Electromagnetic analysis of fully superconducting motor for electric aircraft

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Abstract. In order to reduce carbon emissions, there is considerable interest in all-electric aircraft for transportation. Fully superconductor motors will be required to meet the high specific weight requirements, which are >10 kW/kg for the NASA N3-X plane. This paper summarizes the results of electromagnetic analysis generated using the FEMM magnetics code, along with the Lua scripting language, to determine the optimum motor configuration for a 4 MW, 3000 rpm fan motor. In considering ac loss, the analysis assumes Bi-2212 stator windings and both iron-tooth and air-core designs are considered. The best selected case consists of an 8-pole configuration utilizing an armature current density of 100 A/mm².

1. Introduction

Aircraft emissions, including carbon dioxide, nitrous oxide and particulate matter, are known to contribute significantly to global warming [1]. Therefore, there is now considerable interest in developing all-electric aircraft for transportation. An example of this is the NASA N3-X plane, which will utilize superconducting generators and fan motors.

A summary of some of superconducting motors and generators which incorporated superconducting rotors and normal-conductor stators is provided in table 1 [2]. These machines had power densities, including the frame, ranging from 0.17 to 8.8 kW/kg, which is not sufficient for aircraft where a value of > 10 kW/kg is required. Therefore, in this study, a fully-superconducting motor is considered, incorporating superconducting cables in the stator as well.

| Motor               | Year | Rating (MW) | Speed (rpm) | Power Density (kW/kg) |
|---------------------|------|-------------|-------------|-----------------------|
| GE                  | 1978 | 20          | 3600        | 0.17                  |
| Westinghouse        | 1978 | 300         | 3600        | 1.83                  |
| Westinghouse        | 1978 | 120         | 3600        | 2.97                  |
| GE                  | 1980 | 20          | 7000        | 0.06                  |
| AMSC                | 2001 | 3.7         | 1800        | 0.75                  |
| Siemens             | 2004 | 4           | 3600        | 0.58                  |
| AMSC                | 2004 | 5           | 230         | 0.25                  |
| AMSC                | 2007 | 36.5        | 120         | 0.49                  |
| GE                  | 2008 | 1.3         | 10000       | 8.8                   |
| FAMU, Georgia Tech, NASA | 2009 | 2700         | 0.16        | 5.3                   |

For this study, the 4 MW, 3000 RPM superconducting fan motor for the NASA N3-X aircraft is used as a case study. The baseline specifications for this motor are provided in table 2. This efficiency includes both warm and cold losses, with ~0.08% allocated for warm stator losses and ~0.02% allocated for cold armature losses.
Table 2. N3-X 4 MW, 3000 RPM fan motor specifications.

| Parameter       | Unit | Value |
|-----------------|------|-------|
| Output Rating   | MW   | 4     |
| Motor Speed     | RPM  | 3000  |
| Efficiency      | %    | 99.9  |
| Voltage         | kV   | 5-10  |
| Power Density   | kW/kg| 10    |

2. Optimization Methodology

The superconducting optimization is achieved using an approach called “novice design assistant,” which is taught by Kirtley [3]. This approach utilizes computational power and motor design parameterization to generate numerous designs—both good and bad—using a random optimization. One of the main challenges in using this approach is to specify reasonable ranges for the input parameters.

The parametric model for this study is shown in figure 1. The main parameters are the backiron outer radius, \( R_{CO} \), along with three (3) parametric ratios: \( \alpha \), armature ratio; \( \beta \), backiron ratio and \( \gamma \), gap ratio. The number of pole-pairs, \( P \), and armature fill factor, \( FF \), are also specified. In Figure 1, the 4-pole case \( (P = 2) \) is shown with an 80% slot fill factor \( (FF = 0.80) \). Also shown is an air gap between the armature and stator backiron. This 1-inch gap provides adequate space for a cryostat vacuum required to place the warm stator backiron outside the cryostat required for the cold superconducting stator winding. It should be noted that the cold stator teeth serve as flux diveters and that the associated losses will also be cryogenically cooled.

For a given optimization run, a range for each parameter is specified. There is some trial-and-error required to find the best ranges for these parameters in order to make sure that minimum-weight machine cases will be found. For each optimization run, three FEMM cases are run; these are as follows:

- **Run 1** (Phase A Only) to determine armature co-energy, \( E_A \)
- **Run 2** (Phase A and Rotor) to determine rotor amp-turns and total co-energy, \( E_{TOT} \)
- **Run 3** (Rotor Only) to determine field winding co-energy, \( E_F \)

For Run 1 (Phase A Only), the co-energy, \( E_A \), is determined by applying the armature current density, \( J_A \). For Run 2, Phase A remains ON, and the rotor amp-turns are incrementally increased until the backiron reaches saturation at a specified level, which, in this case, is 2 T; the co-energy for this case is termed \( E_{TOT} \). Subsequently, the co-energy for Run 3 (Run 3 (Rotor Only) is found by turning off the armature; this co-energy is termed \( E_F \). Then, the mutual co-energy, \( E_M \), is calculated by:

\[
E_M = E_{TOT} - (E_F + E_A) \tag{1}
\]

The machine rating per unit length, \( PL \), may be expressed in terms of these co-energies and other pertinent parameters, such as the load angle, \( \delta \), and phase angle, \( \Phi \), as:

\[
PL = 1.5 \omega \cos \Phi \left( E_M \cos \delta + 3 E_A \sin \Phi \right) \tag{2}
\]

Using (2), the active length of the machine can be easily calculated by dividing \( PL \) by the machine rating. Then, the volumes and weights of the backiron and armature can be determined. The additional weight of the frame has not been considered for this study.
3. Case Study: 4 MW, 3000 RPM Motor

Using the baseline specifications of table 2, several optimizations were conducted. The ranges for the various input parameters are provided in table 3. This parameter primarily determines the machine reactances. A typical gap dimension is ~5% of the machine radius—thus the value of $\gamma = 0.05$.

| Table 3. Specified range of optimization parameters. |
|--------------------------------------------------|
| **Parameter** | **Range** |
| \( R_{oo} \) | 6-16 inches |
| \( \alpha \) | 0.020-0.100 |
| \( \beta \) | 0.025-0.125 |
| \( \gamma \) | 0.05 |
| \( P \) | 2, 3 or 4 pole-pairs |
| \( FF \) | 0.30-0.90 |

The results are plotted in figure 2 thru figure 6 showing the relationship between \( R_{oo} \), \( \alpha \), \( \beta \), \( P \) and \( FF \), respectively. The key observation for each plot is that the specified range does indeed allow an optimum, or minimum machine weight, to be obtained. Also, the optimum case (to be discussed later) is depicted by the square box symbol. Some interesting observations from these plots are as follows:

1. The superconducting winding enables a thin radial armature build (figure 3).
2. There is an optimum value of armature thickness, \( \beta \), of 0.075.
3. There is an optimum value of fill factor, \( FF \), of 0.60. Lower values require thicker armatures, while higher values lead to premature iron tooth saturation.
4. Higher pole-count leads to lower weight (figure 5); however, higher pole-count leads to higher armature field rate (T/s).
5. An armature field rate of > 750 T/s leads to a minimum weight machine Figure 7.
Figure 2. Relationship between machine weight and $R_{OO}$.

Figure 3. Relationship between machine weight and $\alpha$.

Figure 4. Relationship between machine weight and $\beta$.

Figure 5. Relationship between machine weight and $P$.

Figure 6. Relationship between machine weight and FF.

Figure 7. Relationship between machine weight and peak armature field rate.
4. Point case selection

After having run the appropriate number of optimization trials, it is necessary to apply design filter to find cases which satisfy the specifications shown in table 1, in particular the machine weight of $>10$ kW/kg. The best case is summarized in table 4.

| Case                  | Symbol | Units     | Value |
|-----------------------|--------|-----------|-------|
| Rating                | MW     |           | 4     |
| Voltage               | $V_A$  | kV        | 7.5   |
| Current               | $I_A$  | A         | 178   |
| Armature Current      | $J_A$  | A/mm$^2$  | 100   |
| Density               |        |           |       |
| Pole Pairs            | $P$    | pole-pair | 4     |
| Backiron Outer Radius | $R_{OO}$ | in     | 10    |
| Armature Fill Factor  | $FF$   |           | 0.60  |
| Armature Ratio        | $\gamma$ |         | 0.020 |
| Backiron Ratio        | $\beta$ |           | 0.075 |
| Active Length         | $L$    | m         | 1.6   |
| Active Weight         | $W$    | kg        | 445   |
| Specific Density      | kW/kg  |           | 9     |
| Peak Armature Field   | $B_{ARM}$ | T     | 0.7   |
| Peak Field Rate       | dB/dt  | T/s      | 850   |
| Total Cold Losses     | $W$    |           | 800   |
| Cold Tooth Losses     | $W$    |           | 330   |
| Conductor AC Losses   | $W$    |           | 470   |
| AC Loss Target        | mW/A-m |           | 0.75  |
| Stator Core Loss      | $W$    |           | 1800  |
| Stator Core Loss %    | %      |           | 0.045 |
| Total Losses          | $W$    |           | 2600  |
| Overall Efficiency    |        |           | 99.94 |

5. Effect of armature current density, $J_A$

For the previous study, an armature current density, $J_A$, of 100 A/mm$^2$ was selected, and this section explains that selection. For the iron-tooth designs, assuming a fill factor of 0.60, a separate optimization run was performed varying $J_A$ from 25 to 175 A/mm$^2$, showing a minimum in the 100-125 A/mm$^2$ range as shown in figure 8. Therefore, the 100 A/mm$^2$ value was chosen as it is an easier target for the wire manufacturer.

![Figure 8. Relationship between machine weight and $J_A$.](image-url)
6. Conductor ac loss target

Wire manufacturers typically talk of ac losses in terms of the unit mW/A-m. Therefore, for this study, we have used this same unit to communicate the target ac loss for each motor design. This value is calculated using the following equation:

\[
\text{TARGET} = \frac{\text{LOSS}}{\text{STATOR VOLUME} \times J_s}
\]

(3)

As mentioned previously, \(~0.02\%\) of the motor rating, or \(~800\) W, is allowed for the cold armature losses, so this value is used in (3) to calculate these targets. In addition, some fraction of the cold armature losses come from the cold tooth heating, assuming a value of 10 W/kg at 2T and 400 Hz [4].

In figure 9, all of the cases are presented in terms of this calculated loss target versus the peak armature field rate. This information is useful for the superconducting wire manufacturer to determine conductor architecture required to reduce the ac losses to the required level.

![Figure 9. Relationship between ac loss target (mW/A-m) and armature field rate (T/s).](image)

7. Conclusion

In conclusion, this parametric optimization approach is useful in identifying 2D point designs for future fully-superconducting motor and generator designs for electric aircraft. In this initial study, a design with \(~9\) kW/kg was identified.

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