Experimental Study on Quench Detection of a No-insulation HTS Coil Based on Raman-scattering Technology in Optical Fiber

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Quench Detection Methods - Conventional

- The quench detection of the HTS magnets is an important technique to protect them from burning out.
- Two methods are applied: voltage measurement and thermocouples.
- Voltage measurement: difficult to detect quench in a short time.
- Thermocouples: discrete sensing problem and difficult installation.

Voltage measurement


Thermocouples
Quench Detection Methods - Optical Fiber Sensor

Optical Distributed Temperature Sensors (DTS) System

Measurement device
- I/O light signals
- Demodulating light signals to temperature information

Optical fibers
- Measuring temperature
- Transmitting light

Advantages
- **Distributed** detection along HTS tapes.
- Good **insulation** performance.
- High **anti-interference** capability (insensitive to electromagnetic field).
- **Lower cost** in quench detection (communication optical fiber is applied for the sensor).
- Size is **thin enough** to **encapsulate** along the both edges of the HTS wire using metal tapes.
Research Status - Rayleigh-scattering

J. Schwartz’s Group in North Carolina State University

- Time resolution: 30 ms
- Spatial resolution: 5 mm
- No influence on the structure of HTS magnets.
- The DTS system based on interrogating Rayleigh-scattering is effective in quench detection.
- Rayleigh-scattering signals mixed by temperature and strain.

Optical fibers were mounted on the surface and edge of HTS tapes.

Optical fibers were encapsulated with HTS tapes.

Research Status - Raman-scattering

Our Group

The structure of Optical Fiber-HTS composite tapes

- We proposed the combined structure in 2014.
- Relevant patents have been acquired in China.

Patent

Application date: Dec. 17 (2014)
Authorization date: Aug. 8 (2017)
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2 Principles of Raman-scattering

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4 Results and Discussion

5 Conclusion
Principles of Raman-scattering

A commercial multimode optical fiber is used for temperature measurement.

The optical fiber is combined with “Core”, “Cladding” and “Coating”.

Light pulses transmit in the optical fiber according to the total reflection principle.
Principles of Raman-scattering

- An incident light is input into the fiber and Raman-scattering light can be received by measurement device.

- The **amplitude** of Raman-scattering light is related to the **temperature** of the fiber.

- The temperature rise can be calculated according to the change of Raman-scattering light.

- Raman-scattering light is only sensitive to temperature.
Distributed Temperature Sensors (DTS) System

The DTS system includes a **measurement device** and an **optical fiber**.

**Details:**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Time resolution</td>
<td>1 s</td>
</tr>
<tr>
<td>Temperature accuracy</td>
<td>0.1 K</td>
</tr>
<tr>
<td>Output light power</td>
<td>30 W (Peak)/4.6 mW (Average)</td>
</tr>
<tr>
<td>Light pulses repetition</td>
<td>19.2 Hz</td>
</tr>
<tr>
<td>Pulse width</td>
<td>8 ns</td>
</tr>
</tbody>
</table>
Sample Fabrication

The epoxy (STYCAST 1266) was used to fix the optical fiber.

The NI HTS pancake coil before winding optical fiber (a), the combined structure of Optical Fiber-HTS pancake coil (b) and the structure diagram (c).

- The optical fiber was set on the top surface of the coil turn-by-turn.
- The 2-m long multimode optical fiber was used to enwind 7 turns.

**TABLE I**
PARAMETERS OF NI HTS COIL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width and thickness of HTS tape</td>
<td>4.2 mm×0.3 mm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>80 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>98 mm</td>
</tr>
<tr>
<td>Total length of wire</td>
<td>8.3 m</td>
</tr>
<tr>
<td>I_c @ 77 K</td>
<td>112 A</td>
</tr>
<tr>
<td>Turns of coil</td>
<td>30</td>
</tr>
<tr>
<td>Inductance</td>
<td>0.14 mH</td>
</tr>
</tbody>
</table>

**TABLE II**
PARAMETERS OF WOUND OPTICAL FIBER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Mode</td>
<td>Multimode</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Dispersion coefficient</td>
<td>15 ps/(nm.km)</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.4785</td>
</tr>
<tr>
<td>Gain</td>
<td>1</td>
</tr>
</tbody>
</table>
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Results and Discussion

Critical currents was measured before and after quench, respectively.

Results:
• The measured critical current of the NI coil is **112 A** before and after the quench test.
• There is no irreversible damage in the coil after quench.
Results and Discussion

- A time delay between the quench moment and rapid temperature change moment is about 10 seconds.
- The highest temperature of 94 K is observed at 1.2 m of the optical fiber.
- The maximum temperature is saturated during 150 ~ 220 s.

Discussion:
- The time delay of 10 s might because:
  - The time resolution of 1 s for the DTS system is not enough.
  - The “coating” affects to the thermal propagation from the NI coil to the optical fiber.
  - Epoxy layer.
Results and Discussion

The temperature of the middle part in the NI coil is the highest, up to 94 K.

Discussion:
The critical current density is the lowest due to the maximum magnetic flux density of the near middle part in the NI coil.
Conclusion

• The NI HTS coil covered by a 7 turns optical fiber verified the feasibility of Raman-scattering technology for the temperature measurement during quench.
  - Optical fiber sensors can be operated in liquid nitrogen (77 K).
  - Raman-scattering light is only sensitive to temperature change.

• The highest temperature of 94 K is observed at 1.2 m of the optical fiber and this area is the near middle part of the NI coil during quench.

In the future:

• We will try to optimize the time resolution of the DTS system.
• The more direct combining methods of optical fibers and HTS tapes should be considered.
Thank You!