



21, rue d'Artois, F-75008 PARIS

<http://www.cigre.org>

CIGRE US National Committee 2022 Grid of the Future Symposium

New HTS Cooling Method Can Help with Transmission Line Siting

S.A. CONANT, K. THOMAS, J. HARRISON, M. LUKE, N. SHIELD, S. ASHWORTH
VEIR, Inc.
USA

SUMMARY

When high-temperature superconductivity was discovered in the 1980s it set off a flurry of excitement for potential applications across multiple sectors, including the power sector. However, unlike uses in the medical industry, which was poised to take immediate advantage with new magnetic resonance imaging (MRI) machines, it was understood that applications in the power sector would take more time to develop – estimated at one to two decades back then. Power sector applications would require long superconducting tapes, connections to an electric grid with high reliability requirements, and expensive cooling systems. Despite the challenges for power sector, the opportunity was viewed as significant given high-temperature superconductors' (HTS) incredible power flow capacity across a very small wire. The prospect of moving power long distances in narrow rights of way with negligible losses held great promise.

Thirty years later, the promise of a superconducting transmission lines that can move five to ten times the amount of power as a conventional is within reach for commercial deployment in the power sector. A breakthrough in cooling that uses an open-loop system that evaporates liquid nitrogen along the entire length of HTS transmission lines is now under development. The new approach is inspired by work originally done at the Los Alamos National Laboratory, U.S.A. in 2010. The new cooling architecture removes many of the constraints for transmission posed by closed-loop systems, such as complex, mechanical cooling substations, heavy dielectric materials, and underground installation. For the first time HTS may be deployed overhead over long distances and provide a cost competitive alternative to conventional overhead conductors.

This paper reviews the development of HTS in the power sector and introduces new work being done to develop scalable cooling systems for overhead, long distance applications. This recent advancement in superconducting transmission lines emerges at a time when the need for new transmission lines and the opposition to their installation is greater than ever. New superconducting overhead lines can carry five to ten times as much power as conventional copper or aluminum conductor-based lines at any given voltage. The increase in power is achieved overhead with no increase in tower height or expansion of right of way. The compactness should ease many of the permitting challenges faced by projects today where substantially increased capacity can only be achieved with increased voltage, taller towers,

and wider rights for way. The ability to use existing rights of way for more capacity opens a path to less controversial siting and project permitting.

KEYWORDS

HTS, superconductors, overhead transmission, distribution, distributed cooling, liquid nitrogen, renewable energy integration, permitting, right of way

1 The Dawn of High-Temperature Superconductivity

It was called “The Woodstock of Physics”. Thousands of scientists descended on a New York City hotel in March of 1987 to discuss the latest findings in superconductivity. The crowded ballroom was abuzz about the newest discovery of high-temperature superconductivity.¹ First discovered by the Dutch physicist H.K. Onnes in 1911 at 4 Kelvin, superconductivity, the condition of zero resistance in certain materials, was of immense scientific interest. Yet its practical commercial application was not economic due to the limited availability and cost of the liquid helium needed to produce the low temperatures. So, in 1986 when it was discovered that certain rare earth elements showed the same superconducting qualities at 77 K, the temperature of liquid nitrogen, the technical and commercial applications for high-temperature superconductivity seemed boundless.

The discovery spurred a flurry of government and private sector activity poised to drive new industries in all sectors of the economy. In November 1988, Congress passed the “National Superconductivity and Competitiveness Act”.² President Reagan signed the bill into law. A month later he issued Executive Order 12661 establishing a National Commission on Superconductivity. Spurred by competition from Japan, the U.S. investment in superconductivity research was substantial. Between fiscal year 1987 and 1990, U.S. research dollars increased from \$45 million to \$107 million. At that point, however, applications in the electric power industry were seen as more than 15 years in the future “if... feasible at all.”³ Private sector companies were not discouraged. They saw great promise for the power sector. New companies were founded, and trade organizations created in 1987, such as American Superconductor (AMSC) and the Council on Superconductivity for American Competitiveness that included member organizations such as the Electric Power Research Institute (EPRI).⁴

2 Electric Power Applications

When HTS was discovered, commercial applications in the electric power sector were only considered possible 20 to 30 years in the future. Immediate advances came first in medical applications where magnetic resonance imaging (MRI) was already using helium for low temperature superconductivity (LTS). In 1987 there were two dozen companies selling more than 500 MRI machines to medical facilities around the world.⁵ LTS had been operating in the power sector with government and industry support as early as the 1970s. Brookhaven National Lab operated a project for 14 years. Still, unlike the medical industry there were no economic applications or established companies immediately poised to speed the transition to HTS applications in the power sector. At the time the oxide ceramic HTS material was brittle and hard to work with. Producing the longer HTS tapes needed for power transmission would be difficult. There were also technical challenges to cooling systems that required underground installation. There was an understandable hesitancy to risk integration of the

new technology into a network of electric lines where reliability was the top priority for any element on the system. A 1990 report by the Department of Energy Office of Technology Assessment, that assessed power sector applications for superconductivity, deemed the market outlook for transmission was “discouraging” because of the high capital cost of placing lines underground.⁶ Yet, the report concluded: “Transmission lines appear to be one of the few electric power applications where the incremental advantage of HTS at 77 K over LTS is very significant.” HTS could reduce cost by 30 percent compared to LTS. The report cited an EPRI study that estimated HTS lines with capacities as low as 500 MVA “may be economically feasible”.⁷

Supported by private capital with federal grants, including funding for the DOE’s Superconducting Partnership Initiative, AMSC worked to design and manufacture first generation (1G) of HTS tapes, made from bismuth strontium calcium copper oxide (BSCCO), while looking for opportunities to demonstrate power grid applications. By 1995, the first prototype HTS line design, including joints, terminations, and cryogenic cooling, was complete. Soon after, the first complete cable and system was installed and tested. By 2001, the world’s first grid connected HTS system was staged for demonstration at Detroit Edison’s Frisbie substation where three superconducting cables were to replace nine copper cables. Pirelli Cables and Systems led the effort, using the 1G superconducting tapes provided by AMSC.⁸ Unfortunately, the project was never energized, in part due to vacuum jacket leakage in the cooling system.⁹

Work on HTS power lines accelerated, prompted in part by continued public and private investments well as advances in the superconducting tapes used to carry current. Over the next several years, HTS demonstration projects were set up and working across the U.S. and internationally. In April 2008, the Long Island Power Authority (LIPA) commissioned the world’s first transmission voltage HTS power cable at its Holbrook substation. The 138 kV cable ran 600 meters with a power carrying capacity of 574 MVA and a current of 2,400 Arms. AMSC, Nexans, and Air Liquide were partners on the project with LIPA. Federal funding to support the demonstration came from the DOE’s Superconductivity Partnership Initiative aimed at developing long length HTS transmission lines at high voltage.¹⁰ The project used 155 kilometers of AMSC’s 1G wire in Phase 1. Other projects were set up around the U.S. In Columbus, Ohio, Southwire/Ultera demonstrated a 3-phase, 13.2 kV line that ran 200 meters at AEP’s Bixby substation. In Albany, New York, Sumitomo installed a 350 meter 3-phase, 34.5 kV cable of 1G wire at National Grid’s Riverside and Menands Niagara Mohawk Power Company substation.

Both the Long Island and Albany projects included a phase II that demonstrated the first use of second generation of superconducting tapes. When they were first produced in 2003, 2G tapes were projected to lower the cost of HTS wire to 2 to 5 times less than the cost of 1G wire.¹¹ Second generation (2G) tapes were made from yttrium barium copper oxide (YBCO). They had greater flexibility, enabled higher carrying capacities, and could be manufactured more easily in longer lengths.¹² Long Island used a 2G tape made by AMSC. Albany used of 2G wire provided by SuperPower.¹³ All the demonstration projects were technical successes, and fully grid compatible. They all had protection and control just like a conventional cable, and the 'superconductivity' was invisible to the control room.

3 Cooling Challenges for Power Sector HTS Applications

Superconductivity research continued coincident with the roll out of demonstration projects. In May 2006, the DOE Office of Science convened a workshop on the “Basic Research Needs for Superconductivity”. Among the issues identified was the need for better superconductors and improvements in refrigeration. In fact, the Office of Science linked the two concepts: “... refrigeration is still a major cost element, making discovery of new materials with even higher operating temperatures a technology driver.”¹⁴ The shift from LTS to HTS had triggered a ten-fold decrease in cooling costs but more cost reductions were needed.¹⁵ Despite significant advances in HTS tapes with the transition from 1G to 2G wire, the Office of Science found that there was a need to double or triple their performance in order reduce losses on AC cables, “thus decreasing cryogenic costs.”¹⁶ Eight years later, when the Coalition for the Commercial Application for Superconductors identified four fundamental challenges for superconductors, refrigeration was second on the list after cost.¹⁷ By then superconductors were confined to niche applications on the grid’s low voltage distribution systems – high voltage, long distance transmission applications were still out of reach unless better HTS material was discovered or better cooling.

4 Distributed Evaporative Cooling of HTS for Electric Transmission

While most researchers and superconductor experts were looking at the limitations to superconductor applications for transmission as a problem presented by cooling systems linked to underground lines and the HTS materials, in 2011, a small but important body of work emerged from the Los Alamos National Laboratory that took a different approach. Instead of looking for better tapes and more efficient mechanical refrigeration systems, researchers Steve Ashworth and David Reagor looked at a different way to cool the existing HTS tapes. Ashworth and Reagor noticed that while great advances had been made in HTS tapes, how superconductors were cooled had not changed in almost 50 years. They decided to explore a new method of cooling that would address the barriers that the large cooling stations presented to the long-distance deployment of superconductors. Instead of chasing more efficient refrigeration or looking for better conductors to ease the thermal load, they instead chose to use the coolant itself – liquid nitrogen – as part of the solution. To keep the nitrogen and the tapes they cooled at 77K, Ashworth and Reagor designed and tested an open loop cooling system that evaporates a small portion of the liquid nitrogen. Allowing a small amount of liquid nitrogen to change from a liquid to a gas, the system used the latent heat of vaporization to provide twenty times the cooling power of the sensible cooling used in the closed loop cool methods in all earlier HTS applications.

Ashworth and Reagor’s proposed approach could potentially overcome many of the challenges posed by the earlier closed loop cooling methods. First, the need for large, complex cooling stations and infrastructure with multiple moving parts and a dependence on a reliable local power supply was removed. Second, the passive open loop cooling system was more energy efficient than even the very best closed loop refrigeration systems. Third, the new approach eliminated the “hot spots” that formed and constrained the amount of power a long HTS line could carry. And fourth, the approach eliminated temperature “jump” points at terminations and splices where there is no separate liquid circulation system.

Beyond mitigating challenges that had been encountered in earlier HTS transmission projects, the distributed evaporative cooling approach could also open new doors for superconductor applications on the power grid. Because the liquid nitrogen is cooled continuously along the

full length of the conductor, the cryostats needed to keep the nitrogen cold can be much smaller and lighter. In turn, this enables the HTS lines to be deployed overhead with air as the dielectric, just the same as conventional overhead conductors. Therefore, there is no need for expensive underground installations or complex dielectrics that must operate at cryogenic temperatures. As a result, instead of being limited to short distances and primarily distribution level applications, this new evaporative cooling technique has the potential to enable cost effective, reliable HTS transmission lines at higher voltages and power levels over distances of 100 kilometers between cooling stations^{18 19} and total distances comparable to conventional conductors with minimal losses. A short distance, proof-of-concept overhead line was constructed at Los Alamos National Laboratory in 2010. However, further development of the concept at DOE was largely discontinued roughly a decade ago as the funding was cut in part due to the perception that practical applications remained somewhat far off in the future.

Today, VEIR, a venture capital backed company located in Woburn, Massachusetts, is building on the work at Los Alamos National Laboratory. VEIR is working to commercialize and deploy the open loop cooling system concept for HTS lines. The company aims to build products that can achieve the high reliability, efficiency, sustainability, and cost-effective requirements the power grid requires. This work involves significant testing and development of the components and overall system of an HTS transmission line using an open loop distributed evaporative cooling system that can be deployed at any voltage level – transmission, distribution, and generation – in overhead, underground, and on-ground grid installations.

5 Conclusion – New HTS Cooling Can Open the Door to Less Controversial Transmission Siting

The challenges to the electric grid and the need to build more transmission lines is greater today than ever before. Climate change, the need to integrate more renewable energy, and shifts in load due to growing electrification, especially electric vehicles, is placing enormous pressure on the grid. Numerous studies including one often cited by Princeton University, indicate that under some scenarios, the U.S. must double or triple its current transmission grid capacity.²⁰

The need for expanded transmission capacity comes at a time when the challenges posed to siting new transmission lines are greater than ever. High profile projects, such as attempts to bring hydropower from Canada to New England, encounter severe opposition that focuses on siting. Many segments of the Clean Line Project, a high-voltage direct current (HVDC) line from the Midwest to Tennessee, faced similar siting objections.²¹ Smaller, local projects that do not cross state lines are not immune to public opposition that most often focuses on visual impacts and/or land taking for additional right of way. Underground lines are often looked at but are prohibitively expensive and can also raise right of way challenges. Cost effective alternatives are needed. Transmission lines that can carry more five to ten times the capacity of existing lines at the same voltage. The increase in power can be achieved overhead with no increase in tower height or expansion of right of way, which are often the sources of public opposition. In addition, the ability to avoid right of way expansion to increase capacity within a corridor means less environmental impact to wetlands, wildlife habitat, and historic sites. Avoidance of these impacts should ease public opposition and help accelerate the permitting process.

The potential to develop high capacity, long distance HTS transmission lines using distributed evaporative cooling systems overcomes the constraints imposed by closed loop refrigerated cooling systems for HTS lines. For the first time, long-distance, very high capacity, and high voltage HTS lines that avoid many environmental and siting constraints are possible.

BIBLIOGRAPHY

-
- ¹ U.S. Congress, Office of Technology Assessment, *Commercializing High-Temperature Superconductivity*, OTA-ITE-388 (Washington, DC: U.S. Government Printing Office, June 1988.) p. 3.
- ² The United States was fearful of losing ground to Japan which was aggressively pouring money into HTS research and development. (See U.S. OTA, June 1988)
- ³ U.S. Congress, Office of Technology Assessment, *High-Temperature Superconductivity in Perspective*, OTA-E-440 (Washington, DC: U.S. Government Printing Office, April 1990). pp. 5-8.
- ⁴ The organization later changed its name to the Coalition for the Commercial Application of Superconductors (CCAS) to better capture member interest and goals. CCAS, March 2013.
- ⁵ OTA-E-440, p. 47.
- ⁶ OTA-E-440, p. 34.
- ⁷ OTA-E-440, p. 34.
- ⁸ Norman Steve, Marco Nassi, Massimo Bechis, Pierluigi Ladie, Nathan Kelley, Cristopher Wakefield, “High temperature superconducting cable filed demonstration at Detroit Edison”, *Physica C*, Volume 354, May 2001, pp.49-45, 50.
- ⁹ U.S. DOE Office of Electricity Delivery and Energy Reliability, “High Temperature Superconductivity Market Readiness Review: Investigation of the status of HTS technology, the requirements of key applications and barriers to future success”, prepared by Navigant Consulting, Inc. August 2006, p.32.
- ¹⁰ F. Schmidt, J. Maguire², T. Welsh, S. Bratt, “Operation Experience and further Development of a High-Temperature Superconducting Power Cable in the Long Island Power Authority Grid.” *Physics Procedia* 36 (2012). pp. 1137-1144.
- ¹¹ “American Superconductor receives DOE funding”, *Power Engineering*, September 26, 2003.
- ¹² U.S. DOE Office of Science. *Basic Research Needs for Superconductivity – Report on the Basic Energy Sciences Workshop on Superconductivity*, May 8-11, 2006. p. 4.
- ¹³ Navigant Consulting, p. 30.
- ¹⁴ U.S. DOE Office of Science. *Basic Research Needs*, p. 4.
- ¹⁵ U.S. DOE Office of Science. *Basic Research Needs*, p. 141
- ¹⁶ U.S. DOE Office of Science. *Basic Research Needs*, p. 4.
- ¹⁷ Coalition for the Commercial Application of Superconductors (CCAS), “Superconductivity: Present and Future Applications”, IEEE Council on Superconductivity, 2014, p 3.
- ¹⁸ S.P. Ashworth and D.W. Reagor, “A novel cooling scheme for superconducting power cables.” *Cryogenics*, January 4, 2011.
- ¹⁹ At the time of its installation in 2007 Long Island Power Authority/American Superconductor was the longest project at 610 meters. The AmpaCity project in Essen, Germany later exceeded that with a length of 1000 meters. State Grid Shanghai Municipal Electric Power Company recently announced a 1200-meter cable that runs 35 KV at 2,200 amps. Zheng Xin, “Shanghai opens superconducting line”, *China Daily*, December 23, 2021.

²⁰ Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik,, E. J., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K. and Swan, A., Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report, Princeton University, 15 December 2020.

²¹ See Russell Gold’s 2020 book, “Superpower: One Man’s Quest to Transform American Energy”.