Testing of machine wound second generation HTS tape Vacuum Pressure Impregnated coils

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Abstract. Delamination of second generation (2G) High Temperature Superconducting (HTS) tapes has previously been reported when using resin based insulation systems for wound coils. One proposed root cause is the differential thermal contraction between the coil former and the resin encapsulated coil turns resulting in the tape c-axis tensile stress being exceeded. Importantly, delamination results in unacceptable degradation of the superconductor critical current level. To mitigate the delamination risk and prove winding, jointing and Vacuum Pressure Impregnation (VPI) processes in the production of coils for superconducting rotating machines at GE Power Conversion two scaled trial coils have been wound and extensively tested. The coils are wound from 12mm wide 2G HTS tape supplied by AMSC onto stainless steel 'racetrack' coil formers. The coils are wound in two layers which include both in-line and layer-layer joints subject to in-process test. The resin insulation system chosen is VPI and oven cured. Tests included; insulation resistance, repeat quench and recovery of the superconductor, heat runs and measurement of n-value, before and after multiple thermal cycling between ambient and 35 Kelvin. No degradation of coil performance is evidenced.

1. Introduction

The exciting prospect of superconducting rotating machines with a vastly reduced footprint, mass and greater efficiency has tremendous promise for a range of applications, from high power wind generators (> 10MW) to Ship propulsion drivetrains [1-3]. It is these benefits that have motivated academic institutions and machine manufacturers alike to pursue High Temperature Superconducting (HTS) rotating machine design. Several promising prototype machine designs have now been realised, however the price of the HTS material, usually used in the form of tape, remains key to any commercial proposition. In the last decade this has prompted development of second generation (2G) tape which promised reduced manufacturing costs and tape prices.

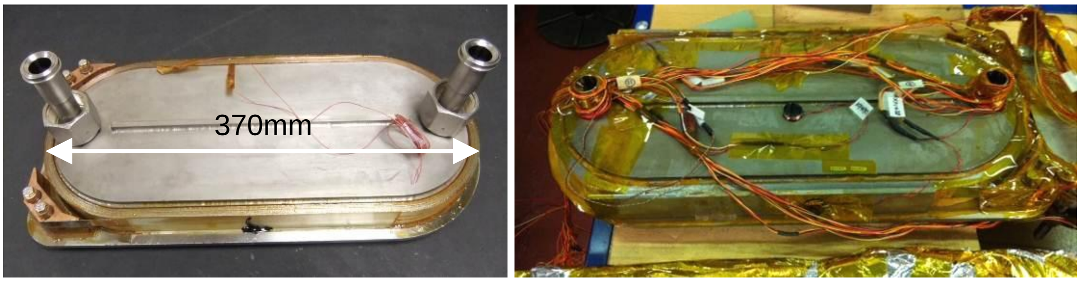
It has been reported by some workers that testing of second generation tape sometimes resulted in delamination of the tapes when using resin based insulation systems for wound coils [4-7]. One proposed root cause is the differential thermal contraction between the coil former (the mechanical structure upon which the coil is wound) and the resin encapsulated coil turns resulting in the tape c-axis (direction normal to tape length and widest tape face) tensile stress being exceeded. This represents an engineering challenge as delamination of the tape results in an unacceptable degradation of the superconductor critical current level.

As part of a series of tests at GE Power Conversion to mitigate against this risk in HTS machine manufacture, and to prove winding, jointing and VPI processes in the production of coils for superconducting rotating machines, two scaled trial coils have been wound and extensively tested. This paper reports the results of these process validation tests.

2. Coil design

The coils are pre-production down-scaled coils. Winding processes including: winder tension, jointing, in-process test and VPI processes are as for full scale superconducting field coil production.

Two coils have been manufactured and tested as detailed and results are reported below. The first of these was manufactured by a third tier supplier and the second was fully manufactured at GE Power Conversion's Rotating machines factory in Rugby, UK (figure 1).



(a) Coil #1 (b) Coil #2

Figure 1. (a) Coil #1 (manufactured by Zenergy GmbH), (b) Coil#2 (manufactured by GE, Rugby), shown instrumented for testing

The coils are wound from 12mm wide 2G HTS tape Copper Laminated 'Amperium' (Specification: 225A Ic (77K, 0T), AMSC measured: 281A) supplied by AMSC. This product has a wide solder fillet promoted as increasing the c-axis strength [8].

The coils are a simple 'racetrack' with straights of 220mm and end radius of 75mm. Coils are formed in 2 layers with 30 turns each, 60 turns total, wound onto stainless steel coil formers. To prove jointing processes the coils are wound in two layers which include both in-line and layer-layer joints subject to in-process test. The chosen resin insulation system is vacuum pressure impregnated (VPI) and oven cured.

3. Experimental design

3.1. Objectives

The objectives of the testing are:

- To characterise the quench and recovery of 2G HTS coils.
- To measure critical current and qualify the winding process (i.e. test what if any impact is evident on the critical current)
- To check for degradation or failure due to delamination within HTS tape layers or between HTS tape and former/insulation.
- To qualify both: in-line and layer-layer jointing processes

3.2. Test arrangement

Cernox sensors have been connected to the test coil arrangement to monitor the temperatures at the following critical locations: coil former top and bottom plate, coil terminals, each side of the coil (outside faces), cryostat current lead feed-through and current lead thermal dump. A Lakeshore supplied cryogenic Hall effect probe is positioned in the centre of the top plate of the coil former to measure magnetic flux.

The whole arrangement, coil, current leads and mechanical support (also acting as thermal break to room temperature) is wrapped in Multi-Layer Insulation to prevent radiation heat transfer and placed in an vacuum chamber evacuated to better than $2x10^{-5}$ mbar to prevent convection heat transfer. The arrangement is cooled by copper buswork between a Cryomech AL330 G-M coldhead and the coil former. The temperature of test coil can be cooled to a minimum of 35K. Heaters mounted on the coldhead can be used to control the temperature of the thermal buswork and test coil using a Lakeshore temperature controller.

The coil power is supplied by an Agilent 6690A DC power supply (0-15 V, 0-440 A and can be controlled by setting either the voltage or current) via a 0.01 Ω ballast resistor. A 600 A diode is connected directly across the feed-though terminals to provide a 'freewheel' current path and prevent overvoltage from the inductive coil in the event of accidental disconnection of the cables from the power supply (high di/dt condition).

4. Results & Discussion

4.1. Coil performance – baseline characterization

At room temperature the insulation was verified post VPI, i.e. >10GΩ at 500V between coil and former.
With the coil cooled to 35K the coil current was raised in steps to 440A without allowing temperatures to stabilise. This resulted in flux density of approximately 136mT, see Table 1 for full results. Resistance of the coil was monitored and as predicted was not observed to reach the critical current limit at this operating point.

The measured flux density was 31.5mT at 100A compared with 30mT predicted by Finite Element modelling at the Hall probe position.

4.2. Coil critical current, pre thermal cycling

The purpose of this test is determine the critical current for the coil at a known temperature, to compare with that after thermal cycling. The temperature controller was set to hold the coil temperature stable at 59K (62-63K on the current leads) when not energised. The coil current was gradually increased until the coil voltage measurements achieve the equivalent of 1 μV/cm, an industry accepted level at which to record critical current. Critical current was recorded at 370A. This represents 95% of the calculated critical current assuming no degradation from that measured by the tape manufacturer. 5% degradation is as expected from coil winding and is within design margins. The n-value was extracted by Least Squares Regression curve fitting and recorded as 27.

4.3. Thermal cycling

Both test coils have been thermally cycled to 35K and back to greater than 0 °C eight times. This temperature range ensures that the coil has been through the superconducting transition every cycle and differential thermal contraction stresses within the coil assembly have been applied.

In addition critical current was measured before and after the thermal cycles on both coils. Table 1, outlines the main test results for the test coils chronologically as performed. Visual inspection of the coils after completion of the tests in Table 1 revealed no signs of de-bonding of the tape or insulation system selected.

4.4. Coil critical current, post thermal cycling

Critical current is recorded before, after 5 and after 8 thermal cycles. Neither coil showed degradation after thermal cycling. For example Coil 2 critical current values, based on an equivalent of 1µV/cm, are: 370A, 370A and 373A respectively. The variability is likely due to measurement error and not considered significant.

Table 1. Test results of the 2 test coils

Test	**Coil #1**	**Coil # 2**
Post wind IR*	PASS	PASS
Post VPI IR*	PASS	PASS
Number of thermal cycles (440A applied in superconducting state)	5	8
Final Ic	370A @60K	373A @59.0K
Inductance (FE model, 10Hz)	1.76mH	1.76mH
Inductance (measured, 440A, 35K)	1.75mH	1.73mH
Flux density (FE model, 440A)	136mT	136mT
Flux density (measured, 440A, 35K, at coil centre position)	Not measured	141mT
Post cycling IR*	PASS	PASS

* IR stands for Insulation Resistance, a PASS is recorded if >10GΩ at 500V between coil and former.

5. Conclusion

Further confidence in the insulation system, winding and jointing process is provided by verifying that the critical current has not degraded after thermal cycling and the resulting mechanical stresses due to the differential thermal contraction within the tested 2G HTS coils. This added to the evidence of practical testing of larger coils and the Hydrogenie machine effectively demonstrates the viability of the insulation system and coil design employed at GE Power Conversion for HTS rotating machine field coils using 2G HTS tapes.

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