Progress in HTS Power Applications in the United States

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Synopsis: The field of high temperature superconducting (HTS) power applications is very active in the United States. On the one hand, it is driven by the needs of the electric power grid, which has suffered from declining investment for many years. HTS cables, reactive power devices and fault current limiters address power grid issues. An HTS-based dynamic synchronous condenser is the world's first commercial power product. On the other hand, there is great interest from the US military in applications such as ship propulsion motors, lightweight generators, gyrotron microwave sources and degaussing cables.

Keywords: high temperature superconductor, HTS wire, HTS cable, synchronous condenser, fault current limiter, ship propulsion

1. Introduction

The United States spearheads the worldwide development and commercialization of high temperature superconductor (HTS) power applications.

This activity is based on the availability of robust, high performance and long-length HTS wire.¹⁾ Along with their zero-resistance DC current flow, these wires have achieved a current carrying capacity of over 100 times that of conventional copper in typical power applications, as illustrated in **Fig. 1**. With its Devens manufacturing plant in Massachusetts, American Superconductor (AMSC) has been for many years the world's leading manufacturer of first generation (1G) HTS wire, based on multifilamentary composite of the $(\text{BiPb})_{2.1}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ superconductor. It produces and ships over 300,000 m a year into a variety of applications, and offers a variety of wire configurations with performance at 77 K of from minimum 115 to minimum 155 A in lengths up to 1,000 m. AMSC and Intermagnetics General's (IGC) SuperPower (SP) subsidiary in Schenectady, New York, are both actively developing the second generation (2G) HTS wire based on a coated conductor architecture with $\text{RE}_1\text{Ba}_2\text{Cu}_3\text{O}_7$ (often called YBCO for short), where RE stands for yttrium or other rare earth elements. There are additional efforts at MetOx in Houston and Oxford Superconducting Technologies in New Jersey. Although production of 2G wire is still limited, AMSC and SP are leading the world in establishing manufacturing lines already producing over 1,000 m per month, enabling the first applications demonstrations with 2G wire.²⁾ AMSC has reported a performance of 70 A (159 A/cm-width) at

77 K in its 0.44 cm wide laminated wire architecture over 85 m. SP has reported 107 A/cm-width at 77 K in its 0.4 cm wide electrodeposited-copper-stabilized wire over 206 m.

Fig. 1 Compared to a massive 1,000 A copper cable, 9 AMSC HTS 1G wires carry as much current at 77 K (courtesy of AMSC)

Perhaps the main driver for HTS applications in the United States is the state of its electric power grid, which suffers from years of declining investment. As evidenced by a series of major blackouts in recent years, the grid is dangerously overloaded and lacks the reactive power needed for adequate stabilization. As cities grow and require increased power, the ability to place overhead power lines or even underground cables to service dense urban areas has become extremely limited. Furthermore, in most large urban centers, fault currents are growing with the addition of new power sources and are reaching the limits of circuit breaker technology. It is becoming increasingly recognized that all of these issues can be addressed with HTS technology. The US Department of Energy ((DOE) has sponsored a major program developing grid-related power applications, through an innovative program called the Superconductivity Partnership with Industry (SPI).²⁾ But there have also

Received March 1, 2006

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been fully industrially-funded projects, such as AMSC's development of a commercial HTS-based dynamic synchronous condensers, with partial support by the Tennessee Valley Authority (TVA).

The other main driver for HTS applications in the United States is the Department of Defense. The Office of Naval Research has sponsored a major program on HTS-based ship propulsion motors at AMSC, while the Air Force has sponsored developments such as lightweight high-power-density generators for airborne applications and Active Denial gyrotron systems.

2. HTS Cables

Under its SPI program, DOE has sponsored a series of HTS cable projects of increasing sophistication over the years.²⁻⁴⁾ At present, the world's longest-operating HTS demonstration, shown in **Fig. 2**, is a three-phase cold dielectric, 12.4 kV and 1250 A, 30 meter HTS cable system, developed by the Southwire Company of Carrolton, Georgia, along with Oak Ridge National Laboratory (ORNL) and supplying 100% of its power to Southwire's industrial manufacturing complex in Carrolton since January 2000. The 1G wire was supplied by IGC, as well as by Nordic Superconductor Technologies from Denmark. The system has operated for over 30,000 hours. It can withstand a 12 kA, 1 sec fault current and has successfully survived a direct lightning strike directly in the HTS yard. This project continues under the auspices of Ultera, a Southwire/nkt cables Joint Venture.

Fig. 2 Southwire 30 m 12.4 kV HTS cable installation in Carrolton, Georgia. With over 30,000 hours of operation, it is the world's longest operating HTS system.²⁾

A second SPI project is underway with Ultera, in collaboration with American Electric Power (AEP), to install a 200 m 13.2 kV, 3.0 kA cable system in AEP's Bixby substation in Columbus, Ohio.²⁾ Other partners

include ORNL for research, testing and cryogenic design, Praxair for cryogenic system design, construction and operation, and AMSC for the HTS wire. The system will be installed underground, with field-installed cable joints built in an underground manhole. The cable uses the novel cryogenic-dielectric "triax" design, with the three phases wound concentrically, thus eliminating the need for a shielding layer and minimizing the wire cost. After successful testing of a 5 m cable and terminations, the full cable has now been constructed and delivered to the Bixby site, with energization expected by mid 2006. The one triax cable will replace 9 1000 kcmil copper cables in a 3x3 duct bank, demonstrating the superior compactness of the HTS cable and maximizing the use of existing rights of way. By offering transmission level power at distribution voltage, permitting issues are vastly eased, and substations in dense urban areas can be reduced in size as smaller breaker and switching stations only.

Another active SPI project is the Albany Cable Project, bringing together SuperPower as project manager and 2G wire supplier, Sumitomo Electric as 1G wire and cable supplier, BOC as cryogenic supplier and Niagara Mohawk as host utility.²⁾ The project is also supported by New York State funds through NYSEDA. A goal of the project is to address real-world utility concerns including installation, maintenance, reliability and compatibility with the existing grid. The 350 m 34.5 kV 800 A cable will link the Menands and Riverside substations in the Albany area of New York State. The site is now prepared, cryogenic infrastructure installed and the cold-dielectric, 1G three-phase cable with three individually shielded phases in one compact cable structure shipped from Sumitomo for installation projected in early 2006. In a further phase of the project, a 30 m section of cable built from 2G wire will be connected through a joint on one end of the 1G cable. A four layer 1 m prototype cable with 2G wire has been successfully fabricated and tested.

The third SPI cable project addresses the first transmission voltage level installation, in the Long Island Power Authority (LIPA) grid in New York State.²⁾ The project brings together AMSC as project manager and wire supplier, Nexans as cable supplier, Air Liquide as cryogenic supplier and LIPA as host utility. The cable, connecting to the Holbrook substation on Long Island, is 610 m long, and will operate at 138 kV with a capacity of 2,000 A or 574 MVA, by far the largest rating of any in-grid HTS project worldwide. Each of the three phases consists of a separate shielded cold-dielectric cable using 1G wire. 30 m system tests are in progress, to qualify the cable up to a 161 kV rating. The terminations and test site are shown in **Fig. 3**. All the wire has been delivered, and cable manufacturing will begin upon completing of the high voltage testing, with installation targeted towards the end of 2006.

Fig. 3 161 kV rated terminations in a Nexans test of a prototype cable for the 138 kV transmission-level LIPA cable project.

Another interesting application of HTS cable technology is in degaussing systems for navy ships.⁵⁾ A current loop installed around the circumference of a ship's hull can cancel out the ship's magnetic signature arising from magnetic materials used in the ship's construction. This is particularly important to protect ships from magnetic influence mines. A recent study⁵⁾ projects that an HTS cable system can offer significantly reduced weight and volume compared to a conventional system based on copper.

3. HTS-Based HTS Machinery

Reliance Electric/Rockwell Automation started HTS motor development in collaboration with AMSC under a DOE SPI program.^{2,6)} This led to a 1000 hp motor tested in 2000. This was a 60 Hz 1800 rpm ac synchronous motor with four poles, with HTS field coils manufactured by AMSC using its 1G wire. Rockwell Automation now continues its program in collaboration with SP, directed to the goal of ultra-efficient HTS motors. The present project focuses on the use of 2G wire supplied by SuperPower, and a 7.5 horsepower, 1800 rpm motor using a total of 26 m of 2G wire has been demonstrated at 77 K.²⁾ The project also involves research on cost-reduction and reliability improvement technologies. Rockwell sees 2G wire as key to making HTS industrial motors viable in the range above 1000 hp.

As a direct industrial investment, AMSC designed, fabricated and demonstrated in 2001 a 5000 hp four pole 60 Hz motor in which both rotor and stator were optimized for a compact design.⁶⁾ The motor used AMSC 1G wire. Then, under an Office of Naval Research contract, AMSC designed and fabricated a 5 MW 230 rpm high torque ship propulsion motor, again using HTS coils fabricated from its 1G wire. The air-core, liquid-cooled stator was produced by Alstom in Rugby, England. The cooling system was closed cycle gaseous helium with Gifford McMahon (GM) refrigerators. This motor was delivered to the Navy at its Center for Advanced Power Systems at Florida State University in Tallahassee, where it successfully underwent full load and simulated ship testing.⁷⁾ As shown in **Fig. 4**, the motor is dwarfed by two conventional 2.5 MW load motors, demonstrating the remarkable size advantage, and corresponding weight advantage, of the HTS machine. This is of particular importance in ship applications. The motor has now been delivered to a Navy facility in Philadelphia for noise signature testing. Through the elimination of magnetic components in both the rotor and stator of this machine, cogging torques associated with the magnetic material are eliminated, making the HTS motor much quieter than conventional iron-based motors.

Fig. 4 AMSC 5 MW 230 rpm HTS ship propulsion motor is dwarfed by two 2.5 MW load motors at the right, demonstrating the major advantage of HTS rotating machine technology in size and weight.

The success of the 5 MW motor led to a follow-on contract with ONR for a 36.5 MW ship propulsion motor, in collaboration with Northrop Grumman Marine Systems and Ship Systems, Ideal Electric Company, Syntek, Mississippi State University, CAPS, and MSCL LLC.⁶⁾ This high torque, 120 rpm motor, also based on 1G wire, is capable of driving the Navy's new generation of destroyer, called DDX. Its weight of

75 tons is a major advantage compared to over 300 tons for conventional alternatives. Construction is well underway, as illustrated in **Fig. 5**, and the motor is expected to be delivered to the Navy in September 2006. This is by far the largest and most powerful HTS equipment manufactured to date.

Fig. 5 Assembled rotor of AMSC/Northrop-Grumman 36.5 MW, 120 rpm motor.

Perhaps the most remarkable development in the area of rotating machines has been AMSC's manufacture, with partial support of TVA, of a ± 8 MVAR dynamic synchronous condenser.^{3,6)} The synchronous condenser is essentially a generator without a real power source. It can be of great value in an electric power grid as a supplier of dynamic reactive (out-of-phase) power for voltage support and power factor correction. Lack of adequate dynamic reactive power support has been implicated as a key factor in most of the recent blackouts in the United States and around the world. The HTS synchronous condenser, like other HTS rotating machines, benefits by its small size and fast-reacting transient voltage support. The trailerized unit, shown in **Fig. 6**, is cooled by three GM refrigerators. It was installed in 2004 at Gallatin, Tennessee, next to a steel plant where the arc furnace generated significant flicker, that is, noise and significant voltage sags, into the surrounding grid. Acting as a flicker compensator, the synchronous condenser experienced over 5,000,000 reactive power events over a year period, successfully demonstrating its robustness and capability.⁸⁾

Fig. 6 AMSC's trailerized ± 8 MVAR dynamic synchronous condenser.

Now, TVA has placed a commercial order to AMSC for two additional HTS synchronous condensers, rated at 12 MVAR, for delivery within a year. This is the world's first commercial order for HTS power equipment, and as such it is a major benchmark for the entire field of HTS applications. These units will also be fabricated using AMSC's 1G wire.

There has been active work on generators as well. General Electric (GE) Global Research and GE Energy, working with American Electric Power and Oak Ridge and Los Alamos National Labs, working under a DOE SPI program, fabricated and tested a 1.8 MVA generator using AMSC 1G wire.²⁾ The system had a conventional iron core with an air-cooled conventional armature. The HTS coils on the rotor were cooled in a closed cycle cryogenic system with two-stage GM cryocoolers. They then moved on to design a 100 MVA generator, with a focus on improved efficiency and retrofit of existing generators with HTS rotors.²⁾ GE recently closed down this project, citing an inability to meet GE's internal commercial benchmarks at the present state of the technology.

The US Air Force is actively sponsoring development work on lightweight multimewatt high-speed ($>10,000$ rpm) generators for directed energy weapon (DEW) and other airborne applications.⁹⁾ This includes a program with Long Electromagnetics (LEI) to construct a test rig or pseudo generator, allowing rotor coils to be replaced by different HTS coils for high rotational speed testing with a simple stator coil configuration in open cycle liquid hydrogen. A more substantial HTS generator program has been awarded to GE for construction of a fully operational power system. These programs will use 1G wire initially but then transition to 2G.

4. Other Applications

Waukesha Electric Systems, a leading US transformer manufacturer, manages an ongoing transformer development project under the SPI program.²⁾ An initial phase of this project, directed to a 5/10 MVA transformer demonstration, involved SuperPower Inc. as system designed and manufacturer, ORNL for research and testing support, and Energy East as the involved utility. This phase has been concluded because of dielectric failure during testing. Ongoing work is focused on dielectric testing of cryogenic materials, prior to the initiation of a new demonstration.

Another area of great interest for HTS application is for fault current limiters (FCL). An SPI project managed by SuperPower brought together Nexans as materials supplier of the bulk rods used in the project, ORNL and LANL for research and testing support, and AEP as a host utility, with additional support from the Electric Power Research Institute (EPRI).²⁾ The goal of the project was to demonstrate a 138 kV FCL after an initial phase. The system design is based on a matrix configuration and enhanced switching using magnetic fields. In a first phase of the project, a single-phase 8.8 kV FCL was demonstrated, limiting a prospective 25.6 kA current to 21.4 kA. However, during work on the second phase, failure under high voltage testing has caused this project to be placed on hold.

AMSC has earlier proposed an approach to FCL design using 2G wire, which has a much faster switching characteristic than the bulk rods, as well as the potential for much lower cost.¹⁰⁾ In an alliance with Siemens, which has earlier built FCL systems using thin film YBCO, AMSC's 2G wire has been wound into bifilar coils, and rapid switching and recovery has been demonstrated in a liquid nitrogen bath.¹¹⁾ Discussions are under way for a project to demonstrate an in-grid FCL based on 2G wire.

An SPI project addresses flywheel energy storage, with Boeing as project manager and bulk materials supplier, Ashman Technologies supplying a motor/generator controller, Ballard Power Systems supplying the power electronic system controller, Toray Composites supplying high strength composite materials, Praxair supplying cryogenics, Argonne National Laboratory (ANL) supplying the superconducting bearing, and Southern California Edison as host utility.²⁾ A 100 kW/ 5 kWhr UPS flywheel system has been constructed and is under test. A 10 kWhr system is also under preparation.

Because of the dielectric difficulties which have arisen, particularly in the earlier transformer and FCL SPI projects, DOE has initiated a program at ORNL of strategic dielectric and high voltage research called the Cryogenic Dielectrics Initiative.²⁾ The project has

studied the breakdown strengths and partial discharge of fiberglass reinforced plastic, polyetherimide and epoxy materials in both liquid and gaseous nitrogen. A mechanism of material aging has been found in desorption of air condensate at low temperature, contributing to partial discharge.

On the US Department of Defense (DOD) side, a program called Active Denial targets the use of microwaves power as a non-lethal system crowd-dispersal. The microwaves are generated by gyrotron sources which require a several Tesla magnetic field. Present low temperature systems suffer from the extra weight, complexity and cool-down time of low temperature superconductors. Under contract from DOD, Cryomagnetics of Oak Ridge, Tennessee, has built and tested a 3.6 Tesla magnet system using AMSC 1G wire and operating at 37 K with a GM refrigerator.¹²⁾ However, further simplification and increased temperature operation is being sought through the use of 2G wire, so as to enable airborne or humvee operation with rapid cool-down times.

In conclusion, the rapid rate of progress in these many HTS projects, coupled with the launching of the first commercial HTS-based power product – the dynamic synchronous condenser – bodes well for the continued leadership of the United States in this important and multi-faceted field.

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