Measurement of a Conduction Cooled Nb₃Sn Racetrack Coil

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Introduction

Superconducting magnets and generators can have a much higher power density than their conventional counterparts. Such a high power density is an advantage for offshore wind turbines, where the size of the nacelle and tower are important cost factors. For all-electric aircraft, the superconducting power density and higher power per unit weight are the driving factors for the consideration of superconducting motors and generators. This is enabled by superconducting machines because the superconducting windings can achieve magnetic fields above those of conventional windings, and energy density goes as the square of the field. A new generator design by Haran uses field coils which surround a rotating induction coil. The induction coil is Cu, but the field coils are made from either Nb₃Sn or YBCO, and have high fields, about 6-8 T in present designs. Presently, Nb₃Sn is the more affordable option, and leads to very high power density designs.

The design for this machine calls for a set of racetrack-like windings placed to form a cylindrical winding in side of which the induction coils rotate. In a previous paper, a design for one of these Nb₃Sn racetrack coils was given, along with field and stress modeling, and the coil construction and winding was described. In this work, we describe the test results on that coil, including current and field measurements at the target temperature as well as at higher temperatures.

In the final machine as designed, the system would use cryocoolers with the coil conduction cooled using thermal straps. In this work, we use conduction cooling, but for simplicity we use a liquid helium reservoir as the cooling basins connected to the cooling straps, rather than a cryocooler. Nonetheless, we are able to see the performance of the coil in conduction cooled mode, as well as the temperature gradient of the coil. The coil measured here is the one which was modeled and described previously in 1. Herein we report the results from the successful manufacture and testing of a prototype coil.

Manufacture

The conductor (strand 3635), manufactured by Hyper Tech Research, Inc., has 0.7 mm OD before insulation and contains 185 superconducting filaments. The non-Cu area fraction was 46.6%. Pure Cu was used as the interfilamentary matrix. The wire was insulated with a s-braid before winding.

Coil Winding

• Wound counter-clockwise with 1239 m of wire, with 11 turns per layer and 95.75 turns in total.
• The winding pack had a length of 618.1 mm, a height of 70.7 mm, and width of 9.5 mm.
• Heated to vacuum at 62°C for 120 hrs plus ramp-up and cool-down.
• Current leads were soldered with 450° Pb-Sn solder.
• Epoxy impregnated by vacuum infiltration at a pressure of 7.10 Torr, with flow duration of 7 hours and curing time of 24 hours.

Instrumentation

• Three type thermometers sensors were used:
  • one at the current leads at the top
  • one at the center point of the coil
  • one at the bottom end of the Cu support rods.
• Two Hall sensors attached for magnetic flux measurement:
  • one on-axis
  • one off-axis at the point of maximum magnetic field.
• Type E Thermocouples:
  • Bonded to the coil using Stycast 2850F E
  • Insulated from the coil using thin tissue paper

Voltage taps

Table 1. Wire and coil specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Diameter</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Strand Count</td>
<td>185</td>
</tr>
<tr>
<td>Non-Cu Area</td>
<td>46.6%</td>
</tr>
<tr>
<td>Wire Material</td>
<td>Pure Cu</td>
</tr>
</tbody>
</table>

Experiment

Measurement of the coil in the voltage mode. It is a very safe way to run the magnet and it is done to prevent the possibility of overvoltage during the coil. This is V 1 and V 2 for the final run of 4.2 K. After some positive training of the coil as shown in Figure 4. The voltage is not zero because it has an inductive component (we are measuring a magnet). The curves are not flat with an effect similar to the ramp rate changes during measurement as an effect of the fact that we use voltage mode. The ramping rate was 0.01 V/s, and the average current ramp rate above 400 A was approximately 1.2 A. The maximum turn-off voltage hysteresis was set at 1 V. We can see that the temperatures of the coil rises slightly for the coil end near the current taps, this is to be expected for a cryocooled coil unless very high additional cooling is present. All runs were fairly similar, although some positive training was seen. The transition was by quench, again not unexpected for an LTS coil running at high currents to in conduction cooled mode.

The results in measurements of the coil in the current mode. The benefit of this is that it provides a flat V-I curve, although that comes with an inductive voltage offset. The V-I curve for this run is shown in Figure 5. Current was applied with an initial ramping rate of 1 A/s, which was reduced to 0.8 A/s near 300 A. This reduction in ramp rate explains the change in noise and inductive offset at 300 A. The maximum turn-off voltage hysteresis was set at 300 mV.

Results.

The coil showed some positive training, but the best values obtained are shown in Table 2. The highest Iₚ was 435 A. This is above the target current of 425 A, with some margin. There is also a temperature margin, since the last portion of the coil was at 7.3 K at transition (see below). The target S (at the highest spot on the coil exterior) was expected to be 37 °C at 450 A, and that is consistent with our measurement of 36.7 °C at 440 A.

Table 2. Critical/quench current of coil and maximum field at various temperatures

<table>
<thead>
<tr>
<th>Run</th>
<th>Coil Temp</th>
<th>Iₚ</th>
<th>Max Field (T) On-axis</th>
<th>Max Field (T) Off-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>440</td>
<td>438</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>430</td>
<td>435</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>420</td>
<td>428</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>410</td>
<td>414</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7. Critical current vs temperature of coil

Next Steps

The next coil to be tested will be an MRI style isomeshal coil for applications in 5-11 T full body, or 3T field MRI systems. It will be made from about 1.6 km of 0.7 mm 217-pattern Nb₃Sn strand, and will have an OD of 914 mm. As with the previously described racetrack coil, the upcoming MRI coil will be conduction cooled.

Summary

A Nb₃Sn coil was fabricated, cooled, and tested. A small amount of liquid helium below the coil was used as the cold reservoir with the coil cooled by conduction through the cooling legs. The operational current target of 1 = 425 A was achieved, with both current (450 A) and temperature (3.8 K) margin. The field reached 3 T at the outer can of the coil, as expected by modeling. The coil met the needed targets for the winding design with a noticeable margin.

References