ELECTRIC POWER RESEARCH INSTITUTE

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

HIGH-TEMPERATURE SUPERCONDUCTING WIND TURBINE GENERATORS

THE TECHNOLOGY

Advanced generators for off-shore large wind turbines with higher efficiency and easier grid integration.

THE VALUE

Support industry's quest for larger scale off-shore wind platforms in the 10–15 MW range.

EPRI'S FOCUS

Assess prototypes performance, accelerate technology's first off-shore demos units deployment.

TECHNOLOGY OVERVIEW

Wind power— already one of the fastest growing forms of power generation—will make a major contribution to the future energy mix. However, in order to sustain that high growth rate into the next decade, the industry will likely have to start tapping offshore wind resources, creating a need for wind turbines that are larger, require less maintenance, and deliver more power with less weight.

A superconducting generator has the potential to improve performance while, at the same time, reducing the unit's weight and size. In addition, they can be built with less than 1% of the quantity of rare earths required for manufacturing the currently most frequently used permanent magnet (PM) generators. Superconduction, hence, may allow the setting up of efficient, robust, and compact wind power plants at reduced building, operating, and maintenance costs.

Superconductivity is the unique ability to conduct electrical current with little or no resistance when cooled to "critical" temperatures. High-temperature superconducting (HTS) materials are a family of elements that demonstrate superconducting properties at temperatures significantly warmer (~77K or -196°C, the boiling point of liquid nitrogen) than "ordinary" or metallic superconducting materials (<30K or -243°C) that may require liquid helium cooling.

Superconducting generators and motors use superconductive coils with almost zero electrical resistance instead of conventional copper wire. Therefore, they feature low electrical resistance losses and high efficiency. The reduced heat generated from the low electrical resistance losses also helps to greatly reduce the size, in turn reducing the quantity of material used for production.

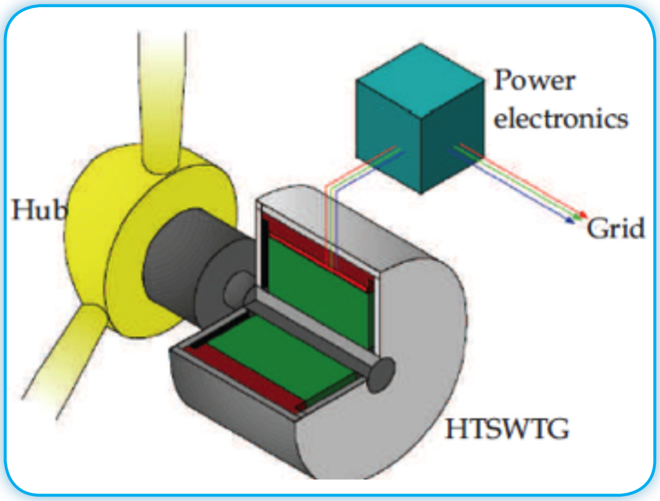

Figure 1. Schematic of a direct drive HTSWTG system [2]

In order to maintain the superconducting state of the coil, extremely low temperature cooling is needed. Therefore, superconducting generators and motors require advanced thermal/electrical insulation and cryogenic cooling technology.

Cooling arrangements play a crucial role in the success of the HTS machines. When designing the cryogenic system, the ease of operation and maintenance, minimum complexity and cost, and integration with the superconducting machines need to be considered. Early low-temperature superconducting (LSC) designs used liquid helium to achieve temperatures of ~4.2K (-269°C), whereas the latest HTSs use liquid nitrogen or even inexpensive liquid hydrogen to cool the

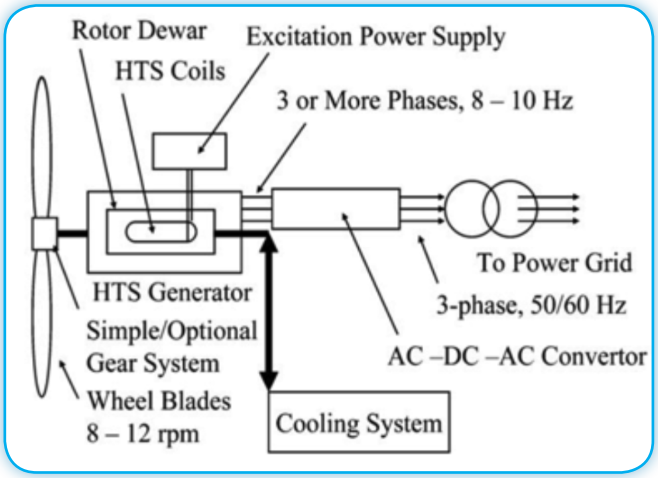

Figure 2. Schematic diagram of an HTS generator system [1]

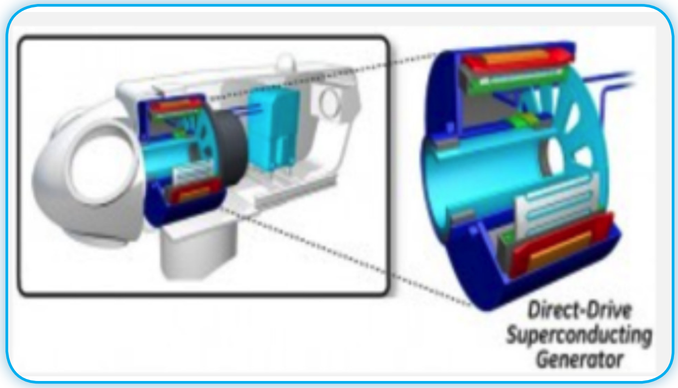

Figure 3. Direct-drive HTS wind turbine generator [12]

superconductors down to between 77K and 125K (-196°C and -148°C). The cost of cryogenic cooling systems depends more on operating temperatures than anything else; therefore, the overall cost constantly drops as the critical temperatures of HTS increase.

Since superconducting machine design is still evolving and is highly dependent on the superconducting materials used, the industry cannot rule out any viable topology at this stage of development. In the literature, a variety of HTS machine types have been reported. These include homopolar machines, induction machines, and, in the majority, synchronous machines. A feasible design of a high-temperature superconducting wind turbine generator (HTSWTG) is based on the synchronous generator with a copper stator and a superconducting rotor. HTS coils are generally wound in the form of very thin racetrack tapes due to their ceramic features. When installed on the rotor, they provide a constant magnetic field similar to the PMs.

The HTS synchronous machines can be further broken down into four different types:

Type 1: Conventional stator and HTS rotor with magnetic pole bodies

This type offers gains in efficiency due to minimized rotor loss, but it does not offer a substantial reduction in weight and dimension.

Type 2: Conventional stator and HTS rotor with non-magnetic pole bodies

This type offer gains in efficiency due to minimized rotor loss and reduced costly cold magnetic materials and complex thermal insulation. However, it needs more HTS wires to establish the necessary flux density.

Type 3: Air-gap stator winding with HTS rotor with magnetic pole bodies

This type produces significantly higher flux density at the air gap than a conventional stator and, thus, decreases the mass and size of the machine. However, the rotor iron can operate highly saturated so that the efficiency is reduced.

Type 4: Air-gap stator winding and HTS rotor with non-magnetic pole bodies

This type allows significant reduction in weight and dimension and also minimizes potential high-cost cold magnetic materials, but it requires more HTS wires.

Since wind energy is a cost-sensitive market, the capital cost is paramount in producing large machines. For offshore wind turbines, the mass saving is more important than size and high efficiency. Therefore, the actual compromise is made between low cost, low mass, and high efficiency. For the direct-drive wind generators, both types 3 and 4 can offer the advantage of lower mass. The cost balance between the two relies largely on the relative cost of HTS wires against other materials (cold and warm irons, copper, etc.). Based on the existing production pricing for iron and second generation (2G) HTS wires, type 4 may be a more cost-effective solution.

The design considerations and challenges of an HTSWTG are associated with optimizing the use of materials and space while meeting electrical, mechanical, thermal, economic, and reliability requirements. Typical parameters involved are: low mass and size, minimum use of superconductors, low capital cost, high efficiency, and high levels of reliability and stability.

Regarding grid integration into the power network, HTSWTGs have faster dynamic responses compared with conventional wind turbine generators, may provide a larger dynamic stability limit, and also are able to provide better damping than conventional generators because they are more resistant to grid transient faults.

BASIC SCIENCE

In 1911, superconductivity as a physical phenomenon was discovered by Kamerlingh Onnes during a low-temperature conductivity measurement of mercury (Hg). In this experiment when the temperature dropped to 4.2K (-269°C), the resistance of the Hg dropped below the measuring device's limit and was taken virtually as zero. From then on, superconducting technology became more and more attractive in various areas including energy, information, transportation, medical, scientific instruments, defense, etc. Since then, earlier-developed metallic low-temperature superconductors (LTSs) always operated at 4.2K (-296°C) or below, which requires the use of costly liquid helium refrigeration for cooling purposes. Due to the complexity and cost of liquid helium refrigeration equipment, the LTSs were rarely used in applications.

A breakthrough was made in 1986 with a lanthanum-based cuprate perovskite material that had a transition temperature of 35K (-238°C). Replacing the lanthanum with yttrium (that is, making yttrium barium copper oxide [YBCO]) raised the critical temperature to 92K (-181°C). This temperature jump is particularly significant because it allows liquid nitrogen as a refrigerant, replacing liquid helium. This is important commercially because liquid nitrogen can be produced relatively inexpensively, even "on site," avoiding some of the problems (for example, solid air plugs) that arise when liquid helium is used in piping. The HTS materials label is typically reserved for those with a critical temperature greater than the boiling point of liquid nitrogen (77K or -196°C).

The question of how superconductivity arises in HTSs is one of the major unsolved problems of theoretical condensed-matter physics. The mechanism that causes the electrons in these crystals to form pairs is not known. The superconducting state is limited by critical flux density, critical current density, and critical temperature. Technological research focuses on making HTS materials in sufficient quantities to make their use economically viable and to optimize their properties in relation to applications.

Two key physical properties are identified in superconductors: one is zero resistance, and the other the complete diamagnetic phenomenon. In electrical power applications, zero resistance is often used as it implies high current capacity and extremely low ohm loss. However, diamagnetic and superconducting normal state transition properties are also of important practical value.

Using the high current density and, consequently, the high magnetic field density generated by the current, superconducting coils, cables, generators, motors, transformers, and magnetic energy storage systems have been invented and developed.

Superconducting wire is wire that is made of superconductors. Its advantages over copper or aluminum include higher maximum current densities and zero power dissipation. Its disadvantages include the cost of refrigeration to cool to superconducting temperatures (often requiring cryogens), the danger of wire quenching (a sudden loss of superconductivity), the typical inferior mechanical properties, and the cost of wire materials and construction. Often the superconductor is a filament in a copper or aluminum matrix that carries the current if the superconductor should quench for any reason. The superconductor filaments can form a third of the total volume of the wire.

Looking to the future, it would be highly desirable for the next-generation room-temperature superconductors (RTS) (precisely, temperatures above 0°C or 274K) to be developed for commercial availability. When such a day comes, superconductivity would offer unprecedentedly significant benefits in cost savings and performance improvement and would revolutionize every aspect of electrical machine design.

POTENTIAL IMPACT

Wind turbines wound with superconducting wire instead of regular copper could turn today's 2–3-MW generators into +10-MW superconducting direct-drive generators to enter the offshore wind-power market [23]. The absence of the gearbox is the main benefit, and the reduced weight and size is secondary. However, the main challenge of the superconducting direct-drive technology is to prove that its reliability is superior to the alternative drive trains based on gearboxes or PMs.

Superconducting wind turbines are expected to play a unique role offshore since conventional technology cannot achieve the necessary "power per tower." The increase in power density provided by superconducting turbines significantly reduces generator weight and maximizes the power per tower, turning wind power into a more economically viable alternative.

Theoretically, large generators with superconductors can be increased to +10 MW while, at the same time, reducing a unit's weight and size. Superconducting generators can also be built with less than 1% of the rare earths required for manufacturing the current PM generators.

The innovative direct drive should reduce transport and maintenance costs and extend the turbine's service life.

Improved fault ride-through (FRT) capacity of the HTSWTG would help minimize the need for maintenance and the likelihood of machine breakdowns.

Application of HTS coils to large wind turbine generators will provide potential benefits for wind turbine development in lowering the overall cost of wind energy while improving energy efficiency.

VALUE TO THE INDUSTRY

- Superconducting technology may enable significant improvements to the generator and eliminate the gearbox. Researchers estimate that they can cut the cost of offshore wind turbines by approximately 30%. They also say that a superconducting drive system could reduce the cost of operating wind turbines and boost wind turbine life as well [19]. Recent studies conducted by GE Power Conversion show that the lifetime energy saving for a superconducting wind turbine compared to a conventional machine could be as much as 20% for offshore or desert machines above 10 MW [16].
- The keys are in reducing the size and weight of the generator, while dealing with the lower shaft speed and higher torque needed to support industry's quest for larger-scale wind platforms (in the 10–15-MW range), to maximize clean wind power opportunities in the United States and around the globe.
- Superconducting wind generators use high magnetic fields, requiring less steel than conventional generators, and only 1% of the rare earths prevalent in PM machines, reducing the dependency on such materials.

- The larger potential power levels of these machines, coupled with better energy-conversion efficiency leads to more favorable economies of scale (for example, fewer towers for a given wind farm output) that will reduce the cost of energy produced by wind turbines.
- Superconducting generators may provide a larger dynamic stability limit and better FRT capability, facilitating their integration into the power network.

The estimated timeframe for commercial deployment of the first HTSWTG units is ~5 years. Machines based on RTSs are probably around 10–15 years away.

STATE OF THE TECHNOLOGY

There are a number of developers of different types and concepts of superconducting wind turbine generators. The level of maturity for the main design construct of large-scale HTS generator manufacturers is estimated as follows [7]:

8 MW and Beyond – Proposals/Investigations			
Manufacturer	**Transmission**	**Generator**	**TRL* (1-9)**
American Superconductor (AMSC)	Direct drive	**HTS- 10 MW Sea-Titan** HTS super-conducting field winding/copper armature winding.	5–6
Converteam	Direct drive	**HTS- 8 MW** 2G YBCO-coated HTS wire/air gap design.	5–6
General Electric	Direct drive	**LTS- 10–15 MW** LTS (43K/-230°C) rotor windings. Rotating armature.	6–7
Advanced Magnet Lab	Direct drive	**MgB2 10 MW** Fully supercon-ducting gene-rator. Supercon-ducting field and armature winding.	5–6

** TRL – technology readiness level*

Key enablers for HTS machines include:

- Cost reduction
  - Reduce the cost of HTS wire (all-chemical conductor manufacturing process/volume production)
  - Reduce the cost of cryogenic and vacuum manufacturing (components such as cryostats and large stainless steel structures/ investigate the use of lower-cost materials that are not normally used in cryogenic and vacuum engineering)
- Industrialization of cryocoolers
  - Low maintenance or maintenance free
  - Able to withstand high G forces due to rotation for rotor-mounted coolers
  - Able to produce higher efficiencies
- Industrialization of low-temperature rotating coupling
  - Robustness and long-term reliability are important.
  - Susceptibility to misalignment needs to be reduced.
- Industrialization of instrumentation and components (high-pressure vacuum gages, valves, etc., capable of withstanding high G forces due to rotation
- Industrialization of high-vacuum pumps (qualify for high Gs due to rotation and minimize maintenance)

European Union (EU) project SUPRAPOWER and Department of Energy Advanced Research Project Agency-Energy (ARPA-E) research and development (R&D) projects to advance the next generation of wind technology are funding superconducting machines and HTS wire development.

National laboratories such as Brookhaven, Oak Ridge, and Los Alamos in the United States, Karlsruhe Institute of Technology (ITEP) in Germany, and many universities worldwide are involved in R&D projects for HTS wire improvement and new generator concepts development.

An active patent development from Toshiba, Mitsubishi, Westinghouse, Converteam, ABB, Doosan, AMSC, GE, and Siemens is associated with superconducting and superconducting machine development.

The benefits of applying HTS technology to large wind generators are compelling. It is estimated that approximately five to seven years is the time to market for commercial HTS generators, starting with large offshore 10–15 MWe machines [6].

PUBLIC LITERATURE

There are a number of articles and publicly available technical reports that address the issue of superconducting wind turbine generators. See the links below:

- "Comprehensive Assessment of Direct -Drive High Temperature Superconducting Generators in Multi-Megawatt Class Wind Turbines." URL: http://www.nrel.gov/docs/fy11osti/49086.pdf
- "High Temperature Superconducting (HTS) Technology for Generators." URL: http://orbit.dtu.dk/fedora/objects/orbit:107410/datastreams/file_10145277/content
- "Development of Superconducting Wind Turbine Generators." URL: http://orbit.dtu.dk/fedora/objects/orbit:111354/datastreams/file_10376734/content
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NEXT MILESTONE

Superconducting technology has the potential to provide technical solutions to the upscaled offshore turbines (+8–15-MW range), which will lower the production cost of electricity over the +20-year lifetime of the entire wind farm, but the primary challenge of the superconducting direct-drive technology is to prove that it has superior reliability to the alternative drive trains based on gearboxes or PMs.

A strategy of successive testing of superconducting direct trains in real wind turbines of the ~10-KW, 100-KW, 1-MW, and 10-MW ranges will be followed to secure the accumulation of reliability experience, with large-scale demonstration projects that will validate long-term performance and operations and maintenance (O&M) cost advantages afterward.

AMSC and Converteam have built superconducting motor prototypes for the U.S. Navy, and Converteam built a small HTS hydro-generator (TRL ~ 5–6). An example of superconducting direct wind application is the recent (April 2013) successful completion by GE of trials of its Hydrogenie 1.7-MW LTS wind generator [16] at the GE Power Conversion facility in Rugby, England (TRL ~7).

Cost of future HTS tape must come down by a factor of 10 to be competitive with PM technology. Brookhaven National Laboratory, funded by ARPA-E, is working to develop an improved superconducting wire for wind generators (TRL-3).

The EU-supported SUPRAPOWER is a four-year project targeted to develop a large direct-drive superconducting offshore wind turbine. One key development will be a rotating low-cost cryostat to cool the superconducting coils to 20K (-253°C) through pure heat conduction that will also require highly effective thermal insulation (TRL-4).

Commercial deployment of +8-MW offshore wind turbine superconducting generators is expected in a five to seven year timeframe (~2020) [6].

INDEPENDENT ASSESSMENTS

No independent assessments of pilot/demonstration testing of superconducting wind turbine generator machines performed by other organizations are publicly available at this time.

"Comparative Assessment of Direct Drive HTS Generators in Multi-MW Class Wind Turbines" was published by the National Renewable Energy Laboratory (NREL) in October of 2010 (NREL/TP-5000-49086) using an AMSC high-temperature superconductor direct-drive 10-MW design [4].

COLLABORATION

CURRENT COLLABORATORS

Collaboration and commitment are needed from the wind turbine manufacturers, HTS tape manufacturers, and wind turbine operators. Large-scale demonstrators are needed to test performance and reliability. GE and Oak Ridge National Laboratory (ORNL) are collaborating in the development of a 15-MW superconducting wind turbine generator. For the EU-funded SUPRAPOWER, project companies from Germany (Karlsruhe Institut Technologie, Oerlikon)), Spain (Acciona, Tecnalia), Italy (Columbus Superconductors), and UK (University of Southampton) are collaborating.

Nonproprietary copies of the EU/DOE funded project reports will be available when projects are finalized.

These companies have expressed an interest in this technology and a willingness to participate in some superconducting generator R&D projects: KEMA (Netherlands), E-On (Germany), Doosan (South Korea), Hitachi (Japan), Sumitomo (Japan), Advanced Magnetic Labs (United States), and ASG Superconductors (Italy).

EPRI ENGAGEMENT

The Electric Power Research Institute (EPRI) is not currently engaged with any of the above-mentioned technology developers of superconducting generators for large wind turbines.

Original-equipment manufacturers involved in the development of new larger offshore wind turbines are the primary targets at the level of development of this technology, which may provide a competitive market advantage to successful early adopters.

EPRI's role as a provider of independent technology/prototype results assessment may be further explored if it is in the interest of our funders, but commercial interests of the industrial partners may be a barrier.

For EPRI to engage in independent evaluation of performance and reliability, the TRL should be 7 or higher when the first-of-a-kind machines are available for extended testing..

OPPORTUNITIES FOR COLLABORATION

EPRI's role regarding this technology could take one or more forms:

- As an *observer of the development and testing of the prototypes* announced for the different superconducting key technologies.
- As a *provider of independent assessment of the first pre-commercial units* to monitor "as-built" long-term reliability, efficiency, and O&M costs versus design targets. This may be of interest for reducing the risk and financial cost of subsequent applications.
- Further engagement of EPRI as a *participant in the development, construction, and testing of new prototypes*. This would require substantial funding, which is not in EPRI's current R&D plans.

NEXT STEPS

Key next steps in the development are plans to scale up the TRL from 5–6 to 7–8. Paving the way to early commercial deployment will require addressing issues mainly associated with HTSWTG cost reduction and reliability improvement such as:

- Development of low-cost, high-performance HTS wire/tape to reduce the cost of HTS generators
- Development, optimization, and testing of lower cost cryocoolers that can reliably and efficiently cool the coils to the critical temperatures required
- Development and testing of the HTS optimized generator topology concept to reduce the cost and weight and maximize the power per tower for offshore wind turbines
- Construction/field testing of pre-commercial demonstration units to validate performance and reliability as a first step to early commercial deployment

EPRI may contribute to accelerating the development and deployment of this technology through tailored collaboration and funding of on-going prototypes to be tested during the next few years, as well as performing later independent performance assessments of the first commercial on-shore and offshore field-deployed units, if this would be in the interest of our members.

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