The Status of HTS Motors

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***Abstract*—The status of High Temperature Superconducting (HTS) motor development is presented. HTS synchronous machines have been under development for over 12 years around the world. The unique characteristics for selected applications such as ship propulsion are discussed. The beneficial charateristics of air core HTS motors for ship propulsion include high power density, high efficiency and low noise production. This paper also addresses recent developments including a 5,000 HP 1800 rpm 4 pole prototype and the ongoing construction of a 5 MW 230 rpm motor. The 1800 rpm motor is a prototype constructed to validate technologies for industrial motors and generators and the 230 rpm motor is being constructed to validate technologies for ship propulsion motors in the range of 25 MW and 120 rpm.**

I. Nomenclature

HTS – High Temperature Superconductor, eg Bi2223 multifilamentary conductor in a silver matrix.

LTS – Low Temperature Superconductors, eg NbTi and Nb_3Tn

II. Introduction

High Temperature Superconductors (HTS) are defined as the class of materials which exhibit nearly zero resistance at temperatures above 25K. Low temperature superconductors have been used in development since the mid 1960's and achieved commercial viability in applications such as magnetic resonance imaging in the 1980's. In 1986, Alex Muller and Georg Bednorz discovered a ceramic compound with metallic oxides, that superconducted at 35 degrees kelvin. and development of rotating machines began within a few years of its discovery[1-7]. 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 simple, 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.

A superconductor operates within a three dimensional space constrained by magnetic field, current density and operating temperature. The superconductor quenches (i.e. looses its superconducting property) if any of these constraints is violated. A LTS conductor normally operates at about 5K cooled by liquid helium and upper permissible temperature is typically about 6K. Since the heat capacity of materials is very low at 5K, only a small heat input raises the temperature of the conductor sufficiently to initiate a quench. The helium refrigerators are complex, big and expensive to operate. On the other hand, HTS conductor could be cooled with much cheaper liquid nitrogen for making low field devices. For high field applications, such as motors and generators, HTS conductor could be operated at about 30K. The cooling at such temperatures could easily be accomplished by refrigerators available off-the-shelf. At these temperatures, the heat capacity of metals is over 3 orders of magnitude higher than at 5 K. The HTS winding can absorb much larger energy input without an appreciable rise in the temperature. Moreover, the HTS conductor loses its current carrying capability very gradually. These two effects make HTS winding resistant to quenching.

The HTS conductor is becoming widely available in US, Europe and Japan. American Superconductor has started large scale production of Bi2223 conductor that is available for wide range of applications.

III. HTS Machine Characteristics

To date most HTS machine employs superconducting field winding on the rotor and a conventional copper winding on the stator. Its major components are identified schematically in Figure 1. Design concept for a 25 MW, 120 RPM motor was presented in 2000[8]. The rotor assembly includes an HTS field winding operating at ~35K, 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. An external field cooler module for cooling the field winding is also located at the non-driven end of the shaft. The superconducting field winding generates about 1.5 tesla in the motor air gap – this is a factor of 2 higher than in conventional machines. This high air gap field could generate 3 tesla that saturates the teeth and causes excessive heating. The iron teeth are, therefore, eliminated. The space formerly occupied by iron teeth could be used to accommodate stator winding. The combination of higher air gap field and more space for stator winding enhances power density of the HTS machines by a factor of 3 to 4. Besides being compact, the HTS machines also possess the characteristic of low synchronous reactance (~ 0.3 pu). The low synchronous reactance translates to a much smaller voltage regulation between no-load and full-load with only a small 10-15% variation of the field current.

The field winding is cooled with cryocooler refrigerators which are available off-the-shelf. Each refrigerator delivers about 100W of cooling power at 30K with 7 kVA input power. These coolers are currently being used widely by MRI and high vacuum industries.

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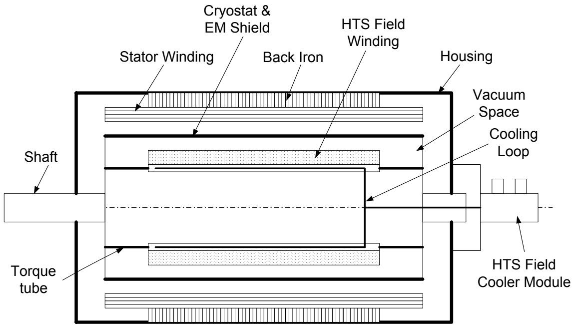

Figure 1: HTS Machine Component Layout

The HTS machines are more efficient than conventional machines both under full-load and partial-load conditions. The higher efficiency is achieved by eliminating resistive losses in the field winding – the refrigerator power is a very small component (< 10%) of the total losses in large machines. The armature copper loss represents 40% of motor losses. Under partial load conditions, armature copper losses go down significantly resulting in no significant drop in motor efficiency down to 30% load.

Since the HTS machines do not employ iron teeth in the stator, noise due to tooth vibration is eliminated. Only structureborne noise is experienced which has been shown to be much lower than Navy requirements. Because the HTS machines do not employ saturated iron, the harmonics generated by the field winding in the armature region are negligible as shown in Figure 2. Normally in a conventional machine, the 5^{th} harmonic is about 8% and the 7^{th} harmonic is about 6%. Compared with these, harmonics in HTS machines are essentially zero. The HTS machine armature also projects very small harmonic fields on the rotor surface, which translates into very small heating of the rotor surface.

Harmonic number	Generated by field in armature	Generated by armature at the rotor surface
1	1	1
3	$-7.527\cdot10^{-4}$	0.014
5	$2.582\cdot10^{-3}$	-0.01
7	$-3.358\cdot10^{-5}$	$2.502\cdot10^{-3}$
9	$6.368\cdot10^{-6}$	$7.892\cdot10^{-4}$
11	$-8.983\cdot10^{-6}$	$-4.332\cdot10^{-4}$
13	$-1.494\cdot10^{-7}$	$1.451\cdot10^{-4}$
15	$-7.472\cdot10^{-8}$	$1.149\cdot10^{-4}$
17	$7.477\cdot10^{-8}$	$-4.944\cdot10^{-5}$
19	$1.865\cdot10^{-9}$	$1.673\cdot10^{-5}$

Figure 2: Harmonic generated in armature and at rotor surface (25 MW, 120 rpm)

IV. 5,000 HP MOTOR STATUS

American Superconductor self funded the development of a 5000 hp, 1800 RPM motor for demonstrating HTS field winding, its cooling system and air-core (iron toothless armature) winding. In July 2001, world's largest HTS motor was developed with American Superconductor's multifilamentary composite HTS wire. This motor undergoing factory testing is shown in Figure 3 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, cryocooler system and a novel armature winding cooled with fresh water. The motor was load tested to 5,900 hp steady state and 7,000 hp peak in the fall of 2001.

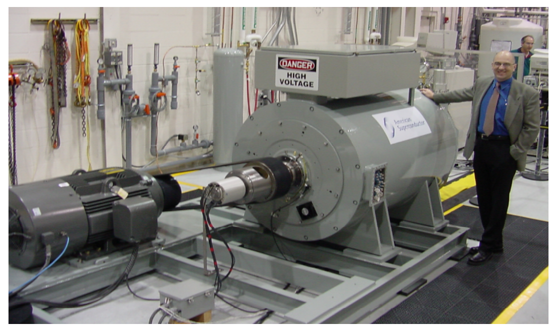

Figure 3: 5000 hp, 1800 RPM HTS motor under test

The major parameters and characteristics of the motor (as measured) are summarized in Table-1. The machine operates at 6.6 kV and has a low synchronous reactance (0.32 pu). Transient and sub-transient reactances are similar to conventional machines. Its efficiency at full-load was measured to be 97.7%.

Table 1: 5000 hp motor characteristic parameters

List of parameters	**value**
Motor output	Motor output 5000 hp (nominal, tested to 7,000 HP transient, and 5900 HP maximum steady state)
Speed	1800 rpm
Pole number	4
Line voltage	6.6 kV
Full load efficiency	97.7 %
Operating power factor - leading	0.99
Straight length of machine	23.2 inches
HTS field inductance	8.8 Henry
HTS field current	156 Amps
Stator resistance	0.10 Ohm
Stator current	333 Amps
Load angle at full load	-17.069 deg
D-axis synchronous reactance	0.32 pu
Q-axis synchronous reactance	0.32 pu
D-axis transient reactance	0.27 pu
D-axis subtransient reactance	0.173 pu
Q-axis subtransient reactance	0.173 pu
Stator short circuit time constant	0.031 sec

The successful testing of the motor has demonstrated that

HTS field and its cooling system. The cooling is accomplished by cryocooler refrigerators mounted in stationary reference frame and coolant was transferred to rotor through stationary to rotating coupling. The high power density stator was demonstrated. It is conduction cooled with fresh-water, i.e. water is not at high potential. These technologies are forming basis for development of ship propulsion motors and generators.

V. 25 MW Propulsion Motors

HTS synchronous motors have been in development for ship propulsion since 1997[7]. The Navy funded the conceptual design of a 25 MW motor to evaluate the potential benefits of motor design using high temperature superconductors. With ONR the following goals listed in Table 2 were set for the motor:

Table 2. 25 MW Motor Goals

List of parameters	Value
Nominal Rating	25 MW
Line Voltage	4160 volt
Speed at full-load	120 rpm
Efficiency at full load	>96%
Structureborne Noise	<60 dB
Design Life	30 yrs

ONR has expressed potential interest in POD mounted motors which lead to the selection of motors with backiron diameter limited to 2.3 meters.

A parametric study of polecount and MMF vs. machine size led to the selection of the 6 pole design shown in Figure 4 and consists of a six pole air core design producing approximately 1.6 Tesla in the airgap. The cryocooler assembly can either be mounted independently or integral with the stator frame.

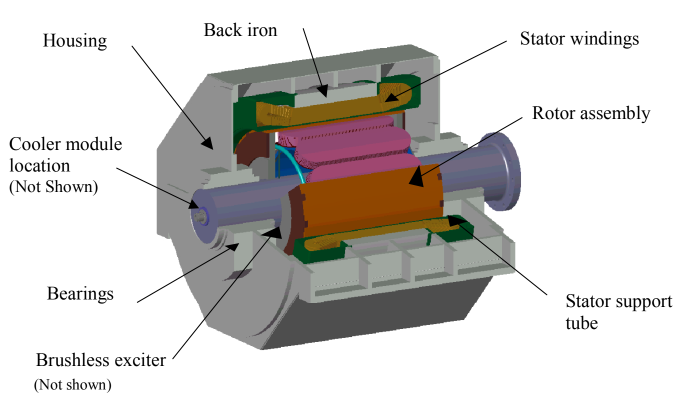

Figure 4: 25 MW, 120 RPM Ship Propulsion Motor

The estimated weight is 60-70 tons depending on the details of the frame and bearing assembly. The length over the end turns is 2.5 meters and the OD of the backiron is 2.4 meters.

The motor performance has been electrically modeled and its characteristic parameters are summarized in Table 3.

The HTS motor losses are dominated by the resistive losses in the stator copper winding as shown in Figure 5. This loss component is 86% of the total losses. On the other hand, power input to the cryogenic refrigerator is quite small – less than 5% of the total losses. The motor efficiency generally improves at partial loads because the stator loss reduction is proportional to square of the stator current.

The efficiency at part load is of interest in the naval application since very little of a typical mission profile is at full speed and power. Assuming power is cubic in speed, the efficiency (including refrigeration) is presented in Figure 6. The part load efficiency is predicted to improve down to about 10% of power or 46% of speed. Even at 30% speed (2.7% power) the efficiency is estimated to be over 94%.

Table 3: 25 MW Motor Concept Predicted Performance

List of parameters	Value
Number of Phases	9
Line Voltage	4160 volt
Speed at full-load	120 rpm
Phase current	622 A
Load angle	19.1 deg.
Synchronous Reactance`	0.34 pu
Transient Reactance	0.275 pu
Subtransient Reactance	0.19 pu
Overall Efficiency	97.5%
Predicted full speed structureborne noise	47 dB

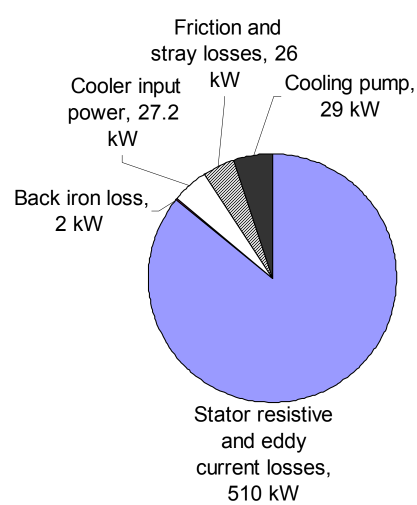

Figure 5: Estimated Distribution of Losses

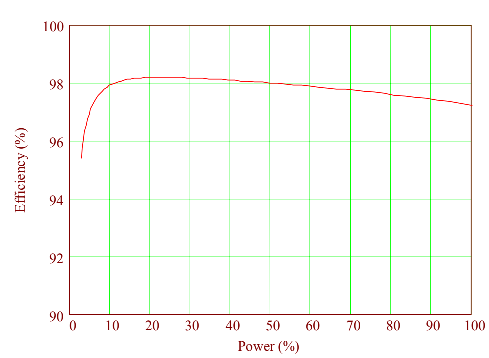

Figure 6: Efficiency at part load and speed

The high field level in the machine reduces the machine size and weight and puts force on the backiron. The deflection and predicted noise of the backiron was presented in Figure 7. The predicted noise levels at full excitation are well within the required limits and could be made even lower at the expense of additional back iron thickness and weight.

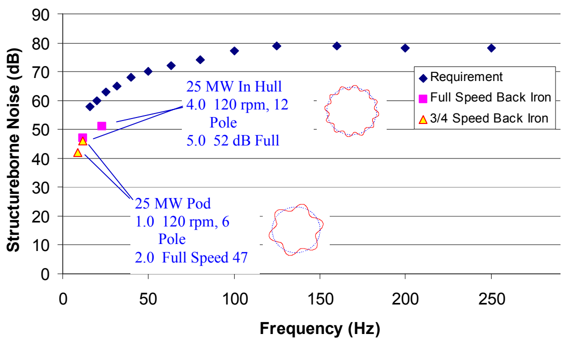

Figure 7: Structureborne Noise Prediction

The conceptual design of the 25 MW 120 rpm machine suggests a compact design with potential efficiency and acoustic advantages. Theses potential advantages can only be validated in the construction and testing of hardware. The Navy is presently funding the fabrication of a scaled version of the 5 MW described in the next section.

VI. 5 MW Model Motors

A scale motor was selected as a logical next step in the development of large ship propulsion motors. The appropriate scale was selected based on a machine with 1/10th the torque of a full-scale machine. The resulting physical sized of the machine is approximately 70% of the full machine assuming the machine dimensions are uniformly scaled and the current densities remain constant.

The objective of the scaled motor is to validate the technologies in the 25 MW 120-rpm motor. It was decided to scale the machine to be no less than 1/10th the torque of the full scale machine. An increased propulsor speed of 230 rpm was selected consistent with the lower torque. The goals are summarized in Table 4:

Table 4: 5 MW Motor Goals

List of parameters	Value
Torque	0.2 MN-m
Speed	230 rpm
Power	5 MW
Line Voltage	4160 volt

Assuming the current density in the rotor and stator remain the same, the torque of HTS machines without iron teeth scale roughly as the 5th power of dimension. The scaling of the 5 MW machine is therefore roughly 70% of the 25 MW machine. The resulting machine is summarized in Table 5.

The general characteristics of the model motor selected for validating the 25 MW components is presented in Table 6. The design has reasonably high efficiency even with the use of full refrigeration system sized for the 25 MW motor to fully qualify this motor.

Table 5: Selected Model Motor Predicted Characteristics

List of parameters	Value
Geometric scaling from 25 MW	~0.7
Estimated weight	26 tons
Number of Poles	6
Motor Outside Diameter	1.6 m
Motor length over end turns	1.6 m
Number of Phases	3
Speed at full-load	230 rpm

Table 6: AMSC 5 MW motor predicted characteristics

List of parameters	Value
Full Load	
Line current	714 A
Load angle	18.1 deg.
Synchronous Reactance`	0.32 pu
Transient Reactance	0.24 pu
Subtransient Reactance	0.15 pu
Overall Efficiency	96.8 %
Predicted full speed structureborne noise	55 dB
Part load prediction	
Part load speed	115 RPM
Power at partial load	0.625 MW
Overall efficiency at partial load	98.4%

The 5 MW motor has been selected to be of a representative physical size to permit use of components representative of those used in the full-scale 25 MW motor. The detailed design of the motor is nearing completion and fabrication of selected components has begun. The 5 MW model motor will be completed this year with testing planned for early next year.

VII. Future Trends

These designs are based on present and near term forecast performance of Bi2223 superconductor. As overall current density of HTS conductors improves, increasing current densities and reducing conductor cost, the size of machines will be reduced almost in inverse proportion to the achievable current density.

Progress in refrigeration can also impact future machines. Simple pulse tube refrigerators could further reduce the cost and power requirements of the required rotor refrigeration systems. These systems have the advantage of no cold moving parts, which further increases system reliability.

These material and equipment trends coupled with the trend toward electric drive in Naval applications and commercial shipping result in a unique opportunity for HTS motor systems.

VIII. Acknowledgment

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IX. References

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