Technology Collaboration Programme
by iea

High–Temperature Superconductivity for Resilient Electric Grids

Developed by the International Energy Agency's
High–Temperature Superconductivity Technology Collaborative Program

October 2024

Superconductivity
INTERNATIONAL ENERGY AGENCY

Abstract

Recent natural events and increasing demands on electric power grids have heightened utility concerns about resiliency, but superconducting technology has the potential to improve the resiliency of power grids. While utility adoption of superconducting technology began decades ago, its use worldwide remains limited. Further utility adoption requires a clear understanding of the technology and its performance, potential, and costs – particularly compared to more conventional technologies offering similar capabilities.

The purpose of this document is to show how electric grid applications using high-temperature superconductivity have played a role, or are planned to play a role, in improving grid resilience. One definition of grid resilience is "*the ability to limit the* ***extent, severity****, and* ***duration*** *of* ***system degradation*** *following an* ***extreme event***."

Transmission and distribution systems worldwide are facing varying challenges based on location and circumstances. Some of these challenges include:

- Providing N-1 redundancy
- Increased power density without the need for new high-voltage lines
- Increasing renewable integration and grid flexibility
- Increasing fault currents

This document shows how HTS applications can and have been used to solve real-world grid problems for each of these challenges.

Acknowledgements

This document was developed by the International Energy Agency’s (IEA’s) High-Temperature Superconductivity Technology Collaborative Program (HTS TCP). The IEA HTS TCP works to identify and assess the potential applications and benefits of superconductivity and to determine what technical, economic, and regulatory barriers must be overcome to achieve those benefits. The IEA HTS TCP develops technical communication documents through its contracting parties that provide information for various stakeholders. More information is available at www.ieahts.org.

This document was produced using the guidance of IEA HTS TCP Executive Committee members and relevant international experts.

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Chapter 1: Introduction

Superconducting technology holds promise for enhancing resilience, an increasingly pressing consideration for utilities given the rise of weather-related incidents and escalating demands on the power grid. Utility adoption hinges on a comprehensive grasp of the technology, including its performance capabilities and associated costs, especially when compared to alternative solutions offering comparable functionalities.

This document shows how electric grid applications using high-temperature superconductivity (HTS) can play a role in improving grid resilience. Chapter 1 provides a working definition of resilience and the technology readiness of several superconducting applications for energy delivery systems. Chapter 2 offers four examples of electric grid challenges. Chapter 3 highlights examples of how utilities have overcome each challenge by using HTS applications, which played a role in improving resilience.

A comprehensive assessment, including technology challenges; manufacturing readiness, costs, and commercialization potential; and comparisons with technologies offering similar capabilities, is beyond the scope of this document and detailed in other published works.[1]

1.1 Definition of Resilience

The definition of resilience has been challenging for utilities and standard authorities. Despite attempts by organizations worldwide in the power and energy engineering communities to define resilience, there is no universally accepted definition. Resilience is a multi-dimensional and dynamic concept. However, the International Council on Large Electric Systems (CIGRE) Working Group SC C4.47 has researched and formulated a definition and key actionable measures as an integral part of the definition. CIGRE defines electric grid resilience as "*the ability to limit the* ***extent, severity****,* *and* ***duration*** *of* ***system degradation*** *following an* ***extreme event***."[2]

This definition emphasizes the importance of ensuring that the electric grid can continue providing power to essential services and critical infrastructure, even in the face of disruptions such as natural disasters, cyberattacks, or physical attacks.

In addition to the ability to withstand and recover from these events, grid resilience also encompasses the ability to maintain asset integrity, meaning that the grid's physical components and infrastructure remain functional and reliable throughout and after the event.

Overall, CIGRE's definition of electric grid resilience highlights the need to ensure the continued provision of essential services and the preservation of infrastructure assets during extreme events. More information about grid resilience was developed by IEEE.[3]

1.2 Technology Readiness of High-Temperature Superconductor (HTS) for Energy Delivery Systems

The International Energy Agency's High-Temperature Superconductivity Technology Collaboration Program (IEA HTS TCP) analyzed energy delivery applications for HTS. This effort resulted in a Readiness Map illustrating the Technology Readiness Levels (TRL) over time in HTS applications.

The international experts assessed the present degree of technical development of transmission, substation, and distribution HTS applications in the energy delivery sector and estimated the pathway to the commercialization phase. Figure 1 shows a summary of this analysis. Instead of using a specific TRL number 1-9 for each application, they are categorized into low, medium, and high TRL levels. Superconducting fault current limiters and medium-voltage AC cables to interconnect substations at the low side of the transformer are currently at a high TRL, as they can be purchased in the market. High-voltage AC and DC cables are at a medium TRL and could reach a high level TRL level in 2030-2035. Superconducting transformers are at a low TRL, and they could reach a high TRL level by 2030-2035.

This document will focus on superconducting cable and fault current limiter projects that have been used to overcome electric grid challenges.

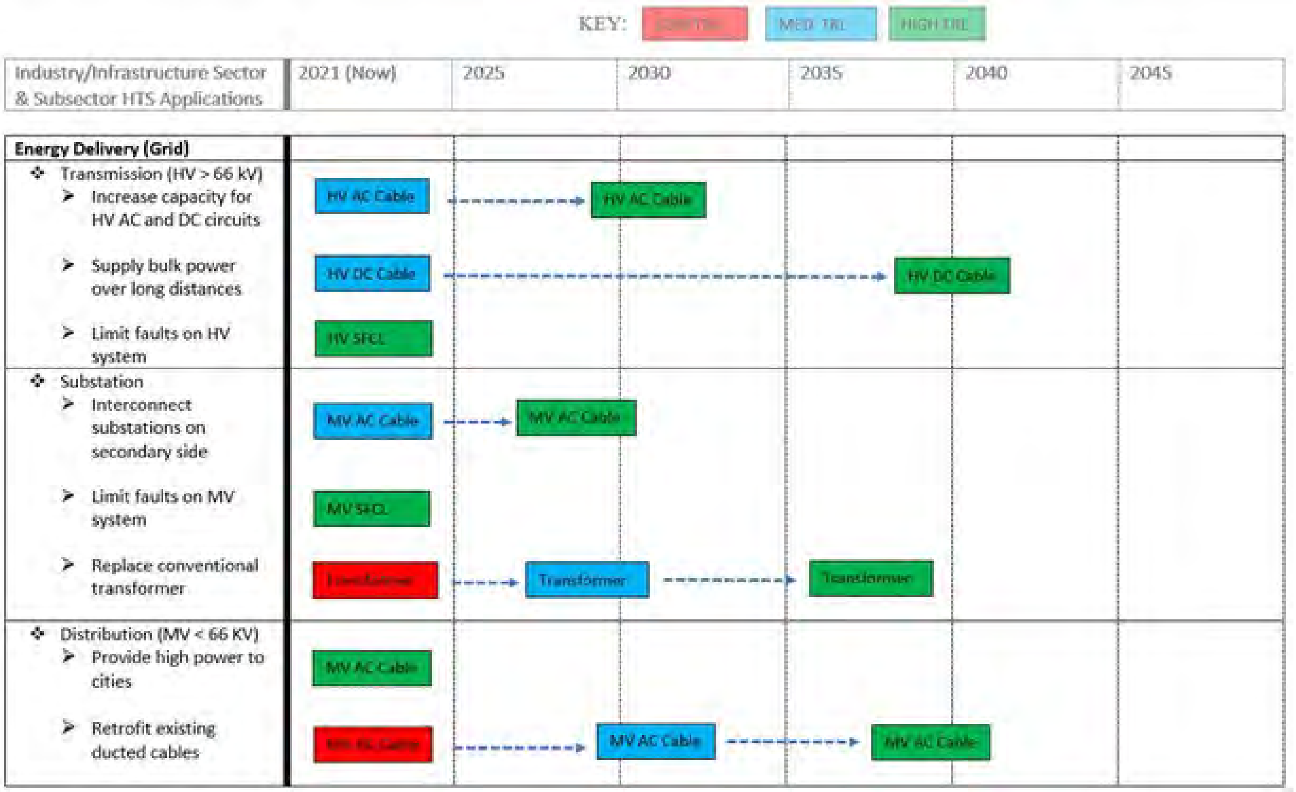


Figure 1. Technology Readiness Levels are indicated from 1-9. For the purposes of this document, TRL levels 1-3 are specified as “low”; TRL levels 4-6 are specified as “medium”; TRL levels of 7-9 are specified as “high”.

1.3 Cryogenic Systems

Superconductors exhibit zero electrical resistance and expel magnetic fields when cooled below a critical temperature. For most high-temperature superconductors (HTS), this critical temperature is above the boiling point of liquid nitrogen (~77 Kelvin or -196°C) but still requires cryogenic temperatures to maintain the superconducting state. Some low-temperature superconductors require even colder temperatures, often using liquid helium (~4 Kelvin or -269°C).

Two main cooling methods, open and closed systems, are used for superconducting applications. In an open system, liquid nitrogen is continuously supplied from a storage tank and must be regularly refilled. While this method has lower initial costs and high reliability, it requires frequent maintenance. In contrast, closed systems use cryocoolers to recirculate and re-cool the nitrogen, eliminating the need for regular refills. The choice between open and closed systems depends on factors such as cost, reliability, and maintenance requirements.

Various cooling methods, both open and closed, are available for use in superconducting applications and have been successfully implemented. For example, a superconducting fault current limiter open system operating at one bar pressure has the longest operating experience, while a recently commissioned 220 kV current limiter utilizes a closed system with an operating pressure of five bar.[4]

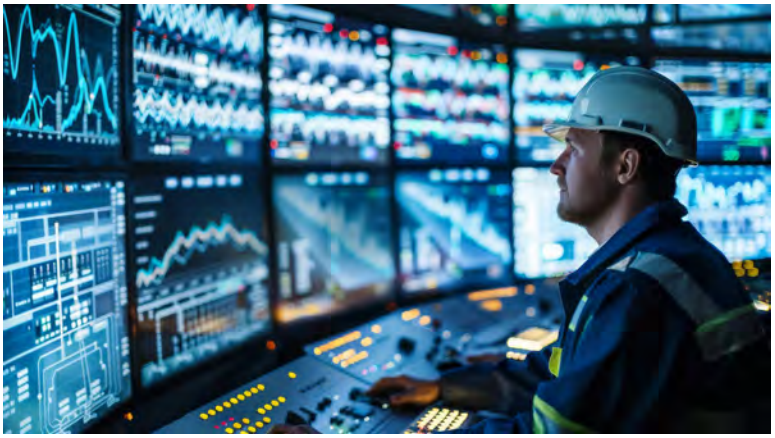
Chapter 2: Electric Grid Challenges

The transmission and distribution systems around the world are facing varying challenges based on location and circumstances.[5] Some of these challenges include:

- Providing N-1 redundancy
- Increased power density without the need for high-voltage lines
- Increasing renewable integration and grid flexibility
- Increasing fault currents

2.1 Providing N-1 Redundancy

Electric utilities implement N-1 redundancy to ensure reliable and uninterrupted power supply to consumers. N-1 redundancy refers to the capability of the system to continue functioning even if one of its primary components or transmission lines fails. In some critical electric supply areas, the utility may aim for N-2 or even N-3 redundancy.



Multiple Generation Sources

Utilities often have multiple power generation sources to provide redundancy. If one source fails, the others can continue supplying electricity to the grid. To be effective, this may require independent transmission lines to the same area of the grid (see below).

Transmission Lines

Electric utilities maintain a network of transmission lines that carry power from the generation sources to the distribution systems. These transmission lines are designed with redundancy in mind. If one transmission line fails, power can be rerouted through alternate lines to avoid disruption.

Substations

Utilities have strategically placed substations throughout their network. Substations receive high-voltage power from the transmission lines and step it down to a lower voltage suitable for distribution. Substations typically have redundant equipment, including transformers and switchgear, to ensure uninterrupted service in case of a failure.

Distribution Networks

Electric utilities operate extensive distribution networks to deliver electricity to homes, businesses, and other end-users. These networks are designed with multiple paths and feeders to distribute power. If a single feeder or circuit fails, power can be rerouted through alternative paths to maintain supply.

Monitoring and Control Systems

Utilities employ sophisticated monitoring and control systems to continuously monitor the grid's performance. These systems detect faults, failures, or abnormalities in real-time and automatically activate redundant components or alternate routes to restore power supply or minimize disruption.

Maintenance and Inspection

Regular maintenance and inspections are conducted on critical components, such as transmission lines, substations, transformers, and switchgear, to identify potential challenges before they cause failures. Proactive maintenance helps prevent N-1 events by addressing weaknesses or replacing aging equipment.

Planning and Load Management

Utilities perform load forecasting and planning to manage power demand effectively. By understanding the expected load on the system, utilities can ensure that generation and transmission capacity are available to meet demand, even if some components are offline for maintenance or due to unexpected failures. Planning is performed using future load forecasts and new infrastructure anticipates greater capacity than needed at the time of installation.

Overall, electric utilities implement a combination of redundant components, alternate paths, advanced monitoring systems, and proactive maintenance to achieve N-1 redundancy. This approach helps ensure a reliable and robust power supply to customers, even in the face of equipment failures or unforeseen events.

HTS Applications Provide N-1 Contingency

Ideally, substation assets like transformers and switchgear must be fully utilized as much as possible–typically at or above 100% capacity during brief peak load periods–and continue to serve the load in the event of a partial outage, such as the loss of one of several transformer banks or a transmission voltage feeder.[6] These two needs sometimes can be at odds, 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 land cost, environmental concerns, public opposition, and permitting complexities and delays.

An alternative solution, which addresses both challenges, is to connect two or more geographically or electrically neighboring substations at their secondary, low-voltage buses. Particularly if different transmission lines feed individual substations on the high voltage side, reliability will be improved. Conventional copper or aluminum buses and cables are either impractical or impossible to connect these substations because of very high currents at the secondary voltages and the associated ohmic losses with this approach. On the other hand, this connection arrangement 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 assumes that there is spare capacity at one of the substations and a low probability of experiencing an outage in both substations simultaneously. This scenario becomes even more attractive when more than two substations are linked.

An example of an HTS project for redundancy is the Resilient Electric Grid project in Chicago, Illinois, United States. This HTS installation permanently increases the design of a substation to N-2 reliability from the current N-1. This is achieved by interconnecting two 12 kV distribution terminals within the substation. Prior this installation, the two 12 kV terminals were separately served by multiple 138kV/12kV transformers, which were and are connected at the transmission side, but had no connections at the 12 kV level.[7] More information about this project is found in Section 3.1.

2.2 Increase power density without the need for new high-voltage lines

Permitting low-voltage and high-voltage lines in the electric grid involves different considerations due to their varying characteristics and potential impacts. HTS cables offer many advantages over conventional technologies, including some unique sustainability characteristics and others with respect to public and social acceptance. These advantages have been thoroughly documented in other documents.[8] Here are some key differences in the permitting process for low-voltage and high-voltage lines and overhead and underground lines:

Regulatory Authority

The regulatory authority responsible for permitting low-voltage lines is typically at the local level, such as municipal or county authorities in the United States. In Switzerland, for instance, low-voltage lines are under federal law. They often have jurisdiction over the installation and maintenance of low-voltage distribution lines, which carry power to residential and commercial areas. In contrast, high-voltage transmission lines, which transport bulk power over long distances, fall under the purview of state or federal regulatory agencies. Switzerland’s federal law, for instance, covers high and low voltage.

Environmental Impact Assessment

The level of environmental impact assessment required for low-voltage lines is usually less extensive compared to high-voltage lines. Low-voltage lines primarily operate within established rights-of-way and built-up areas, where potential environmental impacts are relatively limited. High-voltage transmission lines, on the other hand, may traverse longer distances, potentially impacting sensitive ecosystems, habitats, and scenic areas. As a result, more detailed environmental impact studies and mitigation plans are typically required for high-voltage line permitting.

Public Engagement

Public engagement and community outreach processes may differ for low-voltage and high-voltage lines. Low-voltage lines often involve interactions with local communities, residents, and businesses near the distribution infrastructure. Community engagement efforts can focus on addressing specific concerns related to construction, aesthetics, and potential disruptions during installation. High-voltage line projects, especially those involving new corridors or significant upgrades, generally require broader public engagement due to potential impacts on multiple jurisdictions, landowners, and stakeholders along the transmission route.

Permitting Process and Timelines

Permitting processes for low-voltage lines are typically more streamlined and less time-consuming than high-voltage lines. Local permitting authorities for low-voltage lines may have established procedures and quicker turnaround times, often dealing with simpler applications. In contrast, high-voltage line permitting involves multiple layers of review, including environmental impact assessments, public hearings, and the potential involvement of state or federal regulatory bodies. These processes can be more complex, involve more extensive documentation, and may have longer timelines. This limits how quickly utilities can right-size their grid infrastructure in response to trends like the increasing demand for electricity (which is increasingly concentrated into constrained spaces) and the pace of climate change. These two nearly ubiquitous forces are presenting challenges for utilities.

Engineering and Design Requirements

Engineering and design requirements for high-voltage lines are more stringent due to the higher voltages involved. High-voltage lines require specialized engineering studies to ensure proper insulation, clearances, and safety considerations. While still subject to design standards, low-voltage lines, often have more straightforward engineering requirements and follow established industry guidelines for distribution system design.

HTS Alleviates T&D Line Permitting Challenges

HTS cables have a smaller footprint, so superconductor corridors are up to ten times narrower than those for conventional cables and lines.[9] This saves money, minimizes disruption, and dramatically accelerates the deployment of new infrastructure.

HTS cables use trenches, so utilities can install them in many locations without the need for digging dedicated tunnels, and they are viable options for short-distance (i.e., < 1 kilometer) underwater applications. AMSC and one of the largest electric utilities in the U.S., ComEd, have partnered to install a medium voltage HTS AC cable system that loops together three downtown Chicago sub-transmission voltage substations into a network, increasing reliability and resiliency. The Chinese Academy of Sciences installed a 1.3 kV and 10 kA DC cable in 2012.[10] Another DC HTS cable was installed in South Korea that was 80 kV and 3.13 kA in 2015.[11]

Superconducting cables carry a higher power load by increasing amperage versus voltage. Therefore, new cables could be low or medium voltage for permitting instead of high voltage. Instead of supplying electricity at 400 kV through a copper cable, a 132 kV superconducting cable can be used. Similarly, conventional 132 kV cabling can be replaced by a 33 kV superconducting cable.[12] Bringing power into cities at a lower voltage not only reduces permitting and other regulatory burdens, but it also reduces the need for step-down transformers, which allows for savings in land acquisition and civil works costs. In many urban utility territories, conventional underground transmission cables are reaching the end of their useful life, which HTS cables are well-suited to replace – especially considering that many of them are oil-filled, which is potentially hazardous as the cooling and voltage management medium.

In a similar application, a utility may defer the acquisition of land and permit(s) for a new substation to serve predicted load growth beyond the capability of local grid assets. A low-voltage HTS cable would permit extending the low-voltage bus of an existing nearby substation into the neighborhood experiencing load growth. At lower voltage, the switchgear at the distant termination of the HTS cable will be much smaller than a new substation and potentially easier to site. An added advantage of this accrues from the essential indeterminacy of load forecasting. The utility will have deferred substantial capital investments even if the new load is slower to develop or does not materialize at all.

Taken together, these advantages and efficiencies allow superconducting cables to concentrate power into space- and permit-constrained areas more effectively, increasing power densities without the need for traditional high-voltage lines and associated grid components. Additionally, HTS cables can be permitted more quickly since they can use existing rights of ways, improving the ability of utilities to meet growing demand for electricity in time.

2.3 Increasing Renewable Integration and Grid Flexibility

As previously discussed, multiple sources of power generation with strategically placed transmission and distribution substation assets can enhance the redundancy–and therefore resiliency–of electric grids. While the integration of renewables into electric grids does present several challenges that must be addressed, the diversity and complementary intermittency of renewable energy resources like solar, wind, geothermal, and bioenergy gives utilities many more options to recover from grid disturbances and outages. [13] Additionally, renewable sources are typically far more geographically dispersed, or distributed, than many conventional sources of power, which can help utilities establish clusters of power generation, connected by microgrids, that can disconnect from the grid and operate independently during extreme grid events.[14] From this perspective, renewable energy can enhance the resiliency of electric grids.

However, there are several challenges associated with the growing integration of renewable energy.

Intermittency and Variability

Renewable energy sources such as solar and wind are inherently intermittent and variable in their generation. The availability of sunlight and wind can fluctuate, leading to fluctuations in power output. This intermittency can pose challenges for grid operators in maintaining a balance between electricity supply and demand, as the grid needs to ensure reliable and stable power supply even during periods of low renewable energy generation.

Grid Stability and Frequency Control

The integration of large amounts of intermittent renewable energy can impact grid stability and frequency control. Sudden changes in power output from renewable sources can affect the grid's frequency, which needs to be maintained within a narrow range. Grid operators must employ various measures, such as advanced control systems, energy storage, and flexible generation resources, to mitigate the impact of renewable energy intermittency on nominal voltage and frequency control.

Grid Reinforcement and Upgrades

Integrating higher levels of renewable energy often requires grid reinforcement and upgrades. Transmission and distribution infrastructure may need to be expanded or enhanced to accommodate the increased power flow from remote renewable energy generation sites to population centers. This includes building new transmission lines, upgrading substations, and improving interconnection capabilities to ensure efficient and reliable power delivery.

Reduction in System Inertia

The increasing integration of renewable energy sources, such as solar and wind, can lead to a reduction in system inertia on the power grid. System inertia refers to the ability of a power system to maintain stability and respond to sudden, short-duration changes in supply and demand. Unlike conventional power plants with large rotating masses, renewable energy sources have minimal or no rotating masses.[15] Solar panels directly convert energy without relying on rotating mechanical parts. This lack of rotating masses reduces the inherent inertia provided by conventional generators, making the grid more sensitive to sudden changes in power supply or demand. Sudden changes in generation or load can lead to frequency deviations, which must be quickly corrected to prevent disruptions. Grid operators must employ advanced control systems, energy storage, and flexible resources to provide rapid response and maintain grid stability in the absence of significant system inertia.

New grid assets, like grid-forming inverters, distributed energy storage, cross-sector interoperability, distributed optimization and climate–energy integrated models, could ameliorate some of these challenges. However, the penetration of these technologies into electric grids today is far more limited than would otherwise be necessary to significantly curtail or eliminate these concerns, along with the widespread use of integrated climate, weather, and energy system models in utility infrastructure planning and real-time operations.[16]

HTS Applications Facilitate the Energy Transition to Renewable Energy

HTS cables have the potential to facilitate the development of renewable energy by minimizing environmental impacts and enabling an overall more sustainable transmission of electric energy. One of the benefits may be an increased public acceptance due to the low visual impact with a subsequent reduction of approval time.[17]

Often, solar or wind-farm installations are a long distance from load centers, requiring significant new high-voltage transmission resources. In addition to the previously discussed permitting and installation difficulties that transmission lines face, alternating current (AC) transmission lines over distances greater than, say, 160 kilometers (100 miles) must be overhead lines, which often face public opposition and require periodic substations to provide for reactive losses on the lines. HTS lines, however, have smaller footprints that can be built underground, which minimizes visual impacts. While superconducting applications do require cryogenic tanks, HTS cables eliminate the need for periodic substations along the route by transmitting power without losses at lower voltages, requiring only substations at their termination in load centers, which themselves have smaller footprints.

HTS cables could also transport multiple energy sources at once. One such vision is the co-delivery of electricity and hydrogen fuel. HTS DC cables can be designed to carry both electricity and hydrogen fuel simultaneously when hydrogen is used in cryogenic systems. The high-current capacity of superconducting cables allows for efficient electricity transmission, while the same infrastructure can transport hydrogen as a secondary component. This integrated approach provides a cost-effective and space-saving solution for transporting both forms of energy. Moreover, the hydrogen coolant in the long lines may be compressed when delivery needs are low, resulting in a form of energy storage.[18]

SCARLET, an ongoing European Project, is developing superconducting cables for multiple purposes. One is to link remote renewable energy sites to the grid, including offshore installations. This initiative prioritizes compact solutions with minimal visual impact. Another cable will function as an export cable, transmitting energy from offshore wind farms to the mainland. Another cable, paired with liquid hydrogen transport, will connect renewable energy sources—whether onshore or offshore—to ports, ground transport, and industries requiring both electricity and hydrogen. This application aligns with the development of hydrogen as an energy carrier and storage medium.[19]

2.4 Fault Currents

Electric utilities are experiencing increased fault currents on their systems due to several factors, such as increased power demand and use of distributed generation, grid interconnection and integration, and electric vehicle charging.[20] A fault is an unintentional short circuit, or partial short-circuit, in an electric system. Various phenomenon, 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.

Increased Power Demand

As power demand grows, utilities are expanding their generation and distribution infrastructure to meet the increased load. With more power flowing through the system, fault currents can also increase. This is particularly true in areas with high population density or rapid industrial development.

Distributed Generation

The rise of distributed generation, such as rooftop solar panels and small wind turbines, adds additional power sources to the grid. While distributed generation offers environmental benefits, it can also contribute to increased fault currents. In some cases, the fault currents from distributed generation sources may exceed the levels traditionally encountered in the grid, requiring utilities to adjust their protection systems accordingly.

Grid Interconnection and Integration

The integration of renewable energy sources, such as solar and wind farms, into the grid has increased interconnections and interdependencies. These interconnections can result in higher fault currents, especially during grid disturbances or faults in one part of the system that propagate through interconnected lines. In Germany, for instance, short-circuit currents are rising due to grid extensions; by 2045, more than 10,000 km of new transmission grid onshore is needed.

Electric Vehicle Charging

The growing adoption of electric vehicles (EVs) places an additional load on the electrical grid. EV charging stations can draw significant power, and in the event of a fault, they can contribute to higher fault currents. Utilities must consider the impact of EV charging infrastructure on fault current levels when designing and upgrading their systems.

HTS FCL Devices offer improved grid protection from Fault Currents

HTS cables can be designed with inherently fault current limiting capabilities. Another application that can effectively reduce fault currents in utility grids is a fault current limiter (FCL). Currently, two broad categories of FCL technologies exist – high-temperature superconducting (SFCL) and solid-state (SSFCL). SFCLs can handle much higher fault currents compared to solid-state devices. Superconductors have inherently high current-carrying capacities, allowing SFCLs to effectively limit fault currents without the need for bulky and expensive semiconductor devices. Conventional circuit breakers or fuses can protect the system from damage but often isolate one or more sections of the system, resulting in loss of service to some customers or loss of capacity to serve load. A SFCL also allows in association with a series inductance for the nearly continual, very shortly interrupted operation of the electrical system with reduced voltage instabilities.

During a fault condition, such as a short circuit or electrical overload, the fault current in the grid can increase to high levels. SFCLs are designed to respond intrinsically to these fault currents rapidly. When a fault occurs, it introduces impedance into the circuit. This impedance limits the fault current magnitude, reducing the stress on the grid components. SFCLs could help to prevent utilities from taking steps like splitting their system, which could affect reliability and resiliency.

SFCLs have fast response times, allowing them to act immediately when a fault is detected. They can reach their resistive or high impedance state within microseconds, limiting the fault current to a predetermined level. By suppressing the fault current quickly, SFCLs help protect grid equipment, such as transformers and circuit breakers, from damage and mitigate potential disruptions in the power system. Once the fault condition is cleared, SFCLs automatically return to their regular operating, low impedance state and enable the normal flow of current through the grid. This automatic self-recovery feature ensures that the SFCLs do not introduce unnecessary impedance during regular system operation. Examples of SFCL projects can be found in Section 3.8.

The main benefit to utilities for superconducting FCLs is their value related to circuit breakers and high-impedance transformers. Another benefit has to do with losses in comparison to the use of reactors for high-voltage transmission system applications. For managing increasing fault currents on high-voltage transmission systems, an SFCL may have as much as one-tenth the losses of conventional equipment and/or strategies.

Chapter 3: Project Examples

There are several examples of existing and planned HTS applications designed to improve resilience for utility grids. Table 1 summarizes utility challenges and how various grid projects were developed to overcome them.

Table 1. Examples of existing and planned HTS projects that are designed to provide grid resilience.

Projects (and status)	Providing N-1 Redundancy	Increased Power Density	Increasing Renewable Integration	Fault Currents
ComEd Cable (energized)	👍	👍		
Ampacity (deenergized)	👍	👍		👍
KEPCO Munsan Cable (planned)	👍	👍		
NEDO Cable (energized)		👍		
Shanghai Cable (energized)	👍	👍		
SuperLink Cable (planned)	👍	👍	👍	
Super Rail Cable (planned)		👍		
SCARLET Cable (planned)		👍	👍	👍
Superconducting FCLs			👍	👍

3.1 ComEd Cable

Figure 2. Termination of the Resilient Electric Grid cable in Chicago, Illinois. *Photo courtesy of AMSC*

The Commonwealth Edison (ComEd) Resilient Electric grid project, energized in the city of Chicago, is designed to demonstrate the benefits of HTS cables. AMSC and ComEd, one of the largest electric utilities in the U.S., have partnered to install a medium-voltage HTS AC cable system that loops 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 was energized in August 2021 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 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.[21]

The cable system protects 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 project also has a low environmental impact as there are near zero thermal and electromagnetic fields.

On May 28, 2019, the Federal Energy Regulatory Commission (FERC) of the United States approved a first-of-its-kind rate base cost recovery method for Chicago’s two-part REG system installation, stating that while the system is at distribution voltages, it provides transmission-level functionality and can be treated as a transmission asset for cost recovery purposes. This further reduces financial risk for utility customers and provides a precedent for attractive cost recovery for REG system installations.[22]

ComEd describes the installation of HTS transmission facilities as providing dual benefits:

- provide a new looped transmission path on the U.S. electric grid, which is the first permanent installation using high-temperature superconductor technology
- provide resilience and reliability to the Chicago Central Business District at a lower cost than any potential alternative.

3.2 Essen Cable (AmpaCity Project)

HTS cables can be used to increase capacity at existing substations or serve as the primary source for new substations. This can be achieved by replacing transmission voltage conventional cables with distribution voltage HTS cables, which can eliminate the need for new transformation at the substation. This approach is considered if the new/expanded substation is space-constrained or the cable route between the source substation and the new/expanded substation is not well suited for transmission voltage cables. The HTS cables serve the function of an extended bus to the load substation, creating flexibility in the location of new transformation.

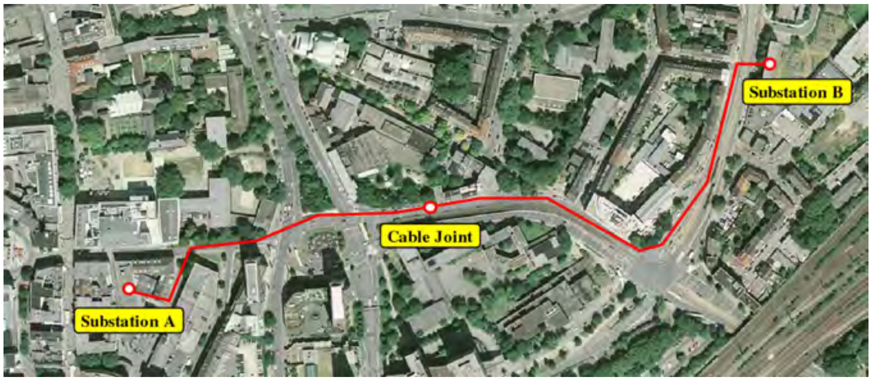


Figure 3. HTS cables in the AmpaCity project in Essen, Germany.

The application of HTS cables in the AmpaCity project in Essen, Germany demonstrated this approach. The project increased capacity at the urban substation Dellbrugge (substation A in Figure 3), which was severely space-constrained. The conventional solution was to run a 110kV transmission cable from the suburban substation Herkules (substation B) to Dellbrugge and install a new transformer at Dellbrugge.[23] However, this would be cost-prohibitive. The HTS cable (10kV, 2310A, 40MVA) allowed the new transformer to be installed at Herkules (instead of Dellbrugge) and bring the new power to Dellbrugge at the local distribution voltage, eliminating the need to install large equipment at Dellbrugge and simplifying the permitting and cost of the new cable right of way.[24] The cable operated from March 2014 to March 2021, which was longer than originally planned. The cable was decommissioned because the utility did not want to continue to fill the open system cryogenic tank.

3.3 KEPCO Munsan

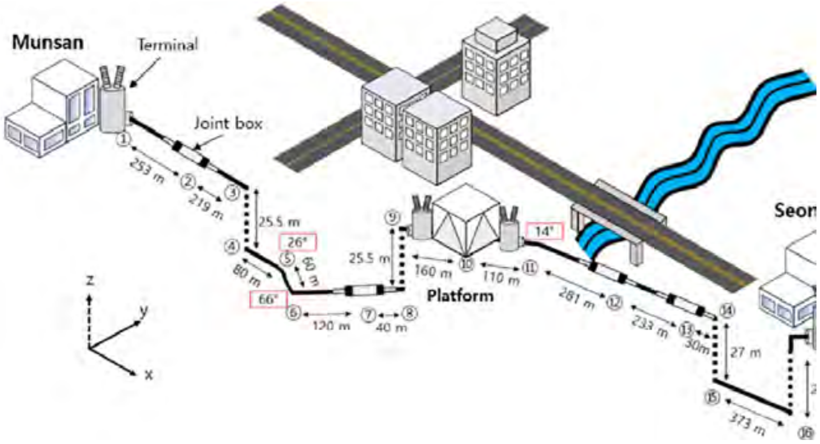


Figure 4. Schematic of KEPCO's Munsan cable project. *Image courtesy of KEPCO.*

KEPCO plans to install 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 high-voltage transmission lines and substations from urban areas. 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 actual installation environment. The thermohydraulic 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.[25]

3.4 NEDO Cable

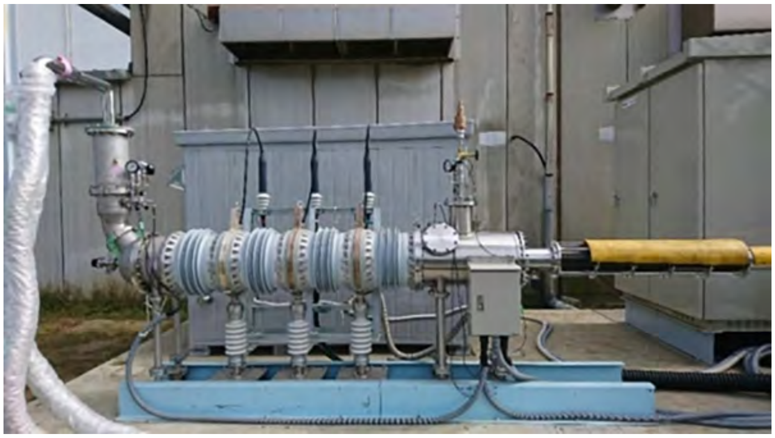


Figure 5. Terminal of tri-axial superconducting cable. *Photo courtesy of NEDO.*

The New Energy and Industrial Technology Development Organization (NEDO), SWCC Showa Cable Systems Co., Ltd. (SWCC), and BASF Japan Ltd. (BASF) have completed the world's first demonstration test of a tri-axial superconducting cable system installed in a commercial chemical plant. The project was completed at BASF Japan's Totsuka site (Totsuka Ward, Yokohama City) in November 2020 and ceased operation in September 2021. The testing proved the system is capable of supplying power reliably for about one year. A condition of this test was that it was necessary to use the plant's existing facilities, so the cable was installed on an existing rack about 5 meters above the ground. Therefore, it was necessary to bend the cable 90 degrees (bending radius 1.5 meters) at four locations; the cable's flexibility allowed it to be installed without any problems. Although the flow path of liquid nitrogen becomes narrower at bends with a compact cable, it can flow over long distances (approximately 400 meters round trip) in the system without any problems, confirming that it can be used for complex plant layouts.[26]

3.5 Shanghai Cable

Shanghai Electric Cable Research Institute energized a 35kV 2.2kA HTS cable project in Shanghai, China. It is a 3 in 1 type cable that is 1.2km long. The cable used approximately 170 km of REBCO wire with cooper lamination with an average piece length of 150m. The project was energized in December 2021 and connects two 220 kV transformer stations in the commercial business district and is still operational. The project partners include Shanghai Superconducting Technology Co., Ltd, Shanghai Electric Cable Research Institute, and the State Grid Corporation of China.

3.6 SuperLink

The SuperLink project is a superconducting power cable that is planned for installation in the center of Munich, Germany. The 12 km underground power link is expected to be the longest superconducting power cable solution in the world. The SuperLink design has a power rating of 500 MW and a voltage level of 110 kV, which is slated for installation between two substations – in Menzing in the west of the city and the load center in the south of Munich. The project will use existing ducts to keep the construction work at a minimum.[27] Partners of the project include SWM, NKT, Linde, THEVA, University of Applied Sciences South Westphalia, and KIT.

3.7 DC Electric Railway in Japan

DC electric railway systems are widely used in Japan including metropolitan areas. The DC electric railway systems have some essential issues such as feeder line voltage drop, regeneration cancelation, energy losses. These issues can be solved by introducing superconducting power cable. But to introduce a new technology to commercial railway lines, government approval is required. To get the approval, the performance of superconducting feeder cables must be verified, including reliable current transmission capability, stable cooling, short circuit current, withstand voltage, etc.

Development, demonstration and tests of the superconducting power cables have been carried out by the Railway Technical Research Institute. They have already been developing and testing superconducting cable systems for more than a decade. A preliminary test of a superconducting feeder cable at the Ohito Station on the Izuhakone Railway Sunzu line was successful. The test confirmed that it was viable as a feeding system.[28] The superconducting cables cleared all the tests required for commercial operation and passed technical inspection by the Ministry (of Land, Infrastructure, Transport and Tourism (MLIT)) in March 2023, and this technology is now ready to be applied to commercial railway lines.[29]

3.8 Super Rail

The Super Rail project will install two superconducting DC cables near Montparnasse station in Paris. This is the first time that cables of this type will be integrated into a rail network and is set to be the first permanent installation in France on any network. These power cables will help secure the network at a time when rail traffic is constantly growing in large cities. Nexans and its partners won the project supported by the French government in the frame program “France 2030”. This initiative is coordinated by SNCF Réseau.

3.9 Fault Current Limiter Projects

Table 2 below provides examples of superconducting fault current limiters (SFCL) projects that successfully improved grid resilience. A more exhaustive list of projects was developed by KIT.[30,31] Extensive research has also been conducted on which locations superconducting fault current limiters can be placed on the electric grid.[32] Example locations include generator connection, network coupling, busbar coupling, shunting current limiting reactors, transformer feeder, and closing ring circuits. A CIGRE Working Group (WG 13.10) also identified several installation points for fault currents that included bus ties/couplings in incoming feeders or outgoing feeders. [33]

This document does not detail the different types of superconducting and solid-state fault current limiters. However, the various SFCL topologies are well documented in other publications.[34] The sections below highlight successful examples of SFCLs that have been energized in electric grids worldwide.

3.9.1 Innopower SFCL

Innopower and Guangdong Power Grid have successfully developed several prototype SFCLs with nominal voltage ranging from 10 kV to 500 kV. A 220kV/300MVA device was installed at the Shigezhuang substation, Tianjin, China.[35] It was designed to limit the fault current from 50 kA rms to 30 kA rms. Another project rated at 500 kV/1800 MVA was tested on a single phase in the China Southern Power Grid Corporation territory.[36]

Figure 6. Innopower 220 kV/ 300MVA FCL. *Photo courtesy of Innopower.*

3.9.2 ASSiST SFCL

A resistive SFCL was developed and tested in the public electric power grid of Augsburg, Germany as part of the 'ASSiST' project. The project aimed for prolonged operation beyond its duration to limit fault currents at a grid feeder point. The SFCL demonstrated robust design, passing electrical tests, including a two-phase fault, and maintaining stable cryogenic conditions during cooling system outages. The technology reduced loss by shunt reactors and provided valuable insights into grid behavior at medium voltage levels. The unit was commissioned in March of 2016 and decommissioned after four years of extended operation. The SFCL proved its performance and robustness, serving as a reference for further commercialization.[37]

Figure 7. ASSiST FCL in Augsburg, Germany. *Photo Courtesy of Siemens.*

3.9.3 KEPCO SFCL

The Korea Electric Power Corporation has undertaken the development and grid operation of SFCLs in response to the increasing fault current in Korea. A 22.9 kV SFCL has been successfully operated unmanned on a distribution line at Icheon Substation. KEPCO also developed a 154 kV SFCL with a superconducting element successfully designed and tested in a unit module. In 2016, the superconducting element was integrated into a single-phase 154 kV SFCL with the cooling system and other components at their Gochang Power Test Center.[38]

Figure 8. 154 kV SFCL developed by KEPCO. *Photo courtesy of KEPCO.*

3.9.4 AmpaCity SFCL

As part of the Essen Cable project, a 12 kV / 2400 A fault current limiter protected a 10 kV / 40 MVA superconducting cable.[39] Developed by Nexans for RWE (now Innogy), the local utility, the project is situated in Essen, which is part of the Ruhr area with a population exceeding 5 million and is a significant industrial district. The AmpaCity SFCL has a 2.4-kA rating, the highest value for resistive SFCLs installed in the grid to date. The device became operational in 2014 and has operated smoothly for many years since its commissioning.

3.9.5 SuperOx SFCL

The need for centralized heating in winter in Moscow, Russia has led to a considerable portion of electrical generation being located inside the city, resulting in unusually short distances between generation and consumers. The introduction of intensive cross-linked polyethylene cables, coupled with rapid consumption growth in the 21st century, has caused the fault current level to double over the last 20 years.[40] The SuperOx company developed a SFCL with a nominal voltage of 220 kV and a rated current of 1200 A for use in a high-voltage substation in the UNECO utility service territory. The device is a three-phase dead-tank apparatus equipped with a closed-cycle cryocooling system using liquid nitrogen for cooling and insulation. The SFCL was installed at the substation parallel to existing air-core reactors. The device has consistently demonstrated its design characteristics, including variable electrical load transfer, reliable performance of the redundant cooling system, and effective limitation of in-grid fault currents during operation. The cryogenic system's pressure and liquid nitrogen temperature and level remained within nominal operation intervals during grid faults. Following fault clearance, the device successfully returned to normal operation. Despite multiple cryocooler stops during in-grid operation, the SFCL remained fully functional due to the redundant design of the cooling system and continuous power supply during cryocooler maintenance.[41]

Table 2. Selected Fault Current Limiter Projects from Electric Grids Around the World

Lead Company	Country	Year	Operating Characteristics	Grid Location
Innopower and Guangdong Power Grid	China	2011	220 kV / 800 A	Shigezhuang substation
Applied Materials	United States	2013	15 kV / 1 kA	Outgoing feeder
Nexans/RWE (now Innogy) - AmpaCity	Germany	2014	12 kV / 2.4 kA	Connect two substations and in combination with other superconducting components
Siemens - ASSiST	Germany	2016	10 kV / 817 A	Outgoing feeder
KEPCO	Korea	2016	154 kV / 2kA	Gochang Power Test Center
SuperOx	Russia	2019	220 kV / 1.2 kA	On a 220 kV line which is placed between 220 kV/20 kV substations

End Notes

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