Design of cooling system and temperature characteristics analysis of high temperature superconducting demonstrative synchronous generator

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The cooling system of a demonstrative high temperature superconducting (HTS) generator, in which solid nitrogen (SN_2) was used as cryogen to keep the operating temperature of HTS synchronous machine, is presented in this paper. Operation process of cooling system is illuminated and main circulation parameters of cooling system are also investigated. Furthermore, temperature characteristics of rotor are calculated by finite element method (FEM) software ANSOFT. The simulated results show that temperature field was uniform and the maximum temperature of HTS coils is lower than 30 K during normal operation.

INTRODUCTION

Applying HTS conductors in the rotor of synchronous machines allows the design of future motors or generators that are lighter, more compact and features an improved coefficient of performance [1]. There are two types of rotor configurations in existing conceptual designs and actual prototypes of HTS machines: iron core rotor [2] and nonmagnetic rotor [1, 2]. Almost all HTS rotating machines were fabricated as racetrack coils of Bi-2223/Ag HTS tapes operating at temperature range between 20 K and 30 K in order that the HTS machines could possess sufficient over current capacity and endure bigger vertical component ($B_{\perp}$) of magnetic flux density passing through the surface of HTS tapes.

A 100KVA HTS demonstrative synchronous generator was designed in this paper. Its tasks were to pursue the minimal volume of HTS magnets and utilize the configuration characteristic of conventional generator. Its hybrid rotor has three novel aspects: the HTS magnets are installed on a warm iron core; four Dewar flasks having racetrack outline were distributed symmetrically and SN_2 was used as cryogen. Furthermore, evaporative cooling technology was applied to solve the cooling problem of the stator, which is more effective than air-cooling technology and more safety than water inner cooling technology. Magnetic invar rings were used between adjacent HTS coils of the field windings to divert the normal component of the magnetic field away from the Bi2223 superconducting tapes. Design parameters of the generator model are shown in Table 1. Figure 1 is the 3-D sketch of the 100KVA HTS demonstrative generator. Consumed HTS conductors in this model were one seventh of the generator with nonmagnetic core rotor [4]. Comparing with generators, which had conventional iron core, the values of magnetic flux density at air-gap were identically approximate. However, AC losses were decreased sharply, and the loads of cooling system were consequently reduced. It is easy to exclude AC magnetic field from the stator by placing a cold copper shielding cylinder around the rotor. The main difficulty of this configuration is to design and manufacture Dewar flasks of racetrack type because of their special outline.

Table 1 Parameters of the HTS generator model

Rating	100 kVA
Speed	1500 rpm
Armature	380V/152A Evaporative cooling
Housing dimensions	Diameter 660 mm Length 520 mm
Frequency	50Hz
Number of pole	4
Field winding	57A/30K SN_2+GHe
Magnetic flux density at air-gap	0.74 T

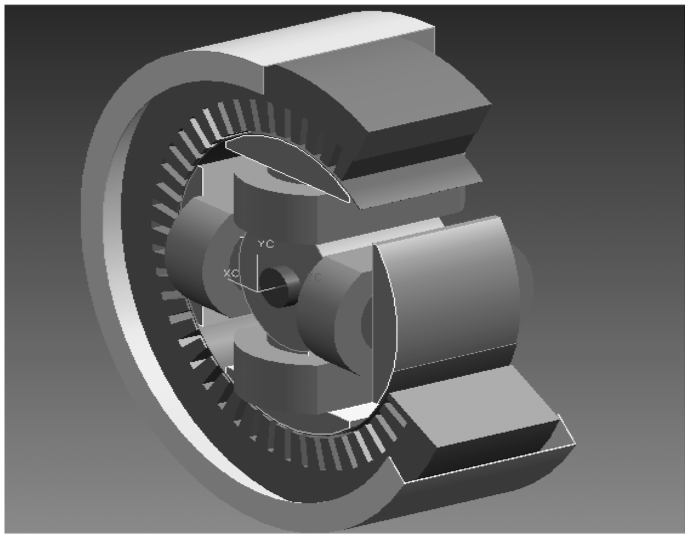

Figure 1 3-D sketch of HTS demonstrative generator

DESIGN OF ROTOR COOLING SYSTEM

The cooling system is one of the important components of HTS machine, of which function is to take heat away rapidly and maintain the superconducting property. Therefore, the robust and reliable cooling system is required for HTS generators to operate for a long time. In the design, SN_2 as cryogen and GHe as circulation medium were used after investigating the cooling system of HTS rotating machines [1, 2, 3, and 4]. The sketch is shown in Figure 2.

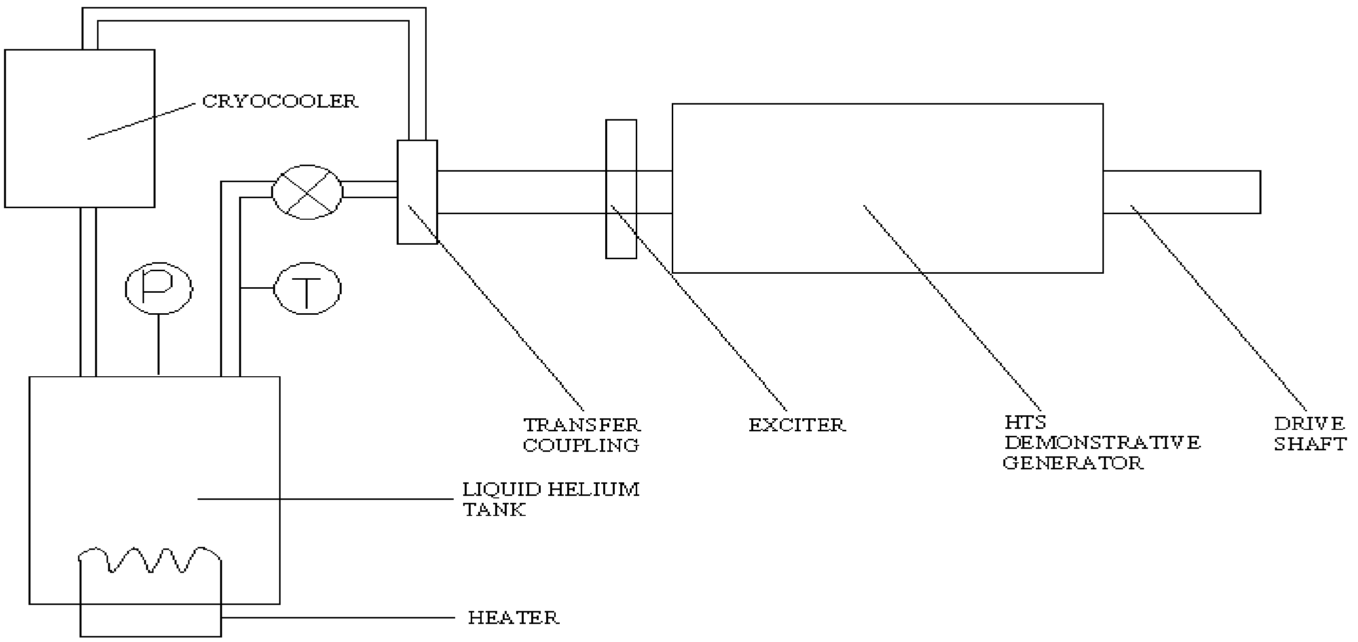

Figure 2 Sketch of the cooling system

<u>Operation process of cooling system</u>

In HTS generator model, liquid nitrogen (LN_2) was transported into the space of magnets, and then liquid helium (LHe) was forced into the heat exchanger of racetrack Dewar flasks to solidify LN_2 before generator working. During normal operation, LHe in liquid helium tank was boiled to gas by the action of heater. By controlling the status of heater, GHe (10-15 K, 0.13-0.20 MPa) was flowed through transfer coupling into heat exchanger to absorb heat from HTS windings. As a result, GHe was heated up and forced into cryocooler through transfer coupling, and then became LHe again returning to liquid helium tank. GHe (15 K) was forced into the heat exchanger continuously and cooled SN_2 down to maintain the temperature of magnets. The rotor of HTS synchronous rotating machine was cooled by thermal capacity of SN_2 and its temperature was kept below 30 K. The delivered cooling power could be determined from measured mass flow, inlet and outlet temperatures. By varying the valve, the cooling power could be regulated directly.

Calculation of main parameters of cooling system

The load on the cooling system is composed of two parts. One part is the leakage of Dewar flasks, which is mainly caused by the conduction of supporting and cervix configuration of Dewar flasks. The leakage of one Dewar flasks was estimated about 0.8 W according to the level of fabricative technology. Another part is AC losses of HTS windings and magnetic invar rings. There are three loss mechanisms in AC losses of HTS windings: hysteresis loss, eddy current loss and coupling loss; however, it is difficult to obtain the accurate results by theoretical analysis. According to the references [1, 3, 4], it was estimated as 2 W in each pole.

The pressure loss of GHe through rotor is an important parameter for the design of GHe circulation of cooling system. Fluid flowing in rotating pipe was influenced by pressure, centrifugal force and Coriolis force. The pressure loss is 0.028 MPa because of centrifugal force, which can be calculated from formula 1. In fact, the effect of Coriolis force ($F_c = 2m\upsilon \times \omega$) is to change the direction of the velocity vector and increase the friction coefficient as pressure does. However, Comparing with centrifugal force, the effects of pressure and Coriolis force can be ignored because the circulation medium is gas. Therefore, the GHe pressure loss through rotor is about 0.028 MPa.

$$\Delta P_c = 5600\left(\frac{n}{1000}\right)^2 \rho r^2 \qquad (1)$$

with ΔP_c: pressure difference, n: speed of rotor, ρ: density of GHe , r: maximal distance to shaft center line of heat exchanger pipe.

Convective heat transfer coefficient h (turbulent flow) between GHe and SN_2 can be obtained from formula 2. This formula is simplified from Dittus-Boelter equation [5].

$$h = \left(\dot{m}\right)^{0.8} \Big/ d^{1.6} \qquad (2)$$

with h: convection heat transfer coefficient, $\dot{m}$: mass flow of GHe, d: diameter of heat exchanger.

INVESTIGATION ON TEMPERATURE CHARACTERISTICS OF ROTOR

The temperature characteristics were simulated at steady state by ANSOFT. The calculated results indicate that temperature range is between 24.14 K and 24.38 K while the GHe (15 K) velocity is 0.2 m/s. Thermal gradient of field is shown in Figure 3 with vectors and contour respectively. Thermal flux of field is illustrated in Figure 4 with vectors and contour. The field dimensions are 80 mm×20 mm. Each pancake is assumed to occupy the 5 mm×7 mm space (including insulation layer), and the space of magnetic invar ring is 4 mm×7 mm. The diameter of heat exchanger is 10 mm.

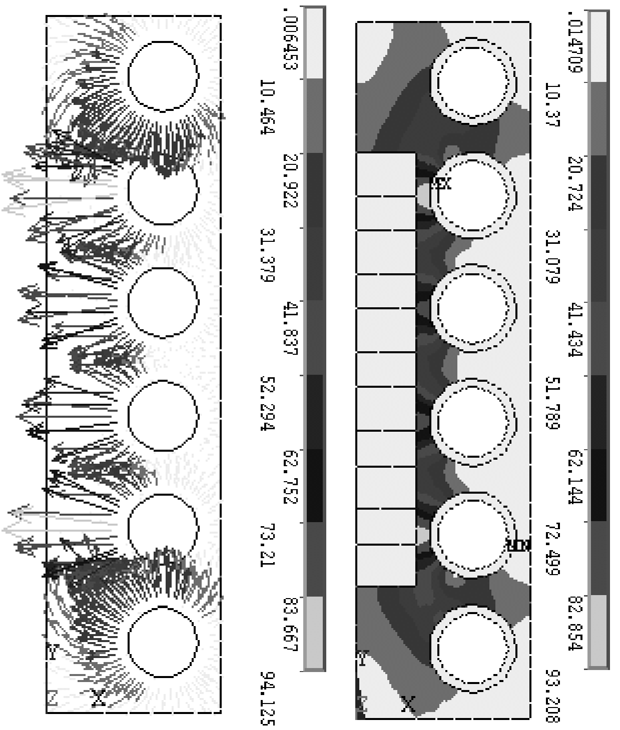

Figure 3 Thermal gradient vectors (left), contour (right)

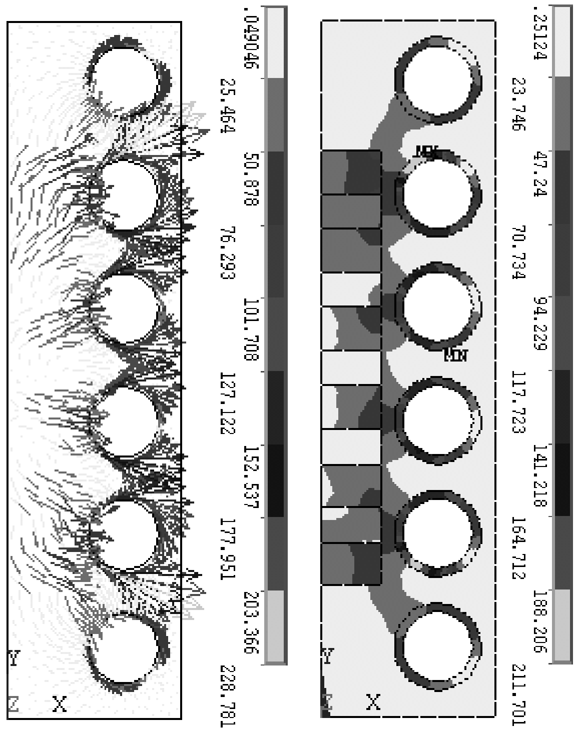

Figure 4 Thermal flux vectors (left), contour (right)

CONCLUSIONS

The cooling system of 100kVA HTS demonstrative synchronous generator has been designed. The pressure losses of GHe through rotor were analyzed. It can be inferred that centrifugal force has significant impact on GHe flow, and the effects of pressure and Coriolis force can be ignored. The steady temperature field was also simulated by ANSOFT, and the results indicate that the maximal temperature of HTS coils was lower than 30 K and distributed uniformly, while the GHe (15 K) velocity was 0.2 m/s.

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