3D electromagnetic design and electrical characteristics analysis of a 10-MW-class high-temperature superconducting synchronous generator for wind power

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Abstract

In this paper, the general electromagnetic design process of a 10-MW-class high-temperature superconducting (HTS) synchronous generator that is intended to be utilized for large scale offshore wind generator is discussed. This paper presents three-dimensional (3D) electromagnetic design proposal and electrical characteristic analysis results of a 10-MW-class HTS synchronous generator for wind power. For more detailed design by reducing the errors of a two-dimensional (2D) design owing to leakage flux in air-gap, we redesign and analyze the 2D conceptual electromagnetic design model of the HTS synchronous generator using 3D finite element analysis (FEA) software. Then electrical characteristics which include the no-load and full-load voltage of generator, harmonic contents of these two load conditions, voltage regulation and losses of generator are analyzed by commercial 3D FEA software.

Keywords: electrical characteristics, 2G HTS wire, HTS synchronous generator, magnetic field distribution

1. INTRODUCTION

There are some differences of electromagnetic design between conventional and superconducting generator because superconducting generator using the 2G HTS wire hasn’t shorter air gap and iron core structure of rotor and stator which prevent flux leakage to air-gap outside.

In case of conventional generator, because structure of machine consists of iron core which is used to concentrate the magnetic flux in large part except for winding space of coils, a results of magnetic field distribution has a nearly no difference between 2D and 3D electromagnetic design. However, in case of superconducting generator, the adversely effects of leakage flux which decrease the performance of generator can’t be ignored because superconducting generator without iron core structure has a much leakage flux than conventional generator. Therefore, to enhance the performance and reliability of generator system, 3D electromagnetic design including 3D magnetic field distribution should be necessarily performed.

In order to analyze more detailed characteristics of HTS generator, 3D FEA software is utilized to reduce the design errors which are caused by leakage flux due to the air-gap of over 50 mm and structure of air-core type. Moreover, we also consider the end part effect of HTS field coils which has a maximum magnetic flux density related to mechanical stability. In this paper, first of all, 2D conceptual electromagnetic design model of the HTS synchronous generator has been redesigned including the rotor and stator design after that 3D magnetic field distribution and operating current (I_{op}) analysis of HTS field coil which affect generator performance have been performed. Last but not least, steady state operation characteristics of generator during the rated operation have been analyzed by commercial 3D FEA software.

2. ELECTROMAGNETIC DESIGN AND ANALYSIS OF A 10-MW-CLASS HTS SYNCHRONOUS GENERATOR

2.1. Electromagnetic Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model I</th>
<th>Model II</th>
<th>Model III</th>
<th>Model IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output power (MW)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Rated output voltage (kV)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Field coil current (A)</td>
<td>207</td>
<td>207</td>
<td>207</td>
<td>207</td>
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<tr>
<td>HTS wire length (km)</td>
<td>1036</td>
<td>1158</td>
<td>1060</td>
<td>1635</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>96.71</td>
<td>96.78</td>
<td>96.61</td>
<td>97.69</td>
</tr>
<tr>
<td>Rotor pole</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Synchronous reactance (p.u)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Stator current density (A/mm²)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Weight (ton)</td>
<td>136</td>
<td>137</td>
<td>139</td>
<td>206</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>50.72</td>
<td>49.09</td>
<td>51.9</td>
<td>69.9</td>
</tr>
</tbody>
</table>

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TABLE I BASIC DESIGN MODELS OF THE 10-MW-CLASS HTS GENERATOR.
Table II presents some basic design proposals of a 10-MW-class HTS synchronous generator for wind power, which are designed by 2D numerical analysis method. Model I is selected in 2D conceptual electromagnetic-design taking into account 2G HTS wire length and efficiency, volume and weight of generator among the above design proposals in order to analyze the electrical characteristics of HTS wind generator [1].

Table II lists the design parameter specifications of the 10-MW-class HTS synchronous generator designed by 2D analytical design code and 3D FEA software, and the resulting conceptual design is displayed in Fig. 1. Direct drive train is adopted as drive train system of the 10-MW-class HTS generator in this design which has a low rotating speed of 10 rpm.

Generally, because of merit of compatibility between the generator and commercial power converter, generator design which has a high rated frequency by increasing the number of the generator poles is more economical. However, the weight and volume of generator are increased and efficiency of generator is reduced. Therefore, in order to achieve a compact volume, lighter weight and meet the minimum frequency of 2 Hz which is applicable to commercial power converter, the number of field pole is limited to a 24-pole when design HTS synchronous generator.

Table III shows materials used for electromagnetic design and weight of configuring part of the HTS generator. From calculation results of approximate weight of generator through the mass density property of materials used in each configuring part, total weight of generator is estimated at approximately 127.49 ton. A mechanical shield which accounts for the large volumes among configuring part of generator and a rotating shaft with a high mass density material for the mechanical strength of rotor take up about 65% of the generator weight. Also, the total volume of generator is calculated to 40.74 m³.

Fig. 1. Schematic diagram of the 10-MW-class HTS synchronous generator for wind power.
TABLE IV
SPECIFICATIONS OF THE 2G HTS WIRE.

<table>
<thead>
<tr>
<th>Conductor Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor type</td>
<td>(Gd,Y)BCO</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>0.16</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>6</td>
</tr>
<tr>
<td>Critical current [A] @77 K, SF</td>
<td>≥ 120</td>
</tr>
<tr>
<td>Critical tensile strength [MPa] @77 K</td>
<td>550 (longitudinal direction)</td>
</tr>
</tbody>
</table>

Fig. 3. Cross sectional view of air-core-type stator coils.

One HTS field pole for the 10-MW-class synchronous generator consists of eight layers of double-pancake (DP) coils with an insulating plate in between two pancake coils and is shown in Fig. 2.

The race-track-type HTS field coils are wound by the way of insulating winding method with electrical insulating layer of 0.027 mm. The width and thickness of the 2G HTS wire have 6 and 0.16 mm, respectively. Furthermore, the specifications of the 2G HTS wire manufactured by SuperPower Corporation used to design the HTS field coils are listed in Table IV. Minimum critical current value of the 2G HTS wire has over 120 A at the cooling temperature of 77 K in the self-field condition. 2G HTS wire includes the copper stabilizer of 0.1 mm thickness.

The length per pole of the 2G HTS wire, which is important for designing the superconducting rotating machine, is approximately 45 km. Furthermore, the total length of the 2G HTS wire is approximately 1077 km. Also, the number of winding per pole is 9602.

The stator is designed by an air-core stator manufactured by Fiber Reinforced Plastics (FRP) which is capable of high voltage of generator terminal by increasing the dielectric strength of stator. Stator winding type is double layer & full pitch and the total number of stator slots is 144. There are series winding of eight turns in each layer and cooling channel between stator slots of two layers as shown in Fig. 3. Three-phase armature coils of stator wound by flat type copper.

A relatively lower current density of stator increases manufacturing costs of generator because of increasing the amount of copper used for stator winding. On the other hand, it is possible to manufacture HTS generator that has a high efficiency by reducing the stator cooling loss. Therefore, stator current density is set at 3 A/mm².

In order to use Modular Multilevel Converter (MMC) system that has a high voltage level of 6 ~33 kV and can achieve the compact and economical wind turbine system by eliminating the grid-side step-up transformer, the rated output voltage of generator is designed to 6008 V [2].

2.2. Electromagnetic Analysis

Fig. 4. The magnetic flux density distribution on the central section of the straight part of HTS field coil: (a) perpendicular direction and (b) parallel direction.

Fig. 5. The magnetic flux density distribution at the curve part of HTS field coil: (a) composite value, (b) radial (perpendicular) and (c) parallel direction.
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Fig. 6. Distribution of electromagnetic force at the curve part of the race-track-type HTS field coil.

Fig. 7. The characteristic curve of the 2G HTS wire in perpendicular direction.

Fig. 4 shows the 3D magnetic field distribution of (a) perpendicular and (b) parallel direction on the central section of the straight part of HTS field coil calculated from the 3D FEA software. The maximum magnetic flux density of the perpendicular and parallel direction reaches about 5.83 T in a single-pancake (SP) coil in the 1st and 16th layer, 9.38 T in SP coil in the 7th layer, respectively.

We also investigated the magnetic field distribution of the parallel direction at the curve part of HTS field coil as shown in Fig. 5. As results of the maximum magnetic flux density analysis, the composite value, radial and parallel directions are 11.38, 5.46 and 11.15 T, respectively.

Consequently, the results of the 3D magnetic field distribution analysis show that the maximum value of the perpendicular and parallel magnetic field that determines a critical current and the Lorentz force are approximately 5.83 T and 11.15 T, respectively.

Fig. 6 shows the distribution of electromagnetic force which is related to mechanical stress. From the direction of the HTS wire width (ab-plane), the Lorentz force generated in the HTS field coil caused by the magnetic field in the parallel direction (B//ab) creates a radial stress and hoop stress along the curve parts HTS field coil. Additionally, the compressive force acts as a shear stress because of the perpendicular (B//c) magnetic field [3]. Lorentz force (F_r) acts as a radial direction at the curve part of HTS field coils because of maximum value of parallel magnetic flux density (11.15 T) as shown in Fig. 6.
Fig. 7 shows the in-field property of 2G HTS wire used to calculate the operating current of HTS field coils for 10-MW-class HTS generator [4]. HTS wire has the critical current ($I_c$) properties which depend on various operating temperatures of HTS wire and various directions of magnetic flux density affecting HTS wire surface. Because the critical current of HTS wire is decreased by magnitude of magnetic field in perpendicular direction as shown in Fig. 7, it is necessary to calculate the critical current of HTS wire for designing the reliable HTS field coils.

Because the operating temperature of the 10-MW-class HTS generator is targeted from around 40 to 30 K, in-field property of 40 and 30 K in Fig. 7 and also magnetic field of perpendicular direction in Table V used to calculate the critical current of HTS wire. As a result of magnetic field distribution analysis, since maximum magnetic flux density of the perpendicular direction is generated at the straight parts of HTS field coil, critical current is calculated on basis of that of straight.

Fig. 8 and Fig. 9 represent critical current characteristics curve based on in-field property of 40 and 30 K, respectively. In case of operating temperature in 40 K, critical current of each SP coil varies from 266 to 563 A. Because maximum magnetic flux density of the perpendicular direction is generated at 1SP coil, the lowest critical current is calculated in SP coil in the 1st layer. Operating current of HTS field coils is set to 232 A which reaches about 87% of critical current. This value isn’t a sufficient level to operate HTS field coil in the transient state which has a potential to create a quench.

Therefore, operating temperature of HTS generator is needed to be decreased in order to have a stability margin of operating current. Also, in case of using the equal HTS wire, operating current can be selected based on 266 A which is critical current of SP coils in the 1st and 16th layer. Meanwhile, in order to increase efficiency of using wire and reduce the manufacturing cost of HTS field coils, it is necessary to choose optimized wire according to the critical current in each SP coils. Especially, in case of SP coil in the 9th layer, efficiency of using wire is lower because operating margin ($I_{op}/I_c$) is approximately 2.4 which means that critical current of SP coil in the 9th layer has 2.4 times greater than operating current of HTS field coil.

In case of operating temperature in 30 K, 432 A of critical current in SP coil in the 16th layer has 1.8 times greater than 232 A of operating current of HTS field coil. Although this value is considered to have high operating reliability so that efficiency of using wire is lower. It is concluded that to set operating temperature in 35 K levels is reasonable design.

3. ELECTRICAL CHARACTERISTICS ANALYSIS OF A 10-MW-CLASS HTS SYNCHRONOUS GENERATOR

Fig. 10 shows magnetic flux density distribution of the 10-MW-class HTS synchronous generator during the rated operation (field current of 232A, rotation speed of 10 rpm and rated load resistance). Maximum magnetic flux density in HTS field coil is 11.38 T and the maximum magnetic flux density in radial direction ($B_r$) at the central points of double-layer armature windings in circumferential direction which directly affects to output performance of HTS generator is approximately 1.8 T.
Fig. 11 shows no-load and full-load terminal voltage waveform at the three-phase armature winding. The root mean square (RMS) values of no-load and full-load phase voltage are 3495 V and 3469 V, respectively.

Because the harmonic components included in electrical output power causes increasing noise, vibration and electrical losses of the generator and cost of the Power Conversion System (PCS), harmonics contents of electrical output power such as output voltage and load current must be considered in the design step [5]. Total Harmonic Distortion (THD) is defined as the ratio of sum of RMS values of the harmonic components to RMS value of fundamental component and used to calculate the harmonics contents.

Fig. 12 shows results of Voltage Total Harmonic Distortion (VTHD) of no and full-load phase voltage. As results of VTHD for no-load voltage, A, B and C phase are 2.3, 2.9 and 1.9%, respectively, and are obtained lower levels of harmonics components which make sinusoidal waveform of HTS generator electrical output as shown in Fig. 11. Those values do not pass PCS so VTHD can be improved.

In case of air-core type HTS generator, these results are attributed to the characteristics of the non-harmonic components due to without iron core which saturates the magnetic flux in stator slots. Therefore, superconducting generator can reduce the noise, vibration and electrical losses and increase economic efficiency of wind turbine including the PCS through elimination of harmonics.

Table VI summarizes some results of the electrical characteristics analysis, which is computed by full-load analysis. Output power capacity per each phase and total output power of HTS generator is approximately 3.3 and 10.02 MW, respectively. Also, average value of the voltage drop in three-phase is calculated as 126 V.

The voltage regulation of the generator means the degree of changes in the terminal voltage due to the application of loads on the generator and is expressed by (1)

\[
e = \frac{V_O - V_n}{V_n} \times 100 \% \tag{1}
\]

where \(e\), \(V_O\) and \(V_n\) are the voltage regulation, no-load, and full-load terminal voltage, respectively.

One of the ideal characteristics of generator is voltage stability which is to provide a constant voltage from generator to power systems regardless of load changes. In other words, the voltage stability increases as the voltage regulation becomes smaller [6]. It is difficult to reduce the voltage regulation less than 15% even with additional excitation control of the field coil so that voltage drop of conventional synchronous generator is large according to the load conditions because of large synchronous reactance (about 1.0 p.u). However, since synchronous reactance of HTS generator in this design is 0.1 p.u, voltage regulation is a relatively low levels as 3.65% with resistance load. This value is a below level of that of 5% without excitation controls and does not pass PCS [7]. Therefore, it is concluded that the margin for improvement of voltage regulation remains.

Table VII lists generator loss analysis results. The total loss of generator is calculated to approximately 382.5 kW and the armature copper loss reaches almost 93% of the total loss of generator and is about 356 kW.

Since three-phase output power of the 10-MW-class HTS generator, which is computed by above electrical characteristics analysis in Table VI is approximately 10.02-MW, generator efficiency is calculated as about 96.326% from a commercial efficiency of generator.

### 4. CONCLUSIONS

This paper has discussed the general electromagnetic design process of a 10-MW-class HTS synchronous generator. Electromagnetic design model regarded to suitable designs of 10 MW class HTS generator is selected and analyzed to consider the practical considerations such as HTS wire length, efficiency, volume and weight of machine.

With the dramatically development on 2G HTS wire production by 2020 to achieve economical price level of manufacturing cost for large scale wind generator compared to conventional generator, it is estimated that the production capacity will be increased 36 times, whereas the manufacturing cost will be decreased 10 times [8]. As consequently, total estimation of 1077 km 2G HTS wire length in order to manufacture the field coil of 24 poles for
10-MW-class HTS generator is certainly economically suitable for fabricating with the acceptable price level. Generator efficiency considering the electrical losses and mechanical loss was approximately 96.3% and volume and weight of generator related to wind turbine construction in economic and technical aspects were estimated to 127.45 ton, 40.74 m³, respectively.

As results of electrical characteristics analysis of HTS generator, THD and voltage regulation of generator were 2.36 and 3.65%, respectively. We will be conducting the additional study considering detailed design of HTS field coils including structural and thermal design. In addition, cryogenic system which is currently being developed and studied will be applied to design superconducting generator system.

ACKNOWLEDGMENT

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REFERENCES


