTS cables involves integrating the vacuum cryostat in the splice joint. The few HTS cable systems in existence have not yet proven out the best designs and methods for achieving highly reliable splices in the field.

3.1.2. Supply bulk power over long distances – HTS DC Cables

Renewable energy resources are often located far from load centers, requiring the transmission of bulk power over long distances. Geographical differences and weather-related conditions across continental expanses can lead to situations where the ability to move bulk power from one region to another may be key to both economic operation of power systems and emergency response to natural or man-made disasters. While overhead HV AC and DC transmission lines are suitable and in current use, they can involve substantial environmental and land (ROW) utilization and permitting issues. Underground HTS DC cables are ideal for such situations, having the potential of transmitting 10’s of GW, over distances exceeding 2000 km while exhibiting the smallest ROW requirements of any transmission technology.[8] Moreover, power losses are less than conventional overhead transmission lines and are independent of the level of power transmitted.[9] Thus, HTS DC cables have the potential to be cost competitive with overhead extra-high voltage (EHV) AC and traditional HVDC transmission technologies.[10]

HTS DC cables become particularly beneficial when the transmission length is long.[11] In this regard it is noteworthy that cryogenic system requirements are substantially more exacting than for short-length AC cable systems installed in suburban and urban locations.[12] Cryogenic refrigerators must be placed at relatively frequent intervals along the line (nominally, in flat regions, every 10-25 km; in mountainous areas, every 1 km).[13] Because of the distances involved and the likelihood that some regions of the transmission line may not offer suitable power for refrigerators, alternative means for supplying that power must be provided. A similar situation may exist for periodically placed vacuum pumping stations, depending on cable system design.

Worldwide, there has been interest in developing and demonstrating HTS DC cables because of their potential to solve energy production imbalances across large geographical regions. However, as with HTS AC cables, projects to date have been short, 1-km or less. Even so, there has been significant progress in addressing design and engineering issues.

A 2009 feasibility study by the Electric Power Research Institute (EPRI) established the technical feasibility and economic attractiveness of an interregional (1500-2000 km) 10 GW HTS DC cable system using REBCO (2G) HTS wire.[14] The European Best Paths project (described below) used the EPRI study as one of its starting points, but ultimately selected MgB_2 as the conductor.[15] Nevertheless, the EPRI work significantly advanced the state of the art for superconducting DC cables and provided both the incentive and basis for further advancements in the field.

In 2011 the Institute of Engineering, Chinese Academy of Sciences (IEE-CAS) installed and energized the world's first HTS DC cable in a commercial/industrial setting. The 360 meter, 1.3 kV cable, with a rated current of 10 kA, interconnects an alumina electrolyzer plant with a nearby utility substation. At the time, the cable was the longest and highest power installed and operating HTS DC cable in the world.

In 2014, Korea Electric Power Corporation (KEPCO), LS Cable & System, and AMSC collaborated to energize the world's first high voltage direct current (HVDC) HTS cable on Jeju Island in Korea. The 500 meter, 80 kV DC cable was powered by AMSC's Amperium® HTS wire and installed in KEPCO's electricity grid.[16] The project operated for two years and was deenergized in October 2016.[17]

Figure 4 DC Cable installed on Jeju Island, Korea

In 2016, a 1-km, 20 kV, 2.5 kA superconducting dc power transmission system was built and tested in Ishikari City, Hokkaido, Japan, ("Ishikari Project"). The objectives of the project were to design and verify the validity of a system for practical use, and also to obtain the properties required for long length cable systems for bulk power transmission.[18]

In 2018, The European Best Paths research project culminated with the first-ever successful qualification on a test platform of a full-scale 320 kV HVDC superconducting loop. This loop comprises two terminations and a 30 meter length of cable carrying a current of 10 kA for a rated power transmission capacity of 3.2 GW.[19] The vision and objectives of the Best Paths HVDC project grew out of earlier conceptual studies of intercontinental transmission line connecting solar energy farms in Africa with European electric grids.[20]

In St. Petersburg, Russia, the Federal Grid Company of Unified Energy System (FGC UES) is planning a HTS DC cable link between two urban HV substations. The HTS DC cable will be 2500 meters in length and will operate at 20 kV with a power rating of 50 MW. While the intended outcome of the project is to improve grid reliability in the urban area, it will also demonstrate and further advance HTS DC cable technology.[21] Components of the cable have been manufactured and tested. The cable is expected to be constructed and energized by the end of 2021.[22]

Analysis: While there have been successful demonstrations of HTS DC cables at shorter lengths, there are no systems that are complete and qualified, let alone operational, at lengths greater than one kilometer. Therefore, similarly to the situation with HV HTS AC cables, today's TRL level for HTS DC cables is ranked at "medium". In contrast with HTS AC cables, however, the longer-term prospect of energizing DC cables at useful lengths is still far in the future. This is because of the inherent greater complexity and cost of DC transmission lines, the predominance of AC as the preferred mode of power transfer, and the present market-led focus on HTS AC cables. It should be noted that undertaking a transmission project, whether using conventional solutions or HTS, is challenging because of permitting and right of way issues, and significant capital costs. Therefore, conducting a long length project will take longer than short length projects. The amount of HTS wire required for a very long cable may also strain worldwide manufacturing capacity.

Barriers to advance TRL level: The barriers for advancing TRL levels for HTS DC cables are similar to those for high-voltage HTS AC cables, with some important differences. Refer to the section above for greater detail on issues common to both cable systems.

Factory Testing: As with AC cables, successful installation and operation requires a satisfactory means to affirm voltage integrity and performance ("acceptance testing") for 100% of all cable reels shipped. The same impossibility of achieving this goal for AC cables with today's cable insulation designs applies also to DC cables. However, the criticality is much greater due to the substantially greater number of shipping reels in a long-distance DC cable project. Moreover, electrical insulation of DC cables, whether conventional or superconducting, presents additional design issues not encountered in AC cables. Methods for achieving a good dielectric for a DC cable are, today, highly proprietary to the companies that manufacture these cables. The same will likely be true for HTS DC, elevating the importance of testing.

Cryogenic and Vacuum Systems: Due to its length, a HTS DC cable system for bulk power transmission has significantly more complex requirements for the cryogenic and vacuum systems than do the relatively short length AC cable systems. Relevant issues requiring further study and optimization include use of alternate cryogens, impact of altitude changes along the line, means of leak avoidance and monitoring, spacing of vacuum pumps and refrigerators, means for maintaining vacuum over long periods, and repair of vacuum leaks. The long length of the line over varied terrain and the statistical certainty that leaks will develop over time drives these issues. Optimized engineering designs for cryogenic systems equipment and infrastructure have yet to be produced for long-length transmission lines. After optimization efforts, prototype demonstrations of intermediate-length lines (e.g., > 10 km) are needed to identify best practices for both design deployment of cryogenic systems over long distances.

Cable Splices: As for AC cables, splice and terminations are components requiring further development of best designs and methods for achieving highly reliable splices in the field. Reliable splices are all the more critical for long length lines due to the statistically greater probability of failures in the field from the large number to be installed. Additionally, as for DC cable insulation, splicing DC cables presents greater challenges than for AC cables.

3.1.3. Limiting faults on high voltage system – HV SFCLs

A fault is an unintentional short circuit, or partial short-circuit, in an electric system. A variety of factors such as lightning, downed power lines, or crossed power lines cause faults. During a fault, excessive current—called fault current— flows through the electrical system. Circuit breakers or fuses protect the system from damage but in doing so often isolate one or more sections of the system resulting in temporary loss of service to some customers or loss of capacity to serve load. A fault current limiter (FCL) limits the amount of current flowing through the system and allows for the continual, uninterrupted operation of the electrical system.

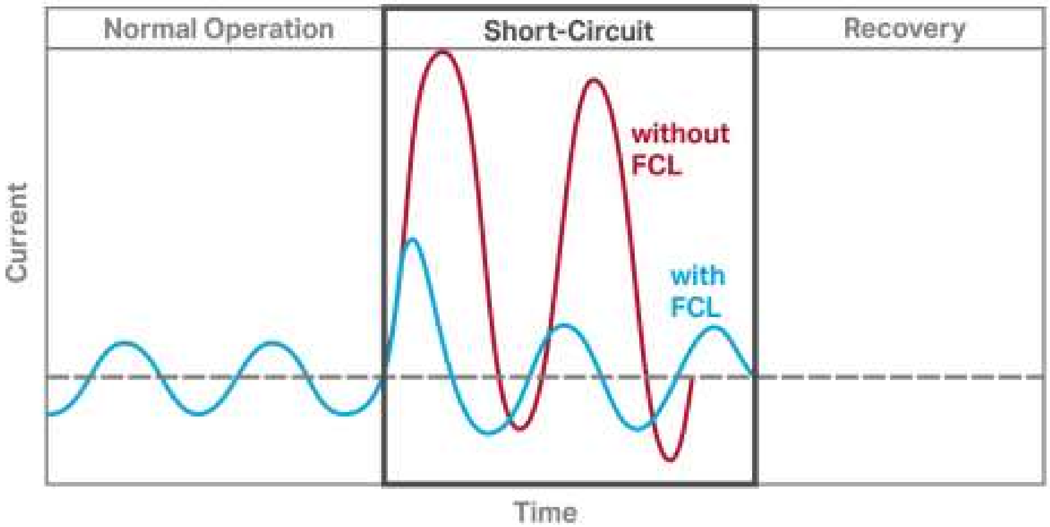

Figure 5. Short circuit on a transmission or distribution line

This graphic shows when a short circuit (or fault) occurs, a transmission or distribution line's current can spike and cause damage to upstream equipment. An FCL would limit the current to normal levels in less than one cycle.

The need for FCLs is driven by rising system fault current levels as energy demand increases and more distributed generation and clean energy sources, such as wind and solar, are added to non-optimal locations on the distribution network. The table below shows some of the traditional solutions and HTS solutions for dealing with fault currents.

Technology	Features
Explosive fault limiting fuses	• Available today for voltages under 35 kV • Service call required to replace blown fuse
Series reactors	• Used routinely in the electric grid • Consume reactive power and may impact grid dynamics
Superconducting FCLs	• No impedance on the T&D grid • Passive operation

This document defines a high voltage system as being at or greater than 66 kV.

In June 2012, after the development of a 35-kV SFCL, Innopower continued to develop a 220-kV (300 MVA) saturated iron-core type SFCL. The State Grid of China installed the device at the Shigezhuang substation in the Chinese State grid in Tianjin, China. It was planned for a three-year live grid operation to test its feasibility.[23]

Figure 6. SFCL of 115 kV under commercial service at Glow

In April 2015, Advanced Materials (AMAT) announced that it received orders for two transmission-class SFCLs from Glow Energy, an independent power producer in Thailand. As the utility company planned to connect the additional generation capacity to the 115-kV line, the increased fault current was to be reduced prior to coupling with the power grid.[24] AMAT manufactured two sets of resistive type SFCLs, each with ratings of 115 kV and 900 A. They were installed at the secondary side of the transformers at Map Ta Phut Industrial Estate of Glow Energy grid in Rayong, Thailand, and commissioned on July 2016. This may be the first commercial activity of an SFCL application in the private sector.

In December 2019, a 220 kV superconducting fault current limiter (SFCL) three phase unit was put in a permanent operation. The SFCL is at the 220/20 kV Mnevniki substation (UNECO grid company). The device was developed by SuperOx and is the first superconducting element in the Russian electrical grid. Further review of the technology is considering to expand the use of the breakthrough SFCL technology in Russia.

The Korean Electric Power Research Institute (KEPRI) has developed a single-phase prototype of the resistive SFCL with ratings of 154 kV and 2000 A.[25] The SFCL was installed at the Gochang Power Testing Center, KEPCO, for various performance tests including a short-term connection to the 154 kV line. Manufacturing and field test of a three-phase unit are under planning.

Analysis: There have been several examples of high voltage HTS FCL energized in real grid operations. At least one is under commercial service in a utility. Therefore, HV SFCLs were ranked at a TRL of "high" today.

3.2. Substation

Substation applications in this analysis include interconnecting two or more substations in order to improve asset utilization and system resiliency; limiting faults on the medium voltage system; and replacing conventional transformers with HTS based devices.

3.2.1. Interconnecting substations on the secondary side of the transformer

Electric substations are the means to distribute power from high voltage transmission lines to lower voltage loads, which may be end-use customers or intervening medium voltage distribution systems. While not as large a portion of the utility's capital budget as transmission and distribution lines, substations represent a significant investment. They are also a major electrical component in the utility infrastructure for both meeting electric demand and providing reliable power.

Load growth, or decline, presents multiple challenges for electric utilities serving dense urban or suburban areas. Because substantial time is involved in designing, permitting and constructing a new substation a utility must plan for and even construct new substation capacity far in advance of the actual need. If the projected need does not materialize, capital resources are wasted. Another challenge for utility planners is the proliferation of computer-based equipment and consumer electronics, which has put a premium on providing reliable power. Substations figure largely in the utility's ability to serve these needs.

With the above considerations, it is important that substation assets (e.g., transformers, switchgear, etc.) be both fully used as much as possible (i.e., typically at or above 100% capacity during brief peak load periods) and ideally be able to continue serving load in the event of a partial outage (e.g., loss of one of several transformer banks, or a transmission voltage feeder). These two needs sometimes can be at cross purposes, since ensuring reliable power often means having spare, and therefore unutilized, transformer banks in the substation. Conventional solutions to these needs often dictate either the expansion of existing substations or the construction of new ones. Particularly in dense urban areas, but also in many suburban neighborhoods, there often are difficulties in doing either of these. Factors impeding this path include limited availability and/or cost of land, environmental concerns, public opposition, and permitting complexities and delays.

An alternative solution, which addresses both issues, is to connect two (or more) geographically or electrically neighboring substations at their secondary (low voltage) buses. Particularly if individual substations are fed by different transmission lines on the high voltage side, reliability will be improved. However, using copper or aluminum buses or cables is either impractical or impossible because of very high currents at the secondary voltages and the associated ohmic losses with this approach. On the other hand, this presents an ideal application for a low or medium voltage HTS cable since achieving high currents is a unique feature of superconductors. For example, for two substations that individually do not have sufficient transformer capacity in the event of an outage at one of them, linking their secondary voltage busses makes it possible to provide reliable power for both. This is based on the twin assumptions that there is spare capacity at one of the substations and that there is a low probability of experiencing an outage in both substations at the same time. This scenario becomes even more attractive when more than two substations are linked.

The concept of linking substations at the secondary side has yet to be proven in practice but a fault-tolerant HTS AC cable suitable for this application has been designed and laboratory tested. An important demonstration project now underway in the city of Chicago is designed to demonstrate the benefits of this application of HTS cables. AMSC and Commonwealth Edison (ComEd), one of the largest electric utilities in the U.S., have partnered to install a medium voltage HTS AC cable system that will loop together three, downtown Chicago sub-transmission voltage substations into a network, increasing reliability and resiliency for all to N-3 (meaning up to three failures can occur before losing the ability to provide electricity to all consumers served by those substations). The project is part of the ongoing U.S. Department of Homeland Security (DHS) Science and Technology Directorate's initiative to secure the United States' electric grid against extreme weather and other catastrophic events. The high current density of AMSC's REG™ cable is a key advantage for ComEd, as it enables a very compact installation footprint that is ideally suited for creating new power links in densely populated urban areas where space is at a premium.

The REG™ system provides protection against catastrophic effects resulting from the loss of critical substation facilities in urban areas by interconnecting and sharing excess capacity of nearby substations, while preventing high fault currents. The result is enhanced protection from cascading failures and widespread power outages on the power grid. The design selected for the REG™ project also has a low environmental impact as there are near zero thermal and electromagnetic fields.

The HTS cables will use AMSC's Amperium™ superconductor wire. Nexans will manufacture the cable for the REG™ project at its specialized superconductor facility in Hannover, Germany. The cable installation in Chicago is scheduled for the end of 2021.

KEPCO is planning to install a two, 1 km long 23 kV/60 MVA triaxial HTS power cables to interconnect the Munsan and Seonyu 154 kV substations. A 23-kV Smart Superconducting Switching Platform (SSSP) will replace a large 154-kV substation. The goal is to eliminate from urban areas the high voltage transmission lines and substations. A thermo-hydraulic analysis of the single and dual cooling systems has been conducted to investigate the applicability of the external and internal return paths with the detailed geographical characteristics of the real installation environment. The thermo hydraulic analysis model and results will be used as a design and operation guide for a cryogenic cooling system for the future installation of the triaxial HTS power cable between the two substations.

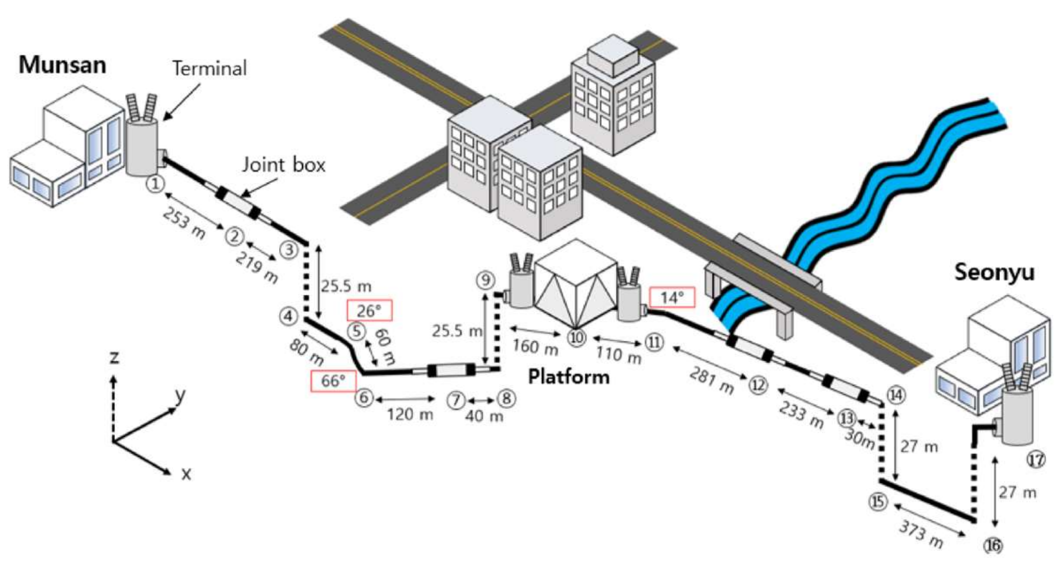

Figure 7 Layout of a triaxial cable to connect two substations

Analysis: While there at least two projects in the planning stages that would use medium voltage HTS AC cables to interconnect distribution substations, there have been no actual in-the-field demonstrations. On the other hand, the type of HTS AC cable to be used in this application is very similar in most respects to the high voltage AC cables discussed earlier and for which there have been successful demonstrations. Moreover, there have been successful laboratory tests for the specific type of cable to be used in the Chicago project. Therefore, today's TRL level is ranked at "medium". In view of the planned near-term deployment in Chicago, as well as the possibility that there exist multiple opportunities in other cities for this application, the progress from "medium" to "high" is expected to be rapid, perhaps in around five years.

Barriers to advance TRL level: The barriers for the medium voltage AC cable for this application are virtually the same as for other HTS AC cable applications. See previous sections for discussion of these barriers. However, the separation between urban substations will generally be less than one or two kilometers. reducing the criticality of issues that are driven by cable system length. On the other hand, the fault limiting requirements on the cable for this application are unique.

Fault Current Limiting Capability: Interconnection of two substations on the secondary side will effectively double the available fault current for any of the downstream breakers and feeders in both substations. Except in the case of new construction (which would not likely be the case for this application) these substation breakers and feeders will have fault current ratings corresponding to the single substation in which they are connected. Thus, this application will require the installation of either a separate fault current limiting device in series with the HTS cable, or a cable that has inherent fault current limiting capability, or both. The application may also require a sophisticated switching set up to ensure that fault duty of any component is not exceeded in the event of faults elsewhere in the system as well as in any of the connected stations. Fault-current-limiting cables have been designed and laboratory tested but not field tested. Some designs rely on a particular type of superconducting wire, also not widely field tested, if at all. Series connection of a fault current limiter (FCL) has been demonstrated, but not in scenarios such as the present application. Significant field testing time (i.e., calendar time) for all viable approaches is necessary because fault incidents are random and cannot be planned. The time to field prove the proposed approaches is therefore a limiting barrier.

Limiting faults on medium voltage system – MV SFCLs

As there have been several applications of HV SFCLs, there are even more examples of using them on the medium voltage system. Some examples are shown below, and this is not an exhaustive list.

In 2012, an Italian SFCL program was conducted by Ricerca sul Sistema Energetico (RSE). A 9-kV, 3.4-MVA SFCL was developed and installed to protect a distribution feeder in Milan in a medium voltage substation, San Dionigi, of the utility A2A Reti Elettriche S.p.A. This SFCL experienced an artificial three-phase fault, with a prompt limitation of the fault current by a factor of approximately 2. It was field-tested until June 2014, and RSE is working on upgrading the device to a 15.6-MVA unit.[26]

In 2014, Applied Materials conducted a field test at the Knapps Corners Substation, Central Hudson Gas & Electric in the State of New York, USA, of a 15.1 kV SFCL. This resistive type SFCL was sponsored by the New York State Energy Research Development Authority and successfully responded to 31 fault currents before being commissioned in 2017.

This report does not differentiate the TRL levels of different SFCL types such as magnetic shield, bridge type, saturated iron core, or resistive. However, all of the recently installed SFCLs are resistive type, which suggests that they are more technically mature than other types.[27]

Analysis: There are more than 20 SFCL operating at the medium voltage in real grid operations. Therefore, Medium voltage SFCLs were ranked at a TRL of "high" today. This document highlights only a few examples to illustrate this ranking.

One issue for MV SFCLs is the reliability of HTS tapes. In MV applications, 2G HTS tapes are often required because they limit the overall quantity of tape that is needed with the same limitation factor. They are able to limit the AC losses during normal working conditions, which avoids the need of large amounts of cooling power. However, 2G tapes may show some issues from the point of view of the HTS layer uniformity which could affect the overall reliability of the device. Another barrier is proving to MV grid operators that the increased cost due to the HTS tape and cooling system is economically viable when considering the SFCLs grid benefits. A techno-economic analysis might be required in order to compare SFCL devices with the conventional systems.

3.2.2. Replacing conventional transformers

Superconducting transformers offer several benefits over conventional technologies. These include a 50% reduction in size and weight and 50% improvement in energy savings. However, realistic energy savings will only be possible for large scale transformers e.g. 1MVA and above. This is because of the combination of AC loss, current lead loss and cryostat losses. The HTS efficiency comparison is worse if the loading is low, as the current lead loss and cryostat loss is independent of load. Conventional transformers have persistent safety issues as the degradation of paper insulation and degradation of the dielectric properties of oil which can lead to dielectric breakdown and resulting fires and explosions. Superconductor transformers have no oil and so avoid these risks. This is particularly valuable for transformers placed inside buildings. They also offer low short circuit impedance with higher stability, less voltage drops and less reactive power requirements with no consequent reduction in life. A special characteristic that could make them attractive is the relative ease with which fault-current limiting capability could be incorporated. Only a few grid tests have taken place. To be effective they would require development of a suitable solid dielectric.[28]

In 2012, the first current limiting superconducting transformer with HTS Roebel winding was validated in a laboratory in New Zealand. It was a three-phase device with nominal power of 1 MVA.[29] This is on the very low end of the "medium" TRL level.

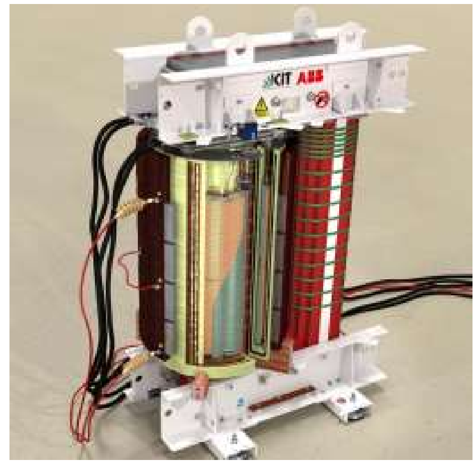

Figure 8 Manufacturing and test of a 1 MVA transformer from KIT and ABB

In 2017, KIT conducted an experimental proof of concept of a fault current limiting superconducting transformer with a nominal power of 577 kVA. It had a voltage ratio of 20kV/1kV and a fault duration of 60 ms. This is on the high end of the "low" TRL level.

In 2017, SuperPower led a team to develop requirements for a fault current limiting transformer with base performance of: 28 MVA, 69/12.47 kV and 30-50% reduction in prospective fault current. The project did not result in a full-scale transformer device, but the production quantity lengths of FCL transformer 2G HTS conductor have been successfully produced and the functionality of the conductor has been demonstrated. A FCL transformer module was tested at the Center for Advanced Power Systems (CAPS) at Florida State University. [30]

From 1998-2010, Kyushu University led a significant development effort in transformers. To reduce AC loss, they developed the coil-level transposition method which is a viable alternative to using a Roebel cable for the low voltage winding. The efficiency of these transformers was demonstrated to be above 99%.[31] [32] [33]

More information about other projects can be found in a EUCAS Short Course on Superconducting Transformers.[34]

Analysis: An HTS transformer is arguably one of the most difficult of the superconductivity AC power applications to develop because of the need for very low AC losses, adequate fault and surge performance, and rigors of the application environment. Worldwide activity in HTS transformer R&D is behind many of the other applications. There is currently very little R&D being conducted on HTS transformers. Though research is being pursued in a few laboratories and universities around the world, HTS transformers are only at a developmental stage. There have been approximately 15 superconducting transformer projects and most of those projects occurred over two decades ago. There have been several recent successful demonstrator developments with a rating up to 4 MVA and medium voltages. There is still a need for more three phase medium voltage prototypes in long term field tests. There is a differentiation between the two types of HTS transformer capabilities. The HTS transformer with no fault current limiting capability was rated as a "medium" TRL level (even though on the low end of the TRL band). The HTS transformer demonstrated at KIT with fault current limiting capability was rated as a "low" TRL level (though at the higher end of the low TRL band). Therefore, a composite rating of today's TRL rating was "low".

Barriers to advance TRL level: AC losses in the system will require ongoing reduction through advances in the conductor fabrication, (filamentation to handle hysteretic loss, transposition to handle coupling loss) but clear paths have been demonstrated to reach these goals (SuperPower project). For the next steps, it is recommended that further demonstration and development projects be undertaken to validate the technology and to incorporate advances in conductor and cryogenic cooling. In particular, the potential use of HTS conductors for the LV, high current windings should be evaluated. As with other new technologies, the utility industry has been slow to adopt a new device without significant runtime data. Future demonstrations and prototypes will provide this data that could enable this technology to begin to enter the marketplace.

The challenge for fault current limiting HTS transformers is to meet the usual short circuit current duration standard of 2 s and then to continue operation on clearing the fault. This cannot happen if the transformer windings have absorbed a large amount of energy, heating the HTS windings to near room temperature.

It is a complex task to produce a unified cryostat for 3 phases and minimize penetrations through the cryostat walls. Cryostats must be non-metallic and exclude the ferromagnetic core.

Economic obstacles are significant. Given the higher capital cost is it more likely transformers can be first commercialized in applications such as traction transformers or for indoor locations where risk and safety is of paramount concern.

3.3. Distribution

Distribution applications in this analysis include providing cables to city centers for high voltage AC power and retrofitting ducted cables.

3.3.1. Provide high power to cities – MV AC Cables

As urban density increases around the world, utility companies are tasked with bringing greater power to areas with increasingly limited space available in which to site the substations that transform high voltage transmission power to the medium to low voltages for electric consumers. Limited space for transformer stations means higher costs for power. Moreover, conventional power transformers utilize oil, a combustible and environmentally hazardous substance for cooling. While not common, power transformers sometimes fail catastrophically allowing oil to spill or catch fire. Elimination of transformers in city centers, or at least reduction in their size, would help solve both land cost and environmental safety issues. However, this can only be achieved by bringing power into city centers from outside at the lower voltages utilized by customers. With conventional cables this would be impractical, if not impossible due to ohmic losses and greatly increased number of underground cable circuits requiring more right of way and higher costs. Medium voltage HTS AC cables, on the other hand, are capable of bringing transmission level power into densely populated areas at distribution level (customer utilization) voltages because of higher current capability. As well, such cables may require even less right of way than a transmission voltage cable. In some cases, deployment of HTS cables may permit elimination altogether of the transformer at the receiving end. In such a situation the low-voltage substation would consist of only the more environmentally benign and space saving switchgear banks required to distribute power to end users.

HTS cables to provide this kind of service would likely fall into the length range of 1 to 10 km, though exceptions to this would certainly occur. The voltages employed in urban networks typically range from around 10 kV in smaller cities to as much as about 70 kV. HTS AC cables with voltages in this range have been demonstrated in multiple nations in the last decade, with some permanent, in-grid installations now existing. However, lengths of the demonstration and in-grid cables have been just one to a few kilometers. The feature of this application that is different from other, short-length HTS cable applications, is not the cable per se, but the specific scenario of using medium voltage AC cables in situations that historically have demanded the use of high voltage transmission lines due to the high level of power being provided. This application presents one of the most easily apprehended value propositions for HTS cables and, accordingly, is the application garnering the greatest support at present.

In 2014, the world's longest superconducting cable was energized into the power grid in Essen, Germany. In that project, an HTS AC cable was deployed to reduce the number of inner-city transformer substations. The 1 km cable connects a 10 kV distribution substation with a major 110 kV sub-transmission substation. The cable replaced one of two conventional 110 kV lines while rendering obsolete one of two transformers at the 10 kV substation. This cable has been running as expected since it was first energized and the utility has decided to make it a permanent part of their grid operations so that it is not considered a demonstration.

In 2019, the Korea Electric Power Corporation energized an HTS power cable, called the Shingal Project, to connect two 154-kV substations with a 23 kV, 50 MVA HTS cable over a distance of 1 km. The project is significant as it is the first superconducting project to start using 23 kV HTS cables commercially in a grid application.[35] The project demonstrates that a distribution voltage cable can eliminate a higher voltage transmission feeder into a city center.

In April 2020, Shanghai Electric Cable Research Institute began developing a 35 kV, 2.2 kA HTS cable project in Shanghai. The cable is a 3 in 1 type (three HTS cables in one cryostat) and will have a length of about 1.2 km. It will be installed between Changchun substation and Caoxi substation, replacing 4 circuits of conventional, XLPE insulation cables. The anticipated fault current is 25 kA for 2.0 seconds. The prototype cable passed the type test in October 2019. The project will be energized in 2021.[36]

In November 2020, NEDO, SWCC SHOWA Cable Systems Co., LTD, and BASF Japan Ltd. installed a 200 m three-phase coaxial superconducting cable. It has been installed at the BASF Japan's Totsuka Site (Totsuka Ward, Yokohama City) and started verification tests aimed at energy savings in the factory, reduced operating costs and safety of cable system cooled with liquid nitrogen. Demonstration tests will be conducted until the end of September 2021. Through this verification test, it is expected to accelerate the introduction of HTS cables in private factories to reduce power loss in manufacturing facilities and to promote the use of renewable energy.

Analysis: There have been successful demonstrations of AC cables at distribution voltages at or below several kilometers in length. There is also a commercial project. These projects have provided extensive data on lifetime and performance. Therefore, today's TRL level is ranked at "high".

Barriers to advance TRL level: The "high" TRL level accorded this application may be further strengthened by continued operations in the above-described projects, as well as by new projects. It is important to realize that the highest possible technical readiness may require a period of (calendar) time of operation in order to demonstrate operation over the full range of expected mission conditions. This means not only extended times at a given utility site, but multiple deployments in different environments and for different customers.

3.3.2. Retrofitting existing ducted cables

In North America and some other locations in the world, high voltage transmission cables are installed in pipes or ducts. Some pipe ducts use oil or gaseous nitrogen for cable electrical insulation. Sometimes the cables are installed in banks of several ducts, with spare, unused ducts available for either circuit uprating, or replacement of a failed segment. When these pipe and duct bank routes feed urban distribution networks from regional high voltage transmission systems, there is an opportunity for replacement of the high voltage cables with medium voltage HTS cables, similar to the application described above. The difference however, not insignificant, is that the HTS cable is pulled through the existing pipe or duct, so that little new construction is required. No ground need be broken to lay new cable. Termination stations would require minimal alteration. For the reasons cited above, this is also an ideal application for HTS cables.

Although a similar retrofit project for a high voltage AC cable has been proposed (see discussion above regarding Netherlands TenenT) there have been no demonstrations to date.

Analysis: Although there have been successful demonstrations of AC cables at distribution voltages serving urban centers, none have involved utilization of existing pipe or duct bank infrastructure. Although the HTS cable in this application may be the same, there would also be additional considerations requiring additional design and/or construction. Examples would be the possible need for revised or alternate methods for cooling the cable (particularly if longer than 1 km); too great spacing between splicing vaults; insufficient space in the vault for the (longer) HTS cable splice; or some combination of these. Given the unknowns at present for this application, today's TRL level is ranked at "low". Moreover, the opportunities for this application are not thought to be nearly as numerous as for other, previously described applications. Therefore, the progress to higher TRL levels is expected to be slower.

Barriers to advance TRL level: Because this application would utilize the same medium voltage HTS AC cable as used in other applications described above the barriers to advance the TRL level are the same as those. Factory testing of cable reels, optimized cryogenic and vacuum systems, and splicing are included. In particular, the fact that the ducts and the splicing vaults already exist, though a potential construction cost saver, can also present challenges. The challenges are quite site-specific and must await actual demonstrations to prove the viability of this application.

4. Summary

HTS technology has sufficiently matured for use in many areas, including electricity grids, industry, and transportation. However, impediments to the technology's deployment include the high cost of HTS conductors and the need for suitable, low-cost and reliable cooling systems. In addition, fully assembled systems must demonstrate reliable operation in post-laboratory development applications over long periods. To achieve the highest TRLs and, therefore, gain acceptance in the marketplace it is essential to build and operate prototypes in environments like those of the final applications. Moreover, prototype systems must undergo much longer demonstrations than those to date. One study in the 1990s (unpublished) by the U.S. Department of Energy and the Electric Power Research Institute showed that electric utility planners and engineers wanted to see HTS cable system technology demonstrations lasting 10 years before they would consider the technology as a replacement for conventional cables. More recent trends and drivers in the industry could help increase market pull for superconductivity. Resilient electric grids and energy efficiency are areas in which superconductivity can play a role and add value over conventional solutions.

5. Acronyms

BSCCO	Bismuth - Strontium - Calcium - Copper – Oxide
FCL	Fault Current Limiter
HV	High Voltage
HTS	High Temperature Superconductivity
IEA	International Energy Agency
LTS	Low Temperature Superconductivity
MgB2	Magnesium Diboride
MV	Medium Voltage
Nb3Sn	Niobium-Tin
Nb-Ti	Niobium-Titanium
REBCO	Rare earth - Barium - Copper Oxide
SFCL	Superconducting Fault Current Limiter
Tc	Critical Temperature
TCP	Technology Collaborative Program
TRL	Technology Readiness Level
YBCO	Yttrium Barium - Copper Oxide

6. Acknowledgements

This document was developed by the International Energy Agency's High Temperature Superconductivity Technology Collaborative Program (IEA HTS TCP). The IEA HTS TCP works to identify and assess the potential applications and benefits of superconductivity, as well as what technical, economic and regulatory barriers must be overcome to achieve them. Through its contracting parties, the HTS TCP develops technical communications documents that provide information for a range of stakeholders. More information available at www.ieahts.org.

This document was produced using the expertise of IEA HTS TCP Executive Committee members and relevant international experts. Further updates will be made, including a synthesis of the possible technical achievements that could take place in the near future.

The table below shows the members of the TCP.

Country	Name	Organization
Canada	Dr. Julian Cave Dr. Frédéric Sirois	*Hydro Quebec* *Polytechnique Montréal*
Finland	Dr. Risto Mikkonen Dr. Antti Stenvall	*Tampere University of Technology* *Tampere University of Technology*
Germany	Dr. Tabea Arndt Prof. Mathias Noe Prof. Bernhard Holzapfel	*Karlsruhe Institute of Technology* *Karlsruhe Institute of Technology* *Karlsruhe Institute of Technology*

Italy	Dr. Luciano Martini (Chair) Dr. Michele de Nigris	*Ricerca sul Sistema Energetico – RSE S.p.A.* *Ricerca sul Sistema Energetico – RSE S.p.A.*
Japan	Mr. Yasunori Yajima Dr. Hiroyuki Ohsaki (Vice-Chair) Mr. Susumu Kinoshita	*NEDO* *The University of Tokyo* *NEDO*
Republic of Korea	Dr. Hyung Suk Yang Dr. Jeyull Lee	*KEPCO* *KEPCO*
Switzerland	Dr. Bertrand Dutoit Dr. Carmine Senatore Mr. Roland Brüniger	*Ecole Polytechnique Fédérale de Lausanne* *University of Geneve* *Swiss Federal Office of Energy*
United States	Merrill Smith Joe Hagerman	*Department of Energy* *Oak Ridge National Laboratory*

All IEA HTS TCP members contributed to formulating the research, developing the survey, and discussing, reviewing and revising the document. In particular, Brian Marchionini, Steven Eckroad and Don Mosteller effectively drafted the roadmap document. Giuliano Angeli, Laura Serri and Luciano Martini led the effort of revising and commenting on the document to reach the final version ready for publication.

7. References

[1] Horizon 2020, The EU Framework Programme for Research and Innovation.

[2] Public Service Commission of Wisconsin, "Underground Electric Transmission Lines", May 2011.

[3] *Guidelines for the Lift Extension of Substations: 2002 Update*. EPRI, Palo Alto, CA: 2002. 1001779.

[4] https://www.theva.com/wp-content/uploads/sites/3/2019/06/190603_PI_HTS_Muenchen_SWM_EN.pdf.

[5] https://www.nkt.com/news-press-releases/nkt-is-developing-the-prototype-for-the-worlds-longest-superconducting-power-cable.

[6] Geon Seok Lee, Condtion Monitoring of 154 kV HTS Cable Systems via Temporal Sliding LSTM Networks, IEEE*Access*, August 18, 2020. *Digital Object Identifier 10.1109/ACCESS.2020.3014227.*

[7] Hunju Lee, *Recently started and planned projects in Korea*, presentation at International Superconductivity Industry Summit (ISIS) meeting, 10 June 2021.

[8] J. McCall, et al, *DC Supergrid Implementation Using Compact Very High Capacity Superconductors for Bulk Power Transport*, CIGRE 2011 Bologna Symposium - The Electric Power System of the Future: Integrating Supergrids and Microgrids**.**

[9] J. McCall, B. Gamble and S. Eckroad, *Combining Superconductor Cables and VSC HVDC Terminals for Long Distance Transmission***,** IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply, 2010.

[10] J. McCall, et al, *loc cit.*

[11]https://www.researchgate.net/publication/336562012_Low_voltage_and_large_current_DC_superconducting_power_cable_designs_for_10_km_to_100km_transmission_line_using_experimental_data_of_Ishikari_project.

[12] See, for example, the approach to vacuum and cryogenic system design in W. Hassenzahl, et al, *A High-Power Superconducting DC Cable*, IEEE Transactions on Applied Superconductivity, Vol. 19, No. 3, June 2009.

[13] *Program on Technology Innovation: A Superconducting DC Cable.* EPRI, Palo Alto, CA: 2009. Report No. 1020458 [available to the public at www.epri.com], p. 8-23.
[14] *Ibid*.
[15] https://www.nexans.com/newsroom/news/details/2019/06/Nexans-completes-successful-qualification-testing-of-%E2%80%98Best-Paths%E2%80%99-superconductor-cable-for-HVDC-power-links.html.
[16] https://ir.amsc.com/static-files/f9c77314-406f-4b61-a14f-7f5b9632689d.
[17] Chulhyu Lee, *Recent Progress and Research Activities on HTS Power Cable Application in KEPCO*, Invited oral presentation 3LOr2A-01 given at ASC 2018, October 28-November 5, 2018, Seattle (USA).
[18] Noriku Chikumoto, et al, Second Cooling Test of 1000-m Superconducting DC Cable System in Ishikari, IEEE Transactions on Applied Superconductivity, Vol. 26, No. 3, April 2016.
[19] https://www.nexans.com/newsroom/news/details/2019/06/Nexans-completes-successful-qualification-testing-of-%E2%80%98Best-Paths%E2%80%99-superconductor-cable-for-HVDC-power-links.html.
[20] Institute for Advanced Sustainability Studies (IASS): Brainstorming Workshop "Transporting Tens of Gigawatts of Green Power to the Market," May 12-13, 2011, Potsdam, Germany (unpublished presentations).
[21]https://www.researchgate.net/publication/272361337_Status_of_HTS_cable_link_project_for_St_Petersburg_Grid
[21] Private correspondence, V. Sytnikov – S. Eckroad, February 6, 2020.
[23] Ok-Bae Hyun, Progress in Superconductivity and Cryogenics Vol.19, No.4, (2017), pp.1-11, Brief review of the field test and application of a superconducting fault current limiter.
[24] https://www.appliedmaterials.com/company/news/press-releases/2015/04/applied-materials-receives-order-for-two-transmission-class-superconducting-fault-current-limiters.
[25] Heesun Kim, et al., "Development and Test of a Cooling System for a 154 kV Superconducting Fault Current Limiter," KEPCO Journal on Electric Power and Energy, vol. 1, no. 1, pp. 141 - 144, 2015.
[26] Luciano Martini, et al., The First Italian SFCL: From Design to Live-Grid Testing Activity and Effective Current Limitation of a Severe Three-Phase Short-Circuit: Innovation for the Electric Grids, World Scientific Series in Applications of Superconductivity and Related Phenomena, In book: Superconducting Fault Current Limiter (pp.273-298).
[27] Ok-Bae Hyun, *loc cit.*
[28] D. Lindsay and S. Eckroad, U.S. Patent 8,391,938 B2, March 5, 2013.
[29] Glasson et al, IEEE TASC Vol 23, No. 3, June 2013, Doi 10.1109/TASC.2012.2234919.
[30] FCL Transformer Program DE-OE0000244.
[31] Iwakuma, M et al. (2015) Development of a 3f-66/6.9 kV 2MVA REBCO Superconducting Transformer, IEEE Transactions on Applied Supercond. 25 (3) 5500206
[32] Yamamoto, T., Yasukawa, Y., et al. (2005). Development of 66 kV/6.9 kV 2 MVA prototype HTS power transformer. *Physica C Superconductivity*, 426-431, 1402-1407.
[33] Funaki, K., Iwakuma, M., Kajikawa, K., Takeo, M., Suehiro, J., Hara, M., et al. (1998). Development of a 500 kVA-class oxide-superconducting power transformer operated at liquid-nitrogen temperature. Cryogenics, 38, 211-220. Iwakuma, M., et al. (2011). Development of a REBCO superconducting transformer with current limiting function. IEEE Transactions on Applied Superconductivity, 21(3), 1405-1408.
[34] https://indico.cern.ch/event/626654/attachments/1523851/2381804/Superconducting_Transformers_-_Dr._Mathias_Noe.pdf.
[35] Chulhyu Lee et. al, Progress of the first commercial project of high-temperature superconducting cables by KEPCO in Korea, Published 17 February 2020, IOP Publishing Ltd, Superconductor Science and Technology, Volume 33, Number 4.
[36] https://www.isupercon.jp/iss2020/program-site/abstract/ap/AP8-2-INV.html.