Simplex optimization of shield coil geometry for increasing magnetic shielding performance of air-core superconducting generator

J M Oh¹, T K Bang², G H Jang², J I Lee², K S Haran³, H W Cho¹,⁴

¹Dept. of Electrical, Electronics, and Comm. Eng. Edu., Chungnam Nat’l University, Daejeon, 34134, Korea.
²Dept. of Electrical Engineering, Chungnam Nat’l University, Daejeon, 34134, Korea.
³Dept. of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61820, U.S.

E-mail: hwcho@cnu.ac.kr (corresponding author)

Abstract. This study deals with the simplex optimization of a shield coil geometry for improving the magnetic shielding performance of fully air-cored superconducting generators. The superconducting generator in this study has a 10 MW-3000 rpm class, fully air-cored, rotating armature structure designed for electric propulsion aircraft applications. The magnetic flux radiated to the outside of the machine is shielded by the shield coil, and the shielding performance is determined by the shape of the shield coil. In this study, the design of the shield coil is developed using simplex optimization to improve the shield performance. The shape optimization is conducted using the simplex optimal design method, and the validity of the designed shield coil is verified by comparing the shielding performance of the initial and the optimized models.

1. Introduction

Currently, research on propulsion systems for electric propulsion aircraft is being conducted globally, but it is primarily conducted by the National Aeronautics and Space Administration (NASA). The electric propulsion aircraft will be equipped with high-capacity electric motors and generators equipped with superconducting technology [1]. NASA is planning the technology development phase for high power density superconducting electrical equipment in detail. The current level of specific power for superconducting electric power equipment, as presented by NASA, is about 6.6kW/kg; however, the current goal is to achieve up to 41.4 kW/kg (in non-cryogenic conditions) by 2035 without utilizing special cooling systems [2].

Superconducting machines can support a current 100 times greater than that of general electric machines employing copper wires, which subsequently reduces volume and weight. In superconducting machines, high power density (or high specific power [kW/kg]) and high terminal voltage are achievable. Moreover, high usage of copper, which is a technical limitation of general electric machines, can be minimized.

In the case of applying air-core field and armature without using ferromagnetic electrical steel, it is possible to achieve high current density operation and high efficiency operation without use of iron. Additionally, it would be possible to produce a large-capacity electric machine with a high power density and a relatively light weight. Therefore, the superconducting machine, which is smaller in volume and...
has higher power density than the conventional system, is emerging as a new technological alternative for high-capacity power applications; these applications include electric propulsion aircraft and ultra-large wind turbines of over 10 MW capacity.

When constructing the magnetic circuit for a superconducting machine in air-core topology, the iron core on the armature side must first be removed. Furthermore, it is essential to design the rotating armature inside the device and the superconducting field coil outside the machine in order to concentrate the armature magnetic flux. Additionally, the air-core superconducting machine has a high air-gap flux density generated by the field coil and shield coil to reduce the magnetic flux leaking to the outside. As a result, there are relatively low power losses due to the lack of an iron core, and the low weight enables high power density and high specific power while the usage of superconducting wire increases.

This study deals mainly with the air-core superconducting generator applied to the electrical system of an electric propulsion aircraft. In particular, we conducted a study on the design of the shield coil to reduce the magnetic flux radiated to the outside. The optimal design of the superconducting shield coil was arrived at using the simplex optimization method, and the magnitude of the magnetic flux density radiated to the outside was minimized. On verifying the output of the superconducting generator with the optimally designed main field coil and shield coil, the validity of the optimal design and algorithm was confirmed.

2. Optimal design of air-core superconducting generator

2.1. Air-core superconducting generator

The field-side electromagnets of the conventional superconducting machine supply magnetic flux to the air-gap and the armature via superconducting wire on the ferromagnetic iron core. The structure therein is the same as that of the general winding type synchronous machine in which a rotating field electromagnet is located inside and a stator iron core is placed outside. However, it is most advantageous to concentrate the field flux on the air-gap and the armature side and place the rotating armature inside the machine to minimize leakage of the armature flux for air-core electromagnetic structures. This is the best way to maximize the specific power of superconducting electrical machine. Figure 1 illustrates the concept of an air-core superconducting generator. The rotating armature is installed inside and the shield coil was installed outside to prevent leakage of the field flux outside of the machine. Additionally, installing the shield superconducting coil outside the superconducting main field coil is a relatively new concept. Figure 2 contains a full drawing of the designed 10MW 3000rpm class superconducting generator, and Table 1 lists the design specifications.

![Figure 1. Concept of air-core superconducting generator.](image-url)
Figure 2. Full drawing of designed superconducting generator.

Table 1. Design specifications.

| Item                  | Value |
|-----------------------|-------|
| Rated power (MW)      | 10    |
| Rated speed (rpm)     | 3000  |
| Rated voltage (kV)    | 6.5   |
| Outer diameter (m)    | 1.025 |
| Pole counts           | 8     |

2.2. Optimal design variables
Figure 3 shows the optimal design variables with key parameters for actively shielded air-core superconducting machine. The design consists of 4 pole-pair main field windings in the stator(outside) with actively shielded coils. Here, $D_{sa}$ is the shielding coil aperture, $D_{ms}$ is the distance between the main field coils and shielding coils, and $W_s$ is the shielding coil width.

![Diagram](image)

Figure 3. Optimal design variables for superconducting coil - 1 pole model.

2.3. Simplex optimization algorithm
The geometric shape formed by a set of $n+1$ points in an $n$-dimensional space is called a simplex. The simplex method is an optimization technique to move the simplex gradually toward the optimal point
by comparing the value of the objective function at each vertex of the simplex model formed by the set of \( n+1 \) points in an \( n \)-dimensional space. The movement of the simplex is performed using three operations: reflection, expansion, and contraction[3]-[5].

Reflection: As shown in Figure 4(a), \( X_r \) is reflected by \( X_h \) (the highest value of the objective function), assuming that the objective function of \( X_r \) is the smallest value. \( X_r \) is obtained by equation (1).

\[
X_r = (1 + \alpha)X_0 - \alpha X_h
\]  

(1)

where, \( X_0 \) is the centroid of all \( X_i \) except for \( i = h \) and \( \alpha \) is the reflection coefficient as defined by equation (2).

\[
\alpha = \frac{\text{distance from } X_r \text{ to } X_0}{\text{distance from } X_h \text{ to } X_0} \text{ and } \alpha > 0
\]  

(2)

Figure 4 shows the reflection process in 2D. The direction of movement is always away from the least optimal result, so the movement will be toward the \( n \)th simplex having the optimal point (1\( \rightarrow \)2\( \rightarrow \)3\( \rightarrow \)2\( \rightarrow \)3\( \rightarrow \)4\( \rightarrow \)4\( \rightarrow \)5\( \rightarrow \)6\( \rightarrow \)n\( \rightarrow \)n\( \rightarrow \)n+1\( \rightarrow \)n+2).

Expansion: If the resultant \( X_r \) from the reflection process satisfies \( f(X_r) < f(X_h) \), it can be expected that further movement will be along the direction from \( X_0 \) to \( X_r \), further decreasing the value of the objective function. \( X_r \) is expanded to \( X_e \) obtained using equation (3).

\[
X_e = \gamma X_r - (1 - \gamma)X_0
\]  

(3)

where, \( \gamma \) is the expansion coefficient as defined by equation (4).

\[
\gamma = \frac{\text{distance from } X_e \text{ to } X_0}{\text{distance from } X_h \text{ to } X_0} \text{ and } \gamma > 0
\]  

(4)

Contraction: If the resultant \( X_r \) from the reflection process satisfies \( f(X_h) > f(X_r) > f(X_i) \) for all \( i \), then \( X_h \) is replaced with \( X_r \), and \( X_r \) becomes the new \( X_h \). Then, the simplex can be contracted using equation (5).

\[
X_c = \beta X_r - (1 - \beta)X_0
\]  

(5)
where, $\beta$ is the contraction coefficient as defined by equation (6).

$$\beta = \frac{\text{distance from } X_c \text{ to } X_0}{\text{distance from } X_h \text{ to } X_0} \text{ and } 0 \leq \beta \leq 0$$

In this study, we define that $\alpha = 1, \beta = 0.5, \gamma = 2$, and the design vector $X(x_1, x_2, x_3)$ is $(D_{ms}, D_{sa}, W_s)$. The constraints are as per (7)-(10).

$$30 \leq D_{ms} \leq 70 \text{ [mm]} \quad (7)$$
$$40 \leq D_{sa} \leq 240 \text{ [mm]} \quad (8)$$
$$10 \leq W_s \leq 40 \text{ [mm]} \quad (9)$$

Outside average $B_r \leq 60 \text{ [mm]} \quad (10)$

3. Optimization results and discussion

Figure 5 shows that outside magnetic flux density decreases with the iteration, and Figure 6(a) and 6(b) show the variation of $D_{ms}$ and $W_s$ respectively. $D_{ms}$ is related with volume of the superconducting generator, and $W_s$ is related with the shield coil turns and the cost and usage of superconducting wire. The minimum outside flux density is derived at just the 30th iteration of the algorithm, so only a little time is required for analysis.

![Figure 5. Iteration of maximum flux density results.](image)

Figures 7 and 8 show the conversion of the design variables. $X(D_{ms}, D_{sa}, W_s)$ of the initial simplex in three-dimensional space are $X_1(40, 140, 18)[\text{mm}]$, $X_2(38, 220, 12)[\text{mm}]$, $X_3(30, 150, 15)[\text{mm}]$, and $X_4(35, 170, 10)[\text{mm}]$. The initial simplex moves toward the optimal area via reflection, contraction, and expansion; eventually, the simplex is contracted to the optimal point $X_{op}(34, 204, 40)[\text{mm}]$. Figures 9 and 10 show the magnetic flux density distribution of the initial model $(D_{ms} = 40[\text{mm}], D_{sa} = 140[\text{mm}], W_s = 18[\text{mm}], 448 \text{ turns of shield coils})$ and optimal model $(D_{ms} = 33[\text{mm}], D_{sa} = 206[\text{mm}], W_s = 40[\text{mm}], 1000 \text{ turns of shield coils})$. As shown in Figures 9 and 10, the magnetic field propagation outside the optimal model is almost zero. However, the optimal model has more than twice the shield coil turns than the initial model. Figures 11 and 12 show the flux density distribution at the outside and airgap of the
Figure 6. Optimal value selection. (a) iteration of $D_{ms}$ (b) iteration of $W_s$.

Figure 7. Conversion of design variables. (a) 3D plot for all variables, (b) $D_{ms}$ vs. $W_s$.

Figure 8. Conversion of design variables. (a) $D_{ms}$ vs. $W_s$, (b) $D_{sa}$ vs. $W_s$. 
designed air-core superconducting generator. As shown in the Figure 11, the flux density analysis results confirm that the magnetic flux density at the outside is remarkably reduced. Figure 12 shows that the maximum airgap flux density of the air gap region is about 14.4% smaller than that of the initial model.
4. Conclusion
In this study, the optimal design of the shield coil of a 10MW air-core superconducting generator for the application of electric propulsion in aircraft was investigated. The shape design was performed to minimize the magnetic flux radiated outside the machine while maintaining the output of the generator. By applying the simplex algorithm, the optimum values for the width of the shield coil, the coil aperture, and the length to the main field coil were derived. As a result, the shape of the shield coil enabling minimization of the magnetic flux density radiated outside the machine was determined, and the change of the external magnetic flux density and the air-gap magnetic flux density was analyzed. When the externally radiant flux density is minimized, the generator output reaches 10.15MW, which is about 3% lower than that of the initial model. This means that the size of the generator should have a design margin according to the shape of the shield coil when a full air-core superconducting generator is designed. In the future, detailed research considering the force generated between the main field coil and the shield coil and the amount of superconducting wire required for this generator will be performed, along with an economic analysis.

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References
[1] Rosario R D A Future with Hybrid Electric Propulsion Systems: A NASA Perspective Turbine Engine Tech. Symp. 2014.
[2] Clarke S 2015 IEEE Transportation Electrification Conference and Expo Doc. ID 20150000748.
[3] Kim I W, Woo D K, Yeo H K, Jun H K 2012 IEEE Vehicle Power and Propulsion Conference 196.
[4] Han W, Dang C V, Kim J W, Kim Y J, Jung S Y 2017 IEEE Trans. Magn. 53 Art. ID 538106904.
[5] Balachandran T, Lee D S, Haran K S 2019 IEEE International Electric Machines & Drives Conference DOI 8785227.