Superconductor Motors for High-Speed Ship Propulsion

Innovation in High-Speed Ship Propulsion Technology Drives Smaller, Lighter, Less Costly and More Efficient Motors

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Top of cryocooler refrigeration unit in the five-megawatt ship propulsion motor developed for the U.S. Navy. (Photo courtesy of American Superconductor.)

Technological advancement is driving more cost effective and efficient applications and procedures in businesses throughout the world. In the marine industry, a broad range of innovative technologies are being explored for commercial and military applications.

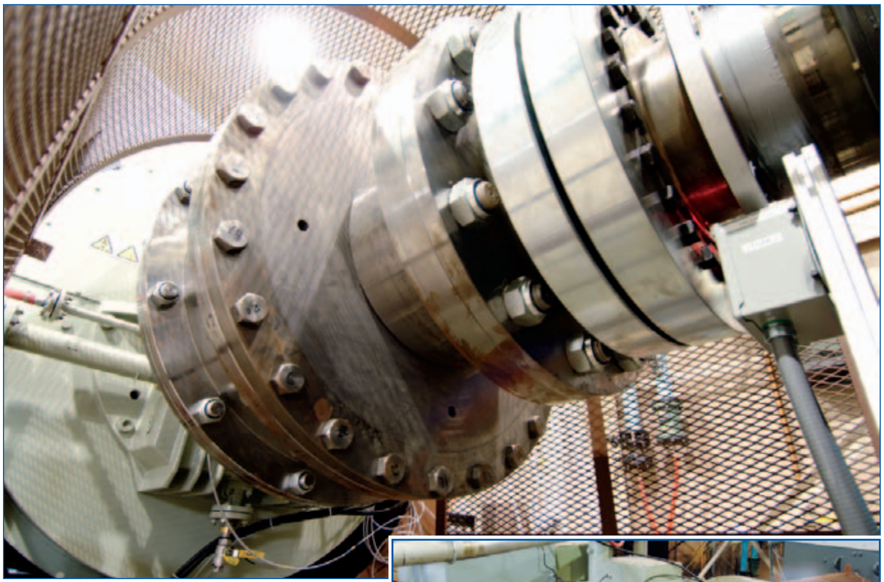
One of the fastest-moving changes affecting the marine industry is the conversion to electric ship propulsion. In fact, industry analysts MSCL Inc. forecast that the conversion to electric ship propulsion will accelerate the growth of the current $450 million ship propulsion motors and generators market to $2 to $4 billion annually in the next 10 years. The expected compound annual growth rate for electric motors and generators for ship propulsion application is expected to be more than 20 percent. Today, nearly 100 percent of all cruise ships, and many cargo ships, have transitioned to electric motor propulsion systems. In 2000, the U.S. Navy also announced its intention to transition to electric propulsion motors for future Navy ships, and their research is well on the way.

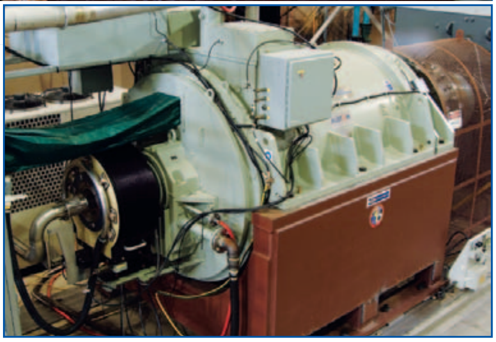
One of the most promising of the technologies related to this major shift to electric ship propulsion is the development of high-temperature superconductor (HTS) wires for powering marine propulsion motors. The machines use rotor coils wound with HTS wires, which can conduct more than 150 times the electric current than copper wires of the same dimensions, with no resistance. These characteristics offer product developers the ability to design components with HTS wire—such as coils for electric motors—that deliver much higher power density at higher electrical efficiency.

The power-dense components made with HTS wire allow product developers to reduce the size of the electric machines they build. For example, that reduction can be as small as one-third the size and weight of conventional synchronous machines. In the case of large electric machines, such as motors or generators, not only does this dramatically reduce their physical size, it also substantially cuts their weight, manufacturing and maintenance costs. They are also much more fuel efficient because of the zero electrical resistance of the HTS wires. The new technology enables broader applications of pod configurations. The critical size and weight savings also provides a key benefit for increasing the flexibility of ship design.

Significantly, the HTS motors involve no major changes in fundamental motor technology. The machines operate in the same manner as conventional motors: they are essentially standard AC synchronous machines that capitalize on the unique electrical properties of superconductor wire. The key difference in gaining their substantial advantages comes from replacing copper rotor coils with HTS rotor coils.

Another advantage of using HTS wire in the rotor is that it allows the rotor to run “cold,” so the motor avoids the thermal stresses experienced by conventional machines during normal operation. In the past, the inability to achieve proper thermal





(Above) Shaft coupling on a five-megawatt HTS ship propulsion motor delivered to the Office of Naval Research. (Photo courtesy of American Superconductor.)

(Right) A five-megawatt HTS ship propulsion motor under steady state operational conditions at the Center for Advanced Power Systems at Florida State University. (Photo courtesy of American Superconductor.)

management has been a key impediment to developing power-dense, high-torque motors required for naval and commercial marine applications. Stresses caused by heat in other advanced, high-power motors often necessitate costly motor repair and refurbishment.

HTS wires take on their unique conducting abilities when cooled, and cooling requirements are simple. The system used to cool the wires consists of standard, off-the-shelf cryogenic refrigeration systems. These are then hardened and engineered to meet at-sea conditions.

Another advantage to HTS-powered marine propulsion systems is that they do not require the rotor and stator magnetic iron "teeth" necessary for traditional AC-synchronous marine motors. Iron teeth on the rotor and stator produce pulsations as the teeth go in and out of alignment due to the changing magnetic field to which they are exposed. Therefore, HTS-powered systems without iron teeth are inherently far quieter than traditional AC synchronous motors. This also permits flux densities above the saturation flux density of iron, resulting in smaller, lighter machines.

An HTS field winding generates a high-intensity magnetic field in a small volume. The field winding is powerful enough to produce high fields without requiring iron teeth to carry the flux. Use of a traditional iron-toothed stator is possible; however, it naturally degrades the power density of the machine due to the inability of iron teeth to carry highmagnetic flux. The optimal design of the stator has no magnetic teeth (i.e., an air-core winding). This design allows the entire space between the inner diameter of the back iron and the inner diameter of the stator region to be filled by the stator winding. In the absence of iron teeth, the stator coils are subjected to very strong alternating magnetic fields. In order to bring the associated eddy current losses to acceptable levels, the stator coils need to be constructed out of fine Litz wire.

When HTS-powered rotors are used, a large air gap is formed that allows the designer to maximize power density while independently tuning the machine parameters, such as synchronous and sub-transient reactances, to meet a variety of system requirements. For example, the synchronous reactance can be adjusted to reduce the change in field current required for a change in output. These features also include the operation at unity power factor to lower the electric drive rating and cost, lower capacitance to ground to minimize the impact of the drive switching frequency on the motor and manageable fault current (achieved by operating the HTS motor at higher voltages, up to 10 kilovolts) to reduce the breaker requirements. HTS motors and generators can also accommodate larger harmonic currents than conventional machines due to the attenuation of harmonic fields in the larger air gap and the capability to withstand heating in the conductive electromagnetic shield on the motor.

Ship design flexibility is one of the major benefits of this new HTS technology. The smaller sized HTS-powered motor enables marine architects to place the propulsion system itself closer to the propeller (in-hull design). As a result, the propulsion system can have a shorter drive shaft with a less extreme angle of approach, and motor location will have less effect on the optimum fluid-dynamic performance of the hull/propeller. This unique effect will also allow more room in the design for passengers, freight or weapons systems (in the case of naval vessels).

HTS propulsion motors are a proven technology and development is rapidly advancing. In September 2004, a five-megawatt motor commissioned for the U.S. Navy from American Superconductor (AMSC) was successfully operated under full-load conditions, demonstrating full torque at full power, and is currently undergoing dynamic testing at the Navy's Center for Advance Power Systems. This five-megawatt motor has the power output of a motor that would propel smaller commercial merchant and passenger vessels.

The U.S. Navy has also commissioned a 36.5-megawatt motor, the power level required to propel a passenger cruise ship or larger cargo or military ships.

HTS motor technology is now in a position to deliver highly compact, lightweight, high efficiency, inherently quiet propulsion motors to meet the needs of space-constrained high-speed ships. Motor, HTS wire and cooling technologies have matured sufficiently to permit economic development of propulsion motors for high-speed ships. This same technology can also be applied to the next generation of naval generators based on the five-megawatt and 36.5-megawatt naval motor developments combined with

AMSC's experience with HTS synchronous condensers (a type of generator) for utility applications. The experience with these systems has confirmed that HTS motors will be much smaller, lighter, less costly, more efficient and inherently quieter than conventional technologies. These factors are vital considerations in designing future commercial marine and military projects. /st/

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Bruce Gamble, director of engineering at American Superconductor, has more than 25 years' experience in advanced technology development, including superconductivity and electromagnetic equipment. He holds a B.S. in mechanical engineering from Clarkson College of Technology and an M.S. in mechanical engineering from the Massachusetts Institute of Technology.