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Development Status of Superconducting Rotating Machines

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***Abstract*:** Advances in High Temperature Superconductors (HTS) are enabling a new class of synchronous rotating machines (*SuperMotors* and *SuperGenerators*) that can generically be categorized as *SuperMachines*. Compared to conventional machines of equivalent rating, these *SuperMachines* are expected to be less expensive, lighter, more compact, efficient, and provide significantly superior stable operation in a power system. The field windings are made with HTS conductor material (BSCCO, or Bi-2223) which operates at 35-40 K and can be cooled with inexpensive, off-the-shelf cryocoolers available from a number of manufacturers throughout the world. As will be discussed, these advanced *SuperMachines* are attractive for use in industrial as well as naval and commercial maritime industry applications. This paper discusses recent *SuperMachine* work at AMSC and other companies. HTS rotating machine technology is maturing rapidly, and electricity producers as well as the end-users will undoubtedly benefit enormously from these advancements.

I. INTRODUCTION

The advent of high-temperature superconductivity has created the opportunity for a quantum leap in the technology of large electric machines. HTS-based motors and generators will be smaller, lighter, more efficient, and less expensive to manufacture and operate than conventional machines. The potentially significant cost, size, weight and efficiency benefits of superconducting machines will change the dynamics of the electrical machinery industry. This unique situation leads to reduced manufacturing costs.

The initial use for HTS motors will likely be in transportation applications, particularly naval and commercial ship (marine) electric propulsion, where critical size and weight savings will provide a key benefit by increasing ship design flexibility. Electric drive has already penetrated the cruise ship segment of the market because of its marked advantages over competing mechanical systems. The increased power density and operating efficiency as well as other benefits of HTS based marine propulsion systems will significantly further expand the attractiveness of electric propulsion systems. HTS motors are ideal for use in pumps, fans, compressors, blowers, and belt drives deployed by utility and industrial customers, particularly those requiring continuous operation. These motors will be suitable for large process industries such as steel milling, pulp and paper processing, chemical, oil and gas refining, mining, offshore drilling, and other heavy-duty applications.

Superconducting wire in its Low Temperature Superconductor (LTS) form has been in widespread use now for over 30 years, and commercial applications today range from high-powered particle accelerators to sensitive resonance imaging systems utilized for medical diagnostics. General Electric and Westinghouse independently conducted large superconducting generator design studies during the 1970’s; both approaches were based on LTS wire. General Electric also built and tested a 20 MVA superconducting generator in the 1970’s, and a Japanese consortium built and tested a 70 MW generator during the 1990’s. These machines employed LTS wire made up of a niobium-titanium (NbTi) alloy. The high current density achievable in superconducting electromagnets makes it possible to create very compact and power-dense rotating machinery. However, even at such large ratings, the complexity and cost of the refrigeration equipment, and the challenging nature of thermal isolation systems that are necessary for allowing LTS materials to operate at an ultra-low 4K, have made any conceivable commercialization of this early superconducting technology in rotating machine applications a prohibitive concept.

However, rapid advances in the development of HTS wire over the past 13 years have resulted in superconducting electromagnets that can operate at substantially higher temperatures than those made of LTS materials, and which as a consequence can utilize relatively simpler, less costly, and more efficient refrigeration systems. These factors make HTS wire technically suitable and economically feasible for use in the development and commercialization of motor and generator applications at power ratings much lower than could be considered with LTS wire.

American Superconductor Corporation (AMSC) has built and tested a 5000 hp, 1800-RPM motor for industrial market. They have also developed a design for a 5 MW HTS (“model”) model motor for ship propulsion; this motor demonstrates technologies to be employed in a full-size 25 MW, 120 RPM HTS motor. The model motor is scheduled for completion and testing by the end of 2002. AMSC has also developed a conceptual design for a 50 MW, 3600-RPM HTS generator. Other companies are also developing *SuperMachines*. A 1000 hp, 1800-RPM motor funded under the SPI program, and built by a team consisting of Rockwell Automation, AMSC, and others, was successfully operated in May 2000. Siemens demonstrated a 550 hp, 1800-RPM motor in the summer of 2001. GE has just won a DoE-SPI contract for the design and development of a 100 MVA HTS generator.

The discussion in this paper is centered on applications of HTS *SuperMachines* to an All-Electric Ship. Figure 1 shows a single line diagram for a ship electrical system employing superconducting generators, propulsion motors and general-purpose industrial motors.

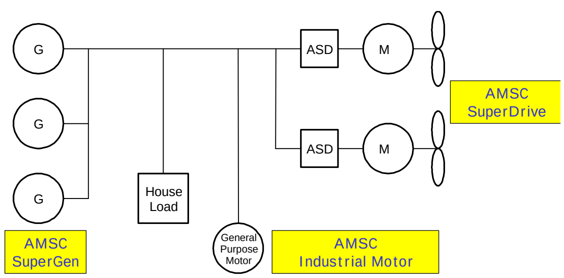

Figure 1: Ship electrical system components

II. HTS Wire Status

Over the past ten years, the performance of multifilamentary composite HTS wire has continually improved. Currently, AMSC is producing this wire at a rate of about 500km/year and the end of 2002 will produce 10,000 km/year in its new factory. This Bi-2223 high current density wire is available for industrial applications and prototypes. Bi-2223 high strength reinforced wire is able to withstand close to 300 MPa tensile stress and 0.4% tensile strain at 77K. Reinforced wires provide a mechanically robust and reliable product, which are suitable for making high performance prototype propulsion motors and generators.

III. SuperMachine Topology

The major components of a rotating machine employing HTS winding is shown in Figure 2. Only the field winding employs HTS cooled with a cryocooler subsystem to about 35-40K. The cryocooler modules are located in a stationary frame and a gas, such as helium, is employed to cool components on the rotor. The stator winding employs conventional copper winding but with a few differences. The stator winding is not housed in conventional iron core teeth because they saturate due to high magnetic field imposed by the HTS winding.

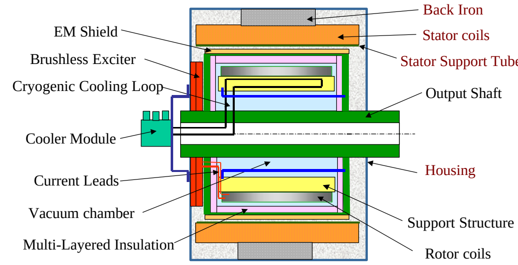

Figure 2: A block diagram of an air-core machine

IV. SuperGenerator

Compared to conventional generators, HTS generators are expected to be less expensive, lighter, more compact, efficient and reliable, and significantly superior at maintaining power system stability. They also exhibit higher efficiency under partial load conditions and could operate as virtual condenser to deliver its rated current.

The *SuperGenerator*[1] shown in Figure 3 has three major subsystems; 1) rotor, 2) rotor cooling and 3) stator. Physically, this generator is expected to be about half (1/2) the length and two-thirds (2/3) the diameter of a conventional machine. This generator has a low synchronous reactance of 0.28 pu but the transient and sub-transients reactances are similar to those of conventional machines. The overall efficiency of the generator is 98.6% which is retained down to 1/3rd of the rated load. The majority of losses (65%) are in the conventional copper armature winding. The cryogenic cooling system power consumption is merely 2% of the total losses in the machine. *SuperGenerator* produces nearly clean AC voltage in the stator winding. Both rotor and stator windings generate minimal harmonics. The field winding produces 2% of 5th harmonic voltage in stator winding; all other harmonics are negligible.

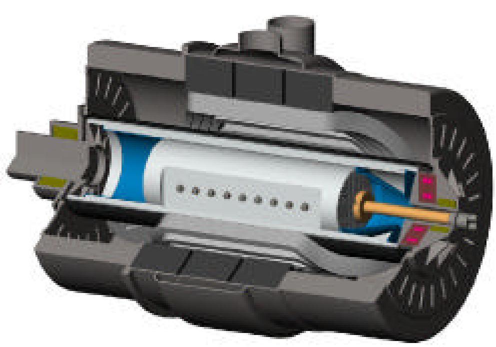
Figure 3: SuperGenerator assembly

V. SUPERDRIVE FOR SHIP PROPULSION

Modern electric drive has many advantages over competing mechanical systems. The advantages include redundancy, reliability, better fuel economy in many circumstances, reserve power when needed, better use of internal space allowing revenue producing space elsewhere, quietness, easier maintenance and improved ship safety.

A conceptual design has been developed[2] under an Office of Naval Research (ONR) contract for a 25 MW, 120-RPM HTS motor for ship propulsion. In order to demonstrate the key technologies employed in the 25 MW motor, a 5 MW motor preliminary design has been completed.

The 25 MW, 120-RPM HTS *SuperDrive* motor shown in Figure 4 is 2.65 m in diameter and 2.08 m long. It weighs 60 k-kg and generates structureborne noise of 48 dB at full-speed. The motor employs a 6.6 kV stator winding that is cooled with freshwater. The HTS rotor winding is cooled by off-the-shelf cryocoolers positioned in the stationary reference frame - a defective cooler could be replaced in less than 30 minutes without having to stop the motor. The motor has an overall efficiency of 97% at full speed and 99% at 1/3rd full-speed; this includes power consumption by the HTS rotor cooling system, but does not include losses in the Adjustable Speed Drive (ASD).

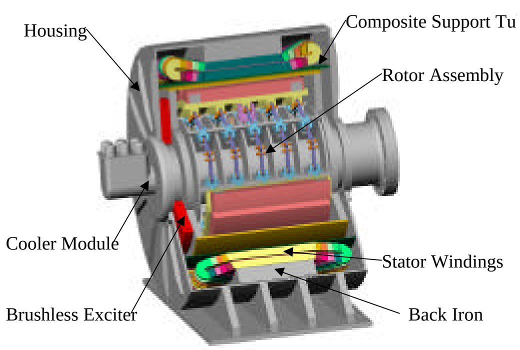

Figure 4: 25 MW ship propulsion motor

SuperGenerators and SuperDrive motors employing HTS technologies are compact, light and several points higher in efficiency (even at partial loads) will enable design of more economic ship for both in-hull and in-pod propulsion options.

VI. INDUSTRIAL SUPERMOTORS

The world's most powerful *SuperMotors* were developed with American Superconductor's first generation HTS wire. American Superconductor has demonstrated a 5,000 HP, 1800-RPM synchronous motor in July 2000. This *SuperMotor* undergoing factory testing is shown in Figure 5 in the fall 2001. The rotor assembly includes the HTS field winding operating at cryogenic temperature (~35 K), its support structure, cooling loop, cryostat and electromagnetic (EM) shield. The stator assembly includes AC stator winding, back iron, stator winding support structure, bearing and housing. This motor has met all design goals by demonstrating HTS field winding, cryocooling system and a novel armature winding cooled with fresh water.

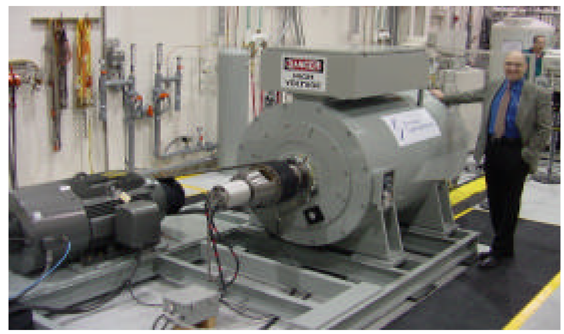

Figure 5: AMSC 5000 hp motor under test

V. CONCLUSIONS

The HTS technology is revolutionizing how electrical power is created, transmitted, stored, managed, and utilized. These HTS-based designs fundamentally change the value proposition for electric motors and generators and demonstrate that HTS technology has attained a proven level of maturity that is suitable for bringing high quality commercial products to market today. The successful design, fabrication and operation of two *SuperMotors* proves that the key technologies essential for the commercial introduction of HTS motors and generators are high performance, sufficiently robust, and affordable. HTS *SuperMachines* will be more compact, lighter, and more efficient than the conventional machines. Their small size and weight will translate to lower cost. HTS windings operating at an easily attainable temperature level (~35K), and cooled with low cost and dependable off-the-shelf refrigerators, will result in the fielding of highly reliable *SuperMachines*.

VI. REFERENCES

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