Designs of 10 MW Air-core and Iron-core HTS Wind Power Generators

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Abstract – High Temperature Superconducting (HTS) synchronous generators can be designed with either an air-core type or iron-core type. The air-core type has higher efficiency under rated rotating speed and load than the iron-core type because of the iron losses which may produce much heat. However, the total length of HTS wire in the air-core type is longer than the iron-core type because the generated magnetic flux density of the air-core type is low. This paper deals with designs of 10 MW air-core and iron-core HTS wind power generators for wind turbines. Fully air-core, partially iron-core, and fully iron-core HTS generators are designed, and various stator winding methods in the three HTS generators are also considered, such as short-pitch concentrated winding, full-pitch concentrated winding, short-pitch distributed winding, and full-pitch distributed winding. These HTS generators are analyzed using a 3D finite elements method program. The analysis results of the HTS generators are discussed in detail, and the results will be effectively utilized for large-scale wind power generation systems.

Keywords: Direct-driven, Offshore wind power, Superconducting generator, Superconducting wire, Wind power generation

1. Introduction

Offshore wind power capacity contributed 470 MW to worldwide installations of wind power in 2011. The total installed capacity of offshore wind power from January of 2012 to October of 2012 was 1,314 MW. Offshore wind farms are currently under construction in Belgium, Denmark, Germany, the UK, China, Korea, and Japan with a total expected capacity upon completion of nearly 100 GW. The average annual growth rate for new installations is expected to be 81.8% until 2016 [1].

A direct-drive type high temperature superconducting (HTS) synchronous generator has a smaller physical size and a higher power density per volume ratio than conventional generators. Because of these advantages, HTS generators are becoming an interesting solution to the need for large scale wind turbines [2-4]. The HTS generators can be designed with either an air-core type or iron-core type. The air-core type has higher efficiency under rated rotating speed and load than the iron-core type because of the iron losses that can produce a significant amount of heat. However, the total length of the HTS wire in the air-core type is longer than the iron-core type because the generated magnetic flux density of the air-core type is low [5-7].

The main objective of this paper is to design 10 MW air-core and iron-core HTS wind power generators which are

the fully air-core, partially iron-core and fully iron-core generators to find an optimal design for large-scale wind power generation systems. The various stator winding methods of the HTS generators are also considered for more details of the optimal design, such as short-pitch concentrated winding (SCW), full-pitch concentrated winding (FCW), short-pitch distributed winding (SDW), and full-pitch distributed winding (FDW). The magnetic field distribution of the HTS generators is analyzed using a 3D finite elements method (FEM) program.

The most efficient design, the fully iron-core HTS generator with FDW, is recommended considering all items such as torque ripple, efficiency, volume, weight, and total length of HTS wire. The analyzed results will be effectively utilized for large-scale wind power generation systems.

2. Basic Design of the 10 MW HTS Generators

2.1 HTS wire and iron-core properties

The thickness, width, and minimum bend diameter of the HTS wire are 0.1 mm, 4 mm, and 11 mm, respectively. The detailed specifications of the engineering critical current density versus the perpendicular magnetic field of the HTS wire at the operating temperature are referred from SuperPower Inc. [8]. The iron cores in the three types of generators are exposed to a high magnetic field. The material of iron cores such as in the magnetic shield, rotor body, or stator body is M-27.

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(a) B-H curves of a relatively low magnetic field

(b) B-H curves with a high magnetic field

Fig. 1. The magnetic curves of the iron-core and air-core

Iron manufacturers generally provide the magnetic properties under 2 T. In the range of the significantly high magnetic field over the saturation magnetic field of iron-core, the magnetic properties of iron-core should be defined [9, 10].

Fig. 1 shows the nonlinear magnetization curve (B-H curve) and relative permeability of M-27 and the linear magnetization curve of air-core.

2.2 Three types of the HTS generators

The three types of HTS generators consist of an HTS rotor coil, rotor body, vacuum vessel, stator copper coil, and stator body. Among the three types, the fully air-core type, which contains a rotor body and a stator body, uses nonmagnetic material such as stainless steel and fiber reinforced plastics. The magnetic shield in the fully air-core type uses magnetic material such as laminated silicon steel (M-27). The partially iron-core type with a stator body and a rotor body consists of M-27 and SUS304. In the case of the fully iron-core type, M-27 is used in the rotor body and the stator body. Fig. 2 shows the configurations of the fully air-core type HTS generator and iron-core type HTS generators. The partially iron-core type

(a) Fully air-core HTS generator

(b) Iron-core HTS generators

Fig. 2. The configurations of the HTS generators

Table 1. Basic design specifications of the 10 MW class HTS generators

Specifications	Value
Rated output power	10.5 MW
Rated line-to-line voltage	6.6 kV
Rated armature current	918.5 A
Rated rotation speed	10 rpm
Rated torque	10 MNm
Operating temperature	20 K
Num. of rotor poles	24
Num. of DPC layers	5

and the fully iron-core type have the same configuration.

The basic design specifications of HTS generators in wind power systems are shown in Table 1. The drive-train of the HTS generators is the direct-drive type, and the space factors of the HTS rotor coil and stator copper coil are 0.8 and 0.5, respectively. The HTS rotor coil is a racetrack type double pancake coil (DPC), and the current density of stator copper coil considering water cooling is 6 A/mm². The air gap length and effective length of DPC are 20 mm and 500 mm.

3. Detailed Designs of the HTS Generators Considering Stator Winding Methods

The stator winding methods are divided into a single layer and a double layer winding. The single layer winding

has one coil side per slot, while the double layer winding has two coil sides per slot. The double layer winding can be classified as a full-pitch or a short-pitch winding.

When the two coil sides of the stator coil are 180 electrical space degrees apart, the winding is the full-pitch winding method, such as FCW or FDW. When the two coil sides of the stator coil are less than 180 electrical space degrees apart, the winding is the short-pitch winding method, such as SCW or SDW.

In the case of SCW and FCW, the number of slots is 72 due to the concentrated winding i.e. one slot per pole per phase. In HTS generators with SDW and FDW, the number of slots is 144 due to the distributed winding, with two slots per pole per phase.

Fig. 3. Winding diagrams of the HTS generators

Table 2. Control parameters of the 10 MW HTS generators

Fully air-core type				
Stator winding	SCW	FCW	SDW	FDW
Operating current (A)	106	106	106	106
Turns of DPCs	1,350	1,260	1,287	1,260
Num. of stator slots	72	72	144	144
Turns of stator coils	50	50	25	25
Partially iron-core type				
Stator winding	SCW	FCW	SDW	FDW
Operating current (A)	109	109	109	109
Turns of DPCs	1,000	975	980	975
Num. of stator slots	72	72	144	144
Turns of stator coils	50	50	25	25
Fully iron-core type				
Stator winding	SCW	FCW	SDW	FDW
Operating current (A)	104	104	104	104
Turns of DPCs	920	920	923	923
Num. of stator slots	72	72	144	144
Turns of stator coils	50	50	25	25

Fig. 3 shows the winding diagrams of the HTS generators. The magnetic field effects of the generators are different from each stator winding method. Hence, the control parameters of each generator should be controlled to generate the rated line-to-line voltage. Table 2 shows the control parameters of the HTS generators. The operating currents apply a 20% safety margin of critical currents in the superconducting field coils.

4. Simulation and Comparative Analysis

4.1 FEM analysis results of the HTS generators

The 1/24 models for the 10 MW HTS generators are designed in detail and simulated using 3D FEM tool. Table 3 shows the total harmonic distortion (THD) values of the HTS generators.

The voltage THD while powering 100% resistive load of a synchronous machine must be less than 5% [11]. Therefore, all designs are appropriate to standard IEC 60034-1 conditions.

Table 3. THD values of the three types of 10 MW HTS generators

Stator winding	SCW	FCW	SDW	FDW
Fully air-core type (%)	0.51	0.49	0.45	0.18
Partially iron-core type (%)	3.75	3.05	1.67	1.87
Fully iron-core type (%)	3.20	3.10	2.00	3.01

Table 4. Losses and efficiencies of the 10 MW HTS generators

Fully air-core type				
Stator winding	SCW	FCW	SDW	FDW
Stator coil (kW)	154	154	154	154
Stator body (kW)	-	-	-	-
Vacuum vessel (kW)	2.88	2.21	1.02	0.92
Rotor body (kW)	-	-	-	-
Windage loss (kW)	0.17	0.17	0.17	0.17
Total loss (kW)	157.1	156.4	155.2	155.1
Efficiency (%)	98.50	98.50	98.50	98.50
Partially iron-core type				
Stator winding	SCW	FCW	SDW	FDW
Stator coil (kW)	154	154	154	154
Stator body (kW)	9.1	6.75	7.80	7.13
Vacuum vessel (kW)	72	38.4	21	20
Rotor body (kW)	-	-	-	-
Windage loss (kW)	0.15	0.14	0.14	0.14
Total loss (kW)	235	199	183	181
Efficiency (%)	97.76	98.10	98.26	98.28
Fully iron-core type				
Stator winding	SCW	FCW	SDW	FDW
Stator coil (kW)	154	154	154	154
Stator body (kW)	8.21	6.71	7.74	7.19
Vacuum vessel (kW)	42	30	12	12
Rotor body (kW)	0.42	0.42	0.42	0.42
Windage loss (kW)	0.14	0.14	0.14	0.14
Total loss (kW)	204.8	191.3	174.3	173.8
Efficiency (%)	98.05	98.05	98.05	98.05

The torque ripple is an important property to consider when designing a rotating machine. A lower torque ripple is required to minimize the vibrations and noise of the machine, and to maximize the lifetime of the machine.

The torque ripple depends on the stator winding methods, slot shapes of stator, and so on. In this paper, the torque ripples of HTS generators are only analyzed using stator winding methods. Fig. 4 shows the electromagnetic torque waveforms of three types of HTS generators. The torque ripples of the fully air-core types are lower than the partially iron-core types and fully iron-core types because the magnetic field of the stator parts in fully air-core types is uniformly distributed. Of the iron-core types, the partially iron-core type with SDW and the fully iron-core

(a) Fully air-core types

(b) Partially iron-core types

(c) Fully iron-core types

Fig. 4. Electromagnetic torque waveforms of the HTS generators

(a) Maximum magnetic field

(b) Perpendicular magnetic field

Fig. 5. Magnetic field values of the HTS generators

type with FDW have the lowest values of torque ripples. An optimal design of stator slot shape will be required to reduce the torque ripple in the future.

The HTS wire is influenced by the perpendicular magnetic field because the shape of the HTS wire is the tape type. Therefore, the operating current is selected by the value of the perpendicular magnetic field. The values of the maximum magnetic field and perpendicular magnetic field of the HTS generators are illustrated in Fig. 5.

Table 4 represents the losses and efficiencies of the HTS generators. The stator coil losses of each stator winding type are equal due to the same total stator coil area. The efficiencies of fully air-core types are the highest at about 98.5%, and the efficiencies of fully iron-core types are a little lower than the partially iron-core types due to the iron loss of rotor body.

4.2 Comparative analysis of the HTS generators

The HTS generators must be designed to use the least possible amount of HTS wire because the cost of the wire accounts for a substantial proportion of the manufacturing cost. However, in order to design the overall wind power system, the weight and volume of the HTS generators must also be considered. Fig. 6 shows the total length of the HTS wire and the volume and weight of generators. The volume and total length of the HTS wire in the fully iron-core type generators with SCW and FCW are the smallest

Fig. 6. Total length of the HTS wire, volume and weight of the 10 MW HTS generators

Table 5. Specifications of the 10 MW fully iron-core type generator with FDW

Specifications	Value
Rated power (MW)	10.5
Rated output voltage (kV)	6.6
Rotating speed (rpm)	10
Axial length (m)	0.5
The number of poles	24
Turns of DPC	923
Total length of HTS wire (km)	390
Operating current (A)	104
Maximum magnetic field (T)	7.90
Perpendicular magnetic field (T)	7.25
Stator winding method	FDW
The number of stator slots	144
Turns of copper coil	25
Air-gap length (mm)	20
Diameter of SCSG (m)	5.33
Volume of SCSG (m³)	24.09
Active weight of SCSG (ton)	104.6

and shortest. The weight of the fully air-core type generators with FCW and FDW are the lightest because the mass density of the nonmagnetic material is lower than the magnetic material.

All items considered, the design of fully iron-core type generator with FDW is recommended for the 10 MW class wind power system because weight and volume of three types of the generators are not significantly different, however, the total length of the HTS wire shows a huge difference over 200 km between the fully air-core types and fully iron-core types. Among the stator winding methods of fully iron-core types, FDW has the lowest torque ripple.

Table 5 shows the specifications of the 10 MW fully iron-core type generator with FDW. The maximum magnetic flux density of the fully iron-core type generator with FDW is about 7.89 T at HTS field coil as depicted in Fig. 7, and the Fig. 8 shows the magnetic flux density of HTS rotor coil in fully iron-core type generator with FDW.

Fig. 7. Magnetic flux density of 1/24 model of the 10 MW fully iron-core type generator with FDW

Fig. 8. Magnetic flux density of 1/2 model of rotor coil in the 10MW fully iron-core type generator with FDW

5. Conclusion

This paper deals with designs of large scale air-core and iron-core HTS wind power generators to reduce their weight and volume and the total length of HTS wire. The three types of HTS generators such as fully air-core, partially iron-core, and fully iron-core are designed considering the various stator winding methods. As a result, the THD values of the HTS generators are less than 5%, and the torque ripple of air-core type HTS generator with FDW is the lowest. In the case of the partially iron-core type with SDW and fully iron-core type with FDW, the torque ripples of these stator winding methods are lower than other stator winding methods. The efficiencies of the three types of HTS generators are 98% similar to each other. The volume and total length of the HTS wire in the fully iron-core type generators with SCW and FCW are the smallest and shortest. The fully air-core type generators with FCW and FDW are the lightest in weight. All items considered, the design of fully iron-core type HTS generator with FDW is recommended for the 10 MW class wind power system. The results will be effectively utilized to design a large-scale HTS generator for wind power systems.

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