Contact resistance and current sharing in superconducting cables

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This work was supported by the National High Magnetic Field Laboratory which is supported by National Science Foundation through NSF/DMR-1644779 and by the US Department of Energy under the grant number DE-EE0007872
Problem: $I_c$ dropouts along conductor length

- Inevitable defects in REBCO manufacturing
  - Drops in $I_c$ along length
- Magnet design
  - Minimize hot spot formation
  - Use best pieces of conductor
  - Frequency of $I_c$ drops > Frequency of long defect free tapes
- Promote current sharing
  - Current bypass local $I_c$ drops
  - Use variable $I_c$ (VIC) tapes in winding
  - Increased yield of viable tapes

What frequency of $I_c$ drops can we tolerate?
Conductor on Round Core (CORC®) Cables

• Manufactured by Advanced Conductor Technologies (ACT)
• Flexible cables
• Multiple layers of REBCO tapes
  • Wound around Cu core
• Current sharing depends on tape-to-tape contact resistance $R_c$
• Promoting flexibility could increase $R_c$
  • Lubricated tapes
  • Not soldered
$R_c$ and Current Sharing in CORC® Cables

• How do winding parameters affect $R_c$?
• Is $R_c$ low enough to promote current sharing?
  • Over what length?
  • 1 m long samples $\rightarrow$ comparable to 1 coil turn

**4 CORC® Cables Constructed by ACT**

<table>
<thead>
<tr>
<th>Cable</th>
<th>Winding Tension (N)</th>
<th>Winding Lubricant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Cable (CO)</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>High Tension Cable (HT)</td>
<td>50% higher</td>
<td>Normal</td>
</tr>
<tr>
<td>No Lubricant Cable (NL)</td>
<td>Normal</td>
<td>None</td>
</tr>
<tr>
<td>High Conductivity Lubricant (HC)</td>
<td>Normal</td>
<td>High Conductivity</td>
</tr>
</tbody>
</table>
Cable Geometry

- 2 mm wide Superpower tapes
- 2.78 mm diameter Cu former
- 3 Layers
- 2 tapes per layer

L = 50 cm
**$R_c$ Measurement (SF, 77 K)**

- Forced current to transfer between tapes
  - $I_{in}$ Layer 2
  - $I_{out}$ from Layer 1 and Layer 3
- Ramp current to 10 A
- Determine $R_c$ from $V(I)$ curves

$\text{Diagram:}$

$L = 50 \text{ cm}$
**$R_c$ Results**

<table>
<thead>
<tr>
<th>Cable</th>
<th>Average $R_c$ ($\mu\Omega \cdot cm^2$)</th>
<th>Open Symbols: Outer Layer $\rightarrow$ Middle Layer</th>
<th>Closed Symbols: Inner Layer $\rightarrow$ Middle Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner Layer</td>
<td>1140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Layer</td>
<td>373</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>High Winding Tension</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner Layer</td>
<td>2182</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Layer</td>
<td>648</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>No Lubricant</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner Layer</td>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Layer</td>
<td>176</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>High Conductivity Lubricant</strong></td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner Layer</td>
<td>73</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Best REBCO-REBCO lap joints\(^1\)
  - $R_c \sim 0.1 \mu\Omega \cdot cm^2$
- ReBCO-Substrate under pressure 2.4-144 MPa\(^2\)
  - $R_c = 20 - 100 \mu\Omega \cdot cm^2$

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Effects of Cable Bending on $R_c$

- Performed the same $R_c$ measurements
- 77 K, Self-field
- Ramp current to 10 A
  - $I_{in}$ Layer 2
  - $I_{out}$ from Layer 1 and Layer 3

<table>
<thead>
<tr>
<th>Bending Diameter (cm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>
$R_c$ in Control Cable

Open Symbols: Outer Layer $\rightarrow$ Middle Layer
Closed Symbols: Inner Layer $\rightarrow$ Middle Layer

30% original $R_c$

80% original $R_c$
High Tension Cable

Open Symbols: Outer Layer $\rightarrow$ Middle Layer
Closed Symbols: Inner Layer $\rightarrow$ Middle Layer

23% original $R_c$
No Lubricant Cable

Open Symbols: Outer Layer $\rightarrow$ Middle Layer
Closed Symbols: Inner Layer $\rightarrow$ Middle Layer

$50\%$ original $R_c$
So What happens if there is a defect?

• Created defect in Tape 5 of HC cable
  • Decreased tape width by ≈ 50%
  • Decrease Local $I_c$ by ≈ 50%
• Energize “Good” and “Defect” tapes in parallel

How will the current transfer between tapes?
Current Bypass Defect?

- Current split evenly between tapes
- Current > defect Ic transfer to good tape
- After defect current transfer back
Current Transfer at Leads?

- Current split unevenly between tapes
- Defective tape carries $I_c$ of defect
Current Transfer and Remain in Good Tape?

- Current split evenly between tapes
- Current > defect Ic transfer to good tape
- After defect current does not transfer back
Current Transfers in Cable

\[ I_{out} (Good) \approx 0.6 \ I_{tot} \]
\[ I_{in} (Defect) \approx 0.5 \ I_{tot} \]
\[ I_{in} (Good) \approx 0.5 \ I_{tot} \]
\[ I_{out} (Defect) \approx 0.4 \ I_{tot} \]

\[ I_{out} \neq I_{in} \]
\[ \rightarrow \text{Current sharing within cable} \]
Current Remains in Good Tape

Voltage Before Defect = Total Voltage

Voltage After Defect = 0

\[ I_{in} - I_{out} \]

\[ V^+ - V^- \]
Length required for current sharing?

\[ E_c = 1 \mu V/cm \]

\[ E_c \times L = I_{tr}R \]

\[ R = \frac{R_c}{nA_x} \]

Length Required for Current Transfer

\[ L = \sqrt{\frac{I_{tr}R_c p}{2A_x N_{tapes}E_c}} \]

\[ n = \frac{2N_{tapes}L}{p} \]

\[ n \approx 250 \text{ per meter} \]

L ranged from 20 cm to a few meters
Further work by Jeremy Weiss and Danko Van der Laan

- ACT constructed cables containing tapes with a significant drop in $I_c$
- 3 layers, 6 tapes (2 tapes per layer)

<table>
<thead>
<tr>
<th>Cable</th>
<th># Defect Tapes</th>
<th>Layer with Defect</th>
<th>Insulation Between Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIC-01</td>
<td>1</td>
<td>Middle</td>
<td>No</td>
</tr>
<tr>
<td>VIC-02</td>
<td>1</td>
<td>Middle</td>
<td>Yes</td>
</tr>
<tr>
<td>VIC-03</td>
<td>2</td>
<td>1-Middle 1-Outer</td>
<td>No</td>
</tr>
<tr>
<td>VIC-04</td>
<td>2</td>
<td>1-Middle 1-Outer</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Comparison of VIC cables

With Current Sharing Enabled
- 1 defect
  - Retains 83% of $I_c$
- 2 defects
  - Retains 74% of $I_c$

With Current Sharing Disabled
- 1 defect
  - Retains 64% of $I_c$
- 2 defects
  - Retains 55% of $I_c$
Conclusions

• $R_c$ in CORC® is relatively large for current transfers on 1 m length
  • Changes in lubricant reduce $R_c$ by an order of magnitude
  • Bending cable reduces $R_c$

• Evidence of current sharing was obtained → It’s more like a railway switch
  • About 20% of current in 1 tape was observed to transfer for $R_c \approx 50 \mu \Omega \cdot cm^2$

• Working on $R_c$ measurements in magnetic field as well as investigating current sharing in VIC cables