32T Superconducting Magnet Protection System

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## Coil Parameters

<table>
<thead>
<tr>
<th>Coil Parameters</th>
<th>HTS</th>
<th>LTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coil 1</td>
<td>Coil 2</td>
</tr>
<tr>
<td>Field Contribution</td>
<td>10.8</td>
<td>6.2</td>
</tr>
<tr>
<td>Operating Current</td>
<td>173</td>
<td>173</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>40</td>
<td>164</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>140</td>
<td>232</td>
</tr>
<tr>
<td>Coil Height</td>
<td>178</td>
<td>320</td>
</tr>
<tr>
<td>Ramp to full field</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Self inductance</td>
<td>17.0</td>
<td>194</td>
</tr>
<tr>
<td>LTS to HTS Mutual</td>
<td>22.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>inductance</td>
<td></td>
</tr>
</tbody>
</table>
Conductor Performance

Improved with later acquisition date

Short sample $I_c$ varies within piece length
Average $I_c$ generally increased with time

Mostly M4
(2014-early 2015)

Mostly M3,
early deliveries

Ordered in sequence on increasing $I_c$
# Heater Design Parameters

<table>
<thead>
<tr>
<th>32T Protection Parameters</th>
<th>Coil 1</th>
<th>Coil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater active area percent</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Heater disk resistance @ 4.2K</td>
<td>3.3 Ohms</td>
<td>5.1 Ohms</td>
</tr>
<tr>
<td>Number of heaters (clusters)</td>
<td>18</td>
<td>34</td>
</tr>
<tr>
<td>Number of heaters in series (1 cluster)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Number of heater clusters in parallel</td>
<td>6</td>
<td>17</td>
</tr>
<tr>
<td>Heater Current</td>
<td>23.7 A</td>
<td>23.2 A</td>
</tr>
<tr>
<td>Total Heater Voltage</td>
<td>287 V</td>
<td></td>
</tr>
<tr>
<td>Weighted Average Heater Power</td>
<td>0.15 MW</td>
<td></td>
</tr>
</tbody>
</table>
Protection Circuits
Distribution

Coil 1
Heaters

Coil 2
Heaters

Positive Lead

Negative Lead
31 Lead-acid batteries in series
- Batteries are distributed across 11 shelves in 2 racks
- Battery Capacity - 100 A*hr
- Idle terminal voltage – 390 V
- Load terminal voltage – 270 V
- Peak Current – >600 A
- Pulse Duration – 1.0 sec
- 250 A Bussman Fuses at positive terminals

600 A DC

Battery Voltage 1
Battery Neg to Ground
Heater Current

Fuse Voltage (V)

Time at current (s)

Voltage

Time (s)

Heater Current

Battery Bank
Battery Bank has a peak possible current of 1600 A and the switch boxes must be able to break it.
Protection Logic - Balancing

HTS has 2 parallel detection systems for redundancy

Primary HTS Protection Channels
1. \( V_1 - V_3 \)
2. \( \alpha V_2 - (V_1 + V_3)/2 \)
3. \( V_4 - V_6 \)
4. \( \beta V_5 - (V_4 + V_6)/2 \)
5. \( V_{\text{lead in}} = V_i - V_k \)
6. \( V_{\text{lead out}} = V_i - V_j \)
7. \( V_{\text{bus out}} = V_a - V_k \)
8. \( V_{\text{bus in}} = V_e - V_i \)
9. \( V_{\text{jumper}} = V_h - V_d \)
10. \( V_d \) to Ground
11. Quench Com Loop

Secondary HTS Protection Channels
1. \( \text{Coil1} - C_0 * \text{Coil2} \)
2. \( \text{Coil1} + C_0 * \text{Coil2} \)
3. Quench Com Loop
# Protection Logic

## Thresholds and Filtering

### Primary Trip Thresholds

<table>
<thead>
<tr>
<th>Channel</th>
<th>Voltage Threshold</th>
<th>Fault Counter Delay</th>
<th>Low Pass Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $V_1$-$V_3$</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>2. $\alpha V_2$-(V$_1$+V$_3$)/2</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>3. $V_4$-$V_6$</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>4. $\beta V_5$-(V$_4$+V$_6$)/2</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>5. $V_{lead \ out}$</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>6. $V_{lead \ in}$</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>7. $V_{bus \ out}$</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>8. $V_{bus \ in}$</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>9. $V_{bus \ mid}$</td>
<td>100 mV</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>10. $V_d$ to Ground</td>
<td>30 V</td>
<td>14 ms</td>
<td></td>
</tr>
<tr>
<td>11. Quench Com Loop</td>
<td>1 V</td>
<td></td>
<td>60 Hz</td>
</tr>
</tbody>
</table>

### Secondary Trip Thresholds

<table>
<thead>
<tr>
<th>Channel</th>
<th>Voltage Threshold</th>
<th>Zener Diode Filter</th>
<th>Low Pass Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $\text{Coil1} - C_0 \times \text{Coil2}$</td>
<td>500 mV</td>
<td>1.8 V</td>
<td>30 Hz</td>
</tr>
<tr>
<td>2. $\text{Coil1} + C_0 \times \text{Coil2}$</td>
<td>8 V</td>
<td>1.8 V</td>
<td>30 Hz</td>
</tr>
<tr>
<td>3. Quench Com Loop</td>
<td>TTL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The data in the following slides was taken under the following conditions:

- HTS Coils were energized
- LTS Power supply was controlling current at 0
- The protection system was active
- All normal zones were initiated by the heaters and not spontaneous
- Faults occurred at roughly 5 T
47.6 A Trip – Fault Signal

- V4-V6 Passes Threshold
- Quench Declared
- Fault begins
- To recover
- Heaters Activate

Graph showing voltage over time with markers indicating key events.
47.6 A Trip – Normal Zone Development

Extraction Resistor Engaged

Mid-plane Modules Show higher resistance

Heaters Activate

Heaters Deactivate

Coil2 Ends remain mostly superconducting

Voltage

Time (s)
47.6 A Trip - Evolution

Heater Pulse

Slight Current Reduction

HTS Fully Superconducting
51.2 A Trip – Evolution

- Slight Current Reduction
- V1 Thermal Run away
- Heater Pulse
Conclusion

• Quench Protection System and Interlocks are working as designed
• Mechanical motion has been observed and activated the protection system
• Heater Current is slightly low – more batteries will be added for a total of 36
• The current at which the heaters begin to be effective is close to prediction
• Only a limited fraction of $I_c$ has been reached in the conductor
• No damage has been observed