

## **SUPERCONDUCTOR MOTORS FOR HIGH SPEED SHIP PROPULSION**

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Abstract: High speed ships like the X-Craft, Littoral Combat Ship, and Joint High Speed Vessel are expected to require about 40 MW of propulsion power to achieve the required speed. Today, this power is typically provided through four mechanical drive water jets of about 10 MW each, operating at about 600-rpm. In the future, superconductor technology may enable the Navy to consider electric drive for this application. A notional design has been developed for high speed electric propulsion using four superconductor motors. Each motor would be approximately 1.7 m in diameter, 1.9 m in axial length and ~20,000 kg in weight - it can be built now by using the high-temperature superconductor (HTS) motor technology in development at American Superconductor (AMSC) since the early 1990s. This HTS motor technology has been demonstrated by the successful construction and testing of motors for industrial, utility and ship propulsion applications. The following examples validate the readiness of HTS motor technology for ship propulsion:

- 5 MW, 230-rpm sub-scale HTS marine propulsion motor already tested in 2004 at full torque and full power by the Center for Advanced Power Systems (CAPS) for the Navy's Office of Naval Research (ONR).
- The current 36.5 MW, 120-rpm HTS prototype motor development program at AMSC, which is specified to be compatible with the DD(X) destroyer, has successfully passed its Detailed Design Review milestone in October 2004 with no discrepancies. This motor's fabrication is on schedule for delivery to the Navy in fall-2006.

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 the Navy's future all electric warships. The 10 MW, 600-rpm HTS motors would be about the same frame size as the already tested 5 MW, 230-rpm motor.

### **I. INTRODUCTION**

The U.S. Navy has decided that its future ships will be all electric, i.e. electric power will be utilized for propulsion motor systems as well as for other loads. New technologies and techniques are emerging to manage the generation and utilization of such electric power on a ship. Moreover, lighter and more compact subsystems that will fit on ships that have very constricted space are being sought. A high-speed ship is small and it can benefit substantially from compact propulsion systems, and HTS propulsion motors are the ideal candidate for such ships. These motors are compatible with standard variable speed drives (VSDs) and they meet both U.S. Navy and commercial electric ship requirements, reducing both drive development effort and recurring costs.

The HTS ship propulsion motors offer a range of benefits and advantages for both naval and commercial shipping applications [1-5], including the following:

- Up to three-times higher torque density than alternative technologies, HTS machines are more compact and lighter in weight. The size and weight benefits make HTS machines less expensive and easier to transport and install, as well as allowing for arrangement flexibility in the ship.
- Absence of iron stator teeth reduce the structureborne noise
- High efficiency from full-to-low speed, boosting fuel economy, sustained speed, and mission range, all key mission parameters for warships.
- Isothermal field winding is well suited for repeated load changes.

There are other significant advantages to an HTS motor propulsion system when compared to conventional technology. The absence of iron teeth forms a large air gap and allows the designer to maximize the power density while independently tuning the machine parameters, such as synchronous and sub-transient reactances, to meet the following system needs:

- Operation at unity power factor to lower the electric drive rating and cost
- Lower capacitance to ground minimizes the impact of the drive switching frequency on the motor
- Manageable fault current (achieved by operating the HTS motor at higher voltages, up to 10 kV) reducing the breaker requirements.

HTS machines can 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 EM shield on the motor. This feature also reduces the need for harmonic filters and their associated weight and volume.

A typical Navy ship, such as the DD(X) destroyer, needs two propulsion motors, each rated at 36.5 MW, 120-rpm. Such large motors have been built using conventional technology [6] but they are four to five times heavier than the ONR funded 36.5 MW HTS motor being built by AMSC.

Under an ONR contract, AMSC supplied a 5 MW, 230-rpm HTS propulsion motor and a commercial VSD for validating technologies required to design and build large ship propulsion motors and for developing motor production processes to minimize development time and cost. The key technologies tested include the following:

- A full-scale refrigeration system
- Representative-scale field windings
- Support and excitation systems
- High current density liquid-cooled stator technology.

The 5 MW HTS motor [7] was factory tested at ALSTOM in Rugby, U.K. It was delivered to the U.S. Navy in July, 2003. This demonstration motor validated both the

overall design and component design approaches for full-size propulsion motors. The 5 MW motor testing began in August 2004 at CAPS where it was load tested to 5 MW for several hours [7, 8]. Additional, more extensive, testing continues to fully characterize the motor and to validate ship system analysis codes being developed by CAPS. The 5 MW motor coupled to two 2.5 MW induction motors is shown in Figure 1 at the CAPS facility.



Figure 1: 5 MW HTS motor coupled to two GE 2.5 MW load motors at CAPS

Because of the excellent test results of the 5 MW motor, ONR contracted with AMSC to design and build a 36.5 MW, 120-rpm HTS motor - conceptually shown in Figure 2.

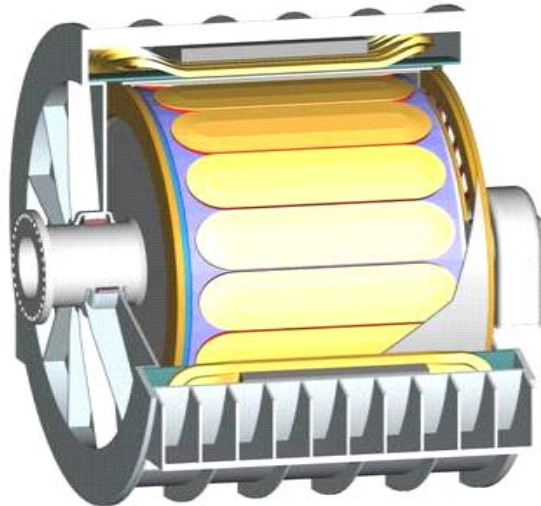


Figure 2: Conceptual 36.5 MW, 120-rpm motor under construction for delivery to ONR by fall-2006

This motor employs an HTS field winding that operates at  $\sim 32$  K and is expected to weigh 75 tonnes, which includes the weight of its stator and rotor cooling equipment. The Detailed Design Review (DDR) of this motor was completed on October 6, 2004 with no discrepancies, and currently it is on schedule for delivery to ONR by fall-2006.

## II. CONFIGURATION OF PROPULSION MOTOR

The major components of HTS-based propulsion motors are illustrated by the 5 MW HTS ship propulsion motor shown schematically in Figure 3. The rotor assembly includes an HTS field winding operating at 32 K, its support structure, cooling loop, cryostat and electromagnetic (EM) shield. The stator assembly includes an AC stator winding, back iron, stator winding support structure, bearing and housing. An external cryocooler module used to cool the field winding is also located at the non-drive end of the shaft.

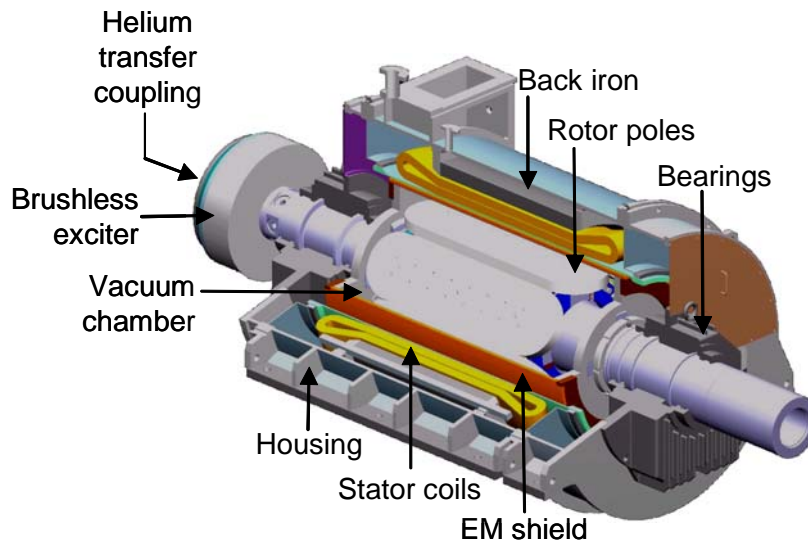


Figure 3: American Superconductor's 5 MW HTS marine propulsion motor

The field winding consists of several HTS coils that are conduction-cooled through the support structure. The primary components of the rotor assembly are as follows:

- HTS field winding
- Cooling system
- Torque tube (for transferring torque from the “cold” (cryogenically-cooled) environment to the “warm” shaft ends)
- Room-temperature EM shield.

The field winding is an assembly containing six polesets, each fabricated using first generation (1G) HTS wire (BSCCO-2223) [9,10] that is designed to withstand the powerful magnetic and mechanical forces experienced in the rotor. Specific electrical and mechanical characteristics of 1G wire can be found on the American Superconductor website ([www.amsuper.com](http://www.amsuper.com)). The HTS polesets are attached to a metallic support structure, which not only provides mechanical support but also a path for conduction cooling.

The polesets and support structure are enclosed in a vacuum-sealed cryostat that minimizes radiant heat input and provides the insulated operating environment required by the HTS field coils. An EM shield, which is located at the outside surface of the cryostat, performs the following functions:

- Protects the field winding by attenuating asynchronous fields produced by the stator winding
- Carries high transient torque during a fault
- Provides damping for low frequency torsional oscillations.

The EM shield, which directly transfers torque to the warm shaft, is designed to be mechanically robust to withstand the large forces generated during faults, and is designed to absorb heating caused by negative sequence currents.

A refrigeration system, which uses cold circulating helium gas in a closed loop, maintains the HTS field winding at cryogenic temperature. Helium gas is circulated through cooling channels located inside the rotor. The closed cooling loop runs from the turning rotor body to externally located, stationary Gifford-McMahon (GM) cold heads. Because this design does not require rotating gas coolers, commercial off-the-shelf (COTS) refrigeration components can be used. The refrigeration system achieves high reliability by employing n+1 modular, single-stage GM coolers and long-life seals in its helium transfer coupling.

The stator winding employs no magnetic iron teeth and is designed with Class F insulation but operates at Class B insulation temperatures. The stator coils employ copper Litz conductor, which is made up of small diameter insulated and transposed wire strands. Because the stator winding bore surface experiences a high magnetic field that would saturate the iron teeth of a conventional stator, the HTS motor's stator armature winding does not employ iron teeth. With no iron teeth in the winding region, the support and cooling of the stator coils require special attention. The back EMF in this motor is nearly a pure sine wave and the harmonic field components are much smaller than those observed in conventional motors.

### III. SUPERCONDUCTOR MOTOR CONCEPT FOR HIGH SPEED SHIPS

High-speed ships were studied in an "HTS Benefits for Ship Systems" study [11] conducted for ONR in 2004. The study concluded that motor operating voltages up to 10 kV are possible. However, a 6 kV motor voltage was selected for this study to keep the high-speed ship motor design similar to the already built and tested ONR 5 MW, 4.2 kV motor [7]. Four 10 MW, 600-rpm propulsion motors for high-speed ships were assumed for this study. The design of the 10 MW motors was based on the 5 MW, 230-rpm motor with the following modifications:

- "Special" coils for the rotor HTS field winding
- Single layer stator winding cooled with dielectric oil
- 3-phase, 6 kV stator winding.

A 10 MW, 600-rpm motor concept is shown in Figure 4. Both 1G and 2G HTS wires were considered for the HTS field winding. The 2G winding current density was assumed to be twice of 1G coils. The lowest weight and size are feasible with a compact stator winding and 2G wire [9] HTS field coils. A development effort is required to realize this design.

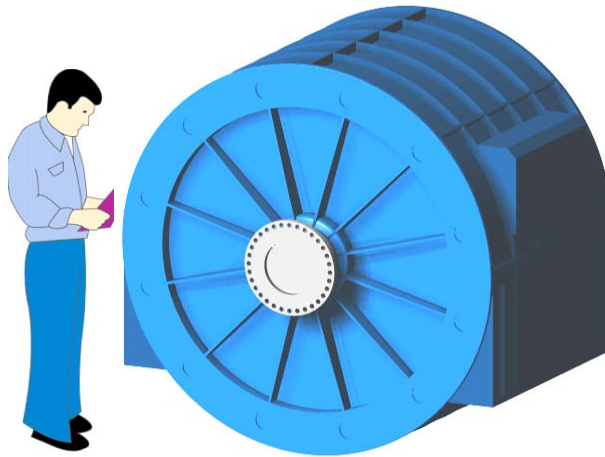


Figure 4: 10 MW, 600-rpm motor concept

*Requirements for 10 MW Propulsion Motor*

Specific requirements for the 10 MW motor are summarized in Table I. It is designed for operation at 6 kV in order to eliminate transformers that add considerable weight and size to the ship system.

Table I: 10 MW, 600-rpm Motor Requirements

Parameter	Value
Motor rating	10 MW
Power factor	1
Line voltage	6 kV
Rotational speed	600 rpm
HTS rotor winding	1G or 2G
Stator winding	Oil cooled

*Magnetic Design for 10 MW Propulsion Motor*

A 2-D scoping study was conducted to identify the attractive attributes (minimum weight, volume and length) of the 10 MW motor. The design space was scanned within the following additional constraints:

- 4, 6 and 8 poles
- Single and double layer windings
- Machine active length ( $L_s < 1\text{m}$ )

This process was repeated for 1G and 2G wires [9] in the rotor field windings with no constraint on motor short-circuit torque, which is controlled by sub-transient reactance. Motor design summaries for 1G and 2G wire based motors are provided in Figure 5 and Figure 6, respectively. Both figures suggest that a 6-pole machine with a single layer winding is the optimum design point.

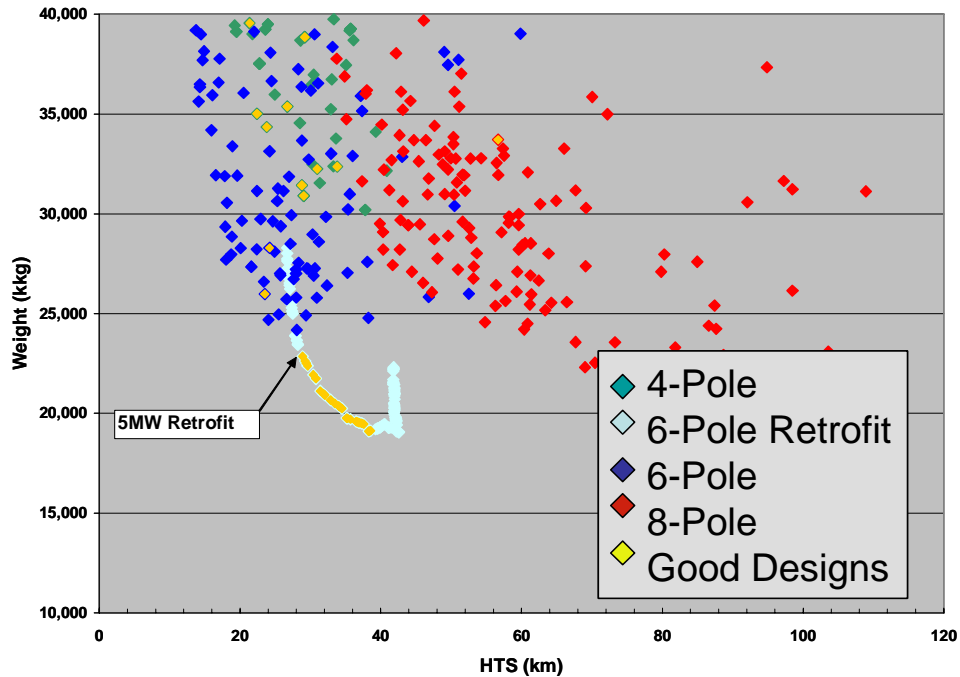


Figure 5: Optimization runs for 10 MW, 600-rpm motor (1G wire)

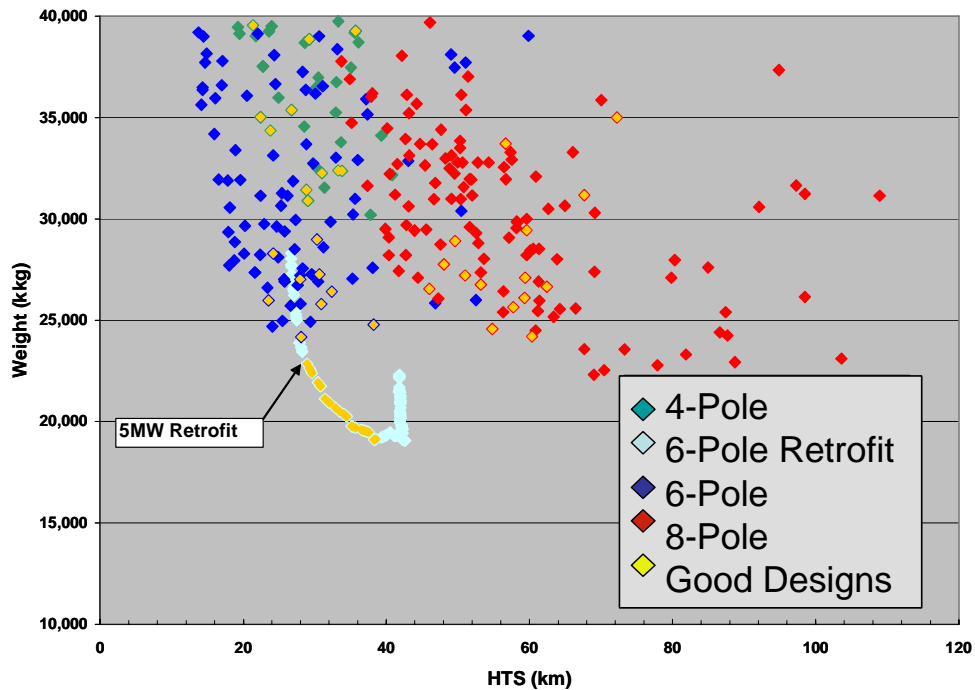


Figure 6: Optimization runs for 10 MW, 600-rpm motor (2G wire)

Having identified the optimum design point, more detailed analysis was performed with AMSC proprietary 3-D design code for 4, 6 and 8 pole machines using 1G and 2G wire field windings. Each design was constrained to produce similar sub-transient reactance ( $\sim 0.2$  pu) for keeping short-circuit torque at a manageable level. Results of this analysis are summarized in Table II.

Table II: Comparison of 4, 6, and 8 pole 10 MW motors with sub-transient reactance constraint

Poles	Weight (k-kg)		Length (m)		Diameter (m)	
	1G	2G	1G	2G	1G	2G
4 SL	16	12	1.99	1.22	1.77	2.32
6 SL	21	16	3.00	2.11	1.55	1.82
8 SL	17	12	1.89	1.15	1.69	2.01

These results indicate that an 8-pole machine is lighter and shorter and, therefore, a better design point for both 1G and 2G wire machines. Thus, the 8-pole machine is selected as a baseline for the 10 MW, 600-rpm motor.

The 10 MW motor characteristics for optimized designs are summarized in Table III. Compared with the 1G wire motor, the 2G wire motor is 30% lighter in weight, 20% smaller in volume, 40% shorter in length, 10% smaller in footprint and has 0.2% higher efficiency. However, the 2G motor is 20% larger in diameter than the 1G motor.

Table III: 10 MW Motor Characteristics

Parameter	New Motor (1G Wire)	New Motor (2G Wire)
Motor rating, MW	10	10
Number of phases	3	3
Line voltage, kV	6	6
Rotational speed, rpm	600	600
Number of poles	8	8
Line current (full load) – total/phase, A	960	960
Motor efficiency at full-load, %	99.1	99.3
Motor diameter, m	1.69	2.01
Motor axial length, m	1.89	1.15
Motor weight, k-kg	17	12

#### *Mechanical Design Considerations for 10 MW Propulsion Motor*

The design of the rotor and stator mechanical components follows the same approaches used in the 5 MW, 230-rpm motor design, but with the following changes:

- “Special” coils for the rotor field winding
- Single layer oil-cooled coils for the stator winding

The design philosophy for the field winding coils and single layer stator winding coils is discussed in Section IV.

The rotor concept of the 10 MW motor is similar to the 5 MW motor, which is shown in Figure 7, and includes the following design elements:

- The outer surface of the rotor employs a room-temperature aluminum shield that protects the HTS coils from AC fields generated through the stator coils.
- The HTS coils are cooled with a cold helium gas stream supplied through an axial bore in the shaft.

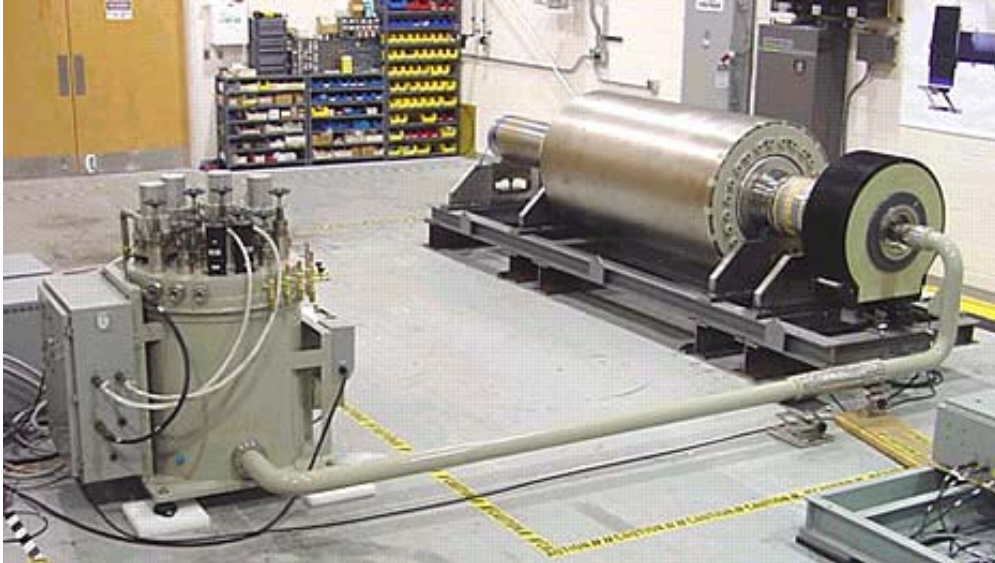


Figure 7: 10 MW motor rotor will be similar to the 5 MW motor rotor shown here

The stator single layer armature winding shown in Figure 8 is assumed for this machine. The coils employ Litz wire conductors cooled with oil using the approach described in Section IV. Non-metallic teeth provide support for the coils to the back iron yoke. The torque is transferred to the frame through metallic struts. The low weight frame is achieved by using a space-frame structure approach.

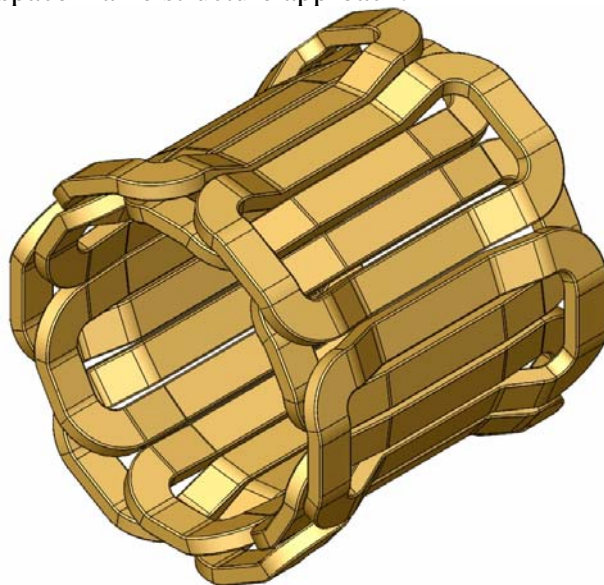


Figure 8: Stator winding concept for 10 MW motor

The overall size and shape of the 10 MW, 600-rpm motor is shown in Figure 4. The lowest weight and size are feasible with a single layer stator winding and 2G wire HTS rotor coils.

#### IV. ENABLING TECHNOLOGIES

The practical design issues of high power density electrical machines based on the HTS technology are discussed in this section. In cases of both the stator and the rotor, the engineering challenges transpire from the combination of structural and thermal operating parameters imposed over machine functional components and sub-assemblies in the small allocated volume.

An additional layer of complexity is associated with the military aspect of the prospective machine application. This aspect typically imposes a strict and severe mechanical shock resiliency on all mechanical assemblies. The design process, therefore, incorporates a loading scenario matrix that contains the various shock incidents combined with normal operation conditions, along with all of the possible internal electrical faults of the machine.

AMSC has identified a number of design solutions that can be incorporated into a broad range of HTS-based electrical machines of various power levels and shaft speeds. Some of these enabling technologies are discussed in this section. Most of the technical solutions presented here have been either fully developed or incorporated into some of the previous electrical machines constructed at AMSC; otherwise they have been researched and proven in sub-scale laboratory experiments.

##### *Rotor Mechanical Design for HTS Machines*

The rotor part of the HTS-based electrical machine is where most of the technical challenges reside. The rotor support structure is designed to support the cold mass and to maintain HTS coils within their strain limits. The thermal system is designed to keep HTS field coils within their allowable temperature limit during all operating modes of the motor.

The current 1G HTS wire produced by AMSC [9-10] has reached the practical level of robustness for wire handling during manufacturing and subsequent operation in practical high speed rotor applications. A key advantage of the recently developed 2G HTS wire is expected to be further improvement of its mechanical characteristics.

The engineering of the HTS coil working environment must incorporate both electrical and mechanical aspects of the design. The “special” shaped HTS coil has been identified as a key qualitative feature, making it possible to construct high performance HTS-based rotors. This “special” coil shape is ideal for providing a well controlled mechanical strain environment for the coil. AMSC has demonstrated this technology in self-funded company programs.

### *Rotor Field Winding Cooling Approach*

HTS wire and cooling technologies have matured sufficiently now to permit economic development of rotating machinery. The wide availability of HTS wire and reliable and less-costly cooling systems are two important components essential for the success of HTS motor and generator programs. HTS wire is now readily available and larger and more ambitious programs are being started. The GE 100 MW generator program [4] and American Superconductor's 36.5 MW motor program are good examples of the emerging trend toward more ambitious projects.

Most of the HTS machines prototyped so far have employed cryocooler refrigerators. A typical cryocooler and its compressor are shown in Figure 9. A cryocooler coldhead is about 4 inches in diameter, is about 14 inches long and weighs about 40 lbs. Its associated helium compressor is a cube with 24-inches side dimensions and weighing 250 lbs.



Figure 9: A Cryomech cryocooler cold head and its compressor

The performance of off-the-shelf cryocoolers has improved significantly in the last seven years. A single stage Gifford-McMahon (GM) cooler can supply 100 W of cooling power at 30 K, as shown in Figure 10. The key features of these coolers are summarized below:

- GM cryocooler output at 30 K has improved by a factor of four over the past seven years
- MTBF of similar GM coolers exceeds nine years
- Input power consumption ~0.1% of output for large propulsion motors.

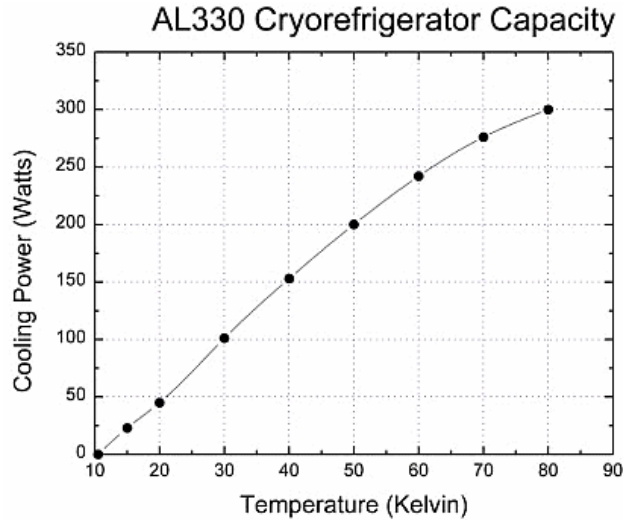


Figure 10: A Cryomech AL330 cryocooler provides 100 W cooling power at 30 K

Cooling systems for larger machines can be built by using the GM cryocoolers as the building block. A cooling system built for the 5 MW, 230-rpm motor, which is shown in Figure 11, employs gaseous helium as a working fluid to transport heat from the HTS windings to the cryocoolers. A similar system will be employed for cooling the 36.5 MW, 120-rpm motor currently being built for ONR.



Figure 11: Cooling system built for 5 MW, 230-rpm motor

Several thousand refrigeration systems have been installed for systems applications such as MRI magnets and semiconductor fabrication. Not only are commercial cryogenic refrigerators readily available, there is also a wealth of reliability and performance data available to support any predictive design for reliability efforts in machines applications.

### *Coolant Transfer to Rotor*

The cryogenic cooling system must be as robust and reliable as possible so that no practical limitation is derived from it and so that customers are not involved in additional services or maintenance. The cooling transfer systems have been successfully built and operated by many different companies; first as part of low temperature superconductor (LTS) projects during the 1970s and 1980s, and more recently as part of HTS projects. In all cases, this component presented the least problems.

### *Stator Mechanical Design for HTS Machines*

An HTS superconductor field winding generates a high intensity magnetic field in a small volume. 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 high magnetic 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.

The structural model of the stator of HTS-based electrical machines is significantly different from its conventional counterpart. The key difference is in the fact that the stator coils are actually the sole recipients of the Lorenz magnetic force. This is in contrast to the conventional stators where most of the force is reacted through the iron teeth instead.

There are three fundamental technical challenges when developing the stator for HTS-based electrical machines:

- Selection of an effective liquid cooling method for the stator coils
- Engineering adequate structural support for the stator coils
- Developing economically viable manufacturing techniques for coil manufacturing and stator assembly.

Iron teeth in a conventional stator provide a thermal path for cooling a stator coil from its sides. In an air-core winding this capability is lost. Two possible choices for forced liquid cooling are:

- De-ionized water
- Dielectric oil.

The apparent benefit of the water cooling is its high thermal performance stemming from the very high heat transfer coefficient across the boundary layer of the internal cooling channel. The problem of de-ionized water cooling, however, is that it requires water tight channels to be embedded within the volume of the stator winding. Oil cooling, while thermally less attractive, is much more practical in implementation. It also provides a substantial advantage to the stator insulation system. Oil cooling of high voltage devices

is a well proven technology (commonly used in transformers and cables). There is a substantial assortment of synthetic and natural oils specifically formulated for this purpose. Advanced, environmentally safe, transformer oils offer high fire retardant capability with excellent chemical long term stability. In addition, the presence of oil around the high voltage stator coil has demonstrated “healing” properties in case of cracking of the solid insulation layers. The oil normally penetrates the failed sections of the coil providing insulating characteristics. Flowing oil can also extinguish electrical discharge on the surface of the coils.

AMSC has successfully demonstrated the oil cooling techniques in the 5 MW motor and by testing prototype oil-cooled coils in the laboratory. The preferred approach for the stator winding is the single layer winding concept shown in Figure 8. This winding was employed in AMSC’s 5000 hp, 1800-rpm, 4-pole motor shown in Figure 12.



Figure 12: Single-layer stator armature employed in AMSC built 5000 HP, 1800-rpm, 4 pole motor

## V. CONCLUSIONS

HTS motor technology is now in a position to deliver highly compact, light weight, 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 now to permit economic development of propulsion motors for high speed ships. Based on the success of both testing the 5 MW propulsion motor and a 36.5 MW motor design under construction, it is possible now to build 10 MW, 600-rpm propulsion motors (or other similar ratings) with minimal risk. The 10 MW motor is about the same frame size as the successfully built and tested 5 MW, 230-rpm motor.

## ACKNOWLEDGEMENT

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