Simulation-Based Design
in
Electrical Engineering

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2018

Simulation-Based Design in Electrical Engineering

- Introduction
- Dielectric Design of HV Products
- Magnetics in Engineering Design
- **Coupled Problem**
- Optimization 1
- Optimization 2

Thermal Design

El-Mech. Design

Dielectric Design

Thermal Design

Thermal Design

- The **second principle of thermodynamics** postulates a heat transport from a body with **high temperature** to a **lower temperature** body

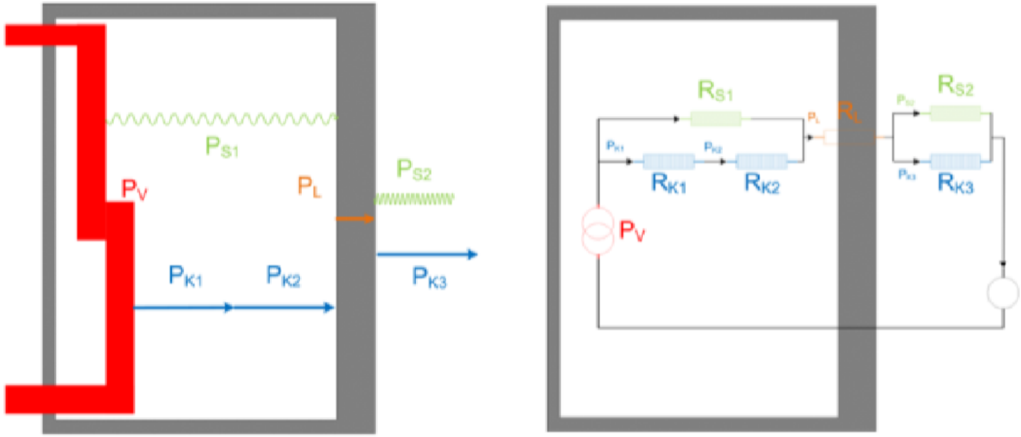
- Four different heat transport mechanisms:

  - **thermal conduction** -> Energy transport of molecules and electrons by diffusion and kinetic collisions (*heat transport within the body*)
  - **thermal convection** -> The energy is conducted to a fluid and as a result of a density change the fluid begins to flow
  - **thermal radiation** -> Known as electromagnetic radiation represented by the kinetic energy of atoms and molecules.
    - Any body above 0K provides this radiation.
    - No need for heat transfer medium!
  - **phase transition** -> Energy needed to energize from one physical state to another

Thermal Design

Thermal analysis

- Thermal Networks
- CAD-based Thermal Analysis

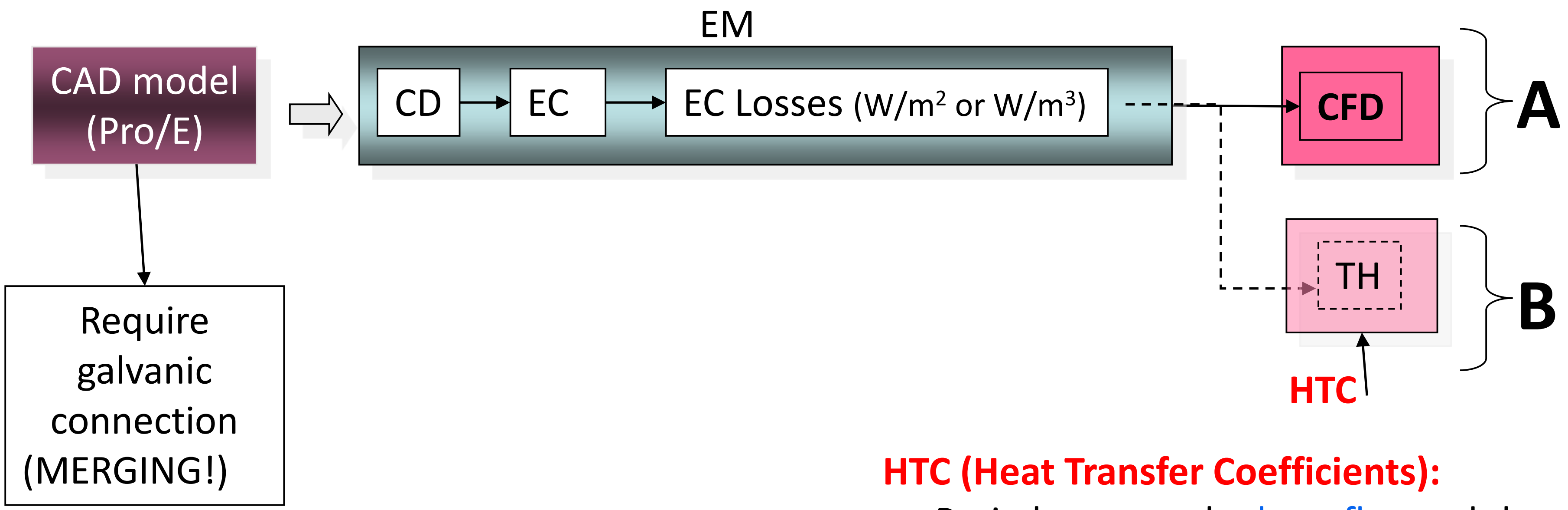


Equivalent to the electrical circuit approach

Thermal Design

CAD-based Thermal Analysis

Analysis workflow



HTC (Heat Transfer Coefficients):

- Ratio between the heat flux and the thermodynamic driving force of the heat flow
- HTC is something called Temperature difference
- HTC[W/(m^2•K)]

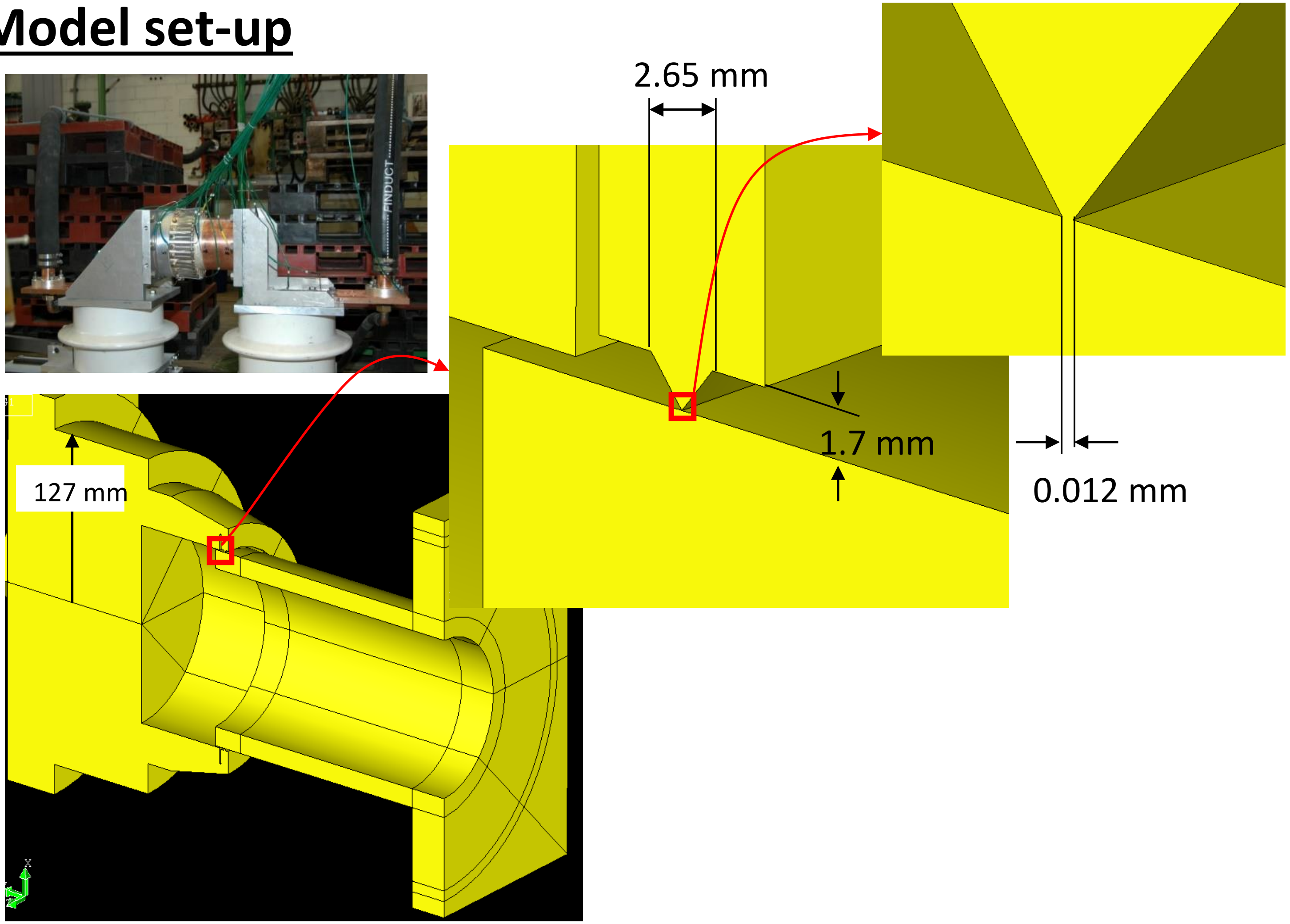
Thermal Design

HECSPS starting switch prototype

- 18 kA: short-time current test after 15 min
- Natural cooling

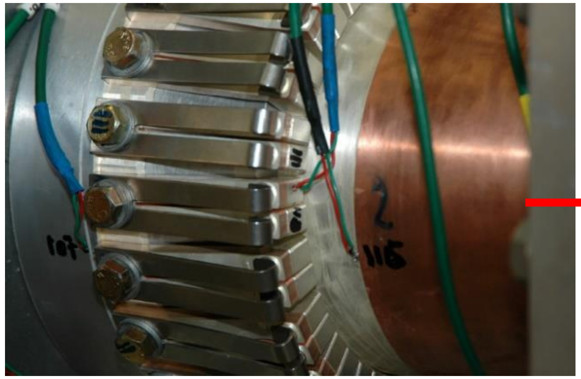
Thermal Design

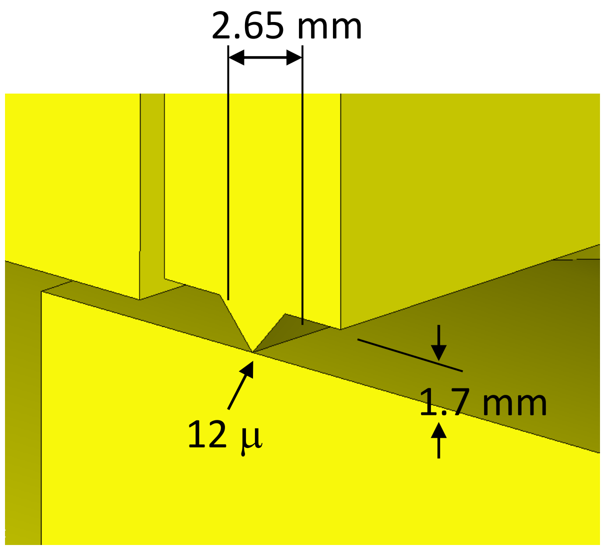
Model set-up



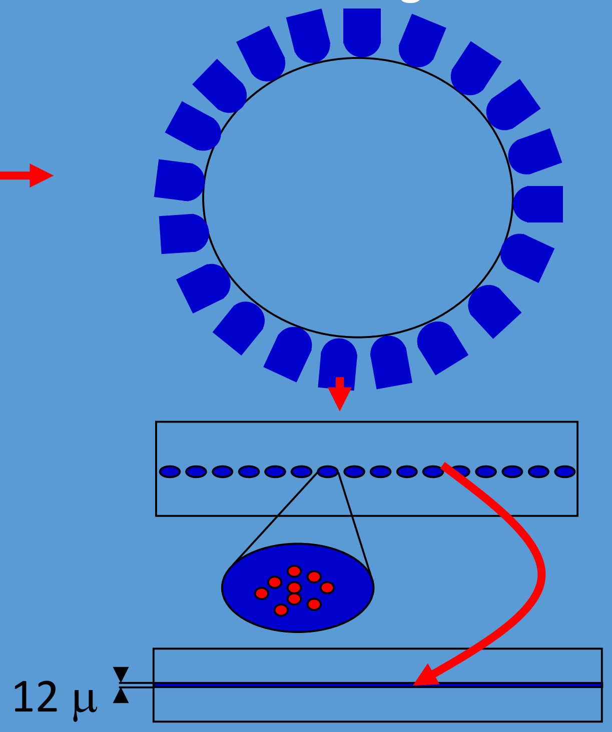
Thermal Design

Contacts arrangement in HECSPS





"Contact bridge" definition



Hertz formula

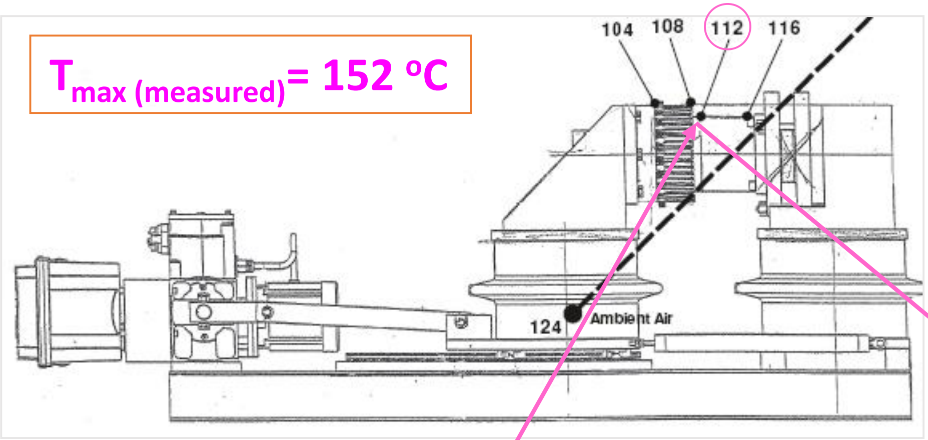
$S_{1\text{-contact}} \sim 0.114\ mm^2$ (for 30 N)

for 48 contacts => $S_{48\text{-contacts}} = 5.47\ mm^2$

Heinrich R. Hertz: **Über die Berechnung elastischer Körper** , in Gesammelte Werke, Vol. 1,Leipzig, Germany 1895

Measured results

$T_{max\ (measured)}$= 152 °C



Approach B (TH)

- HTC=10 [W/Km]
- Sink temperature = 20 [°C]

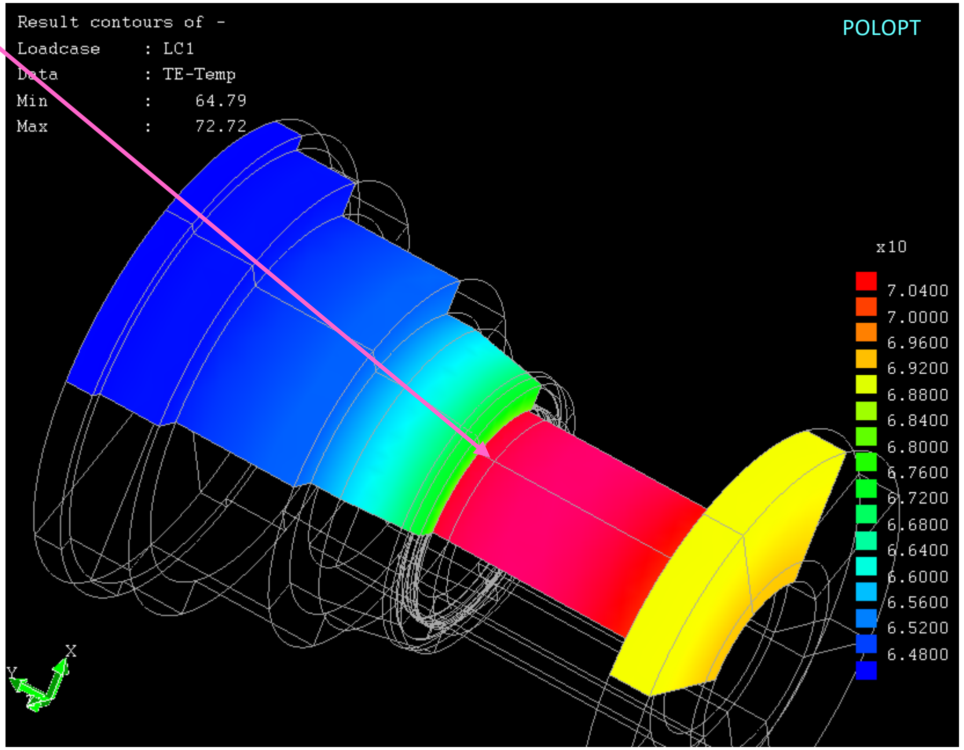


Table 9: Table of the final temperaturefor a test current of 18.0 kA after 10 min testing time

24.06.2005 10:27:03 ABB Schweiz - Hochspannungstechnik AG Hochstrom Labor PTHX-H

Versuchsprotokoll Erwärmungsversuch

Versuchsbezeichnung: 2005-006-04

HECSPS Starting Switch - 18kA @ 50Hz / 10min

- Test Object: HECSPS Starting Switch
- Test Current: 18000 A
- Test Frequency: 50 Hz
- Temperature Rise Test for 10 minutes or conductor temperature of 250 °C (absolute)
- Ambient Air Temperature: 20...30 °C

Run: 2005-006-04; Record: 31

Timestamp: 06.04.2005 15:15:04 (0:15:00 after start of measurement)

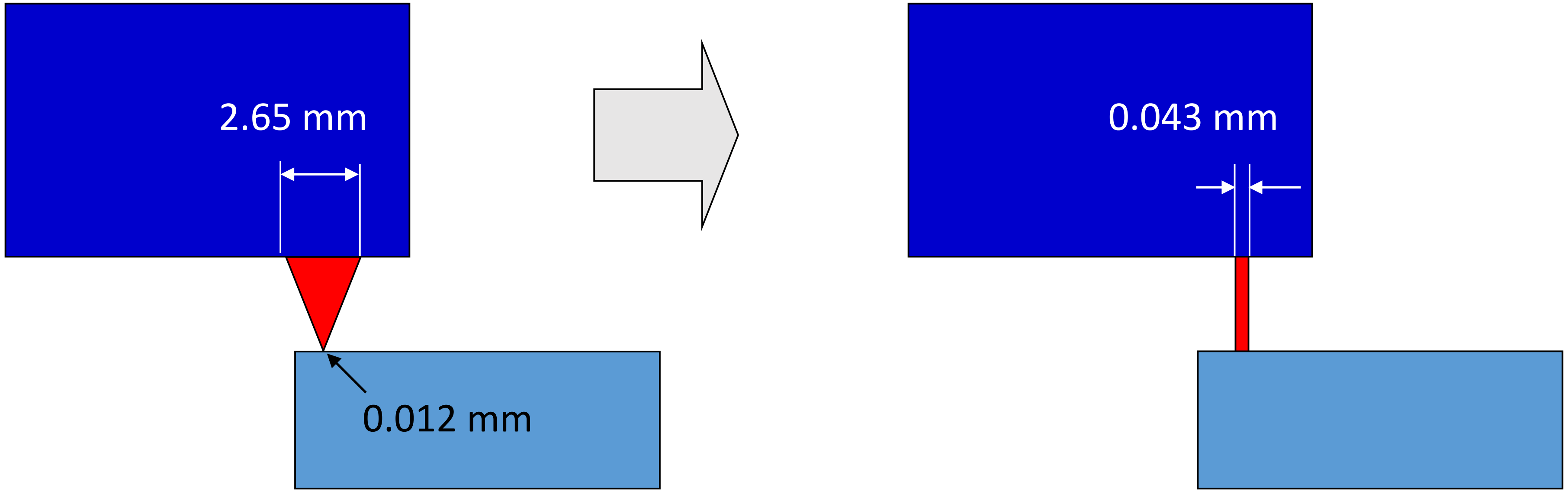
max. Gradient: Chn. : NaN K/h Tref: REF_mean: 25.2 degC

Name	Value	unit	Name	Value	unit	Name	Value	unit	Name	Value	unit	Name	Value	unit
101	126.3	degC	102	1[illegible]5.9	degC	103	156.0	degC	104	158.7	degC	105	153.5	degC
106	149.9	degC	107	[illegible]53.2	degC	108	156.7	degC	109	165.3	degC	110	158.0	degC
111	154.7	degC	112	152.4	degC	113	153.6	degC	114	147.6	degC	115	142.2	degC
116	142.3	degC	117	144.1	degC	118	143.3	degC	119	140.7	degC	120	142.1	degC
121	153.0	degC	122	151.6	degC	123	24.9	degC	124	25.5	degC			

$T_{max\ (simulated)}$= 72.7 °C ?

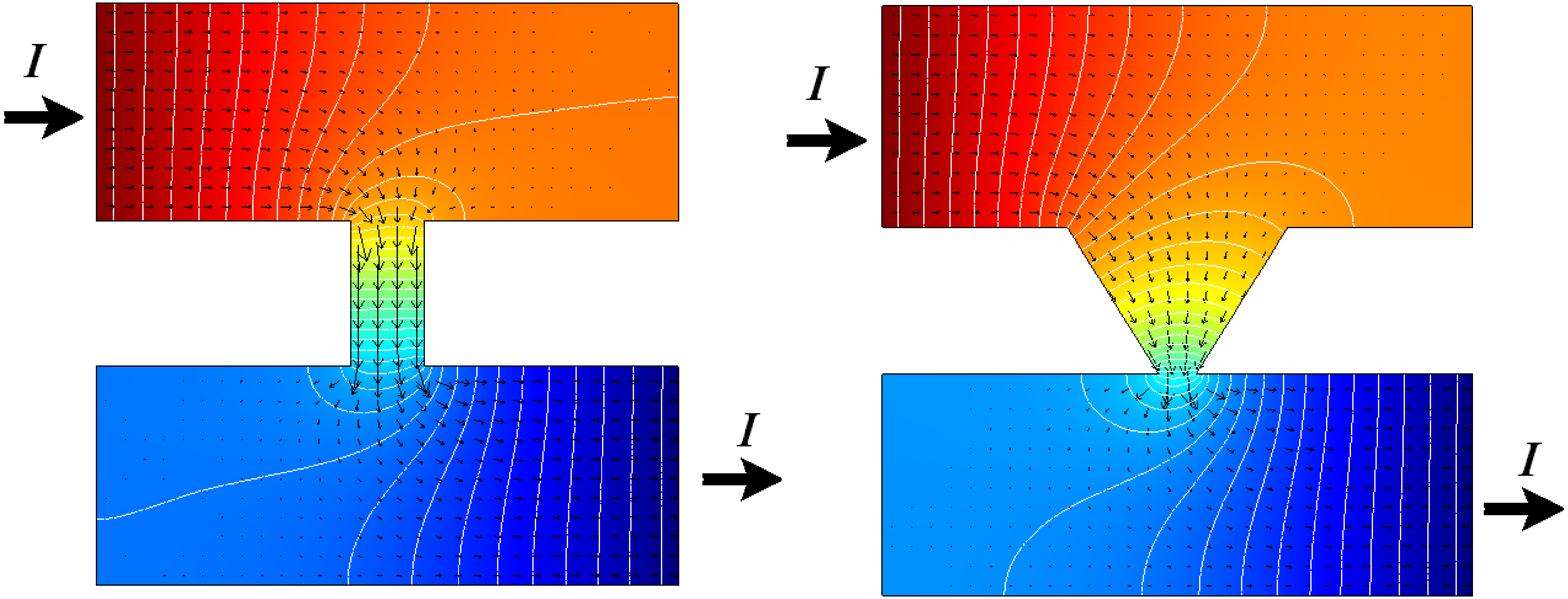
Thermal Design

First (intuitive) try: Resize the gap size



Thermal Design

Simplified representation of the “Contact Bridge”



Bridge contact: case 1

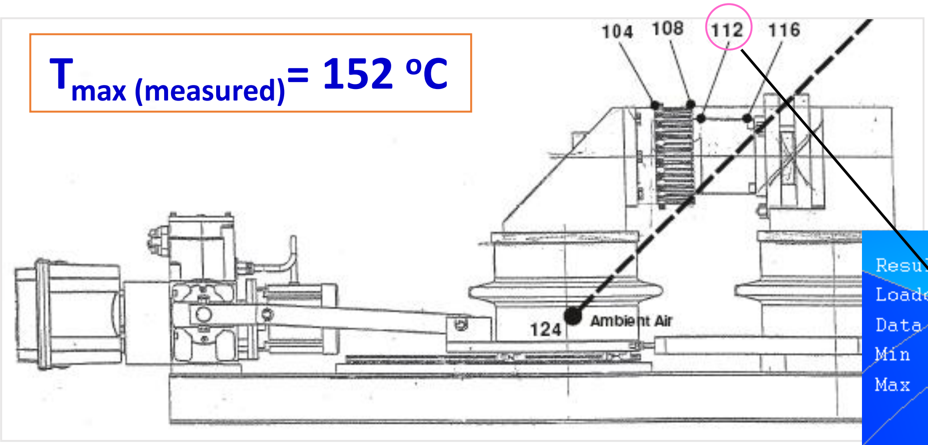
Bridge contact: case 2

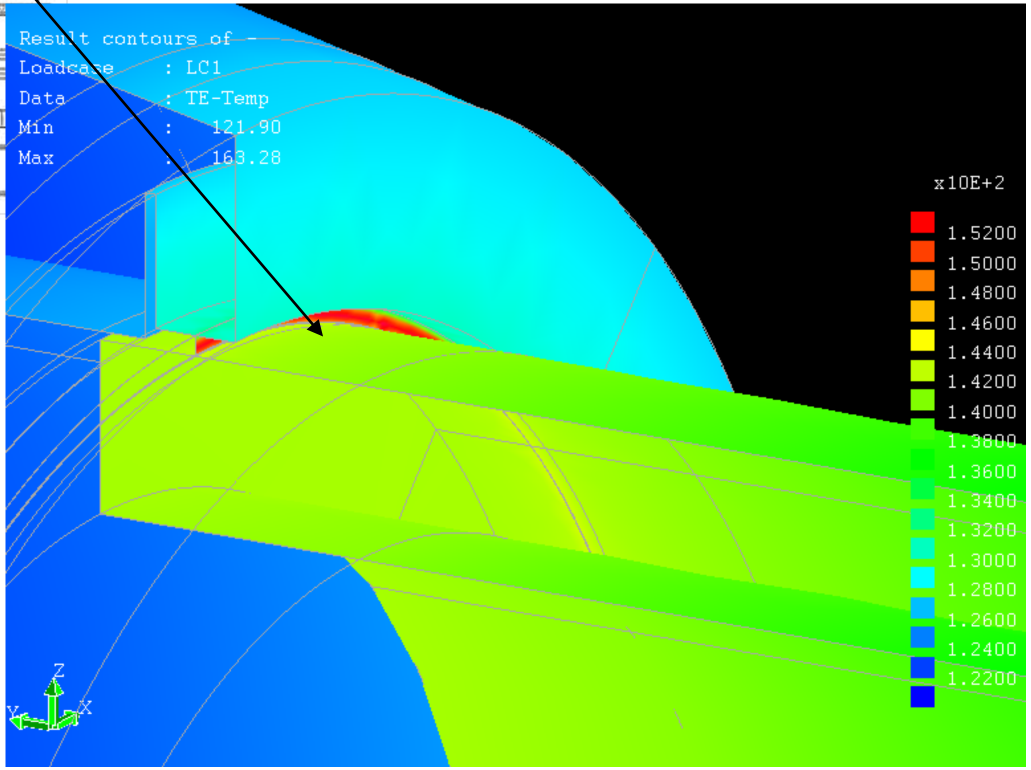
Colours: potential distr.
Arrows: current flow

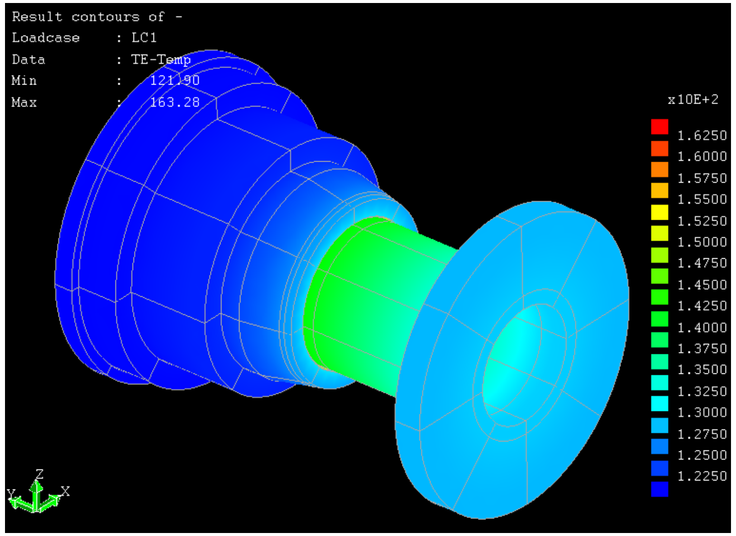
Approach B (TH)

- HTC=10 [W/Km]
- Sink temperature = 20 [^oC]

$T_{max\ (measured)} = 152\ ^oC$







$T_{max\ (simulated)} = 163.2\ ^oC$?

$T_{112\ (simulated)} = 150\ ^oC$

Thermal Design

Concluding remarks

- Modelling of the “Contact bridge” is one of the crucial points in CAD-based thermal simulation!
- If we know the value of contact resistance R_{CB} than we can estimate the size of the “Contact bridge” volume V_{CB}!
- The form of the “Contact bridge” can be arbitrary, preserving that V_{CB} is kept!

Thermal Design

Concluding remarks

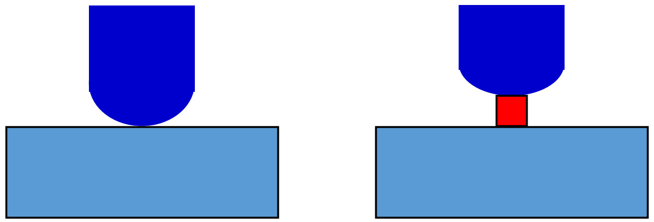
- Going towards CAD-based thermal simulation requires some learning stages!

R_{CB} ⟶ V_{CB}

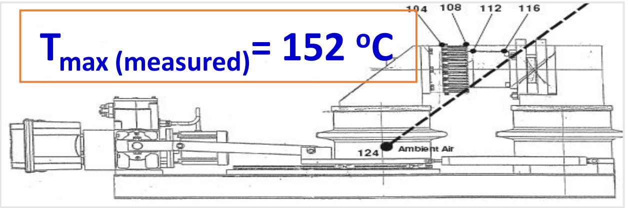
Arbitrary form of V_{CB}

- Size of the V_{CB} can be tailored to the most appropriate geometry! (modelling issue!)

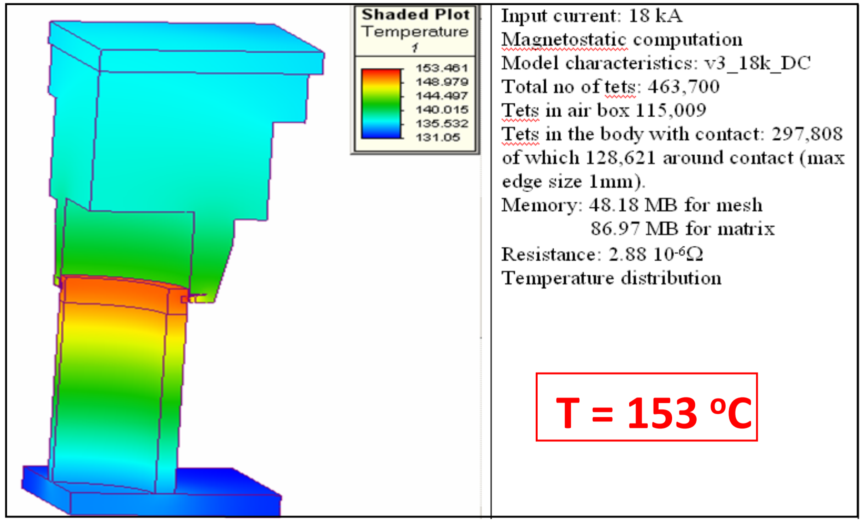
- Skilled CAD-designer can rather fast adapt the model for this type of analysis

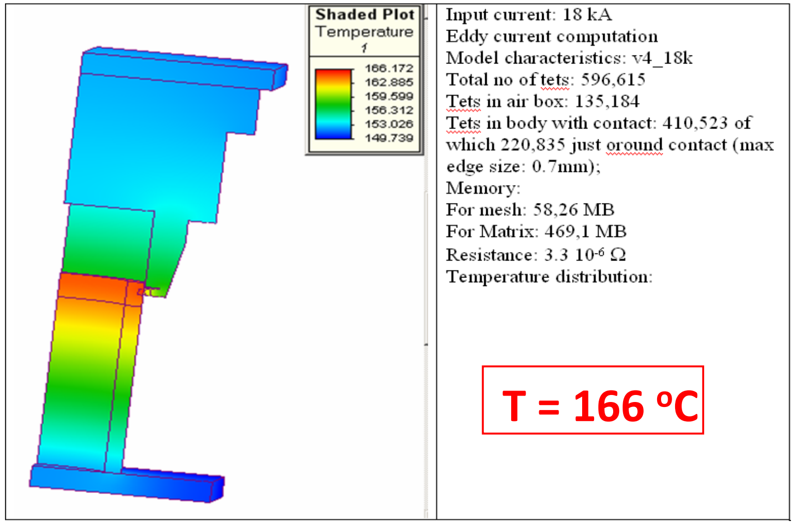


Concluding remarks (cont.)



- FEM-based EM analysis





- Temperature with EC losses is converging towards temperature with MS losses!
- Mesh required for ¼ of FEM model already **½ million** elements!

Already with Approach “B” (HTC), i.e. without complete CFD run, computed temperature is reasonable!

Thermal design

Thermal Design

- Transformers are very efficient devices, with the conversion rate 0f 95-99% of the input power
- Two working regimes during the transformer operations are:
  1. **Non-loaded regime:**
     - Highly inductive device (like shunt reactor)
     - Characterized by two types of losses:
       - **Eddy losses** (due to induced voltages in the laminations)
       - **Hysteresis losses** (due to molecular composition (aligning) of the iron core
  2. **Loaded regime:**
     - Characterized by
       - **Winding loses** (I^2R)
       - **Stray losses** (due to leakage flux interaction with the surrounding structures like bus-bars, clamps, …)

The heat generated by the no-load and load losses is the main source of temperature rise in the transformer!

IEEE C57.12.00-2000 standard

IEEE C57.91-1995 standard

Thermal Design

some numbers ...

ABB: total losses in power transformers = 300.000 kW

1500 USD / kW

1% of 300.000 kW → 4.5 MUSD saving

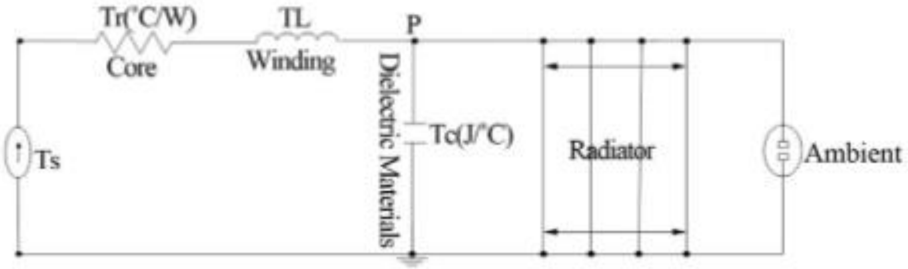
Thermal Design

How to approach loss / overheating problem?

Thermal analysis

Thermal Networks

CAD-based Thermal Analysis

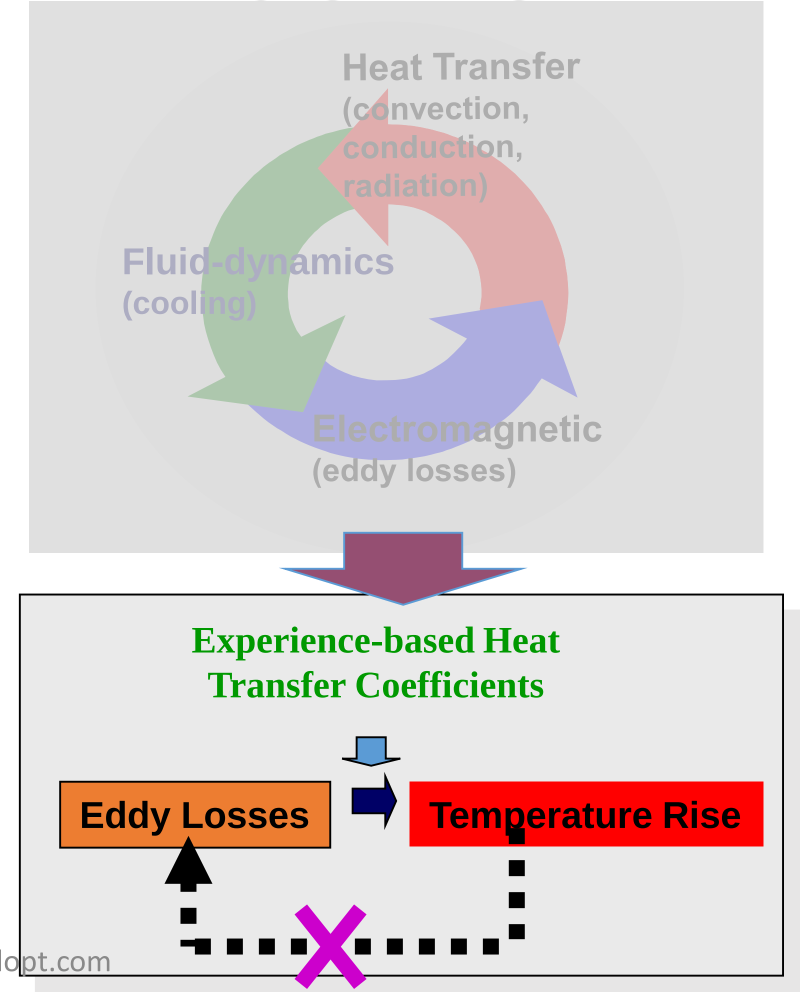


RLC scheme of TN for the transformer

Thermal Design

Task: Calculate the thermal hot-spots caused by the eddy-currents

Real physical cycles

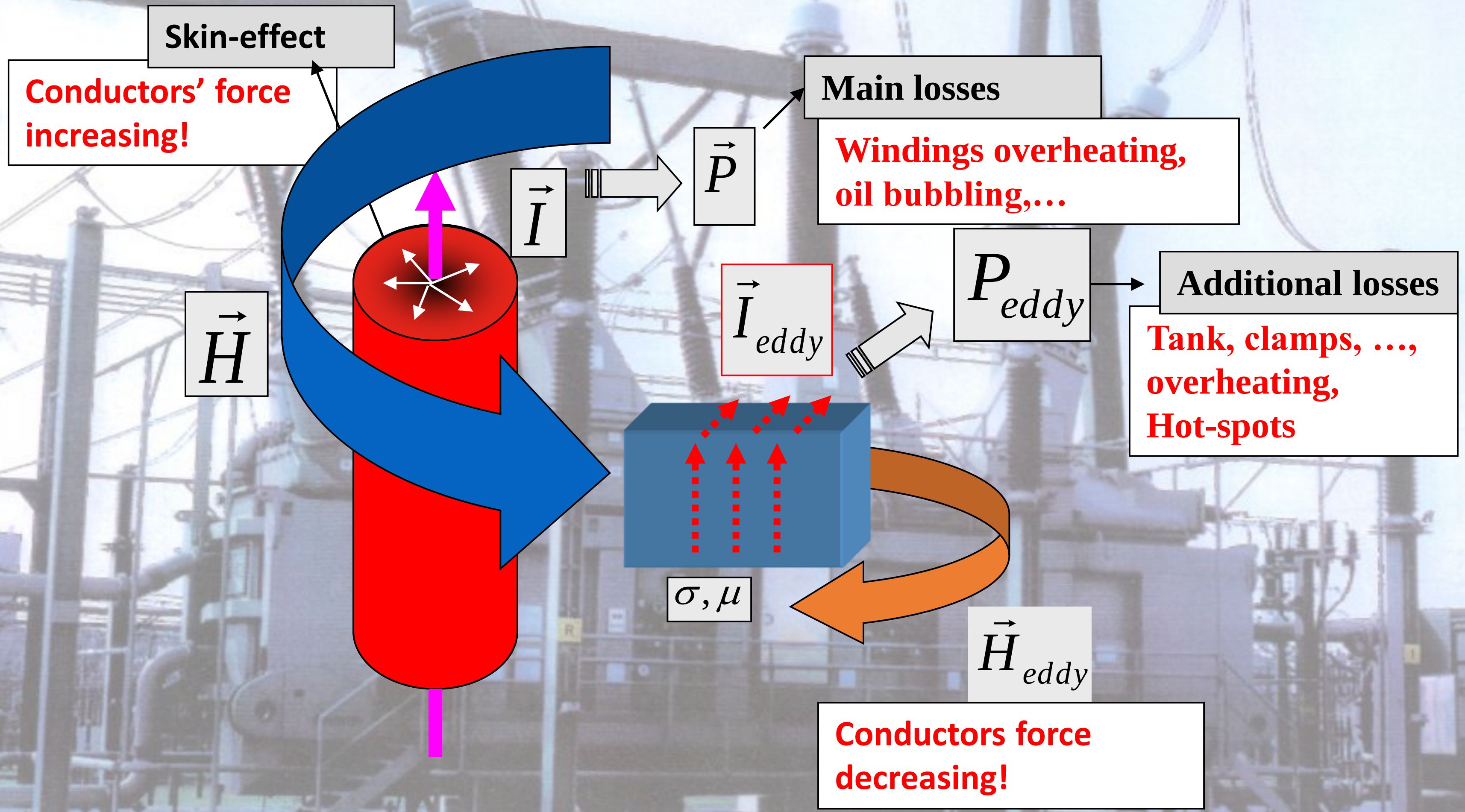


Simplified representation

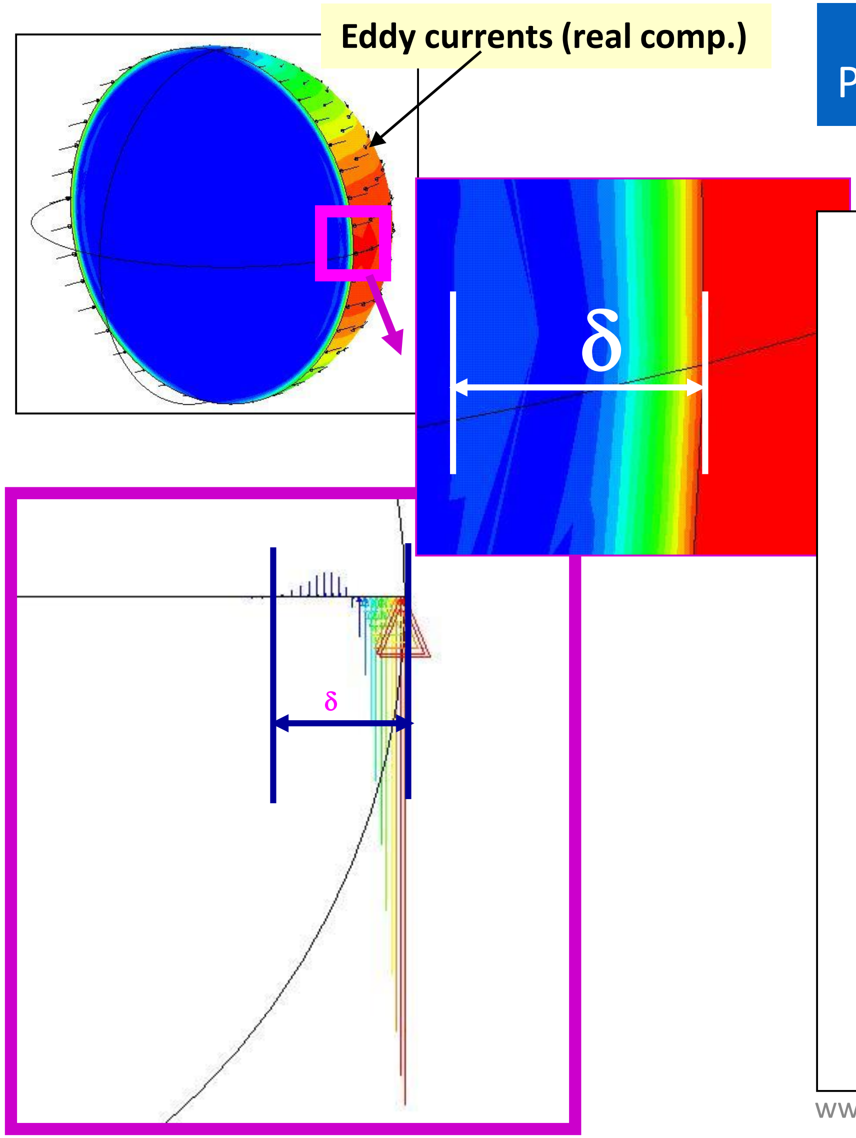
Power Transformers

Exc. Currents – Eddy currents – Skin effects – Proximity effect

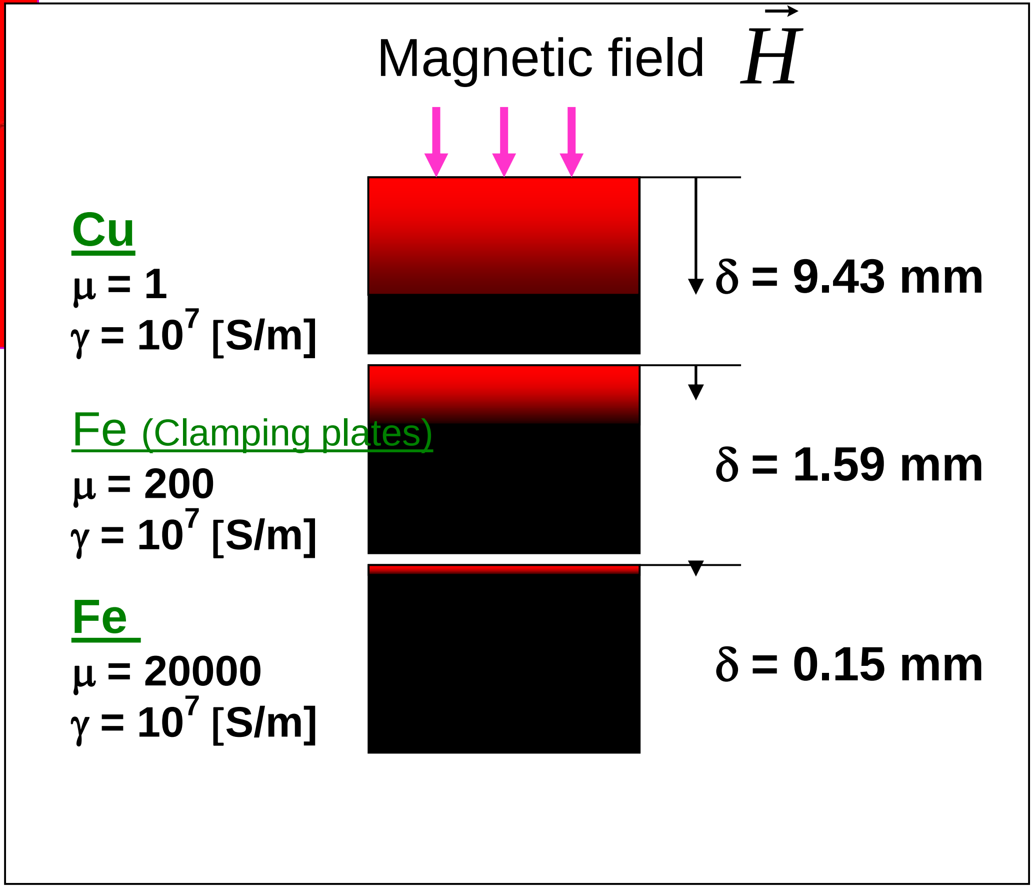
Losses – Forces…



Some (more) physics ...



Penetration depth δ = f(ω,μ,σ)



Simulation in Thermal Design : Critical Issues

EM

Material-dependent EM field diffusion

Treatment of multi-material layered structures (Cu/Fe)

Skin-effect treatment

Multi-connected problem treatment

Non-linearity $\mu = \mu\ (H)$

Total losses (eddy, hysteresis, domain losses)

TH

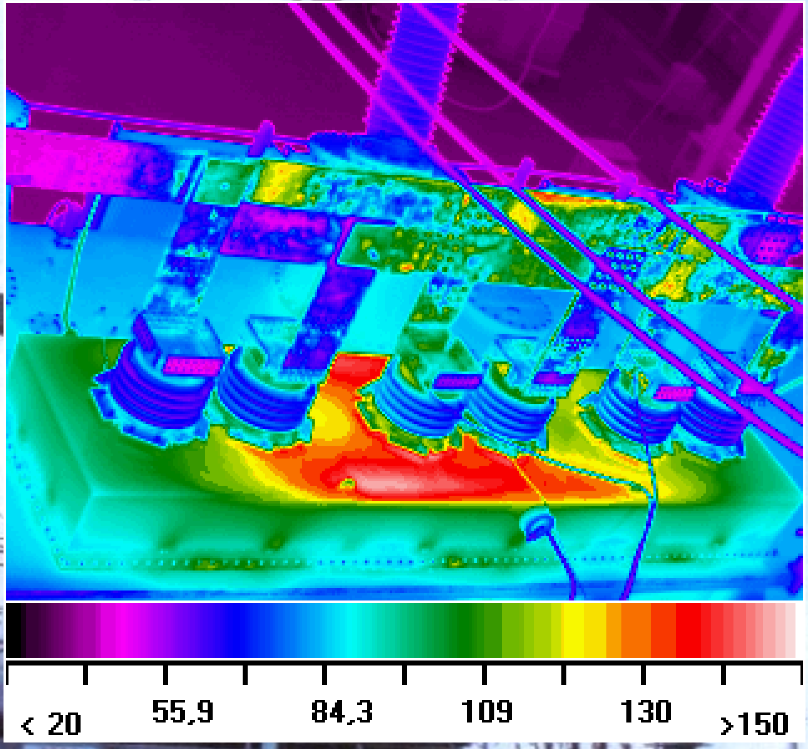
Cooling impact treatment via HTC

Contact problems

Radiation

Modeling / Computation

- Huge aspect ratio in overall dimensions
- Thin / complex tank & bus-ducts structures
- Parallelization required for daily desing



Thermograph scan of the LV bus-bars

Coupled EM-TH Problem

Steady-state problem (EM)

Formulation: $H-\varphi$

$\mathrm{rot\ rot}\ \mathbf{H}^{+} + i\omega\sigma\mu\cdot\mathbf{H}^{+} = 0 \quad \forall \mathbf{r}\in\Omega^{+},$

Equivalent currents

Equivalent charges

$$\frac{1}{2}J_m(\xi)+\frac{1}{4\pi}\oint_{\Gamma}\vec{n}_{\xi}\times\left[J_m(\eta)\times\nabla_{\xi}K(\xi,\eta)\right]d\Gamma-\frac{1}{4\pi}\oint_{\Gamma}\sigma_m(\eta)\left[\vec{n}_{\xi}\times\nabla_{\xi}G(\xi,\eta)\right]d\Gamma=-\vec{n}_{\xi}\times H^{0}(\xi)$$

$$\frac{1}{2}\sigma_m(\xi)-\frac{1}{4\pi}\oint_{\Gamma}\sigma_m(\eta)\left[\vec{n}_{\xi}\cdot\nabla_{\xi}G(\xi,\eta)\right]d\Gamma+\frac{\mu_i}{4\pi\mu_a}\oint_{\Gamma}\vec{n}_{\xi}\cdot\left[J_m(\eta)\times\nabla_{\xi}K(\xi,\eta)d\Gamma\right]=-\vec{n}_{\xi}\cdot H^{0}(\xi)$$

$$\vec{n}\times H_i=\vec{n}\times H_a$$

$$\vec{n}\cdot B_i=\vec{n}\cdot B_a$$

$$K(\xi,\eta)=\frac{1}{4\pi r}e^{-\beta r}\qquad G(\xi,\eta)=\frac{1}{4\pi r}$$

Stationary problem (TH)

$$div\left(\lambda\ grad\ T(\mathbf{r})\right)=0 \qquad \forall\ \mathbf{r}\in\Omega$$

Heat transfer coefficients

Eddy losses

$$\lambda\left[\frac{1}{2}\theta(\mathbf{r})T_1(\mathbf{r})+\int_{\Gamma}T_1(\mathbf{r}')\cdot\frac{(\mathbf{r}-\mathbf{r}')}{4\pi\|\mathbf{r}-\mathbf{r}'\|^{3}}\cdot\mathbf{n}(\mathbf{r}')\,d\Gamma\right]+\alpha\int_{\Gamma}T_1(\mathbf{r}')\cdot\frac{1}{4\pi\|\mathbf{r}-\mathbf{r}'\|}\,d\Gamma$$

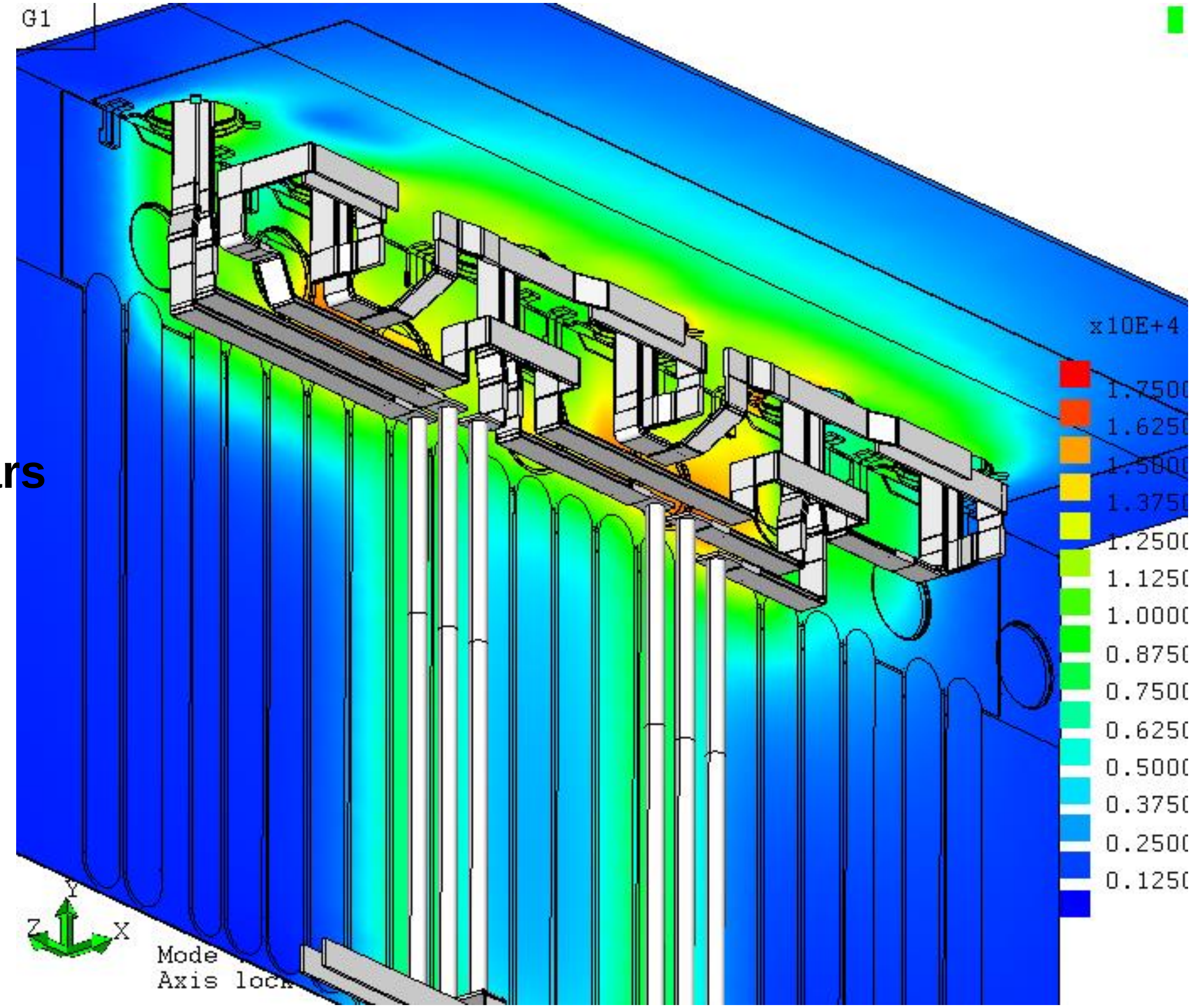
$$=\int_{\Gamma}\dot{q}(\mathbf{r})\frac{1}{4\pi\|\mathbf{r}-\mathbf{r}'\|}\,d\Gamma \qquad \forall\ \mathbf{r}\in\Gamma.$$

$$\lambda\cdot\partial_{\mathbf{n}}T(\mathbf{r})=\dot{q}(\mathbf{r})$$

Thermal Design

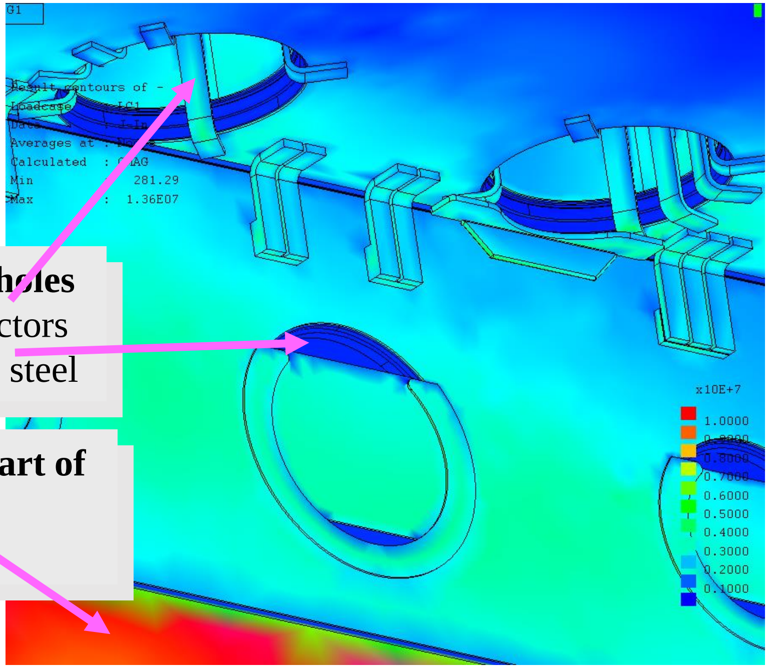
Main features:

- **complex windings / bus-bars structures**



Excitation field produced by the bus-bars structures (complex magnitude) – inner view

Thermal Design



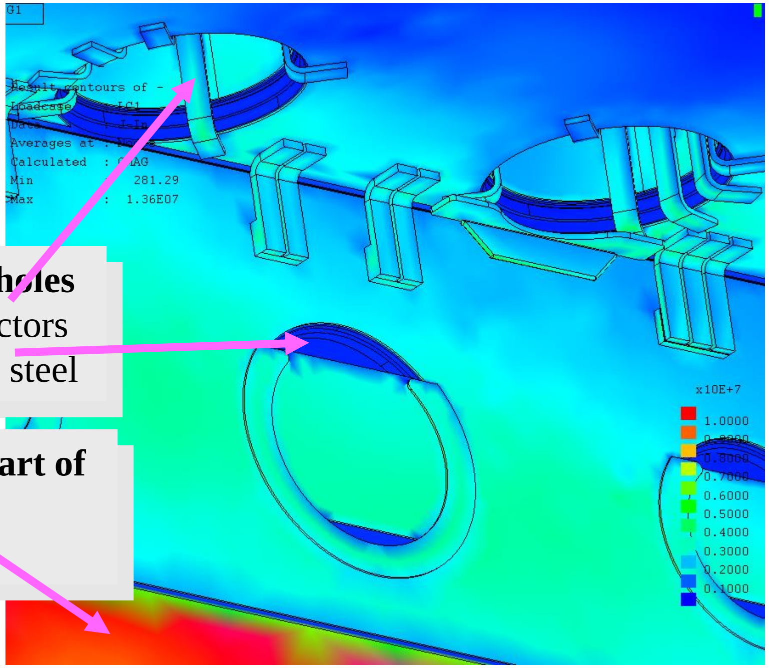
Shielded man-holes
-Cupper connectors
-Non-magnetic steel

Non-shielded part of the tank
-Magnetic steel

Main features:

- complex windings / bus-bars structures
- **different magnetic/non-magnetic materials included => different magnetic field penetration depth**

Thermal Design



Shielded man-holes
-Cupper connectors
-Non-magnetic steel

Non-shielded part of the tank
-Magnetic steel

Eddy current distribution (complex magnitude)
-detailed view on the inner shielding details-

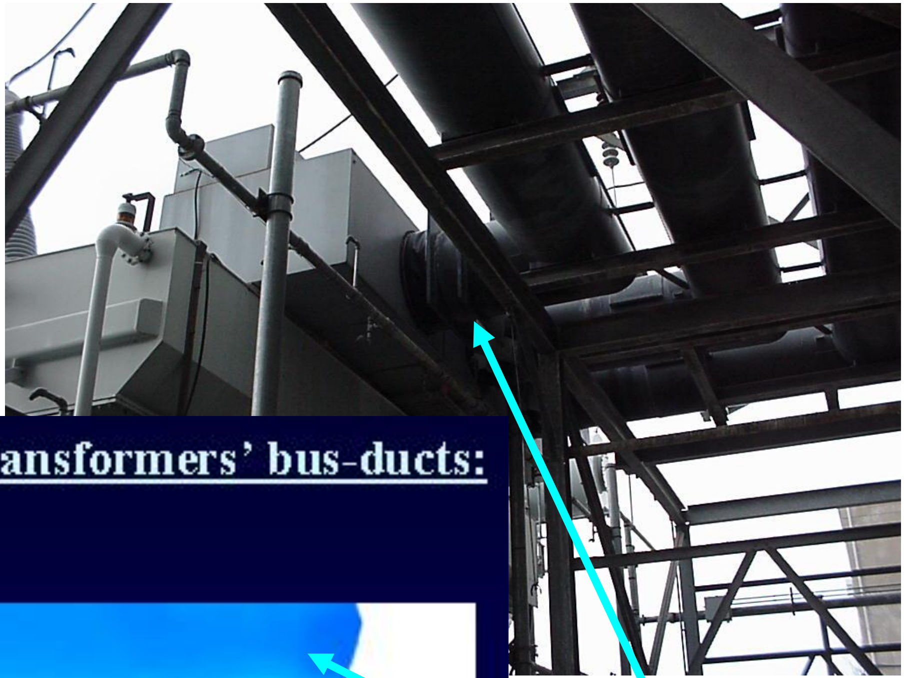
Main features:

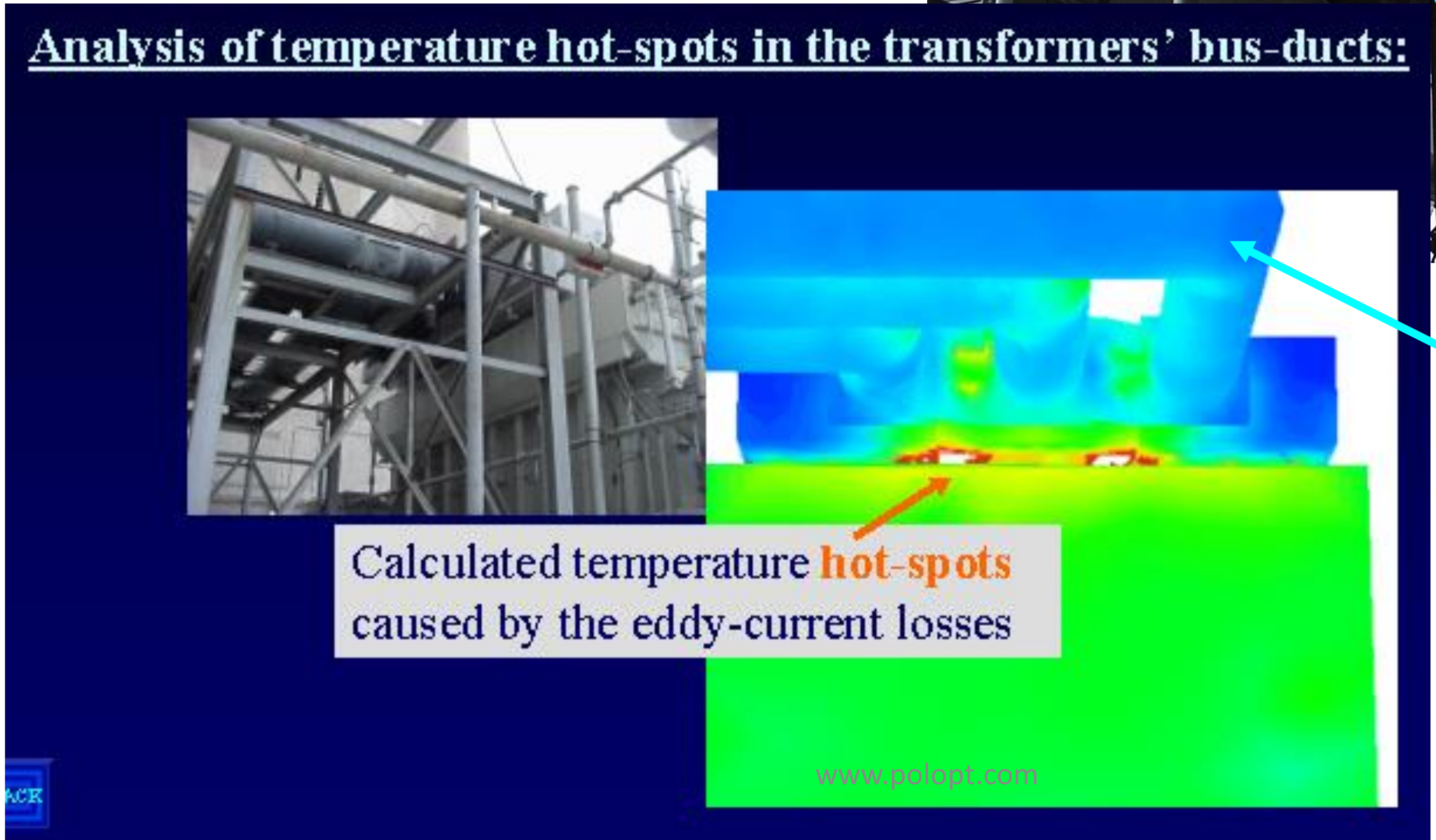
- complex windings / bus-bars structures
- different magnetic/non-magnetic materials included => different magnetic field penetration depth
- **huge aspect ratio in dimensions**
  - 5-20 mm (tank thickness)
  - 4-6 m (overall tank dimensions)

Robust / physics-sensitive meshing preferred!

Thermal Design: Validation

- 985 MVA Transformer,
- Nuclear GSU unit, Commonwealth Edison, Chicago, 2002

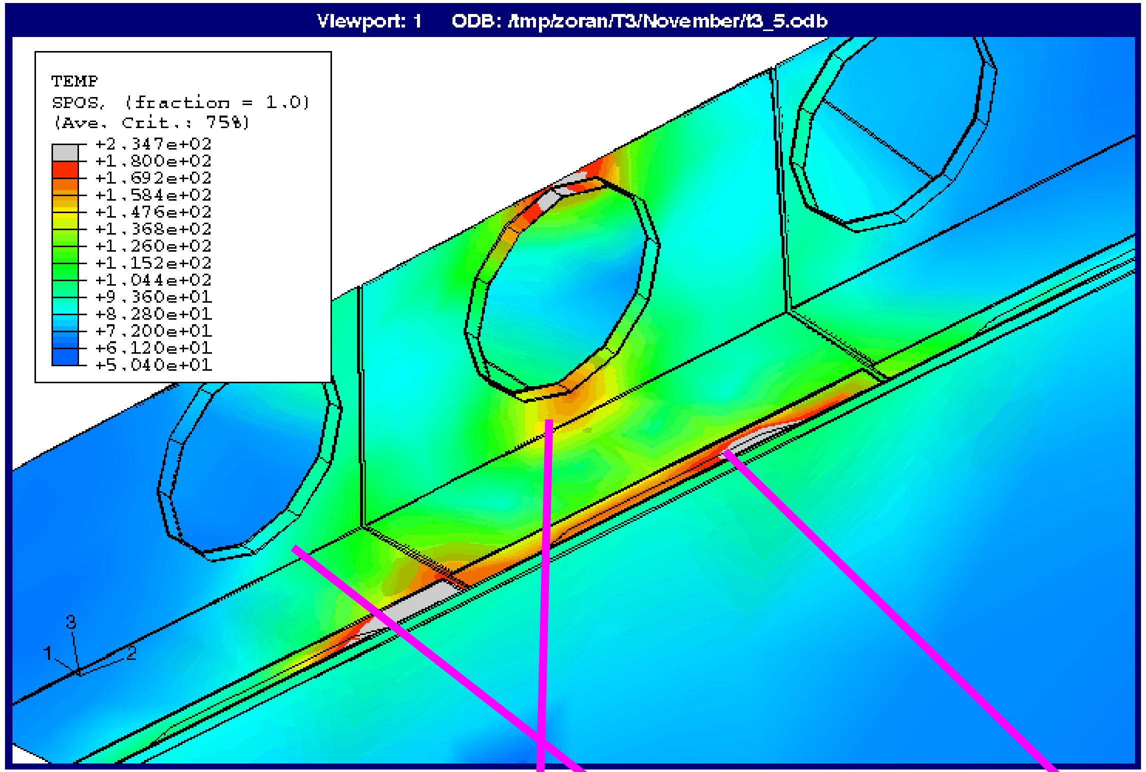


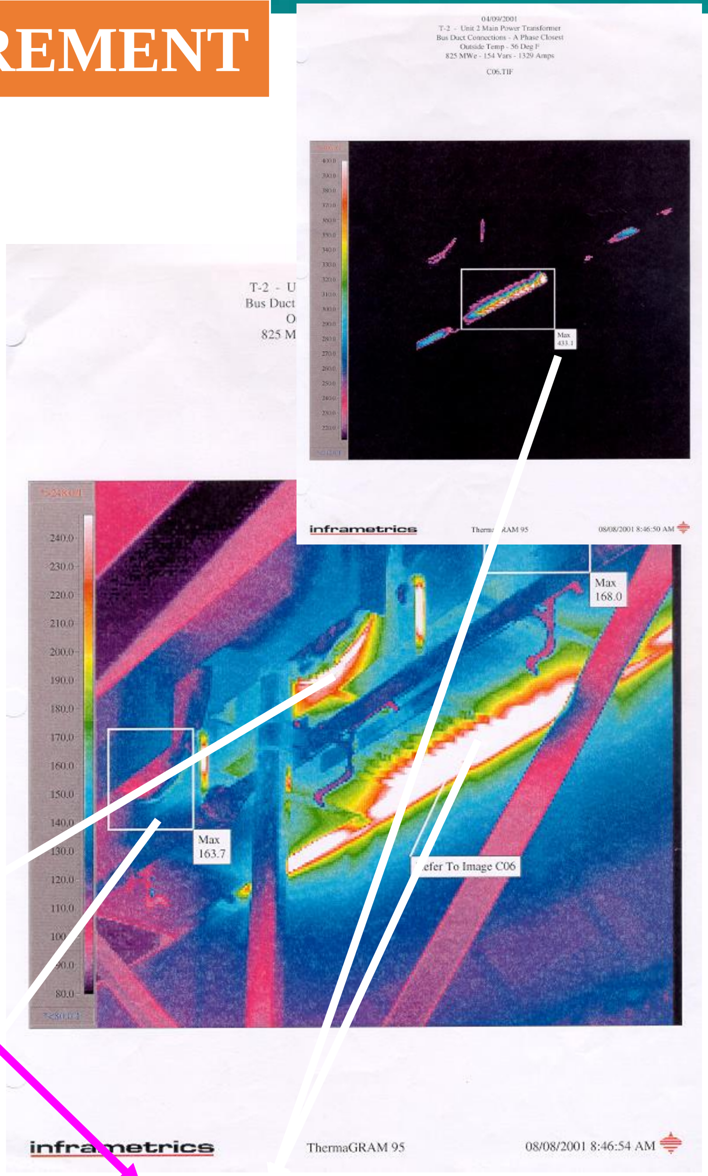


Bus-ducts

SIMULATION

MEASUREMENT





~140 ~125

~80 ~74

~195 ~220