Fabrication and characterization of Bi-2223 coils for generator applications

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A set of race-track pancake coils for a 100 kVA superconducting generator was constructed using high strength reinforced Bi-2223 tapes with co-wound fibre glass cloth and epoxy impregnation. Mechanical and thermal properties of the coil composites were conducted. *I-V* characteristics and the critical current at 77 K of the superconducting coils were measured. The onset and progress of thermal runaway due to over-current were investigated by measuring the temperature rise and overall voltage increase. The outcome of this work contributed greatly to the design stage and quality control of the superconducting generator.

INTRODUCTION

The development of High Temperature Superconducting (HTS) tapes is making significant progress in terms of availability, high Ic, long length and cost. Tapes are often being wound as pancake-shaped coils for use in small or medium scale HTS machines. The design and construction of these coils should minimize degradation of the critical current during construction and improve robustness during operation. Large mechanical and electromagnetic forces during operation as well as forces induced by the manufacturing process and thermal cycling should be taken into consideration.

Comprehensive characterization of the mechanical, thermal and superconducting properties of the coils is conducted as part of a project at Southampton University to design, construct and test a 100 kVA HTS superconducting synchronous generator [1]. The results of this work are crucial for modelling and predicting performances during operation of the generator and also represent a mean of quality control to qualify the coils for use in the machine.

COIL WINDING TECHNIQUE

Ten 40-turn single layer race-track coils are constructed to form the rotor winding of the generator, see Figure 1. The radial and axial lengths of the coils are 188 mm, 364 mm, respectively, whereas the minimum bending radius at the corners is 39 mm. These coils are produced by the react and wind method using a purpose built apparatus. American Superconductor Corporation (AMSC) Bi-2223 stainless steel reinforced tapes with nominal critical current of 115 A (77 K, self field) are used. The tape is co-wound with a fibre glass sheet of thickness 100 μm to provide turn-to-turn insulation as shown in Figure 2.

Figure 1 Photo of ten race-track pancake coils.

The winding apparatus, driven by a DC motor at variable speeds between 4 and 8 rpm, is designed and constructed to handle the race-track shaped coils by resting the feeding spool on a reference race-track former to trace the contour of the coil. A winding tension of 10N is maintained by the use of an adjustable soft brake, which also moves with the reference coil former. Such arrangements help to maintain a constant winding speed and reduce the potential damage caused by the changing diameter of the race-track coil.

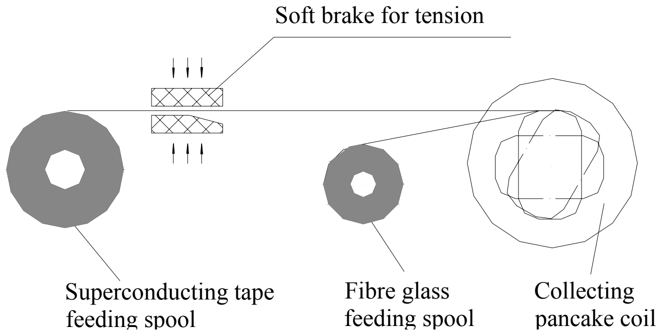


Figure 2, Winding of race-track superconducting coils

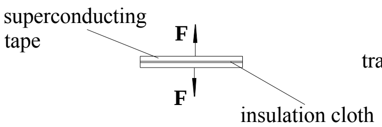
Copper current leads are soldered to the ends of coils, with voltage taps and thermocouples soldered at various locations within the coil. An extra twelve layers of fibre glass sheet is wound to provide further support to the turns. Finally, epoxy resin is vacuumed impregnated to enhance structural integrity of the coils.

COIL CHARACTERIZATION

Mechanical properties

HTS coils are essentially a composite comprising of HTS tape, insulation material of and impregnation epoxy. The configuration and results for the axial tensile, transverse tensile, and axial shear strengths are given in Table 1. For the axial tensile test, the specimens are prepared via vacuumed impregnation of 4 lengths of tapes interleaved by fibre glass sheets. The final specimen is about 1.6 mm thick and 110 mm long. For the transverse tensile test, two superconducting tapes were soldered to brass holders and glued together with a sheet of fibre glass in between. In the shear test, the specimen is formed by overlapping two tapes over a 20 mm long (see Table 1). All the specimens are tested at 77K with a tensile machine and loaded using a purpose built grip chucks.

Table 1 Mechanical test of coil composite

Test Configurations		Test Results
 F F	axial tensile	$\sigma_{0.2}$ = 290MPa σ_u = 380MPa
 superconducting tape, F, F, insulation cloth	transverse tensile	σ_u = 3.8MPa
 F F	shear	σ_u = 3.9MPa

The axial proof tensile strength ($\sigma_{0.2}$) and ultimate tensile strength (σ_u) were obtained using axial load-elongation curve, and are calculated to be 290 MPa (0.2% offset) and 380 MPa, respectively. The ultimate (fracture) transverse tensile strength is 3.8 MPa and the ultimate sheer strength is found to be 3.9MPa. These results, as listed in Table 1, provide crucial data in the design of superconducting machines.

Thermal contraction

Thermal contraction of the coil composite and its constituents (superconducting tape, fibre glass/epoxy) from 77 K to 293 K are measured using a quartz tube dilatometer with a linear variable differential transformer (LVDT) [2]. Due to inhomogeneous nature of the coil composite, the thermal contraction measurements are conducted for both warp and normal directions of the coils, using similar specimens to those for the axial tensile test.

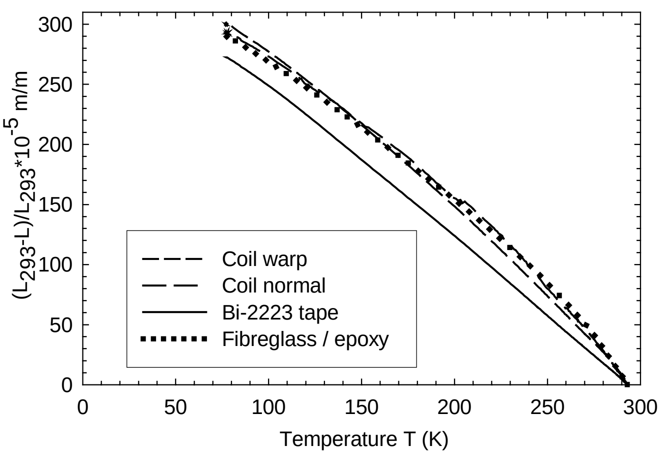


Figure 3 Linear thermal contractions of superconducting coil and its constituents.

The results of these measurements are shown in Figure 3. It can be seen that there are rather small but noticeable difference between the various constituents and the coil composite itself, with the sole superconducting tape having the lowest contraction for the same range of temperature. The total linear thermal contractions from room temperature to 77 K of coil in warp and normal directions are 0.28% and 0.29%, respectively. The total thermal contractions for the sole Bi-2223 tape and fibreglass/epoxy composite are found to be 0.28% and 0.30, respectively.

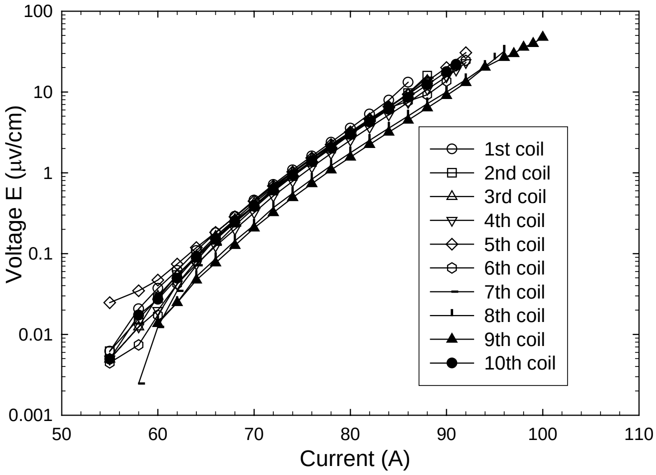


Figure 4 *I-V* characteristic of 10 Bi-2223 pancake coils.

Superconducting properties

The *I–V* characteristics of the 10 coils are determined at 77 K and coil self-field (see Figure 4). The critical currents of the coils are in the range of 75 A ± 3 A, which is about 60% of the critical current of a short sample and broadly consistent with the predicted values using the field dependence of the critical current. The power exponent *n* of the *I–V* curves for the 10 coils found to about 16. It can be concluded that the construction process and the use of coil composite materials prove to be adequate for our performance criteria. The coils also show consistency over several cooling cycles.

In a superconducting winding tape-to-tape joints sometimes become unavoidable. In the generator winding, a lap-splice tape joint in one of the coils is deliberately introduced using Sn–Pb solder. The total joint resistance is measured and found to be 0.15µΩ, which gives contact resistance 0.58 $\mu\Omega cm^2$.

Instability above critical current

As indications to coil stability, the excursions of coil temperature and voltage with time of one of the coils subjected to currents above the critical value were monitored using differential thermocouples in the middle of the coil and end-to-end voltage taps. Such over-current measurements were conducted by submerging the coils in a liquid nitrogen bath at 77K, before and after coil impregnation to examine the effect of epoxy resin to overall heat transfer. The activation of nucleation sites has been varied by cycling the current through the coil for several times.

Figure 5 & 6 shows the temperature and voltage traces of the pre-impregnated and post-impregnated coils with various applied over-currents. It can be seen that the temperature and voltage runaway occurs at 106 A for the pre-impregnated whereas the runaway occurs at lower current of 94 A for the post-impregnated coil. As expected, the temperature and voltage runaway for pre-impregnated coils showed strong dependence on the boiling conditions, as activation of the surfaces inhibits the thermal runaway at 106A (thick lines in Fig. 5a-b). In contrast, post-impregnated coils exhibited only a weak improvement at 93 A (thick lines in Fig. 6a-b), as the impregnation epoxy becomes the dominant thermal resistance. The heat flux of thermal runaway for the post-impregnated coil is 0.2 W/cm^2, well below the onset nucleate boiling. This suggests that thermal runaway is initiated in the natural convection regime, where heat transfer in generally poor. It remains unclear whether full recovery is possible with established nucleate boiling at higher heat flux below the critical heat flux CHF. However the runaway tests were terminated to prevent burnout of coils, which have to be used as part of the superconducting rotor. To verify whether this runaway will stabilize or it is a true runaway, further tests are required to clarify the true nature of this behaviour.

CONCLUSIONS

Ten single layer race-track vacuum impregnated coils are successfully manufactured, and the mechanical, thermal and superconducting properties of the coils are measured. The choices of impregnation and insulation materials and matching thermal contractions of the coil components are crucial for reliable performances of the coils. The coils show a constant performance after several cooling cycles with critical currents in the range of 75 ± 3 A. The proof and ultimate axial tensile strength are 290 MPa and 360~390 MPa, which indicate satisfactory strength for safe operation of the 100 kVA superconducting generator.

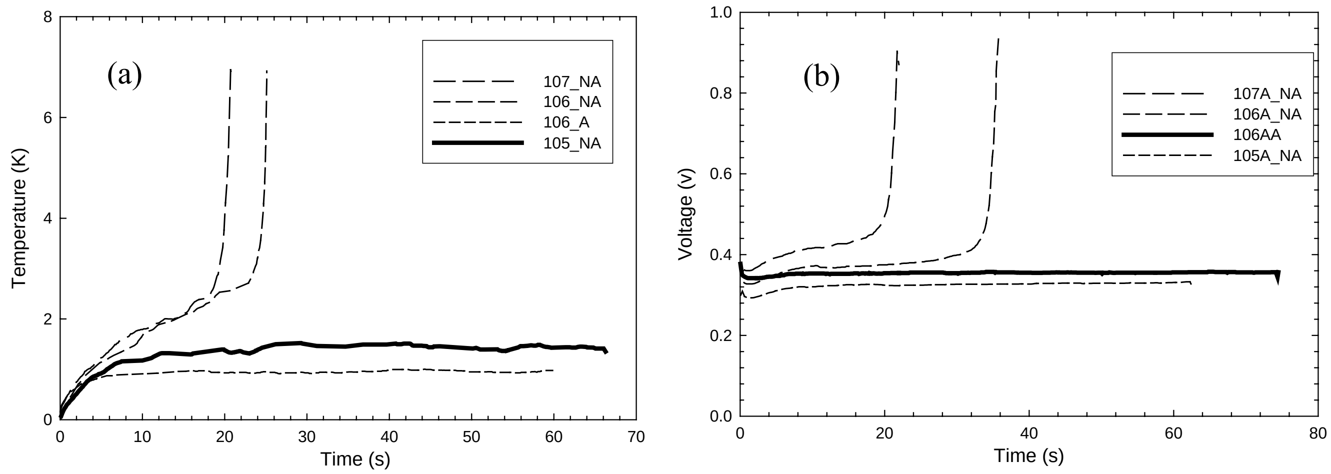


Figure 5 Temperature (a) and voltage (b) excursions at various applied currents for the pre-impregnated coil. (NA: not activated, A: activated.)

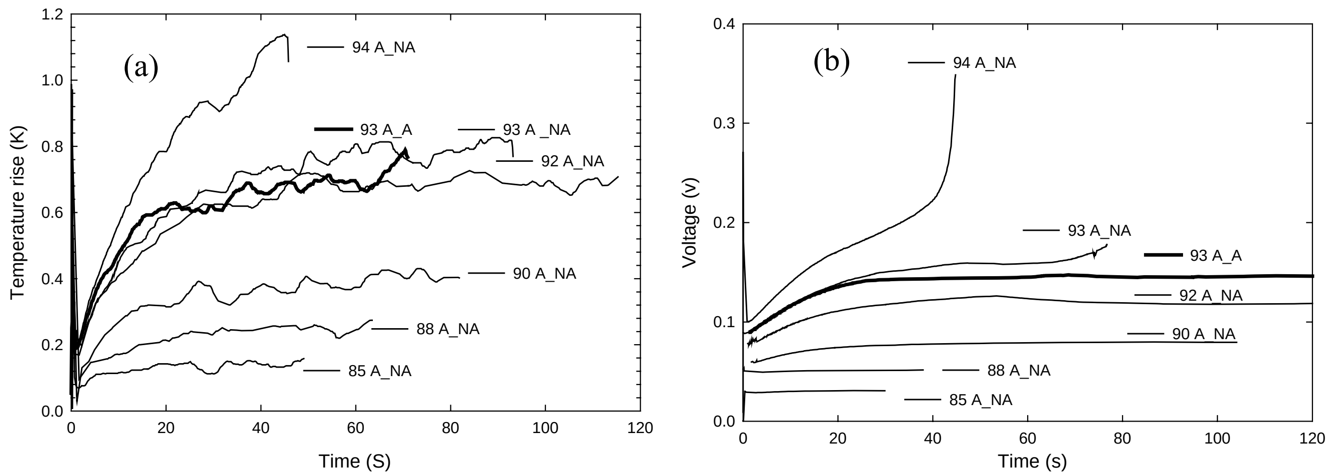


Figure 6 Temperature (a) and voltage (b) excursions at various applied currents for the post-impregnated coil. (NA: not activated, A: activated.)

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