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The 28-MVA FCL Smart Grid Demo Transformer and Modeling Concerns about its Operation under Fault Conditions

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Why FCL-Transformers?

- Aging Grid (140,000 transformers approaching 40 yrs. of service in US grid)
- Energy Saving (Transformer losses 40% of total grid loss)
- Safety and Environment (Liquid-N2 instead of oil)
- Current Limitation (Avoid damages and power interruptions)
Conceptual Design

Three Phases Transformer:
- 28-40.6 MVA.
- 70.5 kV / 12.47 kV.
- Pressurized subcooled nitrogen (70 K, 1.1-3 bar).
- \( \approx 12 \) km (12 mm CCs).
Proposed Tape Architecture

Specifications:

- FCL Requirements: $R_t = 25 \, \text{m}\Omega/\text{m}$.
- Rugged enough to handle insulation on "standard" insulating equipment.
- To be manufacturable and avoid buckling $\rightarrow$ aspect ratio of $\approx 13:1$. 
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Fault Parameters
Fault Current Waveform (2-Windings Circuit Model)

Transformer suddenly grounded at $t = 0$

$$V_p \sin (\omega t + \phi) \begin{cases} RI + L \frac{dl}{dt} & \text{if } t \geq 0, \\ 0 & \text{if } t < 0. \end{cases}$$

For a constant $R$, Laplace transforms and Inverses yield to:

$$I(t) = I_p \left( \sin(\beta - \phi) e^{-\frac{R}{L}t} + \sin(\omega t + \phi - \beta) \right)$$

$$I_p = \frac{V_p}{R \sqrt{1 + \left( \frac{X}{R} \right)^2}}$$

$$\beta = \tan^{-1} \left( \frac{X}{R} \right)$$

$$X = \omega L$$

![Graph showing fault current waveform](image)
Fault duration (SCE)
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Firsts Investigations

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How does HTS change transformers' behavior?

- What is the $X/R$ ratio along the fault event?
- What is the conductors temperature when the fault is cleared?
- How long would be the recovery time under load?
- What would be the effect of the fault level & $I_c$-uniformity on the quench propagation?
The M-T Model (FEM)

An infinitely long, rectilinear and uniform tape to simulate Joule heating.

- 2D cross-section $\mathbf{H}$-formulation
  \[
  \frac{\partial \mu \mathbf{H}}{\partial t} - \nabla \left( \rho \nabla \times \mathbf{H} \right) = 0
  \]

- Coupled with the heat equation i.e. $Q = \mathbf{EJ}$
- Half of the cross-section.
- Simplified architecture.
- AR approx. only for HTS and buffer.
- Current Constraint
  \[
  \int_{\Omega} J_z \, d\Omega = I
  \]
2-Windings circuit Model (load referred to the primary side)

\[ V_p \sin (\omega t + \phi) = \begin{cases} RI + L \frac{dl}{dt} & \text{if } t \geq 0, \\ 0 & \text{if } t < 0. \end{cases} \]

\[ R = R_1(I, t) + \left( \frac{N_1}{N_2} \right)^2 R_2(I, t) \]

\( R_1 \) and \( R_2 \) are the equivalent resistances of the primary and secondary windings. Those resistances vary in time (\( T \) and \( H \)) but also depends on \( I \).

\[ \rho_{HTS} = \frac{E_0}{J_c(T, H)} \left( \frac{|I|}{I_c(T, H)} \right)^{n-1} \]

Differential Algebraic Equation → Backward Differentiation Formulas
Coupling to the M-T Model

- **COMSOL** $\rightarrow$ BDF-IDA
- $R(J_z, T) \rightarrow$ Integration Coupling Variable (FEM)
- Current Constraint linked to the "Global" Circuit Equation
Application Example: Single Phase Transformer

Simulation Parameters (Two Windings model):

- 70.5 kV / 7.2 kV
- $L_1 = 2434$ m, $L_2 = 177$ m
- Leak. Imp. = 13%, $f = 60$ Hz.
- LV winding: 8 strands in parallel
- $I_{c0} @ T = 70$ K $\approx 375$ A/cond.

Note: The Leakage Impedance is defined as the percentage of primary voltage that must be applied to the transformer to produce full load current in the shorted secondary.
Application Example: Single Phase Transformer

(Current & Temperature Evolution for a Single Secondary Winding Tape)

\[ T \approx 300 \text{ K after 50 cycles.} \]
Application Example: Single Phase Transformer...

(Current & Temperature Evolution for a Single Secondary Tape)

- Coated Conductor Submitted to "real" Current Waveforms.
- Dynamic Visualization of the Transformer Characteristics (X/R, T, ...).
- Great Tool to Design Tapes! But...
- Supposed Rectilinear, Infinite and Uniform conductors.
- Suppose that R develops the same way on both side of the transformer.
- Transport Current & External Fields are Difficult to Transpose.
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Challenges and Future Work
Geometry, Heat Transfer & RUL

Example of Transformer Windings.

\[ q \text{ (W/m}^2\text{)} \]

\[ T - T_\infty (K) \]
Non-uniformities & Propagation
Miscellaneous (Solder voids, bubbles, …)

X-ray fluoroscopy of a bounded tape

Solder voids …

Bubbles & Dielectric Properties
In Conclusion

- The FCL-Transformer and the Proposed Tape’s Architecture.
- Coupling Circuit and FE Analysis Provide a Powerful Design Tool.
- Geometry and Non-Uniformities → Needs for 3D?
- Material Characterization Essential to Improve Numerical Models i.e. $R(T, J, H)$, Heat transfer, …
Questions?

Thank you for your interest!

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