Development of Quench Propagation Models for Coated Conductors

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Motivation

• New Air Force applications require high power density systems

• HTS materials can provide desired power density, but size of cooling system has to decrease

• Operation at temperatures near 77K would lead to manageable cooling systems

• In the temperature range of interest, quench detection and protection becomes problematic

• Understanding the physics of quench propagation and developing simulation tool is paramount to the future of 2nd generation wound HTS magnets
Quench is an irreversible transition from superconducting to normal state. Observed as a temperature increase that propagates along the conductor.

<table>
<thead>
<tr>
<th></th>
<th>Operating Temperature (K)</th>
<th>ΔT (K)</th>
<th>Normal Zone Propagation Velocity</th>
<th>Quench Modeling &amp; Simulation</th>
<th>Quench Detection</th>
<th>Quench Experience Base</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LTS</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>NbTc/Nb$_3$Sn</td>
<td>4 - 8</td>
<td>&lt; 1</td>
<td>High</td>
<td>1D/2D/3D OK</td>
<td>Easy</td>
<td>Huge</td>
</tr>
<tr>
<td><strong>HTS</strong></td>
<td></td>
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<tr>
<td>BSCCO</td>
<td>20 - 35+</td>
<td>Several</td>
<td>Low</td>
<td>1D/2D OK?</td>
<td>Difficult</td>
<td>Small</td>
</tr>
<tr>
<td>YBCO</td>
<td>40 - 77+</td>
<td>Several</td>
<td>Very Low</td>
<td>3D Required?</td>
<td>Very Difficult</td>
<td>None</td>
</tr>
</tbody>
</table>

Simulation of Quench Propagation in Coated Conductors

Courtesy Dr. Oberly, AFRL
Project Objectives

• 3 year project sponsored by AFRL

Objectives:
- Understand current re-distribution during quench in coated conductors
- Develop tool to simulate quench propagation in coated conductors
- Simulate quench propagation in coils
- Investigate passive and active quench protection schemes

Develop next generation of "QUENCH" for HTS coils
Superconducting wire topologies

NbTi conductors
- Cu matrix
- Excellent current sharing
- Operation at or below 4.2 K

YBCO conductors
- Layer configuration
- Poor current sharing
- Operation at 55-77 K

BiSrCaCuO conductors
- Silver matrix
- Decent current sharing
- Operation at 25-35 K

Current re-distribution during quench is not obvious:
- Buffer layer is highly resistive
- Physics not well understood

Quench is difficult to detect:
- Thermal resistance is low
- Heat propagates very slowly
- “Resistive voltage” rises very slowly
Conductor Modeling Key Parameters

- Thermal and electrical characteristics of each of the materials forming layers
- Electrical contact resistance between layers
- Thermal contact resistance between layers
- Thermal and electrical diffusivity vs. temperature

This implies to develop model with the help of experimental data

Picture courtesy of X. Wang, J. Schwartz
Simulation of Quench Propagation in Coated Conductors

Proposed Research Approach

• Presented results deal with global simulation
• Conventional current sharing model
• Integrated electro-thermal model
• Physical characteristics depend on temperature
Tape Configuration of Interest

\[ R_{YBCO} = \frac{E_c}{J_{c0}(\sigma,T) \frac{B_0}{|B|+B_0}} \left( \frac{J}{J_{c0}(\sigma,T) \frac{B_0}{|B|+B_0}} \right)^{n(T,B)} \]

\[ J_{c0}(T) = \alpha \left( 1 - \frac{T}{T_{c0}} \right)^\beta \]

- Copper layer (50 \( \mu \)m)
- Silver layer (0.5 \( \mu \)m)
- YBCO layer (5 \( \mu \)m)
- Buffer layer (0.3 \( \mu \)m)
- Nickel layer (75 \( \mu \)m)

Simulation of Quench Propagation in Coated Conductors
Thermal and Electrical Properties of Winding

Very small thermal diffusivity at high temperature (>60 K)

Very slow heat propagation

Very high hot spot temperature
Coil Configuration and Boundary Conditions

- Conduction cooling at 77 K through inner surface
- J=0.6*Jc (2T, 77K) = 1.8*10^8 A/m^2
- Rest of the boundaries are considered adiabatic

\[
C_p(T) \frac{\partial T}{\partial t} = \text{div}(\overrightarrow{\Lambda}(T) \cdot \nabla(T)) + P(T, B)
\]

\[
\overrightarrow{\Lambda} = \begin{pmatrix}
 k_x(T) & 0 & 0 \\
 0 & k_y(T) & 0 \\
 0 & 0 & k_z(T)
\end{pmatrix}
\]
Quench Propagation
Normal Zone Propagation Velocity

- NZP velocity is only a few cm/s
- NZP velocity decreases as temperature increases
- Simulated values in agreement with experimental data
@ 77 K, quench may be difficult to detect through voltage increase across the magnet
Summary and Future Work

• Objectives of the research project
  – Develop simulation code for quench propagation in HTS conductors
  – Develop an engineering design tool to help design and protect HTS magnets

• First phase of the project completed
  – Coupled 3D simulations using global model
  – Good agreement with experimental data

• Future work
  – Develop model at the tape level
  – Increase fidelity by adding other physics to the model
  – Compare to experimental results performed on tapes
  – Explore possibility of using real time models as a detection/protection scheme