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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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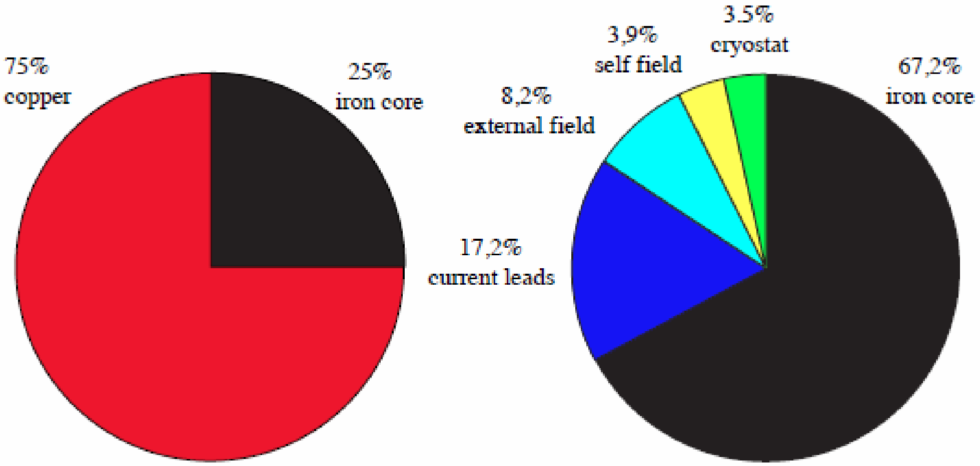
Outline

- **Introduction**
  - Why FCL-Transformers?
  - Conceptual Design
  - Proposed Tape's Architecture
- **Fault Parameters**
  - Fault Current Waveform
  - Fault Duration
- **First Investigations**
  - HTS behavior?
  - The M-T Model
  - Circuit Model
  - Coupling to the M-T Model
  - Application Example: Single Phase Transformer
- **Challenges and Future Work**
  - Geometry, Heat transfer & RUL
  - Non-uniformities & Propagation
  - Miscellaneous (Solder voids, bubbles, . . .)
- **Conclusion**

Why FCL-Transformers?



conventional transformer
total annual loss 839.7 MWh

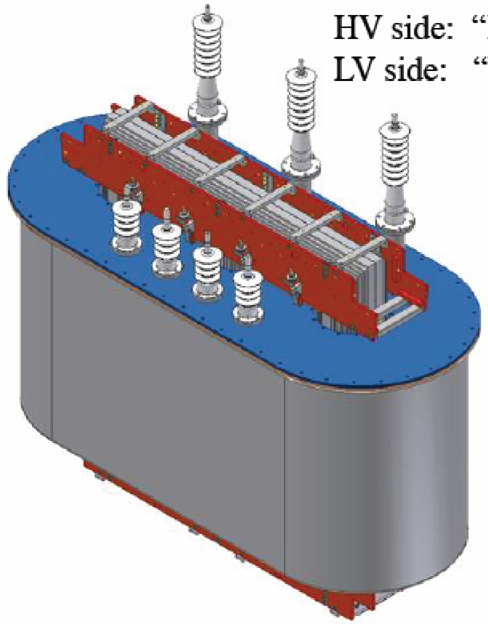
superconducting transformer
total annual loss 160.3 MWh

Partitions on annual energy loss for a conventional and superconducting 63-MVA transformer. Berger et al. J. Physics: Conf. Ser., **234** (2010) 032004

Lakeland FL, August 2007.
Ignition of 14 000 gallons of oil!

- 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)

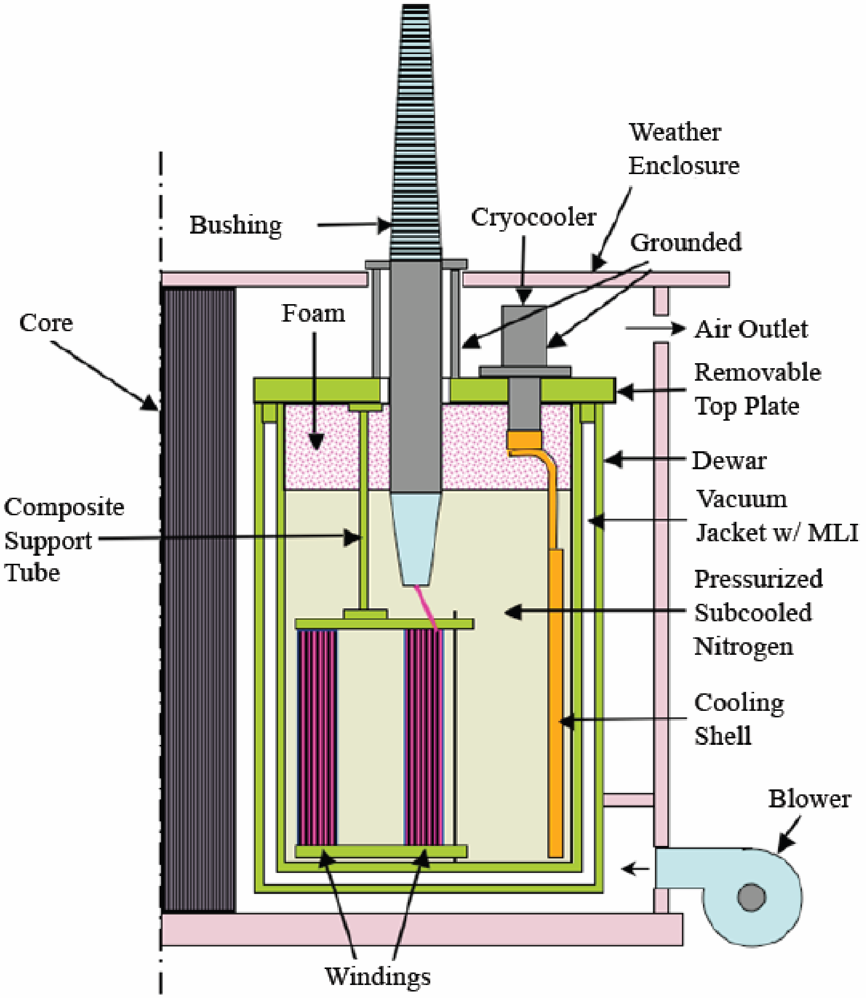
Conceptual Design



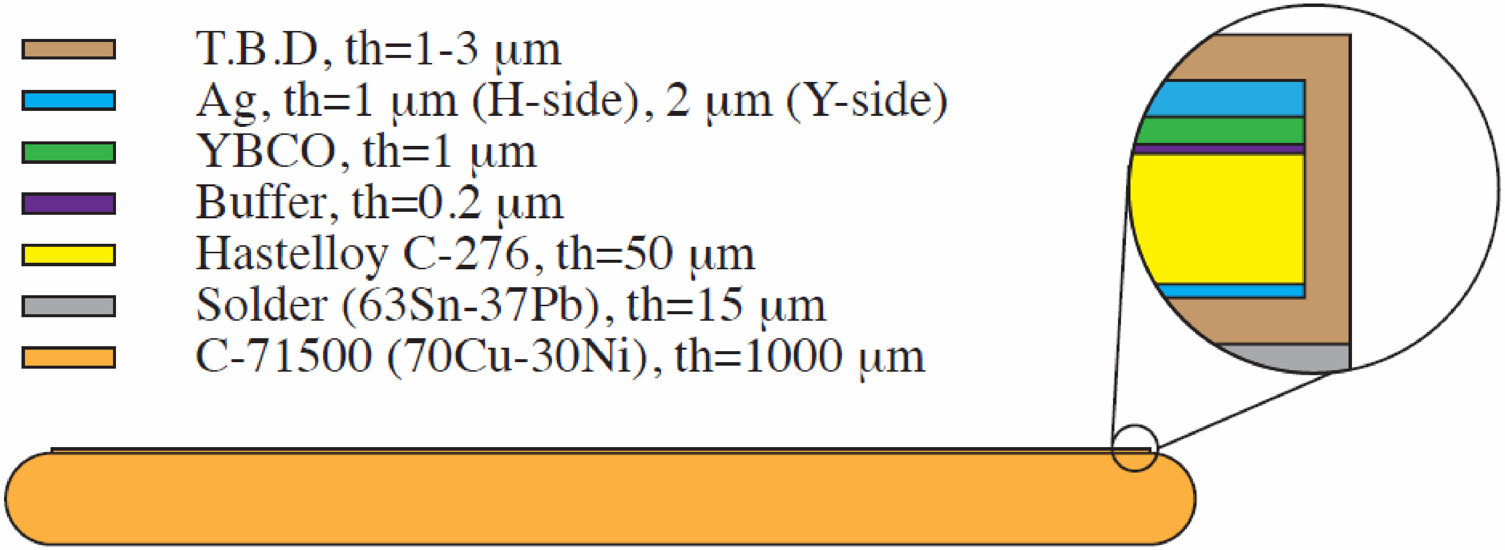
HV side: “Delta”
LV side: “Wye”

Three Phases Transformer:

- 28-40.6 MVA.
- 70.5 kV / 12.47 kV.
- Pressurized subcooled nitrogen (70 K, 1.1-3 bar).
- ≈12 km (12 mm CCs).



Proposed Tape Architecture



🟫 T.B.D, th=1-3 μm

🟦 Ag, th=1 μm (H-side), 2 μm (Y-side)

🟩 YBCO, th=1 μm

🟪 Buffer, th=0.2 μm

🟨 Hastelloy C-276, th=50 μm

⬜ Solder (63Sn-37Pb), th=15 μm

🟧 C-71500 (70Cu-30Ni), th=1000 μm

Specifications:

- FCL Requirements: $R_l = 25\ \text{m}\Omega/\text{m}$.
- Rugged enough to handle insulation on "standard" insulating equipment.
- To be manufacturable and avoid buckling → aspect ratio of $\approx$ 13:1.

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Fault Parameters

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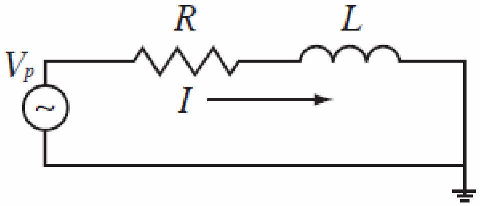
Fault Current Waveform (2-Windings Circuit Model)

Transformer suddenly grounded at $t = 0$



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

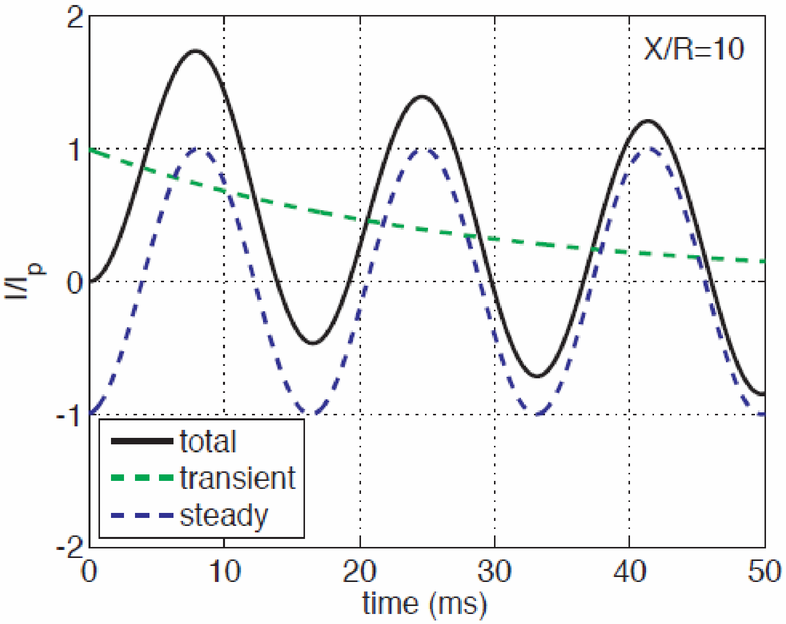
For a constant R, Laplace transforms and Inverses yield to:

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

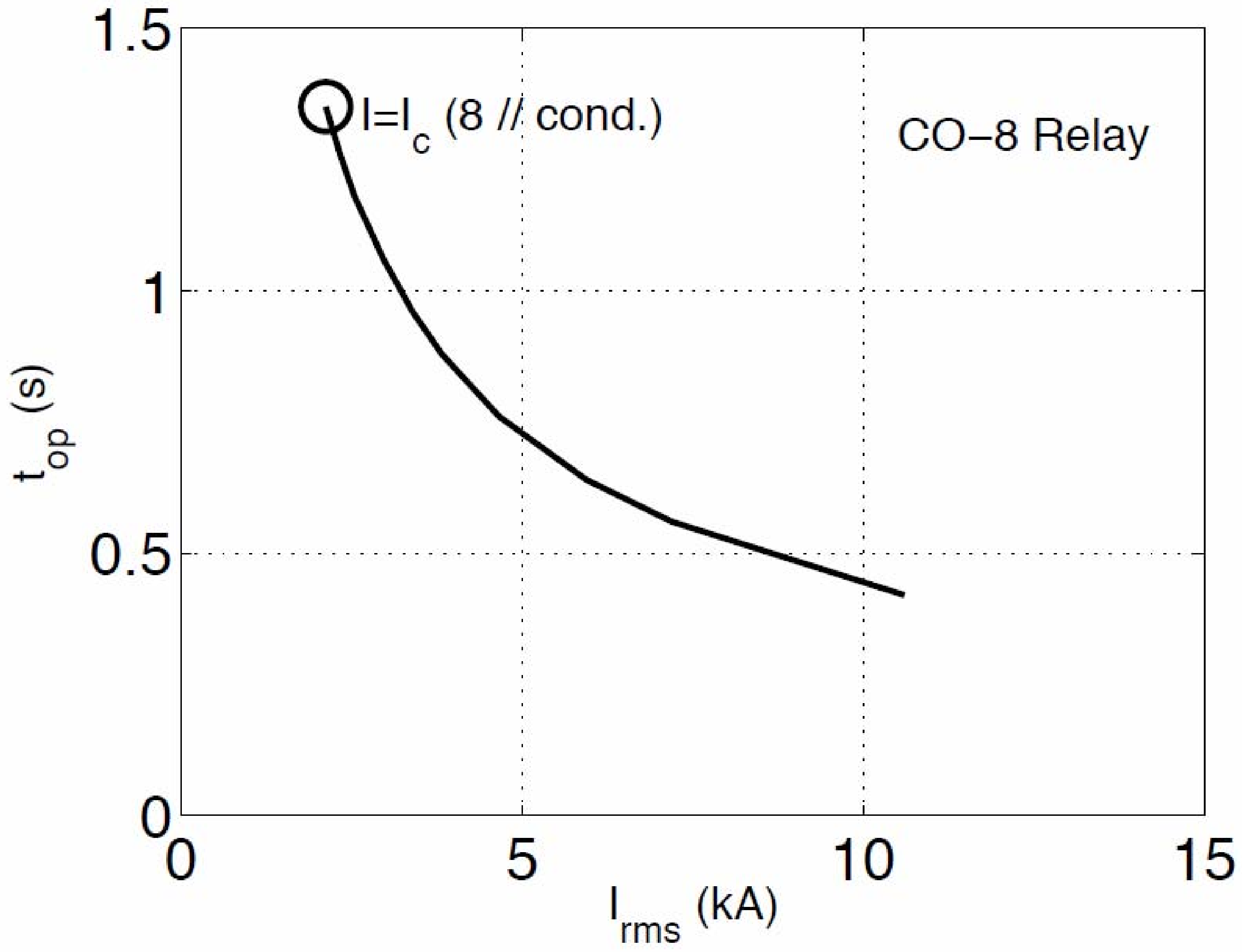
$$I_p = \frac{V_p}{R\sqrt{1+\left(\frac{X}{R}\right)^2}}$$

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

$$X = \omega L$$



Fault duration (SCE)



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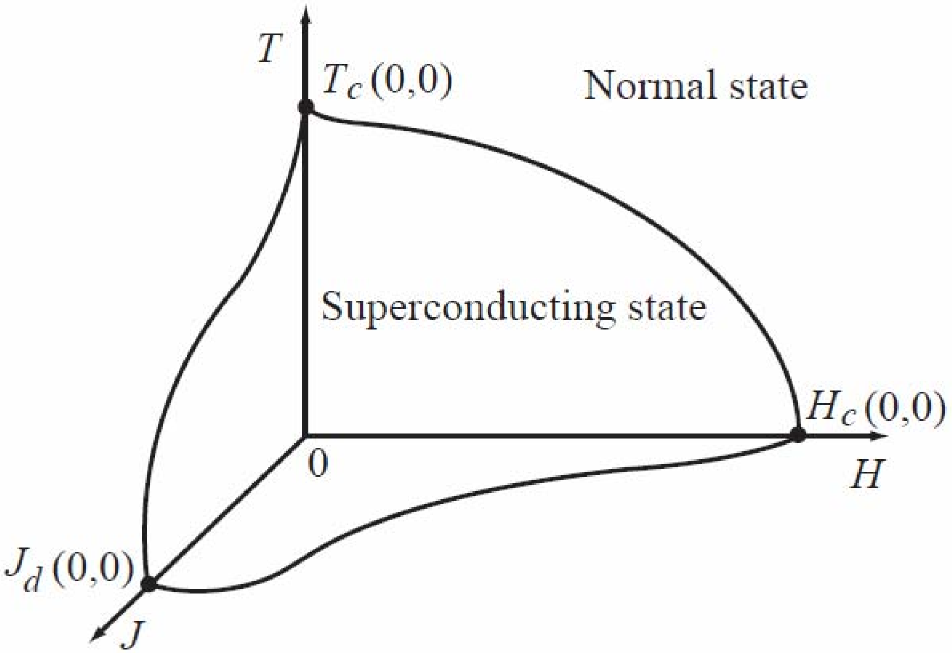
Firsts Investigations

How does HTS change transformers' behavior?



R depends on
T, J and H

- 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)

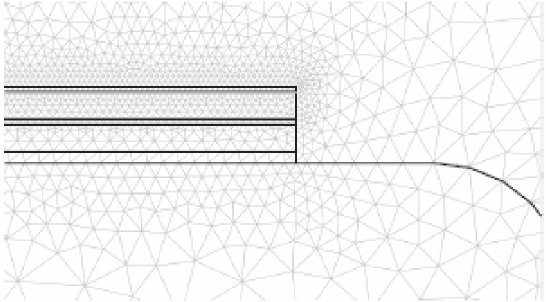
An infinitely long, rectilinear and uniform tape to simulate Joule heating.

- 2D cross-section **H**-formulation

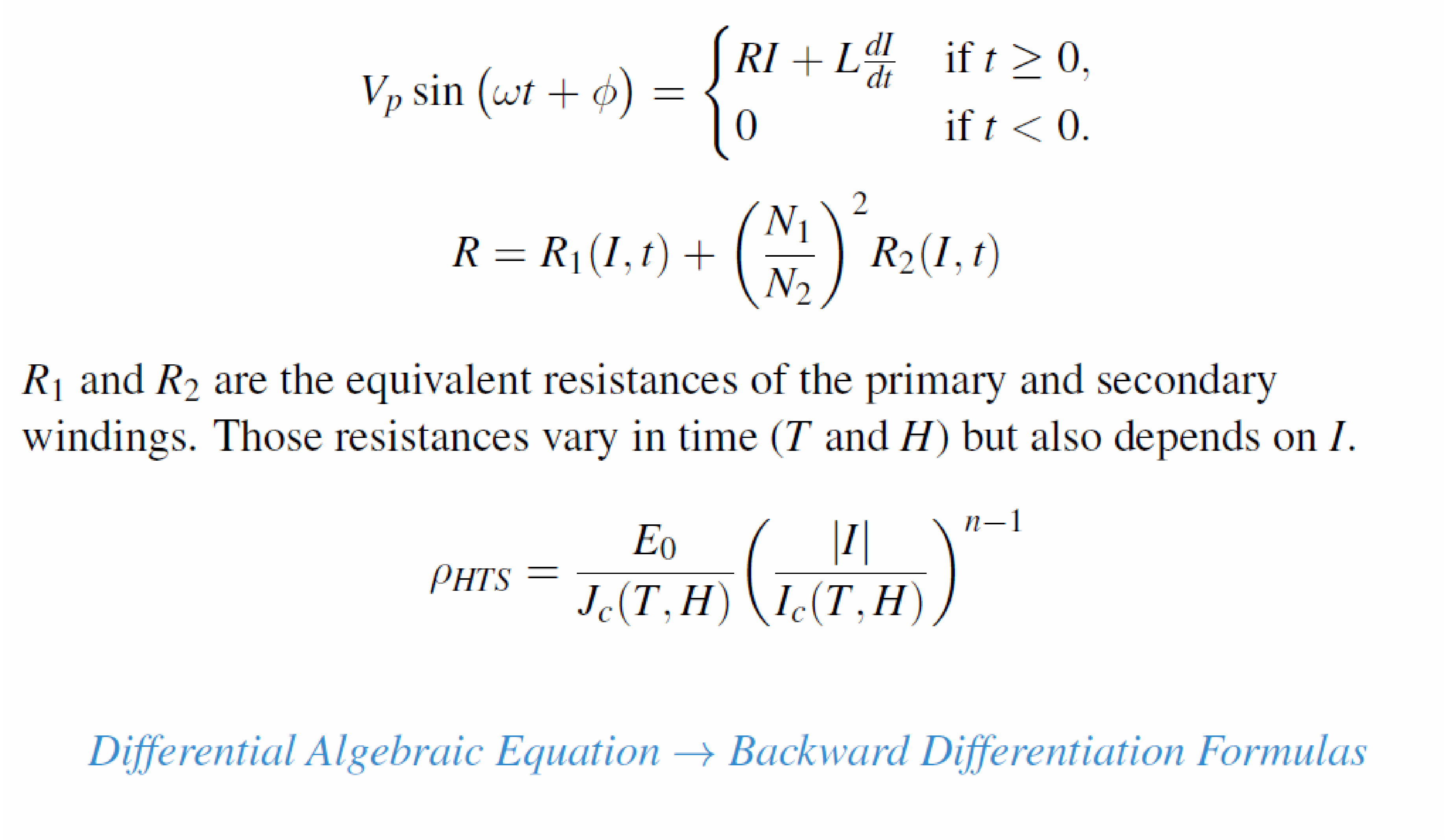
$$\frac{\partial \mu \mathbf{H}}{\partial t} - \nabla\left(\rho \nabla \times \mathbf{H}\right) = 0$$

- 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)



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

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

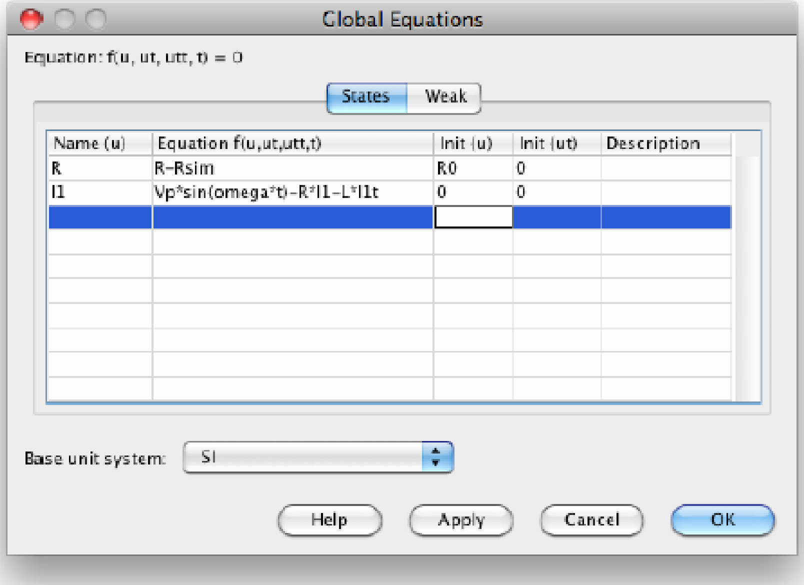
R_1 and R_2 are the equivalent resistances of the primary and secondary windings. Those resistances vary in time (T and H) but also depends on I.

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

Differential Algebraic Equation → Backward Differentiation Formulas

Coupling to the M-T Model

- COMSOL → BDF-IDA
- $R(J_z, T)$ → Integration Coupling Variable (FEM)
- Current Constraint linked to the "Global" Circuit Equation



Equation: f(u, ut, utt, t) = 0

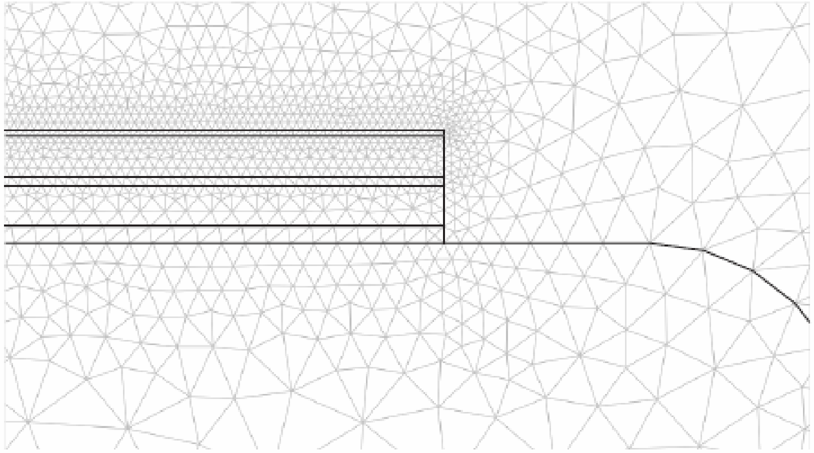
Name (u)	Equation f(u,ut,utt,t)	Init (u)	Init (ut)	Description
R	R-Rsim	R0	0	
I1	Vp*sin(omega*t)-R*I1-L*I1t	0	0	

Base unit system: SI

Application Example: Single Phase Transformer

Simulation Parameters (Two Windings model):

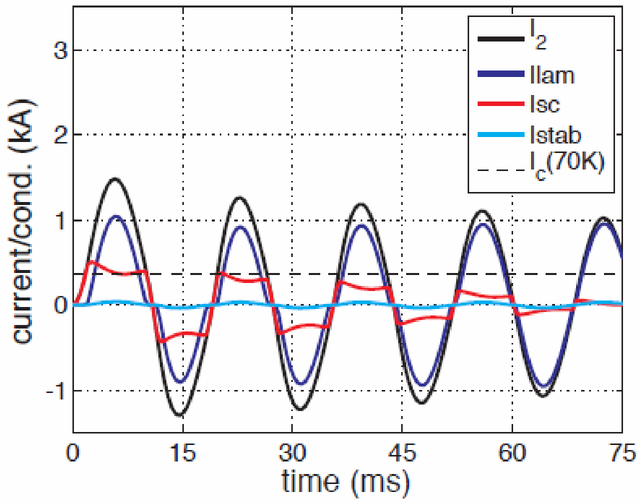
- 70.5 kV / 7.2 kV
- L_1 =2434 m, L_2 =177 m
- Leak. Imp.=13%, f =60 Hz.
- LV winding: 8 strands in parallel
- I_{c0} @ $T = 70$ K $\approx$ 375 A/cond.

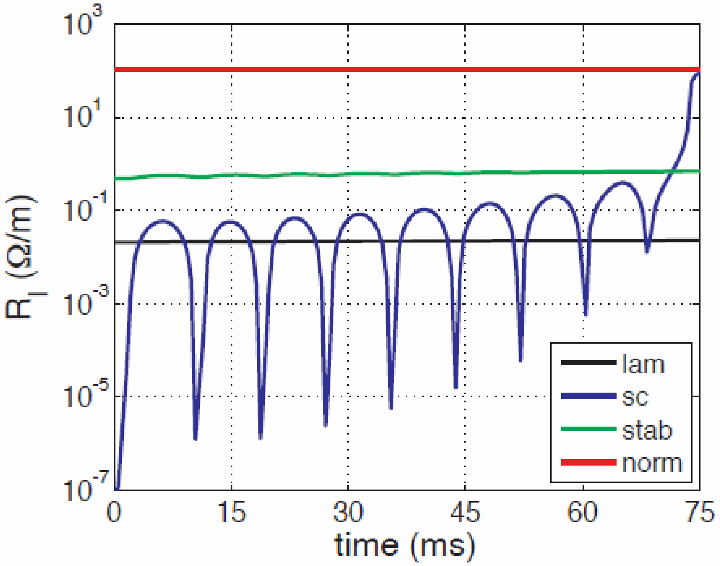


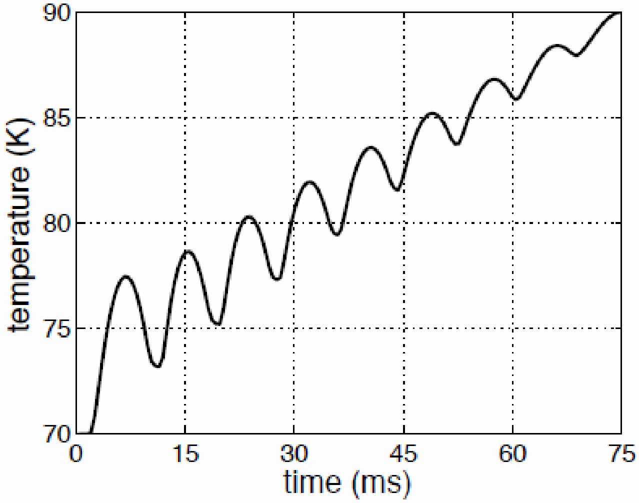
Note: The Leakage Impedance is defined as the percentage of primary voltage that must be applied to the transformer to produce full load current in the shorted secondary.

Application Example: Single Phase Transformer

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

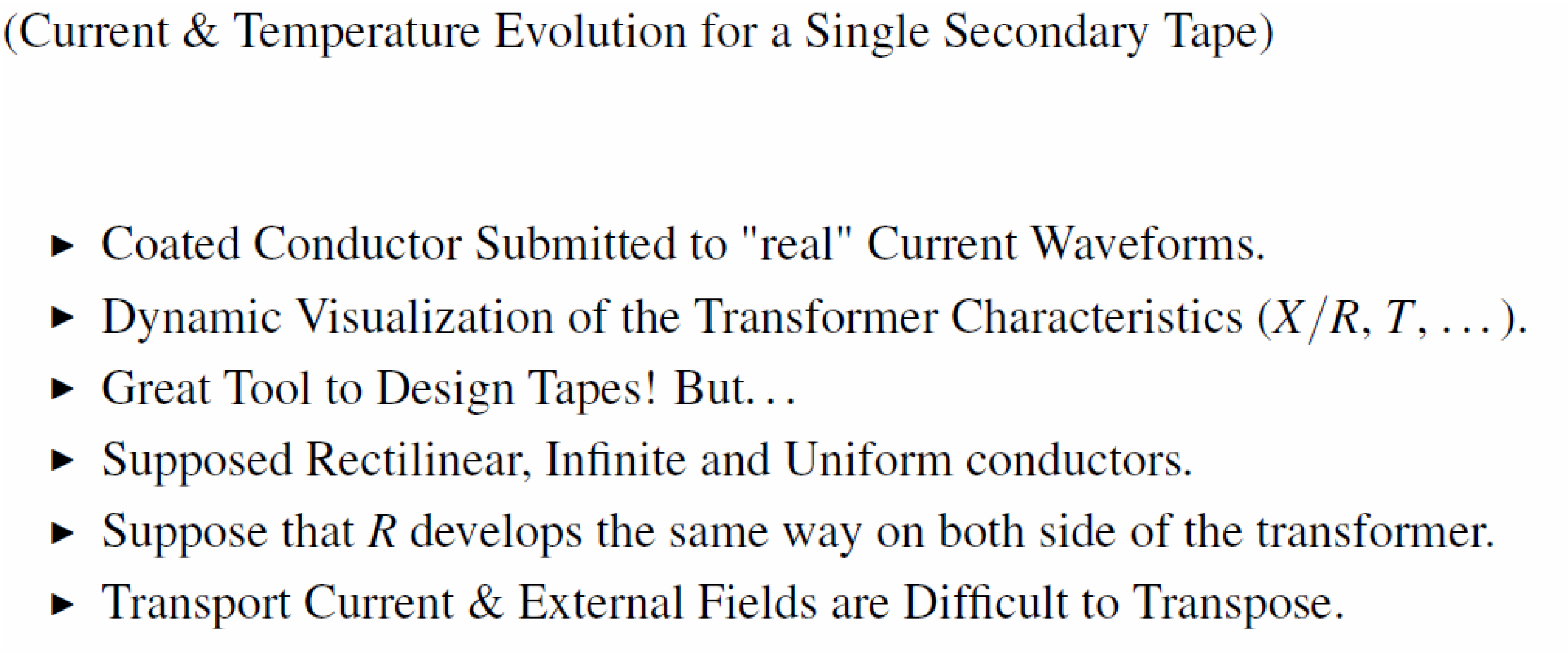






$T \approx 300$ K after 50 cycles.

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, $\ldots$).
- 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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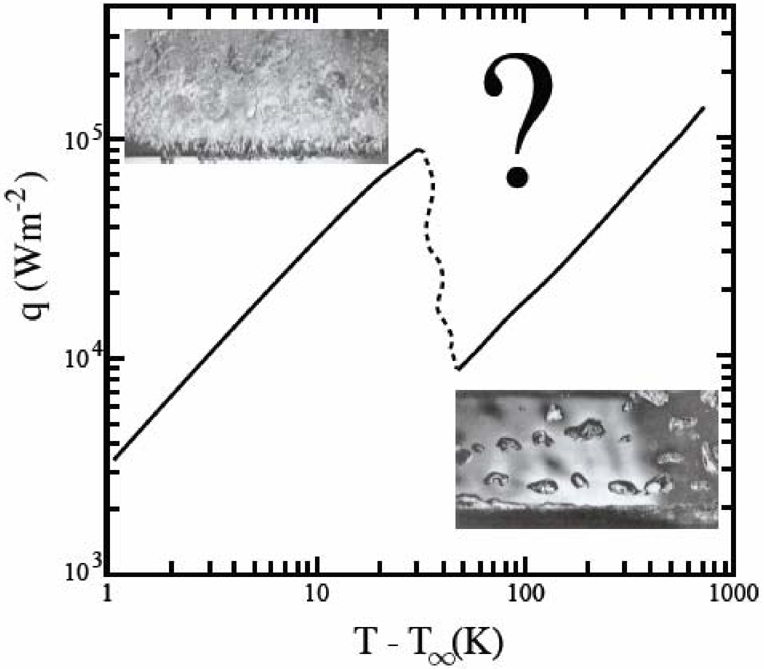
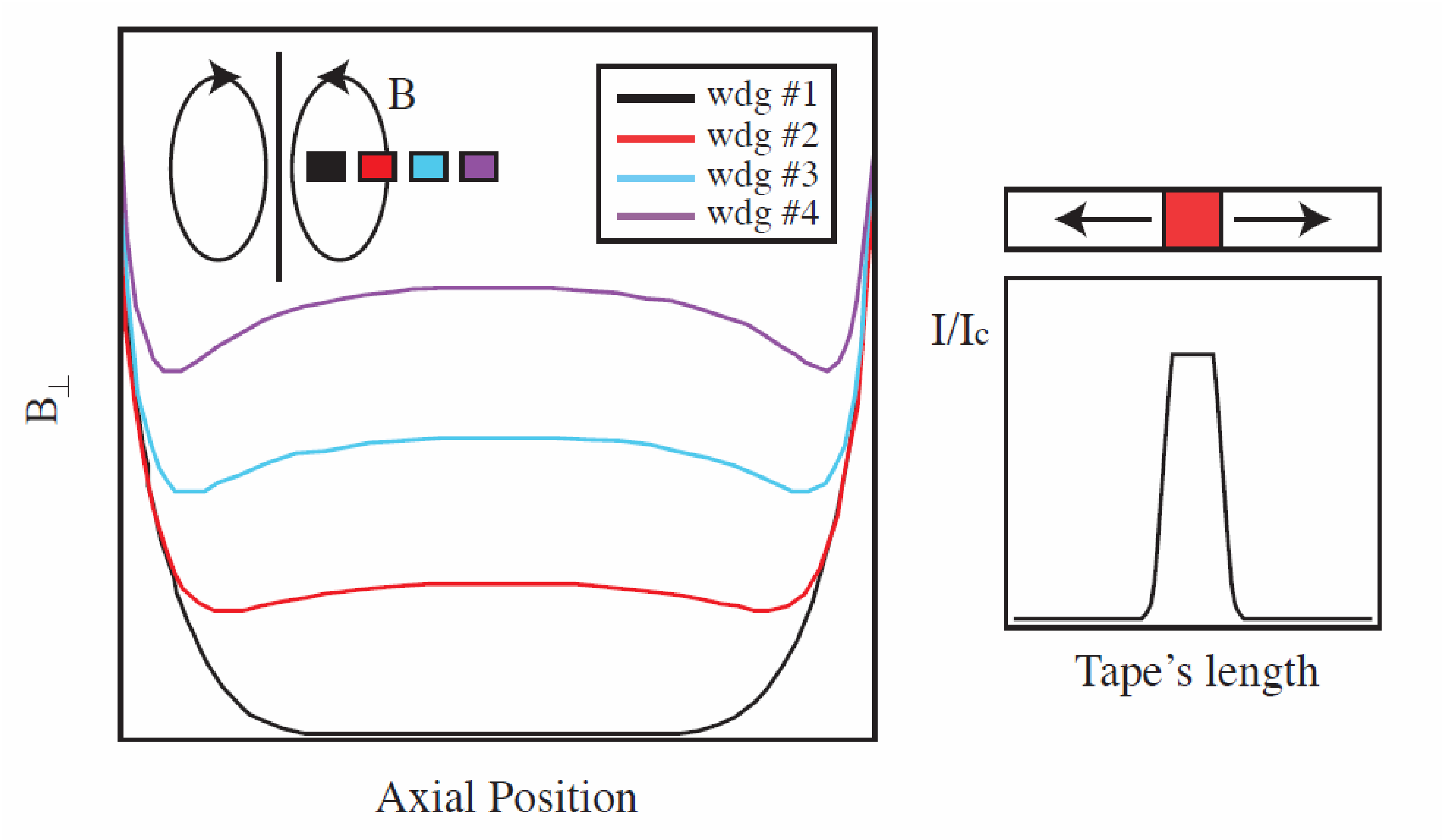
Challenges and Future Work

Geometry, Heat Transfer & RUL

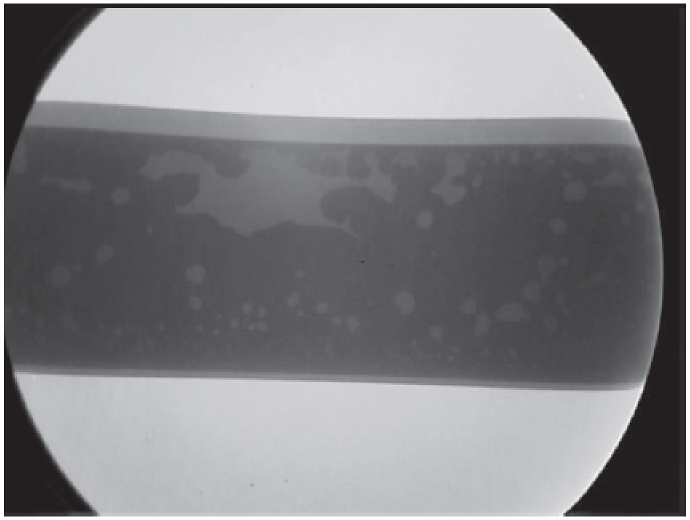
Example of Transformer Windings.



Non-uniformities & Propagation



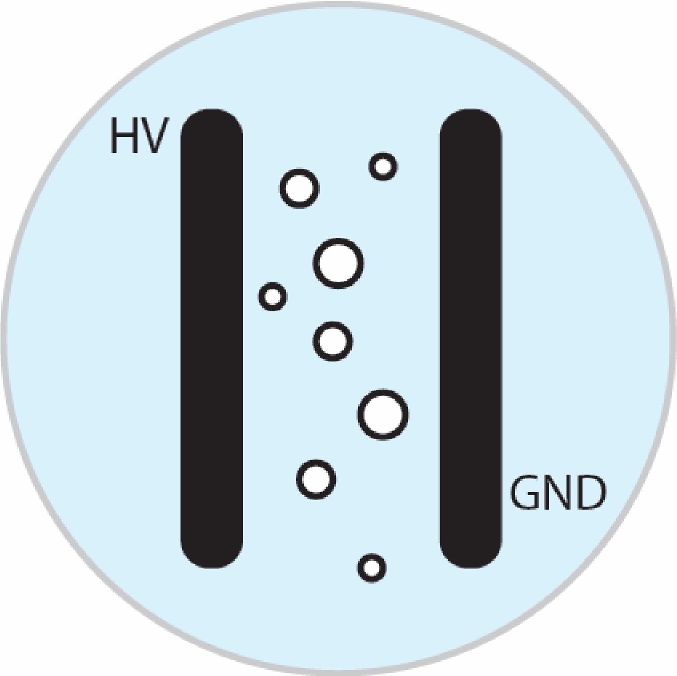
Miscellaneous (Solder voids, bubbles, …)



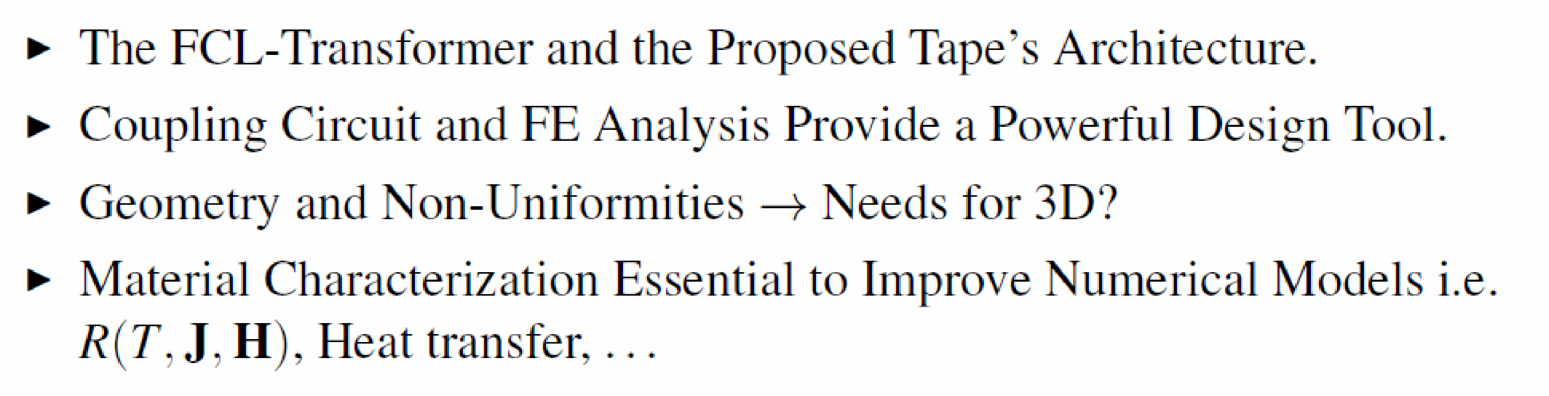
X-ray fluoroscopy of a bounded tape

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. $R(T, \mathbf{J}, \mathbf{H})$, Heat transfer, ...

Questions?

Thank you for your interest!

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