

High Power Density Marine Propulsion Motors with Double-Helix Coils

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Abstract— A new class of marine propulsion motors, that achieves power density far superior from that obtained in conventional superconducting synchronous motor designs, is presented. This is accomplished through the use of a novel coil design called the “double-helix” (DH) coil for the superconducting rotor of a synchronous machine in conjunction with a superconducting stator. This configuration is especially suitable for use with high current capacity superconducting cables, which can be made as multi-strand cables from round wires or as several layers of thin flat conductors. When a high excitation current is applied to a DH coil wound from HTS conductor, the strong magnetic field that is produced can achieve a high power output in a relatively small machine. The rotor lends itself quite readily to high current excitation by means of a flux pump incorporated in a completely superconducting circuit without any external connection to the machine frame. The resulting low inductance, high current design facilitates the quench protection of high energy content coils.

The high power is developed in conjunction with a close-fitting superconducting three phase stator that uses an interleaved structure of conventional saddle-shaped superconducting coils to achieve an efficient flux linkage between the rotor and stator. The AC losses in the superconducting stator may be reduced to an acceptable level by using a two pole configuration with a low frequency (i.e. 2 Hz current for 120 rpm) and small filament conductor.

Index Terms— Rotating machines, superconducting devices, synchronous motor.

I. INTRODUCTION

The full potential of the superconducting propulsion motor is attained in a fully superconducting machine (i.e., an electrical machine where both rotor and stator are superconducting and there are no resistive elements in the rotor circuit). This is based on the following considerations:

- Iron pole pieces (that essentially limit the air gap flux to about 1.5 T) are not used and therefore such a machine is less massive and smaller in diameter.
- The rotor excitation fields can be raised to 4 T or even higher with superconducting coils and thus achieve a high power density.
- Machines with conventional field excitation (i.e., not superconducting circuitry) limit the rotor current to several hundred amperes. This necessitates the use of high inductance coils for large scale applications, a solution that may make quench protection for large power output machines a difficult problem.
- Machines with a superconducting rotor and normal conducting stator need to thermally isolate the rotor and thus require radial space for insulation and a vacuum barrier. This reduces the flux linkage between the rotor and stator coils.
- High current density in superconducting windings reduces the size of the stator coil, to provide more flux linkage and power density.

A fully superconducting machine is feasible if the AC losses in the stator can be reduced to a manageable level. Multi-filamentary superconducting wires can be formed into multi-strand cable that can be used in a 3-phase stator in an all superconducting machine. The hysteresis loss in the superconductor can be reduced with fine filament conductor. The steady state loss depends on frequency, but the propulsion motor application is typically a low frequency machine. In a two pole configuration, that we describe, the operating frequency is 2 Hz in order to bring down the stator AC losses to a manageable level. The stator example uses MgB₂ conductor at 20 K and 2 T maximum field. Present progress in the development of fine filament conductors of this type has indicated that it appears feasible to obtain filaments in the 10 – 15 micron diameter in a conductor with a 25 – 30 % fill factor in the near future [1]. If this can be realized, the hysteresis losses for a 2 Hz machine would be about 45 mW per cm³ of MgB₂ in the stator winding [2]. This level of heat generation can be handled, for example, by a thermosiphon cryocooler system such as described by Schwenterly for cooling HTS transformers in the 20 K temperature range [3].

High rotor excitation current in a quench safe design is feasible using a flux pump excited rotor and high current capacity cable (i.e. 4 – 20 kA) for the rotor coils. This is

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facilitated with the use of double-helix rotor coils [4,5,6] that can be easily manufactured in small diameters with strain sensitive materials such as HTS to make high current, low inductance coils. Thus, the rotor circuit can be made completely superconducting and can operate at arbitrarily high current since the limiting factor is the resistive loss in the junctions between the flux pump and rotor coils (typically 10^{-9} Ω per connection).

II. EXAMPLE OF A 35 MVA 120 RPM MOTOR

Conductor properties

Although MgB2 is the conductor of choice for the stator, the field at the inner layer of the rotor is ~ 4 T. Thus, for operation at 20 K, MgB2 is not suitable for the inner layer. In this case Bi-2212 multi-strand cable that typically has a J_e of about 200 A/mm² at 4T and 20 K [7] can be used. Since the rotor operates at DC, the AC hysteresis loss is not present (except for a relatively small amount when the coil is energized). Thus, the filament size is not a factor in the choice of this conductor and the currently available architecture can be used. It is a 19-element cable made from 7-strand sub-cable of 0.93 mm diameter strands. (Table 1)

The stator conductor, also shown in Table 1, is a multi-strand, flat (Rutherford style) cable made from 0.5 mm MgB2 strands with fine (10 – 15 μ) diameter filaments. For this example, we use a cable made of 19 strands of a 7-strand sub-cable of MgB2 wire. When cabled and rolled into a flat conductor and insulated with 0.5 mm of fiberglass, the effective conductor size is 4 x 25 mm. This relatively large cable is selected for this exercise to bring the working voltage of the machine down to a reasonably low level in order to reduce the electrical stress on the windings and enhance the reliability of the machine. In this case the RMS voltage on the stator would be about 3 kV with an RMS operating current of 4520 A.

Table 1. Properties of machine conductors

	Rotor	Stator
	Round multi-strand cable	Flat multi-strand cable
Conductor type		
Bare cable diameter or size(mm)	14	3 x 24
Insulated cable diameter or size (mm)	15	4 x 25
Conductor cross section (mm ²)	90	26
Max. current (A)	18000	6400
Current density (A/mm ²)	200	245
Max. field (T)	4.0	2.0
Current margin	n/a	37%

Rotor

The double-helix (DH) coil configuration (Figure 1) is used for the rotor coils. The minimum bend radius of the conductors in the DH coil configuration is significantly larger than in racetrack-shaped coils used in conventional superconducting motors and generators. This facilitates the use of strain-sensitive (brittle) materials while keeping substantially smaller dimensions. After individual coil layers are assembled, they are vacuum impregnated with a high-strength cryogenic adhesive to form a strong composite assembly. In addition, an outer thermally shrunk high-strength aluminum alloy shell compresses the rotor assembly to

provide reinforcement against magnetic and rotational forces. This shell can also serve as an electromagnetic shield to reduce the effect of transient fields on the rotor conductor.

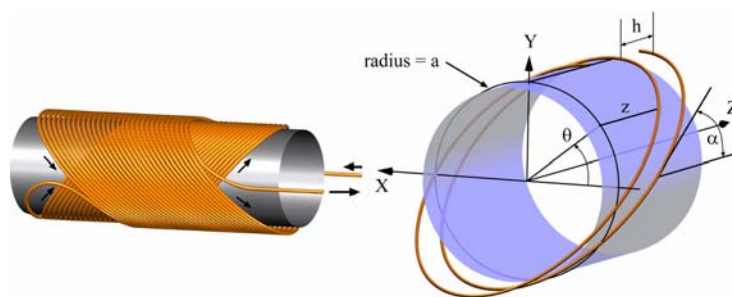


Figure 1: (Left) Layout of double helix winding. The axial field components of the 2 layers cancel each other and the total transverse field is enhanced. (Right) For the case of a dipole, the z coordinate of the conductor path is $z(\theta) = h \theta / 2 \pi + A_0 \sin \theta$ with $A_0 = a / \tan \alpha$, where a is the radius of the coil aperture, α is the tilt angle of the winding with respect to the horizontal axis, and h is the helical advance per turn.

Flux pump assembly

Various configurations of flux pumps have been described, some of which are especially suitable for use with DH rotors of superconducting machines. As shown by van de Klundert and ten Kate [8] the voltage and current produced by a particular flux pump connected to an inductive load is related to the total flux in the normal region(s), velocity of the normal region across the flux gate, and their effective self inductance and resistance. The use of several normal regions in the device increases the total flux produced and thus reduces the time necessary to reach the desired current level. This concept was used by Tsukiji, et al. [9] in the design of high-current-capacity flux pumps for the excitation of rotors for large (200 MW) superconducting generators. Examples were shown of flux pumps that could produce a 10 kA current in an 800 mH coil in less than 20 seconds. However, these devices were rather large and were almost as large as the rotor. Nevertheless, these design principles can be applied to our proposed DH machine in order to minimize the time necessary to achieve full excitation current in the rotor.

Figure 2 shows a 24-element HTS flux pump connected to the coils of a double-helix rotor. The operation of this device requires a suitable flux gate material that can be driven normal by fields of ~ 1 T at 20 K (in this example). A suitable flux gate material for operation at 20 K has been suggested and seems feasible to develop [10]. The normal spot produced by the magnetic field penetrating the regions at the poles of the excitation magnets induces a voltage (of the polarity shown) across each spot. When the flux gates are connected in parallel and each of the rotor coil leads are connected to this source, the voltage causes the current in the coil to increase until the desired level is obtained. At this time the excitation coils are shut off and the rotor coil carries an almost persistent current of several kA. The slowly decaying current can be easily charged up or adjusted to any level by applying current to the flux pump excitation coils.

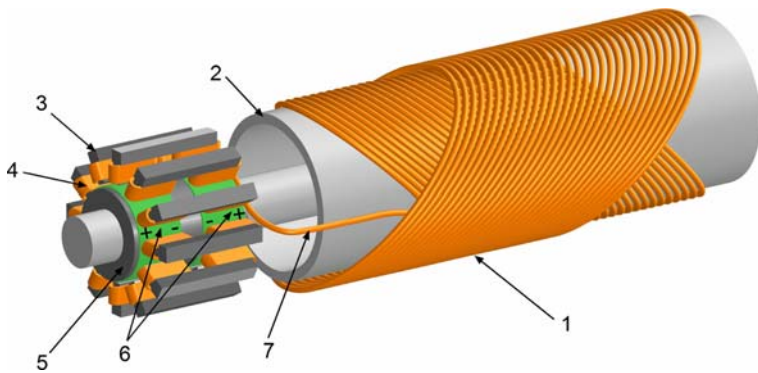


Figure 2. 24-element drum type HTS flux pump connected to a double-helix rotor. (1) A pair of double-helix coils. Multiple pairs are used for increased field and power density. (2) Torque tube support for coils. (3) Stationary core for flux pump excitation magnet. (4) Externally controlled excitation coil (Permanent magnets are an option also.) (5) Rotating iron core of flux pump assembly. (6) Rotating HTS flux gates (thin cylinders, shown in green). Polarity of induced voltage shown and the elements are connected in parallel (not shown). (7) Coil lead (+) connected to flux gate. Other lead (-) is connected to the parallel connection (-) between flux gates (not shown).

Stator configuration

A saddle coil configuration is used for the 3-phase stator because it allows the smallest distance and highest coupling between the rotor and stator windings. The end topology is arranged so that the coils of the three phases can be assembled in an interleaved manner. The method is shown in Figure 3. This requires two types of coil windings, one for Phase a in the form of a cylindrical saddle, and the other for Phases b and c in which the ends are ramped up by one coil layer thickness to allow the end winding to pass over the other Phase coils.

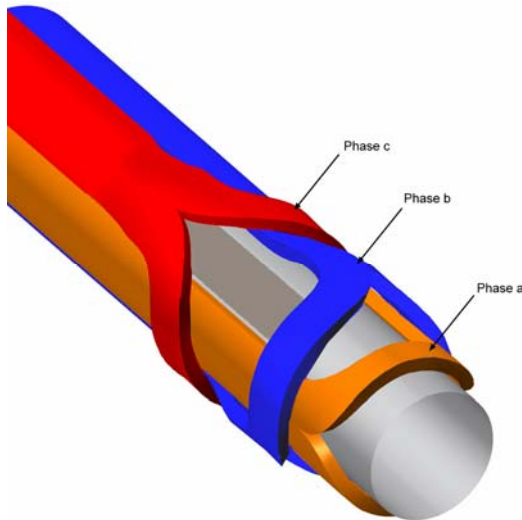


Figure 3. Saddle coil end topology for three phases nested in one layer of the stator. At the other end of the coil, the Phase b and c end positions can be interchanged, and thus Phase b and c windings can be identical.

Cold Mass Assembly

The stator is assembled in the cold mass in a way that is similar to that used for an accelerator magnet. Figure 4 shows how the stator coils are clamped in low carbon steel laminations that compress the coils, resist the Lorentz forces,

and provide magnetic shielding for the motor assembly. The insets show the circumferential flow of cryogen from slots in the laminations to enhance the cooling of the stator.

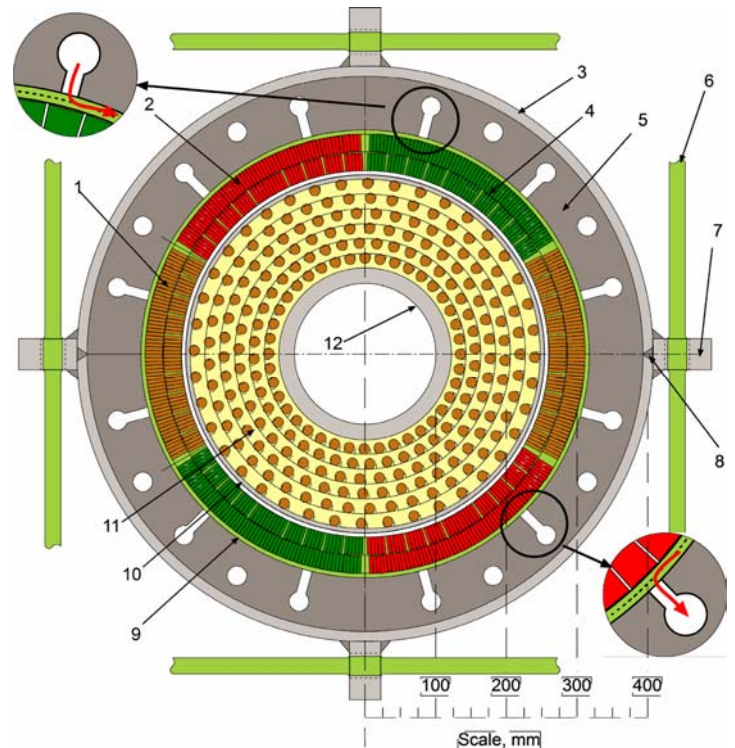


Figure 4: Cross section view of cold mass assembly. (1) Stator phase a saddle coil; (2) Stator phase b saddle coil; (3) cold mass containment shell (SS), pressed and welded to provide radial pre-stress to the stator coil assembly.; (4) Stator phase c saddle coil; (5) Low carbon steel yoke laminations (split into two halves); (6) Low heat leak cold mass support struts; (7) Support strut mounting bar.; (8) Cold mass shell weld; (9) Cooling strip for circumferential flow cooling slots for cryogen flow in and out of cooling strips; (10) Rotor reinforcing cylinder and EM shield (Al alloy clad with pure Al); (11) Six-layer double-helix rotor. (12) Rotor coil mounting and torque tube extension.

Figure 5 shows the method for assembly of the rotor in the cold mass in order to effectively transmit the large amount of torque to the drive shaft. The rotor coil is a vacuum impregnated, reinforced structural assembly that is mounted on a high strength austenitic steel torque tube – drive shaft. The coil assembly has involute spline ends that mesh with the torque tube assembly to provide a high shear strength connection from the coil ends to the drive shaft. When securely clamped as shown, the motor torque can be transmitted to the drive shaft with a high safety margin. The reaction torque on the stator is transmitted to the motor frame by means of several high strength, low heat leak composite support members that are attached to longitudinal supports bars (item #7 in Figure 4 or #9 in Figure 5). The dimensions shown are typical for a 35 MW, 120 rpm machine.

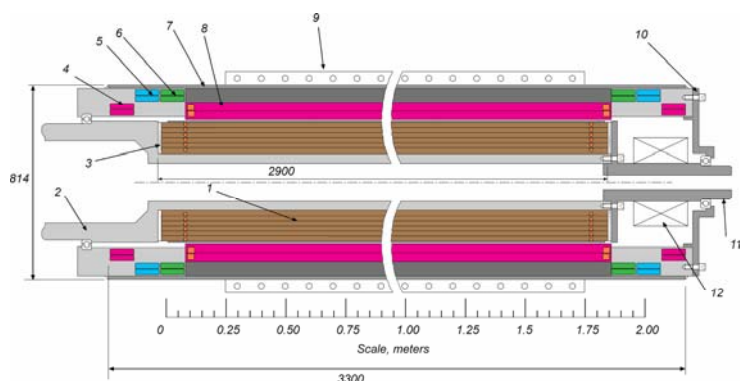


Figure 5. Side view of synchronous motor cold mass. (1) Double-helix 6-layer rotor assembly. (2) Torque tube for rotor. (3) Involute spline torque transmission coupling (used on both ends of rotor). (4) and (8) Stator Phase a. (5) Stator Phase b (coil end). (6) Stator Phase c (coil end). (7) Cold mass closure. (9) Bar for mounting low heat leak high strength stator support members. (10) Clamping plate for stator assembly and flux pump housing. (11) Clamping plate and rotor end support. (12) Flux pump goes here.

Parameters and Performance summary

The performance of this example motor can be computed from the inductances of the coils shown in Figures 4 and 5. The inductance values are listed in Table 2.

Table 2. Coil inductances

Inductances in H	
Coupling coefficient	80%
Rotor Self Inductance	2.495E-02
Rotor leakage inductance	4.989E-03
Stator self inductance	6.720E-03
Stator leakage inductance	1.344E-03
Stator-rotor mutual inductance	1.036E-02
Stator-rotor leakage inductance	2.590E-03
Synchronous Inductance	1.142E-02
Synchronous reactance (ohms)	1.436E-01

The steady state performance parameters of this machine are listed in Table 3. The mass and power densities were estimated for a motor assembly with cryostat. For comparison, this one has a mass of about 20% of a conventional iron dominated machine with a superconducting rotor, thus illustrating the potential power density advance using the proposed technology.

Table 3. Synchronous Motor Estimated Performance

Output power	35	MW
Phase voltage	3000	V
Power factor	0.87	
Power angle	60	
Phase current (RMS)	4520	A
Synchronous reactance	0.468	
Motor line frequency	2	Hz
Motor rated torque	2.84E+06	N-m
Air gap shear stress	1550	kN/m ²
Cold mass diameter	0.81	m
Cold mass length	3.4	m
Estimated motor mass with cryostat	15	tonnes
Estimated power density	2.3	kW/kg

III. CONCLUSION

An example has been shown of a 35 MW, 120 rpm propulsion motor that has about 20 % the mass of a machine using a more conventional design. This has been achieved by using an all superconducting machine with a high-current flux-pump-excited rotor in a quench-safe design. The rotor uses double-helix coils, which can be easily manufactured in compact form with high current capacity, round multi-strand cable with Bi-2212 conductor for operation at 20 K and fields up to 4 T. The double-helix rotor coil could also use rectangular cable made from several layers of tape-type conductors of equivalent area with the same results.

The superconducting stator is feasible since the machine operates at low frequency (i.e. 2 Hz), and fine filament diameter (i.e. 10 -15 μ) MgB₂ which is under development would reduce the stator hysteresis loss to a manageable level.

Using the double-helix coil and flux-pump-excited rotor technology, it is possible to obtain power densities much greater than those which are possible in conventional machines. Thus this technology is also advantageous for other applications such as high power density superconducting generators and induction motors.

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