Superconducting Rotating Machines for Ship Applications*

超電導回転機械の船舶への応用

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高温超伝導体 (HTS) の進展は、モータおよび発電機双方の新しい種類の同期回転機を実現する。同等定格の従来の回転機と比較すると、これら高温超伝導体による回転機は、より安価に、軽く、高効率が期待され、さらに、電力システムにおける極めて優れた安定動作を提供する。界磁巻線は、35～40Kで動作し、世界中の多くの製造業者から容易に入手できるクライオクーラーが利用でき、安価に冷却できる HTS 高温超伝導体 (BSCCO, または Bi-2223) で作られる。このように、これらの先進的機械は、海軍および、商船・海事産業への応用において魅力あるものである。本文では、アメリカスーパーコンダクタ社 (AMSC) および、他の会社における最近の超電導機械技術について述べている。HTS 回転機技術は急速に成熟し、造船会社、ユーザーは、これらの進展により間違いなく多大な利益を受けるだろう。(畑中義博)

Abstract

Advances in High Temperature Superconductors (HTS) are enabling a new class of synchronous rotating machines, both motors and generators. Compared to conventional machines of equivalent rating, these machines 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. HTS motors and generators are attractive for use in naval and commercial maritime industry applications. This paper discusses recent superconducting work relating to these new machines at American Superconductor Corporation (AMSC) and other companies. HTS rotating machine technology is maturing rapidly, and ship builders as well as the

end-users will 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 [state other benefits such as lower cost of operation which opens up new markets, new ship hull designs that result in greater speed, more efficient hydrodynamic properties, etc.] .

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. All electric drives have already penetrated the

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cruise ship segment of the market because of their marked advantages over competing mechanical systems. The increased power density and operating efficiency of HTS-based marine propulsion systems will further expand the attractiveness of electric propulsion systems. HTS motors have practical application use in other industries as well; for example, they can be used in pumps, fans, compressors, blowers, and belt drives deployed by utility and industrial customers, particularly those requiring continuous operation. These motors are 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 use 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 prohibited the commercialization of LTS superconducting technology in rotating machine applications.

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 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 prototype 5000 hp, 1800-RPM motor for the industrial market¹. They have also developed a design for a 5 MW HTS prototype motor for ship propulsion which will demonstrate technologies to be employed in a full-size 25 MW, 120 RPM HTS motor. The 5MW motor is scheduled for completion and testing by the middle of 2003. AMSC has also developed a conceptual design for a 50 MW, 3600-RPM HTS generator. Other companies are also developing superconducting machines. 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 won a DoE-SPI contract (Fall 2001) for the design and development of a 100 MVA HTS generator.

The discussion in this paper is centered on applications of HTS superconducting machines 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 be in volume production in its new HTS wire manufacturing facility in Devens, Massachusetts. 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 propulsion motors and generators.

III. SUPERMACHINE TOPOLOGY

The major components of a rotating machine employing an HTS winding is shown in Figure 2. Only the field winding employs HTS wire 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 a 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. SUPERCONDUCTING GENERATOR

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 condensers to deliver its rated current.

The superconducting generator² shown in Figure 3 has three major subsystems; 1) rotor, 2) rotor cooling and 3) stator. Physically, the generator is expected to be about half (1/2) the length and two-thirds (2/3) the diameter of a conventional machine. The 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. The superconducting generator 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: Superconducting generator assembly

V. SUPERDRIVE FOR SHIP PROPULSION

Modern electric drive s have 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 developed³ 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 Superconducting Propulsion Motor (SPM) shown in Figure 4 is designed to be 2.65 m in diameter and 2.08 m long. It weighs 60 k-kg and generates structure-borne 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 allowing a defective cooler to 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

Superconducting generators and SuperDrive motors employing HTS technologies are compact, light and several points higher in efficiency (even at partial loads) and will enable new designs for both in- hull and in-pod propulsion options resulting in more economic ships.

VI. INDUSTRIAL SUPERCONDUCTING MOTOR

The world's most powerful superconducting motor was 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 superconducting motor 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. The motor was load tested up to 5,900 hp steady-state. Its operating parameters and characteristics are summarized in AMSC website <http://www.amsuper.com/5000hpparameters.htm>

VII. CONCLUSIONS

HTS technology is revolutionizing how electrical power is created, transmitted, stored, 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 superconducting motors proves that the key technologies essential for the commercial introduction of HTS motors and

generators are high performance, sufficiently robust, and affordable. HTS superconducting machines will be more compact, lighter, and more efficient than the conventional machines resulting in a lower cost of operation.

Figure 5: AMSC 5000 hp motor under test

1. Search AMSC website www.amsuper.com for 5000 hp motor
2. S. Kalsi, "A Small-size Superconducting Generator Concept", International Electric Machines and Drives Conference, IEMDC '01, Massachusetts Institute of Technology, Cambridge, MA 02139, 17-20 June 2001
3. S. Kalsi, et al, "Status of the Navy HTS SuperDrive motor for ship propulsion development", Third Naval Symposium on Electric Machines, Philadelphia, PA on December 4-7, 2000