Electromagnetic Design of 10 MW Class Fully Superconducting Wind Turbine Generator

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***Abstract* — We have studied a 10 MW class fully superconducting synchronous machine for direct-drive wind turbine generators. This machine has been designed using two kinds of superconducting wires. Multifilament MgB_2 wires have been used for armature windings. The DC field coils of the machine rotor are made of HTS tapes. Electromagnetic design of the generators has been carried out by FEM analysis. Analysis results show that 10 MW output is achievable with less use of HTS tapes than wind turbine generators having superconducting field coils and copper armature windings. Then, calculated AC losses are low.**

***Keywords* — Wind Turbine Generators, Fully Superconducting Generators, AC Losses, FEM Analysis**

I. INTRODUCTION

With the increasing need for renewable energy sources in the world, the capacity of wind turbine generators has increased up to 7.5 MW [1], and also there are some plans for 10 MW class generators. However, the generator's mass and size increase with the generator capacity, so that the diameter of a 10 MW class wind generator with permanent magnets would be 10 m [2]. To solve this problem, compact and high-power density wind turbine generators are required. High-temperature superconducting (HTS) technology is one of the solutions for this problem. Wind generators using superconducting field magnets have recently been studied in the world [3]-[7].

We proposed 10 MW class fully superconducting synchronous machines for direct-drive wind generators. These machines will be operated at low speed and therefore superconducting wires could be used on the stator side subjected to low-frequency magnetic fields. Fully superconducting generators have been designed using two kinds of superconductors. In the stator part, it is very important to consider AC losses in armature windings. Multifilament MgB_2 wires could be used to reduce AC losses of the armature windings. DC field coils of the rotor should be made of HTS tapes such as Bi or YBCO type superconductors, which have good mechanical properties and J_c-B characteristics even in a high magnetic field.

This paper shows an electromagnetic design of the fully superconducting wind turbine generator. Finite element method (FEM) analysis has been performed to evaluate this generator with the initial constraints on the machine diameter and the operating temperature. This wind turbine generator is designed with changing maximal flux density, B_{max}, at armature windings. Then, generator characteristics, quantity of superconductors, and no- load AC losses are evaluated.

II. DESIGN OF 10 MW CLASS FULLY SUPERCONDUCTING WIND TURBINE GENERATOR

A. Design Conditions

Fig.1 shows the conceptual design of the fully superconducting wind generator using two kinds of superconductors. It means that the field coils are made of

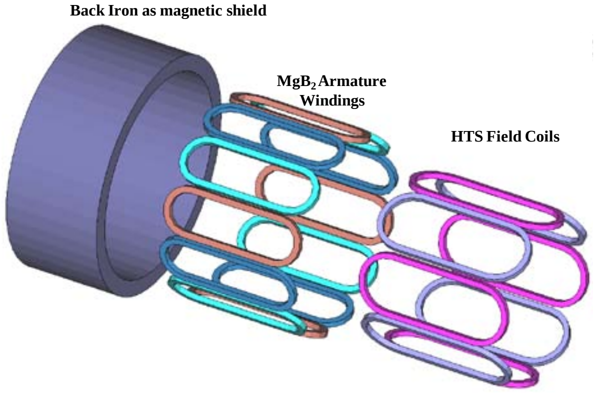

Fig. 1. Illustration of fully superconducting wind turbine generator.

TABLE I INITIAL Design CONDITIONS OF THE FULLY SUPERCONDUCTING WIND TURBINE GENERATOR

Output	10 MW
Rated voltage	3.3 kV as line-to-line voltage
Rated current	1.75 kA as line current
Rated revolutions	10 rpm
Operating temperature	20 K
Diameter	3.67 m
Effective Length	1.5 m

HTS tapes and MgB_2 wires are used as three-phase armature windings. 10 MW class is the challenging target for this study. Table I represents design conditions of this generator. Rated speed is 10 rpm for low speed and very high torque design. This design permits us to use superconductors into the stator side in alternating magnetic field condition. Rated voltage is 3.3 kV line-to-line. 20 K is chosen as the operating temperature for good performance of two kinds of superconductors. Then, conduction cooling system is considered. The generator diameter is chosen as 3.67 m to allow comparison with conventional superconducting wind generators [7]. Back iron is required as magnetic shield. The aim of this design is to realize 10 MW class fully superconducting wind generators with less use of HTS tapes than wind generators having superconducting field coils and copper armature windings. In the following, generators A, B, and C are designed as a function of the maximal flux density, B_{max}, at MgB_2 armature windings.

B. Armature Windings with MgB_2 Multi Filament Wires

Firstly, armature conductors should be designed. Armature windings are designed as concentrated winding structure because of mechanical properties of MgB_2 wires and simple stator structure. Table II shows the specifications of MgB_2 windings introduced by Togano's group in 2010 [8]. This wire has 19 filaments and a hollow cylinder structure. The critical current density, J_c, of this wire varies between 2.0×10^9 A/m^2 at 2.0 T (20 K) and 1.5×10^9 A/m^2 at 3.0T (20 K). We have estimated current capacity in this conductor for the rated line current 1.75 kA. Table III shows the armature conductor specifications. Load factor, 0.8, and packing factor, 0.5, were considered. The current capacity decreases with the increase of B_{max}. Therefore, the cross section of the conductor is expanded.

C. Field Coils with HTS Tapes

Field coils are designed as racetrack structure. HTS tapes are suitable for fabricating field coils. The progress in manufacturing technology made possible good mechanical properties and J_c-B characteristics. Current density is set as 1.68×10^8 A/m^2 in 20 K. B_{max} at field coils should be reduced to less than 9.0 T for easier design of supporting structure of field magnets. The quantity of HTS tapes depends on B_{max} at MgB_2 armature windings. In other words, the low B_{max} leads to less use of HTS tapes. Then good margin can be obtained at the point of J_c-B characteristics. On the other hand, low magnetic flux generated by field coils causes the increase of armature winding length for obtaining the rated voltage. Then AC losses can be increased. Designing superconducting field coils is a trade-off between these considerations.

TABLE II SPECIFICATIONS OF MgB_2 WINDINGS [8]

Diameter	1.3 mm
Number of filaments	19
Outer filament radius R_o	37.5 μm
Inner filament radius R_i	25 μm

TABLE III SPECIFICATIONS OF MgB_2 ARMATURE CONDUCTORS FOR THREE KINDS OF GENERATORS

Generator	A	B	C
B [T]	2.0	2.5	3.0
J_c [A/m^2]	2.00×10^9	1.75×10^9	1.50×10^9
Load factor	0.8	0.8	0.8
Packing factor	0.5	0.5	0.5
Pellarel Number of conductors	34	38	44
Dimension [mm × mm]	9.5×9.5	10.0×10.0	10.8×10.8

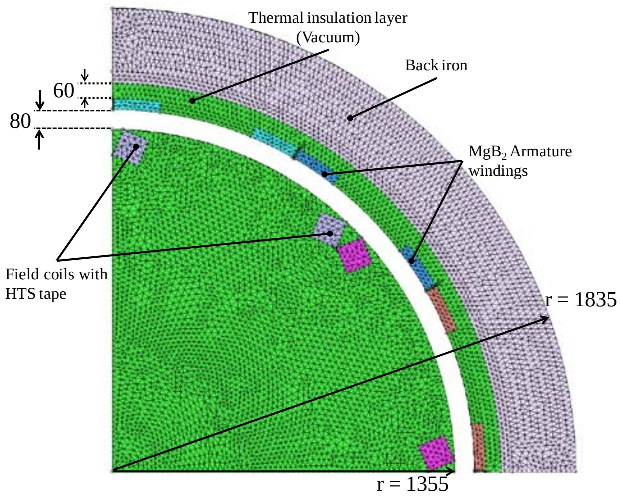

Fig. 2. 2D FEM analysis model for 8-pole fully superconducting wind turbine generator (1/4 model, unit: mm).

III. GENERATOR CHARACTERISTICS WITH FEM ANALYSIS

A. FEM Analysis Models

2D FEM analysis has been carried out ignoring coils end effects. Three kinds of generator models are designed by means of values in Table I and III. Fig. 2 represents the FEM analysis model for the fully superconducting wind turbine generator. For the calculation time reduction, 1/4 model is used. 8-pole has been chosen aiming at AC losses and the length of superconductors. Air gap is set to 80 mm. The fully superconducting generator can be expected to have a reduced mechanical air gap between field coils and armature windings. In this design, we assumed that a 20 % gap reduction is possible in comparison with generators using superconducting field coils and copper armature windings. A thermal insulation layer of 60 mm between the back iron and the armature windings is also considered. The thickness of the back iron is defined so that the strength of the leaked magnetic flux density at 1836 mm is around 0.5 T.

B. Analysis Resuls

Fig.3 shows the output voltage waveforms of three designed generators. Solid and dot lines refer to loaded and no-load voltages respectively. Both waves include harmonics because of the geometrical structure of armature windings. Table IV represents generator characteristics. Each generator satisfies the initial design conditions shown in Table I. 10 MW was obtained successfully with the fundamental wave. Fig. 4 shows maximal flux density at field coils, armature windings, and back irons. We should underline that B_{max} = 5.7 - 8.1 T at the field coils of the three generators is obtained. It can be helpful for designing supporting structure of the superconducting field magnets. Fig. 5 represents the total length of the two kinds of superconductor wires. The quantity of the two wires varies inversely because of changing number of armature windings. In case of generator A, HTS tapes and MgB_2 wires are about 270 km and 275 km respectively. Even generator C requires around 450 km HTS tapes. On the other hand, wind generators having superconducting field coils and copper armature windings require 572 km HTS tapes for field coils [7]. These results imply that the fully superconducting wind turbine generator can realize 10 MW with less use of HTS tapes than conventional superconducting generator.

However, less use of HTS tapes means that many MgB_2 armature windings are required to obtain rated voltage of 3.3 kV line-to-line. The number of the armature windings turns for the generator A is almost twice as much as that of the generator C. Therefore AC losses for the MgB_2 armature windings should be evaluated.

C. Evaluation of AC Losses

The evaluation of AC losses is one of the most important factors for the fully superconducting generator design. We have calculated AC losses, $P_{AC\ loss}$, in no load condition. $P_{AC\ loss}$ is assumed like (1).

$$P_{AC\ loss} = f \times L \times Q \qquad (1)$$

f (Hz) is the frequency of rotational magnetic field. This value depends on the rated speed and the pole number of generators. L (km) is the total length of the armature windings. Q (J/m/cycle) represents the AC loss per wire length and a cycle. Then, Q is calculated with reacted layer; S, filament number; n, and q shown in (2). The AC loss density of a hollow cylinder, q (J/m^3/cycle), is expressed like (3) [9]. It is proportional to R_o, B_o, and J_c. Fig. 6 shows an MgB_2 superconductor filament cross section in applied magnetic field; B_o. This model is based on the Bean model.

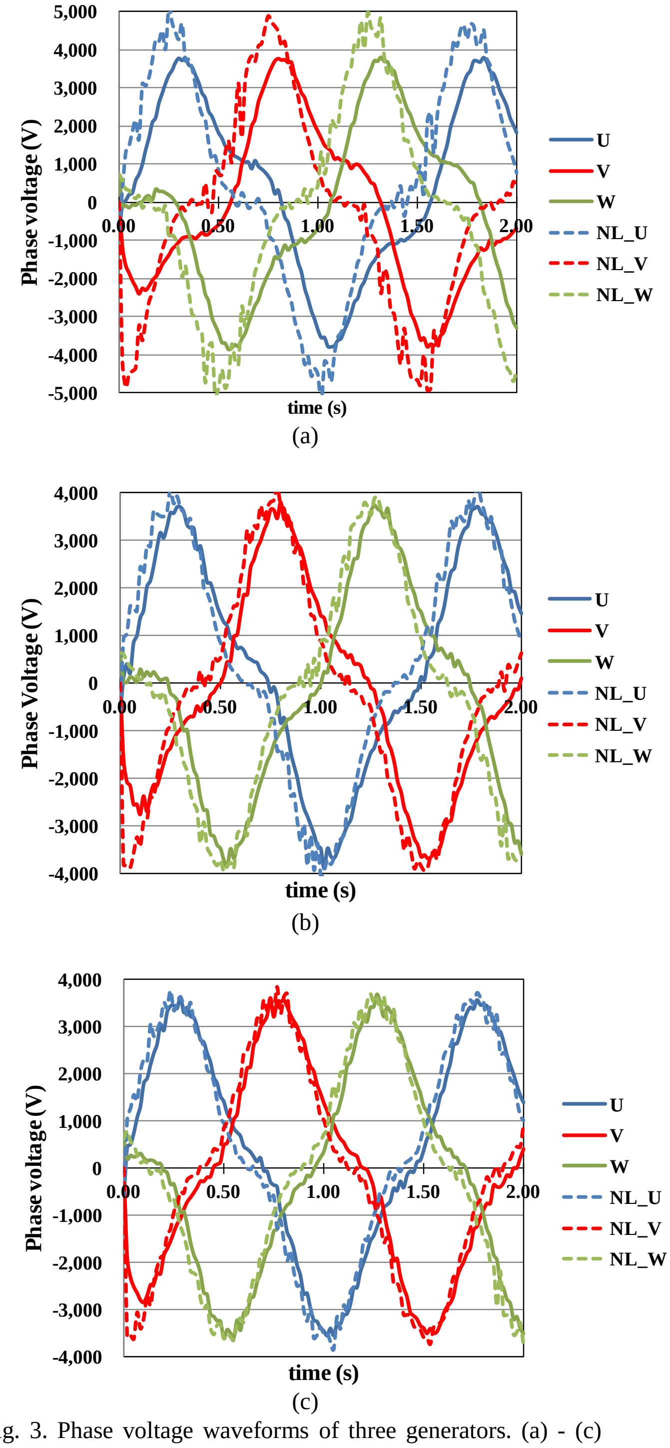

Fig. 3. Phase voltage waveforms of three generators. (a) - (c) represents generator A, B, and C respectively. “NL” in graphs means “No Load”.

TABLE IV FEM ANALYSIS RESULTS FOR THREE KINDS OF FULLY SUPERCONDUCTING WIND TURBINE GENERATORS

Generator	A	B	C
Output [MW]	10.0	10.2	10.3
Line current [kA]	1.76	1.77	1.78
Line-to-line Voltage [kV]	3.31	3.33	3.34
Power factor		0.99	
Field coils			
Current density [A/m^2]		1.68×10^8	
Total current [MA]	1.18	1.54	2.00
Armature windings			
Number of turn	150	92	68
Back iron			
Thickness [mm]	250	285	297
Weight [tons]	31.7	35.7	37.1

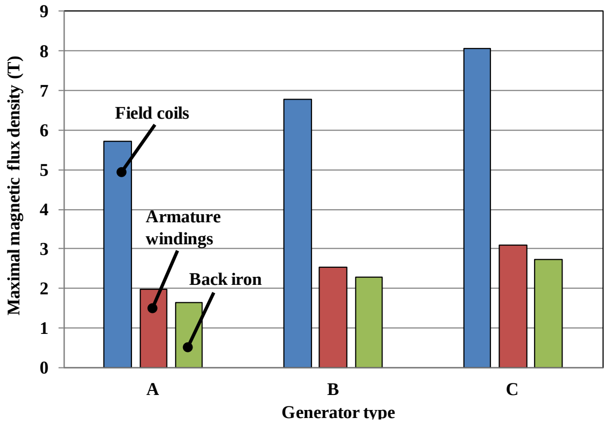

Fig. 4. Maximal flux density at field coils, armature windings, and back irons.

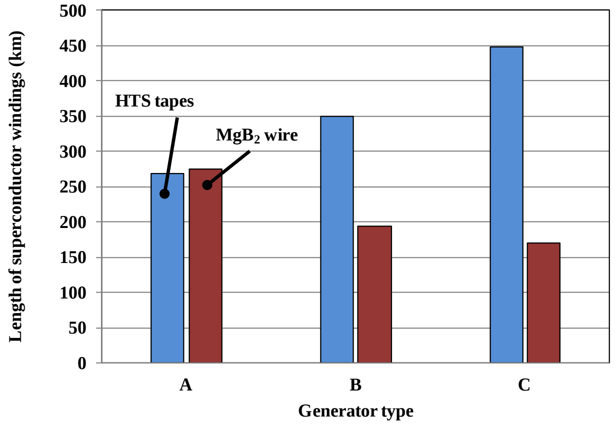

Fig. 5. Total length of two superconductor windings for three kinds of generators.

$$Q = q \times S \times n \tag{2}$$

$$q = \frac{16}{\pi} B_o R_o \left\{ J_c \left[1 - \left(\frac{R_i}{R_o} \right)^3 \right] \right\} \tag{3}$$

Table V shows the AC loss estimation results. These losses are calculated with the values in Table II. Generator B and C were around 1.1 kW. 1.52 kW of generator A causes the increase of the quantity of MgB_2 windings. The frequency f contributed to low AC loss. These results show the merit of using the MgB_2 superconductors for armature windings. The AC losses can be further reduced by optimizing armature windings design.

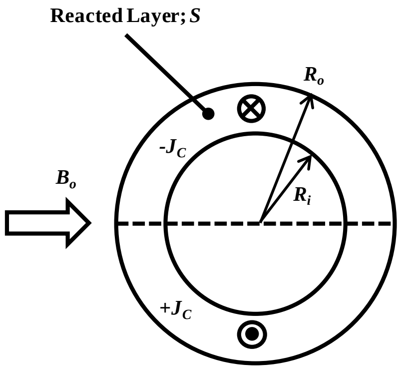

Fig. 6. Cross section of a fully penetrated MgB_2 filament by applied magnetic field; B_o.

TABLE V EVALUATION RESULTS OF AC LOSSES

Generator	A	B	C
f [Hz]		0.67	
L [km]	275	193.3	170.6
Q [J/m/cycle]	0.0083	0.0090	0.0093
AC losses [kW]	1.52	1.17	1.06

IV. SUMARRY

This paper showed an electromagnetic design for fully superconducting wind turbine generator with two kinds of superconductors. Three kinds of generators were designed with different value of B_{max} at MgB_2 armature windings. FEM analysis results showed the 10 MW output is achievable with less than 500 km of HTS tapes. B_{max} at the field coil was less than 9.0 T. These results can be helpful for field magnet design considering mechanical supporting structures. No-load AC losses were estimated to be around 1.1 kW. This result shows that a fully superconducting generator is one of the good candidates for further large scale wind turbine generators. Therefore, further optimal generator design and loss analysis are required.

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