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High Efficiency Megawatt Motor Conceptual Design

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The High Efficiency Megawatt Motor (HEMM) is being designed to meet the needs of Electrified Aircraft Propulsion (EAP). The key objective of this work is to establish a motor technology which simultaneously attains high specific power (>16kW/kg ratio to electromagnetic weight) and high efficiency (>98%) by judicious application of high temperature superconducting wire and integrated thermal management. Another important feature is to achieve the performance goals with an eye to aircraft integration constraints. An electromagnetic analysis was performed which shows that the proposed HEMM design meets the performance objectives if key current capability and mechanical constraints are achieved. Sensitivity of motor power and performance to those parameters is illustrated. The HEMM technology could be applied to a range of aircraft types that require megawatt level electrical power.

I. Introduction

NASA Glenn Research Center is developing the High Efficiency Megawatt Motor (HEMM) with the goal of demonstrating a motor that has both high specific power (16kW/kg electromagnetic weight goal) and high efficiency (99% stretch goal). Electrified Aircraft Propulsion (EAP) is the target application for this electric machine. Requirements for the prototype machine are based on the Single-Aisle Turboelectric Aircraft with Aft Boundary Layer (STARC–ABL) concept. [1] HEMM is a partially superconducting, synchronous wound field machine that can operate as a motor or generator (Figure 1). It combines a self-cooled, superconducting rotor with a semi-slotless stator, allowing the motor to achieve exceptional specific power and efficiency without incurring the external cooling weight penalty which commonly impacts superconducting machines. The combination of the described elements allows a motor to be built that essentially operates like any traditional (nonsuperconducting) motor when viewed externally as

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a system, however it incorporates superconductors on the rotor to create a strong airgap magnetic field that enables specific power and efficiency performance that cannot be achieved using normal conductors or permanent magnets.

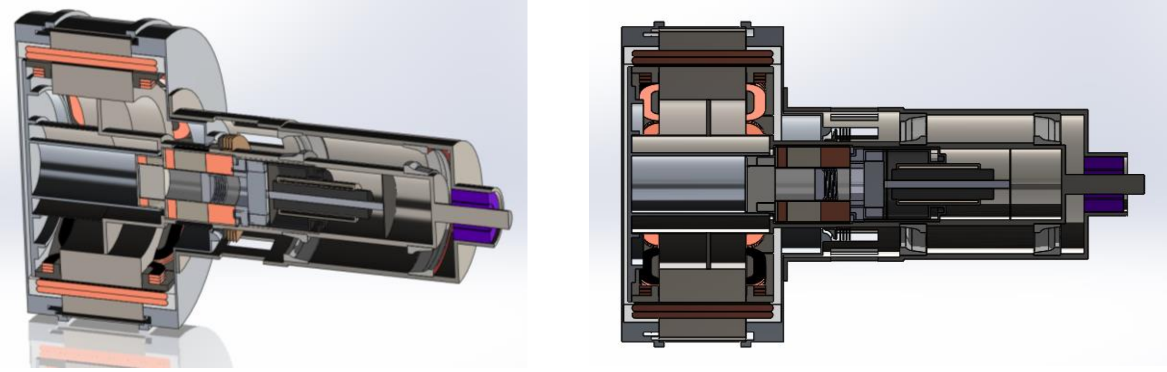


Figure 1. High Efficiency Megawatt Motor (HEMM) concept design

A. Importance of Efficiency

Although at first glance the difference between a 95% and 99% efficient machine may seem insignificant, it is actually quite consequential because the losses, which manifest themselves as heat, are five times lower for the 99% case compared to the 95% case (Figure 2). Electric machine efficiency propagates to aircraft-level impacts through the sizing of the thermal management system, the impact of multiple conversions, and the direct impact to fuel burn.

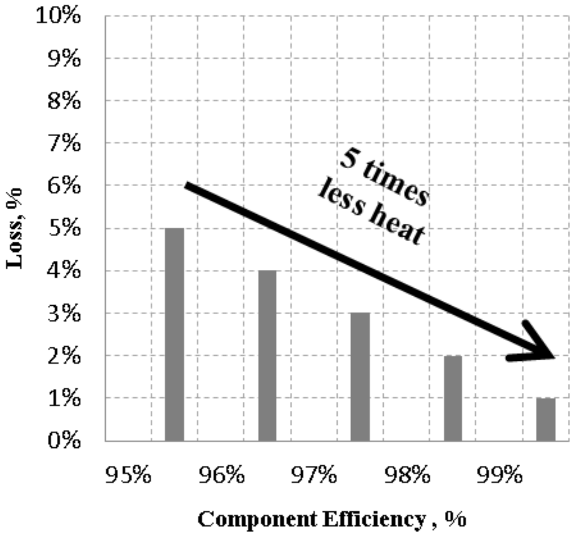


Figure 2. Heat to Be Rejected

Thermal management of electrical components on the aircraft poses new challenges compared to turbine engine thermal management. The aircraft internal combustion or turbine engine's thermal efficiency may range between 10%-50% depending on size; however, in these systems a significant portion of the waste heat leaves with the exhaust, and contributes to thrust. Conversely, in the electrical system all of the waste heat is absorbed locally into the powertrain and structure unless active thermal management is used. The temperature of the waste heat is also important; electrical machines typically have maximum hot spot temperatures between 105-220°C, whereas converters which are used to control motors typically have maximum hot spot temperatures in the 85-150°C range. The components are usually cooled by a flow of air, oil, or water/glycol which needs to be about 10-50°C lower in temperature than the hot spot limit. In the case of an aircraft operating on the worst case hot day, with margin, the rejection temperature for the heat exchanger may be in the range of 60°C. Analyzing these approximate numbers, the thermal system will collect heat in the range of 75°C to 170°C (depending on the temperature ratings of the components), and needs to reject heat at around 60°C. One conclusion from this analysis is that the component temperature ratings probably need to be above 130°C, which rules out the use of some of the lower end materials for these systems. A second conclusion is that the overall temperature delta probably will not be more than 100°C; this is problematic since heat exchanger size scales with the inverse of temperature delta. Heat can possibly be rejected either to the airstream or to the fuel, however, this approach is also potentially problematic. Airstream rejection leads to additional drag, while rejection to the fuel provides a finite heat sink which is already nearing maximum capacity in some aircraft designs.

The impact of component efficiency is compounded by the need for multiple conversions in an electrical system and is translated into a larger total system loss. A direct current-based system with a turbogenerator will be used as an example. The generator is driven from a turbine, turboshaft, or other prime mover, the output is rectified and distributed as dc power, then an inverter is used to drive motors which apply torque to the propulsive fan or propeller. This system has four electrical conversion steps: 1) generator – shaft to ac electrical, 2) rectifier – ac to dc electrical,

3) inverter – dc to ac electrical, and 4) motor – ac electrical to shaft. Figure 3 shows the system with state of the art technology assumptions and Figure 4 with highly advanced technology assumptions.

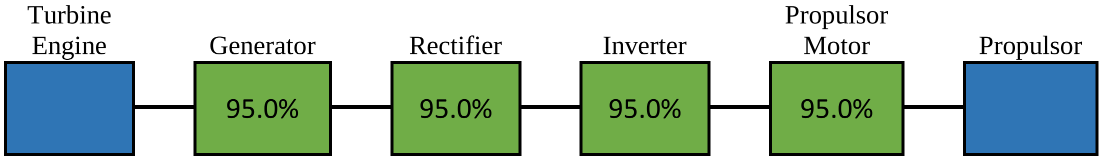


Figure 3. State of the Art Electrical Components

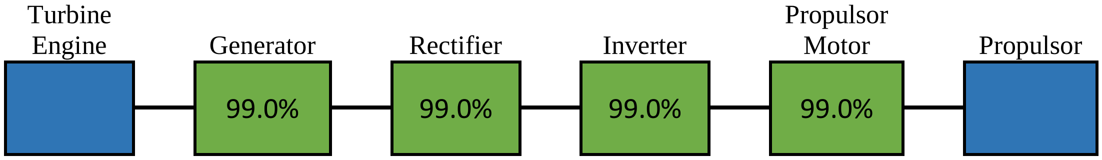
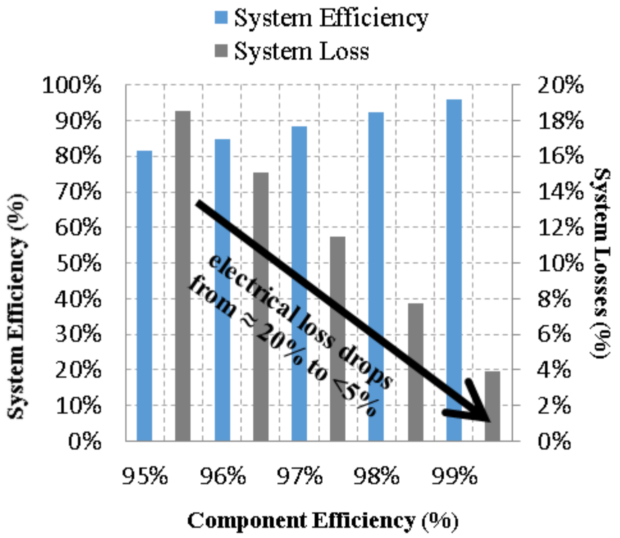


Figure 4. Highly Advanced Electrical Components

Figure 5 depicts the end-to-end drive system losses based on a four conversion dc system, with all four of the components varied between 95 to 99% efficiency. In this system, the end-to-end loss drops from approximately 20% (95% components) down to less than 5% (99% components).

B. HEMM Design Requirements

The aeronautics industry has been challenged on many fronts to increase efficiency, reduce emissions, and decrease dependency on carbon-based fuels. Electrified Aircraft Propulsion (EAP), implemented through turboelectric, hybrid electric, or all electric propulsion has the potential to revolutionize the aviation industry. Previous studies have shown that the weight and efficiency of the power system must be beyond the current



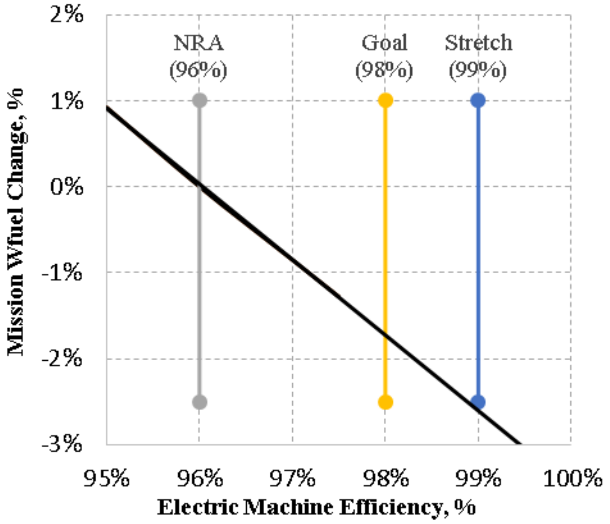


Figure 6. Aircraft Fuel Burn Sensitivity to Electric Machine Efficiency

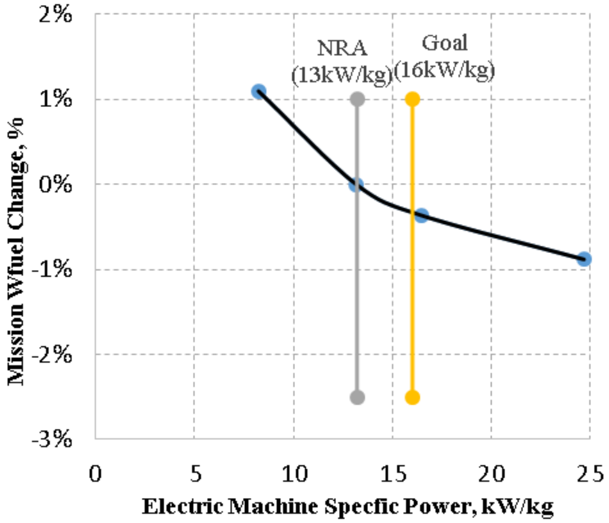


Figure 7. Aircraft Fuel Burn Sensitivity to Electric Machine Specific Power

state-of-the-art to reduce fuel burn on the aircraft.[2,3] Additionally, the exploration of megawatt level components applies to a broad range of aircraft concepts ranging from fully turboelectric or electric systems in the nine passenger size, up to partially turboelectric systems for single-aisle aircraft. The HEMM requirements were derived based on the STARC-ABL single-aisle aircraft concept (Table 1).

Table 1. HEMM Prototype Requirements

Requirement	Rationale
The rated operating power shall be 1.4MW or greater	From generator power requirements in 2016 STARC-ABL Aviation paper
The specific power of the electric machine shall be greater than 16 kW/kg	Combination of STARC-ABL sensitivity analysis and Hybrid Gas Electric subproject goals
The efficiency of the electric machine shall be greater than 98% with a stretch goal of 99%.	Combination of STARC-ABL sensitivity analysis and Hybrid Gas Electric subproject goals
The rated operating speed shall be 6800 RPM	From concept design of STARC-ABL with geared turbofan low spool speed
The thermal management approach shall be based on fluid cooling with an inlet temperature of 60°C and the use of materials rated to 220°C when possible.	Based on a UTRC NRA study of a parallel hybrid single-aisle aircraft with a 1MW motor connected to each turbofan.

II. HEMM Motor Concept Design

A. Motor Design

Permanent magnet, switched reluctance, induction, and wound field machine types are being considered for aircraft propulsion electrical systems. Typically, studies focus on specific power as the key differentiating metric for the selection of the motor type. However, other metrics such as efficiency, speed matching with a load or source, ability to shut down in a fault condition, thermal management constraints, and electrical system integration considerations are equally important for overall system performance.

HEMM is a wound field machine type with a superconducting rotor and normal operating temperature stator.[4, 5, 6] This configuration was selected based on initial trade studies for balanced performance. Another important operational benefit of the wound field machine is that it can be shut down by de-energizing the field winding; unlike the permanent magnet machine; de-energizing removes force from the drive shaft without the need for mechanical decoupling. In this case, the stator of the HEMM is designed to use a typical fluid or air cooling loop. For the prototype machine, it is anticipated that the cooling loop will be a dielectric oil with an input temperature of 60°C. The top level parameters of the motor design are shown in Table 2 and the cross section is shown in Figure 8.

Typically, machines have to trade specific power and efficiency; however, both are crucial for a successful design.[2,3] The HEMM has the potential to achieve high specific power and efficiency goals *simultaneously* because it utilizes superconducting wires in the rotor, which provide a much higher air gap field capability than permanent magnets, normal wound field conductors, or an induction rotor. Employing superconducting coils provides a dramatic improvement in magnetic field generated because the direct current resistance is zero in the superconductor at the

Table 2. Motor Design Parameters

Parameter	Value
Motor	Wound field synchronous
Rated Power	1.4 MW
Rated Speed	6800 RPM
Rated Voltage	1200V
Rated Current	360A
Layout	
Poles	12 pole
Phases	9

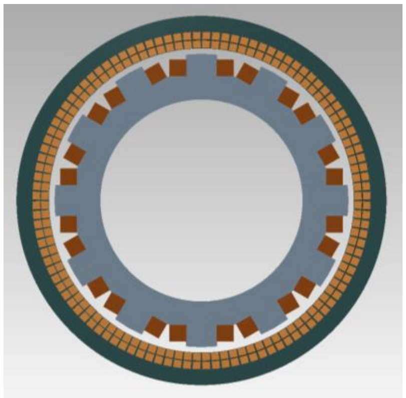


Figure 8. Motor Cross Section

correct operating conditions. However, superconducting machine applications have been limited because superconductors require cryogenic temperatures to operate, which typically requires a separate cryogenic fluid cooling system, adding mass, volume, and complexity to the overall system.

The HEMM incorporates a cryocooler in the rotor of the machine, and connects the cold tip of the cryocooler to the superconducting coils conductively, thereby eliminating the need for any external cryogenic equipment or any cryogenic fluids. A cryocooler is being designed that can lift 50W of heat from a 50K cold tip and reject to a 300K ambient environment. This cryocooler is also intended to be light weight (<10kg), small diameter (<100mm), and able to withstand 6800RPM rotation about its central axis such that it can be integrated in the shaft of the HEMM. As a result of the incorporation of those subcomponents within the motor, HEMM will interface with the aircraft in the same way as any standard electric machine, avoiding the additional mass, volume, and infrastructure which would be required with a traditional superconducting machine.

B. Stator Design

A semi-slotless stator with thin teeth and single turn Litz wire windings is used. The stator parameters are shown in Table 3, and the stator cross section is shown in Figure 9. The teeth do not serve a significant role electromagnetically, however they do provide a heat removal path and a physical constraint for the stator winding. Since this machine uses superconductors, it is possible to achieve a high air gap magnetic field; as a consequence, the stator windings are exposed to a high fluctuating field, necessitating the use of Litz wire to minimize eddy current losses in the windings. Additionally, in order to keep the output voltage of the machine under 1200V, a single turn winding will be used. A nine phase configuration was chosen to allow minimization of the harmonic content and yield a slight performance benefit compared to a three phase machine.

The stator of the HEMM also functions as the vacuum enclosure for the rotor, and has a cooling jacket that runs through the airgap, resulting in a fairly large airgap between the stator and rotor. Although the large airgap impacts performance, the penalty is not as significant in a machine with superconducting field windings as compared to a non-superconducting field winding because the superconducting configuration enables a very high number of amp-turns in a small rotor coil without resistive loss. The vacuum enclosure is incorporated in the stator using a thin wall composite tube. This enclosure maintains vacuum around the superconducting motor rotor, thermally isolates it, and dramatically reduces windage drag losses. The stator is designed with a direct liquid cooling loop, which circulates from a manifold at the inner surface of one end winding, across the length of the air gap, around the other end winding, back through a series of channels in the backiron, and finally across the outer diameter of the first end winding.

Table 3. Stator Design

Parameter	Value
Type	Semi slotless
Iron	
Inner Diameter	306mm
Outer Diameter	377mm
Stack Height	125mm
Slots	108
Slot Width	8mm
Slot Depth	19.5mm
Skew	3.33 degrees
Cooling Channel	3.5 mm
Winding	
Number of Phases	9
Layout	Lap, 2 Layer, Over/Under
Number of Turns	1
Litz Wire	8x8 mm, 6000 strands x 40AWG
Coil Slot Span	9
Phase/Group Offset	6/2

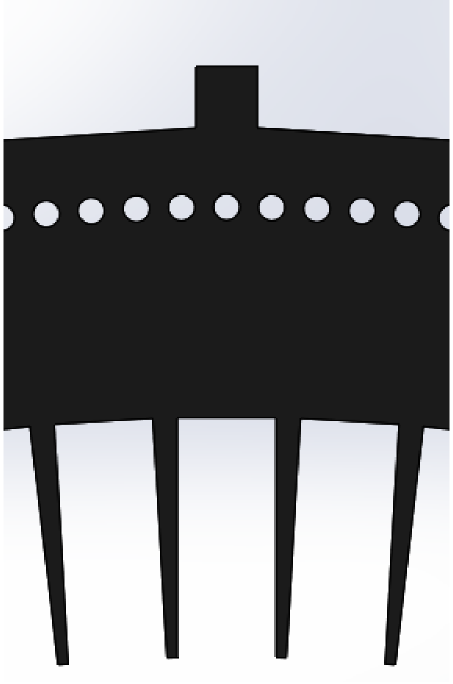


Figure 9. Stator Cross Section

C. Rotor Design

The HEMM rotor is a twelve pole, unlaminated, cobalt iron rotor, wound with dc superconducting coils. Key rotor parameters are shown in Table 4, and the rotor cross section is shown in Figure 10.

The use of superconducting wires to create a high field in a motor without conduction losses greatly improves the electric machine's performance relative to a system that uses non-superconducting windings. In the HEMM application, the superconductor is carrying direct current (dc), not alternating current (ac); thus no new superconductor technology needs to be developed, and the conductive losses in the rotor will be near zero. The challenge in the rotor coil design is to minimize mechanical stress and fatigue while maintaining a good electromagnetic circuit and conductive cooling path. Additional factors that limit the maximum current allowed in the superconductor are the operating temperature and field that the superconductor is exposed to. The current density used in the performance estimate was adjusted to include the impact of these two factors, plus margin.

The rotor coil design risks are minimized by limiting the surface speed of the rotor, and by using a relatively mature superconductor-based composite conductor. The surface speed of the HEMM rotor is 100m/s, which is one third to one half the surface speed of many high specific power motor designs; in addition to the risk reduction, this lower surface speed and corresponding lower rotor speed provides an additional benefit, as it allows the machine to be directly coupled to a turbofan (when utilized as a generator) or to a propulsor, i.e., a fan or propeller (when used as a motor) without the need for a gearbox. The rare-Earth barium copper oxide (REBCO) type superconductors have a relatively high superconducting temperature (92K critical temp), and are commercially available in lengths of several hundred meters. This length is sufficient to wind each level of the proposed HEMM rotor coils using a single piece of wire. Although commercially available REBCO composite tapes are relatively mature, the stability in this application (temperature, cyclic magnetic field, and cyclic, multi axial mechanical stress environment) must still be confirmed.

Table 4. Rotor Design

Parameter	Value
Type	dc wound field
Iron	
Inner Diameter	between 189.4 to 200mm
Outer Diameter	300mm
Length	125mm
Number of Poles	12
Tooth Width	34mm
Coil	
Rated Current	51.5A
Number of Turns	916 turns per pole
Coil Cross Section	14.9 mm wide x 16.75 mm tall
Operating condition	62.8K temperature, 2T field
Conductor	YBCO superconductor 4mm x 0.065mm

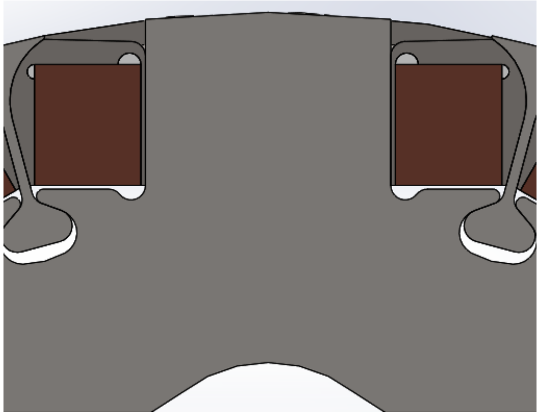


Figure 10. Rotor Cross Section

D. Thermal Conditions

The thermal conditions are key to estimating the performance of any motor. Temperature conditions used for the electromagnetic analysis of the HEMM machine were found through separate thermal finite analysis, and imposed as fixed temperatures for this work. Temperatures of key components are shown in Table 5.

Table 5. Thermal Conditions

Component	Temperature (°C)	Temperature (K)
Stator core	60	333
Stator windings	135	408
End turns	135	408
Rotor core	-213	60
Rotor coils	-213	60

The stator temperature analysis was done by finding anisotropic thermal conductivities for the windings based on the properties of the Litz wire and the potting compound, using the losses estimates from the electromagnetic analysis has the heat loads, and building a simplified thermal FEA model which included the geometric relationships of the motor and the boundary conditions imposed by the liquid cooling loop. Significant uncertainty exists in the estimation of the effective thermal conductivity of the potted Litz wire; tests are planned to reduce that uncertainty.

The rotor temperature analysis was done by estimating the heat load and the cryocooler performance, and building a simplified thermal FEA model to represent the geometry and boundary conditions. The estimated rotor heat load included: radiation heat transfer, heat leak through the torque tube, heat leak through the power leads for the rotor winding, windage losses, and rotor core losses. Rotor core loss is particularly difficult to estimate, because the source is the eddy current and hysteresis losses induced by high order multiples of the stator fundamental frequency, and test data for the magnetic material at these frequencies and temperatures does not exist.

III. Electromagnetic Performance Estimate

An initial electromagnetic performance estimate for the HEMM motor was performed using a commercial sizing code which combines 2D electromagnetic finite analysis with a set of motor design rules. Key parameters are used to define the operating condition of the motor, the rotor and stator magnetic circuit, and the rotor and stator windings. The trade space was explored through manual iteration, in which other modeling and FEA modeling packages were used to perform solid modeling of the motor, detailed 3D thermal, stress, electromagnetic analysis, and also cryo cooler sizing. Mass and performance estimates were made using the motor parameters described in Section II.

A. Torque Estimate

Estimated torque as a function of speed is shown in Figure 11. Torque is current limited and is essentially constant at 2000 N-m from zero speed to the rated speed of 6800RPM. Above the 7500 RPM the torque is voltage limited and begins to drop off.

B. Electromagnetic Mass Estimate

The electromagnetic mass estimate is shown in Table 6. The core mass estimates are based on the use of a cobalt-iron alloy. The superconducting rotor coil mass is estimated using the properties of the copper substrate because that is the dominant wire mass component. For this design approximately 70% of the electromagnetic mass is in the core, and 30% of the mass is in the rotor and stator windings. Litz wire mass is estimated using a packing factor. The total electromagnetic mass is estimated to be 74.2 kg. A 10% mass margin is added to account for design and analysis uncertainties.

C. Loss Estimate

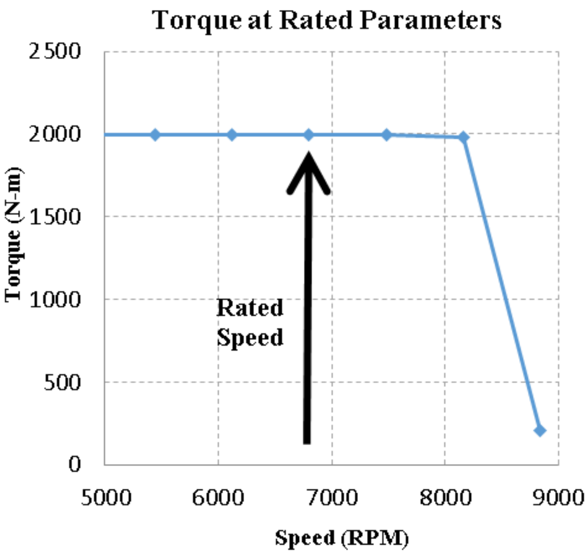


Figure 11. Torque at Rated Parameters

Table 6. Mass Estimate

Component	Mass (kg)
Stator core	21.5
Stator winding	13.77
Rotor core	29.7
Rotor coils	9.4
Total Electromagnetic Mass	74.4
Total Electromagnetic Mass (+10% margin)	81.9

Table 7. Loss Estimate

Component	Loss (kW)
Electromagnetic Losses	9.3
Stator Core	3.9
Stator winding (I^2R)	4.6
Stator winding proximity	0.8
Rotor core	0.009
Rotor coils	0
Other Losses	4
Cryocooler Power	2
Bearings	1
Vacuum Seals	1
Total Losses	13.5
Total Losses(+20% margin)	16.2

A summary of the loss estimation at rated operating condition is shown in Table 7.

Electromagnetic losses were calculated using a combination of the above-described commercial motor sizing code and spreadsheet calculations for stator winding proximity losses. The proximity losses in this machine are significant because the stator winding is directly exposed to a significant AC magnetic field imposed by the rotor field. As a result Litz wire is required to minimize the loss, at the expense of copper packing factor in the stator.

Other losses were calculated using a combination of in-house codes for cryocooler power estimation, and spreadsheet calculations for proximity and bearing losses. Additional losses were calculated separately to account for the total loss in the machine.

The estimated total losses are13.5kW comprised of 9.3kW electromagnetic loss, 1kW due to bearing drag, 2.5kW to power the cryocooler, and 1kW due to seal drag. A 20% loss estimate margin is added to account for design and analysis uncertainties resulting in a total loss with margin of 16.2kW.

D. Rated Performance Estimate vs Requirements

The estimated rated performance of HEMM meets or exceeds the requirements set forth in the beginning of the project (Table 8).

IV. Performance Sensitivity Analysis

A sensitivity analysis was performed on key parameters to understand which parameters have the most significant influence on the HEMM motor capability. This is important because, due to the uncertainty related to the estimates of the analytical models, many aspects of the analytical design of the motor have variances which will be found during performance testing of the final motor hardware.

The analysis is performed by one variable at a time while holding the others constant and then computing how the resultant power, specific power, and efficiency are changing with that variable.

Figure 12 shows the sensitivity of specific power and efficiency to stator current, rotor current, and air gap. Figure 13 shows the motor power sensitivity to those same parameters.

A. Sensitivity to Stator Current

The maximum current capability of the motor is limited by the hot spot temperature. Hot spot temperature is a function of the effective thermal conductivity of the Litz wire, the thermal properties and geometry of the stator iron, and the cooling approach. HEMM uses direct liquid cooling with a fluid temperature of 60°C. Analytical models of various fidelities were used to estimate hot spot

Table 8 - Design vs. Requirements

Requirement	Estimate Performance
The rated operating power shall be 1.4MW or greater	1.42MW
The specific power of the electric machine shall be greater than 16 kW/kg	17.4 kW/kg
The efficiency of the electric machine shall be greater than 98% with a stretch goal of 99%.	98.9%
The rated operating speed shall be 6800 RPM	6800
The thermal management approach shall be based on fluid cooling with an inlet temperature of 60°C and the use of materials rated to 220°C when possible.	compliant

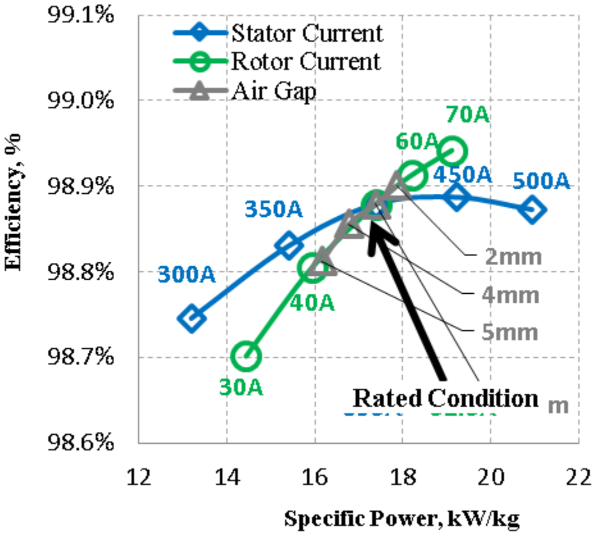


Figure 12. Performance vs. Key Parameters

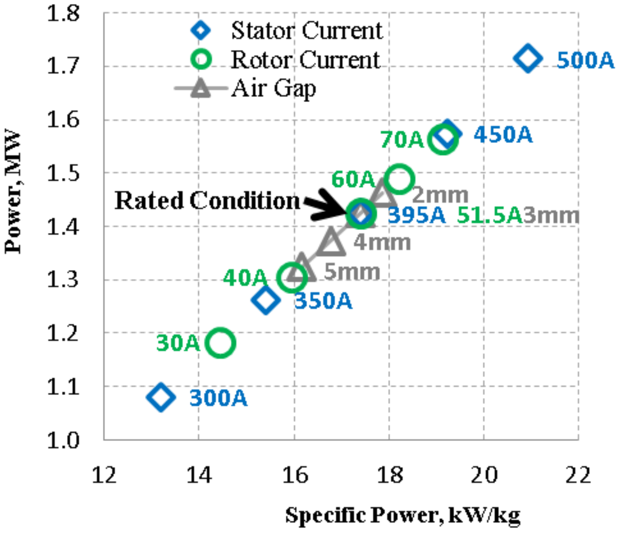


Figure 13. Power vs. Key Parameters

temperature, and coil tests are planned to confirm the estimates. Stator current is varied from 300A to 500A around the 395A rated point in this study.

B. Sensitivity to Rotor Current

The current capability of the superconducting rotor coils is impacted by the coil's temperature and magnetic field exposure. Although, the magnetic field can be estimated with a high degree of accuracy, the coil temperature is more difficult to estimate because it results from the equilibrium between the cryocooler heat lift capability and the sum of the heat leak and heat loss on the rotor. Estimation of the cryocooler performance has uncertainty due to the typical variation between a design code and the resultant hardware, along with the fact that the analytical tools available do not account for the centrifugal forces from rotation which are inherent to this application. The main source of the heat leak on the rotor is due to radiation, which is quite sensitive to the effective emissivities of the surfaces. Rotor current is varied from 30A to 70A around the 50.1A rated point in this study.

C. Sensitivity to Air Gap

Air gap performance sensitivity is particularly interesting in this motor, since the HEMM machine can generate considerably more field on the rotor compared to a non-superconducting machine. The airgap listed is the distance between the tips of the very thin metal stator teeth and the outer diameter of the rotor, however, the effective air gap is substantially larger, since the teeth are completely saturated, and the stator backiron is 19.5mm further away from the rotor than the stator teeth tips.

V. Summary

The High Efficiency Megawatt Motor (HEMM) being designed at NASA Glenn Research Center is a wound field partially superconducting machine. The goal of this effort is to develop an electrical machine with efficiency >98% and specific power when ratioed to electromagnetic mass >16kW/kg. A design has been completed and electromagnetic analysis shows that it will achieve the required performance if critical design aspects close thermally and structurally. Those design aspects impact the maximum continuous stator current, the maximum continuous rotor current, and the air gap. A power and performance sensitivity analysis was performed against those key parameters.

Acknowledgments

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