High Temperature Superconductivity Application Readiness Map - Energy Delivery - Transmission, Substation and Distribution

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***Abstract*—The International Energy Agency's High Temperature Superconductivity Technology Collaboration Program (IEA HTS TCP) analyzed energy delivery applications for HTS. The product was a Readiness Map that illustrates the Technology Readiness Levels (TRL) over time of HTS applications. Assessing these TRL levels is important since the electric power system that supplies our residential, commercial and industrial sectors is experiencing a transition to safer, more efficient and cleaner power supply.**

The international experts assessed the present degree of technological development of the main transmission, substation and distribution HTS applications in the energy delivery sector and estimated the pathway to commercialization phase. Instead of using a specific TRL number 1-9 for each of the applications, 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.

***Index Terms*—Readiness Map, Technology Readiness Levels, Energy Delivery Systems.**

I. Introduction

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.

II. 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 1. The sector this document focuses on is energy delivery, whose applications can be further broken down into transmission, substation and distribution.

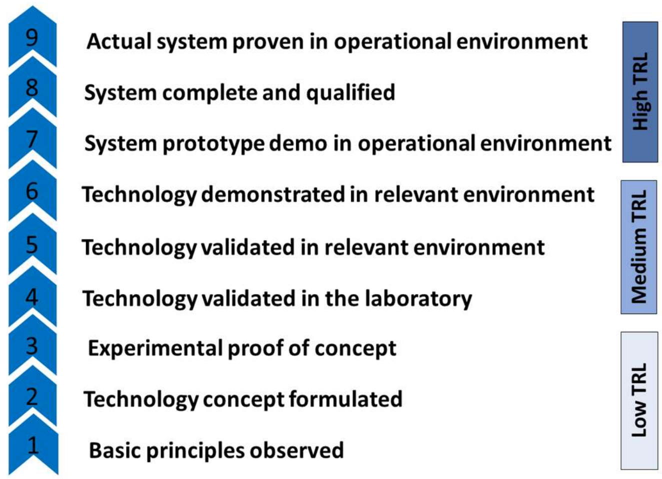

Fig. 1. Technology Readiness Levels are indicated from 1-9. For the purposes of this document, TRL levels 1-3 are specified as "low"; TRL levels 4-6 are specified as "medium"; TRL levels of 7-9 are specified as "high".

III. Technology Readiness Levels – Energy Delivery Systems

Figure 2 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.

LOW TRL | MED. TRL | HIGH TRL

Energy Delivery System	2021	2025	2030	2035
Transmission (HV > 66kV) Increase capacity for HV AC and DC circuits	HV AC Cable	→	HV AC Cable	
	HV DC Cable	→	→	HV DC Cable
Limits faults on HV system	HV SFCL			
Substation Interconnect substations on secondary side	MV AC Cable			
Limits faults on MV system	MV SFCL			
Replace conventional transformer	Transformer	→	Transformer	
Distribution (MV < 66kV) Provide HV AC power to cities	MV AC Cable			
Retrofit existing ducted cables	MV AC Cable	MV AC Cable	→	MV AC Cable

Fig. 2. 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".

A. 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) [1]. 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 [2]. 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 [3]. However, there are some projects that are exploring the use of HTS cables in longer applications [4]. The current TRL level is rated as "medium".

B. 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 [5]. Moreover, power losses are less than conventional overhead transmission lines and are independent of the level of power transmitted [6]. Thus, HTS DC cables have the potential to be cost competitive with overhead extra-high voltage (EHV) AC and traditional HVDC transmission technologies.

HTS DC cables become particularly beneficial when the transmission length is long [7]. 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 [8]. 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) [9]. 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. The current TRL level is rated as "medium".

C. 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 fault 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.

The concept of linking substations at the secondary has been proven in the city of Chicago, Illinois, USA. 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 loops together two downtown Chicago subtransmission voltage substations into a network, increasing reliability and resiliency [10]. 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. The TRL for this application is rated as "high".

D. Limiting faults on medium voltage (<66 kV) system – MV SFCLs

There have been more than 20 SFCLs operating at medium voltage in real grid operations [11]. Therefore, medium voltage SFCLs were ranked at a TRL of "high" today. One issue for MV SFCLs is the reliability of HTS tapes. In MV applications, 2G 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 overall reliability of the device. Another barrier, for MV FCLs and other applications, 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.

E. 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 [12]. The TRL level is ranked as "low" [13] [14].

F. 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.

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 provide extensive data on lifetime and performance. Therefore, today's TRL level is ranked at "high" [15].

G. 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 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. 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 previous described applications. Therefore, the progress to higher TRL levels is expected to be slower.

IV. CONCLUSION

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. 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.

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