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Research paper

Development of a cooling system for superconducting wind turbine generator

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ABSTRACT

This paper deals with the cooling system for high-Tc superconducting (HTS) generators for large capacity wind turbines. We have proposed a cooling system with a heat exchanger and circulation pumps to cool HTS field windings designed for 10 MW-class superconducting generators. In the cooling system, the refrigerants in the stationary and rotational systems are completely separated; heat between the two systems exchanges using a rotational-stationary heat exchanger. The refrigerant in rotational system is circulated by highly reliable pumps. We designed the rotational-stationary heat exchanger based on a conventional shell-and tube type heat exchanger. We also demonstrated that heat exchange in cryogenic temperature is possible with a commercially available heat exchanger. We devised a novel and highly reliable cryogenic helium circulation pump with magnetic reciprocating rotation system and verified its underlying principle with a small-scale model.

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1. Introduction

In recent years, because of problems like global warming, resource depletion, and nuclear power safety, widespread use of renewable energy is gaining traction. Wind power is a promising source of renewable energy; large capacity offshore wind farms is being promoted worldwide. In wind power generation, large wind turbines have become a major trend [1]. Larger turbines reduce the power generation cost and increase the total power generation capacity of the site. This is due to the fact that, given a certain fixed area for wind turbine installation, as the wind turbine spacing interval is proportional to the rotor diameter D, and the output of the wind turbine is proportional to the square of D, the gross power generation capacity (corresponding to electricity sales revenue) can be increased by lining up large-capacity turbines.

In the 2–3 MW wind turbines that are currently mainstream, it is now common to use a multistage gearbox to increase the rotational speed of the generator more than 100 times. However, as the capacities of power generators increase, the technology used to increase the speed ratio in the gearbox will soon reach its limit. Therefore, a direct-drive system without a gearbox is considered promising [2]. However, a major concern in extending the current technology to increase the capacity of the drive train is that it will result in increases in size, weight, and cost. Worldwide research and development is being carried out on a small, lightweight, but large-capacity superconducting generator, as a break-through technology that enables construction of large-scale wind turbines with capacities greater than 10 MW [3–5].

Our group, comprising collaborators from Furukawa Electric Co. Ltd., Mayekawa Manufacturing Co. Ltd., Niigata University, Sophia University, and University of Tokyo, has designed a high-T_c superconducting (HTS) generator with iron core and modular coils, and has studied its feasibility (sponsored by New Energy and Industrial Technology Development Organization: NEDO) [6]. Although the use of an iron core increases the weight compared to an air-core design, a lightweight generator can still be produced. Moreover, compared to an air-core design, the required amount of expensive HTS wire is reduced, suggesting that a superconducting generator that is cost-competitive relative to currently employed generators is feasible. In the NEDO project, Maekawa Mfg. Co. and the University of Tokyo have developed a turbo-Brayton refrigeration technology element with an MTBF (mean time between failures) of more than 30,000 h, using gas helium as the refrigerant. We, AIST, have additionally developed a technology element of the refrigerant transfer coupling, for feeding the coolant supplied by the turbo-Brayton refrigerator to the HTS coil modules in the generator rotor. A group from Furukawa Electric Co., Sophia University, and Niigata University has developed a field winding by using YBCO wire.

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Since installing a refrigerator in the rotational system is difficult, the refrigerant must be supplied from a stationary system to the rotational system, to cool the superconducting rotating machines. In a conventional superconducting rotating machine, the entire rotor is installed in a cylindrical cryostat, and the cryogenic refrigerant is supplied from outside the cryostat. In the case of rotational machines with high-speed rotation, natural circulation of the refrigerant is possible by utilizing centrifugal force. However, in wind generators, the rotational speed of superconducting generators is around two orders of magnitude slower than that of turbine generators (about 10 rpm). Moreover, in order to maintain high critical current in the magnetic field of HTS coils, a refrigerant temperature in the range of 20–40 K is required. In this temperature range, the refrigerants that can be used are either helium gas or liquid neon. Since in both cases, a self-pumping effect does not occur naturally, forcible circulation of the refrigerant by using a pump is required [7]. Moreover, considering the loss in pressure inside the HTS coils, the refrigerant needs to be pumped from the stationary system to the rotational system at several atmospheric pressures [8]. However, there is currently no established method to seal a high-pressure, low-temperature refrigerant. In order to solve these problems, the refrigerants in the stationary and rotational systems have been separated, and a method of mutual heat exchange between the two has been devised. In the rotational system, the refrigerant is circulated by its own pump. Fig. 1 shows a schematic of the cooling system in a superconducting wind generator, with a heat exchanger between the stationary system and the rotational system, and a pump installed in the rotational system.

This paper describes with respect to 10 MW-class superconducting generators for wind power generation, a method to obtain efficient heat exchange between the stationary and rotational system refrigerants, using a heat exchanger placed between the stationary and rotational systems, and an original pump dedicated to the rotational system.

2. Design of 10 MW-class superconducting generator for wind turbines

The designed superconducting generator for 10 MW-class wind turbines consists of 48 HTS coil modules, each placed in its own vacuum chamber. Each coil module corresponds to one pole of the generator. By adopting modular structure, it is possible to keep the massive rotor iron core at room temperature. This results in two features: (1) a cryostat for storing the entire rotor iron core is not required, (2) it is not necessary to develop a torque tube with low heat inleak to transfer huge torque by rotation of the wind turbine to the rotor. The HTS coils in each vacuum chamber is cooled by heat transfer through directly contacted tubes through which the helium gas flows.

In the NEDO project, Furukawa Electric Group successfully fabricated a coil module in which generation of a predetermined level of magnetic field was confirmed. In addition, the heat inleak was measured with the coil module at 30 K. The heat load of the coil module was 42.4 W at the rated current. The breakdown of the heat load was approximately 30% from the transfer tube, approximately 55% from the current leads, and the remaining 15% from conduction through the coil support fixtures and radiant heat. We assumed that 48 poles were fabricated by connecting six coil modules in series, and then placing eight of these sets in parallel. By connecting serial coils with HTS wires in cryogenic temperature, heat inleak from transfer tube and current leads can be eliminated. Heat load from one set of six coil modules connected in series was 76.4 W, and connecting eight of these sets in parallel, the gross heat load of the 48 modules was calculated to be 611.2 W.

The output of the turbo-Brayton refrigerator developed by Maekawa Mfg. Co., is helium gas at 20 K and 2.1 atm. Assuming an approximate 5 K rise in temperature in the pipe connecting the refrigerator to the heat exchanger, the heat exchanger should absorb over 600 W of heat generated in the secondary side rotational system with 25 K helium gas in the primary side stationary sytem.

Assuming an inlet temperature of the 6 serially connected coil modules of 30 K, an outlet temperature of 40 K (ΔT = 10 K), using a heat load of $\dot{Q} = 700$ W with adequate margin, and the specific heat of the helium gas of C_p = 5.2 kJ/kg/K (@25–40 K, 0.1–0.2 MPa), the gas helium flow rate $\dot{m}$, required in the rotational system is given by,

$$\dot{m} = \dot{Q}/(C_p \Delta T) \quad (1)$$

and is estimated to be 13.5 g/s. Since the density of helium gas at 35 K is ρ = 1.5 kg/m^3, this corresponds to 9 L/s. If one pump is installed for each set of 6 serially connected coil modules, for adequate circulation of gas helium, a pump with a discharge capacity of 1.1 L/s is required.

These performance requirements were considered in the development of the heat exchanger and the pump.

3. Rotational-stationary heat exchanger

Based on a counter-flow shell-and-tube heat exchanger design, a heat exchanger with a rotating shell mechanism has been devised. Fig. 2 shows the schematic of the designed rotational-stationary heat exchanger. Low temperature helium gas, fed from the turbo-Brayton refrigerator, flows into the tube on the primary side (stationary side), and heat exchange occurs with the gas on the outer secondary side (rotational side). As described in the previous section, with an inlet temperature of 25 K on the primary side, and assuming a rise of 10 K, the outlet temperature on the primary side was 35 K. On the secondary side, the temperature at the

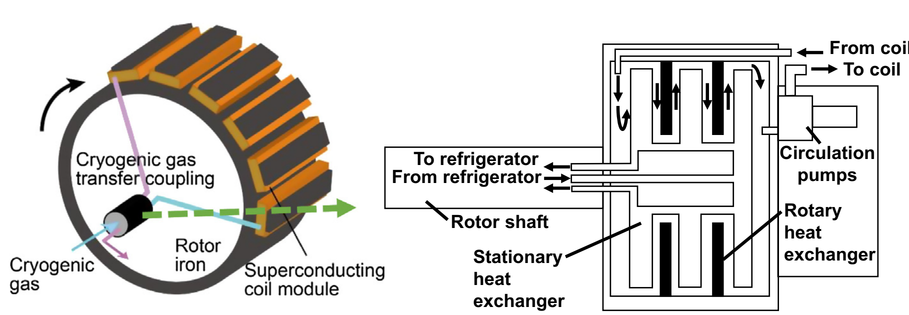

Fig. 1. Schematic of the cooling system in a superconducting generator for wind turbines.

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