3D quench modeling of 2G HTS using T-A formulation and COMSOL

Yawei Wang\textsuperscript{1}, Min Zhang\textsuperscript{1}\textsuperscript{*}, Weijia Yuan\textsuperscript{1}\textsuperscript{*}

1. University of Strathclyde, Glasgow, UK

Results incorporated in this standard have received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 799902". 
Outlines

- Introduction to T-A formulation
- **Quench model based on T-A formula**
- Electromagnetic validation of T-A model
- **Application of 3D T-A quench model on CORC cable**
Introduction: T-A formulation[1]

- Thin shell approximation: the thickness of tape is neglected.
- T-formulation is applied in superconductor domain: current distribution.
- A-formulation is applied in all domain, field distribution.

**T-formulation**
(PDE, COMSOL)
\[
\mathbf{J} = \nabla \times (T \mathbf{n}) \\
\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}
\]

\[
E(J) = E_0 \left( \frac{|\mathbf{J}|}{J_c(B,T_h)} \right)^n \frac{\mathbf{J}}{J_c(B,T_h)}
\]

**A-formulation**
(mf, COMSOL)
\[
\nabla \times \nabla \times \mathbf{A} = \mu_0 \mathbf{J}
\]

Thermal coupling

- Coupling thermal model on shell to T-A formulation model

- **Model approximation 1**: the coated conductor is also equivalent to thin shell in thermal model.
- **Model approximation 2**: the 2G HTS tape is equivalent to two parallel resistances: superconductors and metals.
- **Overcurrent U-I behavior** of 2G HTS tape: this approximated model matches well with tapes with thick Cu stabilizers, which need more tests.
T-A quench model

- Governing equations:

\[ \nabla \times E (\nabla \times T) = \frac{\partial B}{\partial t} \]

\[ \nabla \times \nabla \times A = \mu_0 J \]

\[ J_{cT}(T_h) = \begin{cases} \left( \frac{T_c - T_h}{T_c - T_o} \right)^\beta & \text{if } T_h < T_c \\ 0 & \text{if } T_h \geq T_c \end{cases} \]

\[ J_c(B) = \frac{I_{co}}{S_c} \cdot J_{cT}(T_k) \cdot J_{cb}(B_{par}, B_{per}) \]

Thermal model on shell

\[ \begin{cases} \rho C_p \frac{\partial T_h}{\partial t} - k \nabla \cdot (\nabla T_h) = \frac{Q}{d_s} \\ \mathbf{n} \cdot (-k \nabla T_h) = h(T_h - T_e) \end{cases} \]
T-A quench model

**Advantages:**

1. Thin strip approximation reduce dimension:
   Smaller degree of freedom, faster computation

2. Solvable by commercial finite element software, e.g. **Comsol:**
   Easy to apply stimulations: current and magnetic field

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Model validation (electromagnetic)

- T-A compares to $H$- formulation: Good agreement [3].

Pancake coil with 2000 turns, AC transport current.

Model validation (electromagnetic)

- 3D T-A model compares to measurement:
  Magnetization loss of CORC cable induced by external magnetic field.
  Two layers, REBCO conductor, frequency of external field 130 Hz*

* Measurement data is provided by Dr Grilli, KIT.
3D T-A formula application
3D T-A formula application

CORC cable with two layer in background field 130 Hz, 20.5 mT:
inner layer

Opposite winding direction  Same winding direction

Background field

Normalized current density
3D T-A quench model for CORC cable

- Coupled with a circuit model, which is to calculate the current redistribution among tapes.
- Hot-spot induced quench is studied using the model

\[
\begin{align*}
\frac{dI_n}{dt} &= M_{k,n} \\
I_{\text{sum}} &= I_1 + I_2 + I_3 \\
&k = 1, 2, 3
\end{align*}
\]
3D T-A quench model for CORC cable

- Hot spot and recovery.
- Not current redistribution among turns.

\[ Rc = \infty \]

- external heat disturbance 139 mJ, transport current 200A

Temperature (K)

Current density in superconducting layer

\[ \times 10^8 (A/m^2) \]

Current density in metallic layers

\[ \times 10^8 (A/m^2) \]
3D T-A quench model for CORC cable

- Quench induced by hot spot.
- Not current redistribution among turns.

\[
R_c = \infty
\]

- External heat disturbance 144 mJ, transport current 200A

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\times 10^8 \text{ (A/m}^2\text{)}
3D T-A quench model for CORC cable

- Hot spot and recovery.
- Current redistributed among turns through terminal contact resistance. \( 100\sim1000 \, \text{n}\Omega \) [3]
- NO quench happens with two times external heat disturbance 280 mJ. Thermal stability is enhanced significantly.

3D T-A quench model for CORC cable

- **Quench induced by hot spot.**
- Increasing the terminal resistance to \( R_c = 200 \, \mu \Omega \)
- Hot spot in one tape can induce a overcurrent quench on the other two tapes through current redistribution among individual tapes.
- **Lower terminal resistance leads to higher thermal stability during hot spot quench.**
3D T-A Quench model applications:

- Extremely efficient in 3D calculation for current, AC losses, temperature especially for a 3D geometry.
  - Quench behaviour
  - Current redistribution of YBCO cables via terminals
  - Easily add cooling condition and other heat sources.
  - Easily extend to Roebel cable and insulated coils

- Issues needs to be solved:
  - Current redistribution through tape-to-tape contacts.
Thanks very much for attention
Results incorporated in this standard have received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 799902”.

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