AC Loss Analysis of MgB2-Based Fully Superconducting Machines

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Abstract.
Superconducting electric machines have shown potential for significant increase in power density, making them attractive for size and weight sensitive applications such as offshore wind generation, marine propulsion, and hybrid-electric aircraft propulsion. Superconductors exhibit no loss under dc conditions, though ac current and field produce considerable losses due to hysteresis, eddy currents, and coupling mechanisms. For this reason, many present machines are designed to be partially superconducting, meaning that the dc field components are superconducting while the ac armature coils are conventional conductors. Fully superconducting designs can provide increases in power density with significantly higher armature current; however, a good estimate of ac losses is required to determine the feasibility under the machines intended operating conditions. This paper aims to characterize the expected losses in a fully superconducting machine targeted towards aircraft, based on an actively-shielded, partially superconducting machine from prior work. Various factors are examined such as magnet strength, operating frequency, and machine load to produce a model for the loss in the superconducting components of the machine. This model is then used to optimize the design of the machine for minimal ac loss while maximizing power density. Important observations from the study are discussed.

1. Introduction
Superconducting (SC) machines show promise for significant increases in specific power over conventional designs. SC machines have been proposed and demonstrated for offshore wind and ship propulsion [1–3]; the dramatic increase in specific power also enables weight-sensitive transportation applications, such as electric aircraft, to be considered [4].

Most SC machines developed to date are partially superconducting where some components, typically armature coils, remain conventional (copper or aluminum). Fully SC machines, which have both the field and armature components built from superconductors, can further improve specific power if the increased losses at cryogenic temperatures can be accommodated. The AC losses introduced in fully SC machines are particularly difficult to manage, and these losses are compounded in the high frequency cases present in many electric machines. As a result, fully SC machines are known to be well suited for low frequency
applications such as offshore wind, however in higher speed uses the decision is not as clear. Direct drive turbo-electric aircraft or distributed propulsion aircraft will require machine speeds upwards of 1000rpm, which may or may not be feasible with fully SC machines given the current state of superconductor technology.

The aim of this paper is to determine the frequency and speed range at which fully SC machines offer better performance than similarly sized partial SC machines based on available conductors. This is targeted towards the eventual adoption of superconducting machines in aircraft, which require higher operating speeds and specific power. This analysis is performed through a combination of electromagnetic finite element analysis (FEA) and AC loss calculations.

2. Aircraft application background
There has been significant recent interest in the application of SC technology to future electric aircraft, with a number of publications by major aerospace organisations signaling engagement with the subject [5, 6]. This is motivated by a new interest in the aerospace industry in the electrification of flight. Radical, energy-saving designs can be enabled by electric propulsion, provided very lightweight and efficient electrical components are available.

Early studies on the system-level application of SC machines and propulsive power distribution by Brown [7] and Berg et al. [8] impress the need for ambitious power densities of over 20 kW/kg, which may require fully SC machines to meet. However, the final choice of using fully SC machines will be subject of an aircraft-level optimum taking, among others, the following points into consideration:

A) The mass, volume and power demand of the on-board cryocooling system is as crucial to the aircraft feasibility as the machine performance. Thus, the use of fully SC machines in aircraft will be subject to the losses caused in the machine, the operating temperature required and the cryo-cooling technology available.

B) Fully superconducting machines may help provide high power density at lower speeds, allowing direct drive of propellers without the need for gearboxes, which have additional weight, cooling, efficiency and cost implications.

C) For aircraft system integration, an SC armature can have a major benefit of allowing connection directly to SC cables without the use of heavy current leads and further heat ingress.

3. Machine design background
A general equation that loosely describes the power produced by an electric machine is

\[ P = k_n A B D^2 L \]  

(1)

where \( k \) is a design constant, \( A \) is the electric loading, \( B \) is the magnetic loading, \( D \) is the machine radial diameter, \( L \) is the machine active length or depth, and \( n \) is the rotating speed.

For a given machine volume, improvements in power density can be achieved either electromagnetically (increase \( A \) and/or \( B \) in Eq. 1) or with machine speed \( (n) \).
Superconducting machines achieve higher power for a given size by increasing electromagnetic loading with the high current capabilities of SC wire. Magnetic loading can be improved by replacing permanent magnets or copper field coils with SC coils, which can produce magnetic flux density on the order of 6-10 T [9], and electric loading can potentially be increased by replacing traditional copper armature coils with SC wire.

In this paper, SC machines will be categorized in two groups. The first group, partial SC machines, has a superconducting field component to increase magnetic loading, but the three-phase armature in the machine is still made with copper or other normally conducting materials. In the second group are fully SC machines, which have superconducting wire in both the field and the armature components to increase both the magnetic and electric loading.

Partial SC machines have demonstrated increases in specific power with newer designs proposing upwards of 40 kW/kg. Despite this, there are still significant challenges in SC wire manufacturing, machine cooling, and torque tube design [10].

4. AC Loss

In the fully superconducting machine topology described in this paper, the SC armature coils will carry time-varying current while being exposed to a rotating magnetic field with some phase delay. These conditions will generate heat within the armature coils, a phenomenon known as superconductor AC loss.

4.1. Main types of loss

Loss due to alternating transport current (without changing external field) has been analyzed by Norris and is used extensively to predict SC behavior [11]. Similarly, loss due to a changing external magnetic field (without alternating current) is covered by Carr and Wilson for both bulk superconductors and twisted wire [12, 13]. Both of these losses are characterized as hysteresis losses.

In a practical superconducting wire, SC filaments are embedded in a normally conductive matrix. The matrix will create eddy currents when exposed to alternating fields, which will create loss proportional to the resistivity of the matrix and the inductance of the twisted wire. This will be referred to as a collective coupling loss.

All of these losses can be calculated analytically for SC wires under time-varying magnetic fields using Equations 2 and 3 [13]. Each loss component \( Q \) is calculated in Joules per cycle per meter of wire; \( Q_h \) is the loss due to hysteresis and \( Q_c \) is the coupling loss.

\[
Q_h = \frac{B_m^2}{2\mu_0} \frac{\lambda}{\omega^2 \tau^2} + 1 \left( \frac{\beta}{\omega^2 \tau^2 + 1} \right)^\frac{1}{2}
\]  

(2)

\[
Q_c = \frac{B_m^2}{2\mu_0} \frac{\alpha \pi \omega \tau_\alpha}{\omega^2 \tau^2 + 1}
\]  

(3)

where \( B_m \) is the peak-to-peak amplitude of the magnetic flux swing experienced by the wire, \( \lambda \) is the fraction of the wire that is superconducting, \( \omega \) is the rad/s frequency of the alternating field, \( \tau \) is the LR time constant of the wire cross section, \( \alpha \) is the wire’s internal eddy current
shielding factor, $\beta$ is the ratio of the applied magnetic field to the penetration field strength of the superconducting filaments, and $\Gamma$ is a normalized loss function for hysteresis based on $\beta$.

4.2. Simultaneous field and current

Equation 2 does not account for the increased hysteresis loss due to the addition of transport current under time varying fields, which is what the fully SC machine armature would experience. WJ Carr showed that the resulting increase in AC loss can be approximated with a small, nearly constant multiplication factor for the case of large applied field (large $\beta$) and small transport current [14]. Since a fully superconducting machine would experience strong magnetic fields across the armature and would likely operate well below critical current levels to maintain a factor of safety, this approximation should suffice for this study.

While not extensively tested for circular wires, HTS tapes under simultaneous time varying fields and currents have been analyzed and shown to match Carr’s results for large applied field ($\beta > 1$) [15].

4.3. Rotating field and phase shift

Rotating fields have been shown analytically to reduce the penetration field $B_p$ in SC wire by Prigozhin. This will increase the associated losses by a small scalar multiple near $\frac{\pi}{2}$ [16]. Phase shift effects on simultaneous applied field and transport current losses have been analyzed for SC tapes in various conditions [17, 18]. In general, a phase shift of 90 degrees between the field and current results in a loss minimum while a phase shift of 0 or close to 0 results in a maximum. Since this phenomenon is difficult to analytically model, it is left out of the calculations. A controlled synchronous machine will often operate close to a 0 degree phase shift (i.e. $I_a = I_q$) to maximize torque, so the absence of a phase shift factor is a good worst approximation of the loss.

5. Design Comparison

A partial SC machine design from [4] consists of SC coils carrying direct current to produce magnetic field of 8-9 T maximum. In the air gap this field is up to 3.3 T. The armature carries three-phase current through copper wires. A notable feature of this design is the swap between stator and rotor roles, to ease the cryogenic cooling of the superconducting coils. The stator in this machine consists of the SC field coils and provides the dc field, and the rotor consists of the copper armature coils to create a rotating field. To eliminate ferromagnetic shielding, a secondary set of SC coils is placed on the perimeter of the machine to counteract the magnetic field outside of the machine. This secondary set of coils act as an active shielding mechanism. The basic concept is illustrated with the schematic in Figure 1 below.

The partial SC machine from [4] was designed for aerospace applications, with specifications of 12MW output at 8000 rpm. Figure 2 shows a cutaway section of a CAD model of the motor. From this design, a fully SC machine is proposed that utilizes superconducting wire instead of copper for the three-phase armature. For reasonable cooling
Figure 1: Partial SC motor cross section, showing the positioning of the armature, field coils, and shielding coils

requirements, MgB2 is chosen as the superconducting material operating at 20 K. A summary of initial changes is presented in Table 1.

Figure 2: 3D render of the partial SC motor design

MgB2 was chosen since it has demonstrated high critical current density at medium temperatures with reasonable AC loss. While the current density is lower than Nb3Sn at comparable temperatures, it is still high enough to significantly increase the electric loading in the machine. In Table 1, the field coil current density acts as an indicator of the magnetic loading since the coil and magnetic circuit are fixed, and the armature coil current density acts as a measure of the electric loading.

MgB2 wire, discussed in [19], was chosen for this analysis for its low ac loss and strong critical current characteristics.

5.1. AC Loss Computation
FEA simulations were performed on the machine model using Flux2D to determine the torque, air-gap flux density, and magnetic field distribution on the armature and stator coils.
Table 1: Changes from partial SC to full SC design

| Parameter                  | Partial | Full    |
|----------------------------|---------|---------|
| SC material                | Nb3Sn   | MgB2    |
| Operating temperature      | 4 K     | 20 K    |
| Wire diameter              | 700 µm  | 600 µm  |
| Field coil current density | 400 A/mm² | 200 A/mm² |
| Armature current density   | 7 Arms/mm² | 70 Arms/mm² |

An example of the B field distribution over an armature bar is shown in Fig. 3. This illustrates the change in the B field on a slice of the armature cross section over an electrical half-cycle. In the figure, the vertical axis is the B field magnitude, the horizontal axis is the angular position of the rotor, and the axis going into the page is the radial position on the armature. The B field was initially set to 3 T in the armature to match the partially SC machine design, and was reduced further in subsequent analysis to keep AC losses at a manageable level.

The B field FEA results shown in Fig. 3 were fed into Equations 2 and 3 to determine the hysteresis and coupling losses on a wire-by-wire basis within the armature pole. These losses were then multiplied by the geometric parameters of the machine (active length, number of poles) to determine the total ac loss in the armature.

A cryogenic cooling factor based on available cryo-cooler data [10] was applied to the loss calculations to account for the additional power required to maintain the operating temperature of 20 K. 100 W of input cooling power was estimated to extract 1 W of heat at 20 K.

This process of geometry design, FEA, and AC loss calculation was performed for four different machine geometries derived from the actively-shielded design described in [20] each representing a potential machine application.

The first is an 8 pole machine, intended for higher speed aerospace propulsion...
applications. The second and third are 16- and 20-pole machines with larger diameters intended for ship propulsion or hydro-electric generators. The fourth design has 46 poles, and is intended for a low speed, high power application such as offshore wind turbines. For each of these four designs, length was varied with speed to maintain the same output power, and the AC loss was calculated across these variations.

5.2. Results
The resulting cooling power required to compensate for armature AC losses is shown in Fig. 4 with a reference to rotor speed, which is proportional to electrical frequency. In general, higher speeds lead to increased eddy/coupling losses, which is to be expected. At speeds commonly encountered in industrial or aerospace applications (>1800 rpm), the cooling power is of the same order as the whole rating of the electrical machine. This is of course, undesirable.

![Figure 4: Log-log plot of the required cryogenic power vs rotor speed for the four machine designs at 10 MW](image)

Since the machines were all evaluated at a constant power rating, it should be noted that increasing the speed of the machine will decrease the active length, and thus size and weight, of the machine to maintain the same power. This in turn increases the specific power, or the ratio of power to weight. This suggests that an attractive option is to increase the speed to decrease the specific power. However, there is a tradeoff between specific power and AC loss, as the loss will increase exponentially with speed, indicated in Fig. 4. To compensate for this, the magnetic loading ($B$) and electrical frequency (or pole count) need to be reduced for the high speed applications, negating power density advantages. To clarify this tradeoff, a metric dividing the power density by the required cryogenic power is calculated and presented in Fig. 5. This metric is called the power-density-to-cryo (PDC) ratio. Since weight data was unavailable for this study, a volumetric power density (MW/m3) was utilized.

From this metric, optimal operating speeds are observed for each of the machine designs. As expected, the larger 46-pole machine has this optimum at lower speeds while the 8-pole machine has a higher peak at higher speeds.
Figure 5: Log-log plot of the power-density-to-cryo ratio vs rotor speed for the four machine designs at 10 MW

With this metric of power-density-to-cryo (PDC), the answer to the initial question investigating the feasibility of fully electric machines for aircraft can be attempted. Designs for the 8-pole and 46-pole cases were compared for both full and partial SC machines, and resulting numbers are presented in Table 2.

Table 2: Comparison of partial and fully SC design parameters and results

| Parameter          | Units | Fully SC Design 1 | Fully SC Design 2 | Partial SC Design 1 | Partial SC Design 2 |
|--------------------|-------|-------------------|-------------------|---------------------|---------------------|
| Pole count         |       | 8                 | 46                | 8                   | 46                  |
| Speed [rpm]        |       | 8000              | 10                | 8000                | 10                  |
| Slot depth [mm]    |       | 10                | 10                | 25.4                | 100                 |
| Active length [m]  |       | 0.158             | 0.155             | 0.157               | 1.25                |
| Volume [m$^3$]     |       | 0.09              | 2.0               | 0.088               | 19.75               |
| Power density [MW/m$^3$] |   | 110               | 4.6               | 110                 | 0.5                 |
| Cryo power [kW]    |       | 2208              | 58                | 16                  | 92                  |
| Efficiency [%]     |       | 81.9              | 99.8              | 99.8                | 99.0                |
| PDC                |       | 50                | 79                | 7080                | 5.6                 |

The PDC values of the partial SC designs from Table 2 are shown in Fig. 6. Partial SC Design 1, shown in red, is an 8 pole design with an extremely high ratio of power density to required cooling. The Fully SC Design 1, which was electromagnetically sized to match the power density of the partial version, still underperforms in both PDC and efficiency, making it unfeasible for its intended application. This is to be expected, since the only sources of loss for the partial SC machine are in the armature copper and the dc field coils; this is far lower than the losses in a fully SC machine, which are compounded by the high electrical frequency.

By contrast, Partial SC Design 2, shown in green, has a lower PDC ratio than its fully SC
counterpart. The fully SC machine in this case is operating at such a low frequency that the AC losses are not as significant despite the increased electrical loading. Additionally, minor losses in the field coils are not as drastic for the fully SC design due to the higher operating temperature. In this case, the fully SC design prevails.

![Log-log plot of the power-density-to-cryo ratio vs rotor speed, compared with Partial SC Design 1 (red, upper point) and Partial SC Design 2 (green, lower point)](image)

Figure 6: Log-log plot of the power-density-to-cryo ratio vs rotor speed, compared with Partial SC Design 1 (red, upper point) and Partial SC Design 2 (green, lower point)

6. Conclusion and future work
Given current conductor capability, fully SC machines appear to be only suitable for large, slow applications, with some movement towards 100-500rpm range. This is not unexpected, as high frequencies, strong magnetic field and significant electrical loading all contribute to unmanageable AC loss in higher speed applications. With the described motor model, superconducting wire model, and cooling assumptions, the 8-pole motor is infeasible as a fully SC design above 2000 rpm (132 Hz electrical frequency). Above this speed, it is outclassed by the partially SC version in both efficiency and power density. The 46-pole machine encounters this point around 100 rpm (38 Hz).

While these conclusions may be intuitively obvious, we believe the quantitative results and the analytical method provide a framework to rigorously assess the trade-offs as enabling technologies evolve. For instance, a possible aircraft-based cryocooling solution posited by Berg et al. [8] using liquid CH4 as a heat sink suggests a cooling power of 15 W per 1 W extraction at 20 K; the impact of this improvement in cooling capability for fully SC machine designs can be quickly assessed with the described method, raising the previously described limiting speeds.

One area for future work is in experimental validation of the analytical equations for machine-like conditions. While the AC loss equations have been tested for various isolated conditions, the specific combination of cases for wires within a motor have not been experimentally validated. At the very least, conditions of strong ac magnetic field ($\beta \gg 1$) and simultaneous alternating current for circular wires should be investigated. Testing rotating
fields and phase shift between the field and current would provide additional data for model validation.

Tapes, which are likely contenders for higher-temperature SC machines, have been more thoroughly investigated under machine-like conditions, though still only for weak fields and currents. However, analytical models for tapes can be quite complex with dependencies on orientation, tape construction, coil construction, and other factors not necessarily present with circular wires. Integrating established ac loss models for tapes with the method described in this paper is a logical next step for further study.

7. References

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