100kVA High Temperature Superconducting Generator

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Following significant amendment to our previous published design, this paper presents the main features of the new design of a 100kVA HTS demonstrator generator, which is 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 73-77K. The generator will use an existing stator with a bore of 330mm. In our previous design, it was suggested the use of Invar alloy as the magnetic rotor to reduce the magnetising current and the field in the coils, but this was an expensive and structurally demanding design. In the present design, the rotor core will be built using 9% Ni steel plates. This alloy has excellent mechanical and magnetic properties at temperatures down to 73K. For ease of manufacture, a hybrid salient pole construction is used, and the superconducting winding consists of ten 40-turn identical flat coils. Magnetic rings made of 9% Ni are 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 is placed around the rotor core to exclude ac magnetic fields.

INTRODUCTION

Unlike 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 20K and 30K. 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 77K. It is also possible to have a core-less 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.

OVERVIEW

The machine is a 3-phase 2-pole 100-kVA 3000-rpm synchronous generator with a hybrid salient pole rotor (see Figure 1) which operates in the temperature range 73-77K. Unusually, the superconducting rotor will have a magnetic metallic core. This has two principal advantages. First, it greatly reduces the magnetising current, which allows the rotor to be constructed using much less superconducting tape. Secondly, it allows the flux density in the superconductor to be reduced and its direction to be controlled. It therefore becomes possible to use liquid nitrogen cooling at 77K instead of more expensive and less efficient 'gaseous' helium or neon cooling (at temperatures below 30K) which would be required in a core-less design.

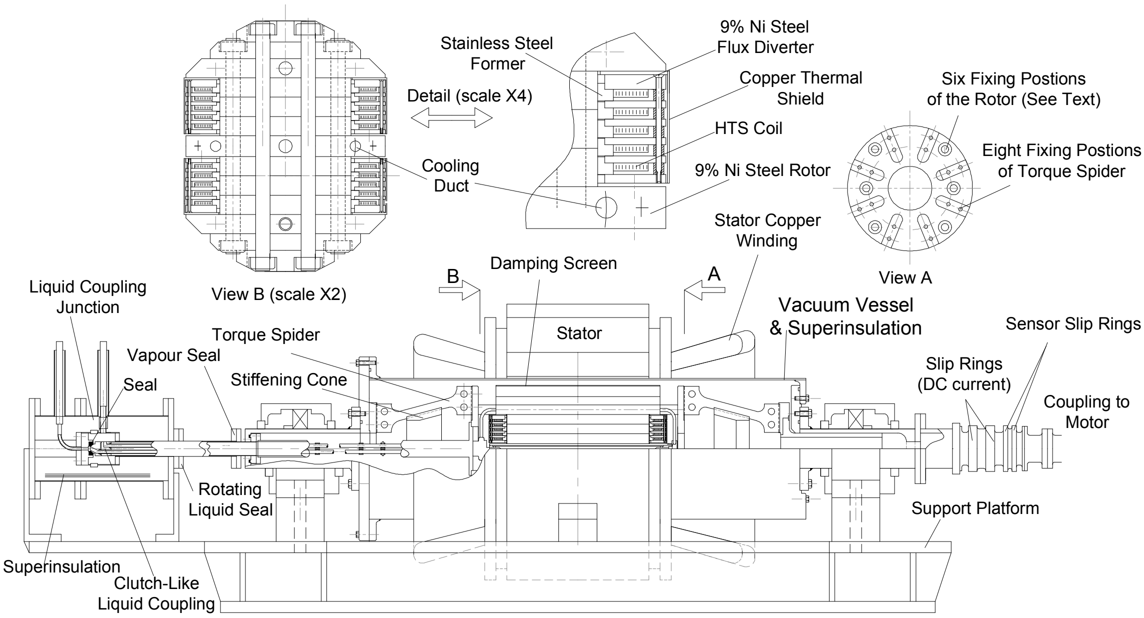

Figure1 Sketch of the 100kVA HTS generator.

Since most ferromagnetic materials are brittle at liquid nitrogen temperatures, the rotor of the generator will be made of 9% Ni steel. The use of Invar (36% Ni, 64% Fe) was also considered, but the low thermal expansion coefficient of Invar presented great difficulty, since it must be connected to non-magnetic structural materials (stainless steel and fibreglass), which have much higher (but similar) thermal expansion coefficients. The rotor core will therefore be made from 9% Ni steel. This material is not produced in thick sections; the rotor core will therefore consist of a stack of different size and shape plates with through bolts (see Figure 2).

At both ends of the rotor, six stainless steel bolts and bushes clamp the rotor body to carefully placed 9% Ni steel plates. This non-magnetic mechanical link is used to break the magnetic circuit. The room temperature stainless steel stub shafts are linked to the two 9% Ni steel plates using a novel design of fibreglass *Torque Spider* to provide the mechanical support required and to reduce the heat influx in to the generator cold space. The torque spider consists of eight fibreglass legs, which are strengthened by a *Stiffening Cone* as seen in Figure 1. To avoid excessive eddy-current losses in the rotor pole faces, a cold copper screen is placed around the rotor core to exclude ac

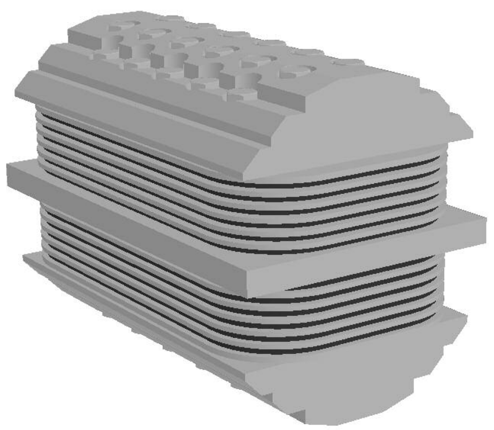

Figure 2 Construction of the rotor core and HTS coils.

magnetic fields. The entire assembly (rotor, HTS winding, torque spider and flanges) is wrapped by layers of superinsulation and encapsulated by the outer vacuum cryostat.

HYBRID ROTOR AND FLUX DIVERTERS

In early designs, the rotor core was of the round rotor type, but with all the slot sides parallel, so that 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 should be used. Instead of placing the rotor winding in slots, separate ferromagnetic rings are placed between the coils. These divert flux around the coils and so reduce the normal component of flux density in the superconductor. Finite element analysis (Figure 3) shows that the magnetic rings virtually eliminate the normal field component in the coils. Thus, the hybrid design retains the advantage of placing the coils in slots, while allowing the coils to be wound separately and fitted to the core later. This greatly simplifies the construction of the rotor.

HARMONIC FLUX CONSIDERATIONS

The generator will use an existing stator from a conventional 100kVA, 3-phase 2-pole machine, which has a 330mm bore diameter and 325mm iron length. A substantial programme of finite element analysis has been undertaken [3] to minimise the problems caused by air-gap flux harmonics, subject to the restrictions imposed by the choice of stator. These problems are of two types, losses in the rotor that must be removed by the cryogenic cooling system, and stator voltage harmonics that can drive currents in the external circuit.

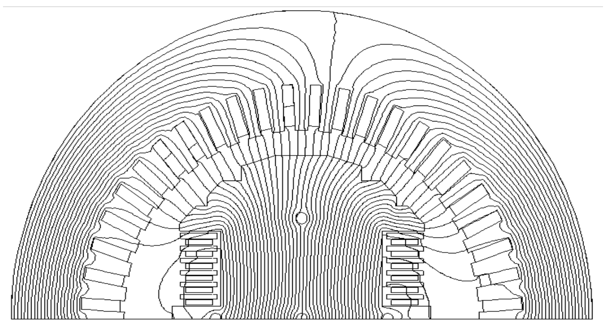

Figure 3 Flux lines in the proposed superconducting rotor at full load (showing one pole)

HTS ROTOR WINDING

The HTS rotor winding is made of ten identical single-layer vacuum impregnated pancake coils connected in series. Each coil has 40 turns of Ag sheathed $(BiPb)_2Sr_2Ca_2Cu_3O_x$ tape (nominal critical current of >100A at 77K and self-field) wound on a stainless steel former and interleaved by a fibreglass sheet. The radial and axial inner diameters of the coils are 168mm and 344mm respectively with a 30mm bend radius at the corners. Each turn is assumed to occupy a 4.5×0.5mm space, and to be placed 0.5mm away from the outer flux diverter ring. The total space allowed for each coil is 6.5mm. With this design, a field current of 63A will produce an air-gap flux density of about 0.66T, while producing a normal field of only 0.038T in the superconductor. This field current will require the winding to operate at about 77K. Operating at lower temperatures would allow a higher field current, which would increase the stator flux linkage, permitting a higher output power without significantly increasing the stator losses.

REFRIGERATION SYSTEM

The required low temperatures are provided using a purpose built closed circuit liquid cryogen cooling system with pipe-network feeding liquid cryogen to the rotor body of the generator. The heat load into the entire generator has been estimated to be around 60W. The refrigeration system can be divided into four components;

Cryostat
The liquid cryogen (N_2 or air) is maintained at sub-cooled temperature and one atmosphere pressure inside a double wall super-insulated cryostat. The inner vessel holds up to eight litres of cryogen and it is thermally connected to a Gifford McMahon cryogenerator (Leybold cool power RGS 120 T), which provide the required cooling power.

Cryogenic pump
A long shaft purpose built submerged pump is used to circulate the cryogen through the pipe-network of the refrigeration system.

Heat exchanger
The cryogen is after-cooled further by using a heat exchanger thermally anchored to the cryogenerator head.

Liquid coupling junction
The liquid cryogen is carried to and from a coupling junction via two flexible vacuum- super-insulated transfer lines. The coupling junction acts as a liquid sealed link between the rotating pipe-network, which supplies the cryogen to the generator rotor and the stationery transfer lines. The junction consists of a clutch-like feeding port, a vacuum capsule and two cryogenic rotating seals.

CONCLUSIONS

A 100kVA HTS superconducting synchronous generator is currently being built at the University of Southampton. The generator uses an existing conventional stator while the rotor is made of 9% Ni steel. The rotor winding is made of ten 40-turn BiPb2223 flat pancake coils. For operation at temperatures close to the boiling point of liquid nitrogen, it is of great importance to reduce the normal magnetic field components in the superconducting tape. This is achieved in our design by carefully modelled and optimised placement of magnetic rings in between the superconducting coils. These rings significantly reduce the undesirable normal magnetic fields. The project has produced important guidelines for the design of power devices using HTS tapes at liquid nitrogen temperatures, which may benefit from the continuing progress in tape performance.

It is generally 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.

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