TECHNISCHE UNIVERSITÄT DRESDEN

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Faculty of Electrical and Computer Engineering Institute of Electromechanical and Electronic Design

Transient Electromagnetic-Thermal FE-Model of a SPICE-Coupled Transformer Including Eddy Currents

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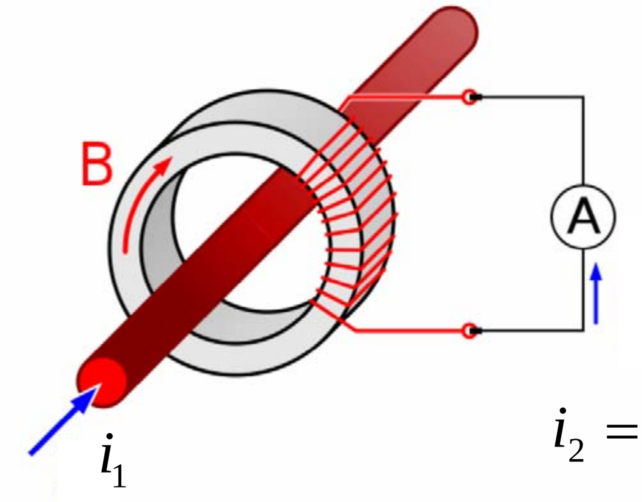
Outline

1. Introduction

Current Transformers

- Used to measure high currents in power grid systems
- Primary winding:
  - Normally only one turn (the power line)
- Secondary windings:
  - Some hundreds up to thousands,
  - Close to short-circuit condition



$$i_2 = \frac{1}{N_2} i_1$$

Quelle: Bienzle (Wikimedia)

Bar-type Current Transformer (Low Voltage)

Quelle: ABB Stotz S&J

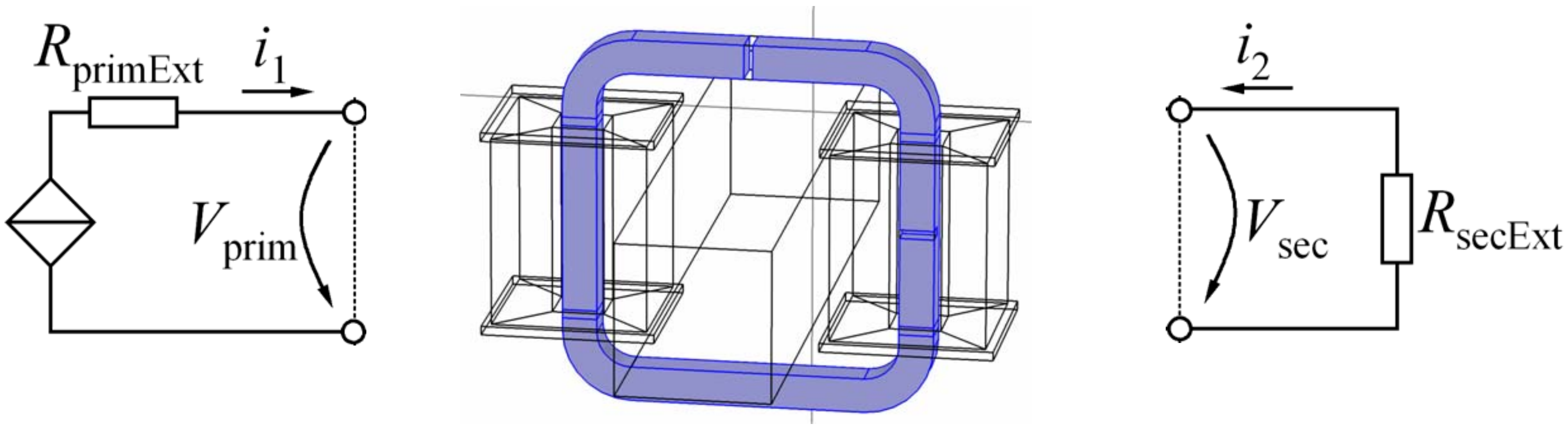
Pole mounted Current Transformer (High Voltage)

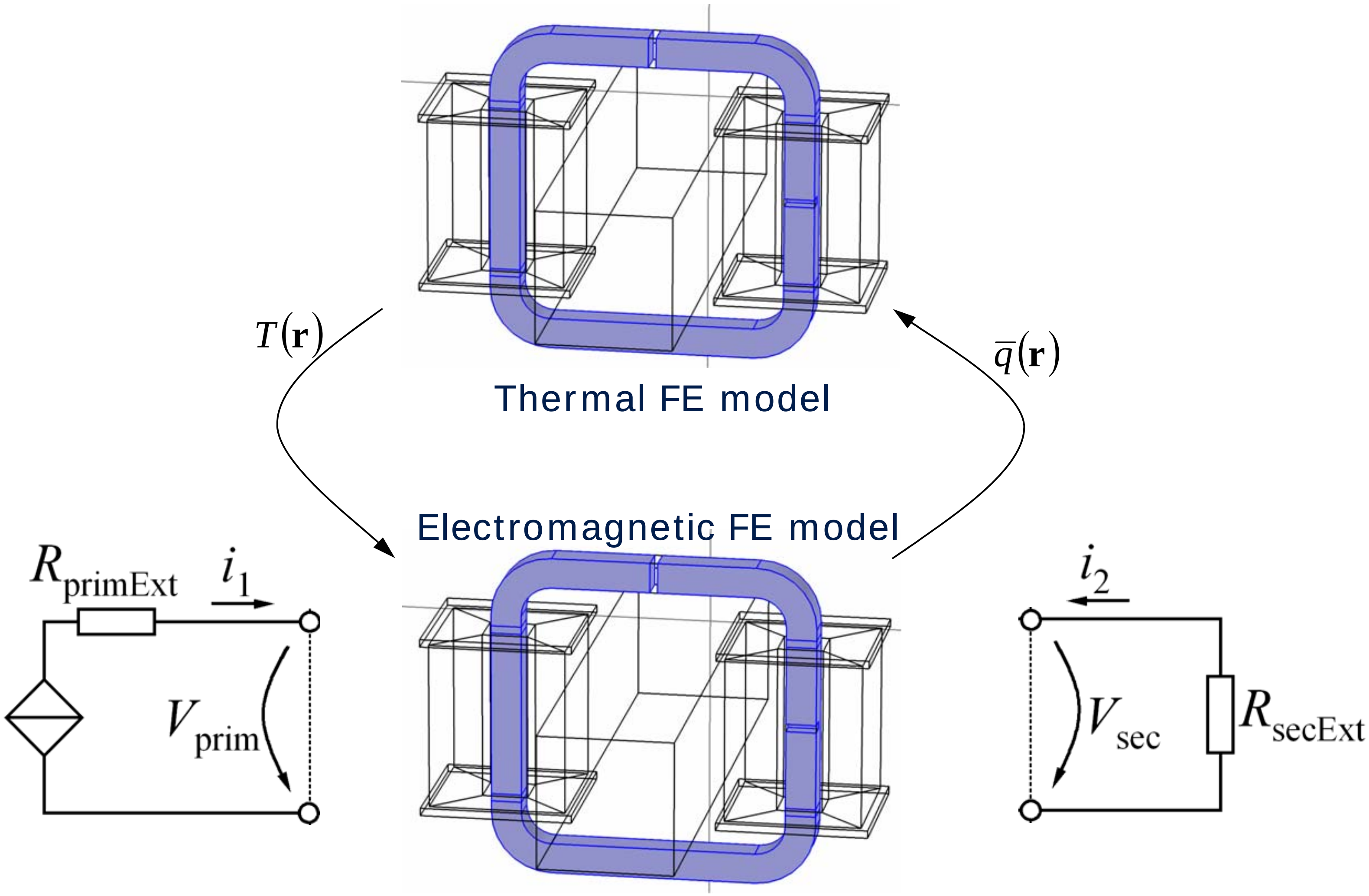
Quelle: ABB

2. Modelling Approach

Coupled Model

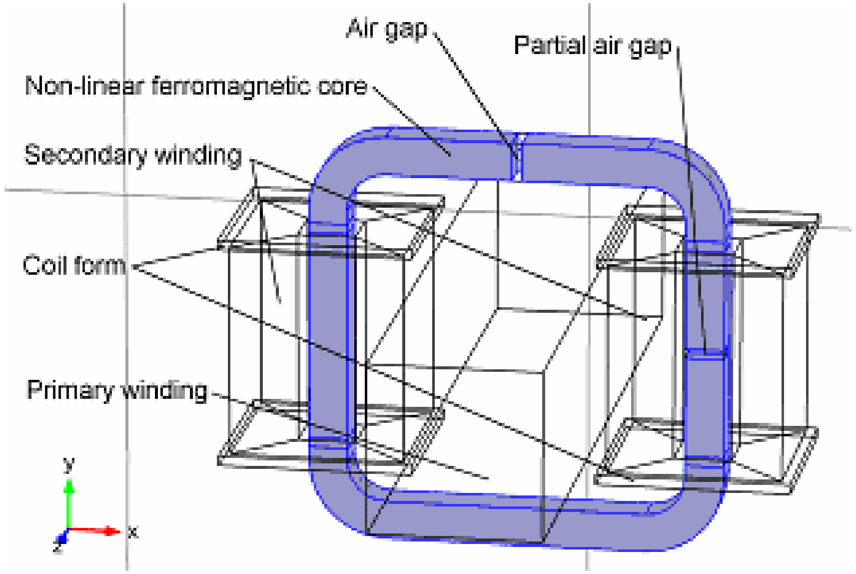
- Electromagnetic FE model of the transformer
- Network models of the primary and secondary circuitry
- Thermal FE model of the transformer




$T(\mathbf{r})$
$\bar{q}(\mathbf{r})$
Thermal FE model
Electromagnetic FE model
R_{primExt}
i_1
V_{prim}
i_2
V_{sec}
R_{secExt}

3. Electromagnetic FE Model

- Parametric geometry
- Ampère's circuital law and Faraday's law of induction
- *mf* mode (magnetic field only) for time-dependent simulation
- Non-linear magnetic material behavior in $\boldsymbol{H} = f(|\boldsymbol{B}|)\boldsymbol{e}_B$ form



Modelling of Eddy Currents

- Power Line (Primary winding):
  - Sinusoidal primary current $i_1(t)$ is modeled as a total current density $J_z(\mathbf{r},t)$ inside of the bus bar
  - $J_z(\mathbf{r},t)$ can not be imposed directly as an external current density

$$J_z(\mathbf{r},t) = J_{ez}(\mathbf{r},t) + J_{iz}(\mathbf{r},t)$$

  - A global equation (*ge* mode) determines J_{ez} inside of the bus bar by

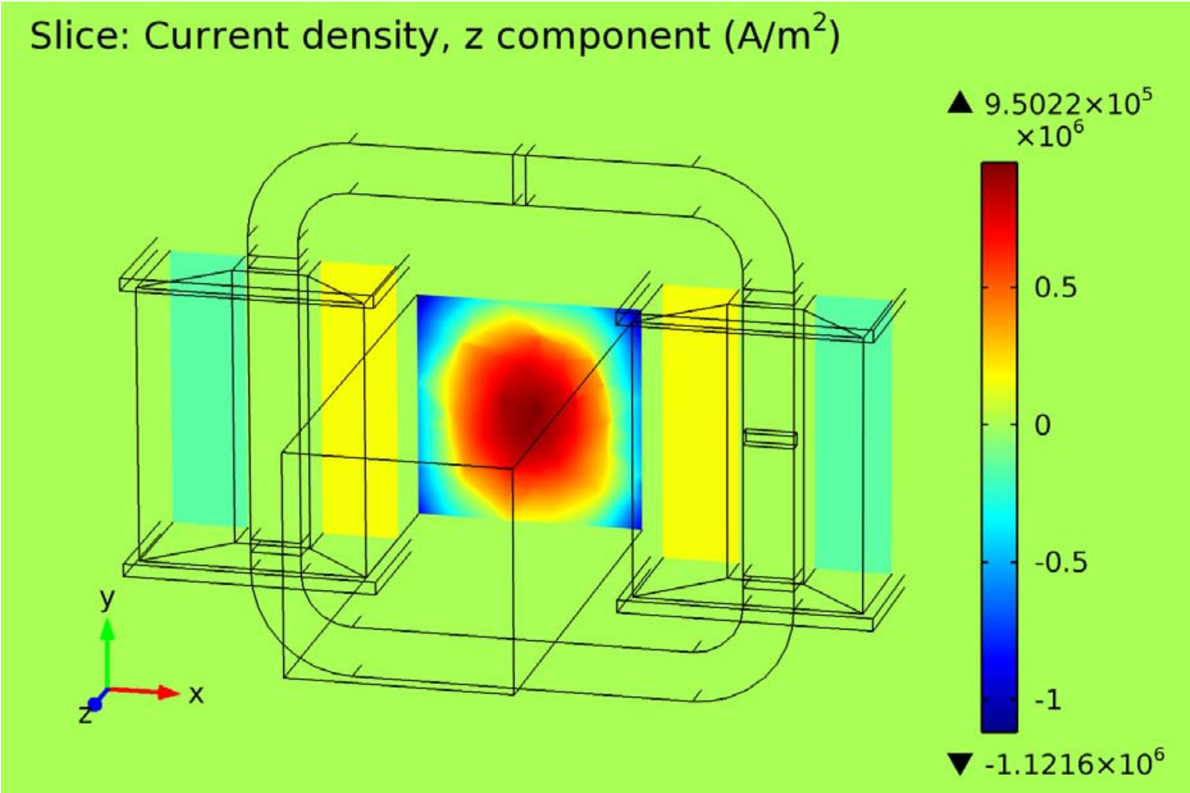
$$i_1 - I_{prim} = 0$$

  - $J_z(\mathbf{r},t)$ in the primary conductor is calculated from

$$I_{prim} = \frac{1}{L_{prim}} \int_{(V_{prim})} J_z \, dV$$

Eddy Current in the Power Line

- Simulated z-component of the total current density with skin effect in the primary conductor (i_{1peak} = 1000 A, R_{secExt} = 20 Ω, t = 0.23 s)

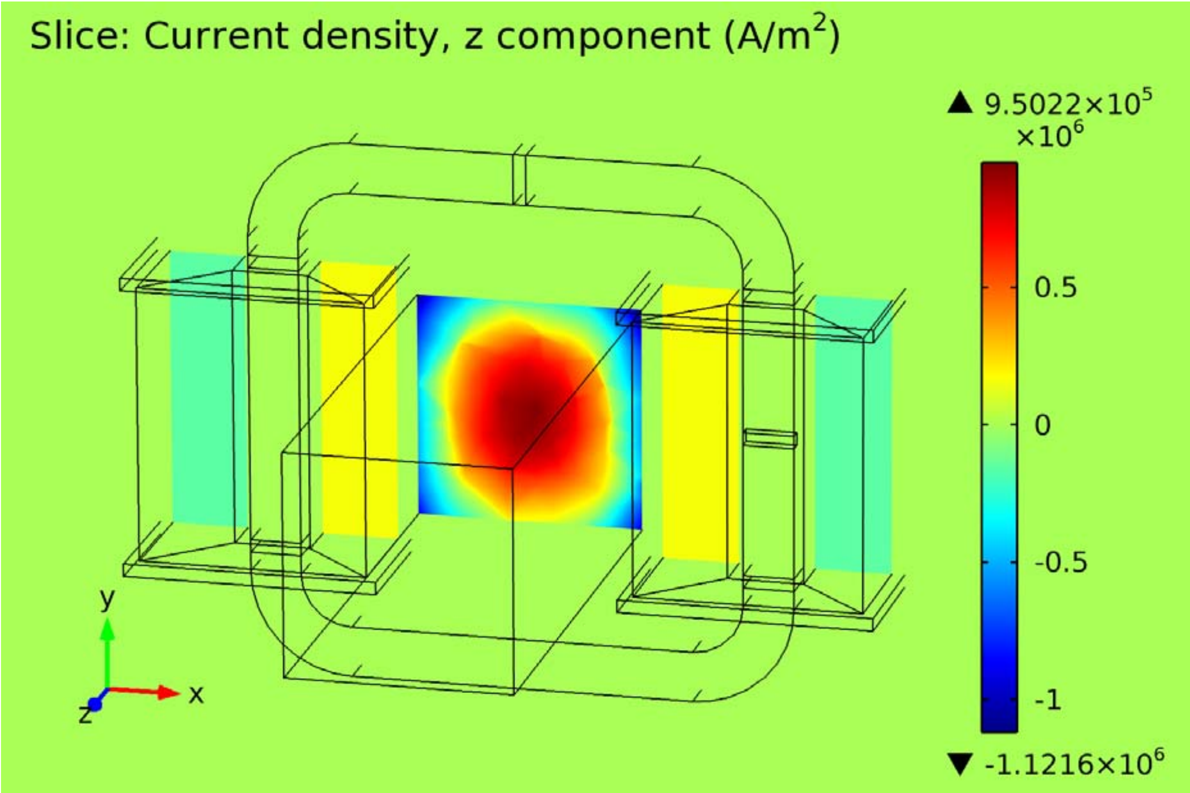


Modelling of Eddy Currents

- Secondary windings:
  - Modeled as bulk material (eight prismatic bodies)
  - Conductivity is set to 10 S/m to supress eddy current effects
  - Secondary current $i_2(t)$ is modeled as an external current density, derived from the induced voltage

Eddy Current in the Power Line

- Simulated z-component of the total current density with skin effect in the primary conductor (i_{1peak} = 1000 A, R_{secExt} = 20 Ω, t = 0.23 s)



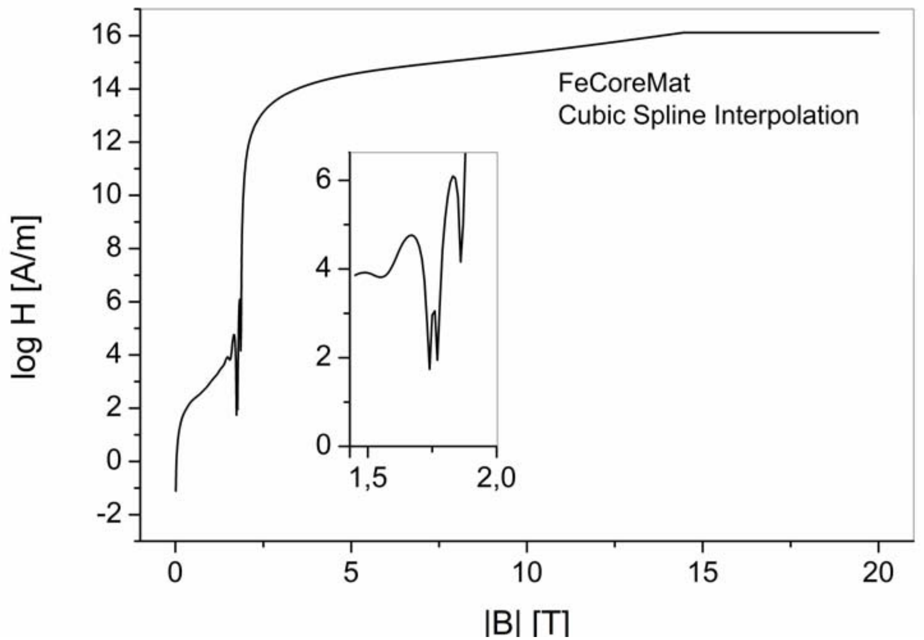
Non-linear Magnetic Behavior

- $\boldsymbol{H} = f(|\boldsymbol{B}|)\boldsymbol{e}_\mathrm{B}$ form avoids circular variable definitions in constitutive relations
- Several approximation approaches with remarkable influence on solution time

Approximation approach	*Relative solution time*
Piecewise cubic interpolation	1.0
Global rational function	1.3
Linear interpolation	4.0
Cubic spline interpolation	≈ 100
Nearest neighbour	no convergence

Non-linear Magnetic Behavior

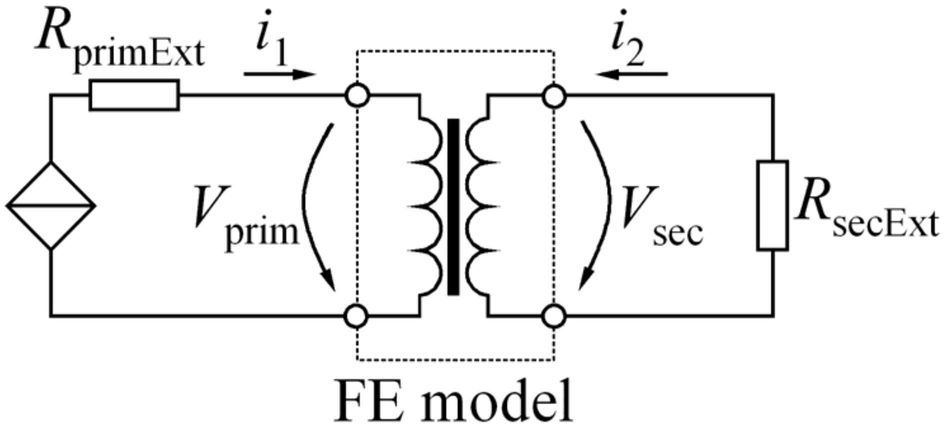
- $\boldsymbol{H} = f(|\boldsymbol{B}|)\boldsymbol{e}_B$ form avoids circular variable definitions in constitutive relations
- Several approximation approaches with remarkable influence on solution time
- Cubic spline interpolation may lead to a non-monotonic curves



Coupling with SPICE Components

- *cir* mode
- Sinusoidal current source at the primary side
- External load resistor at the secondary side coupled to the secondary windings (External I vs. U element)
- Variable

$$V_{sec} = R_{coil}\, i_2 - V_i \qquad V_i = \frac{N_2 (V_1 + V_2 + \ldots + V_8)}{A_{sec}}$$

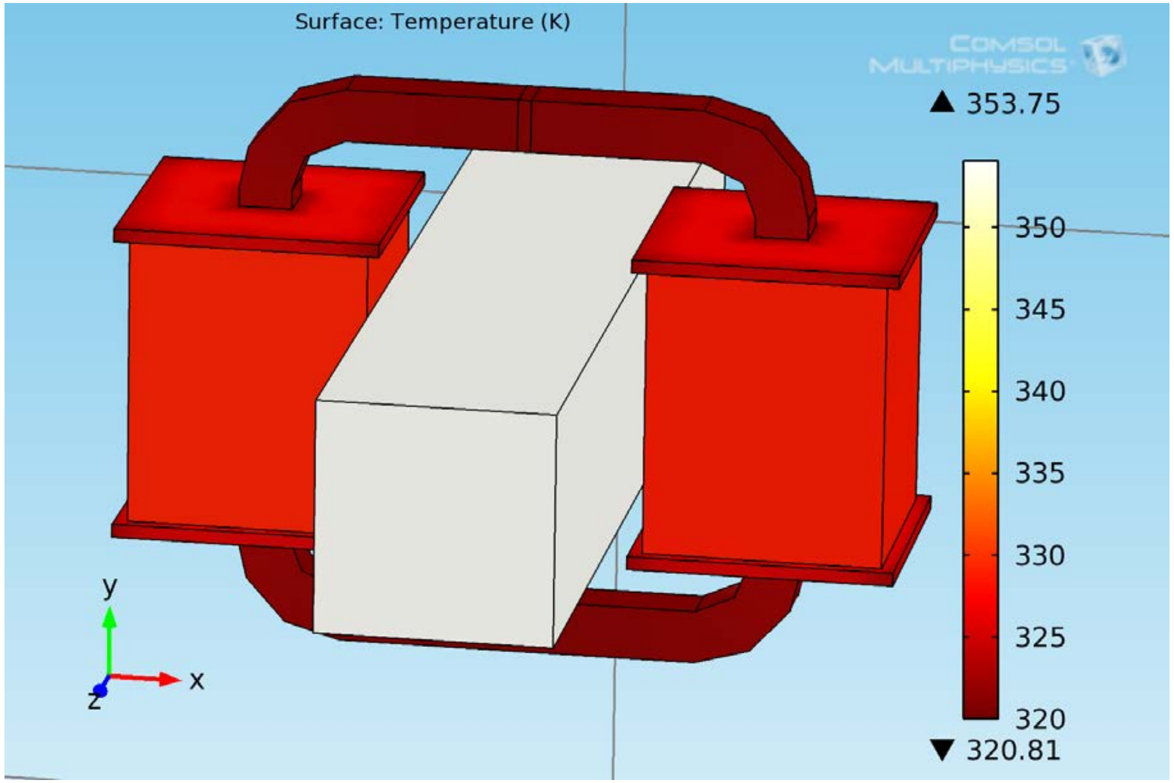


4. Thermal Model

- Temperature-dependent electrical conductivity of the conductors
- Heat conduction in solids applying the *ht* mode
  - Heat sources (mean value over a period of the losses field)
  - Heat conduction in solids and narrow air gaps,
  - Thermal contact resistances between solids which are in mechanical contact
  - External convection on solid-air interfaces applying empirical correlations
- Time-average of the local power loss density in the time interval $[0, t_\mathrm{i}]$

$$\overline{q}(\mathbf{r}, t_\mathrm{i}) = \frac{1}{t_i} \int_0^{t_\mathrm{i}} \frac{[J(\mathbf{r}, \tau)]^2}{\sigma} d\tau$$

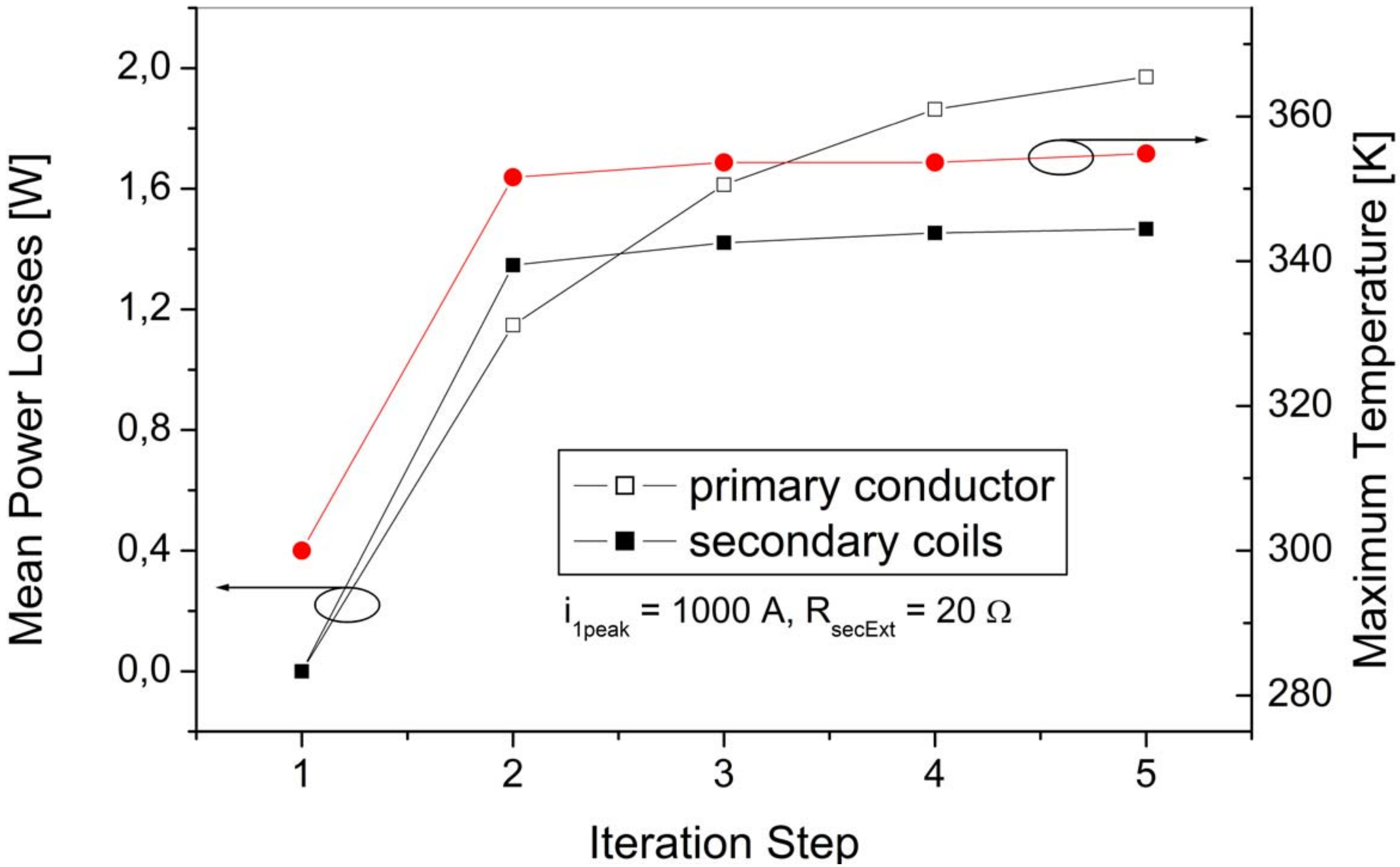
Thermal Model



5. Coupled Time-dependent Simulation

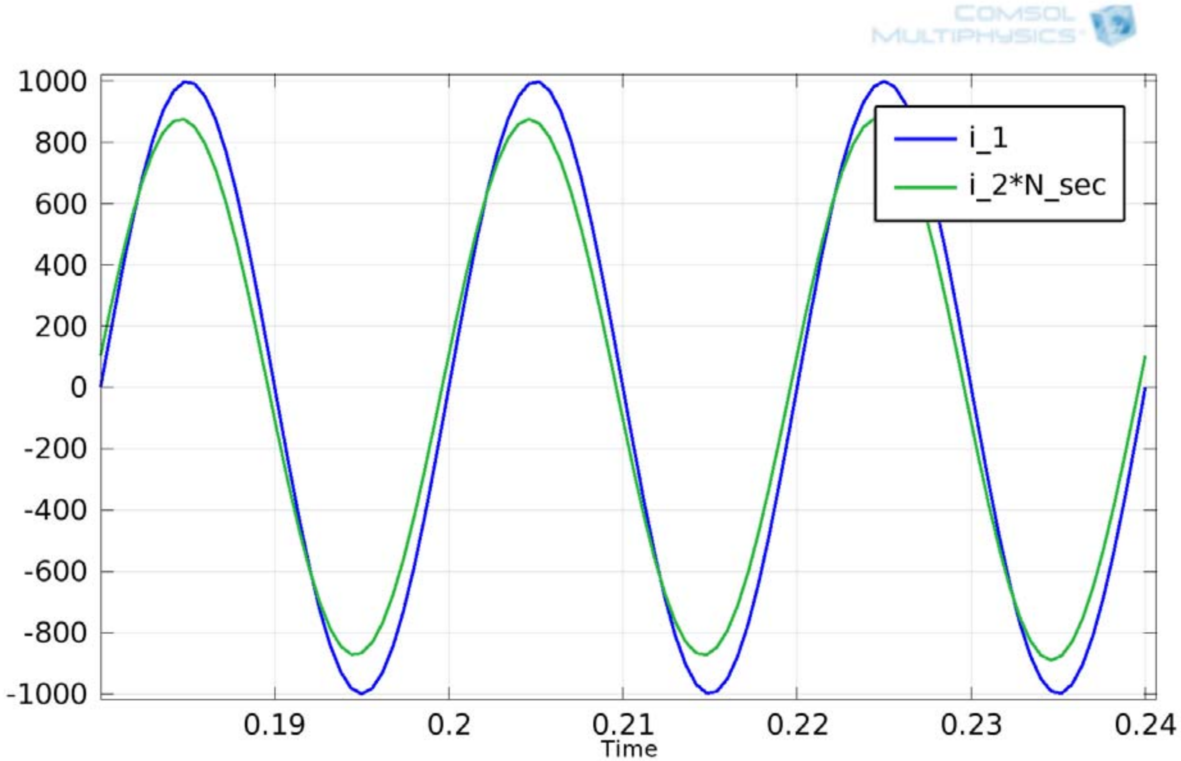
- Time-dependent simulation
- Time scales of the electromagnetic and the thermal model are very different
- Bi-directionally coupling of the electromagnetic and the thermal model
- Iterating alternate solutions:
  - Stationary study steps of the thermal model
  - Time-dependent study steps of the electromagnetic and circuit model

Convergence



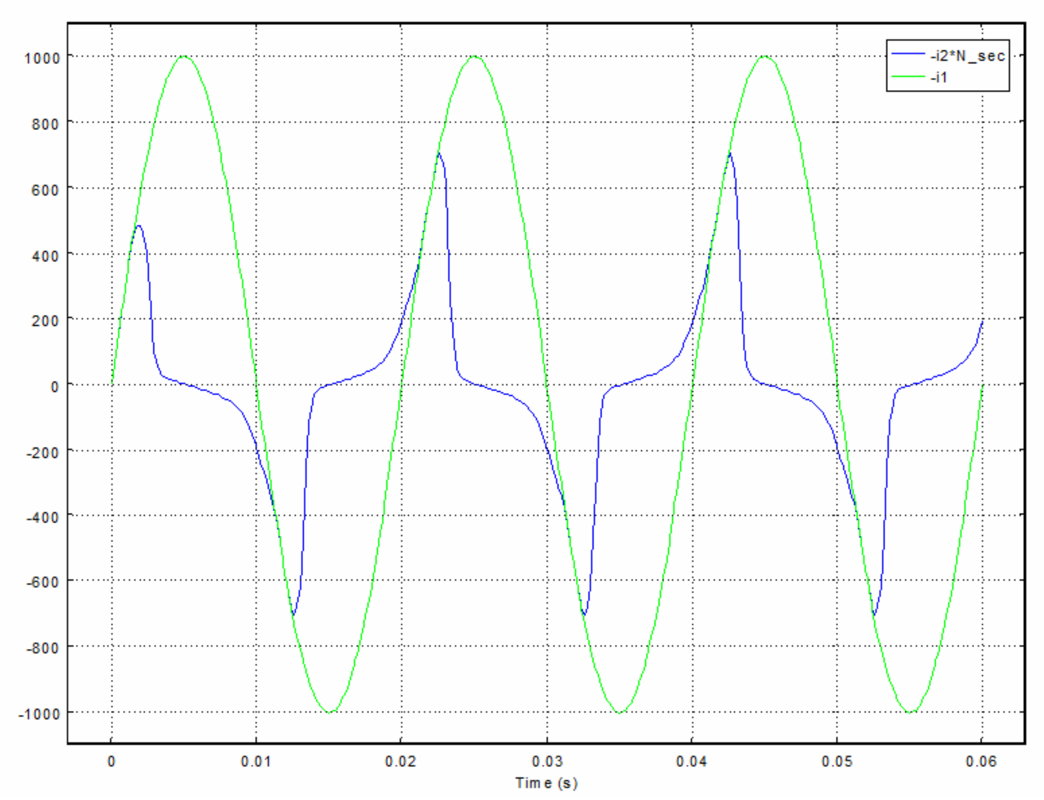
Currents

- Simulated primary current i_1 and secondary current $i_2 \cdot N_2$ ($i_{1\text{peak}}$ = 1000 A, R_{secExt} = 25 Ω)
- Imperfect transformer coupling due to the air gaps in the core



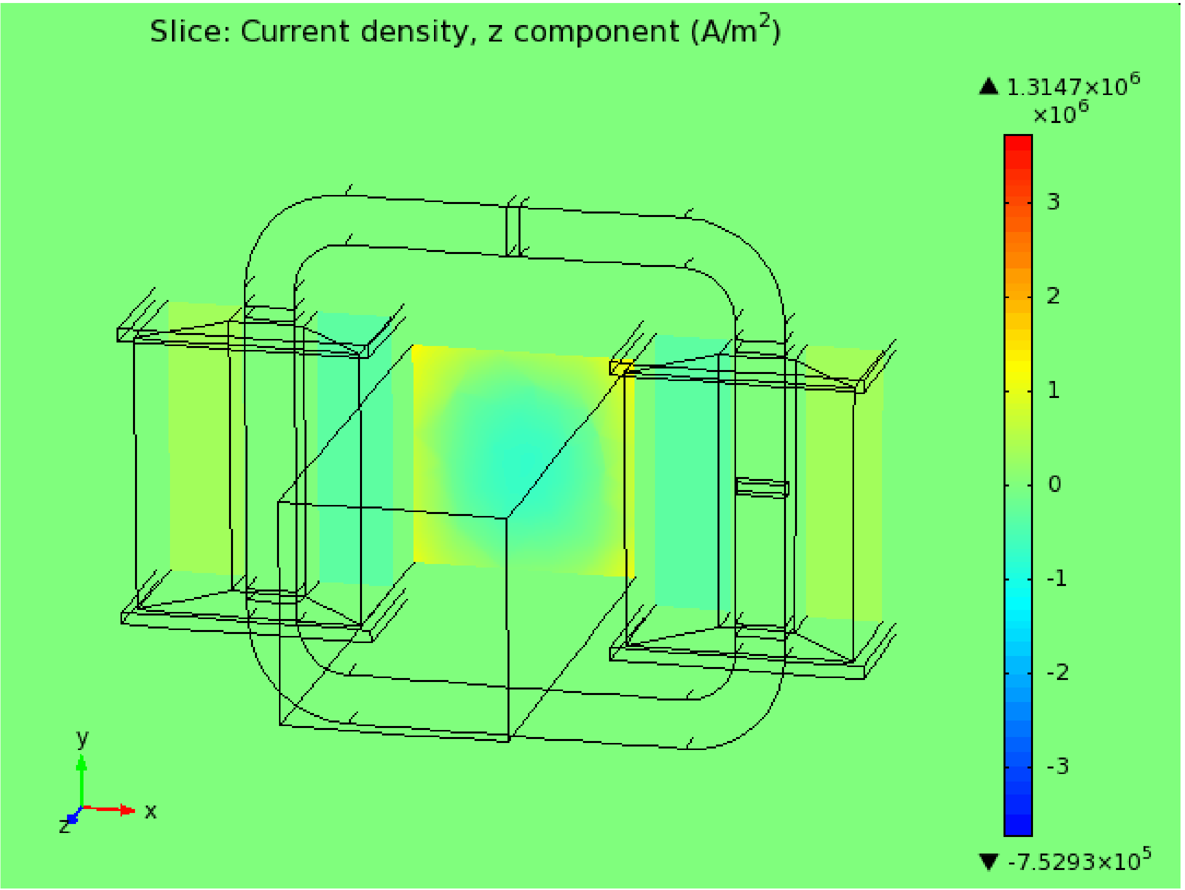
Currents

- R_{secExt} = 1 kΩ
- Deformation of the sinusoidal current due to magnetic saturation in the core



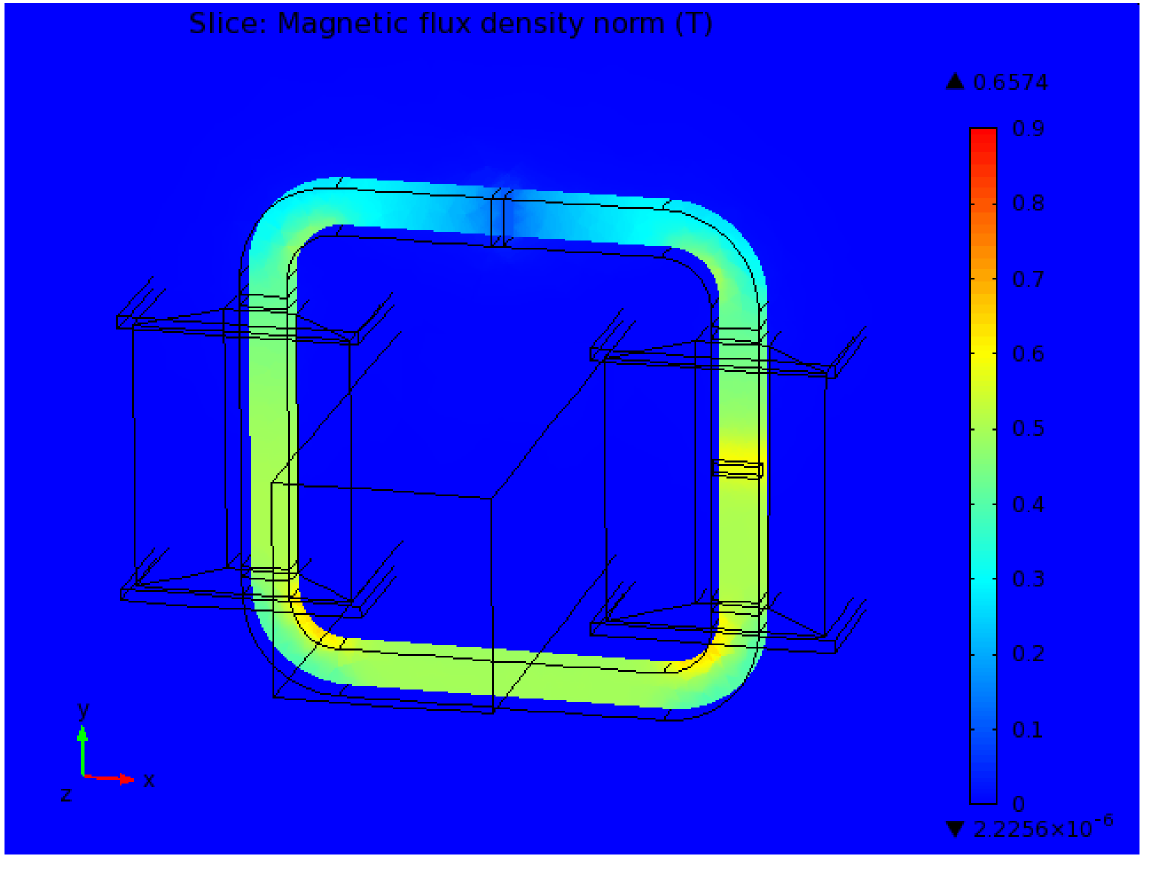
Current density

- $i_{1\text{peak}} = 1000$ A, $R_{\text{secExt}} = 25\ \Omega$



Flux density

- $i_{1\text{peak}}$ = 1000 A, R_{secExt} = 25 Ω



6. Summary

Transient Electromagnetic-Thermal FE-Model of a SPICE-Coupled Transformer Including Eddy Currents

- Time-dependent simulation of a transformer coupled to an external circuitry
- Non-linear magnetic material properties based on experimental data
- Eddy current effects are included using a global equation
- Time-averaged power loss density distribution
- The bi-directionally coupled thermal model considers the influence of the temperature on electrical material properties
- Future work will focus on
  - consideration of the transformer core lamination,
  - the anisotropic material behaviour inside of the coils

Thank you very much
for your attention.