Design of an HTS module coil for a 750 kW-class superconducting wind power generator

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Abstract. Recently, high temperature superconducting (HTS) generators are being studied with the advantages of high efficiency, light weight and small volume compared with the conventional generators. However, the HTS generator requires a large vacuum vessel and has problems such as difficulties in maintenance of the HTS coil. These problems can be overcome through the modularization of the HTS field coil. This paper designs an HTS module coil for a 750 kW-class superconducting wind power generator. The HTS module coil was designed based on the electromagnetic analysis results obtained using a 3D finite element method. For detail structure of the module coil, the heat load analysis and the mechanical stress analysis were performed. As a result, the total heat load was minimized the temperature of the HTS coil could be kept below 30 K. The von Mises stress of the supports was less than the allowable stress of the glass-fiber reinforced plastic material. The design results of the HTS module coil can be effectively utilized to develop large scale the superconducting wind power generators.

1. Introduction

High-temperature superconducting (HTS) generators are more suitable for wind power systems because they can reduce volume and weight compared to conventional generators and thus increase power density [1]-[3]. Many researchers have tried to develop wind power generators with larger capacity, smaller size and lighter weight [4]. However, the HTS generator has its own set problems, such as the need for a huge vacuum vessel and the difficulty of repairing and maintaining the HTS coils. These problems are closely related to the stability of the generators [5]. Furthermore, the HTS generators have high electromagnetic force acting on HTS field coils due to their high current density and magnetic field [6]-[9], and require a current lead (CL) to deliver DC current to the HTS field coil. This CL has a structure exposed to room temperature and causes a large heat transfer load [10]-[12]. Therefore, the modularization of the HTS field coil has been suggested to overcome these problems [13].

The purpose of this paper is to develop a modularized HTS rotor for a 750 kW direct-drive generator, which is smaller in volume and lighter than the UNISON company's U50. The 750 kW-class HTS rotor is composed of 84 module coils. Each module coil consists of an HTS field coil, bobbin, coil support, cryostat and CL, and designed by 3D CAD program. The HTS module coil of the generator was designed based on electromagnetic and heat load analyses, mechanical stress and displacement results obtained using a 3D finite element method (FEM), and the critical current was evaluated by the perpendicular magnetic field density.
As a result, the maximum values of the perpendicular magnetic field and the normal magnetic field of the HTS coils were 2.5 T and 3.9 T, respectively. The total heat load was minimized and a temperature of less than 30 K was achieved in the HTS coil. The von Mises stress of the HTS module coil with the supports was smaller than the allowable stress of the glass-fiber reinforced plastic (GFRP), and displacement was within the acceptable range. The analysis results of the HTS module coil were reflected in the design and discussed in detail. The results will be applied to the design of the HTS module coil to be installed in a 750 kW-class superconducting wind power generator.

2. Design of an HTS module coil for a 750 kW-class HTS generator

2.1 Specifications of the 750 kW-class HTS generator

The 750 kW-class HTS generator consists of rotor and stator parts. The rotor components are HTS field coils, a cryostat and supporting structures, and a rotor body. The stator components are comprised of stator teeth, copper stator coils, magnetic shield. The generator has 84 HTS modules. All the structure of the 750 kW-class HTS generator were drawn by the 3D CAD program as shown in figure 1. Table 1 shows the specifications of the 750 kW-class HTS generator.

| Table 1. Specifications of the 750 kW-class HTS generator |
|---------------------------------|---------------|
| Items                           | Value         |
| Rated output power              | 750 kW        |
| Rated line to line voltage      | 780 V         |
| Rated armature current          | 597.8 A       |
| Rotational speed                | 25 rpm        |
| Rated torque                    | 0.3 MN·m      |
| Number of poles                 | 84 poles      |
| Diameter of the generator       | 3.55 m        |
| Weight of the generator         | 12 ton        |

Figure 1. 3D design of the 750 kW-class HTS generator
2.2. Design of the HTS module coil for the 750 kW-class HTS generator

2.2.1 Structural design of the HTS module coil

The HTS module coil consists of HTS field coils, coil bobbins, supports, a copper block, CLs, a cryostat, and a cooling pipe. To prevent iron loss, stainless steel is used as the material of the cryostat. The coil supports are made of GFRP to improve the heat insulation between the cryostat and the HTS coils. The HTS coils are covered with bobbin and bobbin supports to protect the HTS coils from a high mechanical force.

Figure 2 shows the structural design of the HTS module coils. The 84 HTS module coils were divided into 14 parts; each part was mounted on a cryostat with a copper block and cooling pipes. The liquid neon gas flows inside the cooling pipes to cool the HTS module coils. The HTS coils consisted of three double pancake coils (DPC) in race-track form. The HTS wire was coated with a flat conductor tape, and thickness and width were 0.15 mm and 12 mm, respectively.

![HTS module coils](image)

**Figure 2. Structural design of the HTS module coils**

2.2.2 Structural design of the current lead

The CLs should be designed to minimize the heat load of on the cryogenic system of the HTS wind power generator. Conduction and Joule heat loads of the CLs made of brass were calculated and analyzed. The important factors in designing the CLs are the thermal conductivity of materials and the geometric shapes (length, cross-sectional area and cooling surface area). The minimum heat load and ideal length of the CL can be calculated by equations (1) and (2) [7].

\[
Q_{op} = I \sqrt{\frac{2}{\int_{T_L}^{T_H} \rho(T)k(T)dt}}
\]

\[
L = \frac{1}{I} \int_{T_L}^{T_H} \frac{k(T)}{\sqrt{2} \int_{T_L}^{T_H} \rho(T)k(T)dt}} dT
\]

The thermal conductivity \( k(T) \) and the electric resistivity \( \rho(T) \) are inversely related, according to Wiedemann- Franz law (3). Here, the Lorentz number is \( L_0 = 2.45 \times 10^{-8} \text{ W}\Omega K^{-2} \).

\[
k(T)\rho(T) = L_0 T
\]

where, \( L \) is the length of CL, \( A \) is the cross-sectional area, and \( I \) is the carrying current. \( T_H \) and \( T_L \) represent the temperature of the cold and warm ends, \( k(T) \) is the thermal conductivity, and \( \rho(T) \) is the
electric resistivity [14]. Brass was used as the material for the metal CL because it has better mechanical characteristics than copper. Figure 3 shows the structural design of the HTS module coil. The CLs, including brass current terminals and current feedthroughs, were designed using a 3D CAD program.

![Figure 3. Structure design of the CL](image)

### 3. Simulation results and discussions

#### 3.1 Electromagnetic analysis

The 750 kW-class HTS generator was analysed using the 3D FEM program. The design specifications of the HTS module coil for the 750 kW-class HTS generator were summarized in table 2. Figure 4 shows the magnetic field distributions of a 1/84 model of the 750 kW-class HTS generator. The maximum value of the perpendicular magnetic field and normal magnetic field of the HTS module coil were 2.5 T and 3.9 T, respectively. The operating current was 397.8 A with 40% margin, and the current was determined by the properties of the HTS wire [15].

| Items                          | Value       |
|-------------------------------|-------------|
| Number of poles               | 84 poles    |
| Number of HTS coil layers     | 6 layers    |
| Temperature                   | 30 K        |
| HTS wire width                | 12 mm       |
| HTS wire thickness            | 0.15 mm     |
| Turns of HTS coil             | 136 turns   |
| Effective length of HTS coil  | 449 mm      |
| Operating current             | 397.8 A     |

![Figure 4. (a) Magnetic field distribution and (b) perpendicular magnetic field of the 750 kW-class HTS generator](image)
As a simulation result, the output voltage and rated torque were 551 V and 0.3 MN·m, respectively. Figure 5 shows the output voltage and torque value of the 750 kW-class HTS generator under the full-load condition.

![Figure 5](image_url)

**Figure 5.** (a) Output voltage and (b) rated torque of the 750 kW-class HTS generator

3.2 **Thermal analysis of the HTS module coil**

The total heat load of the HTS module coil, including the Joule heat, the conduction heat load of the CLs and the radiation heat load, the conduction heat load from supports were considered using the 3D FEM program. The heat invasion of the CL was should be close to 0 W which was obtained by changing the thickness of the CL as shown in figure 6. The length and thickness of the CL were 100 mm and 7.7 mm respectively. Figure 7 shows the temperature distribution analysis result of the designed CL. The total heat load of one CL was 20.1 W.

![Figure 6](image_url)

**Figure 6.** Heat invasion of the CL

![Figure 7](image_url)

**Figure 7.** Temperature distribution of the one CL with feedthrough

In order to reduce conduction heat load, GFRP material with low thermal conductivity was used for the support. The length and contact area of the support were 20 mm and 0.078 m², respectively. The conduction heat load of the supports in the module coil was analysed by using a 3D FEM program and compared with the calculated result.

The radiation heat load was evaluated by the Stefan-Boltzmann equation using the 3D FEM program. The radiation heat load between the $N_i$ layer of multilayer insulations is estimated as:
\[ Q_r = \frac{\varepsilon_0}{N_{r+1}} (T_r^4 - T_c^4) \]  

where, \( \varepsilon \) is the effective total thermal emissivity of the materials. In this paper, the emissivity of 0.01 was applied. \( \sigma \) is Stefan-Boltzmann constant. \( T_r \) and \( T_c \) are the enclosure temperature and the thermal shield temperature, respectively [16].

For the simulation, the operating current of 397.8 A was applied. The temperature distribution analysis results of the HTS module coils are shown in figure 8. The temperature distribution in the CLs is shown in figure 8 (a). The temperature distributions in the HTS module coils and the cryostat are shown in figure 8 (b) and (d), respectively. The temperature distribution in the supports of the HTS module coil is shown in figure 8 (c).

As a result, the temperature of the HTS coil was 27.1 K. The conduction heat load from the supports was 39.4 W, and the radiation heat load was 7.59 W, the conduction and Joule heat load from the CLs was 40.2 W. The total heat load of the 750 kW-class HTS generator was 87.14 W. Table 3 compares the calculation results with the simulation results. The total heat load obtained by the calculation was 75.05 W, the total heat load obtained by the simulation was 87.14 W, and the temperature was 27.1 K, which was less than 30 K. The AL325 cryo-cooler was used to cool the HTS module coils. To achieve a temperature of 30 K or less based on the capacity map of the cryo-cooler, the total heat load must be less than 140 W, thus the cooling capacity margin of the HTS module coil is 52.9 W.

**Figure 8.** Temperature distributions of the (a) CLs, (b) HTS module coil, (c) supports and (d) cryostat of the 750 kW-class HTS generator
Table 3. The total heat load of the HTS module coil

| Items                                      | Calculation result | FEM result |
|--------------------------------------------|--------------------|------------|
| Conduction and Joule heat load from the CLs | 37.2 W             | 40.2 W     |
| Current terminals and joint                | 0.35 W             | 0.35 W     |
| Conduction heat load from the supports     | 32.9 W             | 39.4 W     |
| Radiation heat load                       | 4.6 W              | 7.59 W     |
| Total heat load                            | 75.05 W            | 87.14 W    |

3.3 Mechanical analysis of the HTS module coil

Torque is generated due to the magnetic field reaction between the rotor and stator parts. When the generator is in a no-load state, the generated magnetic field does not change because the armature current is zero, but the magnetic field generated under the full load condition is influenced by the armature current, thereby changing the electromagnetic force [1]. Therefore, the mechanical stress due to the electromagnetic force of the 750 kW HTS generator was analyzed under full load conditions.

\[
\tau = \frac{P}{\omega} \quad (5)
\]

where, \(P\) is the rated power, \(\tau\) is the torque, \(\omega\) is the angular velocity. Tangential force acting on a body moving in tangential direction of the body path is given as follows.

\[
F_{\text{tan}} = \frac{\tau}{r} \quad (6)
\]

where, \(r\) is the radius of the rotor. The total torque and the tangential force of the generator were calculated by the equations (5) and (6). The torque and tangential, radial, gravity, centrifugal forces of the HTS module coil were examined. The output torque and the tangential force of one HTS module coil were 3.6 kN and 2.2 kN, respectively. The gravity and the centrifugal forces of the HTS module coils were 1.5 kN and 1.2 kN, respectively.

To analyse the mechanical stress of the HTS module coil, the axial direction and amplitude of the Lorentz force at the HTS field coil are required. The tangential and radial forces of the HTS module coils are shown in figure 9. The maximum amplitudes of the axial direction forces were 15.2 kN (y-axis) and 4.9 kN (x-axis), respectively, as shown in figure 10.

![Figure 9. Tangential and radial force of the HTS module coil](image1)

![Figure 10. Maximum tangential and radial force of the HTS module coil](image2)
Based on the force analysis results, the HTS module coil structure was analysed using a 3D FEM program. The simulation results show that the von Mises stress and displacement of the HTS module coil were 39.3 MPa and 0.03 mm, respectively. Figure 11 and 12 show the von Mises stress and displacement of the HTS module coils with support structures. The module coil support was made of GFRP. The tensile strength of the GFRP material was 280 MPa, allowable yield stress was 93.3 MPa. The stress value of the simulation result was 39.3 MPa which is lower than the allowable yield strength.

4. Conclusions
This paper discusses the design of an HTS module coil for a 750 kW-class superconducting wind power generator. Electromagnetic, thermal and mechanical properties were analysed using a 3D FEM program. The required diameter and axial length of the generator were 3.55 m and 0.7 m, respectively. As a result, the maximum values of the perpendicular magnetic field and the normal magnetic field of the HTS module coil were 2.5 T and 3.9 T, respectively. The conduction heat load from the supports was 39.4 W, and the radiation heat load was 7.59 W, the Joule heat load of the current terminal and the joint was 0.35 W, the Joule and conduction heat load from the CLs was 40.2 W. The total heat load and the temperature of the HTS module coil were 87.14 W and 27.1 K, respectively. The AL325 single-stage cryo-cooler was adopted to cool the HTS module coils. Overall heat load of the HTS module coil was less than the cooling capacity of the cryo-cooler, and the cooling capacity margin was 52.9 W. The tangential and radiation forces of the HTS module coils were 15.2 kN and 4.9 kN, respectively. The von Misses stress and displacement of the HTS module coils were 39.3 MPa and 0.03 mm. The von Mises stress of the HTS module coil with the supports was less than the allowable stress of GFRP, and the displacement was within the permissible range. These results can be applied to the development of large scale HTS wind power generator system.

Acknowledgments
This research was supported by Korea Electric Power Corporation (Grant number: R18XA03), and in part by the New & Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20183010025270).
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