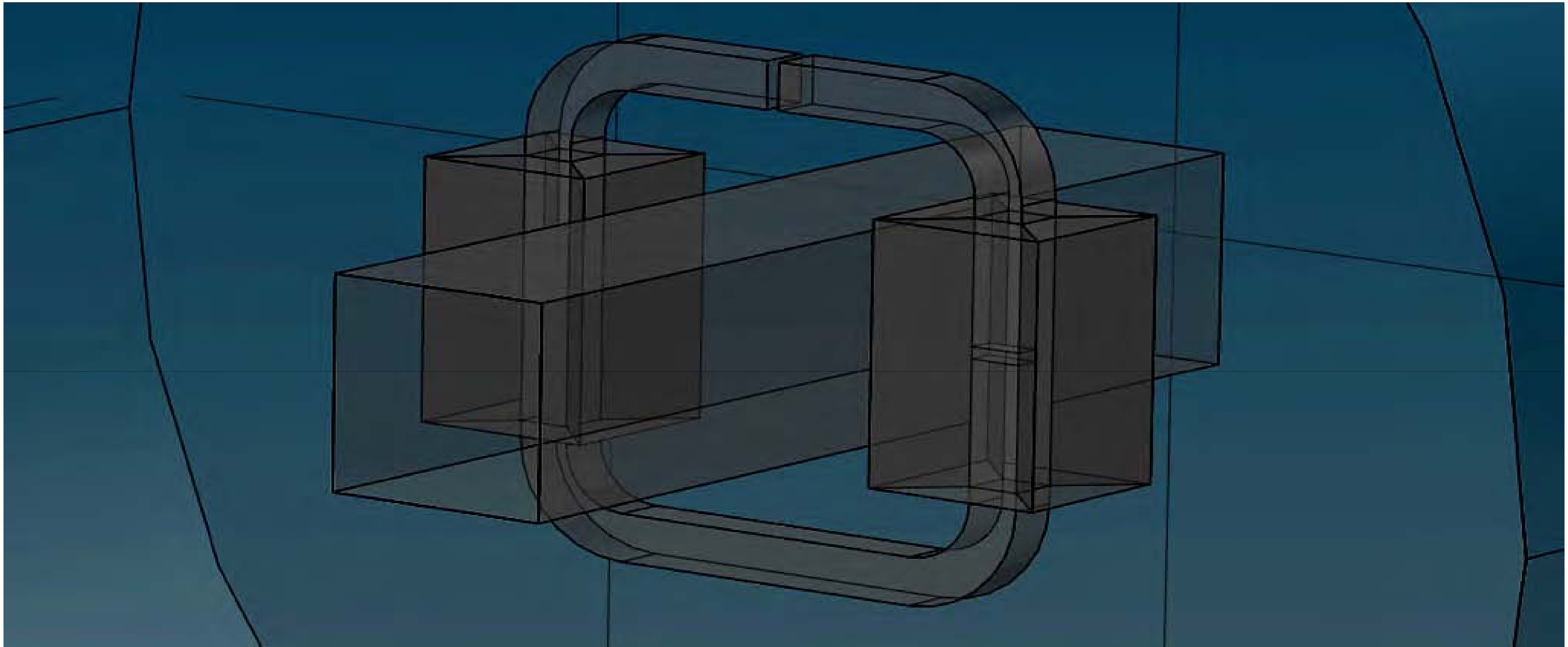
Presented at the COMSOL Conference 2010 Paris



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Transient Finite Element Analysis of a Spice-Coupled Transformer with COMSOL-Multiphysics

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Outline

Introduction

Transformer Modelling

- Magnetic test model
- Coupling with Spice
- Settings

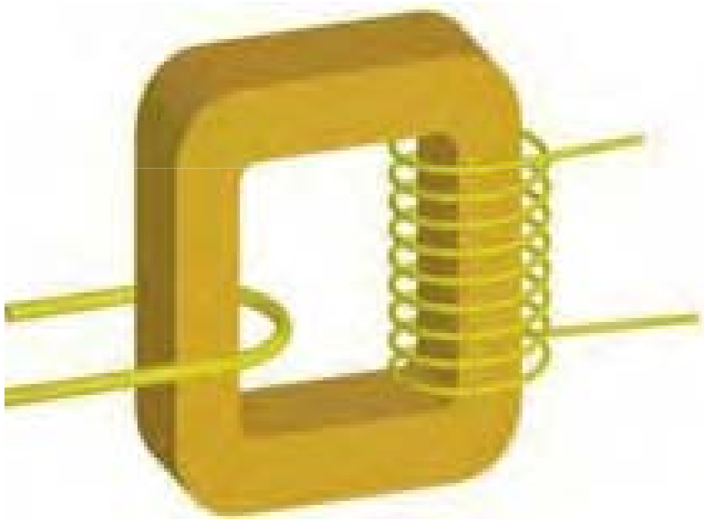
Results

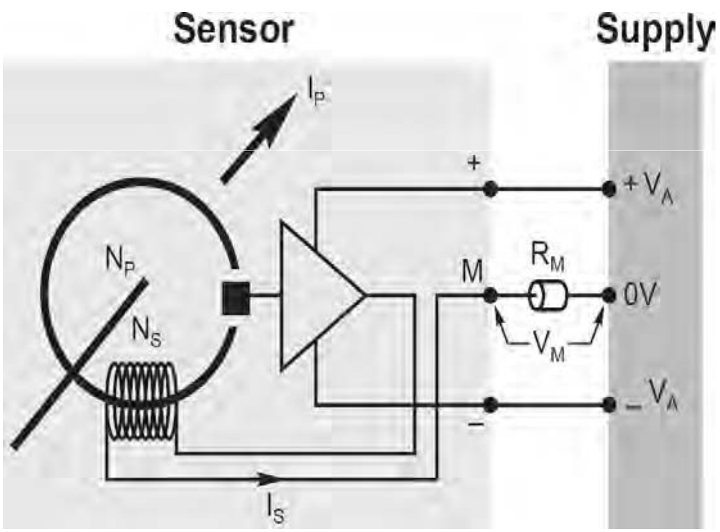
- Transient signals
- Flux density distribution
- Stray fields

Conclusions

Outlook

Introduction
Modelling of Passive and Active Current Transformers





Purpose:

Support the design process by predicting the influences of

- nonlinearities of the magnetization curve (initial permeability, saturation, …)
- special core and winding geometries (air gaps, partial windings, asymmetries, …)
- external and internal stray fields
- eddy currents (both in the core and in the windings)
- magnetic hysteresis
- coupling to electric circuits (transient response)
- thermal effects

in large current and frequency operating ranges

Challenges with FE-Modelling

Combination of requirements:

- 3D geometry (potentially with low symmetry)
- Scale range typically > 100:1 (e.g. air gap / transformer size)
- Magnetic material with (strongly) nonlinear characteristic
- Presence of both injected and induced currents
- Coupling to electric circuits (may be nonlinear as well)
- Transient analysis required
- Modelling of eddy currents (suited mesh required)
- Modelling of magnetic hysteresis
- Bidirectional thermal coupling
- Numerical stability in wide amplitude and frequency ranges

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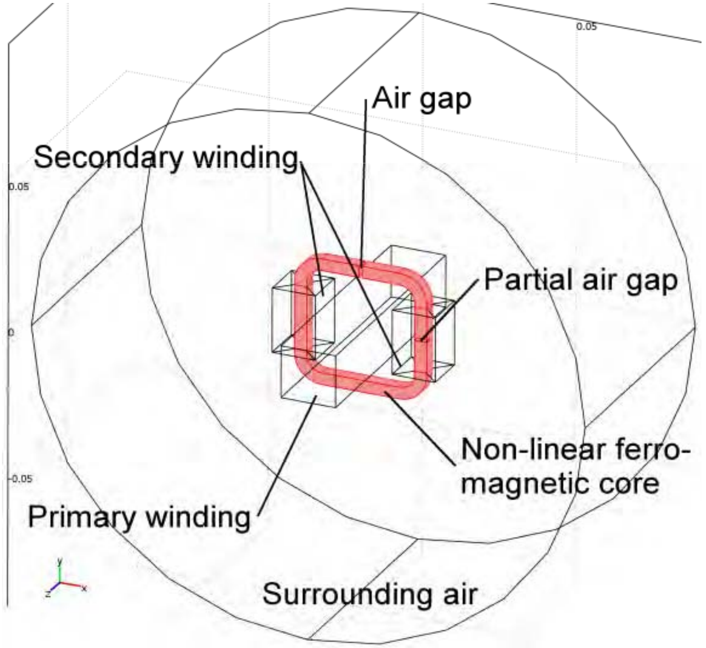
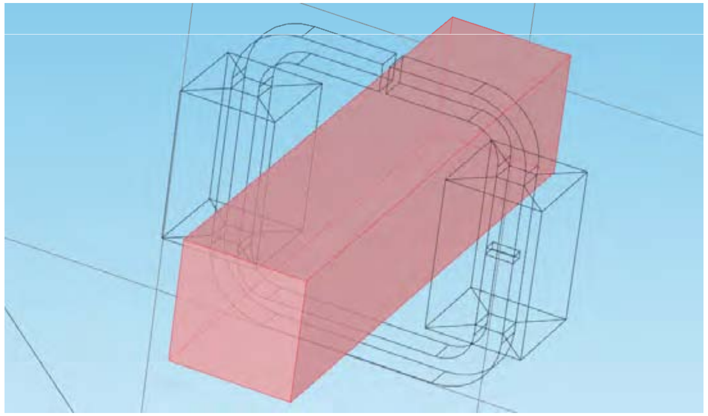
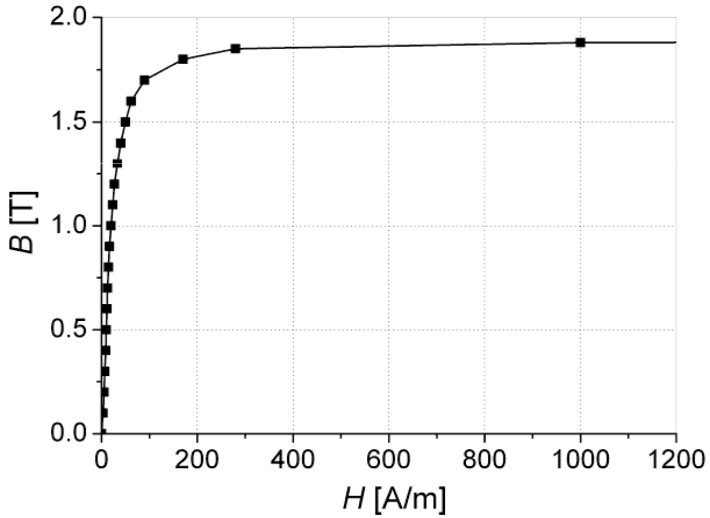
Simulation with COMSOL Multiphysics
Test Model

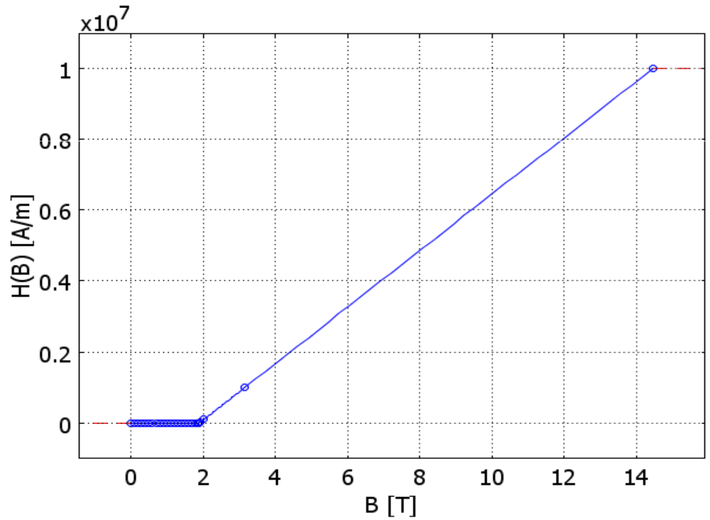




- Square-shaped magnetic core frame with central hole of 3.5 cm width and two different types of air gaps (full and partial)
- Bus-bar type bulk primary Cu-conductor ($N_1 = 1$)
- Secondary winding ($N_2 = 1000$) split into two linear box-shaped sections
- Boundary condition "Magnetic insulation" on outer cylinder surfaces

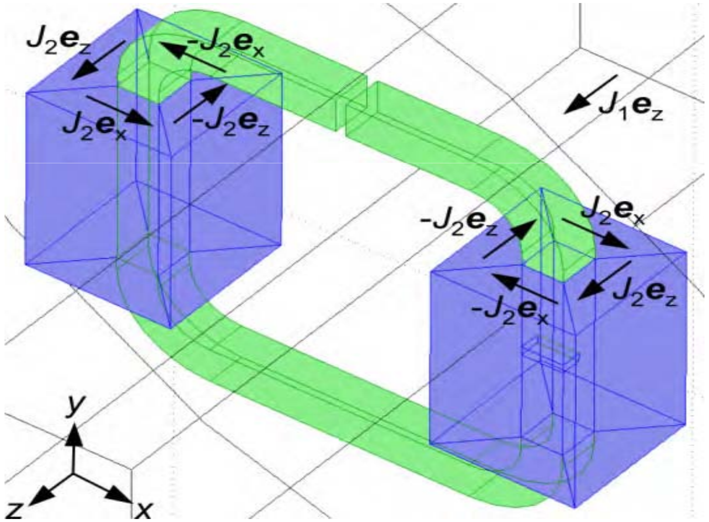
Magnetic Core
Material Characteristic

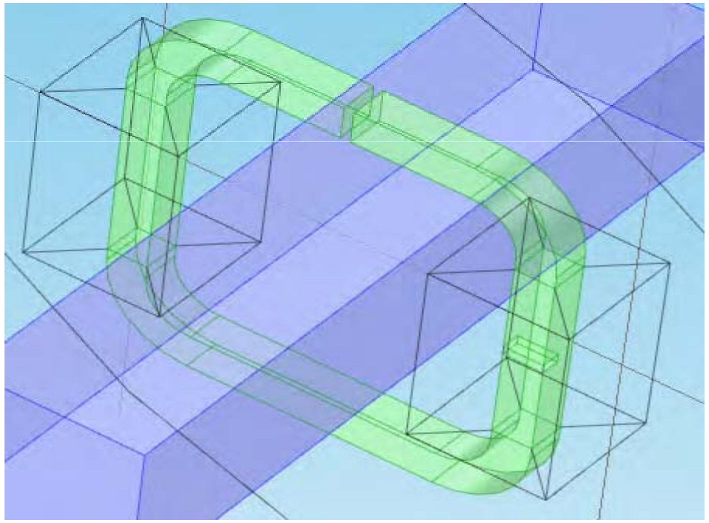




- $FeSi_3$-type magnetic material (M90-23P; $\mu_{max} \approx 50{,}000$)
- Nonlinear characteristic
- Extrapolation with $\mu_{r\ diff} = 1$ up to very high fields for a stable convergence of the solution
- Transient 3D quasi-static magnetic problem: induction currents mode (emqa: vector potential A is dependent variable)
- ⇨ $\boldsymbol{H} = f(|\boldsymbol{B}|)\boldsymbol{e_B}$ (table in the materials/ coefficients library)

Secondary Winding
Current Distribution





- Winding sections composed of 2 x 4 prismatic elements
- Secondary current implemented as a locally constant external current density:

$$\mathbf{J}^{e}{}_{2i}(t) = \frac{N\, i_2(t)}{A_{\text{sec}}} \cdot \mathbf{e}_i$$

- Continuity preserved at the 45° interfaces of the prismatic elements
- Injection of a locally constant primary external current density

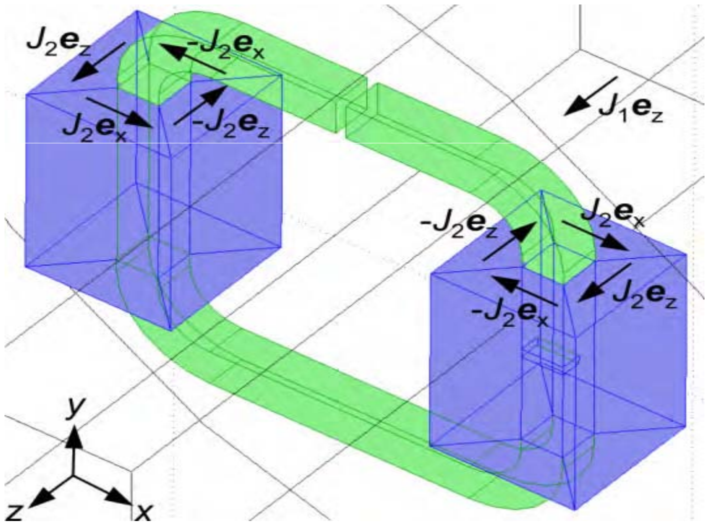
$$\mathbf{J}^{e}{}_{1}(t) = \frac{i_1(t)}{A_{\text{prim}}} \cdot \mathbf{e}_z$$

Secondary Winding
Calculation of the Output Voltage

$$V_{\mathrm{sec}} = R_{\mathrm{coil}} \cdot i_2 - V_{\mathrm{i}}$$

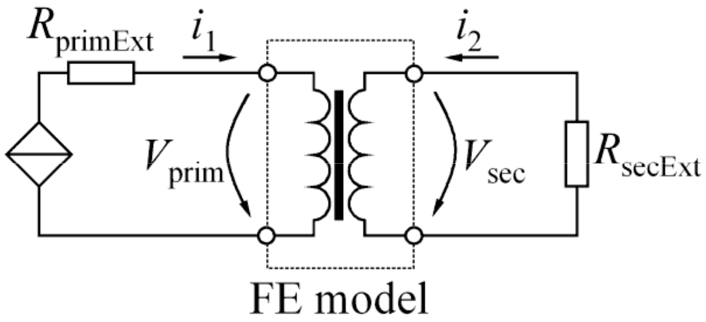
$$V_{\mathrm{i}} = \int_l \mathbf{E}\,\mathrm{d}\mathbf{l} = \frac{N}{A_{\mathrm{sec}}} \cdot \sum_{k=1}^{8} K_k$$

$$K_k = \int_{V_k} E_k \, dV \quad (k = 1, 2, \ldots, 8)$$



- E_k: amplitude of the electric field component in the direction of the current density in k^{th} domain (i.e., E_k = Ex_emqa or E_k = Ez_emqa)
- Calculation of K_k implemented by defining Ex_emqa and E_k = Ez_emqa as integration coupling variables in the respective subdomains.

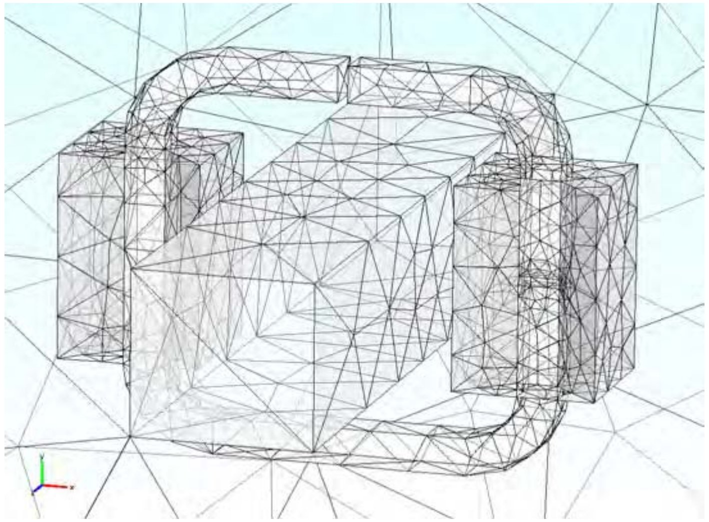
Electric Circuit
Coupling to a Spice Model



- Currents and voltages of the FE-model are linked to the primary and secondary electric circuits
- Transformer here operated in passive mode (without electronic feedback)
- More complex circuit model could be used as an alternative

- I1source 0 1 sin(0 1000 50)
- RprimExt 1 2 1
- X1 2 0 primFEM
- X2 3 0 secFEM
- RsecExt 3 0 1
- .SUBCKT primFEM Vprim i1 COMSOL: *
- .ENDS
- .SUBCKT secFEM Vsec i2 COMSOL: *
- .ENDS
- .END

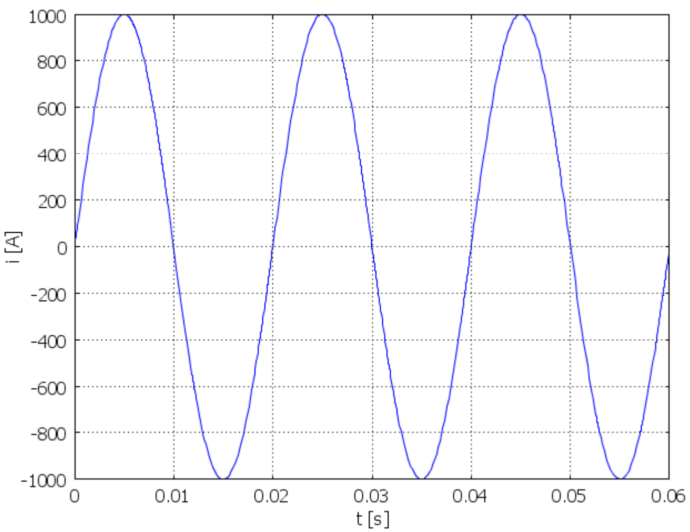
Settings



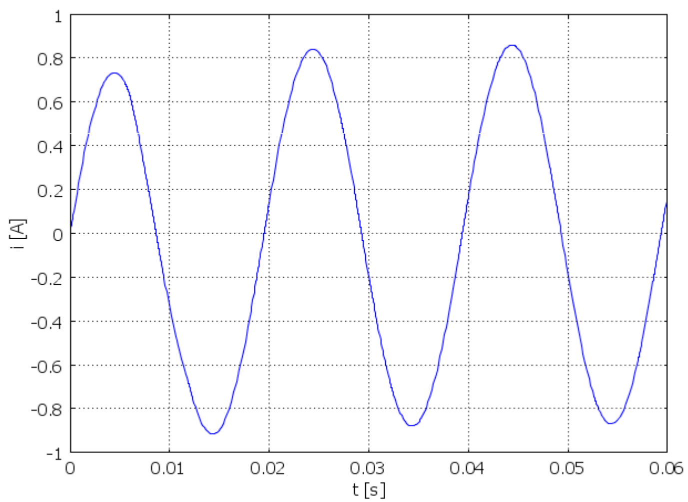
- Coarse mesh with element type “Vector–Linear”
- 14613 degrees of freedom
- Solver: Time dependent
- Time range: 60 ms (3 signal periods)
- Linear system solver: Direct (3.5: PARDISO, 4.0: MUMPS, PARDISO, SPOOLES)
- Solution time: 210 … 440 s* (PC with Intel Core2 Quad CPU 2.40 GHz, 8 GB RAM)

*) dep. on tolerance settings

Results of the Transient Simulations
Primary and Secondary Currents

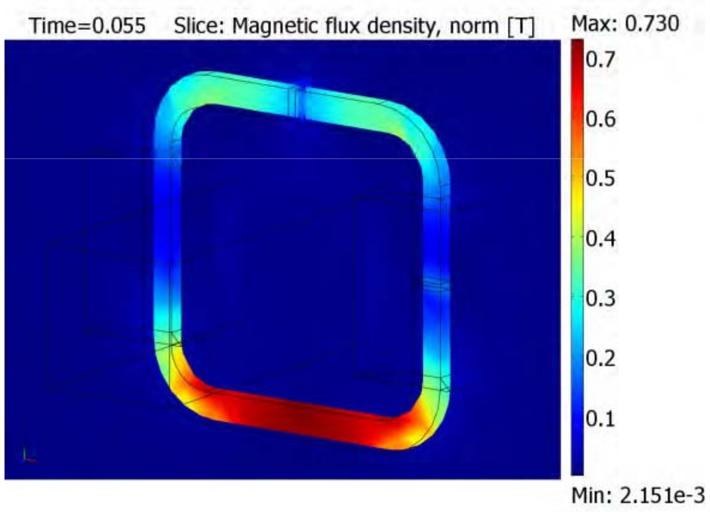


- Primary current (1000 A, 50 Hz)

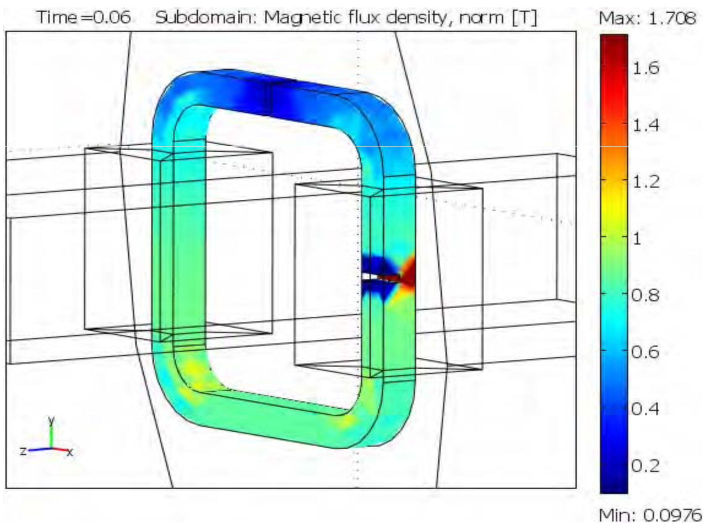


- Resulting secondary current of a “bad” current transformer (1:1000) showing
  - Initial transient response
  - Current error
  - Phase shift

Instantaneous Flux Density Distribution



- Influence of demagnetizing fields from the full air gap (top) and the secondary windings at $i_1(t) = i_{1,max}$



- Snap-shot at $i_1(t) = 0$ with still high induction level close to the partial gap (right) resulting from the phase shift of secondary current

(B: absolute value)

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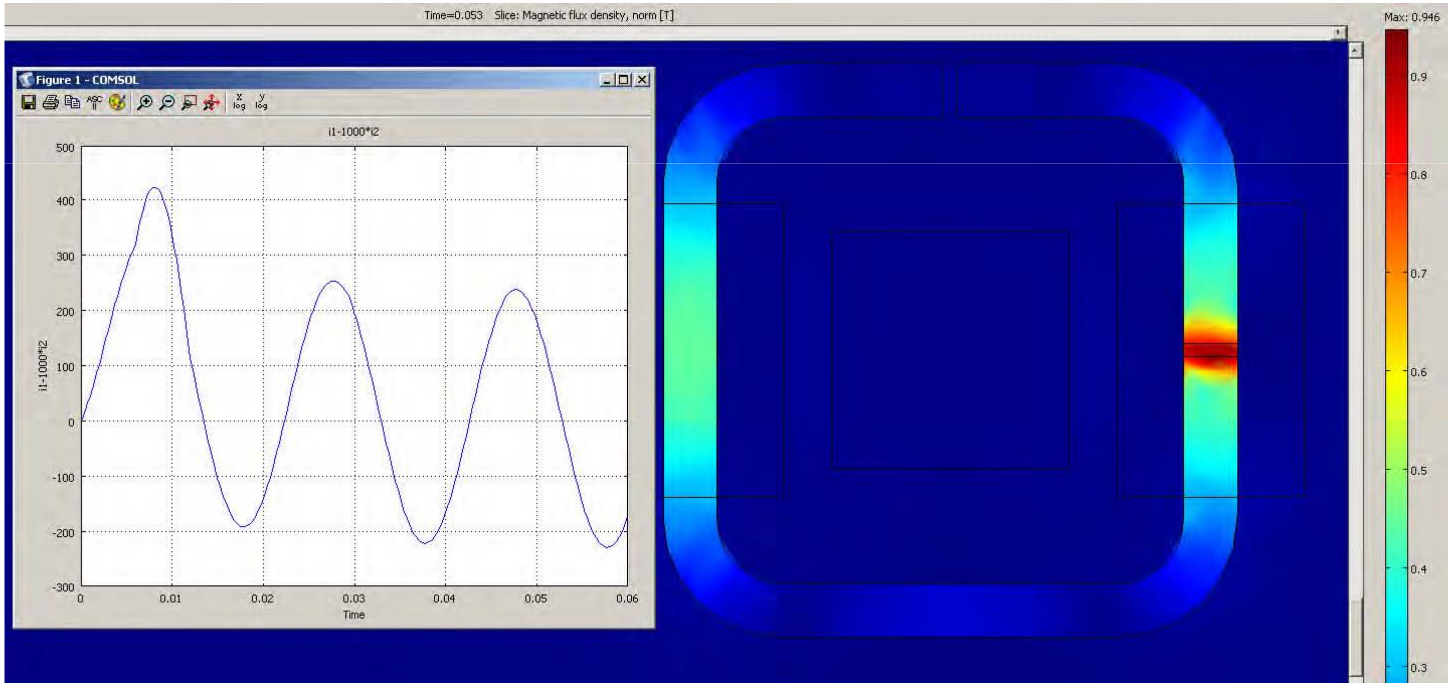
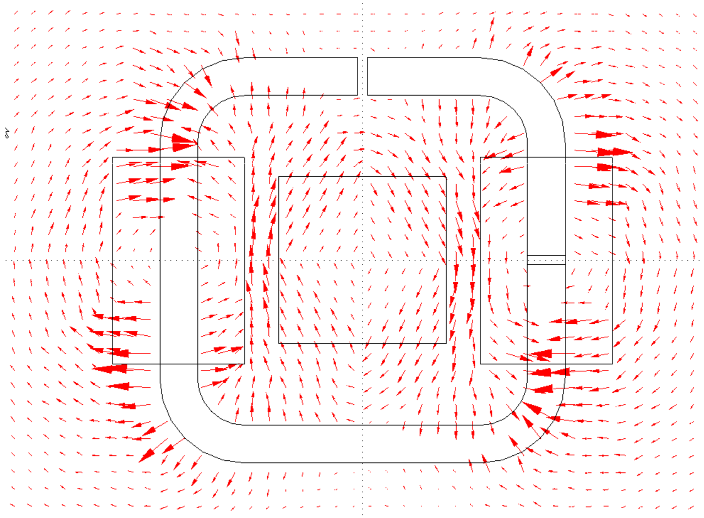
Influence of Stray Fields

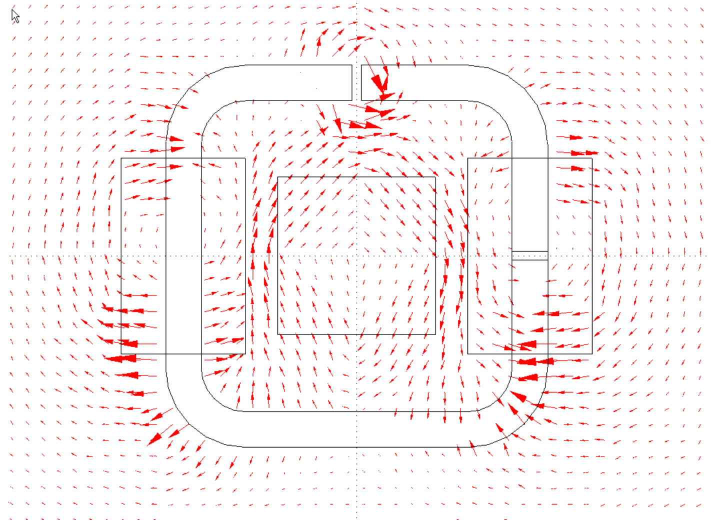


- Even at times when the magnetization current is zero there may be still high local induction levels due to stray fields from the air gaps.
- Stray fields may cause bandwidth limitations and local losses

Stray Field Distribution



- Stray field distribution at zero magnetization current



- Stray field distribution at maximum primary current

Conclusions
Experiences with 3D Transient Magnetic Simulations

- 3D transient FEA with COMSOL and Spice coupling is helpful in the design and for a better understanding of electro-magnetic systems which exhibit
  - more complex core and winding geometries
  - magnetic components with nonlinear materials
  - coupling to external and internal stray fields
  - coupling to electric circuits
- Going from 2D to 3D modelling can be tricky, especially if combined with
  - nonlinearities
  - a large scale range
  - transient analysis

Conclusions II
Experiences with 3D Transient Magnetic Simulations

In order to obtain

- numerical stability and fast convergence of the solution
- broad accessible operation ranges (up to magnetic saturation and high frequencies)
- numerical robustness with respect to geometry and material variation

care has to be taken with respect to

- geometry modelling (avoid curved faces and too many details)
- meshing and element type (avoid inverted elements and high number of DOF)
- solver selection and settings

Outlook
Planned Improvements

- Numerical stability in extended parameter ranges
- Consideration of eddy current effects (currently suppressed)
- Electrical circuits with higher complexity (e.g. electronic feedback)
- Thermal coupling

Thank You!

- Questions?

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