Wind Turbine Generators using Superconducting Coils and Bulks

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Abstract. Wind power generation has been expected as a promising clean energy source in the world. Recently, generation capacity produced by wind power generators has been growing with increasing size of windmills. However, huge nacelles result in extreme load for towers supporting them. We have focused on a wind power generator using superconducting wires and superconducting bulks to solve the problem. Large currents may flow through superconducting wires with zero DC resistance. Superconducting bulks are magnetic shielding materials. These enable reduction of size and weight of nacelles. In addition, large generators using these materials can generate an output power of 10 MW with very large power densities. This paper describes calculation of generated magnetic field and power generation characteristics using three-dimensional finite element method (FEM) analysis of the generators using high temperature superconducting coils and bulks.

1. Introduction
The wind turbine market has been growing rapidly. In particular, off-shore wind energy attracts greater attention recently, and the development of wind turbine generators of higher power rating becomes more important. For higher-power generators, direct-drive synchronous machines are more widely accepted, and they are operated at very low speeds and subjected to quite high torque. Therefore they tend to become very large and heavy [1]. Superconducting technology can be a key to solve this problem, and realize much more efficient, lightweight and compact generators than conventional technologies. Recent progress of high-temperature superconducting (HTS) wires and bulk superconductor with strong flux pinning [2] has enabled to design electric machines with higher power density than conventional machines. There are several types of HTS rotating machines: those using bulk superconductors [3], those using superconducting wires [4], and those using both [5]. There are some studies considering 10 MW class generators [6-8]. For example, an 8 MW class generator using superconductor windings has been developed in Europe [7].

We have studied superconducting synchronous machines, which have bulk superconductors as a magnetic shielding component and HTS coils for DC field generation in the rotor, and armature windings in the stator [8]. The bulk superconductors in the rotor are used as diamagnetic or magnetic shielding components. This paper reports conceptual design of such a type of 10 MW class superconducting generators and their performance evaluation by three-dimensional finite element
analysis. Some parameter dependence of generated magnetic field and power generation characteristics of the superconducting generators are also discussed.

2. Rotor structure and field generation principle
Design of superconducting synchronous generators was carried out. They have the following fundamental features.

- Superconducting coils and bulks for DC field generation in the rotor.
- Copper armature windings in the stator.
- Coreless structure.
- Direct drive.

Figure 1 shows the fundamental rotor structure of the designed superconducting generator. It has seven superconducting coils of 7 m in diameter and many bulk superconductors. Total axial length of this structure is 1.82 m. DC current of 1.86 MA is supplied to each superconducting coil, and the current density is 290 MA/m², which is assumed for the operation temperature of 20 K based on the recent progress of coated conductor [9,10]. The directions of adjacent superconducting coil currents are opposite each other. Bulk superconductors are placed near superconducting coils for magnetic shielding. There are two types of bulk superconductors, (A) bulk superconductors between superconducting coils as main components to produce field modulation in the rotational direction and (B) those placed above superconducting coils and bulk superconductors A for reducing leakage flux between them. The combination of superconducting coils and bulks in the rotor generates a rotating magnetic field with 110 poles. Table 1 gives specifications of superconducting coils and bulks in the rotor.

Figures 2 and 3 show the principle of DC field generation with N-S poles. Currents in the adjacent superconducting coils flow oppositely each other. If there are only two superconducting coils and a single row of bulk superconductors, they generate a homopolar magnetic field with such modulation as shown in figure 3. If there are three superconducting coils and double rows of bulk superconductors arranged alternately as shown in figure 2, they generate alternate magnetic field in the rotational direction.

![Figure 1. Rotor structure having superconducting coils and bulks (110 poles).](image)
Table 1. Specifications of superconducting coils and bulks in the rotor.

| Overall dimensions                  |       |
|------------------------------------|-------|
| Diameter                           | 7.00 m|
| Axial length                       | 1.82 m|
| Number of poles                    | 110   |
| Superconducting coil               |       |
| Cross section                      | 80 mm × 80 mm |
| Total Current                      | 1.86 MA (290 MA/m$^2$) |
| Bulk superconductor                |       |
| A                                  | 200 mm × 200 mm × 40 mm |
| B                                  | 190 mm × 200 mm × 10 mm |

Figure 2. Magnet field generated by superconducting coil currents and bulk superconductors for magnetic shielding.

Figure 3. Magnetic shielding by bulk superconductors (8-pole model). Effective armature reaction torque is generated.

3. FEM analysis

In this study, electromagnetic characteristics of the superconducting synchronous generator for wind turbine were investigated by the three-dimensional finite element method. Magnetic field generated by the rotor components was calculated and the dependence of the magnetic field distribution on the distance from the outer surface of bulk superconductors was examined. Then, interlinkage magnetic flux of the armature coil and the voltage induced by the rotation were calculated, and the output power was estimated. Magnetic flux leakage due to the deterioration of magnetic shielding characteristics finally affects the generator performance. JMAG-Studio [11], FEM software for electromagnetic field analysis, was used in this study. Analysis was focused on the following characteristics:

- Distribution of magnetic field generated by the superconducting components
- Basic performance of the generator
- Influence of magnetic shielding performance

Bulk superconductors were approximately modelled as a diamagnetic component with constant magnetic permeability. In most analysis the relative magnetic permeability of bulk superconductors was assumed $\mu_r = 0.01$. 
4. Results

4.1. Distribution of magnetic flux density
Magnetic field distribution radially outside of the bulk superconductors, where armature windings would be placed, was examined. Figure 4 shows the distribution in the rotational direction ($\theta$) of radial component $B_g$ of magnetic flux density along the arc with an angle of 13° at a distance from the outer surface of bulk superconductors from 10 mm to 40 mm. Magnetic flux density reaches about 3 T to 4.5 T, which is three times or more as high as that of conventional machines. Around $\theta \approx 0°$, 6.5° and 13°, where bulk superconductors are placed, the magnetic flux density become as small as about 0.3 T. However, a peak-to-peak value of magnetic flux density is from 2.7 T to 4.2 T, which is a little higher than that of conventional machines.

4.2. Basic characteristics of generator
Considering the magnetic flux density distribution shown in figure 4, the thickness of cryostat walls, the mechanical clearance between the rotor and the stator, etc., it was assumed that the armature windings were placed outside of the bulk superconductors with a gap of 20 mm. The windings have a square cross section of 50 mm × 100 mm, the length in the rotational direction of about one pole pitch, and the axial length of 1.82 m. Figure 5 shows the armature winding model to calculate its interlinkage magnetic flux and induced voltage when the rotating magnetic field is generated.

Table 2 summarizes specifications of armature windings and basic characteristics of the generator. Analysis results indicate that the total output power of 10.2 MW can be obtained in this superconducting machine. However, more accurate modeling of the load condition is needed to get detailed generator characteristics.
Figure 5. Armature winding model to calculate its interlinkage magnetic flux and induced voltage when the rotating magnetic field is generated.

Table 2. Specifications of armature windings and basic characteristics of the generator.

| Revolution | 10 rpm |
| Output power | 10.2 MW |
| Armature windings |  |
| Cross section | 50 mm × 100 mm |
| Current density | 2 A/mm² |
| One-turn voltage (rms) | 6.3 V |
| Maximum magnetic field \( B_{\text{max}} \) | 12 T (on a superconducting coil) |

4.3. Influence of magnetic shielding performance on armature interlinkage magnetic flux

Interlinkage magnetic flux \( \Phi \) of the armature winding was calculated to examine the influence of magnetic shielding performance. In this calculation, bulk superconductors are assumed as magnetic materials whose relative magnetic permeability is \( \mu_r \). And the penetration of magnetic field into the superconductor is expressed by changing the figure of \( \mu_r \).

Figure 6 shows the dependence of interlinkage magnetic flux \( \Phi \) (peak) of the armature winding shown in figure 5 on the relative magnetic permeability \( \mu_r \) of bulk superconductor for magnetic shielding. Deterioration of magnetic shielding performance of bulk superconductors directly affects the interlinkage magnetic flux of armature winding. Actual bulk superconductors suffer magnetic field penetration due to the finite critical current density and its dependence on the magnetic field. As a result the interlinkage magnetic flux \( \Phi \) decreases, which is dependent on the design parameters. Further studies are needed taking into account more practical properties of bulk superconductors.

5. Conclusions

We have studied superconducting wind turbine generators that have bulk superconductors as a magnetic shielding component, superconducting coils for DC field generation and armature windings. The fundamental machines structure was described with emphasis on the rotor structure, and some results obtained by the three-dimensional finite element method were presented. They indicated that the proposed generator structure has potential to be scaled up to about 10 MW output power. Further studies are needed, taking into account more practical superconducting properties of bulk superconductors, load conditions of the generator, and large mechanical forces.
Figure 6. Dependence of interlinkage magnetic flux $\Phi$ (peak) of the armature winding shown in figure 5 on the relative magnetic permeability $\mu_r$ of bulk superconductor for magnetic shielding.

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