A fully superconducting air-core machine for aircraft propulsion

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Abstract. Partial and fully superconducting (SC) machines promise high power density capabilities required for electric propulsion. These machines need to achieve high power densities while reducing electrical heat losses to minimize the required cryogenic power and subsequent additional weight. Hydrogen powered all-electric planes provide a design space where ac losses are manageable. However, the high electrical frequencies in high-speed fully superconducting machines pose a significant challenge to reducing armature ac losses. In high-speed applications, coupling loss in the SC armature coils dominates and becomes a barrier for practical application of these machines. In this paper a fully superconducting machine is proposed for a hydrogen powered regional all-electric plane. An air core design is considered utilizing low ac loss MgB₂ wires. The design is targeted to achieve 50 kW/kg specific power while requiring ac losses to be less than 3 kW. This study explores the possibility of replacing a passive iron shield with active shielding coils to contain the magnetic flux inside the machine while reducing weight and increasing power density. The study focuses on minimizing weight as well as ac losses in the armature coils. An optimization algorithm is used to determine the trade-offs between iron shield and active shield coil designs. Results show that optimal designs for electric propulsion eliminate the passive shield in favor of active shielding coils - increasing the power density of the machine while maintaining the outside flux density below standard safety limits.

1. Introduction
Commercial electric aviation targets demand higher power density (>20 kW/kg) motors with higher efficiency (>92%) to leverage the weight benefits of electric propulsion [1] - [2]. Fully superconducting (SC) machines have the potential to achieve these high-power density targets by increasing electric and magnetic loading without losing efficiency to ohmic heat losses. However, due to the high-speed requirement of electric propulsion, armature winding ac losses become a significant challenge for fully superconducting machines. This paper investigates the feasibility of a hydrogen fuel-cell powered electric propulsion scheme for a regional commercial all-electric aircraft. A fully superconducting machine is proposed considering 30% of the total available cooling capacity of liquid hydrogen’s latent heat for motor cooling. To increase the power density, an inside-out synchronous machine is proposed where traditional passive shielding is replaced with active SC shield coils. The additional coils are placed radially outward to contain the flux within the machine. Since core loss and saturation are eliminated, higher flux density designs can be achieved with this topology. Initial studies have shown that flux densities up to 3 to 5 times that of conventional iron core designs are possible using superconductors, resulting in a more compact machine. Previous studies of partially SC machines indicated that with a
5 T air gap flux density, 35% volume reduction can be attained with only a 17% increase in superconductor usage [3]. Converting this machine to a fully SC design can potentially offer further performance improvements. However, armature winding ac losses in fully SC machine designs introduce a limitation on the achievable air-gap field strength and frequency. This paper explores fully superconducting, actively shielded machine designs for electric aircraft propulsion. A 2.5 MW, 4,500 rpm MgB$_2$ based fully SC machine design is investigated. A feasibility study of this topology for electric propulsion is conducted considering efficiency, weight, and cost. Special attention is given to modeling and reducing ac losses in the machine. An optimal design is targeted which reduces the SC usage and weight while constraining the total ac loss in the machine below a practical limit of 3 kW. A pole count study is conducted to identify the optimal operating electrical frequency which balances tolerable ac losses with high power density. The results are compared against a traditional iron core machine to evaluate the benefits.

2. Fully Superconducting Machines for Electric Propulsion

Several design studies have been conducted on high-speed fully SC machines for electric propulsion. A compilation and analysis of previously proposed high-speed SC machines is reported in [4]. The authors point out that ac losses are greatly affected by machine topology and that, consequently, an optimization needs to be performed to identify the best topology for minimizing these losses. Most previous design studies demonstrate that fully SC machines have the potential to meet the power density required for electric propulsion. However, minimizing ac losses to reach necessary efficiency levels and reduce cryogenic power and weight is still the roadblock for most applications.

2.1. Conventional Fully SC Designs

Conventional SC machine designs use iron in their stator and rotor, or as the back iron to shield magnetic flux inside the machine. A 1 MW, 12,000 rpm, fully SC machine using MgB$_2$ (Hyper Tech multi-filament wire with 0.18 mm filament diameter, 0.36 mm wire diameter and stainless steel sheath) windings is proposed in [5]. A design with an air-core stator and an iron core rotor is estimated to have 5,378 W of ac losses with a 1 T air-gap flux density. This design resulted in an 850.7 kW machine with a power density of 11.7 kW/kg. An iron core stator design is estimated to have 304 W of ac losses and 3,314 W of core losses. This design resulted in a power density of approximately 6.5 kW/kg. These losses and power densities need to be improved to surpass conventional electric machine power densities and to meet the specifications required for commercial electric propulsion [1] - [2]. Another design study of a 10 MW fully SC machine using REBCO tape (REBa$_2$Cu$_3$O$_y$) is presented in [6]. The performance of an air-core stator, 2-pole machine design is compared at three different speeds (3,000 rpm, 6,000 rpm and 9,000 rpm). Results showed that a 25.6 kW/kg power density could be achieved at 9,000 rpm, while 99.2% efficiency can be obtained at 3,000 rpm. A design operating at 20 K with 1 T air-gap flux density at 3,000 rpm had 49.9 kW of estimated losses, and at higher frequencies this loss increased further. It is reported that half of the weight of the machine came from iron used as a passive shield, and if active shield coils are used instead, the power density could be improved significantly.

A comparison study between a partial SC machine and fully SC machine employing MgB$_2$ (Hyper Tech multi-filament wire with 0.8 mm wire diameter and 25 mm twist pitch) in the armature windings and YBCO tapes as field winding is presented in [7]. EM FEA was carried out on a 5,000 rpm motor at 1.5, 3 and 5 MW; different pole counts were considered. The results showed that fully superconducting motors have the potential to reach a power density of 16 kg/kW. Terao et al. showed that for fully superconducting machines whose air-gap flux density is 1 T, ac losses are over 10% of the rated power - rendering them infeasible for use in electric propulsion. An EM study of 3 MW and 5 MW fully SC machines employing MgB$_2$
(multi-filament wire) cables in the armature coils and YBCO tapes for the field coils is presented in [8]. The 4-pole designs at 5,000 rpm showed that output densities of 19.4 and 25.2 kW/kg could be reached by the 3 MW and 5 MW machines respectively. In this study, the impact of back iron is investigated by varying its radial depth. It is evident that the back iron component adds significant weight and also influences ac losses in the machine. For feasible designs, the ac losses need to be reduced by several kilowatts.

While these design studies provide crucial weight and ac loss information, an optimization to minimize ac losses was never carried out. Since ac losses of a given SC wire and machine weight are influenced by several geometric and operational motor parameters, a multi-objective optimization should be explored to develop a front of optimal designs that minimize both objectives.

2.2. Actively shielded design

Traditionally, a passive iron shield is used to maintain flux within the machine, limiting external flux to accepted levels. The active shield machine topology uses a set of SC coils introduced radially outward from the field coils to accomplish the same task. This increases the power density by eliminating the need for a heavy iron shield. Furthermore, iron losses are also eliminated, resulting in a reduction of associated cryogenic power and system weight. Previously conducted EM studies [3], [9] and [10] demonstrate that an active shield topology has the potential to significantly increase power density. A multi-objective optimization study showed that a 32% reduction in volume can be achieved with a 33% increase in SC usage [9]. A similar study to determine the optimal pole-count for a compact machine showed that a 74% volume reduction can be obtained with 104% more SC usage [10].

3. Cryogenic Hydrogen-Energy Electric Transport Aircraft (CHEETA) Concept

Cryogenic hydrogen-energy electric transport aircraft is a concept proposed to utilize the high specific energy content of liquid hydrogen (LH$_2$) through fuel cell energy conversion and an ultra-efficient distributed electric propulsion system. The concept uses LH$_2$ not only as the energy storage mechanism, but also as a cryogen to enable a highly efficient SC electric system. This enables the usage of SC machines with SC power cables to efficiently convert electrical energy into mechanical energy. Letting gaseous hydrogen used in the fuel cells evaporate by heat losses in the SC motor and cables, the system provides free cryogenic cooling for SC electrical components. If the required cryogenic power to remove generated heat losses in the electrical system is maintained below the available free cooling, an ultra-efficient electrical system could be obtained using this concept. In this study, a plane which uses 920 GJ of total energy during a mission and has 20 MW of combined propulsion is explored. The weight of required LH$_2$ fuel is estimated to be 12,778 kg. Assuming a 0.059 kg/s boil-off rate, 26,383.4 W of total cooling power can be extracted. If 8 motors are used for distributed propulsion, the power of each motor and the available cooling power per motor can be estimated.

\[
\text{Power of each motor} = \frac{20}{8} = 2.5 \text{ MW} \quad (1)
\]

\[
\text{Available free cooling power per motor} = \frac{26,383.4}{8} = 3298 \text{ W} \quad (2)
\]

\[
\text{Targeted power density of each motor} \geq 25 \text{ kW/kg} \quad (3)
\]

Therefore, if each 2.5 MW motor is designed to have ac losses below 3 kW, no additional cryo-cooling refrigeration equipment is necessary. However, a method of cooling that utilizes the available LH$_2$ needs to be developed and will add significant weight to the machine.
4. Proposed fully superconducting machine
In this study a 2.5 MW, 4,500 rpm fully SC actively shielded motor is proposed for electric propulsion. The proposed machine specifications are tabulated in Table 1. However, to demonstrate the trade-offs between active and passive shield designs, a topology which consists of both shielding methods is explored in this paper. A genetic algorithm based optimization software (GOSET) is used to determine the best design suitable for electric propulsion between the two concepts.

Multi-filament MgB$_2$ SC cables are chosen for the armature windings due to their low ac loss characteristics. The same wires are also chosen for the field and shield coils. MgB$_2$ cable specifications are tabulated in Table 2. While setting the field and shield current densities to be at 200 A/mm$^2$, the armature current density is allowed to vary during optimization. However, designs which have more than 50% of the critical current density evaluated at the applied field are considered infeasible as they exceed our risk margin.

Table 1. Proposed Machine Specifications

| Specification                      | Value                     |
|-----------------------------------|---------------------------|
| Power                             | 2.5 [MW]                  |
| Speed                             | 4,500 [rpm]               |
| Power density                     | ≥ 25 [kW/kg]              |
| Air-gap length                    | 5 [mm]                    |
| Outer diameter                    | max 0.5 [m]               |
| Pole number                       | 2, 4, 6, 8, 10, 12        |
| Superconductor                    | MgB$_2$                   |
| Operating temperature             | 20 K                      |
| Operating phase voltage           | 750 V$_{rms}$             |
| Operating current                 | 1111 A$_{rms}$            |
| Armature slots per pole           | 6                         |
| Number of parallel connection     | 4                         |
| Armature current density, RMS     | max 200 A$_{rms}$/mm$^2$   |
| Field current density             | 200 A/mm$^2$              |
| Shield current density            | 200 A/mm$^2$              |

Table 2. MgB$_2$ Conductor Data (D$_{0}$=0.32/d$_{f}$=10/L=5) [mm/μm/mm]

| Parameter                        | Symbol | Value                  |
|----------------------------------|--------|------------------------|
| Critical current density at 20 K and self field 2 T [A/mm$^2$] | $J_c$  | 1780                   |
| SC outer diameter [mm]           | $D_o$  | 0.32                   |
| Filament diameter [mm]           | $d_f$  | 0.01                   |
| Number of filaments              | $n$    | 114                    |
| SC fill factor                   | $\lambda$ | 0.15               |
| Effective fill factor            | $\lambda_e$ | 0.49                |
| Transverse resistivity [Ω-mm]    | $\rho$ | 3.65E$^{-4}$          |
| Effective transverse resistivity [Ω-mm] | $\rho_e$ | 1.25E$^{-4}$         |
| Twist pitch [mm]                 | $L$    | 5                      |
5. Estimating AC Losses in Armature Coils

When alternating fields and currents are introduced to SC materials they generate losses in the form of heat, known as ac losses. These losses are cyclical and increase with both applied frequency and the square of the peak applied flux density. Because motors for electric propulsion operate at high speeds and therefore experience high electrical frequencies, losses in the armature coils are significant and determine the feasibility of a design. In this paper, Carr’s model [11] is used to estimate ac losses in the armature windings. These losses are evaluated across a unit length of wire and integrated over the total volume to compute the total loss. This model is widely used and was tweaked to estimate ac losses at high frequencies in [12] for MgB$_2$ cables and YBCO tapes.

The field required to penetrate the superconductor is evaluated as

$$B_p = 0.4\mu_0 J_c d_f$$

where $\mu_0$, $J_c$, and $d_f$ are the magnetic permeability, critical current density, and filament diameter respectively. The following equations are used to compute hysteresis ($P_h$), eddy current ($P_e$), coupling ($P_c$), and transport current ($P_t$) losses when the peak applied flux density, $B_m$, is much greater than $B_p$.

$$P_h = \frac{4}{3} J_c d_f B_m f \lambda$$

$$P_e = \frac{\pi^2}{k \rho_e} (D_0 B_m f)^2$$

$$P_c = \frac{1}{n \rho_e} (L B_m f)^2$$

$$P_t = \frac{\mu_0 f}{\pi} \frac{I_c}{I_c} \left[ \frac{(1 - \frac{I_0}{I_c}) \ln(1 - \frac{I_0}{I_c}) + \frac{I_0}{I_c} - 0.5(\frac{I_0}{I_c})^2}{\pi (\frac{D_0}{2})^2} \right]$$

where $I_0$, $I_c$, $f$, $\lambda$, $\rho_e$, $L$, and $D_0$ are the operating current, critical current, applied frequency, fill factor, copper matrix effective transverse resistivity, twist pitch, and SC outer diameter respectively. The constants $k$ and $n$ are set to be 4 and 2 respectively for circular, multi-filament SC wires.

6. Optimal Design Scheme

A simulation-based approach is chosen to explore the optimal design. An objective function shown in Equation 9 is formulated to minimize weight and ac losses using the total SC and shield-iron usage in the machine:

$$\min_{(\theta=variables)} \left\{ F_{\text{objective}}(\theta) = [\text{weight, ac loss}] \right\}$$

constrained such that

$$P_{out} = 2.5 \text{ MW}$$

$$\text{Machine Diameter} \leq 0.5 \text{ m}$$

$$\text{Outside Flux Density at 200 mm from OD} \leq 1 \text{ mT}$$

$$\text{Active Length} \leq 1.5 \text{ m}$$

$$J_0 \leq \frac{J_c}{2}$$
In this optimization, only the cost and weight of SC wire and iron yoke are considered. SC wire weight is calculated assuming a race track winding format and is separately computed for the active winding and end-winding regions. The weight of the machine is evaluated from the superconducting volume \( V_{SC} \) and shield iron volume \( V_{SI} \).

\[
V_{SC} = A_a(l_a + l_{a}) + A_f(l_s + l_f) + A_{sh}(l_s + l_{sh}) \tag{15}
\]

\[
V_{SI} = A_{SI}l_s \tag{16}
\]

weight = \( \rho_{SC}V_{SC} + \rho_{SI}V_{SI} \)  \( \tag{17} \)

where \( A_a, A_f, \) and \( A_{sh} \) are the SC cross-sectional areas for the armature, field, and shield respectively and \( l_a, l_f, \) and \( l_{sh} \) are their corresponding end-winding lengths. The stack length and shield iron cross-sectional area are represented by \( l_s \) and \( A_{SI} \) respectively, while \( \rho_{SC} \) and \( \rho_{SI} \) are the respective SC and shield iron densities considered as \( 8.25 \times 10^3 \text{ kg/m}^3 \). Cost of MgB\(_2\) is considered as $2/m and iron cost is considered as $2/kg. AC losses are evaluated only for the armature, and radial variations of flux density within the coils are considered by subdividing the armature cross-section into three paths and computing the average field in each section.

6.1. Optimization Algorithm
A genetic algorithm based optimization is chosen to minimize weight and losses. Optimization is performed by changing the machine design parameters shown in Figure 1. Design boundaries for each variable are tabulated in Table 3.

6.2. Optimization procedure
The open source MATLAB tool box, GOSET, is a genetic algorithm (GA) used for the multi-objective optimization of this machine. A flow chart of the optimization procedure is shown in Figure 2. Due to the non-linear magnetic characteristics of iron, finite element analysis (FEA) is used to determine the flux density at various points in the machine. First, GOSET randomly generates an initial population with variables within the given boundaries. These design parameters are then passed to the FEA tool for modeling and EM analysis of the motor. FEA analysis is initially performed assuming a 1 m stack length and the air-gap flux density and torque production are evaluated. Based on the resulting power output, the stack length is modified to reach 2.5 MW and additional torque production from the end windings is accounted
Table 3. Design Space

| Parameter                                                                 | Minimum | Maximum |
|---------------------------------------------------------------------------|---------|---------|
| Armature slot inner radius ($X_1$) [mm]                                  | 70      | 200     |
| Armature slot radial height ($X_2$) [mm]                                 | 1       | 20      |
| Radial distance between field coils and shield coils ($X_3$) [mm]        | 3       | 50      |
| Field slot radial height ($X_4$) [mm]                                    | 1       | 20      |
| Field slot circumferential width ($X_5$) [degrees]                       | 1       | $f$ (# of poles) |
| Shield slot radial height ($X_6$) [mm]                                   | 0.5     | 10      |
| Shield slot circumferential width ($X_7$) [mm]                           | 0.5     | $f$ (# of poles) |
| Radial distance between shield coil and iron shield ($X_8$) [mm]         | 0.1     | 2       |
| Radial iron shield height ($X_9$) [mm]                                   | 0.1     | 30      |
| Armature current density ($X_{10}$) [A/mm$^2$]                           | 50      | 200     |

for with a 30% increase in torque. These results are then passed back to MATLAB and fed into analytical models to evaluate the losses and weight of the machine. A function then assigns fitness values to the resulting weight and ac losses for use by the GA in developing a new generation of designs. This procedure continues for a specified number of generations. After the optimization completes, an optimal front is extracted from the best results.

Figure 2. Optimization flowchart

7. Preliminary Results
A Pareto-optimal front for the entire design space is shown in Figure 3. Every design in the Pareto-front is a 2.5 MW machine that satisfies the diameter, axial length, and external flux density constraints. Figure 4 shows a Pareto-front of feasible designs for the CHEETA concept. All feasible designs have total losses below 3,000 W. From the results, a clear trade-off between weight and ac losses is evident. From the preliminary results it is evident that pole
count significantly impacts weight and ac losses. Higher pole counts result in lower minimum weight designs; however, the minimum weight is achieved at the expense of higher losses. 8-pole machines showed the best results within the feasible design space. Therefore, 8-pole designs were further explored by opening up the boundaries and increasing the number of generation. The resultant Pareto-optimal front of an 8-pole design is shown in Figure 5. Low ac loss designs use more iron shield and are heavier as a result, while minimum weight designs eliminate the iron shield entirely as can be seen in Figure 6 and Figure 7. Best designs which have both optimal weight and losses also converge towards active shielding alone, shown in Figure 8.

8. Mechanical Design
An inside-out synchronous motor topology will be adopted for this machine. Field and shield coils are placed on the outer rotor while armature coils are placed on the stator. This results in more compact volumetric designs. Figure 9 shows the proposed mechanical design of an optimal motor. The overall machine design is a layered vacuum structure to maximize thermal paths to the windings, and LH$_2$ coolant will be dispersed to the stator and rotor through couplers connected to a fixed shaft. The LH$_2$ will be sent through metal pipes and the heat will be extracted from the winding using conduction cooling. Field and shield excitation will be accomplished using a superconducting brushless exciter as proposed in [13].
Table 4. Comparison of Motors

| Parameter                  | Best Weight Design | Best AC Loss Design | Best Overall Design |
|----------------------------|--------------------|---------------------|--------------------|
| Outer diameter [m]         | 0.249              | 0.249               | 0.249              |
| Axial length [m]           | 0.215              | 1.277               | 0.67               |
| Average torque [Nm]        | 24708              | 4154                | 7917               |
| Air-gap flux density [T]   | 0.814              | 0.33                | 0.464              |
| Outside flux density [mT]  | 0.953              | 0.001               | 0.1                |
| Armature SC length         | 10.921             | 11.554              | 11.224             |
| Field SC length [km]       | 13.435             | 23.640              | 21.186             |
| Shield SC length [km]      | 2.425              | 3.094               | 4.337              |
| Total SC length [km]       | 26.782             | 38.288              | 36.74              |
| Iron shield weight [kg]    | 0.277              | 253                 | 0.924              |
| Total loss [W]             | 4158               | 1502                | 2255               |
| Weight (iron and SC) [kg]  | 18.01              | 278                 | 25.3               |
| Cost (iron and SC) [k$]    | 53.56              | 77.08               | 73.5               |

9. Conclusion and Future Work

In this paper, a fully SC machine is proposed for electric aircraft propulsion. A genetic algorithm based optimization is performed to minimize the machine weight and ac losses. Results show that actively shielded designs result in significant power density improvement compared to their passive iron shield counterparts. A comparison between different pole counts reveals that 8-pole machines best suit the design constraints. A 25 kg (SC and iron only) motor could be achieved with 2,255 W of ac losses. Assuming another 100% of additional weight for additional components a 50 kw/kg specific power motor could be achieved. Utilizing the CHEETA concept, a 99.9% efficient electric propulsion motor could be obtained with a fully SC machine. Nearly all feasible designs have air-gap flux densities between 0.3 T and 0.8 T. As these flux densities are achievable with permanent magnets (PM), future studies will explore the potential of partially SC PM machines. Future work will also focus on experimentally validating the ac loss model used in this study, further developing a mechanical design including a cooling scheme for better weight estimates, and adapting the air-core topology to SC coil-formers. Furthermore, a 3D flux
analysis will investigate the effects of end-windings on torque production.

References

[1] Jansen R, Brown G V, Felder J L, Duffy K P 2015 Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements 51st AIAA/SAE/ASEE Joint Propulsion Conference

[2] National Academies of Sciences Engineering & Medicine 2016 Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions First Edition (The National Academies Press).

[3] Haran K S, Lodder D, Deppen T O, Zheng L 2016 Active shielded high-field air-core superconducting machines IEEE Trans. Applied Superconductivity 26 98-105

[4] Patel A, Climente-Alarcon C, Baskys A, Glowacki B A, Reis T 2018 Design consideration for fully superconducting synchronous motors at future electric aircraft Proc. International Conference on Electrical System for Aircraft, Railways, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (Nottingham, UK, 7-9 November, 2018)

[5] Manolopoulous D C, Iacchetti M F, Smith A C, Tuohy P M 2018 Design of superconducting AC propulsion motors for hybrid electric aerospace Proc. AIAA/IEEE Electric Aircraft Technology Symposium (Cincinnati, Ohio, USA, 9-11 July, 2018)

[6] Komiya M, Aikawa T, Sasa H, Miura S, Iwakuma M, Yoshida T, Sasayama T, Tomioka A, Konno M, Izumi T 2019 Design Study of 10MW REBECO fully Superconducting Synchronous Generator for Electric Aircraft IEEE Trans. Applied Superconductivity 29 1-6

[7] Terao Y, Kong W, Ohsaki H, 2018 Electromagnetic Design of Superconducting Synchronous Motors for Electric Aircraft Propulsion IEEE Trans. Applied Superconductivity 28 1-5

[8] Terao Y, Seta A, Ohsaki H, Oyori H, Moriya N 2019 Lightweight design of fully superconducting motors for electrical aircraft propulsion IEEE Trans. Applied Superconductivity 29 1-5

[9] Lodder D C, Haran K S 2015 Multi-objective optimization of an actively shielded superconducting field winding Proc. IEEE Power and Energy Conference at Illinois (PECI) (Champaign, Illinois, USA, 2015)

[10] Lodder D C Haran K S 2015 Multi-objective optimization of an actively shielded superconducting field winding: Pole-count study Proc. IEEE International Electric Machines & Drive Conference (IEMDC) (Coeur d’Alene, Idaho, USA, 2015)

[11] Carr W J 2001 AC Loss and Macroscopic Theory of Superconductors Second Edition (Taylor and Francis Inc).

[12] Sumption M D 2018 AC loss of superconducting materials in motors and generators for very high density motors and generators for hybrid-electric aircraft 2018 AIAA/IEEE Electric Aircraft Technologies Symp. AIAA Propulsion and Energy Forum.

[13] H J Sung, B.S Go, H Park, R A Badcock, M Park, I K Yu, 2017 Design, Fabrication, and Analysis of HTS Coils for a 10-kW Wind Power Generator Employing a Brushless Exciter, IEEE Trans. Applied Superconductivity 27 1-5