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Homopolar superconducting AC machines, with HTS dynamo driven field coils, for aerospace applications

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Abstract. There is worldwide interest in high-speed motors and generators with characteristics of compactness, light weight and high efficiency for aerospace applications. Several options are under consideration. However, machines employing high temperature superconductors (HTS) look promising for enabling machines with the desired characteristics. Machines employing excitation field windings on the rotor are constrained by the stress limit of rotor teeth and mechanisms for holding the winding at very high speed. Homopolar AC synchronous machines characteristically employ both the DC field excitation winding and AC armature windings in the stator. The rotor is merely a magnetic iron forging with salient pole lumps, which could be rotated at very high speeds up to the stress limit of the rotor materials. Rotational speeds of 50,000 RPM and higher are achievable. The high rotational speed enables more compact lightweight machines.

This paper describes a 2 MW 25,000 RPM concept designs for machines employing HTS field excitation windings. The AC armature winding is made of actively cooled copper Litz conductor. The field winding consists of a small turn-count HTS coil that could be ramped up or down with a contactless HTS dynamo. This eliminates current leads spanning room-temperature and cryogenic regions and are major source for thermal conduction into the cryogenic region and thereby increase thermal load to be removed with refrigerators. For early adaption of this technology for the aerospace applications, this 2 MW machine weighing 380 kg with an efficiency > 99% represents an attractive option.

1. Introduction

The aviation industry is working diligently to develop an all-electric aircraft [1], with liquid hydrogen and fuel cells being considered as the prime generation source for aircraft propulsion [2]. Compact, lightweight, high efficiency motors and generators are essential for such applications [3] [4]. General Electric's Homopolar Inductor Alternator (HIA) is a good example of a prototype for an airborne generator; achieving a power density of ~ 9 kW/kg for a 5 MVA, 35,000 RPM machine [5].

Such AC homopolar synchronous machines are an ideal choice for near term aerospace applications. These machines include both AC armature and Direct-Current (DC) excitation windings within the stationary part of the machine. The stationary excitation winding magnetizes a solid steel rotor, enabling operating speeds limited only by the mechanical stress limit of the rotor steel. The operating speeds are many multiples of conventional power 50/60 Hz machines. Significant cooling requirements limit machines of this type utilizing copper excitation windings to only a few kilowatts. However, megawatt ratings become possible when superconducting excitation coils are used. The superconducting excitation coil is circular in shape and is accommodated in the stator. Its major thermal load is via conduction through current leads that span room-temperature and the cryogenic region of the coil. This thermal load must be removed with a refrigerator, which adds mass to the motor system and lowers overall efficiency. An alternative is to charge the field coil wirelessly using a DC dynamo [6, 7, 8] being developed by Victoria University of Wellington. In DC dynamos, the HTS stator is subjected to a time-varying magnetic field provided by a rotor housing permanent magnets [9, 10]. A time-averaged non-zero DC voltage is developed in the dynamo stator [11]. This voltage is utilized for exciting the field coil [12]. Dynamos capable of delivering kiloamp class currents have recently been demonstrated [13, 14]. Since there are no warm components directly connected to the field coil the cryogenic heat-leak is minimized, enabling the use of high current coil design methodology and quasi-persistent operation. This paper describes 2 MW, 25000 RPM concept designs for machines employing an HTS field excitation winding energized by a DC dynamo.

2. Aircraft Motor Specifications
Table 1 summarises the specifications for the 2 MW 25,000 RPM motor excited with a DC dynamo.

Table 1. Specifications for a 2 MW, 25,000-RPM Aircraft Propulsion Motor

Parameter	Value
Motor Rating	2 MW
Motor Speed	25,000 RPM
Line Voltage	~1000 V
Rated power factor	0.9 lag
Rotor diameter	< 500 mm
Axial length	< 800 mm
Field excitation winding	REBCO
Operating temperature	50 K

This motor design is based on the following assumptions;
a) Synchronous machine with 6-poles
b) Both DC field excitation and AC armature windings are located in the stator
c) Armature 3-phase winding employs a suitable Litz copper wire cable
d) Current density in the Litz copper strands is 6 A/mm^2
e) Armature coils are liquid cooled (water or oil)
f) Superconductor field winding uses Rare-Earth-Barium-Copper-Oxide (REBCO) conductor
g) REBCO windings operate at 50K
h) Field winding is cooled with a cryocooler available off-the-shelf
i) Field winding is charged wirelessly with a DC dynamo
j) Rotor is made of high permeability Carpenter Steel's Aermet 310 magnetic steel
k) Stator laminations are 0.1 mm thick Japanese JNEX-Core (model 10JNEX900)

The design and analysis for such machines is based on reference [15]. A similar machine was previously designed for a flywheel energy storage system [16] but did not incorporate excitation by a dynamo.

3. Motor Configuration
A cutaway diagram of the AC homopolar motor/generator is shown in Figure 1. The shaft and rotor have not been sectioned so as to show the 6-pole layout, with 60° rotationally offset poles. The three armature coil colors illustrate the three phases winding scheme. The HTS coil cryostat and its

surrounding insulation have been omitted for clarity, as has an electromagnetic (EM) shield located between the armatures and the superconducting coils. The ferromagnetic poles are shaped as in any salient pole machine so as to reduce the harmonic and torque ripple to acceptable levels. The motor housing is maintained in a partial vacuum for reducing windage friction drag at high rotational speeds. Frictionless non-contact magnetic bearings are required since mechanical bearings would not be able to operate continuously due to frictional losses and wear. Further configurational details are available in reference [16].

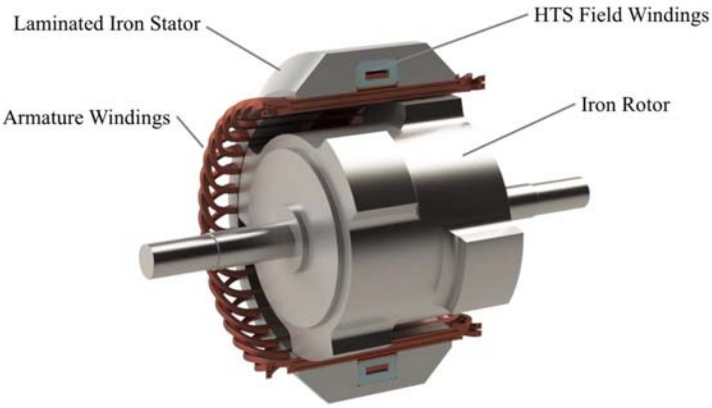

Figure 1. Sectioned view of the AC homopolar motor/generator

Initial sizing is conducted using 2D finite-element analysis (FEA) code. In this approximation the rotor poles are not offset by 90 elect.-degrees as the behavior of interest is the capability of the machine to effectively route flux within the rotor and stator. Figure 2 shows a 2D FEA model cross-section with armature coils housed between iron stator teeth. Note that the slots in the iron core (as shown in the figure) are for quantifying the effect of the iron teeth. In a real machine, the slots and teeth run parallel to the rotational axis of the machine. A double-layer, 3-phase AC winding configuration is selected. The dimensions of this cross-section suit the specifications of Table 1. The location of the field excitation coil is also shown in the figure.

The 2D model of Figure 2 was calibrated with a 3D Opera FEA model shown in Figure 3. Empirical corrections were applied to the 2D model to match the results of 3D model. The 2D model is preferred because of its simplicity and ease of rapidly comparing different designs. The 3D calculated field experienced by the full-pitched stator windings is decomposed into fundamental and harmonics that are listed in Table 2. Most harmonics of concern (5^{th}, 7^{th}, 11^{th} and 13^{th}) are quite small and are not expected to be problematic in creating excessive eddy-current heating in the stator coil.

Preliminary design of the machine is summarized in Table 3. The machine is sized for 2 MW at a 3-phase line voltage of 1292 V. The table also lists preliminary component weights for the machine. The power density of this machine is 5.4 kW/kg, which is comparable with 9.2 kW/kg 5 MW @35,000 RPM machine presented by GE [2]; i.e. 2 MW @25,000 RPM scaled to 35,000 RPM (5.4*35000/25000 = 7.6 kW/kg. Since the power density and efficiency of such machines are highly size dependent, this 2 MW machine could achieve power densities even higher than GE projection in 5 MW rating.

The field coil is designed using SuperPower 3 mm wide HTS tapes with critical current (I_c) enhanced by a factor of 3.3 (to account for thick film conductor being proposed by University of Houston). The self-field I_c for this conductor is 165 A @ 77 K and 690 A @ 50 K [17, 18]. However, the cross-section of HTS coil is very small compared to the allocated cavity size being controlled by cryostat walls. Thus, a higher I_c conductor is likely to have little influence on this machine size or mass. The maximum perpendicular field experienced by the HTS field coil is 0.16 T (at full-load). This field coil creates 1.7 T field in the magnetic iron. It is not desirable to operate the iron at higher field in such machines because they operate on basis of difference in reluctance of magnetic path under a pole and in inter-pole region. Higher magnetic field in the iron will reduce this difference casing increase in machine size and mass. The field coil carries 364 A at full-load. If current leads are employed the thermal load conducted to cryogenic environment would be about 36 W. Estimated thermal conduction through coil cryostat is about 30 W. Using an HTS dynamo, the thermal conduction will be reduced by 90% of that due to current leads (~ 4 W). Thus, total thermal load with and without the dynamo would be 34 W and 66 W, respectively. Table 4 compares the two systems; with current leads and with dynamo.

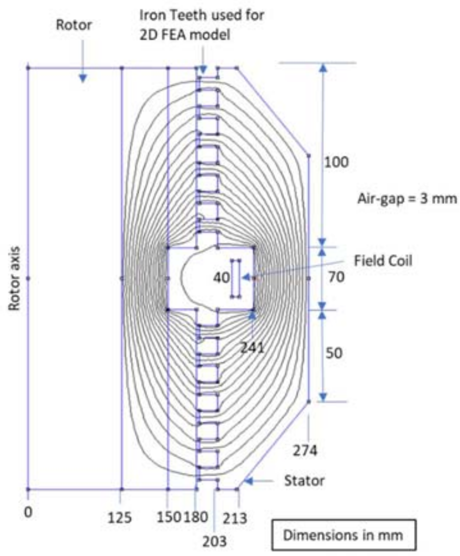

Figure 2. Representative cross-sections of the machine (slots in iron core are intentionally oriented as shown to assess effect of teeth with 2D FEA modelling).

Table 2. Field harmonics experienced by the full-pitched stator coils.

Harmonic	Field(G)	Fraction of fundamental
1	3512	1
3	71.9	0.02
5	162.8	0.046
7	78.4	0.022
9	118.6	0.034
11	39.3	0.011
13	40.6	0.012
15	33.4	0.009

4. Field Winding Details

The field coil is circular in shape with a cross-section of 40 mm x 8 mm and has a mean radius of 212 mm. It has 60 turns of 3 mm wide REBCO conductor – 12 turns/layer and 5 layers. The overall dimensions of the coil cryostat are 70 mm x 33 mm. Inductance of the field coil is 1.19 mH. Field currents at no-load and rated full-load are 188 A and 364 A, respectively. The dynamo to be integrated with this coil is shown in Figure 4. and will be capable of managing field current over this range.

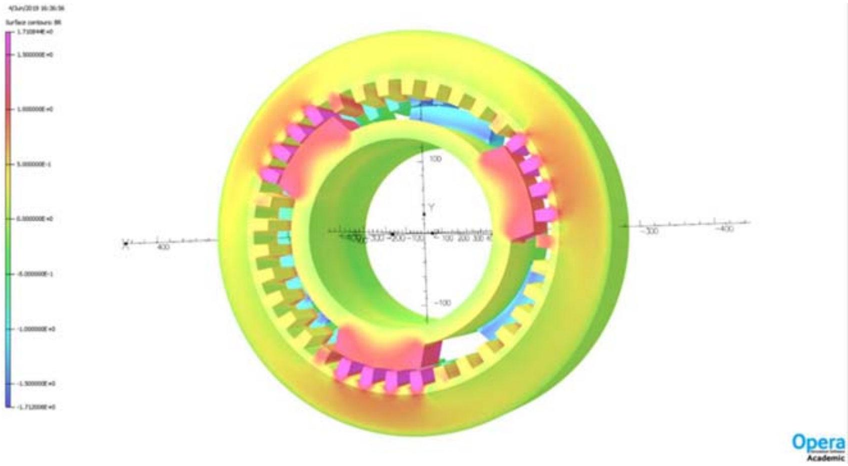

Figure 3. Opera 3-D finite-element model of the machine. Colour scale illustrates the radial field component B_r between ± 1.72 T.

Table 3. Preliminary design summary for the machine with dynamo exciter.

Parameter	Double Layer
Power Rating, kVA	2020
Output power at full-load, kW	2000
Line voltage, V-rms	1292
Phase current, A-rms	922
Overall axial length, m	0.45
Overall diameter, m	0.56
Mass of the machine alone, kg	381
Mass of cryo-cooling system, kg	3
Total mass, kg	383
Efficiency at full-load, %	99.1
Cryocooler load, W	38[a]
Other parameters of interest	
Rated speed, RPM	25000
Number of poles	6
Frequency, Hz	833
Field winding details	
Number of turns	60

Field winding critical current- no-load, A	621
Field winding critical current – rated-load, A	560
Field winding current at rated load, A	364
HTS wire width, mm	3
HTS wire length, m	84
Operating temperature, K	50
Stator winding details	
Active length under each pole, mm	100
Number of armature turns/ph	16
Number of armature circuits	6
Number of coils in armature	36
Number of turns/coil	8
Field coil inductance, mH	1.19
Machine component weight summary	
- Shaft, kg	5
- Rotor yoke, kg	76
- Poles, kg	21
- Stator case, kg	50
- Cooling system, kg	2[a]
Total machine mass, kg	380
Total system mass, kg	380
Torque density, N*m/kg	2.06
Power density, kW/kg	5.4

[a] Calculated using Ref: Ray Radebaugh, "Ray Radebaugh Cryocoolers for Aircraft Superconducting Generators and Motors", NIST, AIP Conference Proceedings 1434. 171 (2012): doi: 10.1063/1.4706918

Table 4. Comparison of field winding thermal load with and without a dynamo.

Description	Current Leads	Dynamo
Thermal conduction through cryostat, W	30	30
Thermal conduction through exciter, W	36	4
Total thermal load, W	66	34
Power input to refrigerator, kW	1.94	1.05
Weight of refrigerator, kg	4	2

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5. Conclusions

The AC homopolar concept currently represents least risky option for aircraft applications in near term. It could be built by integrating components already prototyped and tested. With an efficiency > 99% and power density > 5.4 kW/kg might be acceptable to early adopters, while research continues to seek alternatives to achieve higher efficiencies and power densities. It must be noted that the power density and efficiency of this class of machines are highly rating dependent. For example, a 5 MW, 35,000 RPM machine could achieve power density > 12 kW/kg – exceeding the 9.2 kW/kg reported for the GE machine [5].

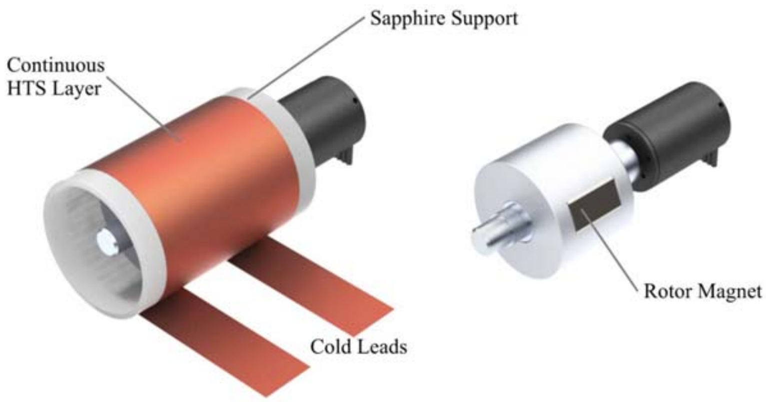

Figure 4. DC HTS dynamo concept to be integrated with the field coil. The right image shows the device with the HTS and sapphire support removed to illustrate the rotating magnet.

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