A Numerical Investigation on AC Losses in the first module of the ITER Central Solenoid

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OUTLINE

- Model description
  - THELMA model
  - Analytical model

- Previous application to relevant case (CS Insert)

- Model application to the CSM1 module
  - Impact of boundary conditions
  - Comparison with experimental results
  - Model simplification

- Conclusions
THELMA_UB model: main assumptions

A superconducting cable is connected by two terminations to a power supply, modeled as a current generator [1], [2].

The conductor geometry can be of any type, CICC or Rutherford, wound in different configurations (rectilinear, pancake, layer).

The cable is modeled with a distributed parameter circuit, with N_ce cable elements (CE), corresponding to either individual strands or groups of strands.

The longitudinal current in the $k^{th}$ CE is the sum of a uniform component $I_{u_k}(t)$ and a difference component $I_{d_k}(\zeta,t)$; the latter is the unknown of the problem.

$$I_{ce_k}(\zeta,t) = I_{u_k}(t) + I_{d_k}(\zeta,t) \quad (1)$$

The CEs interact through contact conductances and mutual inductances.

The electromotive forces are due to the difference currents at locations ‘near’ the selected position, to a uniform current distribution at locations ‘far’ from the selected position, and to the currents in external coils

$$E(x_{ce_k}(\zeta),t) \cdot \frac{dx_{ce_k}}{d\zeta}(\zeta) = - \frac{\partial V_{ce_k}}{\partial \zeta}(\zeta,t) \quad (2)$$

The power law is assumed for the superconductor, in parallel electrical connection with the resistive stabilizer (made of copper and bronze for the Nb$_3$Sn wires)
THELMA UB model: main equations (2/2)

• By subtracting the equation for the last CE from those of the first \((N_{ce}-1)\) CEs, and inverting the reduced conductance matrix, the potentials can be removed:

\[
E_c(\zeta, B, T, \varepsilon) = -\frac{\partial}{\partial \zeta} \left\{ R_c(\zeta) \begin{bmatrix} S(\zeta, t) + C_d \frac{\partial I_d}{\partial \zeta} (\zeta, t) + \int_0^{\zeta_f} K(\zeta, \zeta') \frac{\partial I_d}{\partial \zeta} (\zeta', t) d\zeta' \\ \int_0^{\zeta_f} m_d c(\zeta, \zeta') \frac{\partial I_d}{\partial t} (\zeta', t) d\zeta' - \int_0^{\zeta_f} m_u c(\zeta) \frac{dl}{dt} (t) \right\} - \sum_{i=1}^{N_{ext}} m_e i(\zeta) \frac{dl_{ext_i}}{dt} (t)
\]

\[
E_c = [E_{ce1} - E_{ceN_{ce}}, ..., E_{ceN_{ce}-1} - E_{ceN_{ce}}]^{T}
\]

• A numerical solution of (3) is obtained by means of discretization with \(N_{el}\) linear finite elements and a point collocation method:

\[
M \frac{dy}{dt} = F(t, y(t)) \quad y(t) = y_0
\]

• The unknowns of the problem \((y(t))\) are the values of the difference currents in the internal nodes of the 1D domain \(((N_{el}-1) \times (N_{ce}-1)\) dof)
Analytical model

- The coupling losses were computed both with THELMA_USB and with an analytical model.

- The analytical model is based on a single time constant [3], with calculation of internal field at kth turn:

  \[
  \dot{B}_{i,k}(t) = \frac{B_0}{T_d - \tau} \left( e^{-\frac{t}{\tau}} - e^{-\frac{t}{T_d}} \right), \quad P_{coup}(t) = \frac{n\tau}{\mu_0} \left( \dot{B}_i(t) \right)^2
  \]

- The hysteresis losses were computed, both in THELMA_USB and in the analytical model, with two different formulae depending on the value of the cumulative field variation \( \Delta B \) [4]:

  \[
  \begin{align*}
  \text{if } \Delta B_k &< 2B_p \\
  P_{hys,k} &= (A_{str} \cdot L_k) \frac{\pi \Delta B_k^2}{2 \mu_0^2 \lambda J_c(B_k, T, \varepsilon) d_{eff}} \frac{dB_k}{dt} \left( 1 - \frac{\pi \Delta B_k}{3 \mu_0 \lambda J_c(B_k, T, \varepsilon) d_{eff}} \right)
  \\
  \text{if } \Delta B_k &> 2B_p \\
  P_{hys,k} &= (A_{str} \cdot L_k) \frac{2}{3\pi} \lambda J_c(B_k, T, \varepsilon) d_{eff} \frac{dB_k}{dt}
  \end{align*}
  \]

  where \( B_p \) is the penetration field.

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CSM#1 in test station (courtesy N. Martovetsky, US - ITER)
Model application to previous tests of the CS ITER conductor

- The CS Insert (CSI) is a 43 m long single layer solenoid wound into 9 turns and tested in 2015 in the bore of the Central Solenoid Model Coil (CSMC) at QST in Naka (Japan)
- During the AC loss tests, the CSMC current is ramped and then kept constant; an exponential dump is then triggered with a given time constant
- Conductor winding stages: \((2\text{Sc} + 1\text{Cu}) \times 3 \times 4 \times 4 \times 6\)
Model application to previous tests of the CS ITER conductor

- The mesh includes **1800 nodes** along ~ 43 m, about **7 mesh nodes per twist pitch** of the last-but-one cabling stage.

- A **good approximation of the experimental results** was obtained, with fitting conductances (and time constants) decreasing by a factor 3 between the beginning and the end of the test campaign.

<table>
<thead>
<tr>
<th>Shot #</th>
<th>$T_d$ [s]</th>
<th>$I_{0,CSMC}$ [kA]</th>
<th>$B_0$ [T]</th>
<th>$E_{coup,CSI}$ [kJ]</th>
<th>$n_T$ [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>36-1</td>
<td>19.1</td>
<td>23.1</td>
<td>6.06</td>
<td>0.69</td>
<td>590</td>
</tr>
<tr>
<td>37-1</td>
<td>19.2</td>
<td>36.8</td>
<td>9.68</td>
<td>1.58</td>
<td>530</td>
</tr>
<tr>
<td>40-1</td>
<td>18.3</td>
<td>46.1</td>
<td>12.1</td>
<td>2.17</td>
<td>470</td>
</tr>
<tr>
<td>80-4</td>
<td>18.5</td>
<td>23</td>
<td>6.04</td>
<td>0.20</td>
<td>175</td>
</tr>
<tr>
<td>97-4</td>
<td>18</td>
<td>23</td>
<td>6.04</td>
<td>0.16</td>
<td>143</td>
</tr>
<tr>
<td>129-1</td>
<td>18.5</td>
<td>22.9</td>
<td>6.02</td>
<td>0.14</td>
<td>124</td>
</tr>
<tr>
<td>164-4</td>
<td>18.9</td>
<td>23.0</td>
<td>6.04</td>
<td>0.25</td>
<td>220</td>
</tr>
<tr>
<td>188-4</td>
<td>19.6</td>
<td>45.9</td>
<td>12.1</td>
<td>0.69</td>
<td>149</td>
</tr>
</tbody>
</table>

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CSM#1 in test station (courtesy N. Martovetsky, US - ITER)
Model application to the CSM1 tests

- The tests of the first module of the CS magnet (CSM1) were performed at General Atomics, Poway (US), in 2020.
- The model consists of 40 pancakes, made of 14 turns each.
- The instrumentation of CSM#1 includes temperature, pressure and mass flow rate sensors, at the inlet of all pancakes and at the outlet of pancakes from #2 to #39 [6].
- The AC loss measurements were performed by exponential dumps of the transport current of the CSM#1.

<table>
<thead>
<tr>
<th>$I_{op}$ (kA)</th>
<th>$T_d$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7.3</td>
</tr>
<tr>
<td>15</td>
<td>7.2</td>
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<tr>
<td>20</td>
<td>7.0</td>
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<tr>
<td>25</td>
<td>6.8</td>
</tr>
<tr>
<td>35</td>
<td>6.6</td>
</tr>
<tr>
<td>40</td>
<td>6.5</td>
</tr>
</tbody>
</table>

![Current vs time graph]

Model application to the CSM1 tests

• The losses were computed with THELMA_UB through simulations of all the individual turns of the CSM1 magnet.

• The magnetic field is computed as the sum of the contributions from a uniform current distribution in the upper and lower solenoids 1 and 2, and in the rest of the same pancake excluding the analysed turn.

• The magnetic field generated by the turn under analysis accounts for the non uniform current distribution in the turn.

• The boundary conditions are either given by a uniform current distribution or a short circuit (equipotential surface) at the ends of the turn.
**Single Turn model: assumptions**

- The simulation of individual turns requires **277 separate runs** (554 turns/2 for symmetry)

- The cable was discretized with **24 sub-cables**, as already done for the simulations of the CS Insert

- Each turn was discretized with **8 mesh nodes per twist pitch** of the last but one cabling stage (150 mm).

![THELMA discretization of Turn #1 of Pancake #21](image)
Single Turn model: comparison analytical vs numerical

- Exponential dump from 20 kA, with $\tau = 7.0$ s. The parameters of both THELMA UB and the analytical model are those used to fit the CS Insert results at virgin conditions.

- A good agreement is found between the two models, with a maximum difference of about 10% on the total energy of each turn.
Single Turn model: impact of the boundary conditions

- Exponential dump from 20 kA, with $\tau = 7.0$ s, turn 1 of pancake 1: current and coupling losses at $t = 1.6$ s

- The impact of boundary conditions is limited to about 0.3 m, and affects the total energy deposited in the turn by about 10%
Single Turn model: time evolution of currents and losses

- Currents in 24 CEs in the middle of turn #1
- Currents in 24 CEs in the middle of turn #14
- Coupling losses in the middle of turn #1
- Coupling losses in the middle of turn #14

Exponential dump from 20 kA, with $\tau = 7.0$ s, pancake 20

Bmod

P COUPL [W/m]

Turn #1

Turn #14

r [m]

$|B|$ [T]
A predictive analysis based on the simulations of the individual turns was carried out before the CSM#1 tests. The pancakes with highest AC losses are those at the top and bottom of the module.
Single Turn model: comparison with experimental results

- The only modification applied here with respect to the predictive analysis is the change of the dump time constants from the nominal (7.8 s) to the measured values, in the range from 6.5 to 7.3 s

- The numerical and analytical results are in good agreement with the experimental data.
A 2D fitting procedure was applied to determine the error committed if reducing the number of simulated turns.

The computations were performed by skipping 1, 2, 3 pancakes along the magnet height and 1, 2, 3 turns along the magnet radius.

**Single Turn model: how many turns are needed?**

- Turns #1, 3, 6, 9, 12, 14
- Pancakes #1, 5, 9, 13, 17, 20

- Turns #1, 3, 6, 9, 12, 14
- Pancakes #1, 5, 9, 13, 17, 20
Single Turn model: how many turns are needed?

- The best fitting of hysteresis losses is obtained with a linear fitting, while for the coupling losses the best fitting is obtained with the spline approximation.

- Using 36 turns in total (out of 277) it is possible to approximate the AC loss results with an average error of 1.5% and a maximum error of 2.5% on the total energy deposited in each pancake.
Conclusions and perspectives

- A **numerical model** for the computation of AC losses in a full scale fusion magnet was developed and successfully implemented to the ITER Central Solenoid module.

- The **impact of the boundary conditions** on the results is limited below 10 %. The preferred choice of the boundary conditions is the uniform current distribution.

- The **number of turns** to be analysed **can be reduced from 277 to 36** with a maximum error less than 2.5 % on the losses in each pancake through a suitable 2D interpolation.

- The results of the THELMA model with parameters obtained from tests of the 43 m long CS Insert can be scaled up to the 6 km long CSM#1, with a good **agreement with the experimental data**.

- In **perspective** we plan to apply the model to other CS modules, and to improve it for the **projection of results from tests in SULTAN (SPC)**. Full pancake simulations are under way.
Thank you for your attention!

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