論文の内容の要旨

論文題目　Electromagnetic design of light weight and high power density superconducting synchronous machines for 10 MW class wind turbine generators
（10 MW級風力発電機のための軽量・高出力密度超電導同期機の電磁設計）

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This thesis focuses on electromagnetic design of light weight and high power density superconducting synchronous machines for 10 MW class wind turbine generators. There are three motivations of this research like the following; (1) to propose the world's first fully superconducting generator having YBCO field coils and MgB_2 armature windings, (2) electromagnetic design for three kinds of superconducting and a permanent magnet type wind turbine generators and (3) investigating the electromagnetic characteristics of 10 MW class direct-drive wind turbine generators by means of generator size, weight, HTS wire length, generator losses and so on.

Wind generation is well known as one of the clean energy and the installation of wind energy is increasing annually in global levels. The size of wind turbines has been also increasing from the economical point of view. There are some proposals for over 10 MW class generators. However, the generator's weight and tower cost increase with the generator capacity. It is important to develop lightweight and high power density generators for large capacity wind turbine generators.

High-temperature superconducting (HTS) technology is one of the key solutions. Superconducting wind turbine generators have a potential for realizing compact and high-power density generators and have been studied actively in the world. In general, these generator structures are made of superconducting field coils and copper armature windings.

Fully superconducting generator which has superconducting field and armature windings has a potential to develop more compact and higher output density generator than other superconducting machines. The two coils are put in the same cryostat and it results in air gap reduction. Finally, it is possible to reduce not only generator size. However, the fully superconducting generator has a technical challenging issue; how to reduce AC loss at the superconducting armature windings. In addition to them, the total HTS wire length will be increase and results in higher cost machine. If multifilament MgB_2 superconducting wires are applied into the superconducting generators, it is possible to reduce the AC losses. And also, the MgB_2 wire is so lower cost than usual HTS wires YBCO and BSCCO, that the cost issue can be solved.

Chapter 1 shows the introduction of this study. Firstly, current status of global wind energy installation and large scale wind turbine generator systems are described. The next, superconducting wind turbine generators studied by some company and university groups are introduced as a solution of the issues after explaining technical challenging issues for over 10 MW class. Finally, the overview of this thesis is shown.

Chapter 2 refers design conditions for 10 MW class wind turbine generators. Firstly, the initial design conditions such as output power, current voltage and so on are shown. The next, four generator structures and their cooling system design schemes are described. And also, the design concepts for generator components such as HTS field coils, copper or MgB_2 armature windings and back iron have been explained.

Chapter 3 is for electromagnetic design of permanent magnet type synchronous generators (PMSG). Electromagnetic design and characteristics of the PMSG were investigated with 2D finite element method analysis (FEM). Two kinds of electromagnetic characteristics such as steady and transient state are analyzed.

Firstly, the electromagnetic characteristics in steady state have been investigated. The results showed that the diameter and weight of 10 MW class PMSG was over 13 m and 230 tons respectively. Especially, 13.1 tons of permanent magnet was included in the weight. The current market price of rare earth materials for PM is not stable and the figure seems too much values. As for generator losses at copper armature windings and back iron, the value was over 400 kW. If other losses; mechanical, rotor iron losses and so on are added, the efficiency would be decrease around 90 %. This value could be quite lower than that of other conventional multi MW class wind turbine generators.

Secondly, the characteristics of transient state analysis in sudden three-phase short circuit problem have been analyzed. In this analysis, short circuit torque, current and voltage as well as magnetic flux distributions are discussed. The calculation results showed that the transient torque and current values were around 150 % higher than that of rated values.

It was concluded that PMSG structure had many technical challenges for 10 MW class wind turbine generators.

Chapter 4 shows the electromagnetic design of salient pole type superconducting generators (S-SCG) with 2D FEM. Two kinds of electromagnetic characteristics such as steady and transient state are analyzed like the PMSG. For this investigation, two generators with different pole numbers and outer diameters were designed for these two investigations.

The steady state analysis results showed that the diameter of the two designed S-SCG were 5.45 m with 36-pole (S-SCG-A) and 8.2 m with 60-pole (S-SCG-B) respectively. The results explained that S-SCG structure can reduce over 30 percent of generator diameter comparing to PMSG. And the S-SCG-A and S-SCG-B required 62.0 km and 36.9 km respectively. These results showed that S-SCG was suitable to design multiple and larger diameter structure. Focusing on the generator losses, the individual losses were 360.5 [kW] and 278.5 [kW] respectively. If other losses were added to them, they would increase and their values were not so low. However, from the view point of generator efficiency, S-SCG-B would be better choice than S-SCG-A and PMSG.

As for transient analysis, the transient torque was almost the same value of PMSG. However, the transient current value was a little higher than that of PMSG because of lower synchronous reactance. These values should be compared the later two structures.

The S-SCG has a potential for 10 MW class wind turbine generators from the view point of generator costs.

Chapter 5 explains the electromagnetic design of non-salient pole type superconducting generators (NS-SCG) with 2D FEM. Two kinds of electromagnetic characteristics such as steady and transient state are analyzed like the previous chapters. Two kinds of NS-SCG having the different diameter and 12-pole are designed.

The first generator characteristics showed that both generators could obtain 10.0 MW and their diameters were 4.7 m and 8.4 m respectively. They were named NS-SCG-A and NS-SCG-B. They required quite much amount of YBCO wires than S-SCG structures. In case of NS-SCG-A, it required 1240 km of YBCO wire. This was because of its air-cored structure. As for generator losses, the NS-SCG-A had almost 3.2 % of total output; 320 kW and the NS-SCG-B had 480 kW. Finally, the total generator efficiency would be around 90 % like PMSG. From the view point of the efficiency of generators, the NS-SCG structures had the low performances comparing with S-SCG structures.

Focusing on the second transient short circuit analysis, both generators had quite high transient values of torque and current. In case of transient torque, it was over 16 times higher than rated torque; 10 MNm. And also, the maximum transient current values were over 20 times higher than that of rated current; 2,500 $A_{max.}$

It was concluded that the generator characteristics of NS-SCG structures had many technical challenges.

Chapter 6 focuses on the electromagnetic design of fully superconducting generators (FSCG) which is the original work of this study. Electromagnetic design and characteristics of the FSCG have been investigated with 2D FEM. As shown in the previous chapters, the analyses in steady and transient state are investigated. Two kinds of the FSCG were designed. One is FSCG-A that the maximum magnetic flux density at the armature winding is 1.5 T. And the other is FSCG-B that the maximum magnetic flux density at the armature winding is 2.0 T.

The first analysis in steady state showed that the amount of HTS wire was less than 200 km, the generator diameter was 4.0 m thanks to the lower air gap; 80 mm in case of FSCG-A. On the other hand, FSCG-B required 260 km with 4.0 m. As for generator losses, this structure had no copper loss but AC loss. In this chapter, AC and iron losses are estimated. Especially, the AC loss in this section means “no load” condition and hysteresis loss of MgB_2 superconductor part. The AC losses of FSCG-A and FSCG-B were 1.9 and 1.5 kW respectively. If COP of cooling system and thermal insulation were assumed 0.01 and 100 kW, the total AC losses were estimated at 250-290 kW. These values would be almost 3.0 % of total outputs and not low values for total systems. However, if the armature windings were made with twisted structure, it could have a possibility for AC loss reduction. On the other hand, iron losses in the two generators were 3.0 and 5.9 kW respectively. The ratio of these losses in the total output was only 0.03-0.059 %. These values were quite low comparing with other 10 MW class generators thanks to low frequency like 1.0 Hz.

As for the short circuit problems, the transient torque of FSCG-A was 13.6 MNm. This was almost 1.3 times higher than rated torque; 10.0 MNm. And also, the transient current was 5260 A_{max} which was about twice higher value than rated current 2500 A_{max}. On the other hand the transient torque and current of FSCG-B were 25.5 MNm and 11600 kA_{max} respectively. Comparing with NS-SCG, both values of two FSCG structures are reduced dramatically thanks to nonlinear resistance using the *I-V* characteristics of FSCG contributed to the higher short circuit current area. In other word, when the problem occurred, current-limiting control function based on *I-V* characteristics of MgB_2 had worked at armature windings.

It was concluded that FSCG had good characteristics from the view point of the generator protection from some accidents. FSCG can be a good candidate for the 10 MW class wind turbine generator system.

Chapter 7 discusses the comparison of the electromagnetic characteristics of four designed wind turbine generators in terms of generator diameter, weights, HTS wire length, generator loss and so on. Especially, partial load analysis has been investigated to analyze the generator characteristics with lower wind speed. The results showed that the FSCG and the S-SCG are the best candidates for 10 MW class wind turbine generators from the aspect of size and costs.

Chapter 8 explains the conclusion of this research.