Superconductor-based Machines for Marine Propulsion

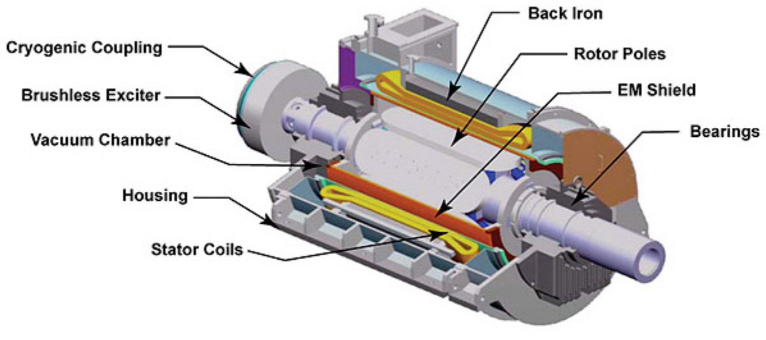
Description of technology

The greatest impact of fuel savings will come from technologies that augment the efficiency of the ship's propulsion system. Superconductor-based machines have been used in advanced naval prototypes since the 1970s but it was the discovery of high temperature superconductors (HTS) in 1986, operable at liquid nitrogen temperatures that made them serious candidates for high performance marine applications. One issue to consider is the generation of heat in HTS wire due to internal losses: whereas losses under dc power operation are negligible, they become larger as the frequency increases and are significant enough at power frequencies (50-60 Hz) to compromise the benefits of the superconductor, especially because their effect is amplified by the refrigeration penalty. This has generally limited the use of HTS to the parts of electric machines carrying dc current.

The electric machine type that has become the most popular recipient of HTS technology is the one known as synchronous machine. In its most common version, the rotating member (rotor) wound with coils carrying dc current (field winding) establishes in the air gap a dc magnetic field. As this field rotates in the bore of the stationary member (stator), it interacts with the windings located therein (armature windings) to generate an output ac voltage at their terminals (generator operation) or, if the armature windings themselves are independently powered with ac current, to generate a torque on the shaft (motor operation). Thus, the dc field winding of a synchronous machine is a natural application for HTS wire.

One obvious benefit of using HTS wire in the field winding is the elimination of the electrical conduction losses, as the HTS operates in a virtually lossless regime, with consequent improvement of the machine's efficiency. An even greater advantage, however, results from the ability of the superconducting field winding to carry much larger currents than normal conductors and, thus, to generate much larger fields than in conventional machines. This allows the operation at higher power density with consequent reduction of machine size and weight for the same power rating.

Of course, the use of HTS wire requires that the field winding be maintained at cryogenic temperatures. This entails the use of a host of auxiliary devices not normally found in a conventional machine: a cryogenic refrigerator, a suitable rotating coupling to transfer the cooling fluid to the spinning rotor, extensive thermal insulation in the rotor including a vacuum jacket, and a suitable ac shield to protect the field winding from time varying magnetic flux components (Figure 1). All these items detract from the theoretical gains in both size and efficiency, but the auxiliary overhead scales less than proportionally to the rated power: the end result, therefore, is more favorable the larger the power rating of the machine. It must be added that, although more complex, a HTS rotor is well within the present state of the art thanks to progress in the technology and reliability of cryogenic apparatus. The widespread use of superconducting magnets in magnetic resonance imaging (MRI) systems, however, has reduced the cost and increased the reliability of cryogenic cooling systems.



Conceptual cutaway view of a superconducting field machine (American Superconducting Co.)

study for Northrop Grumman conducted by J. Herbst and K. Davey of the Center for Electromechanics of the University of Texas, the conclusion was reached that the crossover point where a HTS-based machine becomes more advantageous than a conventional one lies in the range between 5 MW and 10 MW of power per machine(Figure 2). It is not surprising, therefore, that among the leading installations of HTS machines in recent years, are a 5 MW and a 36.5 MW synchronous motors by American Superconductor Co. (Figures 3 and 4)

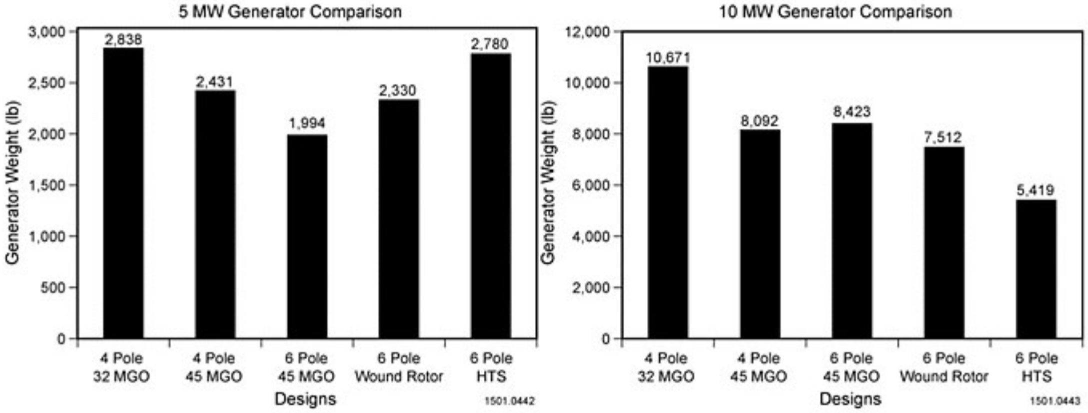


Figure 2: Comparative study of conventional permanent magnet synchronous machines (of various magnet strength, MGO = MegaGaussOerstedt), synchronous machine with normal wound rotor field, and synchronous machine withHTS wire field for the case of 5 MW and 10 MW designs (J. Herbst and K. Davey).

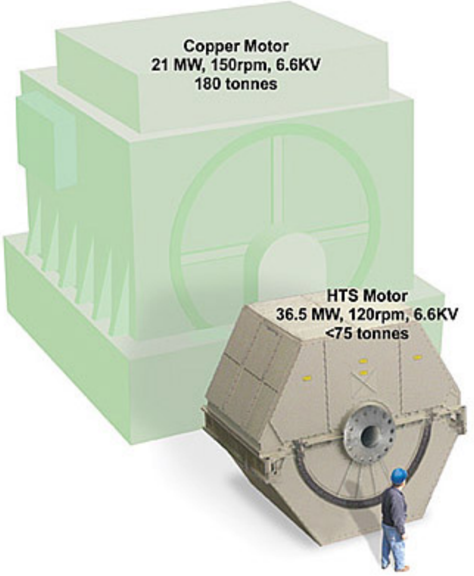


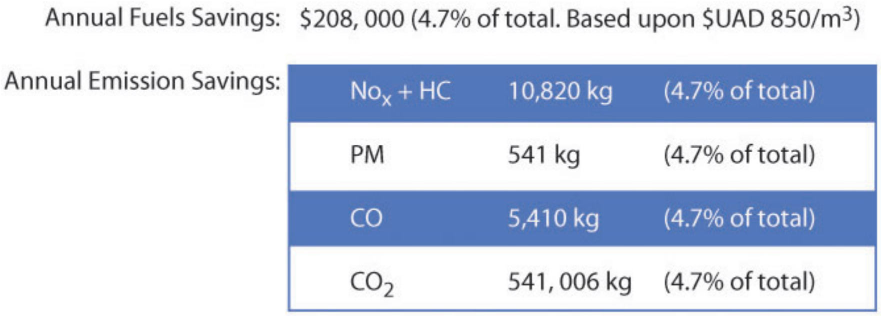
Figure 4: American Superconductor Co.'s 36.5 MW HTS synchronous motor compared to a conventional 21 MW machine.

Figure 3: American Superconductor Co.'s 5 MW HTS synchronous motor under test.

A major impediment to the widespread use of superconducting motors and generators is the superconducting wire. A very fundamental challenge is that the superconducting material is a ceramic and ceramics do not make good wires. Consequently, the wires are very expensive and are fragile, both mechanically and electromagnetically. Recently a superconducting motor was constructed from trapped field magnets. Trapped field magnets are pucks of yttrium barium copper oxide, the superconducting ceramic, that are cooled below their critical temperature of about 80 K in the presence of a strong magnetic field. When the external magnetic field is removed, the pucks retain the field, analogous to permanent magnets in terms of performance but not in terms of the physics of the process. As long as the temperature is held below the critical temperature, the magnetic field will persist for decades. Raising the temperature turns off the magnetic field. Material costs for such systems are much less than for wire-based superconductor systems and even less than conventional motors and generators. There is a public-private partnership with the U.S. Navy to develop these motors today.

Benefits for a 100 m Class Vessel

On the basis of what has been said above, an example is presented for a 100 m class vessel. It is clear that the use of HTS-based machines for a 100 m class vessel should be considered for the largest generators and motors on board. Therefore, an attempt was made to estimate the benefits that would accrue to the vessel from the adoption of HTS-based designs assuming four main generators and the two main propulsion motors. A typical yearly mission profile was estimated, which yielded the following overall results:



Annual Fuels Savings: \$208, 000 (4.7% of total. Based upon \$UAD 850/m^3)

Annual Emission Savings:

No$_x$ + HC	10,820 kg	(4.7% of total)
PM	541 kg	(4.7% of total)
CO	5,410 kg	(4.7% of total)
CO$_2$	541, 006 kg	(4.7% of total)

The cost of each superconducting generator and motor is difficult to project, as these machines have not yet been built on a regular production basis. It seems safe to assume, however, that the cost penalty over conventional equipment will be in excess of one million dollars per machine. Thus, an entire ship installation consisting of four generators and two motors would be at least six million dollars more expensive, resulting in a yearly return from fuel savings of about 3.5% or approximately 28 years straight payback. This assessment is based on a wire-wound superconducting motor. If the Navy's program to develop a trapped field magnet motor succeeds, the economics are expected to be such that these motors and generators would be less expensive than the present system.

It seems clear from the above projections that the use of superconducting motors and generators for a 100 m class vessel cannot be justified on simple financial terms: considerations of the value of the environmental impact and interest in promoting a new technology would have to be the drivers for adopting HTS-based machines on board.