High Temperature Superconductivity
A Roadmap for the Electric Power Sector

2015-2030

iea Energy Technology Network

SUPERCONDUCTIVITY

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EXECUTIVE SUMMARY

This document is a roadmap for high temperature superconducting (HTS) based devices for the application in power system. The document paints a picture of where the HTS industry is at present and what steps it should take to promote widespread adoption of superconducting based devices. It outlines research & development (R&D) challenges and needs in the short, mid and long term that can be tracked using metrics. The intent of the document is not to make predictions about the future nor identify specific organizations to tackle certain problems. The analysis conducted was based on the best data available at the time and this is intended to be the first release document that will be updated in approximately two years.

Key Drivers of Change

- Changing mix of electricity supply to low carbon solutions
- Customer participation in electricity markets
- Expectations for greater reliability and resilience
- Integration of digital devices for managing power systems

The International Energy Agency's (IEA) World Energy Outlook 2014 states the energy system is under stress now and there is a continued rise in global greenhouse-gas emissions in many of the world's fast-growing economies.[1] They reported that global energy demand is set to grow by 37% by 2040 and energy-related carbon dioxide (CO_2) emissions grow by one-fifth. Electricity is the fastest-growing final form of energy, yet the power sector contributes more than any other to the reduction in the share of fossil fuels in the global energy mix. IEA forecasted that approximately 7200 GW of capacity is needed for increasing electricity demand. The IEA projects global electricity generation from renewables to increase by 30% from 2015 to 2020, largely driven by policy support and their improving competitiveness. This increase will require large-scale integration into power systems. These factors contribute in IEA scenarios to a doubling of the annual investment in power grid infrastructure, from approximately 20 billion US$/year today to 40 billion US$/year in 2035.

Currently in the United States, 70% of large power transformers and transmission lines are twenty-five years or older, and 60% of circuit breakers are thirty years or older.[2] A catastrophic failure of a transmission asset threatens system reliability, and changing system dynamics may increase the likelihood that this can happen. As assets are replaced, there is an opportunity to install next-generation, higher-performance components, such as high temperature superconductivity based devices, but overall cost needs to be managed and optimized.

The changes affecting the electric power sector offer an unprecedented opportunity to transform the future grid. Increasing needs for flexibility, reliability, and resilience in the transmission and distribution (T&D) system require technologies and techniques not conceived of when much of the current infrastructure was deployed. During this period of transition, the deployment of new technologies will play a critical role in shaping the future grid. High temperature superconductors are potentially key in the suite of technologies that can help facilitate grid modernization, reduce losses and hence CO_2 emissions and increase energy security.

Superconducting based devices do not simply provide improvements over conventional electric grid technologies; they provide unique solutions to challenges that cannot be achieved otherwise. Examples of technologies that provide these unique solutions include superconducting fault current limiters, generators for off shore wind turbines, superconducting magnetic energy storage, and high-capacity power cables.

While the transition of HTS conductors (this document focuses on three types of wire: YBCO, Bi2223, MgB_2) from lab-scale to grid scale demonstrations has been accomplished, the transition to widespread market maturity faces several challenges. Examples include:

- **Economics.** The cost associated with manufacturing HTS wire due to sophisticated processes, low yields and limited throughput of the manufacturing processes makes it several times more expensive than copper wire. However, it is not reasonable to simply compare the cost of an HTS based device to a conventional one. Because of the unique attributes of HTS devices, a *system* cost analysis should be conducted.
- **Process control**. There is a general lack of manufacturing knowledge in producing HTS wires with nanometer-sized precipitates or phases uniformly distributed over kilometer lengths.
- **Long term reliability.** End users are generally unfamiliar with the materials used in HTS devices and cryogenic systems. Data are not available that proves undiminished product-performance HTS components life time over 30 to 40 years.
- **Business risk.** Uncertainty for total cost of ownership and cost and availability of parts from suppliers in a relatively nascent market.

The following section is the summary of this survey and Table A.1 shows a general trend analysis of HTS based applications of past, present and future based on the data collected. It is important to note that the auspices of the IEA implementing agreement is on High Temperature Superconductivity and this roadmap will focus on this category of wire. However, there are still important partners and product development underway in the Low Temperature Superconductivity arena (LTS). LTS applications are described later in the document.

Technology Assessment

This section describes the present status and future perspectives for HTS technology and power applications from data gathered from HTS experts around the world. The section first describes the current status of the two core components of HTS systems, wires and cryogenic systems. It then provides an assessment of the state-of-the-art in the deployment of HTS systems in its four main applications: Cables, Fault Current Limiters, Generators, Superconducting Magnetic Energy Storage Systems, and Transformers.

Wire

Superconducting wire is the fundamental technology enabling an array of innovative devices. More than 15 companies are working actively to increase the total production capacity of HTS wire. Some companies can manufacture 1000 km/year of wire from the three most widespread materials, Bi2223, YBCO and MgB_2. Cost of the wire is recognized as a key factor for more widespread use in electric power applications; the current cost is around a few hundred $/kilo-amp-meter (kAm) (using critical current (I_c)

at 77 K and self-field) for YBCO and should be reduced to around $10/kAm in 2030 for market maturity based on data collected from this roadmap effort. The $10/kAm level is competitive and has the potential for yielding positive returns for project developers under current market conditions. MgB_2 is now below $10-25/kAm (using I_c at 20 K and around 1 Tesla), but they are aiming at further cost reductions to <$5/kAm by 2020 to enhance the market competiveness. While YBCO is more expensive than Bi2223 and MgB2 it has a higher Ic at high fields and temperatures. Bi2223 costs less than YBCO and aims to reduce the cost by half in 2020 and still lower in 2030. Many companies are conducting research and development to increase over long lengths I_c, which results in lower cost per kAm unit.

Cryogenic Systems

One of the critical components of HTS devices is the cryogenic system. These systems are used for HTS applications to operate at the temperature of liquid nitrogen (77 K or -196°C) and, in some cases, at a lower temperature (below 30 K or -243°C) for applications that involve high magnetic fields. There are several types of cryogenic systems available including:

- The **Gifford McMahon** (GM) system, which is most widely used for LTS commercial products such as Magnetic Resonance Imaging (MRI) machines because it has a relatively long maintenance free period of about 10,000 hours.
- **Pulse-tube** systems operate in a closed cycle, using helium as a working fluid and have no moving parts. The cold is generated by the use of acoustic waves that substitute for the typical pistons or rotating equipment found in other cryocoolers.
- **Stirling cycle** cryocoolers have been available in commercial volumes for HTS electrical devices since 2000. The Stirling cryocooler uses gas bearings, a single piston and displacer, a combination of gas and mechanical springs, efficient heat exchangers and a passive balancer used to minimize casing vibration. Stirling cryogenic system are being developed for high cooling power (>1 kW at 77 K) and reliability using a closed cooling system with a compact design.
- **Turbo Brayton** systems are being developed for power applications and discussed later in this chapter. Most of the data collected for this roadmap was for Turbo-Brayton cryogenic systems. These systems are expected to reach the stage of mass production by 2025 and market maturity by 2030. R&D is still needed to enhance performance, improve the interval time between maintenance operations, and reduce system cost.

Other cryogenic systems are being applied such as an open liquid nitrogen tank and circulation system for a cable and fault current limiter project in Essen Germany. An open system features lower complexity and potentially high reliability, but requires re-filling of a nitrogen storage tank in regular intervals. A closed system only needs electrical power supply after initial filling, but requires higher capital investment and specific methods to ensure availability and reliability.

Cables

There is more than 20 years of operating hour experience with cable projects worldwide.

Among all HTS applications, including non-power devices, the most operational experience has been accumulated in cables. When combining the operating experience of all the cables in the world, there are more than 20 years of operating hours.[3] HTS cable projects have been energized in large scale grid demonstrations around the world ranging from approximately 10 kV—275 kV. Nearly ten cable demonstration projects are under development and are classified into distribution voltage (10 kV—66 kV) and transmission voltage (66 kV—275 kV). Although DC cables are gaining more interest due to their lower losses over hundreds of kilometers, this document focuses on AC cables because of the data available. One of the benefits of HTS cables is that they carry more power at lower voltages compared to conventional cable technologies. HTS cables are being targeted for technical solutions that conventional cables cannot provide. For instance, in dense urban areas with limited underground cable duct space, HTS cables can provide the same amount of power as conventional cables, but in a fraction of the space.

Data collected showed that cables were anticipated to reach market maturity in 2025 to 2030. To reach this stage, R&D is needed to 1) reduce the cost of wire, cryogenic system and cable fabrication, 2) improve safety and reliability of the system and 3) reduce system losses.

Fault Current Limiters

A fault current limiter (FCL) immediately limits the amount of short circuit current flowing through the electric grid and allows for the continual, uninterrupted operation of the electrical system, similar to the way surge protectors limit damaging currents to factories and household devices. The need for FCLs is driven by rising system fault current levels as increasing energy demand and feed-in from distributed generation and clean energy sources like wind and solar, requires further meshing of the grid in order to improve power quality and increase hosting capacity in already overburdened systems.

High-temperature superconducting fault current limiters (SFCLs) use superconducting-based material and reduce fault currents by introducing alarger-than-normal impedance into the path of the fault current. There are several types of SFCLs including resistive, inductive, and shielded core. This document focuses on the resistive type SFCL because many of the past or ongoing projects use this type. Superconducting fault current limiters do not use as much wire when compared relatively to other superconducting applications; each device only uses a few kilometers at most. Therefore, SFCLs could have market maturity around 2025, which together with HTS cables, is earlier than any other HTS application.

Generators

Because superconductivity offers the possibility of smaller and lighter generators than is possible with conventional materials, there is substantial interest for conducting R&D on HTS based machines. One of the key application areas are HTS generators in wind turbines. Demand for wind turbines is increasing because many country's goals are to increase the percentage of electricity being produced by renewables. There is exceedingly high interest in wind power—particularly off-shore wind turbines because there is a plentiful and reliable wind resource. There is also a current trend for turbines with larger rotor swept areas, as these can afford higher annual capacity factors and increase generation in areas with poorer wind source. Large offshore wind turbines of 10 MW or greater require a huge support structure, larger turbine blades and larger generators compared to conventional based devices. HTS based generators have the potential to reduce the weight of these large offshore wind turbines.

Generator projects are being designed using YBCO and MgB_2 wire especially for large off-shore wind turbine generators over 10 MW. At present, they are not in the stage of system demonstration, but simulations and basic studies are being conducted for coils and cryogenic systems. HTS based generators are anticipated to have market maturity in 2030.

Superconducting Magnetic Energy Storage (SMES)

Superconducting Magnetic Energy Storage (SMES) technologies have the ability to store electricity in the magnetic field of direct current. SMES uses a superconducting magnet, which can generate a high magnetic field with negligible losses. This is possible because the current circulates in the resistance free superconducting coils rather than in the coils of copper or other metal conductors, which have resistance. HTS wire is favorable for use in SMES devices because of its high current carrying capacity even at a high magnetic field.

There are several key applications that SMES devices can provide. These include power, energy, and controlling phase of current. A Niobium Titanium based-SMES system (using "low temperature superconducting materials) is running in a liquid crystal screen factory, but a fully integrated high temperature superconducting based SMES system has not yet been made. HTS coils, one of the critical components for SMES, have been developed using YBCO wire in US, Japan and Korea.

The market maturity stage was estimated to occur in 2025 to 2035 for 10—20 MJ SMES used in voltage dips compensation applications. To reach this stage, wire cost lower than $5/kAm will be needed according to the experts consulted for this roadmap effort; and approximately 250—300 km of wire will be needed for a 20 MJ device. For R&D, a large coil fabrication and testing at a high-field will be needed to verify its tolerance for a high hoop stress. MgB_2-SMES operating at 20K cooling could be expected sooner due to the lower cost of the wire.

Transformers

HTS Transformer R&D is arguably one of the most difficult of the superconductivity AC power applications because of the need for very low AC losses, adequate fault and surge performance and rigors of the application environment. Therefore, worldwide activity in HTS transformer R&D is farther behind other applications listed in this document. Projects were started in Japan and in the US, but those efforts have wound down. There is currently very little R&D being conducted on HTS transformers. However, one example is a transformer developed by the Robinson Research Institute in New Zealand that measured energy losses at half of a conventional transformer (please see section 8, page 50).

There was not much data collected for this application in this roadmap document. As a result, it was difficult to obtain when the market maturity and other development stages would occur. Research and development is still needed to reduce cryogenic losses and AC losses in the wire. Moreover, suitable technical solutions are also needed for the key components such as the cryostat, vacuum seal, and current leads.

Table A.1 Trend Analysis.

Area	Past (last ~5 years)	Today	Future (next 5 years)
Policy	National energy strategy documents do not highlight HTS as a potential solution for grid modernization.	HTS based devices rarely mentioned as part of the broader strategy for grid modernization.	HTS based devices are routinely mentioned as a potential solution for grid modernization efforts.
Technical	Successful large scale demonstrations conducted to prove technical feasibility in the electric grid.	Projects/Demo being considered as permanent infrastructure to solve real world electric grid problems.	Devices installed to be permanent components in the electric grid; devices installed without government subsidies.
	Concerns that wire companies would not be able to provide enough product volume. Five companies at most could provide long length wire (>1 km).	Production from wire companies has increased; more than 15 companies are producing HTS wire (several that can produce long lengths of >1000 km/year.) YBCO wire remains several times more expensive than conventional copper.	Wire capacity and performance continues to improve, and is cost competitive compared to conventional technologies. Wire is tailored to suit different operating temperatures and magnetic fields.
	A range of superconducting based technologies show potential for modernizing the electric grid.	HTS cables and fault current limiters have the most operating experience in grid conditions.	Performance and reliability for cables and fault current limiters continue to improve and other applications are demonstrated in the grid.
Market	Decisions to install HTS system based almost exclusively on the device cost.	Evaluating HTS systems being looked at through a different lens; they can provide additional services that conventional technologies cannot.	Decision to install systems will continue to depend on cost, but grid functionality and system aspects will play heavily into decision making.
	General conservative nature of utilities has made it difficult to get HTS devices into the electric grid. HTS is still perceived as a complex technology still to be proven.	Targeted outreach to utilities backed by worldwide HTS project experience is slowly starting to change these end-users perspectives about the potential benefits and risks with HTS devices.	Communications and outreach to utilities and the regulatory community continues to teach them about system benefits; regulatory structures change to better incentivize R&D in innovative technologies like HTS
	Unfamiliarity with cryogenics along with additional cost and maintenance intervals hinder HTS based technology adoption.	Cryogenics require additional power and maintenance cycles that conventional systems do not have.	Costs for cryogenic systems continue to decline and maintenance intervals increase.