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10 MW 급 초전도 풍력발전기용 고온초전도 레이스트렉 코일의 응력 해석†

(Stress analysis of HTS racetrack coils for 10 MW class superconducting wind power generator)

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Abstract The authors designed a high temperature superconductor (HTS) racetrack coil for a 10 MW class superconducting synchronous wind turbine generator. The designed HTS racetrack coil was analyzed by an electromagnetic finite element method (FEM) to determine the magnetic field distribution, inductance, stress, etc. This paper describes the stress analysis and structure design result of the HTS racetrack coil for 10 MW class superconducting synchronous wind turbine generators, considering orthotropic material properties, a large magnetic field, and the resulting Lorentz force effect. Insulated HTS racetrack coils and no-insulation HTS racetrack coils were also considered. According to the results of the stress analysis, the no-insulation HTS racetrack coil results were better than the insulated HTS racetrack coil results.

Key Words : Electromagnetic analysis, Racetrack coil, Stress, Superconducting magnets, Wind turbine

1. INTRODUCTION

The development and introduction of wind power generators has recently advanced in the research and development of renewable energies [1], [2]. The scaling up of wind power generators is a recent trend because of the scale merits, and a high temperature superconductor (HTS) can be a key technology. HTS have zero electric resistance in a DC-current condition. It is possible to develop high current density, a high magnetic field, and high torque generation. For this reason, HTS technologies can make large capacity wind power generators possible compared to conventional wind power generators [3] - [5].

In this paper, an HTS racetrack coil of the rotor magnet for a 10 MW wind turbine generator was investigated. First, a 10 MW wind turbine generator, a magnet bobbin for winding, and their structural parts were designed using the 3D CAD program. MofrotormagnetswereTS racetrack coils, the orthotropic materials properties, a large magnetic field, and the resulting Lorentz force were considered. The finite

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element method (FEM) program was used. According to the results of the analysis, the no-insulation HTS racetrack coil was shown to generally have better characteristics than the insulated HTS racetrack coil.

2. Analysis Model of HTS Wind Power Generator

2.1 Design conditions

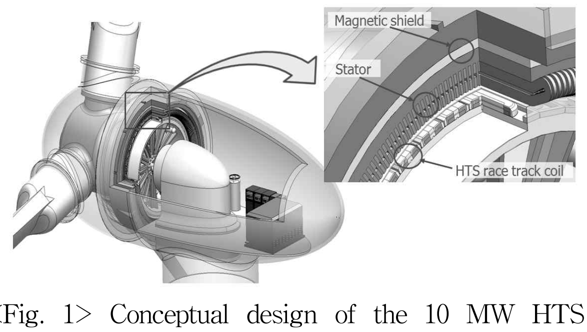
The electro-magnetic design of a 10 MW wind turbine generator with HTS field windings is performed by using FEM analysis. In this study, the direct drive type, 3-phase synchronous generator with a rated voltage of 13.8 kV_{rms} with a 10 rpm revolution is considered. Table 1 summarizes the basic design conditions.

<Table 1> Basic design conditions

Property		Value
Pole number		120 pole
Output power	[MW]	10
Rated voltage	[kVrms]	13.800
Operating current	[A]	< 150
Rated revolution	[rpm]	10
Approx. diameter	[mm]	< 8500
Effective length	[mm]	< 1000

2.2 Shape of the HTS rotor magnet

Fig. 1 shows the conceptual design of the 10 MW HTS wind turbine generator.



<Fig. 1> Conceptual design of the 10 MW HTS wind turbine generator

The HTS rotor consists of 720 double pancake type racetrack coils generating a 120-pole magnetic field. The stator has three-phase double layer armature windings, and a copper 720-slot conductor. The HTS field magnet and the armature radius of the superconducting rotor are 7334 mm. The inner diameter and the straight section length of the racetrack coil are 20 mm and 1000 mm, respectively, and the cross-section dimensions are 112 mm × 48 mm. The bobbin is made of an aluminum alloy. The racetrack coil is wound by YBCO wire and the total length of the wire is 1333 km. Table 2 represents the specifications of the superconducting rotor with a capacity of 10 MW suggested in this paper.

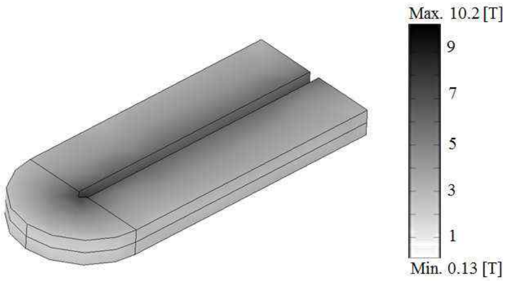
<Table 2> Design specifications

Property			Value
Rotor	Diameter	[m]	120
	Effective length	[m]	7334
	Rotation speed	[rpm]	1
	Bobbin diameter of HTS coil	[mm]	10
	The number of turns per DPC		20
	Number of DPC per pole		800
	The pole pich	[m]	6
	Length of HTS wire per pole	[km]	576.01
	Field current	[A]	11.12
	The number of slot		100
Stator	The number of turns of coil per phase		1300
	The number of wire per coil		78
	Diameter	[m]	7554
	Output voltage	[kV_{rms}]	13800
	Output frequency	[Hz]	10

3. Electromagnetic Analysis of the HTS Rotor Magnet

3.1 The field distribution of the HTS rotor magnet

Fig. 2 presents the electromagnetic analysis results for half of the racetrack coil (one pole) for the 10 MW HTS rotor magnet.



<Fig. 2> Flux density distribution of 1/2 HTS racetrack coil

Operating temperature of the superconducting rotor is 30 K. The operating current of the HTS rotor magnet is 100 A, and the maximum flux density of the HTS rotor magnet becomes 10.21 T. The maximum perpendicular flux density and parallel flux density are 4.04 T and 10.17 T, respectively. The analysis results indicate that the maximum magnetic flux density appears around the inner section of the HTS racetrack coil.

3.2 The Lorentz Force fo the HTS rotor magnet

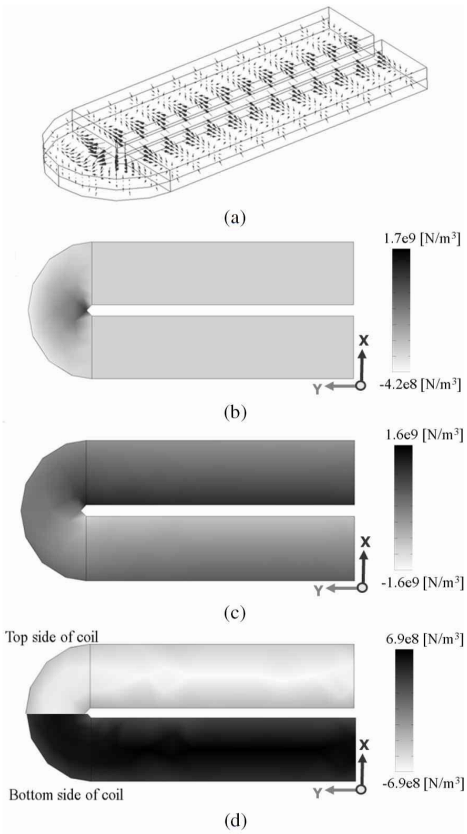
The HTS racetrack coil of the rotor magnet experiences a Lorentz force, which causes instability of the HTS coil. Therefore, it is important to consider the mechanical stress on HTS coils caused by the Lorentz force. Fig. 3 displays the analysis of the Lorentz force distribution by the electromagnetic field that occurs in half of the racetrack coil.

Fig. 3 (a) depicts the direction of the Lorentz force, while Fig. 3 (a), (b), and (d) represent the X, Y, and Z components of the Lorentz force occurring in half of the racetrack coil, respectively.

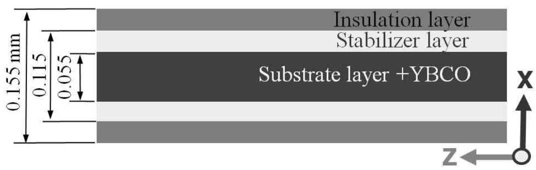
4. Stress Analysis of the HTS Rotor Magnet

4.1 Equivalent model of racetrack coil

Fig. 4 presents a scale equivalent model of a single turn in a HTS racetrack coil for finite element analysis to obtain equivalent properties. In the direction of the X-axis, the HTS wire was stacked with various layers and can be divided into three layers: the superconductor layer, the metal stabilizer for the protection of the superconductor layer, and an insulation layer composed of Kapton and epoxy. In the stress calculations of the HTS racetrack coil, anisotropic analysis is indispensible when representing these properties. The thickness of each layer is so thin that it is necessary to calculate an equivalent model of the material. In Table 3, Young's modulus and Poisson's ratio for each direction are presented.



<Fig. 3> Analysis results of the Lorentz force distribution



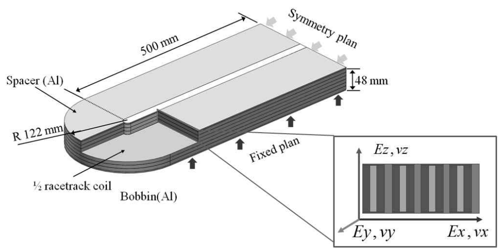
<Fig. 4> Structure of superconducting wire for racetrack coil of HTS rotor magnet

<Table 3> Equivalent material properties

Young's modulus		Poisson ratio	
Ex [Gpa]	10.8	Vx	0.118
Ey [Gpa]	116.4	Vy	0.330
Ez [Gpa]	95.5	Vz	0.118

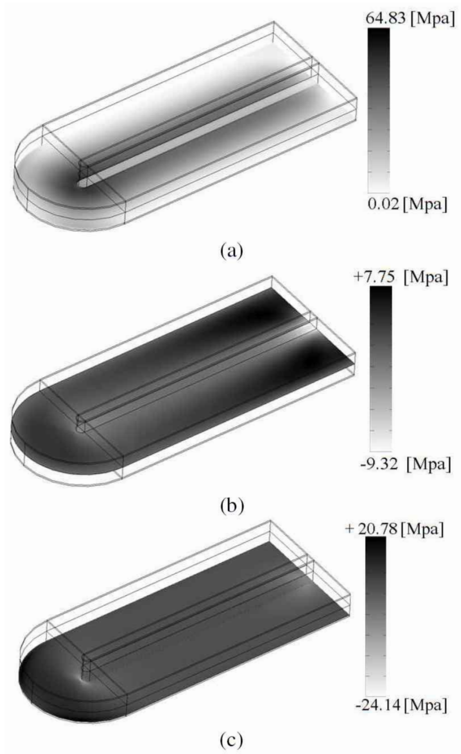
4.2 Stress analysis of insulation HTS racetrack coil

Fig. 5 shows the HTS racetrack coil model used for the stress analysis. Half of the racetrack model was analyzed. A fixed boundary condition was given to the bottom side of the coil because it would be fixed with the rotor body. Furthermore, a symmetry boundary condition was given to the half racetrack coil (Y=0 plane).

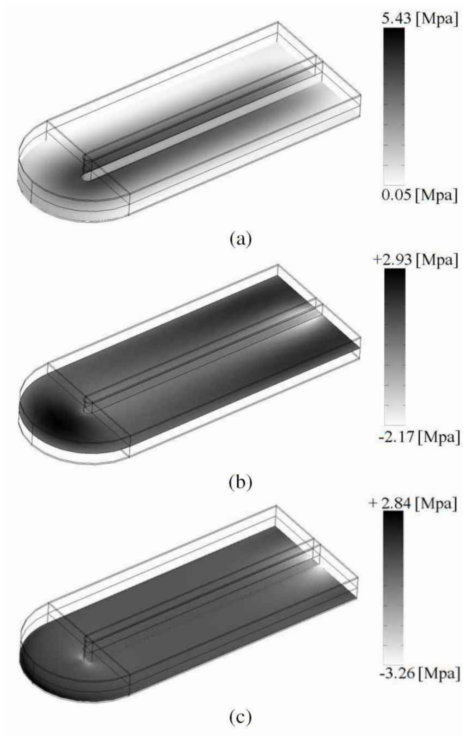


<Fig. 5> Structure of 1/2 HTS racetrack coil model and winding shape of HTS wire

Fig. 6 represents the results of the electromagnetic stress analysis of applying the Lorentz force data of the half of the insulated racetrack coil. The maximum Von Mises stress of the coil is 64.83 MPa, as depicted in Fig. 6 (a), and the radial stresses of the coil are +7.75 MPa and −9.32 MPa, as depicted in Fig. 6 (b). Finally, the hoop stresses of the racetrack coil for the HTS wind turbine rotor are +20.78 MPa and −24.14 MPa, as shown in Fig. 6 (c).



<Fig. 6> Stress analysis results of the insulated racetrack coil



<Fig. 7> Stress analysis results of the no-insulation racetrack coil

4.3 Stress analysis of no-insulation HTS racetrack coil

As the racetrack coil for the superconducting wind turbine generator designed in this paper is operated under DC conditions, the HTS racetrack coil can be operated in ideal conditions without the electric resistance. Therefore, the conductor current flows according to the winding shape of the HTS racetrack coil due to the resistance of the metallic stabilizer. The normal operation of the HTS racetrack coil is available without electric insulation. For electric insulation between the turns of the HTS coil, Kapton tape or other similar material with low intensity and easy deformability has generally been used. As the deformation coefficient of the insulation (Kapton tape) existing between turns of the HTS coil was larger than other materials that compose the traditionally insulated HTS coil, it acted as the cause for increasing the overall deformation rate of the HTS coil. For this reason, it can be predicted that the deformation of no-insulation HTS coils will be less than that of an insulated HTS coil. Favorable mechanical characteristics are also expected. In this paper, the stress analysis for the no-insulation coil model was conducted as an enhanced model of the insulated HTS racetrack coils.

The basic conditions considered for the stress analysis were the same as the insulated HTS racetrack coils. An isotropic condition was considered in the mechanical characteristics of the HTS racetrack coil. Young's modulus and Poisson's ratio of the no-insulation racetrack coil were 22.5 GPa and 0.33, respectively. Fig. 7 shows the results of the stress analysis for the no-insulation racetrack coil. The maximum Von Mises stress of the coil is 5.43 MPa, as depicted in Fig. 7 (a), and the radial stresses of the coils are +2.93 MPa and -2.17 MPa , as depicted in Fig. 7 (b). Finally, the hoop stresses of the racetrack coil for the HTS wind turbine rotor are +2.83 MPa and -3.26 MPa, as shown in Fig. 7 (c).

5. Conclusion

In this paper, stress analysis was carried out in relation to the HTS racetrack coil and bobbin that are to be used in a 10 MW HTS wind turbine generator rotor magnet. In addition, the concept of the no-insulation racetrack coil as a renovated model was suggested, and the stress analysis for the no-insulation coil model was also conducted. From the analysis results, the hoop stresses of the insulated racetrack coil are +20.78 MPa and -24.14 MPa. The hoop stresses of the no-insulation racetrack coil are + 2.84 MPa and -3.26 MPa. In the case of the coil bobbin, the amount of Von Mises stress was analyzed compared to the maximum yield stress of the material composing the bobbin. The maximum Von Mises stresses of the insulated and no-insulation racetrack coil bobbins were 64.83 MPa and 5.43 MPa, respectively. This is much lower than the maximum yield stress (380 MPa) of the material used in the bobbin.

According to the outcome of the stress analysis results, the no-insulation racetrack coil demonstrated better characteristics than the general insulation coil model. Therefore, the no-insulation racetrack coil can be one solution to reduce the structural instability caused by the enlargement of superconducting wind turbine generators.

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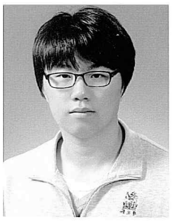

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