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Risk mitigation in the development of a Roebel cable based 1 MVA HTS transformer

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Abstract

Progress is reported on the development of a 3-phase 1 MVA 11 kV/415 V HTS transformer using Roebel cable for the secondary windings. We describe efforts to address risks associated with short circuits, insulation, and heat transfer. We present modelling results for the response of the windings to a short circuit. Sample strands have been tested to demonstrate that cables immersed in liquid nitrogen can survive short circuits. The primary windings use insulated conductor to withstand computed impulse voltages. Breakdown and partial discharge testing confirms that the production insulation scheme is adequate for our design. Heat transfer results are presented for a sample Roebel cable winding.

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1. Introduction

High temperature superconductors (HTS) promise to enable power transformers that offer high efficiency, fault current limiting, reduced size and weight, improved environmental and fire safety performance, and increased operational lifetime when compared to conventional equipment [1]. The main obstacles to successful implementation of a commercially viable HTS transformer are the cost of both the superconducting windings and the cryogenic cooling system [2]. In the current project we aim to

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demonstrate the use of HTS Roebel cable as an effective means of implementing a stable high current winding with low AC loss [3]. Reduction of AC loss is critical to minimizing the heat load on the cooling system (and hence the cooling system capacity and cost). The key design parameters for the transformer are presented in Table 1.

Table 1. Transformer design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltages</td>
<td>11,000 V primary / 415 V secondary</td>
</tr>
<tr>
<td>Maximum operating</td>
<td>70 K, liquid nitrogen cooling</td>
</tr>
<tr>
<td>Target rating</td>
<td>1 MVA</td>
</tr>
<tr>
<td>LV winding</td>
<td>20 turns 15/5 Roebel cable per phase (20 turn single layer solenoid winding)</td>
</tr>
<tr>
<td>LV rated current</td>
<td>1390 A rms</td>
</tr>
<tr>
<td>HV winding</td>
<td>918 turns, 4 mm YBCO tape per phase (24 double pancakes of 38.25 turns each)</td>
</tr>
<tr>
<td>HV rated current</td>
<td>30 A rms</td>
</tr>
</tbody>
</table>

During the course of the project, several areas of concern have been identified that may affect the viability of the transformer. Transformers must be able to withstand short circuit and impulse faults that may occur in the connected network. A practical transformer must be able to accommodate these faults without damage to the transformer. Another area of concern is maintaining the temperature of the Roebel cable below a design upper limit of 70 K. It was thus important to experimentally quantify the heat transfer performance of Roebel cable in liquid nitrogen.

2. Short circuit response

Transformer standards typically specify that a transformer must be capable of withstanding a short circuit of 2 seconds without suffering damage [4]. Such a long duration is not practically achievable with an HTS transformer because the superconductor would need to have so much conductive reinforcement that it would negate the size and weight advantages that are so attractive with an HTS machine [1]. What is proposed for this implementation is to adopt a reduced short circuit withstand duration of 200 ms – a timescale for disconnection that is readily achievable with high speed switchgear [5].

In the event of a short circuit, the current will transfer almost instantaneously from the superconductor into the 20 μm thick copper coating. The resistance of this coating is about $12.5 \times 10^{-3} \, \Omega/m$ for each strand of the cable at 77 K. This will provide significant current limiting – doubling the impedance from the superconducting operating state (from 0.05 pu to 0.1 pu). Furthermore, the resistivity of copper increases about 7-fold from liquid nitrogen temperature to room temperature, so the fault impedance can increase to 0.5 pu or more before the fault is disconnected. AC modeling of response to a short circuit predicts a peak current in the low voltage winding of 14.3 kA which is 36% of the peak that would be expected if limited only by the 0.05 pu leakage reactance of the transformer. Although we have not conducted an AC short circuit test, sample strands have been subjected to several step DC voltage changes from zero up to 16 V/m (about 30% greater than that expected in a short circuit in the LV winding).

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a pu = per unit, the ratio of actual value divided by base value. e.g. A 1 MVA transformer with an impedance of 0.05 pu will exhibit an overload rating of 20 MVA in the event of a short circuit.
winding). The time to heat to room temperature, at greater than 60 ms, was comparable with the AC modeling results. The sample was confirmed to be un-damaged by before-and-after $I_c$ performance testing. The combination of AC modeling and DC testing demonstrates that standard coated conductor with a total of only 40 μm thickness of copper will exhibit useful fault current limiting performance provided the transformer is isolated from the short circuit fault within 200 ms.

3. Electrical insulation testing

An important qualification for the electrical design was to compute how the windings would respond to an impulse on the high voltage windings. A standard specification requires that a transformer of this rating must be able to withstand a 95 kV basic impulse loading (BIL) test. The electrical design calculations identified that the region of greatest concern in the high voltage windings was from one turn to the next. The computed peak turn-to-turn withstand requirement from a 95 kV BIL test is 550 V.

The pancake windings are wound using a standard production insulation scheme on 4 mm wide YBCO superconductor. The insulation scheme is in the form of a 3 mm wide x 0.025 mm thick polyimide self-adhesive tape, wound onto the superconductor with a 1 mm overlap. Insulation performance results from others indicated that there was some uncertainty that the standard insulation scheme was suitable to withstand the required 550 V turn-to-turn [6]. To test the suitability of the insulation scheme, breakdown and partial discharge tests were carried out on a number of short samples submerged in liquid nitrogen. Results were analyzed following procedures described in IEC 62539 [7]. A conservative estimate of breakdown voltage between turns is 2 kV. Impulse strength is expected to be twice this breakdown voltage (4 kV), in line with findings from Cheon et al [6]. We conclude from this that the standard insulation scheme is suitable for our application.

4. Heat transfer experiments

Good heat transfer performance from the 15/5 Roebel cable is particularly important to the success of the transformer. The power dissipation averaged over the LV winding has been estimated to have an upper limit of 1 W per metre of cable strand at rated current. If heat transfer is poor, the cable will become too warm and result in instability, increased AC loss and possible damage to the winding. Experiments were carried out to quantify the heat transfer performance from a sample winding of Roebel cable. The test rig was designed to simulate the geometry of the winding in the transformer. The sample 15/5 Roebel cable was manufactured using poor quality superconductor such that it was non-superconducting at temperatures above 65 K. This allowed current to be passed through the copper stabilizing layer which acted as both a heater (by Joule heating) and a temperature sensor (by measuring changes of resistance). The Roebel cable was wound in a groove machined in a G10 composite former so that only the outside face was exposed directly to liquid nitrogen. Individual strands were instrumented so that the difference in temperature between innermost and outermost strands in the cable could be measured. A photo of the test cable winding is shown in figure 1. Heat transfer tests were carried out for two liquid nitrogen conditions:

- Saturated - the coil is submerged in liquid nitrogen at 77 K and atmospheric pressure.
- Sub-cooled - the coil is fitted within a special vessel that enables lower temperatures to be reached by vacuum pumping on the liquid nitrogen and then releasing the vacuum to produce a transient sub-cooled environment at atmospheric pressure.
The key results from heat transfer experiments are summarized in Figure 2.
Heat transfer experimental results led to the following conclusions:

- The temperature difference between inner and outer strands was typically about 0.1 K. This means that having the cable sitting in a machined groove is not particularly detrimental to heat transfer performance.
- In the saturated case - at 1 W dissipation per metre of strand length - the conductor temperature is typically 0.5 K higher than the bulk LN2 temperature. A clear transition from convective heat transfer to the superior heat transfer of the nucleate boiling regime was apparent.
- In the sub-cooled case – at 1 W/m dissipation the conductor temperature is in the region of 3 K higher than the bulk LN2 temperature. There was no transition to nucleate boiling in the range investigated.

It is apparent that operating the windings in sub-cooled liquid nitrogen introduces a concern that heat transfer performance is degraded. This conflicts with the advantage that sub-cooled liquid nitrogen presents of vastly superior dielectric performance [8],[9]. At present, we are progressing with the concept of a pressurized, sub-cooled liquid nitrogen circulation system. Forced circulation should offer some improvement in heat transfer performance. Further investigation is required to ensure that the eventual heat transfer performance is acceptable for the heat load.

Acknowledgements

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