Development of a coreless HTS synchronous generator operating at sub-cooled liquid nitrogen temperatures

M. K. Al-Mosawi, W. Bailey, C. Beduz, K. Goddard, Y. Yang
School of Engineering Sciences, University of Southampton, Southampton, SO171BJ, UK
E-mail: maitham1@soton.ac.uk

Abstract. This paper presents the current design concepts for a 100kW high temperature superconducting synchronous generator currently being designed at the University of Southampton, UK. The new generator will use the same conventional 2-pole 3-phase stator that was used in the HTS synchronous generator previously constructed at Southampton. The windings consist of 18 pancake coils made from BiPb2223 superconducting tape with a nominal current of 180A at 77K, provided by Sumitomo Electric Industries, Ltd. Tests were performed to determine the mechanical strain limits of the tape. The rotor has no central core, but magnetic pole pieces are used to improve the waveform of the generator. The coils are separated by magnetic diverter rings to reduce the normal field in the tape. The coils and diverter rings are supported by fibreglass formers that extend to the centre of the rotor so that they can be located by the through bolts that hold the stack together. A stainless steel tube encapsulates the rotor to provide a chamber for liquid nitrogen to flood the rotor.

1. Introduction

High temperature superconducting (HTS) power applications have the potential to radically reduce energy losses, which has both economic and environmental benefits. Recent designs for new HTS rotating machinery have steered towards providing for marine applications [1-2]. The construction of the first UK built 100kW synchronous generator, [3] demonstrated the feasibility for using HTS windings which operated at 77K. The original rotor core was manufactured from a 9% NiSteel; structurally suitable for most cryogenic designs and is also highly magnetic which is useful for reducing the magnetising current. The advantages of using a core include; i) a reduction in the amount of superconducting tape used for the windings, ii) allows the direction of the flux paths to be well controlled.

Recent advances in commercially available BSCCO tapes have inspired new work upon a hybrid design [4], featuring no core but retaining the flux diverters from the earlier design. The new machine will also operate at or close to liquid nitrogen temperatures in order retain the commercial attractions associated with the previous design.

Removing the rotor core increases the magnetising current, requiring more superconducting tape and a lower operating temperature. Moreover the core was useful for supporting the coils and conducting heat to the cryogen. Particularly challenging is the requirement for all the coils and diverters to be held together as a single unit. This must be able to cope with the rotational stresses and retain sufficient stiffness to maintain high critical speeds, and still be able to absorb the
thermal contractions of materials. Since the coils carry a higher current than in the previous design and must operate closer to the freezing point of nitrogen, better cooling is required. In this paper we present our solutions to these problems.

2. Design

The generator is a 2-pole synchronous machine with a conventional 3-phase stator. There are five areas of the previous generator which require redesigning in order to develop the coreless machine; i) HTS windings, ii) diverters iii) torque tube sub-assembly, iv) rotor assembly, v) cooling system. The rotor requires a complete revamp, since the coils and diverter rings no longer have the structural support previously provided by the core block.

Some initial estimates suggested that if the core were removed, the weight of the new rotor design could be halved. However, in order to provide the required stiffness to support the coils and a rigid framework capable of transmitting the torque from the drive shaft, the fibreglass coil formers are extended into the hollow space left by removing the core. Although fibreglass is lighter than steel, the requirement for through bolts to hold the stack together limits the reduction in the mass which can be achieved.

To retain liquid nitrogen as the cooling medium, the rotor windings are to be wound from new superconducting tape with a much higher critical current than the tape used for the previous winding. Finite element modelling of the new generator layout has been used to determine its new operating conditions taking into consideration the \( I_c-B \) characteristics of the tape. To obtain an air-gap flux density of around 0.5T, the winding will have to carry a field current of 150 A and will therefore need to operate at a temperature of around 66K. The superconducting coils in the previous machine were indirectly cooled using copper connections to a network of pipes, containing liquid nitrogen pumped in a closed loop. With more heat dissipated due to higher current inputs and a smaller difference between the temperature of the cryogen and the required working temperature of the winding, better heat transfer is required. To achieve this, the liquid nitrogen will need to cool each coil directly.

2.1. HTS windings

The coreless HTS rotor winding rotor consists of 9 single-layer vacuum impregnated pancake coils in each half of the rotor. Each coil has 60 turns and is wound using Ag sheathed BiPb2223 superconducting tape supplied by Sumitomo Electric Industries Ltd. The nominal critical current for this tape is specified as \( >180 \text{ A} \) at 77 K and self-field. Overstraining when bending, pulling or twisting the tape during the winding process can severely reduce the critical current. In order to assess the ability to handle and wind the coils, we measured the critical current of the tape while subjected to different mechanical strains. The critical current was measured by detecting a 1\( \mu \text{V} \) drop over a 1 cm length in the superconducting tape. The result of the initial tests are presented in Figure 1; it should be noted that each set of results are obtained from a single sample. The strain tolerance is the permitted strain before the critical current drops by 5% of its initial unstrained value and is indicated on each of the curves by the dashed line. This type of data is used to set the bend radii and winding tensions for manufacture of the coils.

Since the new rotor is coreless, the coils nearer the centre of the machine must be wider than those near the poles. Coils are wound on temporary formers coated with PTFE and vacuum impregnated in epoxy before being removed from the former and cured. The hardened coil is then placed in a bed pre-machined into a thick G10/40 fibreglass plate, shown in Figure 2. The coil and former assembly is strengthened by a second vacuum impregnation. Figure 3 shows a cross-sectional view of the HTS winding, the gap between each coil and diverter is 0.5 mm. The coils are connected in series using copper strips which are kept as short as possible to ensure low electrical resistance.
Figure 1. – Measurements of mechanical strains of the BiPb2223 superconducting tape, rated at 150 A, at 77K and self field, supplied by Sumitomo Electric Industries Ltd. (A) axial tension, (B) compression, (C) bending, (D) torsion.

Figure 2. – (A) G10/40 fibreglass former showing the bed for the coil, (B) coil positioned in the bed and showing a seat for the diverter ring, (C) framework of the rotor with flanges and torque tube assembly.
2.2. Flux Diverters

The use of flux diverters is primarily aimed at reducing the field normal to the broad face of the tape to increase the critical current of the winding. However without any core, the magnetising current of the generator increases making it more difficult to control the flux density in the coils. The thicknesses of the flux diverters in the coreless design have been optimised in order to maximise the critical current and so to gain higher air-gap flux-density. The waveform was improved by modifying the widths of the diverter rings and changing the shape of the pole pieces.

Each half of the rotor has 8 flux diverters machined from 9%Ni steel, which is magnetic and also non-brittle at cryogenic temperatures. The pole pieces or ‘hats’ are machined from Invar plate, due solely to the unavailability of small quantities of thick plate 9%Ni steel. Invar is also magnetic and used extensively in cryogenics due to its near zero thermal contraction. The centre diverter has been modified in order to accommodate some locations at which it fixes to the end flange and becomes a load bearing feature of the design.

2.3. Torque tube sub-assembly

The torque tube assembly in the old design consists of two stainless steel flanges held together by eight dog-bone-shaped arms, which are machined from G10/40 fiberglass. The structure was reinforced by a central stiffening cone. Since this was successful, we intend to maintain the same shape and use the same materials in the new design. After the mass of the rotor is determined, the number and thickness of the arms will be re-optimised to minimise heat flow whilst maintaining a satisfactory critical speed. Since it is expected that the reduction in the mass achieved by removing the rotor core will not be large, the number of arms required could well remain the same as in the old machine.

2.4. Rotor assembly

The rotor stack is formed from 18 plates of G10/40 fiberglass, each holding a coil and a diverter ring. The top and bottom Invar hats are machined with counter-bores to except 12 × M16 and 4 × M12 stainless bolts. Some of these bolts run through clearance holes, while others have close fitting holes to align the stack. As this stack is cooled, the thickness of the G10/40 coil formers will contract more than twice as much as the length of the stainless steel through bolts. In the central part of the rotor, where there is no 9%Ni steel, this differential thermal contraction would produce about 0.67mm of slack. Movement of loose plates will unbalance the rotor, and may cause damage by impact or fretting. Significant movement of a large part of the rotor could result in a catastrophic failure. It is not possible to eliminate all the slack by tightening the bolts.
through bolts, since this would produce excessive stresses in the bolts when the rotor is warm. However, the thermal contraction of 9%Ni steel is less than that of stainless steel; hence, at the ends of the rotor stack, differential contraction would produce only 0.29mm of slack. Due to the flexibility of the G10/40 material, it is possible to eliminate this much slack by tightening the bolts without imposing excessive stress.

It is not possible to place through bolts near the ends of the rotor stack, since these would pass through the coils. Consequently, the end bolts tend to carry more than their fair share of the centrifugal force. To avoid excessive stresses in the end bolts, some of this load must be carried by the end flanges.

Differential thermal contraction in the axial direction also causes some difficulties. The stainless steel tube that contains the liquid cryogen will shrink more than the rotor. If the ends of this tube were rigidly connected to the ends of the rotor, excessive tensile stress would be imposed along the length of this tube. Instead, we intend to make a flexible or sliding connection between the end of the rotor stack and the end plate that closes the rotating liquid vessel. Unfortunately this requires the addition of intermediate flanges, which increases the mass of the rotor.

**Figure 4.** Sketch of the refrigeration system showing a LIN cryostat. The DC motor drives the pump inside the storage vessel, which is connected to the heat-exchanger and a cryo-generator. Liquid nitrogen is pumped to the heat-exchanger and transferred to the generator by a transfer line at the coupling junction. Warm LIN is transferred back to cryostat via a second transfer line.

### 2.5. Cooling system

In order to achieve direct cooling of each coil, a stainless steel inner vessel sealed against two flanges surrounds the rotor and holds a volume of liquid nitrogen. During full operation, the tube must withstand 9 bars of pressure mainly due to the centrifugal force. The complete refrigeration system is presented in Figure 4 and shows an exploded view of a cryogenic pump. The pump is of a positive displacement type, with the length of its stroke altered by the changing the position of the conrod on the cam fixed to the drive motor. Two types of non-return valves have been assigned to the inlet and outlet in order to assess the feasibility for use in the finalised design. It is
estimated that the cooling system needs to remove about 50W from the rotor assembly. To achieve this with a temperature difference of 1K, we require a flow rate of 1.5L/s. Some initial tests show that the pump described above can deliver 1.3L/s at full stroke. By adding PTFE piston rings and enlarging the exit hole in the cylinder, we expect to obtain the necessary increase in flow rate.

The liquid is pumped from the storage vessel, which is thermally linked to a cryo-generator, and flows through the heat-exchanger, where it is sub-cooled before it is delivered to the generator via a flexible vacuum/super-insulated transfer line. The injection of LIN from the stationary to the rotating part of the machine occurs at the coupling junction. This is a vacuum insulated container with a PTFE clutch that engages with the rotating shaft of the machine to separate the inlet and return liquid flows. Liquid flows into the inner vessel, through a hole in the end flange and is ducted to the other end of the rotor. The liquid then flows freely in the chamber back through another hole in the same flange, back to the coupling junction and returns to the cryostat via a separate transfer line.

3. Conclusions
Design of a coreless synchronous machine has thrown up new problems, particularly with the need to clamp the coils and diverter rings together as a rigid structure without a core for support. The problem has forced us to fill this void by extending all the fiberglass formers to the centre, to accommodate some through bolts for clamping all of the components together. The removal of the core makes heavier demands on the cooling system, since removing the core increases the magnetising current. Although the use of better superconducting tapes helps, the winding itself must operate at a lower temperature than in the previous design. Moreover since the number of turns and the current in the winding have been increased, the losses will also increase. The coils will therefore be directly cooled by flooding the winding with liquid nitrogen.

Finite element models of the coil formers and flux diverters show that the stack can be clamped using through bolts, so that none of the parts become loose due to thermal contraction. However, in order for the machine to run at full speed, some of the centrifugal force must be carried by the end flanges.

A model of the central stack and through bolts has shown that if clearance is provided between the end bolts and the formers, the thermal contraction of the stack relative to the Invar hat can be accommodated. However, further modeling is required to investigate the effect of thermal contraction on the end flanges and the liquid vessel. Unfortunately the problems with supporting and cooling the rotor windings have prevented large reductions in the rotor mass from being achieved.

4. References
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