Structural design and heat load analysis of a flux pump-based HTS module coil for a large-scale wind power generator

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Structural design and heat load analysis of a flux pump-based HTS module coil for a large-scale wind power generator

O Tuvdensuren¹, H J Sung¹, B S Go¹, T T Le¹, M Park¹ and I K Yu¹
¹ Changwon National University, Changwon, GN, 51140, Korea

yuik@cwnu.ac.kr

Abstract. Superconducting generators typically require a power supply, current lead (CL) and slip ring to deliver DC current to a high-temperature superconducting (HTS) coil, which causes a conduction heat load. On the other hand, a flux pump (FP) is possible to supply DC current to the HTS coils of the generator without the heat transfer loads. This paper deals with a structural design and heat load analysis of an FP-based HTS module coil for a 12 MW wind power generator. The structures such as HTS coil bobbins, coil supports, and the connection components between the FP and the HTS coils were designed. The conduction and radiation heat loads of the FP-based HTS module coils were analysed using a 3D finite element method program. The results of the HTS module coil of the generator were compared with a conventional CL-based HTS module coil. As a result, the total heat loads of the FP-based HTS module coil were lower than the conventional CL-based HTS module coil. The structural design and heat load analysis results of the FP-based HTS module coil can effectively be utilized to develop a large-scale HTS wind power generator.

1. Introduction
In the development of offshore wind power generation, the size and weight of wind power generators are increasing, and the capacity of generators is also increasing. Many companies have tried to develop wind power generators with a larger capacity, smaller size and lighter weight. A high-temperature superconducting (HTS) generator is one potential solution for these issues. HTS generators are usually adopted for large multi-megawatts generators [1]-[3].

A large-scale HTS generator has its own set of problems, such as the need for a huge vacuum vessel and the difficulty of repairing and maintaining the HTS coils because all the HTS coils are consisted in one cryostat [4]-[6]. Normally, the HTS coils are connected in a series, if the one HTS coils fails, the other coils break down. To overcome these problems, large-scale HTS generator module coils are structurally separated with an HTS flux pump (FP) or current lead (CL) [7]-[8]. Conventional CL requires a power supply and a slip ring to transfer the DC current to the HTS coil. The CL can be a bridge between the cryogenic environment and room temperature, which causes large heat transfer loads [9]-[11].

The high cooling capacity of cooling systems is therefore important in large-scale HTS wind power generators. On the other hand, a FP can supply DC current to the HTS coils of the generator without the heat transfer loads of excitation systems [12]-[15]. However, an effective structural design and the heat load analysis considering the connection of the FP to the HTS coils are required for the HTS wind power generator.
This paper deals with a structural design and heat load analysis of an FP-based HTS module coil for a 12 MW wind power generator. The 12 MW HTS generator is composed of 30 module coils. The structures of one module coil, such as HTS coil bobbins, coil supports, and the connection components between the FP and the HTS coils, were designed. The conduction and the radiation heat loads of the FP-based and the CL-based HTS coils were analyzed using a 3D finite element methods program considering the two-stage cryo-cooler.

The results of the FP-based HTS coil of the generator were compared with a conventional CL-based HTS module coil. As a result, the total heat load of the FP-based HTS module coil was lower than that of the conventional CL-based HTS module coil. These results and structural design will be applied to a large-scale HTS wind power generator with cooling system.

2. Structural designs of the FP-based and CL-based HTS module coils

The 12 MW HTS generator consists of rotor and stator parts. The rotor components are HTS field coils, a cryostat and supporting structure, and a rotor body. The stator components are comprised of stator teeth, copper stator coils, and a gear to rotate the FP exciter. The generator has 30 HTS modules. Table 1 shows the specifications of the 12 MW HTS generator [3].

| Items                    | Values   |
|--------------------------|----------|
| Rated output power       | 12 MW    |
| Rated line to line voltage | 6.6 kV   |
| Rated armature current   | 1.07 kA  |
| Rated wind speed         | 11.4 m/s |
| Rotational speed         | 8 rpm    |
| Rated torque             | 15.04 MNm|
| Number of poles          | 30 ea    |
| Operating temperature    | 20 K     |

All the HTS field coils are structurally separated and not connected series as shown in figure 1(a). The HTS module consists of HTS field coils, coil bobbins, bobbin supports, a heat exchanger, a CL or FP, a cryostat, and a cryo-cooler. The HTS coils are covered by bobbin supports to protect the HTS coils from a high mechanical force. Heat exchangers are used to transfer heat between the HTS coils and the cold head of the cryo-cooler. The coil supports secures the HTS coils and blocks the heat transfer from the cryostat.

The FP excitors are located in each module and classified as rotating and stationary parts as shown in figure 1(b). The rotating parts have permanent magnets, an iron-shaft, an iron disk, and an FP exciter gear at room temperature. These parts are rotated by interlocking gear teeth of the generator and FP exciter. The stationary parts include an HTS stator wire, an iron-disk, an iron shaft, and an iron-ring at a low temperature. The stationary parts are located in the cryostat of the module to connect the HTS stator wire directly to the HTS field coil.
Figure 1. Configuration of the FP-based HTS module coil

The CL-based HTS module coil consists of an HTS field coil, coil bobbins, bobbin supports, a heat exchanger, current leads, a cryostat, and a cryo-cooler. Figure 2 shows the structure design of the CL-based HTS module coil.

Figure 2. Configuration of the CL-based HTS module coil

The CLs for transferring current from room temperature to the cryogenic environment. To design the CLs, the important factors are the thermal conductivity of materials and the calculating 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).

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

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

(2)

The thermal conductivity \(k(T)\) and the electric resistivity \(\rho(T)\) are inversely related, according to Wiedemann-Franz law (3)

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

(3)

Here, the Lorentz number is \(L_0 = 2.45 \times 10^{-8} \, \text{W} \Omega K^{-2}\). Hence, equations (1) and (2) can be rewritten as:

\[Q_{op} = I \sqrt{L_0 (T_H^2 - T_L^2)}\]

(4)

\[\frac{L}{A} = \frac{1}{I} \int_{T_L}^{T_H} \frac{k(T)}{\sqrt{L_0 (T_H^2 - T_L^2)}} dT\]

(5)

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. The current leads are made up of a normal conducting material at the room temperature end, so copper or brass is used generally. Figure 3 shows the configuration of the CL for the HTS module coil. The current leads including copper current terminals and the cooling block; current feedthroughs were designed using a 3D CAD program.

3. Heat loss analysis of the HTS module coil

**Excitation loss:** The sum of iron and joule heat losses of the HTS FP exciter is the excitation loss. The total resistance of the exciter and operating current were 79 \(\mu\Omega\) and 352 A, respectively. Therefore, the joule heat loss of the exciter was 10 W, and the iron loss of the stator part was 0.2 W. The total excitation loss was 10.2 W in the generator module. The design and analysis of the HTS FP-based exciter were discussed in [5].

**Eddy current loss:** The 12 MW HTS generator adopts three-phase armature coils, which are conventional copper coils at room temperature. They induce eddy currents to the HTS module. The eddy current loss of the HTS module is generated in the coil bobbin, bobbin supports, and heat exchanger. The total eddy current loss in one HTS module coil of the 12 MW HTS generator was 15 W which was analyzed using an FEM program and discussed in [5].

**Conduction and radiation losses in the HTS module coil:** The supports were located in both the 1st and 2nd layers of HTS module. The conduction heat losses of supports are transferred from ambient temperature to the shield and from shield temperature to coil temperature. Based on the capacity map of a two-stage GM cryo-cooler, in the second stage, to achieve the temperature under 20 K at the HTS coils, the total heat load should be less than 27.5 W. In the first stage, the total heat loss should be less...
than 52 W to maintain the temperature of the shield less than 65 K using the two stage GM cryo-cooler in the HTS module.

To reduce the radiation loss of the coil, a radiation shield was used. The radiation loss between the shield and cryostat is estimated as:

$$\epsilon \sigma (T_c^4 - T_r^4)$$

where, $\epsilon$ is the effective total thermal emissivity of the shield, $\sigma$ is the Stefan Boltzmann constant, and $T_c$ and $T_r$ are the cryostat temperature and thermal shield temperature.

### 4. Heat load analysis and simulation results

#### 4.1. Heat load analysis of the CL-based HTS module coil

The thermal characteristics of the CLs were analyzed using a 3D FEM program. For the simulation, the operating current was 352 A. The temperature distribution analysis results of the CL-based HTS module coil is shown in figure 4. The temperature distribution in the HTS coils is shown in figure 4 (a). In the 2nd layer, the cold head temperature was 19 K, as shown in figure 4 (b). The temperature distribution in the supports of the CL-based HTS module coil is shown in figure 4 (c) and (d), respectively.

As a result, the temperature of the HTS coil was 19.8 K. In the 1st layer, the conduction heat load from supports was 14.3 W, and the radiation heat load was 4.9 W, the conduction heat load from the current leads was 31.8 W. The total heat load of the 1st layer was 51 W.

![Figure 4. Temperature distributions in the HTS coil and supports of the CL-based HTS module](image-url)
In the case of the 2\textsuperscript{nd} layer, the temperature of the shield was 63 W. The total heat load of the 2\textsuperscript{nd} layer was 27.3 W. Table 2 shows the simulation results of the total heat load of the CL-based HTS module coil.

| Items                                      | Values |
|--------------------------------------------|--------|
| Conduction heat load from the current lead | 31.8 W |
| Conduction heat load from the supports     | 14.3 W |
| Radiation heat load                       | 4.9 W  |
| Cooling power of the 1\textsuperscript{st} layer | 52 W   |
| Total heat load of the 1\textsuperscript{st} layer | 51 W   |
| Eddy current heat load                    | 15 W   |
| Conduction heat load from the 2\textsuperscript{nd} supports | 12.3 W |
| Cooling power of the 2\textsuperscript{nd} layer | 27.5 W |
| Total heat load of the 2\textsuperscript{nd} layer | 27.3 W |

4.2. Heat load analysis of the FP-based HTS module coil

Figure 5 shows the temperature distributions analysis results of the FP-based HTS module coil. The temperature distribution in the HTS coils is shown in figure 5 (a). Figure 5 (b) and (c) shows the temperature distributions of supports in both layers of the FP-based HTS module coil. Figure 5 (d) shows the temperature distribution in the cooling block of the FP-based HTS module coil.

![Temperature distributions in the HTS coil and supports of the FP-based HTS module](image-url)
As a result, the temperature of the HTS coil was 19.3 K. In the 1st layer, the conduction heat load from supports was 15.5 W, and the excitation load was 10.2 W; the radiation heat load was 4.7 W. The total heat load of the 1st layer was 30.4 W. In the 2nd layer, the total heat load was 27 W. The temperature of the shield was 58 K. The eddy current load was 15 W, and the conduction heat load from supports in this layer was 12 W. Table 3 shows the simulation results of the total heat load of the FP-based HTS module coil.

| Table 3. Results of the heat load analysis in the FP-based HTS module coil |
|-----------------|---------------------|---------------------|
| Items           | Values              |
| 1st layer       |                     |
| Excitation load | 10.2 W              |
| Conduction heat load from the supports | 15.5 W |
| Radiation heat load | 4.7 W |
| Cooling power of the 1st layer | 52 W |
| Total heat load of the 1st layer | 30.4 W |
| 2nd layer       |                     |
| Eddy current load | 15 W               |
| Conduction heat load from the 2nd supports | 12 W |
| Cooling power of the 2nd layer | 27.5 W |
| Total heat load of the 2nd layer | 27 W |

Table 4 shows the comparative analysis results of the heat load between the CL and FP. The total heat loads of CL and FP were 78.3 W and 57.4 W, respectively.

| Table 4. Comparative results of the heat load between the CL and FP |
|-----------------|---------------------|---------------------|---------------------|
| Heat load       | Items               | Flux pump     | Current lead     |
| 1st layer       |                     |               |                  |
| Excitation load/Conduction heat load from the current lead | 10.2 W | 31.8 W |
| Conduction heat load from the supports | 15.5 W | 14.3 W |
| Radiation heat load | 4.7 W | 4.9 W |
| Total heat load of the 1st layer | 30.4 W | 51 W |
| 2nd layer       |                     |               |                  |
| Eddy current load | 15 W               | 15 W          |
| Conduction heat load from the 2nd supports | 12 W | 12.3 W |
| Total heat load of the 2nd layer | 27 W | 27.3 W |
| Total heat load | 57.4 W              | 78.3 W        |

5. Conclusions
This paper discusses the structural design and heat load analysis of an FP-based HTS module coil for a 12 MW wind power generator. The conduction and radiation heat loads of the FP-based HTS coils were analyzed using a 3D finite element method program considering a two-stage cryo-cooler. The design procedure was performed at an operating temperature of 20 K, and the overall heat loss at each layer of the HTS module coil was less than the cooling capacity of each stage of the cryo-cooler. The results of the FP-based HTS coil of the generator were compared with the conventional CL-based HTS module coil. As a result, the temperature of the HTS coil of the FP-based HTS module was 19.3 K, and the total heat load was 57.4 W. The temperature of the HTS coil of the CL-based HTS module was 19.8 K and the total heat load was 78.3 W. The temperature of the FP-based HTS module coil was lower than that of the CL-based HTS module coil because the total heat load of the FP-based HTS module coil was smaller than that of the conventional CL-based HTS module coil. In conclusion, the FP-based HTS module was evaluated to be more advantageous in terms of better cooling capacity and thermal stability margins. The structural design and heat load analysis results of the FP-based HTS module coil can be effectively utilized in the development of large-scale HTS wind power generators.
Acknowledgments
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