Analytical modeling of coupling losses in CICCs, extensive study of the COLISEUM model

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OUTLINES

I – GENERAL CONTEXT

II – EXTENSIVE STUDY OF THE COLISEUM MODEL

III – ANALYTICAL DEVELOPMENTS

IV – CONCLUSION
I – GENERAL CONTEXT

II – EXTENSIVE STUDY OF THE COLISEUM MODEL

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IV – CONCLUSION
Superconducting strands twisted to form stages

Cu core
Sc strands
Cu corona

Superconducting strand

ITER TF cable

ITER CS cable
CICC and coupling losses

Induced current loop characterized by their time constant, $\tau [ms]$.

Shielding coefficient, $n_k [-]$

Coupling losses

$$P = \sum_j n_k \tau_j \left( \frac{dB_j}{dt} \right)^2$$

where

- $\tau$, the time constant of the current loop [ms]
- $n_k$, the shielding coefficient [-]

Experimental data from JT60SA-TF conductor type [1]

Introduction to the COLISEUM model

COLISEUM (COupling Losses analytical Staged cables Unified Model)

Key features of the model

- Analytical
- Predictive
- At various scales
  - Geometrical parameters
  - Inter-stages transverse conductances
- One \((n\kappa, \tau)\) couple per stage
I – GENERAL CONTEXT

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II. Study in non tangential condition

- Until now
  - The COLISEUM model considered unrealistic **virtual cables**: simulation with tangent tubes

- From now
  - Study of the model in **non tangential conditions**. Getting closer to real compacted cables
II. Study in non tangential condition

Each stage is characterized by a penetration coefficient $\gamma$
- $\gamma \in [0;1]$
- $\gamma = 1$: tangential condition
- $\gamma = 0$: fully penetrated

$\gamma = \frac{R_c \text{ tangent}}{R_c}$

- Void rate indicator
  - $\text{VR} \in [0;100]$ %
  - Practical indicator
  - Ratio of the circumscribed area and the area occupied by the elements

Parametric study on Shielding coefficient, $n_k$ [-]
Time constant, $\tau$ [ms]
We will consider that the model reached its limit if $n_k$ and/or $\tau$ are negative or null.

- Case of a one stage cable, $x3$
- Parametric study on $n_k$ and $\tau$

Looking for specific limit
II. Study in non tangential condition

We will consider that the model reached its limit if $n_k$ and/or $\tau$ are negative or null

- Case of a two stages cable, $3\times3$

- Peculiar case for $\gamma_1 = \gamma_2$
- Looking for specific limit
II. Study in non tangential condition

Application of typical void rate value

- Case of a two stages cable, 3x3
- One $\gamma$ coefficient per stage
- Uncoupling $\gamma_1$ and $\gamma_2$
- VR between 25 and 50 %

Void rate as a function of the penetration coefficients combinations

$\gamma_1$ affected 

$\gamma_2$ affected
II. Study in non tangential condition

- Behaviour of the magnetic parameters
  - Case of a two stages cable, 3x3
  - Time constant, $\tau$ [ms]

- Map of the time constants, $\tau_1$ and $\tau_2$

- Void rate overlap

- Negative values of $\tau$ are overlapped in red
II. Study in non tangential condition

- Behaviour of the magnetic parameters
  - Case of a two stages cable, 3x3
  - Shielding coefficient, $n\kappa [-]

- Map of the shielding coefficients, $n\kappa_1$ and $n\kappa_2$

- Negative values of $n\kappa$ are overlapped in red

- Extreme cases are crossing critical areas
Conclusion

- In reality, void rate should not be far from the $\gamma_1 = \gamma_2$ area.
- Consecutive stages should have similar penetration coefficients.
- For typical values of void rate, the COLISEUM model stays far from the critical areas.

- Confident in the results obtained in non-tangential condition
- This will be generalized up to the nth stage.
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III. Development of the current influence indicator

**COLISEUM model output**
- Coupled results and ranks

- Coupled result means that stages are interacting with each other
- The transverse conductance $\sigma$ is $\neq 0$
- No more possible to attribute one $(n\kappa, \tau)$ couple per stage
- Speak about coupled ranks

⚠️ Find an indicator to determine the influence of each stage in each coupled rank
III. Development of the current influence indicator

Method

- Calculation made on current combinations

Analytical background

\[ [l_{p}]_{j} + [\tau_{c}]_{j} [l_{p}]_{j} = [W]_{j}[V]_{j} B_{a} \]

where, \([l_{p}]_{j} = [W]_{j}[V]_{j} = \sum_{k=1}^{n} W_{jk} l_{k}\)

Choose convention to express the contribution

Normalized coefficient \(C_{jk}\)

\[ C_{jk} = \left( \frac{W_{jk}}{\sqrt{\sum_{k=1}^{n}(W_{jk})^2}} \right)^2 = \frac{(W_{jk})^2}{\sum_{k=1}^{n}(W_{jk})^2} \]

- \(W_{jk}\) can be seen as combination coefficient
- \(C_{jk}\) refers to the influence of the current of the \(k^{th}\) stage to the \(j^{th}\) coupled rank

Application

- 3x3x3x3x3 layout

<table>
<thead>
<tr>
<th>(n_{\kappa})</th>
<th>(\tau_{c} [\text{ms}])</th>
<th>Current influence [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.19</td>
<td>97.6</td>
</tr>
<tr>
<td>0.08</td>
<td>4.11</td>
<td>61.8</td>
</tr>
<tr>
<td>0.17</td>
<td>12.09</td>
<td>5.2</td>
</tr>
<tr>
<td>0.11</td>
<td>32.62</td>
<td>0.1</td>
</tr>
<tr>
<td>0.90</td>
<td>93.40</td>
<td>0.0</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>3.9</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>46.1</td>
</tr>
</tbody>
</table>

Red: Dominant stage

- Current influence not directly linked to the magnetic coefficients \(n_{\kappa}\) and \(\tau_{c}\), but to the currents.
- Dominant stages exist
III. Development of the current influence indicator

Parametric studies conducted on the current influence indicator

Current influence as a function of the multiplicity
- Example of a 5 stages cable
- Dominant stages exist
- The higher, the larger the contribution

Current influence behaviour in non tangential conditions
- Case a two stages cable, 3x6 layout
- Example of the 2nd coupled rank
- Specific case for $\gamma_1 = \gamma_2$

- 3x3x3x3x3 layout
- 3x3x3x3x6 layout

- 50% influence
- 4% influence
- 1% influence
- 57% influence

- Contribution to the 2nd coupled rank
- Influence [%] vs $\gamma$ coefficient

R. Babouche
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Conclusion

- Study of the model in non-tangential conditions
  - Limit identified
  - Far from the usual cases. Confident in the model to generalized this study for a n stages cable
- Analytical developments
  - A new indicator of the current influence
  - A new tool to be explored and developed

COLISEUM future developments

- Background work on the model
- Crosscheck with experimental data
- Use of effective geometrical and electrical inputs (tomography, inter-stage conductance measurement)
- Experimental campaign on various CICCs design at the JOSEFA test station @Cadarache
Thank you for your attention
BACK UP SLIDES

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III. Development of the current influence indicator

Analytical background

Real space

\[ [I] + [\tau][I] = [Y]\dot{B}_a \]

\([\tau] : n - \text{by} - n \text{ time constant matrix}\)

\(\dot{B}_a : \text{first derivative of an exciter term}\)

Eigen space

\[ [I] + [V][\tau_c][V]^{-1}[I] = [Y]\dot{B}_a \]

where, \( [\tau] = [V][\tau_c][V]^{-1} \)

\[ [I_p] + [\tau_c][I_p] = [W][Y]\dot{B}_a \]

where, \( [V]^{-1}[I] = [I_p] \)

\( [V]^{-1} = [W] \)

\[ [I_p]_j + [\tau_c]_j [I_p]_j = [W]_j [Y]_j \dot{B}_a \]

where, \( [I_p]_j = [W]_j[I] = \sum_{k=1}^{n} W_{jk}I_k \)

Choosen convention to express the influence

\[ C_{jk} = \left( \frac{W_{jk}}{\sum_{k=1}^{n} (W_{jk})^2} \right)^2 = \frac{(W_{jk})^2}{\sum_{k=1}^{n} (W_{jk})^2} \]

\( C_{jk} \) is the contribution of the \( k^{th} \) uncoupled stage to the \( j^{th} \) coupled rank