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Design of a 100 kVA high temperature superconducting demonstration synchronous generator

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Abstract

The paper presents the main features of a 100 kVA high temperature superconducting (HTS) demonstrator generator, which is designed and being built at the University of Southampton. The generator is a 2-pole synchronous machine with a conventional 3-phase stator and a HTS rotor operating in the temperature range 57–77 K using either liquid nitrogen down to 65 K or liquid air down to 57 K. Liquid air has not been used before in the refrigeration of HTS devices but has recently been commercialised by BOC as a safe alternative to nitrogen for use in freezing of food. The generator will use an existing stator with a bore of 330 mm. The rotor is designed with a magnetic core (invar) to reduce the magnetising current and the field in the coils. For ease of manufacture, a hybrid salient pole construction is used, and the superconducting winding consists of twelve 50-turn identical flat coils. Magnetic invar rings will be used between adjacent HTS coils of the winding to divert the normal component of the magnetic field away from the Bi2223 superconducting tapes. To avoid excessive eddy-current losses in the rotor pole faces, a cold copper screen will be placed around the rotor core to exclude ac magnetic fields.

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1. Introduction

High temperature superconductors (HTS), such as the compounds of Yttrium (YBCO) and Bismuth (BSCCO) will find important applications in electrical power apparatus, including fault-current limiters, transformers, cables, and rotating ma-

chines. Unlike the low-temperature superconductors that require liquid helium, the HTS materials can operate at temperatures up to boiling temperatures of liquid nitrogen, with consequent savings in refrigeration power.

Most existing conceptual designs and actual small demonstrators [1,2] rely on operating BSCCO tapes at temperatures of between 20 and 30 K. It is true that at this temperature BSCCO tapes have much better properties, in particular critical currents are an order of magnitude better than at 77 K. It is also possible to have a core-less

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rotor and racetrack coils similar to those used in LTS designs. However, this necessitates the use of liquid neon or helium gas, increases the cost and complexity of refrigeration plant and reduces thermodynamic efficiency. There is therefore a potential danger of such HTS machines having reliability and maintenance profiles similar to those of LTS designs and therefore not good enough, in comparison with conventional counterparts, for the overall increase in efficiency to offset the generator's initial cost and thus to justify commercial interest.

2. The generator components

2.1. Overview

The machine is a 3-phase 2-pole 100-kVA 3000-rpm synchronous generator with a hybrid HTS rotor (see Fig. 1) with two novel aspects. Firstly, it uses the cheap and reliable liquid nitrogen/air technology with sub-cooling down to 65/57 K. The efficiency of the refrigeration system is greatly increased at these temperatures. The effects of sub-cooling, which were evaluated on our HTS transformer project, are a doubling of critical current density and quadrupling of the normal component of the magnetic field. Secondly, as we still cannot allow the field levels obtainable in BSCCO tapes at temperatures below 30 K, we are using magnetic core rotor design. The superconducting winding consists of 12 identical flat pancake coils, placed around the two pole necks. The use of a magnetic

rotor core reduces the ampere-turns required by a factor of about ten. The rotor core is made of Ni36Fe (invar), which can operate at low temperatures and will provide a good mechanical support for the winding.

2.2. Hybrid rotor and flux diverters

The early designs were of the round rotor type, but with all the slot sides parallel to the quadrature axis so that all the superconducting coils would be flat. In such a rotor, each pair of coils would have a different width and may have a different number of turns. While it appeared that the above design could deliver satisfactory performance, it would be difficult to build. It was therefore decided that a hybrid design (a salient and round combination) should be used. In this hybrid design, flux diverters made of invar are placed between the coils to reduce the normal component of the magnetic field in the coils by diverting flux around the coils, as shown in Fig. 2. This simulates the effect of placing the coils in slots. This design greatly simplifies the construction of the HTS coils, since the coils can be wound separately and fitted to the core later. Moreover, by making all the coils identical, it is possible to produce spare coils to insure against the failure of any one coil. Fig. 2 shows a finite element analysis of the flux lines in one pole of the rotor. It can be seen that the Invar rings virtually eliminate the normal field components in the coils. Moreover, the thick outer rings soften the effects of the pole tips on the air-gap flux-density waveform.

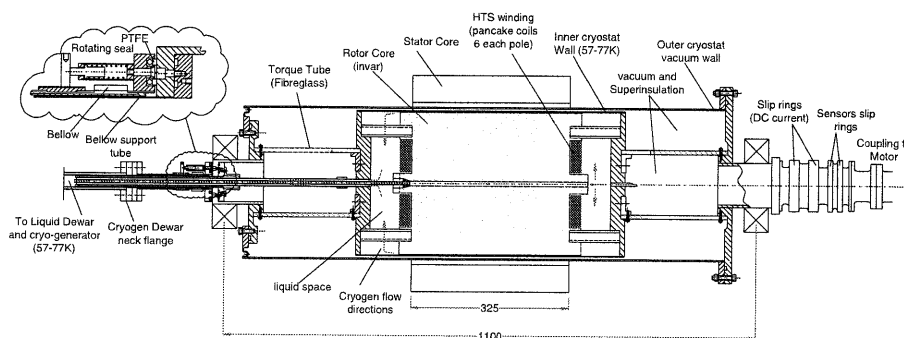


Fig. 1. Sketch of the 100 kVA HTS generator.

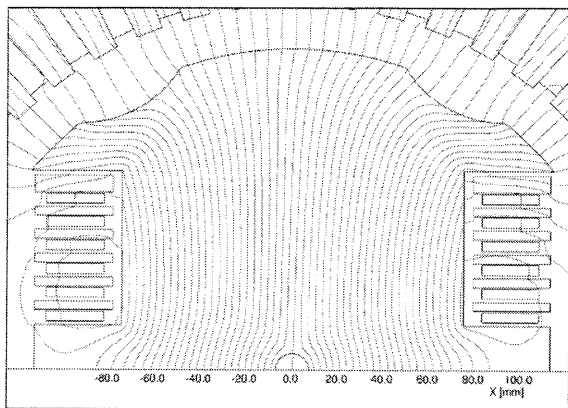


Fig. 2. Flux lines in the proposed superconducting rotor (showing one pole).

2.3. Stator induced harmonic fields

To save on the costs, an existing stator will be used. This stator is from a conventional 100 kVA; 3-phase and 2-pole machine, and has a 330 mm bore diameter and 325 mm iron length. The current and voltage rating of the stator are 193 A and 415 V, respectively. The pitch (14/24) of the stator coils ensures that the winding produces very little seventh harmonic field, while the higher order fields are reduced by the distribution of the phase conductors throughout each phase belt. Consequently, it is the fifth harmonic field which presents the greatest difficulty.

This field appears on the rotor at 300 Hz and, if not controlled, would produce substantial losses in the rotor. Such losses can be greatly reduced by placing a thin (0.5–1 mm) layer of copper over the rotor surface to provide a low resistance path for the eddy currents (noting that high frequency eddy currents are inductance limited in comparison with low frequency eddy currents which are resistance limited). Although the copper layer greatly reduces the losses, it was estimated that the losses in this layer would be about 7.5 W at full load, which would contribute a significant proportion of the load on the cryogenic cooling system.

The rotor pole face shape is mostly at radius 145 mm, but with two scollops each defined by a 50 mm radius and intersecting the 145 mm radius 20°

and 40° from the centre of the pole face. The shaping of the pole face gives a substantial reduction in the fifth harmonic field of the rotor, and hence improves the output waveform of the generator. By the use of finite element analysis, it was estimated that the scollops reduce the fifth harmonic content of the no-load voltage waveform from 3.44% to 1.64%.

2.4. HTS rotor winding

The HTS rotor winding is made of 12 identical single-layer vacuum impregnated pancake coils, each having 50 turns of Ag sheathed BSCCO tapes with a nominal critical current of >100 A at 77 K and self-field, and interleaved by a fibreglass sheet. The radial and axial inner diameter of the coils is 168 and 344 mm respectively with a 30 mm bend radius at the corners and a coil width of 25 mm. Each turn is assumed to occupy a 4.5×0.5 mm space, and to be placed 0.5 mm away from the outer flux diverter ring. The total space allowed for each coil is 6.5 mm. With this design, an air-gap flux density of about 0.75 T can be achieved when operating at 77 K with a DC current of 54 A, which produces a maximum normal field component of 0.05 T in the winding.

2.5. Refrigeration system

For the present generator, a self-pumping liquid cryogen closed circuit with a set mass flow rate has been designed. Liquid cryogen is pumped down a stainless steel tube by utilising the generator 3000 rpm rotational speed. The cryogen passes through the centre of the rotor core, and returns around the outer surface of the rotor and is then returned to the cooling system in an outer concentric tube. The warmed fluid exiting the rotor is cooled by means of a heat exchanger and a cryogenerator of Gifford McMahon type with a cooling power of the order of 100 W at 60 K. To enhance critical current values as much as possible, the cryogen will be sub-cooled near to its freezing point. If liquid nitrogen is used, the minimum usable temperature is approximately 65 K (freezing temperature 64 K). Another attractive option, which we intend to try,

is the use of liquid air; this has a lower freezing point of 57 K allowing the rotor to operate at 58–59 K with an 80% increase in the critical current of the superconductor.

3. Future work and outcomes

It is universally recognised that economic benefits of HTS materials cannot be shown directly on a small machine; nevertheless it will be possible to project our results and demonstrate the principal advantages of our design. The future work and expected outcome of the present research programme are:

1. Build and test a demonstrator generator in order to assess the potential of high temperature superconducting technology in electric power applications, in particular for rotating machines.
2. Study and optimise heat transfer and refrigeration within a rotating cryostat.
3. Conduct a comprehensive program of tests to assess the performance of HTS tapes under operating conditions.
4. Develop computer simulation models for virtual prototyping of devices incorporating HTS elements.
5. Produce flexible design guidelines for electric power devices using HTS tapes that will be able to reflect the continuing progress in tape performance.

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