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Design and test of a simplified and reliable cryogenic system for high speed superconducting generator applications

T. Zhang *, K. Haran, E.T. Laskaris, J.W. Bray

GE Global Research, 1 Research Circle, Niskayuna, NY 12309, United States

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ABSTRACT

Under the contract with Air Force Research Lab (AFRL), General Electric has successfully tested a high speed, superconducting generator for a Multimegawatt Electric Power System (MEPS). As the first successful full-power test of a superconducting generator for the Air Force, the demonstration tested the generator's load up to 1.3 MW and over 10,000 rpm. A key component of the generator system is a closed loop cryo-refrigeration system to cool the field excitation coil at liquid neon temperature. This paper reports the design and tests of the cryogenic system, including the liquid neon dewar, cryogenic cooling loop for the high temperature superconducting (HTS) field coil and the cryostat. Performance data during both short-term load run and long-term non-load run were presented. Also, some key issues to design a reliable cryogenic system for a superconducting generator were discussed.

1. Introduction

Many high power systems will depend on high electric power input and packed in a limited space and within strict weight limits. Conventional generators that provide high electrical power have been developed and optimized over the past several decades, but they cannot provide sufficient power level without paying a significant penalty in size and weight [1]. Superconducting technology, however, will enable high power systems due to superconductor's high current carrying capability and zero ohmic losses. With the major developments of high temperature superconducting (HTS) material, Air Force has initiated the developments of a new class of high power HTS generators that are significantly lighter and smaller. In 2004, the Air Force Research Lab (AFRL) contracted General Electric to develop a Multimegawatt Electric Power System (MEPS). The objective of this program is to demonstrate in ground test of the power system. With other components of the power system, including the gas turbine and power conditioner, the focus is to develop and test a superconducting generator at 1 megawatt (MW) power level and rotor speed over 10,000 rpm.

Trade-off studies have shown that the homopolar inductor alternator (HIA) topology [2] is the preferred configuration for such a high speed superconducting machine [3]. As shown in Fig. 1, the generator comprises the following major components:

(1) A stationary field excitation HTS coil. Due to the high current carrying capability of superconducting material, the HTS field coil provides mmf capability more than one order of magnitude higher than conventional copper coil, and thus enables "air gap" armature winding design.
(2) A solid rotor forging with two sets of salient poles that are offset circumferentially by one pole pitch on either sides of the field coil. Since the rotor is spun at high speed >10,000 rpm, the rotor chamber has to be vacuumed to reduce the windage loss. Two ferrofluid seals were used to maintain the dynamic seal.
(3) An iron back yoke inside the stator that consists of laminated blocks to enable both lower eddy current losses from the high frequency operation and high magnetic saturation. These blocks are also laminated in different directions in order to facilitate the transport of flux radially, axially, and circumferentially.
(4) A conventional armature winding made of compacted Litz copper wires. Ceramic cooling tubes were bonded on both sides of the armature bar using epoxy so that the water running through them can provide direct liquid cooling. The armature winding assembly is bonded to the stator yoke to form a rigid structure capable to withstand fault torques, vibration, and shock loads.

It can be apparently seen that, compared to its conventional counterpart, one substantial design change for this superconducting HIA generator is the HTS field coil and the associated cryogenic

* Corresponding author.
E-mail address: zhangt@research.ge.com (T. Zhang).

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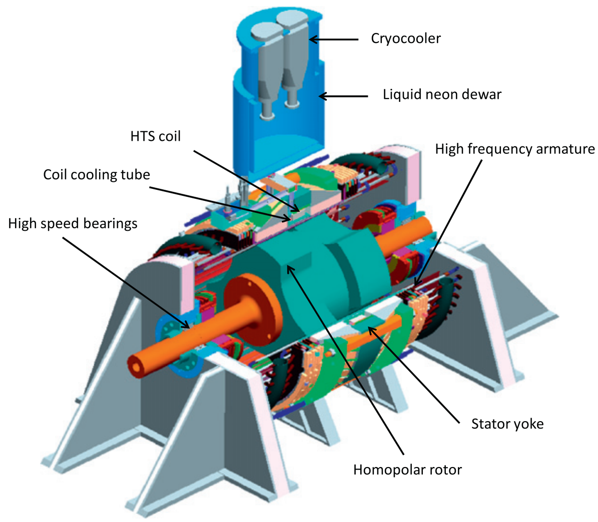

Fig. 1. Schematic of homopolar inductor alternator with HTS field winding.

cooling system. Therefore, among all the engineering challenges including mechanical, electromagnetic and thermal management, a simplified and reliable cryogenic system remains the primary concern.

2. Cryogenic refrigeration system design

Superconducting generator can be basically classified into several different types in term of how the superconducting component is configured:

(1) Air-core superconducting rotor with conventional air-core stator windings. Major disadvantages of this design includes isolation of rotating cryogenic vessel from room temperature stator, dynamic transfer coupling to transport cryogen to the spinning rotor, and the complexity of structural support, toque transmit, and electromagnetic shielding [1,4–6].
(2) Warm iron-core superconducting rotor with air-core stator windings. This concept was used to develop a commercial-class 100 MVA HTS generator featuring a single race-track HTS coil placed around a magnetic iron structure that is connected directly to the shaft extensions [7,8]. Even though the mass of HTS coil and the cold mass held at cryogenic temperatures have been minimized by introducing magnetic iron core, there is still stringent requirements for a reliable cryogenic transfer coupling, and cryogenic refrigeration system.
(3) All-cryogenic superconducting generator with both rotor and stator windings made of superconducting material. In this design, the entire generator resides in a cryogenic jacket and cool down to the operating temperature [1]. The overall efficiency of this type of machine will be the highest by also eliminating the dc ohmic losses of the stator winding. However, the cryogenic system to cool down both the stator and the rotor will be significantly more complicated.

For MEPS superconducting generator, a new configuration was developed. As shown in Fig. 1, the HTS field coil is placed outside the rotor chamber and between two sets of salient poles. When the HTS coil is excited, the ferromagnetic rotor forging is magnetized, and the stator back yoke completes the path for the magnetic flux from one rotor pole to the other. There are many advantages resulting from this design, however one of the most important is the simplification of the cryogenic system. Since the HTS field coil is now stationary as part of the stator, there is no need for a cryogen transfer coupling and rotating cryogenic parts. In addition, this design enables the implementation of a simpler but more reliable vacuum insulation and instrumentation, such as the cryogenic temperature sensors and coil voltage measurement for quench protection.

As the first commercially available HTS superconductor to be made in engineering practical lengths, BSCCO 2223 wire from American Superconductor was used to wind the HTS field coil. To cool down the coil to the designed operating temperature, liquid neon was used as the cooling medium.

Fig. 2 shows the schematic of the cryogenic refrigeration system. It basically consisted of three components: liquid neon dewar, cryogen transfer lines and cryostat for HTS coil (∼40,000 total ampere turns). The cryocooler cold head (Sumitomo® SRDK-400B) sitting on top of the dewar was initially used to liquefy neon gas introduced from a gas cylinder at room temperature. The liquid neon started to accumulate and flow down through two openings at the bottom of the dewar driven by gravity. The cryogen transfer lines guided the liquid neon flow into a neon cooling tube that is attached to the HTS coil. During the operation, liquid neon kept boiling off due to the heat load from HTS coil, which is mainly due to conduction losses from current leads (∼14 W) and AC losses (∼16 W @ 10,000 rpm rotor speed), and parasitic heat load (∼18 W) to the dewar and the cryostat. The neon vapor was then re-condensed to liquid at the re-condenser attached to the cold head. Apparently, this forms a closed-loop cooling circuit.

2.1. Liquid neon dewar

The liquid neon dewar was simply a double-walled cylinder with a vacuum jacket pumped to high vacuum. Multi-layer-insulation was implemented to further reduce the total radiation load. The inner wall of the dewar neck was made of very thin stainless steel sheet, resulting in a minimal conduction heat load.

One important function of the dewar is to provide thermal riding-through capability of the cryogenic system by holding a volume of liquid neon. A performance test showed that this volume of liquid neon can maintain the HTS coil cool at the designed operating temperature for about 5 h after the cryocooler was shutdown, enough to satisfy the mission duration time requirement of high

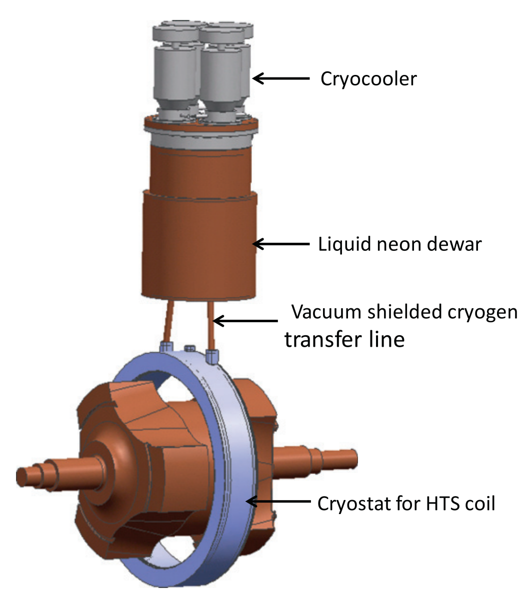

Fig. 2. Cryogenic refrigeration system for MEPS HTS generator.