Strain dependence of Nb_3Sn superconducting properties is known to be responsible for the degradation of transport current capability of large steel jacketed cable-in-conduit conductors (CICCs). The mechanical deformations of the strands in the cables, due to both cool down after heat treatment and Lorentz force during operation, are the main sources of strand-in-cable critical current degradation. The complete modeling of a CICC relies first on the modeling of the single strand with its superconducting filaments then on the modeling of the strands in the cable.

A collaborative action has been launched between CEA/IRFM and Ecole CentraleSupélec, ECS/LMSSMat where CEA takes in charge electrical modeling and measurements whereas ECS is responsible for mechanical modeling and characterizations. The coupling between mechanical and electrical models is made through the build of a strain map in the strand cross-section along each strand which is used as an input to compute the Nb_3Sn critical current density in the electrical model.

I. STRAND CRITICAL CURRENT UNDER BENDING

A simple, compact, VAMAS-like sample-holder was designed and manufactured at CEA-IRFM to measure strand critical current under bending in an industry-compatible test facility. The strand is free to bend, under the centripetal Lorentz force generated by the strand current under the applied magnetic field, in dedicated unsupported lengths over its helical trajectory. Titanium or Stainless Steel (with SS ring) mandrels are used in order to vary the thermal strain.

<table>
<thead>
<tr>
<th>SAMPLE-TYPES TESTED</th>
<th>Unsupported length (per half turn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-VAMAS-B-Ref</td>
<td>0</td>
</tr>
<tr>
<td>Ti-VAMAS-B-08</td>
<td>8mm</td>
</tr>
<tr>
<td>Ti-VAMAS-B-12</td>
<td>12mm</td>
</tr>
<tr>
<td>SS-VAMAS-B-Ref</td>
<td>0</td>
</tr>
<tr>
<td>SS-VAMAS-B-08</td>
<td>8mm</td>
</tr>
<tr>
<td>SS-VAMAS-B-12</td>
<td>12mm</td>
</tr>
</tbody>
</table>

II. STRAND MECHANICAL MODELING

Mechanical modeling performed by ECS using the Abaqus™ code to analyze a quarter of a turn of the strand on its mandrel with symmetries at both ends. The strand (Ø 0.81 mm) was modeled as a homogeneous medium according to previous ECS analyses.

III. STRAND ELECTRICAL MODELING

Simplified 7 (six twisted around one) filament bundles model built in CEA CARMEN code

- Strand length of half a turn modeled with the 12 mm free length at the middle
- Inter-bundle resistances computed from the transverse resistivity
- At each strand end, all bundles connected to a common node through high series resistances ensuring uniform current distribution at ends
- Twist pitch = 14.8 mm
- Computation step over the length = 0.2 mm.

IV. RESULTS OF CARMEN SIMULATION (1/2)

- Low local critical currents due to either high compression or tension
- ‘Resonance’ between the twist pitch and the high strain areas distance

- Strand critical current defined as close as possible to the measurement with:
  \[ \langle E \rangle = E_c = 10 \mu V/m \]
- 2 mm removed at each end to eliminate ends effects

- Bundle currents change on small scales following critical current thanks to low \( \rho_{trans} \)

- However, this transfer is not strong enough to avoid high electric fields up to 40-50 E
V. RESULTS OF CARMEN SIMULATION (2/2)

- Simulation result may be lower than the HRL due to the boundary conditions in CARMEN model: current distribution among bundles is forced to be uniform at strand ends, which is not imposed in the HRL.

VI. CURRENT TRANSFER IN A TWO-STRAND CABLE

- Simple two-strand (6+1 bundles per strand) electrical CARMEN model
- 3 interstrand contacts (1 connected bundle per strand)
- Two weak lengths between contacts (i.e. IC = 24 A vs. 30 A per bundle)

VII. TWO-STRAND CABLE CRITICAL CURRENT

- Bundle currents (Bjk = kth bundle in strand j)

VIII. EQUIVALENT TWO-BUNDLE CABLE MODEL

- Simple ‘two-bundle’ CARMEN macro model to simulate two-strand cable
- 3 interstrand contacts
- Two weak lengths between contacts (i.e. IC = 168 A vs. 210 A per strand)
- Effective contact resistance depends on Rtrans

CONCLUSIONS

A coupled mechanical and electrical modeling has been set to analyze Nb3Sn strand bending experiments on dedicated VAMAS-like mandrels. The first results have shown that the strain map was more complex than expected and that high local strain could lead to strong peaking of local electric field pushing significant current transfer between filaments. First results look promising but both mechanical and electrical models still need to be improved in order to better represent the experiment.

First modeling of current transfer between strands in a CICC performed using a simple two-strand model have shown the complexity of the current transfer at contact points involving inter-filaments current transfer inside connected strands which requires increasing the effective contact resistance when using strand macro models.

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