Numerical analysis on the influence of armature winding configuration on AC loss of 10 MW fully superconducting generators of electric aircrafts

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Abstract. 10 MW fully superconducting generators, comprising REBCO superconducting tapes with various armature winding configurations, were designed. The influences of these configurations, such as a distributed-winding and a concentrated-winding configuration, on AC loss, output power density, and output voltage waveform were evaluated. As a result, the short-pitch distributed-winding model exhibited the best properties among all the models. In particular, the AC loss of the armature winding was approximately half that of the concentrated winding. Furthermore, the distortion factor was lower than 10%.

1. Introduction

Currently, the fuel efficiency and emission of aircrafts have attracted attention as an environmental issue. The CO₂ emissions generated by aircrafts will be approximately 4 times greater in 2040 compared to 2006 [1]. However, stringent emission targets have been set by Flightpath 2050 published by ACARE, which requests a 75% reduction in CO₂ emissions per passenger km compared to the year 2000. An electrical propulsion system with electrical motors is an effective solution, as proposed by NASA [2]. The electrical power required to operate the electric fan is provided by generators driven by a gas turbine and/or batteries. However, current conventional rotating machines, composed of iron cores and copper wires, cannot satisfy the very stringent weight and volume constraints imposed by airborne applications. Superconducting technologies have the possibilities of drastically reducing the weight and improving the output power density. According to numerical analyses, superconducting rotating machines can achieve a high output power density of over 20 kW/kg, much higher than conventional rotating machines [3][4]. Recently, fully superconducting rotating machines have particularly attracted attention.

The AC loss generated in the superconducting armature windings of fully superconducting rotating machines is a serious issue because it may cause a severe temperature increase of the armature windings and result in thermal runaway. To realize the fully superconducting rotating machine, it is necessary to reduce the AC loss generated in the armature windings. For this purpose, various winding methods in the armature windings were compared from the viewpoint of the AC loss. In the case of a concentrated winding, the number of turns in one coil will be larger than that of distributed windings. In the result,
the influence of the armature leakage reactance on the concentrated winding will become stronger than the distributed winding, and the interlinkage magnetic flux applied to the armature winding will be larger. Therefore, the AC loss will be larger in the concentrated winding than in the distributed winding. In addition, improvement of the sinusoidal waveform of the induced load current can also be expected.

2. Design of superconducting generator

2.1. Properties of REBCO superconducting tape

Table 1 shows the parameters of the REBCO superconducting tapes used for the windings. The superconducting layer is EuBa$_2$Cu$_3$O$_y$, a superconducting matrix, and 3.5 mol.% BaHfO$_3$ inclusions. The BaHfO$_3$ inclusions become strong artificial pinning centers to realize a large critical current, $I_c$, in high magnetic fields. Furthermore, outstanding improvement of the $I_c$ for the thick films was achieved by changing the rare earth material to Eu ratio [5]. The $I_c$ at 77 K under self-field exceeded 380 A.

| Width | 5 mm |
|-------|------|
| Thickness | 112 μm |
| Substrate | Hastelloy (100 μm) |
| Buffer Layer | CeO$_2$ (0.62 μm) + LaMnO$_3$ (0.008 μm) + MgO (0.005 μm) + Y$_2$O$_3$ (0.014 μm) + Gd$_2$Zr$_2$O$_7$ (0.055 μm) |
| Superconducting Layer | EuBa$_2$Cu$_3$O$_{y-δ}$ + BaHfO$_3$ [3.5 mol%] (3.6 μm) |
| Stabilizing Layer | Silver (10 μm) |
| Number of filaments | 10 (Laser-scribed) |
| $I_c$ at 77 K, self-field | > 380 A |

The AC loss of the REBCO superconducting tape was measured using a saddle-shaped pickup coil method [6]. The magnetic field dependence of the $I_c$, $I_c$-$B$, was evaluated using the observed magnetization curves. Figure 1 (a) shows the magnetic field amplitude dependence of the AC loss for the non-scribing tapes at 20 K and figure 1 (b) shows the estimated $I_c$-$B$ characteristics at 20 K. A magnetic field perpendicular to the superconducting tape face was calculated using the incident angle to the tape face. When an AC current is applied to the superconducting tape, magnetic fields perpendicular to the tape face cross each other at both ends of the wire in the process of reversing the

![Figure 1](image-url)
current. The hysteresis loss is proportional to the square of the width of the superconducting tape. Therefore, thinning the superconducting layer with a laser will reduce the width of inversion and reduce the hysteresis loss [7]. It is assumed that the superconducting tape was divided into a 10-filament structure by laser-scribing. Compared to the non-scribing tape, the shielding current of 1 filament becomes 1/10 in the case of the 10-filament structure. Therefore, it is expected that the hysteresis loss occupying most of the AC loss of the REBCO superconducting tape is reduced to 1/10 by dividing the tape into 10-filaments.

We calculate the nonlinear resistance of the stator winding using the n-value model. If the tape length is represented as $L$, $V_c$, the critical voltage, is calculated from the equation:

$$V_c = 10^{-4} L (m).$$

The n-value of the REBCO superconducting tape is reported to be approximately 35–40 for a temperature of 20 K and a magnetic flux density of approximately 0–5 T [8]. In addition, $I_c$ is calculated from the observed $I_c$–$B$ curve. As a result, the nonlinear resistance is 0.01–0.03 $\Omega$. This is not the critical value to necessarily affect the calculated data, so we did not consider the nonlinear resistance.

2.2. Winding method

We designed three models for the armature winding configurations: short-pitch distributed (SPD) winding, full-pitch distributed (FPD) winding, and concentrated winding. figure 2 shows the armature winding structures of the three models. The U-phase is connected in the order of U1+, U1-, U2+, and so on. This order does not change for each phase.

Figure 2. Conceptual diagrams for the three models: (a) Short-pitch distributed (SPD) winding, (b) Full-pitch distributed (FPD) winding, (c) Concentrated winding.

Compared with the distributed windings, concentrated windings do not distribute the magnetic path as much, so the waveform of the induced electromotive force will deteriorate remarkably.

For the SPD winding, the ratio of the winding pitch to the magnetic pole pitch is represented as $\beta$. The short-pitch factor $k_p$ is as expressed as:

$$k_p = \sin \frac{\beta \pi}{2}$$

When the number of slots in each pole and phase is expressed as $q$ and the number of phases is represented by $m$, the distribution factor $k_d$ is expressed as:

$$k_d = \frac{\sin \frac{\pi}{2m}}{q \sin \frac{\pi}{2mq}}$$

Therefore, the winding factor $k_w$ is expressed as:

$$k_w = k_p k_d$$
In this study, for the two distributed winding models, \(q\) and \(m\) are 12 and 3, respectively. \(\beta\) is 1 for the FPD winding and 5/6 for the SPD winding. Accordingly, \(k_w\) of the SPD winding model is less than that of the FPD winding model. The induced electromotive force of the generator is proportional to the winding factor \(k_w\). Therefore, the induced electromotive force in the case of the same number of turns is smaller than that of the FPD winding model for the SPD winding model.

The short-pitch factor \(k_{ph}\) for the \(h\)th harmonic is expressed as:

\[
k_{ph} = \sin \frac{h \beta \pi}{2}
\]

In the case of \(\beta = 5/6\), \(k_{ph}\) decreases significantly when \(h = 5\) and 7. Thus, the spectra of the fifth harmonic and the seventh harmonic will reduce in the case of the SPD winding model. Therefore, the waveform of the induced electromotive force of an SPD winding model approaches a sinusoidal wave compared with the FPD winding model. In addition, as the coil-ends are shortened, the SPD winding model has a shorter wire length.

2.3. Design of 10 MW fully superconducting generator

The specifications of the superconducting synchronous generator are shown in Table 2. Four models, SPD winding, FPD winding, concentrated winding, and SPD winding with optimized size, were designed. The former three models were prepared in order to compare the difference in AC loss in terms of the winding method. The models were set to have the same size (diameter and effective length). The last model was prepared to achieve a high power density for the SPD winding by miniaturizing.

| Winding Method       | SPD    | FPD    | Concentrated | SPD (opt.) |
|----------------------|--------|--------|--------------|------------|
| Output Power         | 10 MW  |        |              |            |
| Rated Voltage        | 6900 V |        |              |            |
| Rated Current        | 780 A  |        |              |            |
| Number of Poles      | 2      |        |              |            |
| Frequency            | 100 Hz |        |              |            |
| Number of Revolutions| 6000 rpm |      |              |            |
| Operation Temperature| 20 K   |        |              |            |
| Peak Current-to-Ic Ratio | 0.7 |      |              |            |
| Magnetic Flux Density of Gap | 1.44-1.55 T | |              |            |
| Effective Length     | 1200 mm| 550 mm |              |            |
| Diameter             | 560 mm | 540 mm |              |            |
| Number of Turns of Armature Winding | 12 | 10 | 98 | 30 |

The load lines of these models of the operation temperature, \(T_{op} = 20\) K, are shown in figure 3 (a). The load lines were determined by a straight line extending from the origin, through the operating point, and to the intersection with the \(I_c-B\) curve. The operating point is defined by the value of the current flowing in the field and the armature windings, in a perpendicular magnetic field to the superconducting tape face [9]. All these values were measured during rated operation.

The operating current is represented by \(I_{op}\). The load factor of each winding was defined as the ratio of \(I_{op}\) to \(I_c\). The number of turns and the \(I_{op}\) were adjusted so that the load factor was approximately 70% for the field windings and armature windings. A schematic of the cross-sectional view of the designed generator is shown in figure 3 (b).
The cryostat, container, and shaft were made of GFRP. The thickness of the parts was changed according to the component type regarding mechanical strength. For example, the thickness of the container of the field and armature windings was 10 mm. The thickness of the shaft was 30 mm. The distance of the air gap was 5 mm, respectively. Comparing to a partly-superconducting generator, the fully superconducting generator has the advantage of the length of the air gap due to there being no vacuum chamber in the air gap. An iron yoke was placed outside the cryostat to shield magnetic field leakage from the internal magnetic field. For this reason, the iron loss on the iron yoke was not a thermal load of the low temperature cooler. It was assumed that the armature windings were bath-cooled liquid hydrogen at 20 K and the field windings were cooled with helium or hydrogen gas. The iron yoke used was 50 JN 270 made by JFE Steel, and its thickness was set to 30 mm in all models. It was assumed that the cool heat of liquid fuel, such as liquid hydrogen and LNG, can be utilized. The magnetic field at the air gap was set to 1.44 - 1.55 T for all models.

3. Loss and weight evaluation

3.1. AC loss evaluation

![Image](https://example.com/image.png)

**Figure 4.** Magnetic field distribution in the cross-section of the generator of (a) SPD windings, (b) FPD windings, (c) concentrated windings.
Figure 4 shows the magnetic field distribution in the cross-section of the generator. Comparing the maximum magnetic flux density of the air gap, SPD model and FPD model were 1.55 T but concentrated winding model was 1.44 T. The current and number of turns of field winding of all models are the same so that the difference of the magnetic flux density of the air gap was due to the armature reaction. The concentrated winding model concentrated the magnetic path more than SPD and FPD winding models. For this reason, the magnetic flux applied to the field windings decreased by the magnetic flux from the armature windings due to the armature reaction. The output power decreased because of decreasing the interlinkage magnetic flux. As a result, the number of turn of armature winding of the concentrated winding increased and generated the output power. In term of the iron yoke, the maximum magnetic flux densities of all models exceeded 2.5 T and the magnetic field of the iron yoke was saturated. In addition, the leakage magnetic flux of all models exceeded 0.5 T. In regards to the relationship between the thickness and weight of the iron yoke and the leakage magnetic flux, we plan to examine it moving forward. We consider replacing the iron yoke to the superconducting shield because of reducing the weight and shielding more leakage magnetic field. In the near future, we will report the experimental results of superconducting shield.

Figure 5 (a) shows the AC loss of each winding and the iron loss of the three models, and figure 6 (b) shows the length of the superconducting tape of each winding.

![Figure 5](attachment://image.png)

**Figure 5.** (a) AC loss of each winding and iron loss of the superconducting generator, (b) the length of the superconducting wire of each winding.

As shown in figure 5 (a), the AC loss of the armature winding of the concentrated windings was doubled compared to the AC loss of the FPD windings. This is because the length of the armature winding was approximately twice that compared to the FPD windings, as indicated in figure 5 (b). In the case of the concentrated windings, a large counter electromotive force occurred, as a result, the number of turns of the armature winding increased. Eventually, the AC loss of the concentrated windings became larger. The AC loss of the field winding and the iron loss were small compared to the AC loss of the armature winding.

3.2. **The output power density**

The iron yoke, cryostat, container of armature, armature windings, reel of armature windings, container of field, reel of field windings, field windings, and shaft were considered when calculating the generator dry-weight. The thickness of each part is shown in figure 3 (b). The previous three models were compared with the SPD (opt.) winding model, which is as small as possible. Figure 6 shows the output power density of all the models.
Figure 6. Power density of superconducting generator.

The only difference between the previous three models is the length of the superconducting tape. Hence, the generator weights for the three models were almost the same; thus, the output power densities of the three models were also almost the same, as shown in figure 6. In the case of the SPD(opt.) winding model the effective length and the volume of the iron yoke were both significantly reduced, so the output power density was drastically improved.

Figure 7. Voltage waveform and harmonic voltage spectrum of (a) and (a’) SPD winding, (b) and (b’) FPD winding, (c) and (c’) concentrated winding, respectively.

3.3. The voltage waveform
Figure 7 shows the voltage waveforms and harmonic voltage spectrums of each model. The voltage waveform distortion is due to the higher harmonic wave. In this research, we calculated the harmonic spectrum of the armature winding. The frequency of the fundamental wave was set to 100 Hz and the odd harmonics until the 12th harmonic wave were considered. In the case of considering only the fundamental wave, distortion of the voltage waveform occurred. The SPD winding model has the lowest
distortion factor of 7.50%. Compared to the SPD winding model, the distortion rate of the FPD winding model increased to 10.4%, and the distortion rate of the concentrated winding model increased to 12.4%.

The reason for this difference is the large spectrums of the fifth harmonic and the seventh harmonic. Compared with SPD windings, these were approximately 85% as much as the FPD windings in terms of the fifth harmonic and approximately 60% in terms of the seventh harmonic; approximately 40% as much as the concentrated windings in terms of the fifth harmonic and approximately 45% in terms of the seventh harmonic. By JEC-2130 established by The Japan Electrical Manufacturers’ Association (JEMA), the condition of the compliance standard is that the gas turbine synchronous generator has a distortion factor of 10% or less. The SPD winding model satisfies JEC-2130 requirements.

4. Conclusion
With various winding methods for armature windings, the 10 MW-class synchronous generator comprising REBCO superconducting tapes were designed and evaluated by a numerical analysis. The model adopting the distributed winding had a better result in terms of AC loss and output voltage waveform in comparison with the concentrated winding model. In particular, the AC loss of the armature winding was approximately half compared to that of the concentrated windings. Furthermore, the distortion factor of the SPD winding was lower than 10%. Additionally, the output power density of the SPD model with optimized dimensions reached 26.3 kW/kg. Therefore, in terms of AC loss, the output power density, and output voltage waveform, the SPD winding model is the most suitable for aircraft superconducting generators.

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