NATAL 2011

11º COBEP

The 11th Brazilian Power Eletronics Conference

Natal - RN - Brazil

11th - 15th Sept. of 2011

Short Course, 8 hours duration, in English

Multi-Domain Simulations in Power Electronics: Combining Circuit Simulation, Electromagnetic and Heat Transfer

Andreas Müsing

Marcelo Lobo Heldwein

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Course contents:

- Electromagnetic simulation using the PEEC method
- Magnetic materials and loss modeling of inductors
- Conducted emissions calculation in combination with a circuit simulator
- Thermal modeling of power electronics and PE devices
- Heat sink optimization
- Hands-on training based on the Gecko multidomain simulation platform

Instructors:

Andreas Müsing studied physics and informatics at the Ruprecht-Karls-University Heidelberg and finished his studies in December 2005. The topic of his diploma thesis was the modeling and simulation of laser induced fuel ignition, which was accomplished in cooperation with Robert Bosch GmbH. Since April 2006, he has been a Ph.D. student at the Power Electronic Systems Laboratory, ETH Zürich, where he is performing numerical simulations of power electronics systems.

Marcelo Lobo Heldwein received the B.S. and M.S. degrees in electrical engineering from the Federal University of Santa Catarina (UFSC), Florianopolis, Brazil, in 1997 and 1999, respectively, and his Ph.D. degree from the Swiss Federal Institute of Technology (ETH Zurich), Zurich, Switzerland, in 2007. He is currently an Adjunct Professor with the Electrical Engineering Department at the UFSC. From 1999 to 2001, he was a Research Assistant with the Power Electronics Institute, Federal University of Santa Catarina. From 2001 to 2003, he was na Electrical Design Engineer with Emerson Energy Systems. He was a Postdoctoral Fellow in the Power Electronics Institute (INEP) at the UFSC, under the PRODOC/CAPES program from 2008 to 2009. His research interests include power factor correction techniques, power conversion for future energy distribution, multilevel converters and electromagnetic compatibility for power electronics. Dr. Heldwein is a member of the Brazilian Power Electronic Society (SOBRAEP) and of the Institute of Electrical and Electronics Engineers (IEEE).

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Multi-Domain Simulations in Power Electronics: Combining Circuit Simulation, Electromagnetics and Heat Transfer

Andreas Müsing

XI BRAZILIAN POWER ELECTRONICS CONFERENCE
September 11-15, 2011
Praimar Convention Center

Short Course overview

- ETH Zurich, Power Electronic Systems Lab & Gecko-Research GmbH
- Motivation: Why do we need to combine different Simulation Domains?
- State of the art: Circuit Simulation – Modeling Everything as a Circuit?
- Thermal Simulation of Power Electronic Systems
  - Physics of heat transfer
  - Heat-Sink Modeling
  - HF Losses of Inductors / Transformers
- Electromagnetics simulation using the PEEC method
- Conducted Emissions Calculation in Combination with a Circuit Simulator
- GeckoCIRCUITS: Hands-on training

Switzerland

- 7.8 millions residents
- 4 languages: German, French, Italian, Romansch
- Area: 26000 sq. miles, ~ State of Rio de Janeiro
- What is Switzerland famous for?

ETH Zürich

- ETH - The "Federal Polytechnical School"
- Two main locations in Zürich
  - Historic main building in the heart of Zürich (Gottfried Semper, 1855)
  - Campus in the outskirts (Hönggerberg)

Historical Main Building, Zürich

Zürich City

Campus Science City, Hönggerberg

GECKO RESEARCH

ETH Zürich

16 Departments

Architecture and Building Sciences	Engineering Sciences	Natural Sciences and Mathematics	System-oriented Natural Sciences	Management and Social Sciences
Architecture	Mechanical and Process Engineering	Mathematics	Earth Sciences	Management, Technology and Economics
Civil, Environmental and Geomatic Sciences	Information Technology and Electrical Engineering	Physics	Environmental Sciences	Humanities, Social and Political Sciences
	Computer Science	Chemistry and Applied Biosciences	Agricultural and Food Sciences	
	Materials Science	Biology		
	Biosystems Science and Engineering			

Some numbers:

- In total 17000 students, (35 % international), 10000 employees
- Electrical engineering (D-ITET)
  1000 Bsc/Ma. students, 345 PhD-students
- Power Electronic Systems Lab (Prof. J. Kolar)
  25 PhD-Students, 5 Post-Docs

GECKO RESEARCH

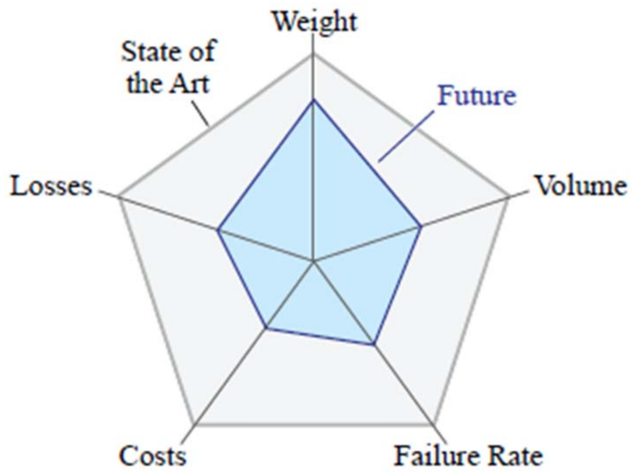
Power Electronics Simulation - Gecko Research

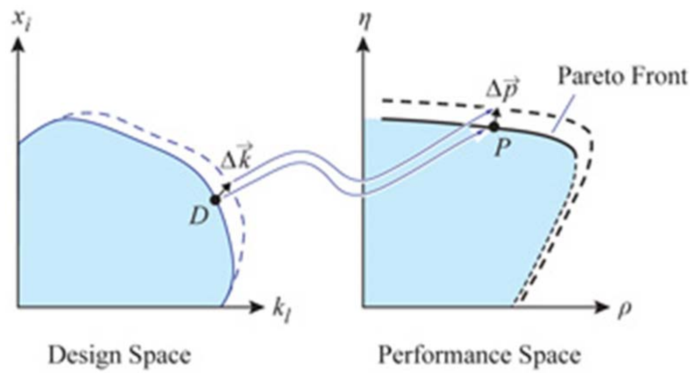
- Gecko-Research is a spin-off company of ETH Zürich
- Founded in 2008 by A. Müsing, Dr. U. Drofenik, Dr. B. Seiler, Prof. J. Kolar
- Specialized software to meet demands of power electronics engineer
- Easy-to-use
- Three tools working together: GeckoCIRCUITS, GeckoEMC, GeckoHEAT
- Multi-domain approach and optimization
- Coupled circuit-, thermal-, and electromagnetic simulation




Motivation

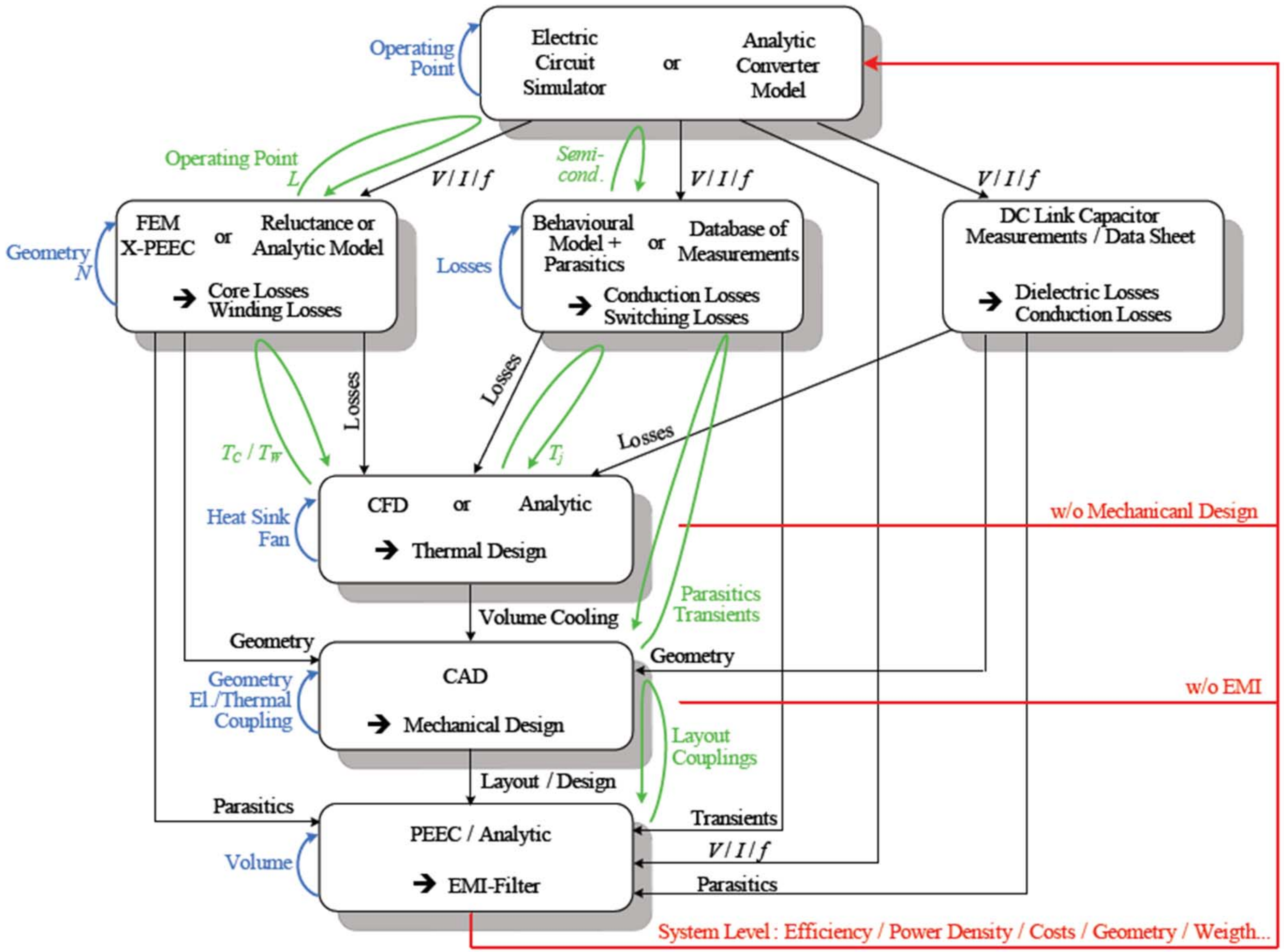
- Power Electronics is not only "Electronics"
- Engineer has to be a "Multi-Talent":
- Circuit Topologies
- Control Strategies
- Thermal design
- Electromagnetic issues
- New materials / semiconductors





GECKO RESEARCH

Coupling of Physical Domains

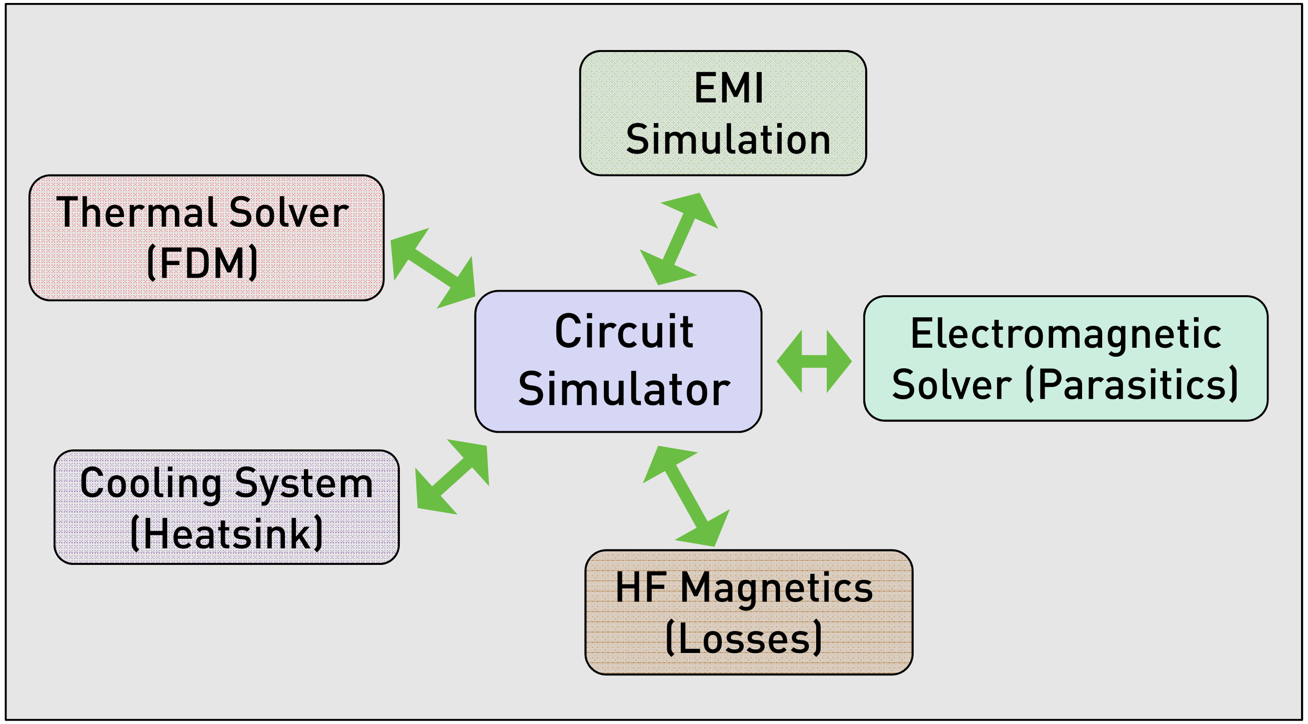


Is this a realistic approach for a PE Design?

Multi-Domain Simulation in Power Electronics

- PE Engineer challenged with different domains
- Circuit Simulator should be „central part" of design toolbox
- Direct tool interconnection not realistic

→ Consider different abstraction levels (model order reduction)



Circuit interpretation possible?

- Power Circuit
- Control?
- Electromagnetics
- Thermal
- Magnetics

Gecko-Research Software Overview

Input
Topology | Device Models | Control Circuit | 3D-Geometry | Materials

GeckoEMC
3D-Electromagn. Parasitics Extraction
Reduced Order Impedance Matrix

GeckoCIRCUITS
Fast Circuit Simulator

GeckoHEAT
3D-Thermal FEM Solver
Thermal Impedance Matrix

HF Magnetics Design Toolbox

EMC Filter Design Toolbox

Reliability Analysis Toolbox

Heatsink Design Toolbox

Post Processing
Design Metrics Calculation

Heat Transfer

Heat Transfer - Overview

- Heat Transfer – Physical Processes
- Thermal Modeling - Stationary
- Thermal Modeling – Cauer / Finite Difference Method (FDM)
- Thermal Modeling – Foster / Impedance Matrix
- Thermal Model of Multi-Chip Power Modules
- Design Examples

Physics of Heat Transfer

- Basic principle: heat always moves from warmer place to cooler place
- Heat transport processes:

  - Radiation, Stefan-Boltzmann Law: $P = \sigma A T^4$

  - Heat Convection $P_H = h\, A\, (T_2 - T_1)$

    Heat transfer coefficient (watts/m^2°C)

  - Heat Conduction

Thermal conductivity (Watts/m°C)

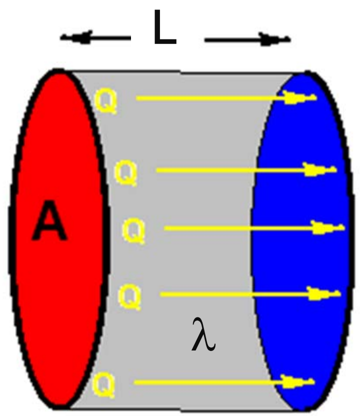
Area of cross section (m2)

$$P_H = \lambda\; A/L\; (T_2 - T_1)$$

Heat flow (watts)

Length (m)

Temperature difference (°C)



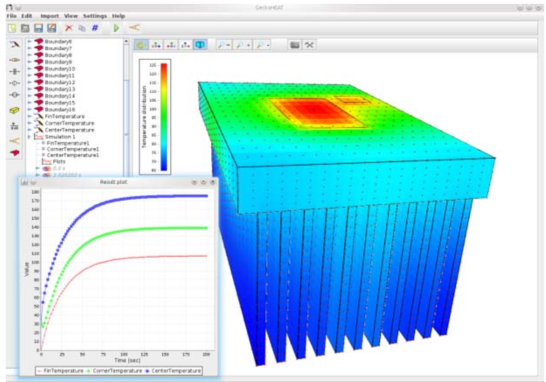
Heat Conduction Differential Equation

$$c_P(T)\cdot\rho\frac{\partial T}{\partial t}=\nabla\left[\lambda(T)\cdot\nabla T\right]+w(\vec{x},t)$$

Assumptions / Simplifications

- Homogeneous media assumed
- Neglect temperature dependency of c_p, λ

→ Linear DEq., fundamental solution is summation of exponential functions



- Descriptive analogy for electrical engineer: thermal resistances and thermal capacitances
- Finite Difference Modeling (FDM) of Heat Conduction (GeckoHEAT): Assume a very huge „thermal“ circuit consisting of R_{th}´s and C_{th}´s

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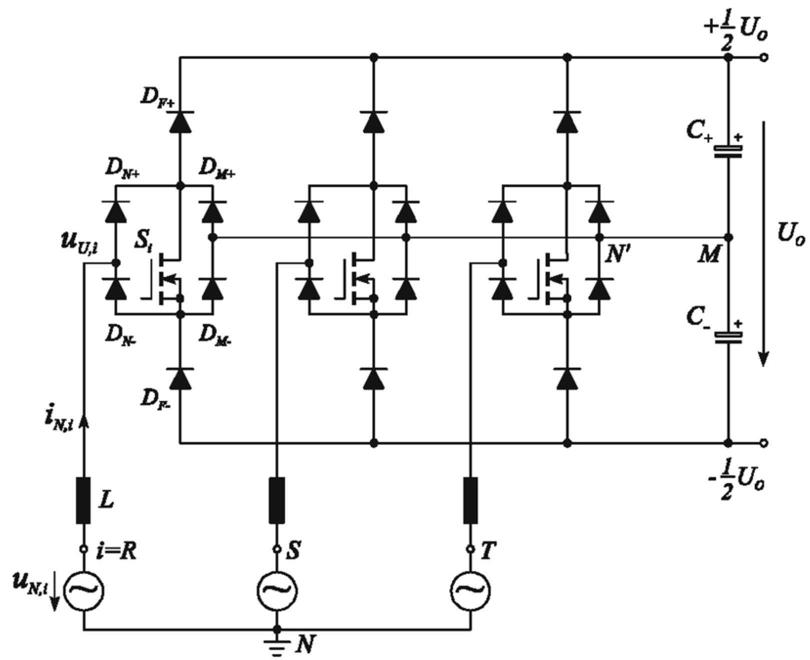
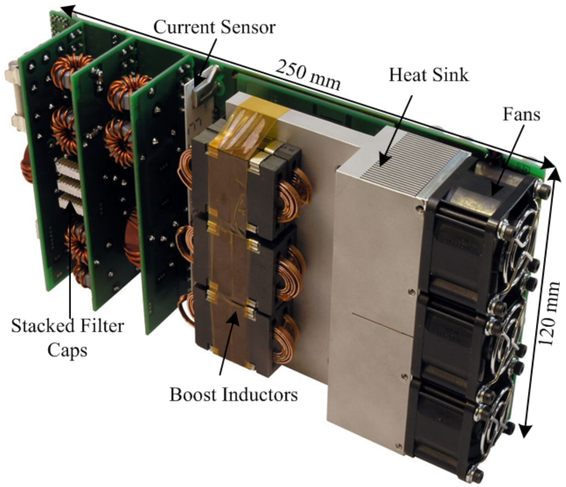
Thermal Modeling – Stationary Design Example (1)

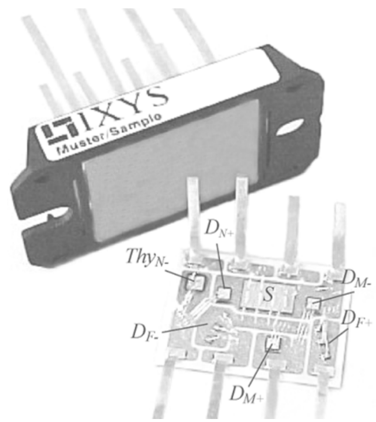
Stationary Thermal Equivalent Circuit

10kW/500kHz Vienna Rectifier 1

→ 8.5kW/dm³ (air-cooling)



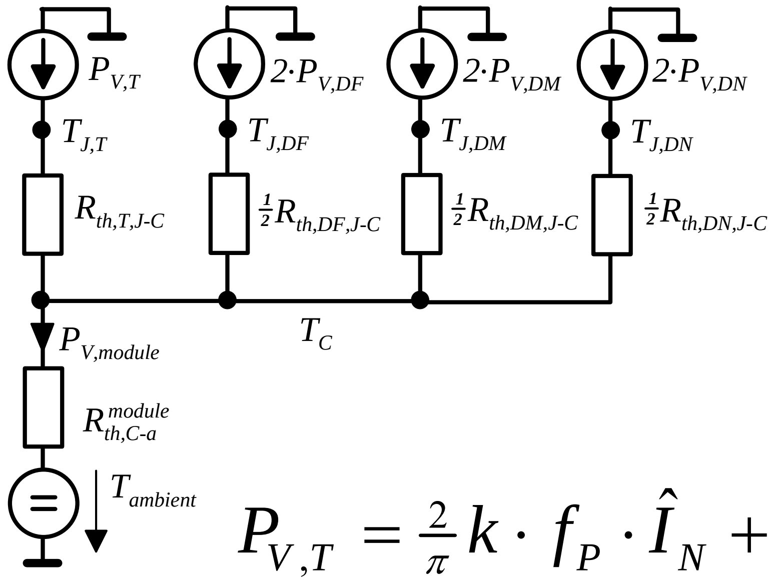


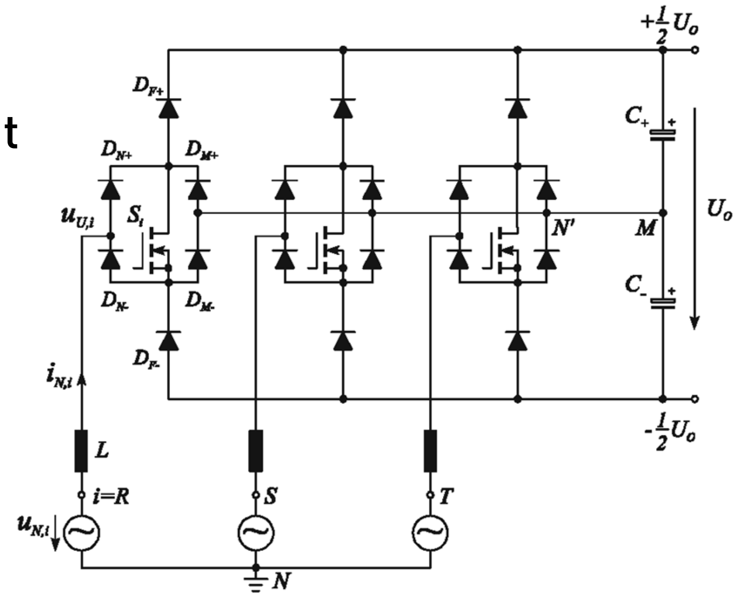


Thermal Modeling – Stationary Design Example (2)

Stationary Thermal Equivalent Circuit

- Analytical equations for rms- and avg-current
- Stationary losses





$$M = \frac{\hat{U}_N}{\frac{1}{2}U_0}$$

$$P_{V,T} = \frac{2}{\pi} k \cdot f_P \cdot \hat{I}_N + r_{DS,ON} \cdot I_{T,rms}^2$$

$$I_{T,avg} = \hat{I}_N \left(\frac{2}{\pi} - \frac{1}{2} M\right)$$

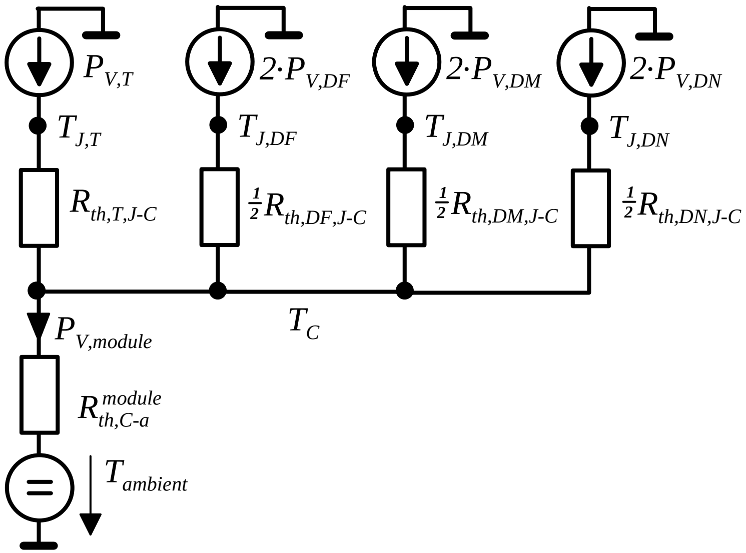
$$I_{T,rms} = \hat{I}_N \sqrt{\frac{1}{2} - \frac{4}{3\pi} M}$$

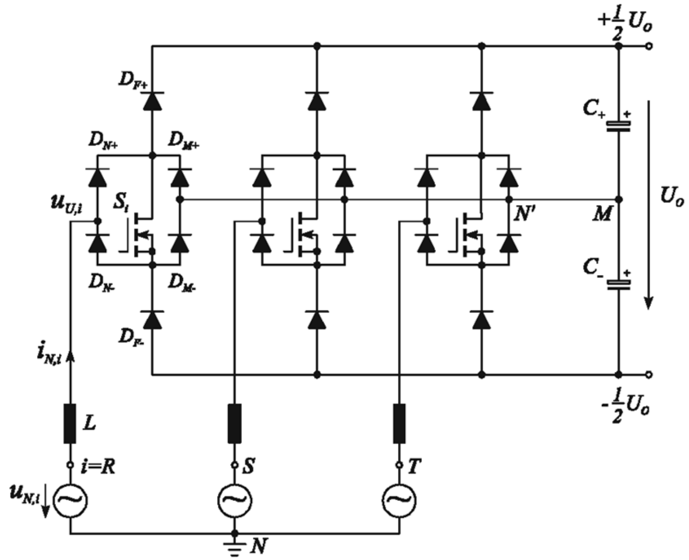
$$P_{V,module} = P_{V,T} + 2 \cdot (P_{V,DN} + P_{V,DM} + P_{V,DF})$$

Thermal Modeling – Stationary Design Example (3)

Stationary Thermal Equivalent Circuit

- Thermal grease
- Average junction temperatures



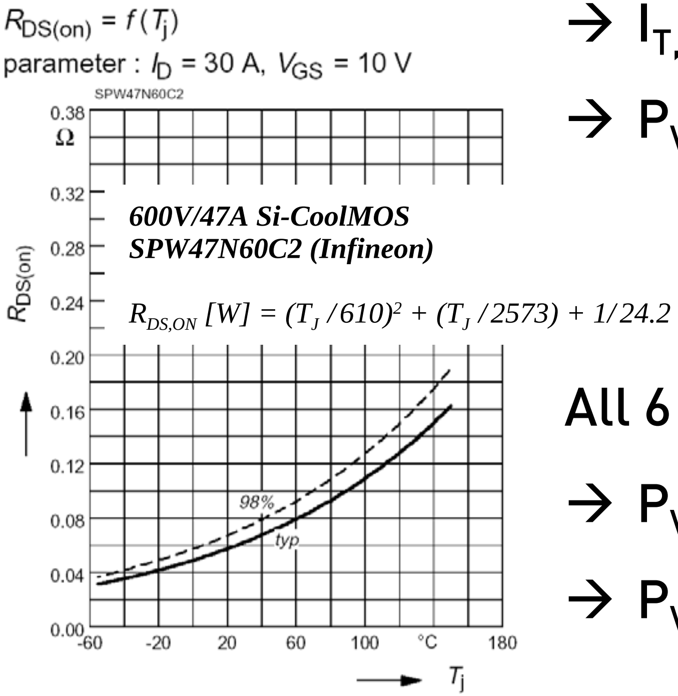


$$R_{th,C-a}^{module} = R_{th,grease} + 3 \cdot R_{th,S-a}^{(HS)}$$

$$R_{th,grease} = \frac{d_{grease}}{\lambda_{grease} \cdot A_{module}}$$

$$T_{J,T} = T_{ambient} + P_{V,module} \cdot R_{th,C-a}^{module} + P_{V,T} \cdot R_{th,T,J-C}$$

Thermal Modeling – Stationary Design Example (4)



Si-CoolMOS:

$R_{DS,on@125°C}$ = 0.14W

$k_{400V@125°C}$ = 11mWs/A

→ $I_{T,avg}$ = 4.78A

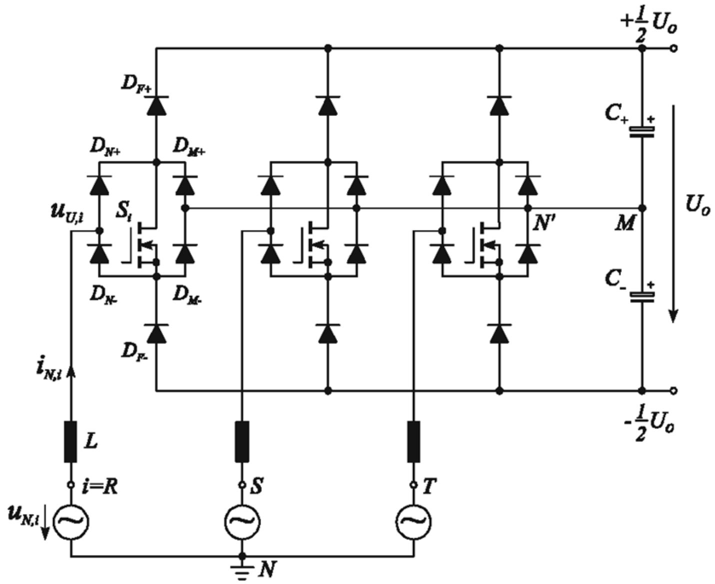
→ $I_{T,rms}$ = 8.23A

→ $P_{V,T}$ = 83.4W

All 6 diodes → 34W

→ $P_{V,Module}$ = 117W

→ $P_{V,Rectifier}$ = 350W



$U_{N,MAX}$ = 327V

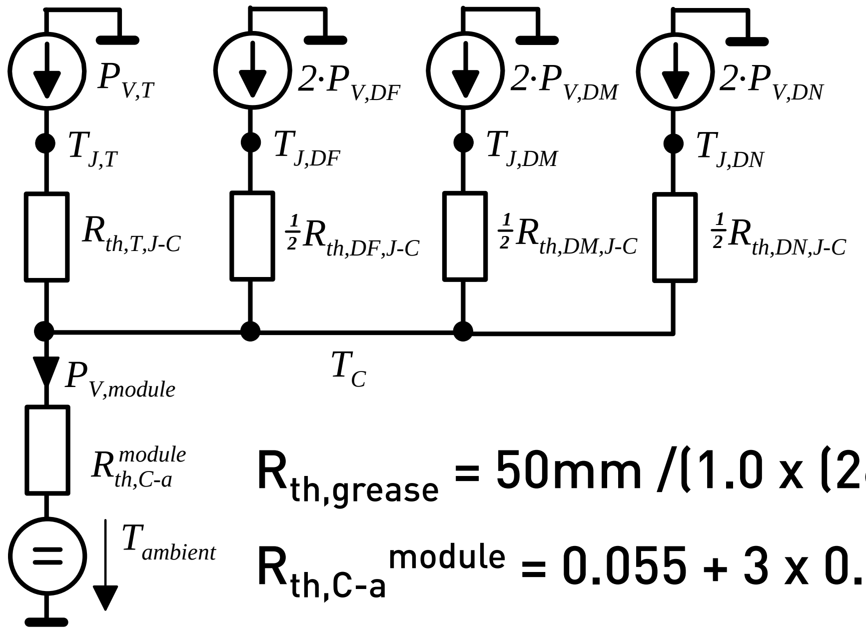
P_{OUT} = 10kW

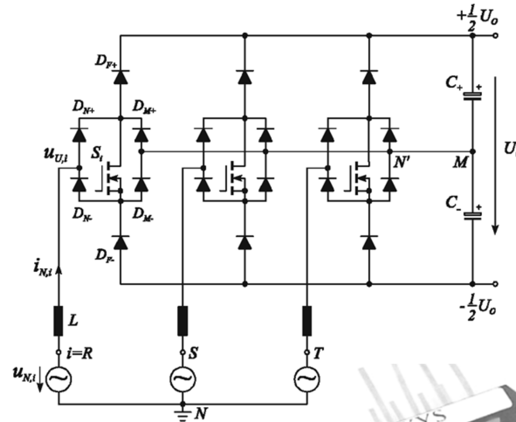
→ $I_{N,MAX}$ = 21A

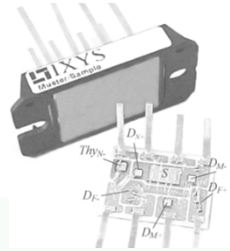
f_P = 500kHz

U_0 = 800V

Thermal Modeling – Stationary Design Example (5)





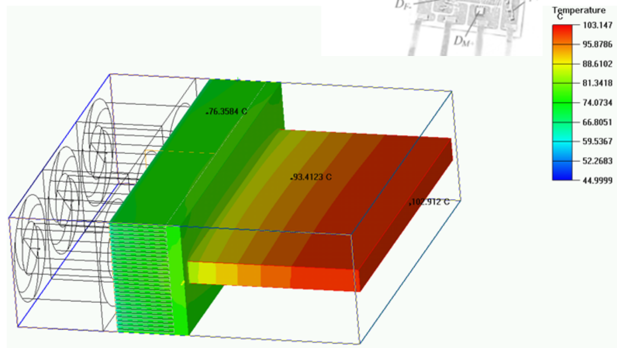


$R_{th,grease}$ = 50mm /(1.0 x (26x35mm^2)) = 0.055K/W

$R_{th,C\text{-}a}^{module}$ = 0.055 + 3 x 0.15 ≈ 0.5K/W

$R_{th,CoolMOS,J\text{-}C}$ = 0.3K/W (datasheet)

$T_{ambient}$ = 45°C



→ $T_{J,T}$ = 45 + 117 x 0.5 + 83.4 x 0.3 =
= 45 + 59 + 25 = 104 + 25 = 129°C

3xFan SanAce 40/28
Optimized Al-HS
$R_{th,S\text{-}a}^{(HS)} = 0.15K/W$

GECKO RESEARCH

Heat-Transfer - Overview

- Heat Transfer – Physical Processes
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- Thermal Modeling – Cauer / Finite Difference Method (FDM)
- Thermal Modeling – Foster / Impedance Matrix
- Thermal Model of Multi-Chip Power Modules
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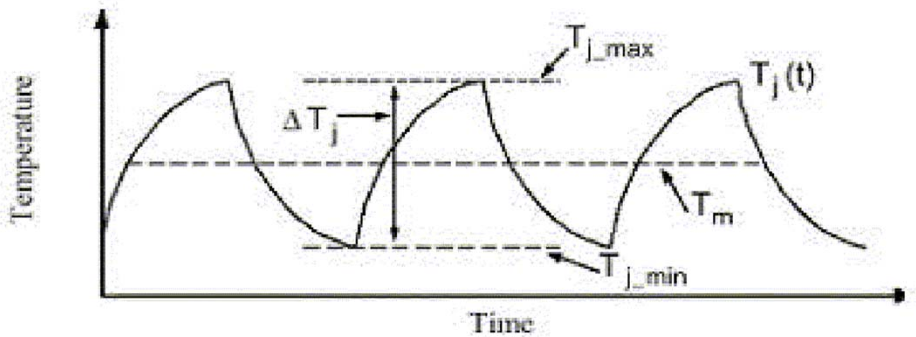
Transient Thermal Modeling – Cauer / FDM Method

Motivation

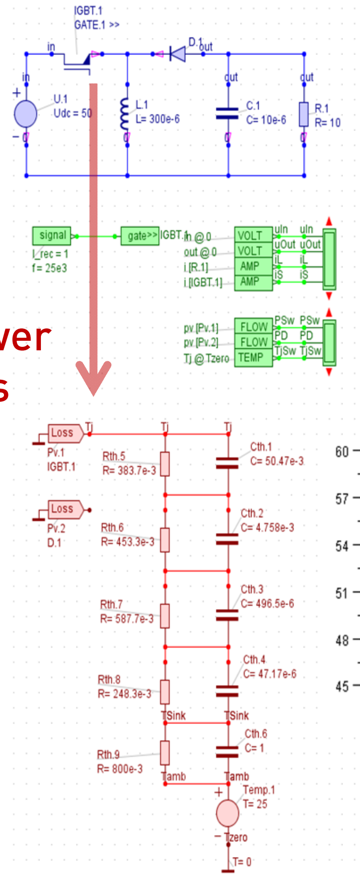
Transient vs. Stationary junction temperatures

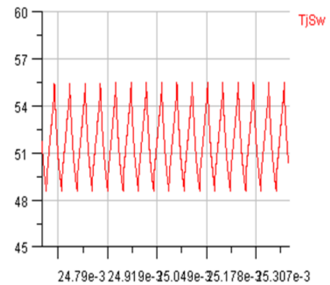
- Maximum junction temperature
- Temperature cycle amplitude
- Short-term overload

→ Our Goal: Transient temperature simulation in circuit simulator



power loss



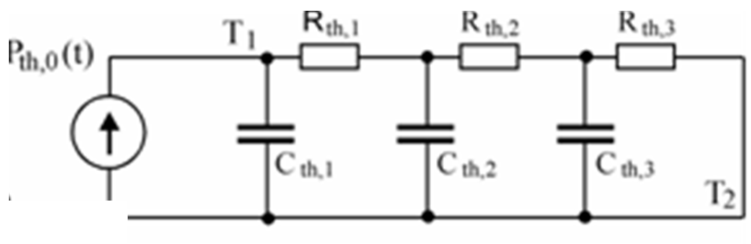


Thermal Modeling – Cauer / FDM (1)

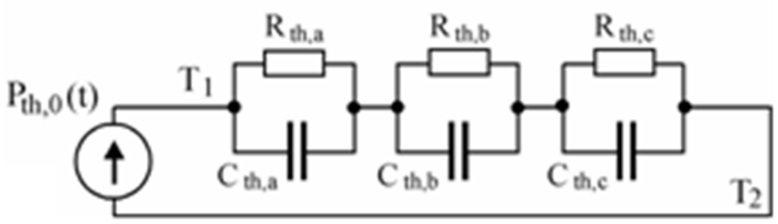
$$c_P(T)\cdot\rho\frac{\partial T}{\partial t}=\nabla\left[\lambda(T)\cdot\nabla T\right]+w(\vec{x},t)$$

Two Methods of Modeling Heat Conduction are typically used:

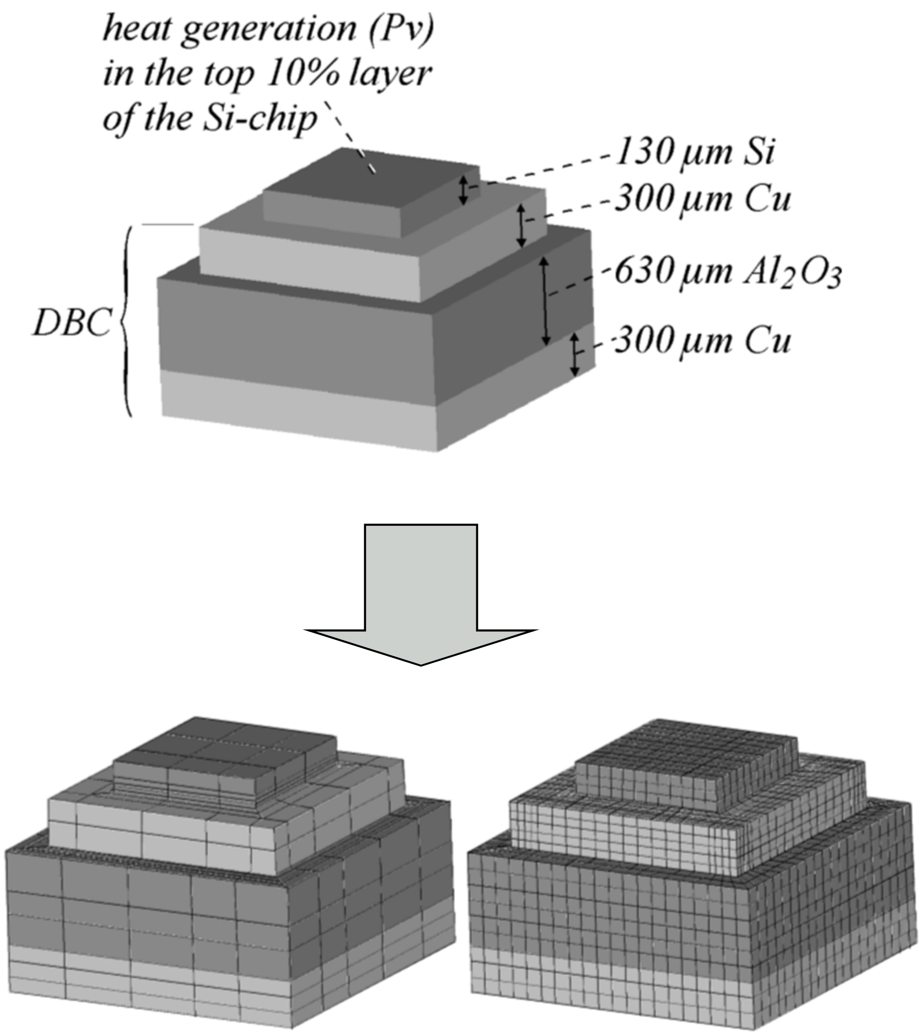
- Cauer-Network / physical mapping → Finite Difference Method (FDM)



- Foster-Network / signal matching → Impedance Matrix



Thermal Modeling – Cauer / FDM (2)

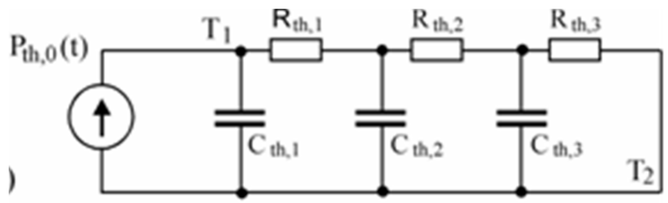


Cauer-Network / physical mapping

→Finite Difference Method

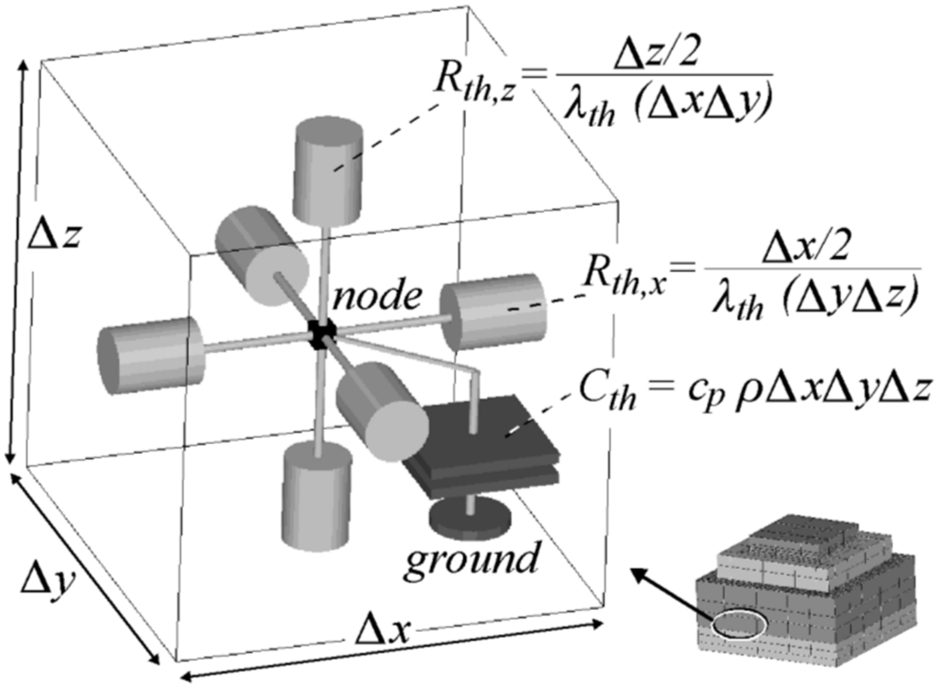
- Accuracy ←→ Many small elements
- Simple model consisting of only a few cells is needed

$$c_P(T)\cdot\rho\frac{\partial T}{\partial t}=\nabla\left[\lambda(T)\cdot\nabla T\right]+w(\vec{x},t)$$



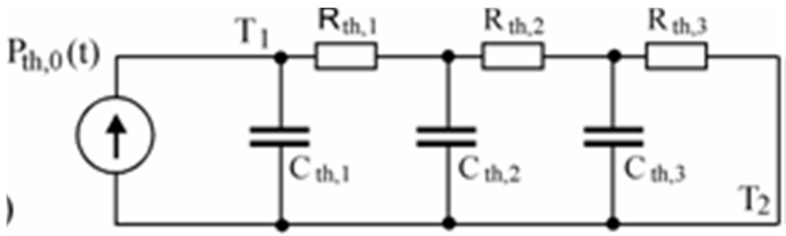
Thermal Modeling – Cauer / FDM (3)

Single 3D-element representing linearized heat-conduction equation

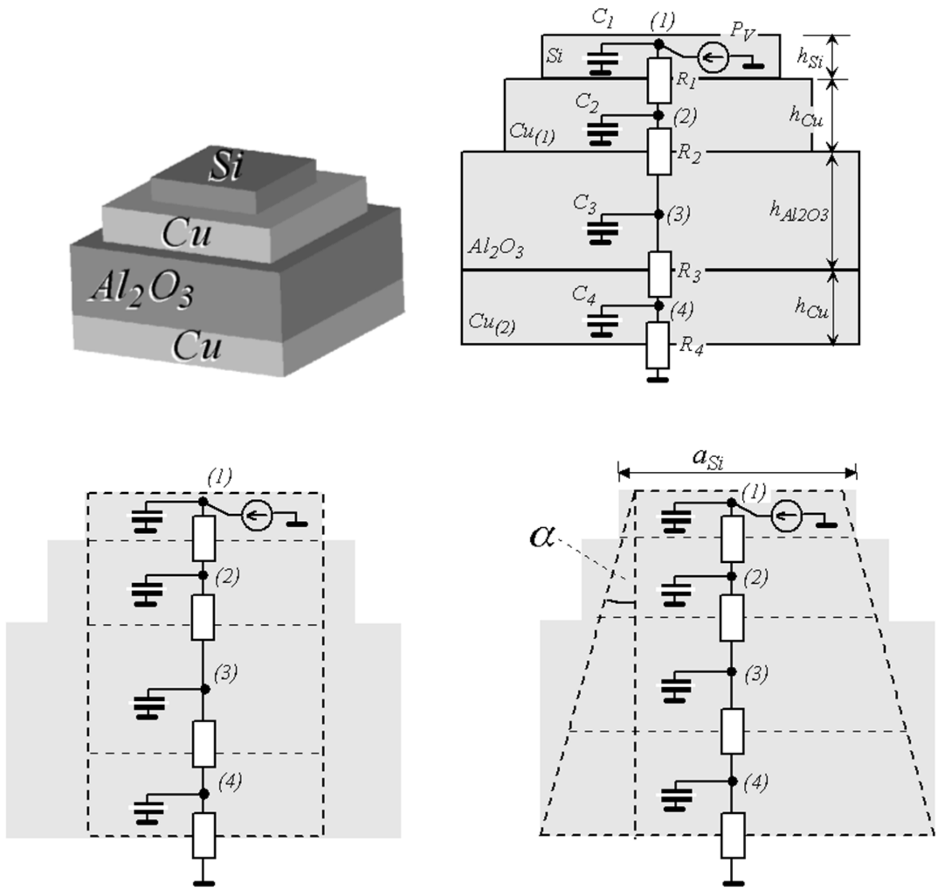


Cauer-Network / physical mapping
→ Finite Difference Method

- Voltage at node (center of element) represents temperature at this point
- Ground represents ambient
- Thermal losses (power) within this geometric element would be represented by current injected into the node (center)

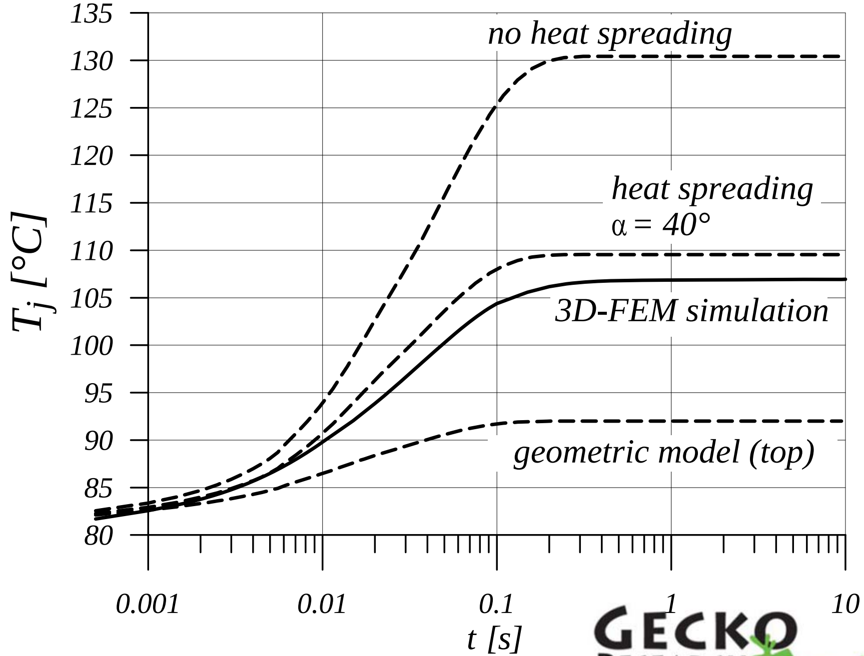


Thermal Modeling – Cauer / FDM (4)

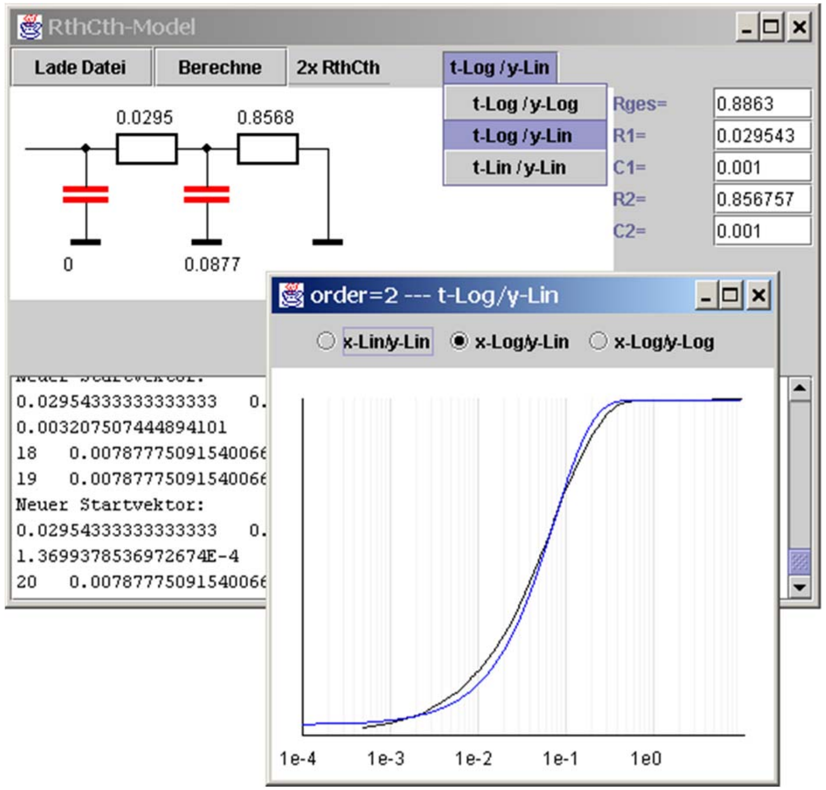


Cauer-Network / physical mapping → Finite Difference Method

- One-dimensional heat flow: Thermal step-response characterizes thermal model
- Where to place what kind of elements?
- Consider heat spreading!



Thermal Modeling – Cauer / FDM (5)

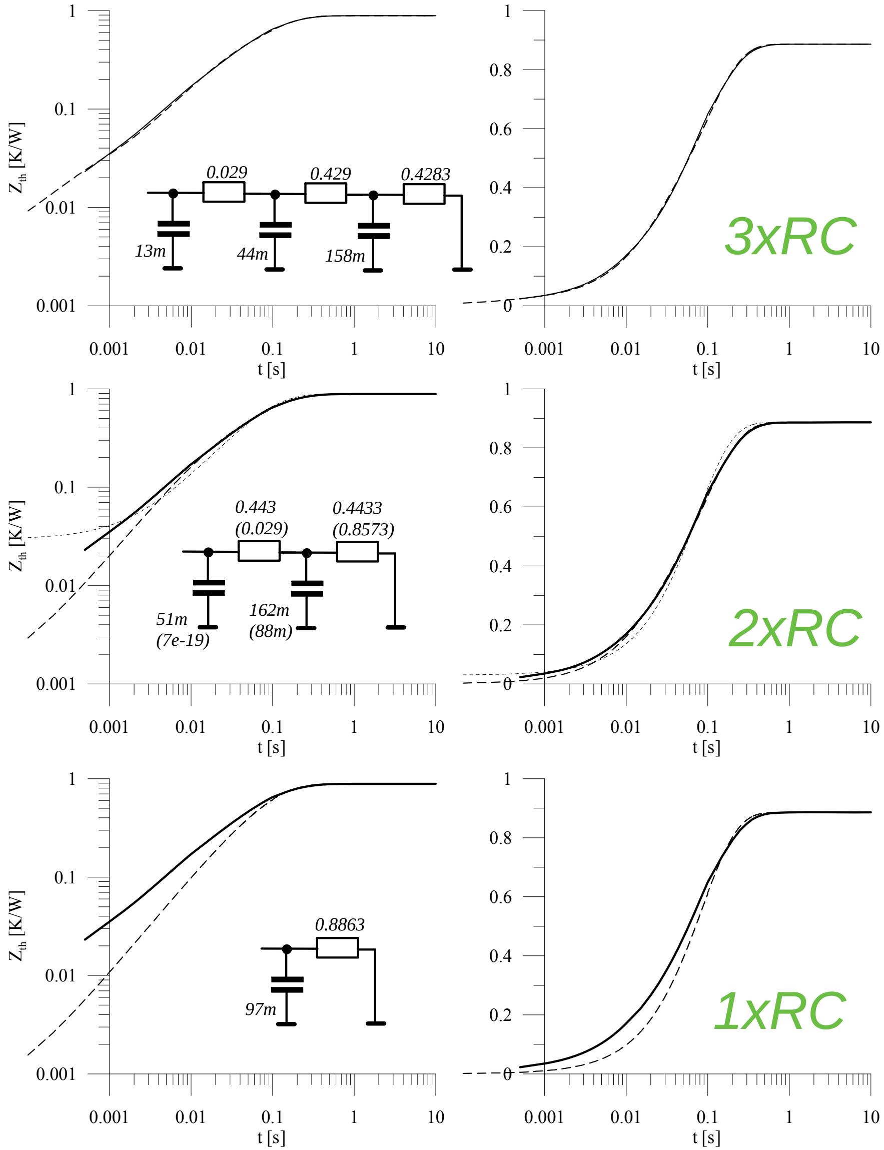


Cauer-Network / physical mapping → Finite Difference Method

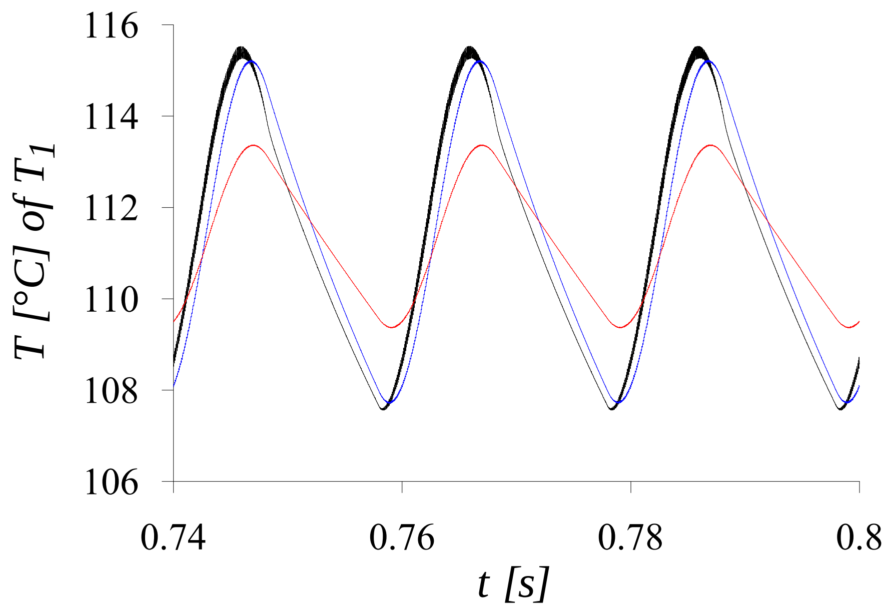
Optimizing element size and location (defined by center-node) for 1D-dim. heat flow:

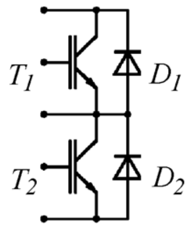
- Measure or calculate (FDM) thermal step response of a given power semiconductor
- RC-topology is defined and search algorithm looks for R- and C-values to match the time-behavior of step response
- If R-values are given, they define certain geometric locations, C-values contain areas of heat spreading

Thermal Modeling – Cauer / FDM (6)

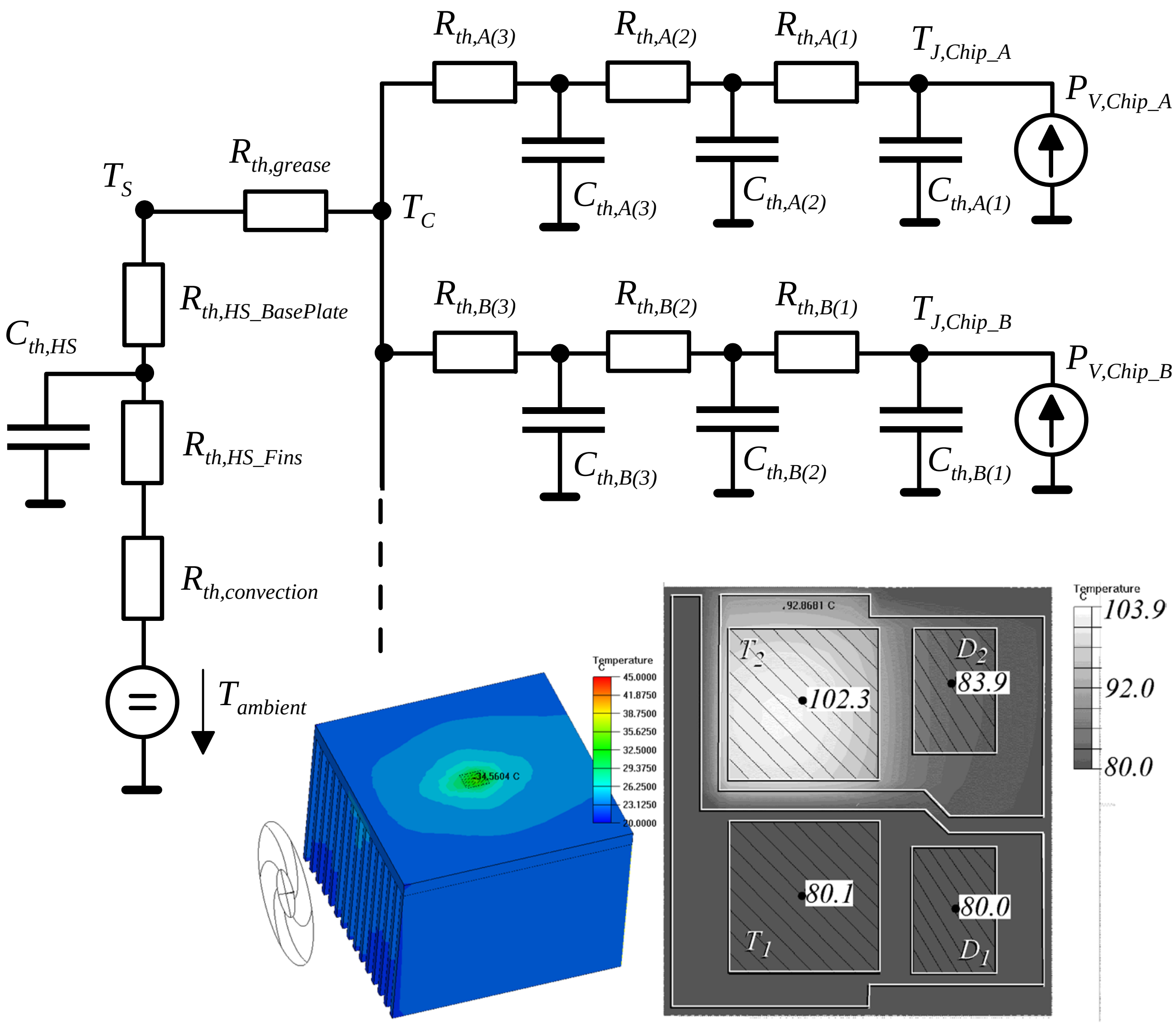


Modeling Error for Different Number of *RC* Elements





Thermal Modeling – Cauer / FDM (7)

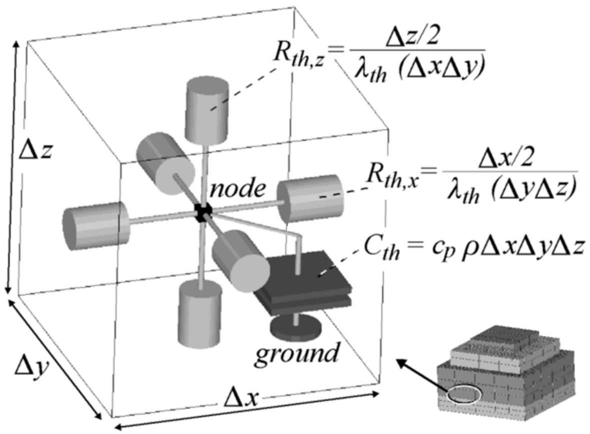


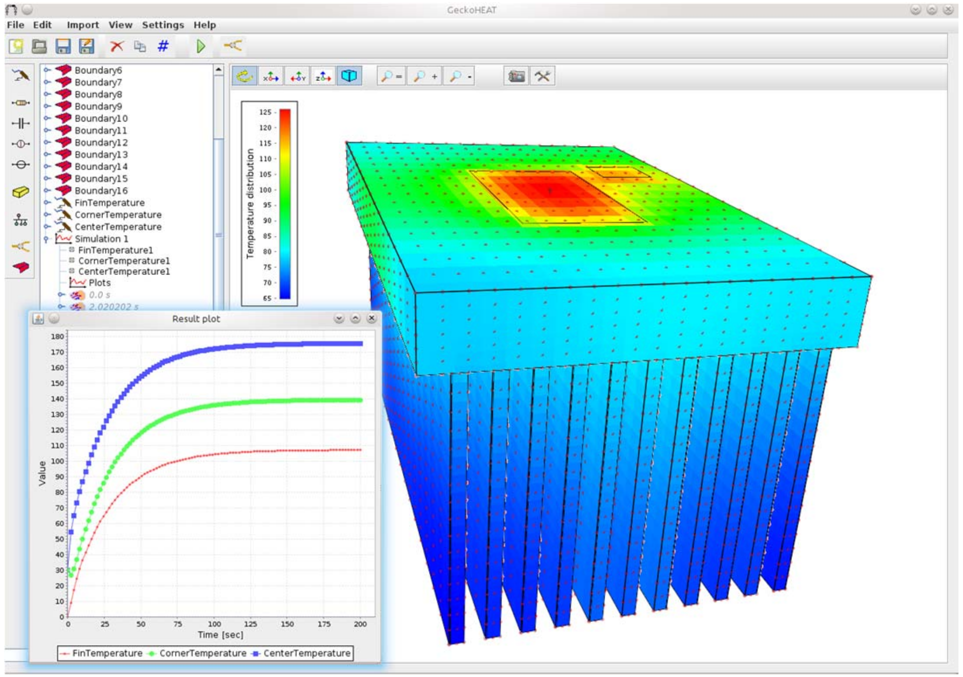
- Thermal Coupling: Chip will heat up the neighbor chips
- Influence of internal copper layer design difficult to describe
- Thermal coupling due to heat sink might dominate
- Accuracy limited!

→ Use full Finite Difference Simulation, e.g. GeckoHEAT

GeckoHEAT – Heat conduction simulation

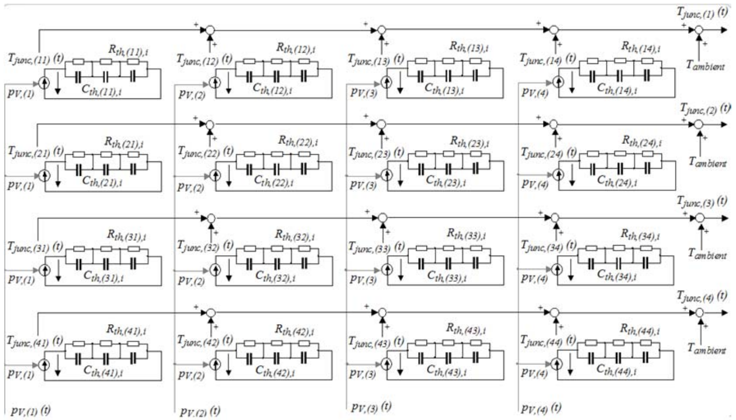
- FDM – based solution of heat equation
- Easy-to-use, very fast
- Various boundary-conditions
  - Power loss density
  - Convection boundary
  - Fixed temperature
- Automatic extraction of thermal impedance network

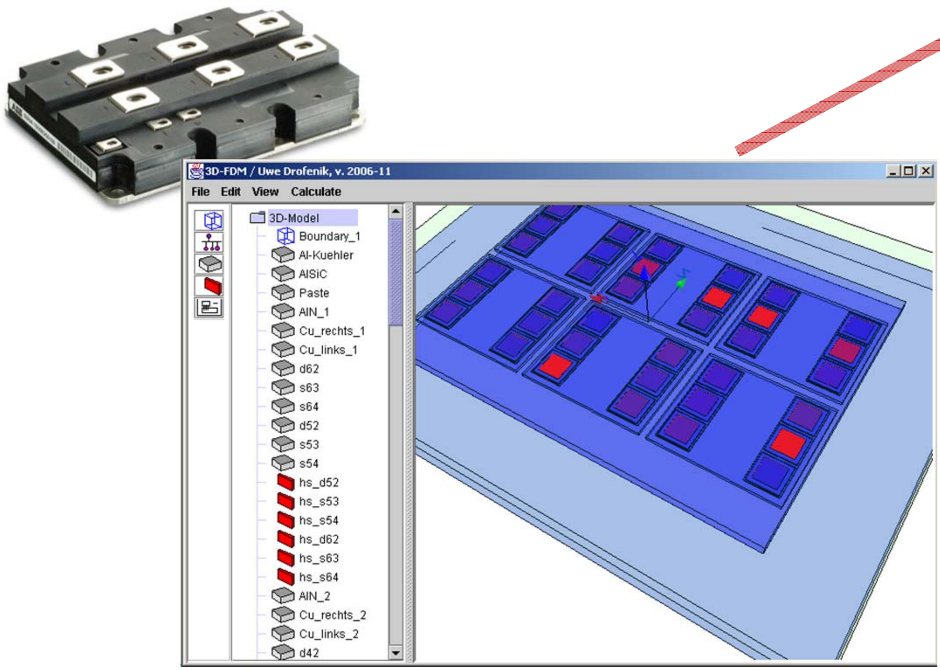


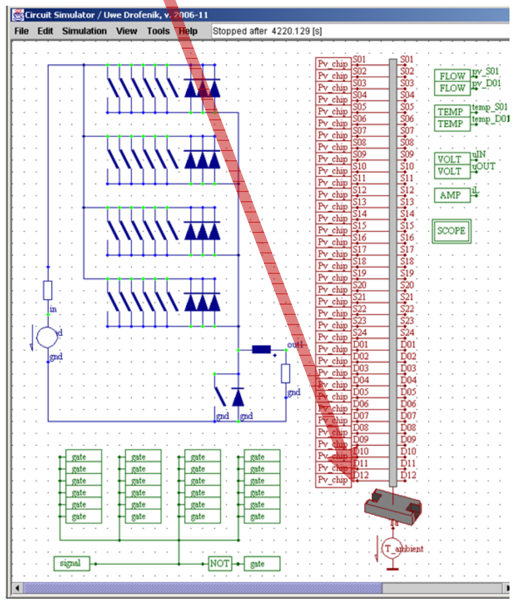


GeckoHEAT – GeckoCIRCUITS Coupling

- Thermal impedance matrix automatically generated from 3D-model of Power Module
- Efficient solution within GeckoCIRCUITS
- Temperature-dependent conduction & switching losses in GeckoCIRCUITS







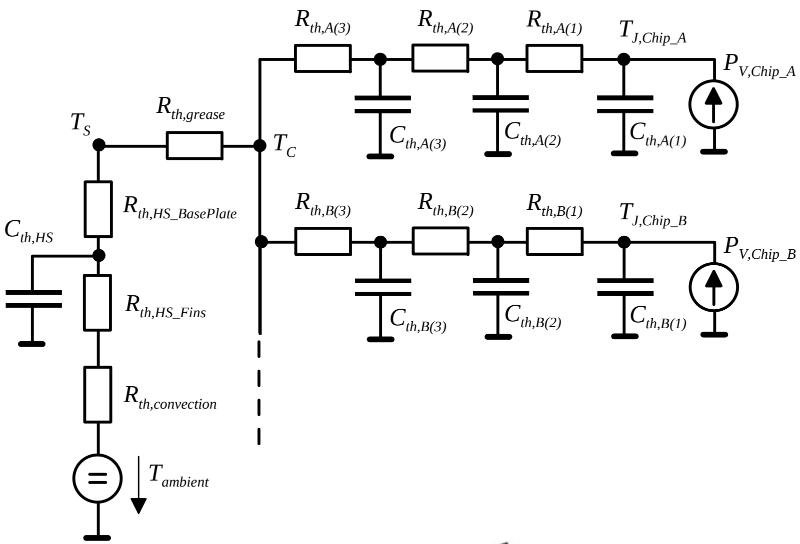
Summary: Thermal Modeling, Cauer / FDM

Cauer-Network / physical mapping

→ Finite Difference Method

Summary:

- Physical model (internal nodes, heat flow into sink) useful for reliability-studies
- Physical models can be coupled!
- Directly connecting chip model to heat sink
- Internal thermal coupling difficult to model
- Systematic network-setup is difficult

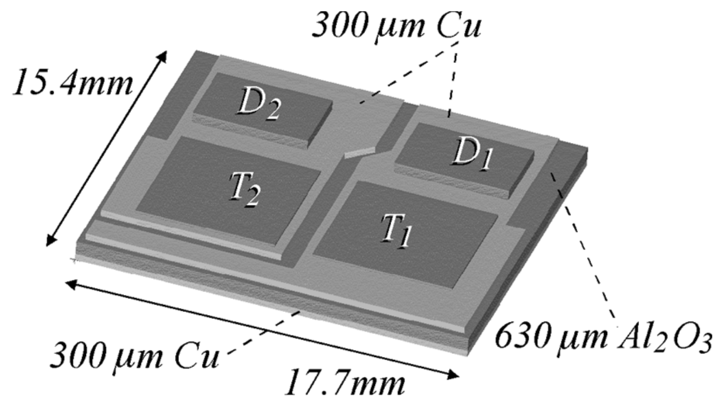


Heat-Transfer - Overview

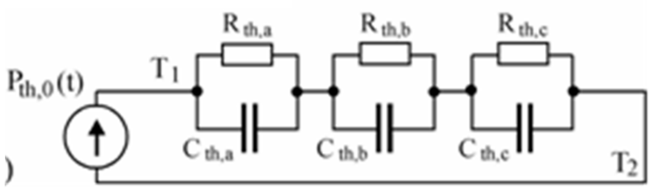
- Heat Transfer – Physical Processes
- Thermal Modeling - Stationary
- Thermal Modeling – Cauer / Finite Difference Method (FDM)
- Thermal Modeling – Foster / Impedance Matrix
- Thermal Model of Multi-Chip Power Modules
- Design Examples

Thermal Modeling – Foster / Impedance Matrix (1)

$$\begin{pmatrix} T_{junc,(1)}(t) \\ T_{junc,(2)}(t) \\ T_{junc,(3)}(t) \\ T_{junc,(4)}(t) \end{pmatrix} = \begin{pmatrix} z_{11} & z_{12} & z_{13} & z_{14} \\ z_{21} & z_{22} & z_{23} & z_{24} \\ z_{31} & z_{32} & z_{33} & z_{34} \\ z_{41} & z_{42} & z_{43} & z_{44} \end{pmatrix} \cdot \begin{pmatrix} p_{V,(1)}(t) \\ p_{V,(2)}(t) \\ p_{V,(3)}(t) \\ p_{V,(4)}(t) \end{pmatrix} + T_a$$



$$c_P(T) \cdot \rho \frac{\partial T}{\partial t} = \nabla\left[\lambda(T) \cdot \nabla T\right] + w(\vec{x}, t)$$

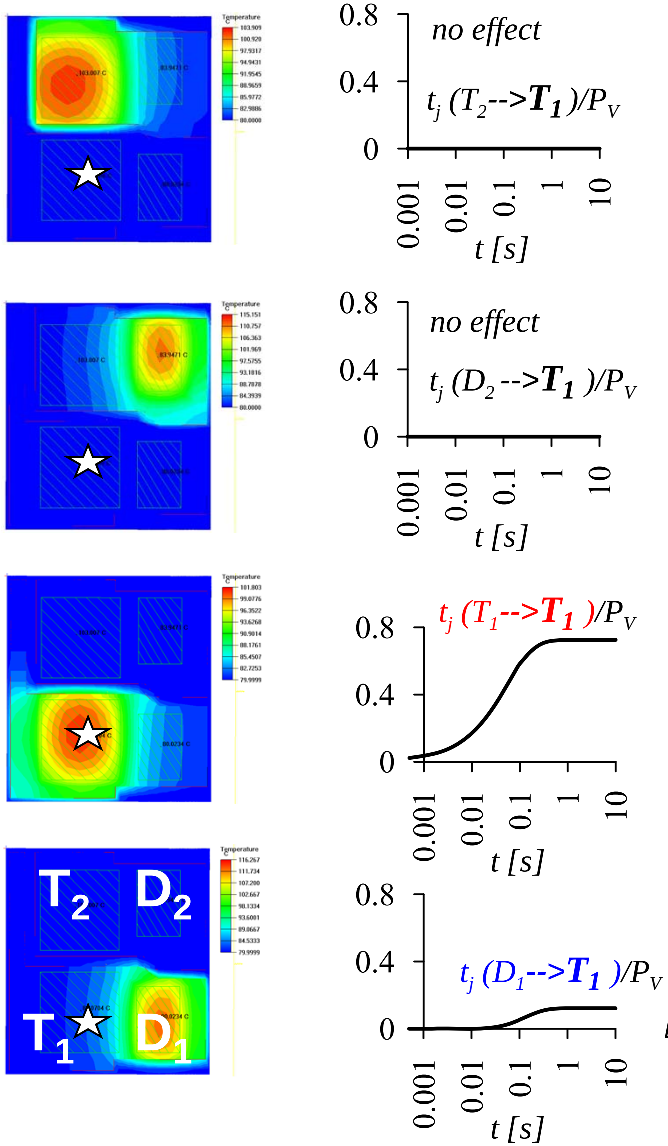


Foster-Network:signal matching
→ Impedance Matrix

Impedance Matrix:

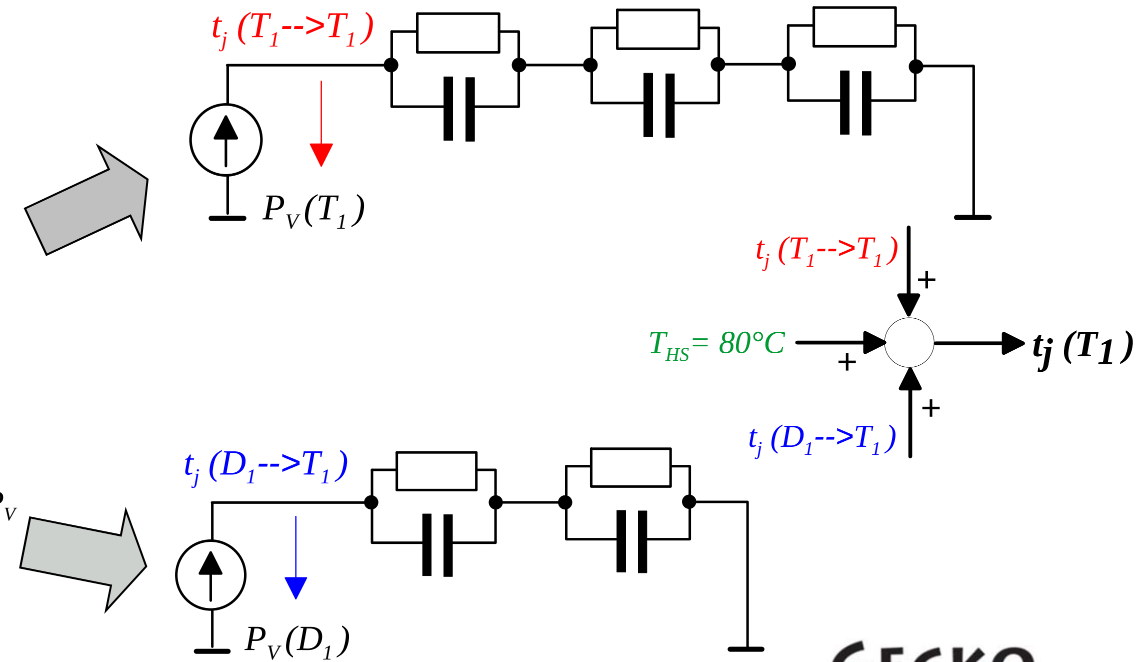
- Assume heat-conduction equation to be a linear differential equation
- Apply superposition: Total temperature at a certain geometrical point is defined by all heat sources
- Model measured thermal impedance $Z_{th,ii}(t)$ with equivalent circuit showing equal step response signals

Thermal Modeling – Foster / Impedance Matrix (2)



Foster-Network / signal matching
→ Impedance Matrix

$$
\begin{aligned}
t_j\ (T_1) = {} & Z_{th,T1\rightarrow T1} \cdot P_V(T_1) + Z_{th,D1\rightarrow T1} \cdot P_V(D_1) \\
& + Z_{th,T2\rightarrow T1} \cdot P_V(T_2) + Z_{th,D2\rightarrow T1} \cdot P_V(D_2)
\end{aligned}
$$



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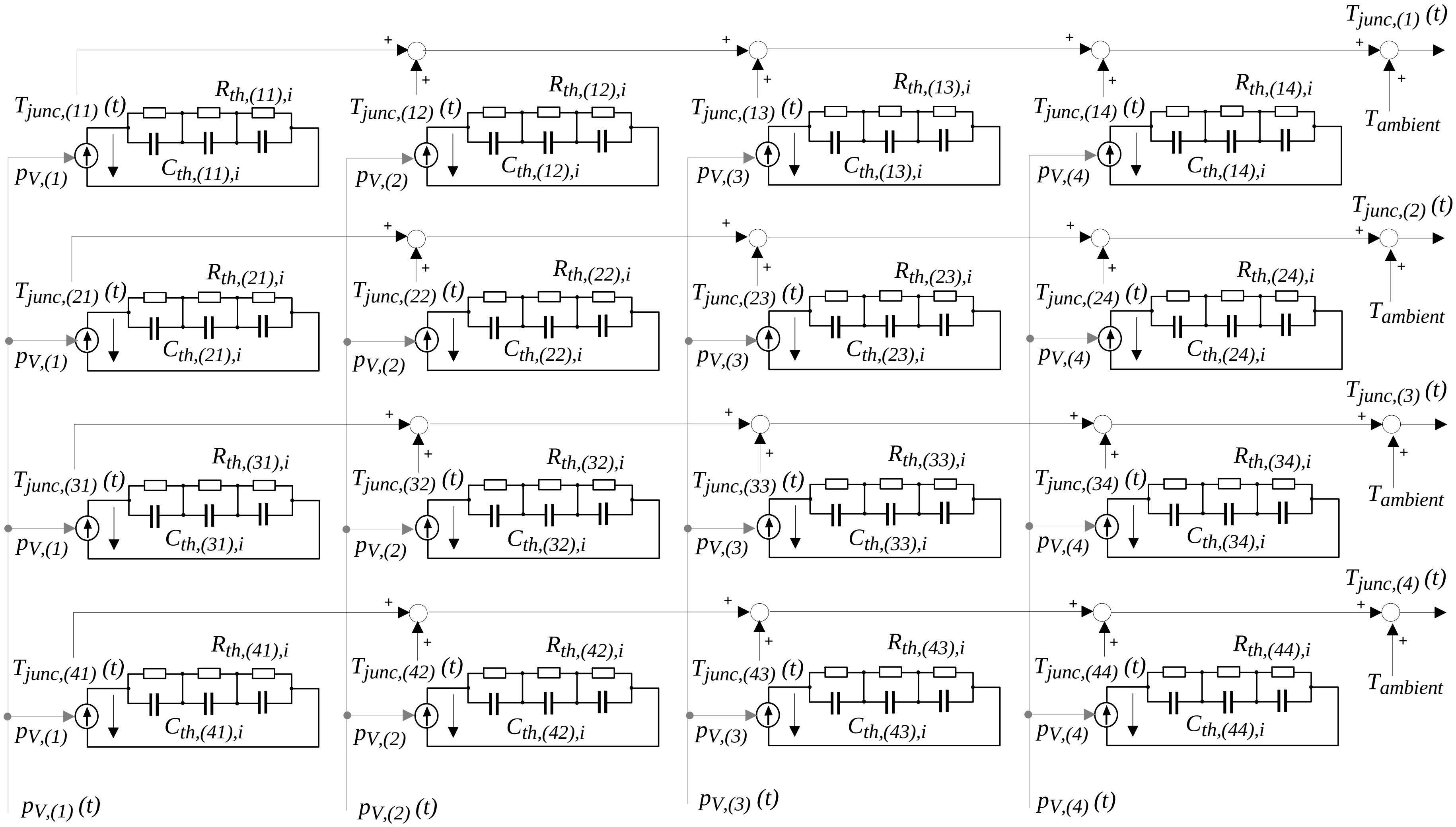
Thermal Modeling – Foster / Impedance Matrix (3)



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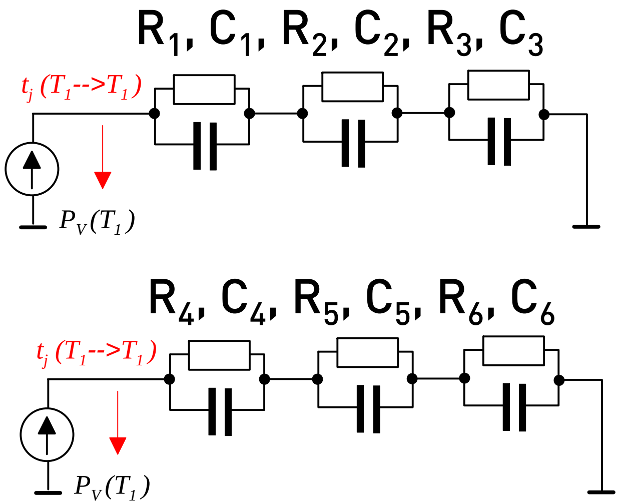
Pittfall – non-physical FosterModel (1)

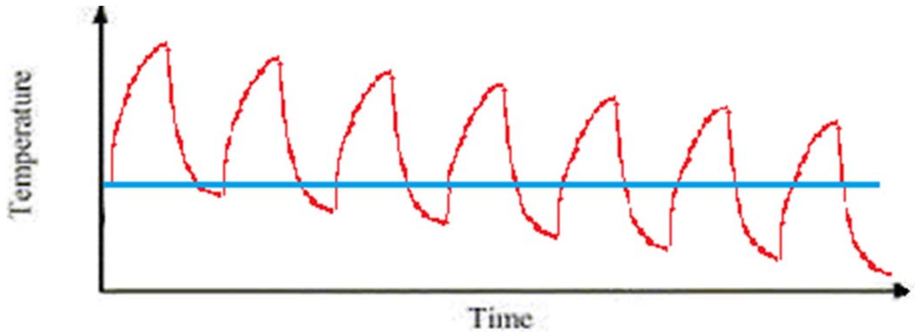
A useless combination of two foster models:

- Reliability analysis: Thermal Foster model from power module supplier
- Heating phase: water cooling switched off
- Cooling phase: water cooling switched on

→ Two separate foster models obtained from the temperature measurements:

→ „Switching“ between both models at cooling phase and heating phase

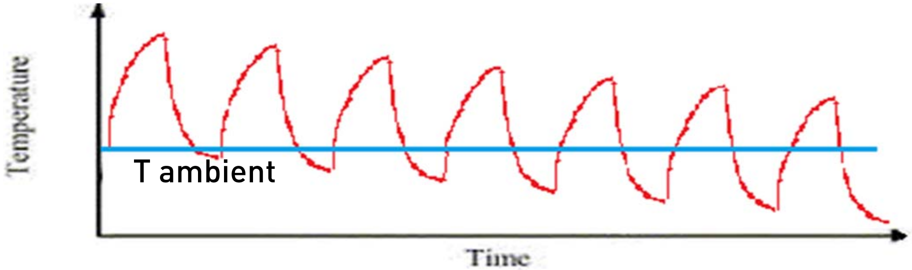


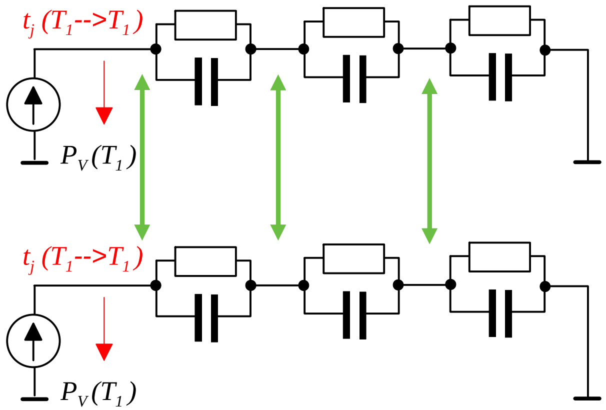


Pittfall – non-physical FosterModel (2)

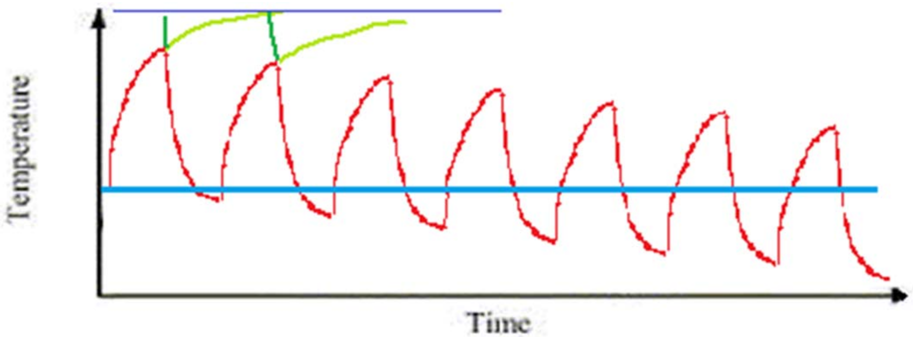
→ Results when combining two foster models were completely useless:

- Switching between both models: how to set the initial conditions (initial temperature of capacitors)?
- Simulated temperature transients falling below ambient temperature!?!





- How about Energy conservation?
- Can we fix the flawed model?



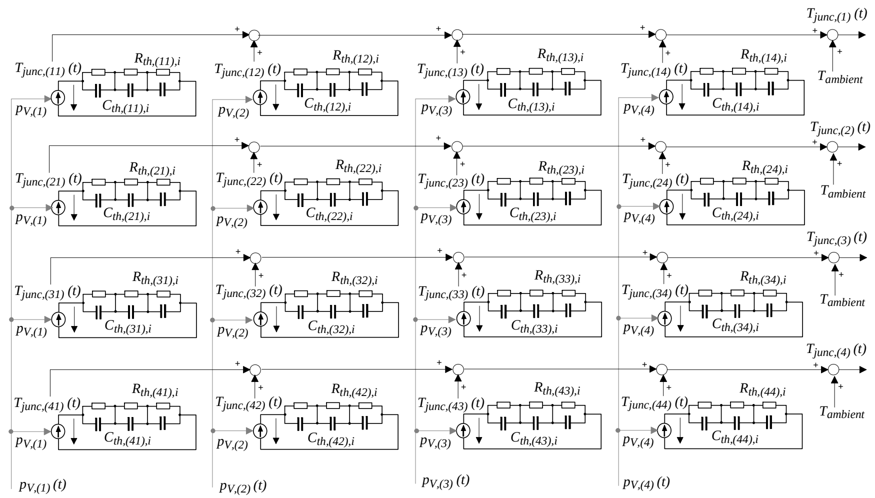
- Idea: Complete heating until equilibrium
- Jump back in time, pre-calculate cooling curve
- This is also useless!

Summary – Thermal Foster Model / Impedance Matrix

Foster-Network / signal matching → Impedance Matrix

Summary:

- Network models signal behavior → no physical model
- No coupling of sub-models possible!
- Heat sink to be included for thermal step response
- Internal thermal coupling easy to model
- Number of heat sources (semiconductors) defines order of thermal impedance matrix
- Systematic network-setup can be easily automatized



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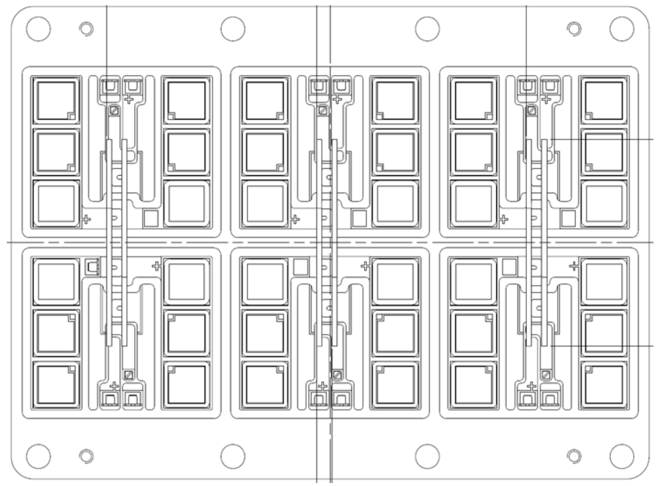
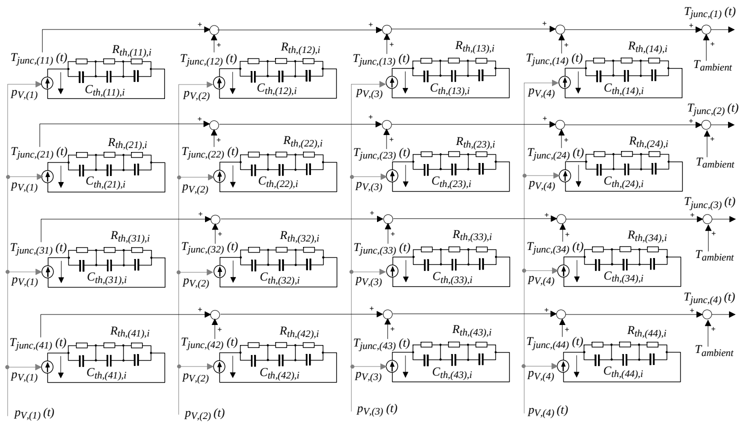
Thermal Model of Multi-Chip Power Modules (1)

What if the thermal impedance matrix is of high order?

Example:



- 3300V/1200A-Multi-Chip power module with 36 internal chips gives matrix order 36
- 36 transient 3D-FDM simulations to get 1296 thermal step responses?
- 36x36 = 1296 networks to be modeled and connected?
- If each network is 3-stage, the total node number will be 3888 → simulation effort of the circuit simulation might be increased by a factor $3888^3 \approx 59 \cdot 10^9$



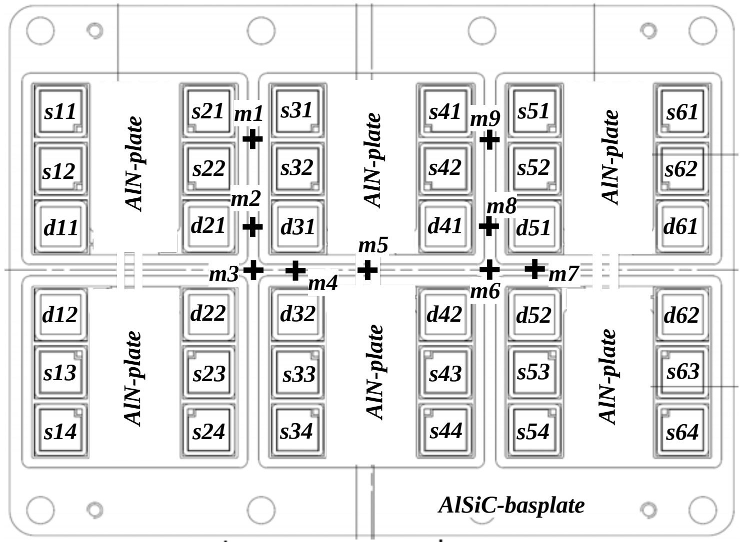
Thermal Model of Multi-Chip Power Modules (2)

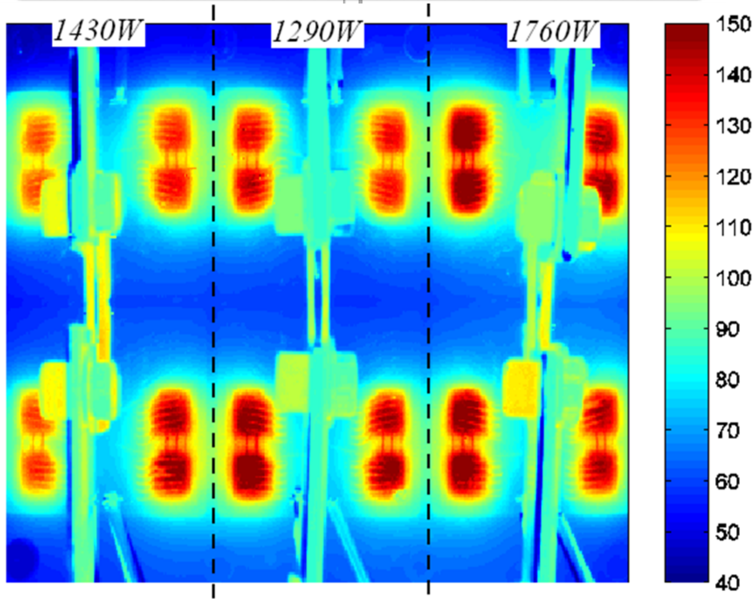
Pts.	T[°C]	pts.	T[°C]	pts.	T[°C]	pts.	T[°C]
s11	*114*	s21	*126*	s31	*128*	s41	*127*
s12	-	s22	*124*	s32	*129*	s42	*124*
d11	*64*	d21	*68*	d31	*66*	d41	*66*
d12	*63*	d22	*68*	d32	*66*	d42	*65*
s13	-	s23	*129*	s33	*129*	s43	*129*
s14	*122*	s24	*131*	s34	*134*	s44	*133*

Stationary temperatures measured via infrared

Pts.	T[°C]	pts.	T[°C]	pts.	T[°C]	pts.	T[°C]
s11	115	s21	122	s31	117	s41	120
s12	116	s22	124	s32	118	s42	121
d11	58	d21	66	d31	66	d41	69
d12	59	d22	66	d32	66	d42	69
s13	117	s23	124	s33	118	s43	121
s14	116	s24	123	s34	117	s44	120

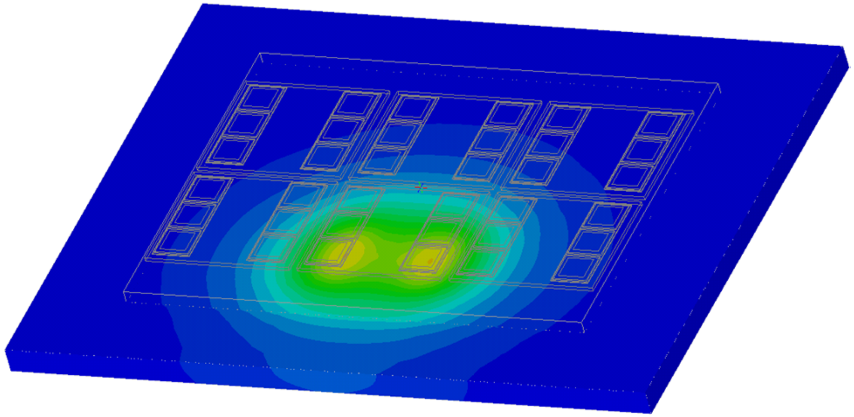
Stationary temperatures via 3D-FEM simulation

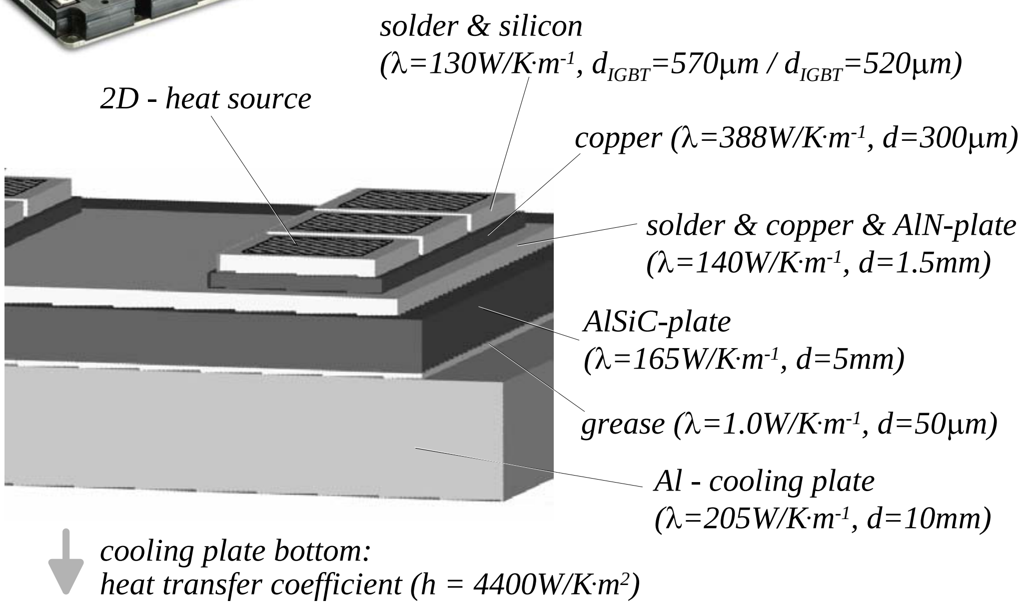




Thermal Model of Multi-Chip Power Modules (3)

3D-FEM model of the 36-chip power module

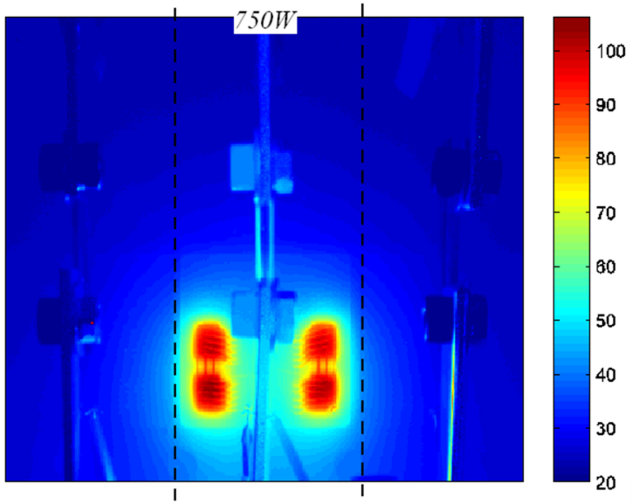




- Water-cooled heat sink modelled as plate with heat transfer coefficient *h* [K/Wm] as boundary condition
- Approximately 1.000.000 elements

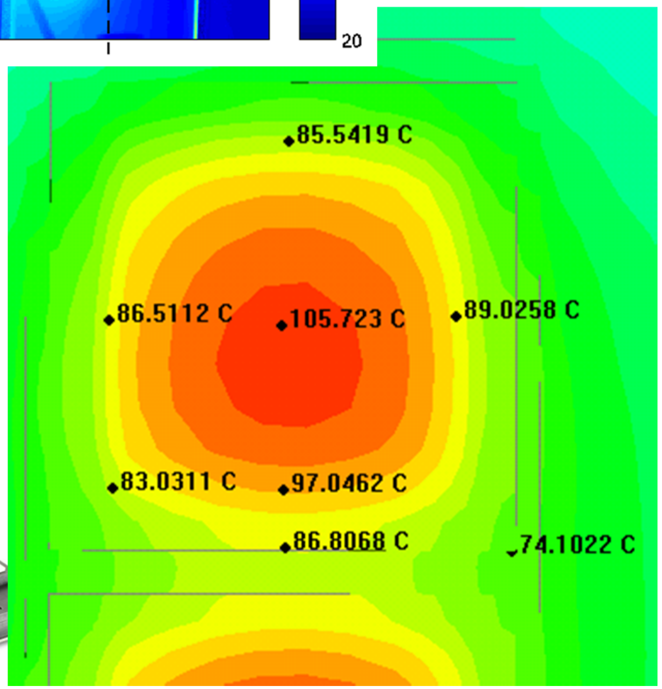
$$h = \left(\frac{\Delta T_{m5}}{P_{V,total}} \cdot A_{HS,AlSiC-plate} \right)^{-1} = \left(\frac{60-20}{4480} \cdot (0.186 \cdot 0.138) \right)^{-1} = 4400 \, \frac{K}{Wm}$$

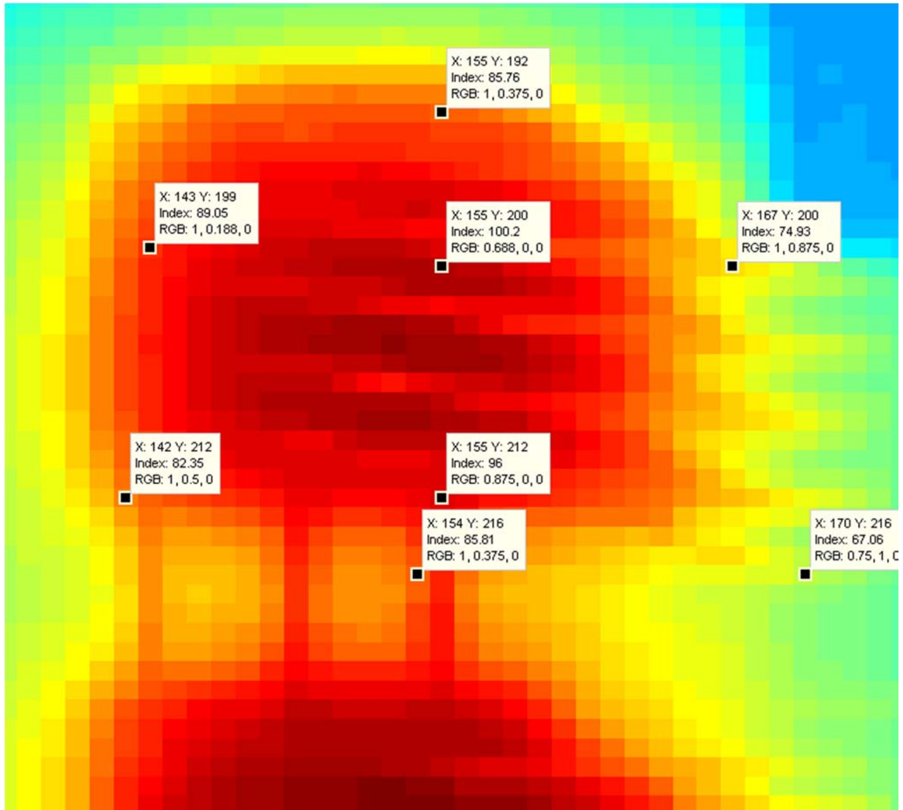
Thermal Model of Multi-Chip Power Modules (4)



3D-FEM model of the 36-chip power module

- Simple 2D-heat source as thermal semiconductor model gives high accuracy (temperature error ≈ 5%)





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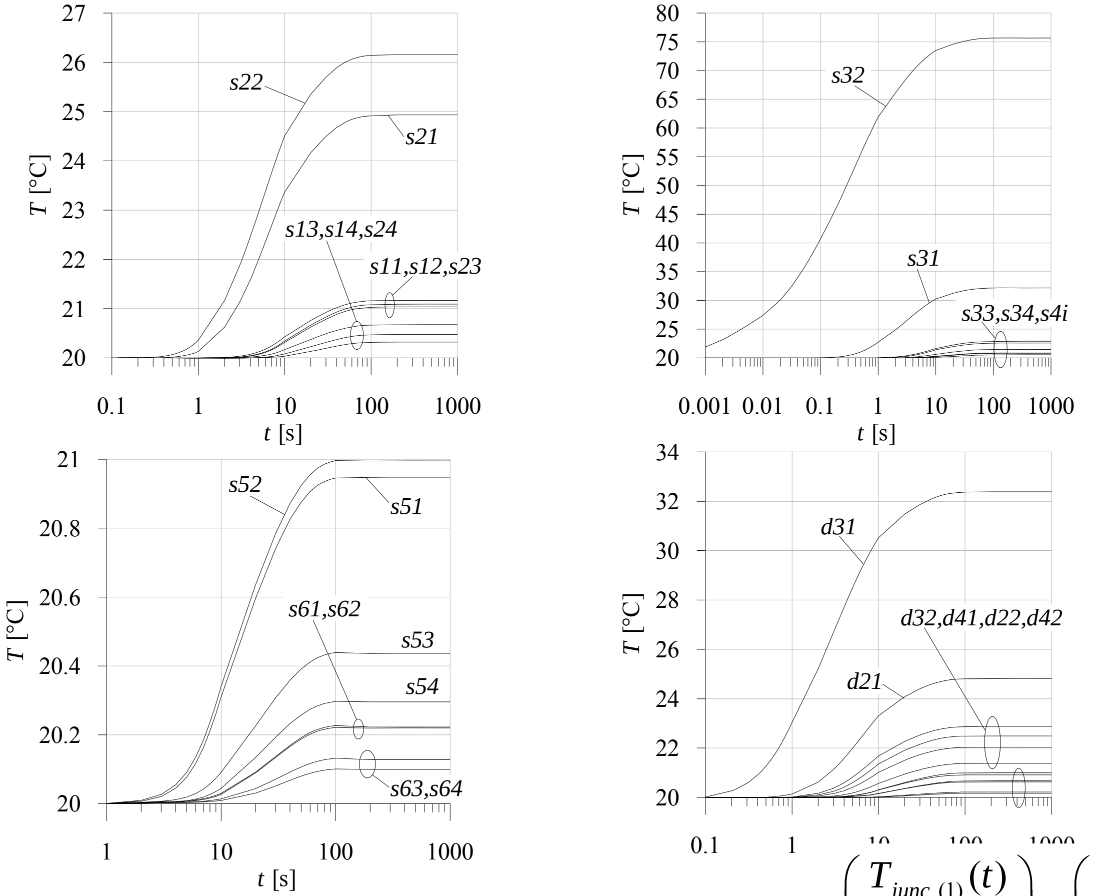
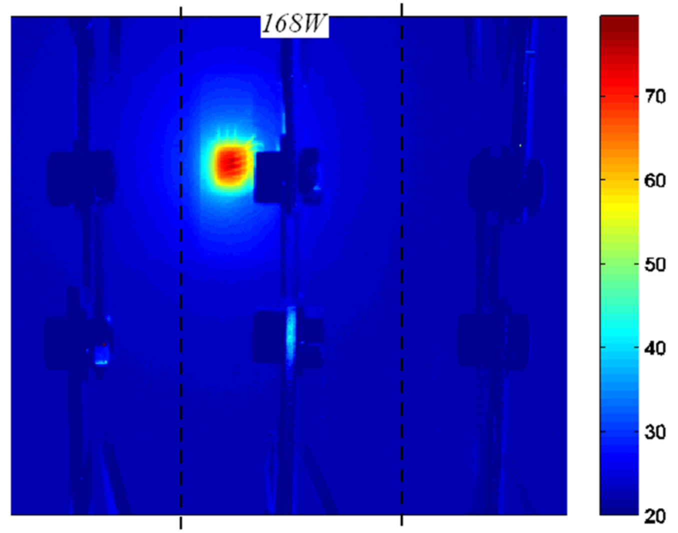
Thermal Model of Multi-Chip Power Modules (5)



3D-FEM simulation of the 36-chip power module → Thermal step responses



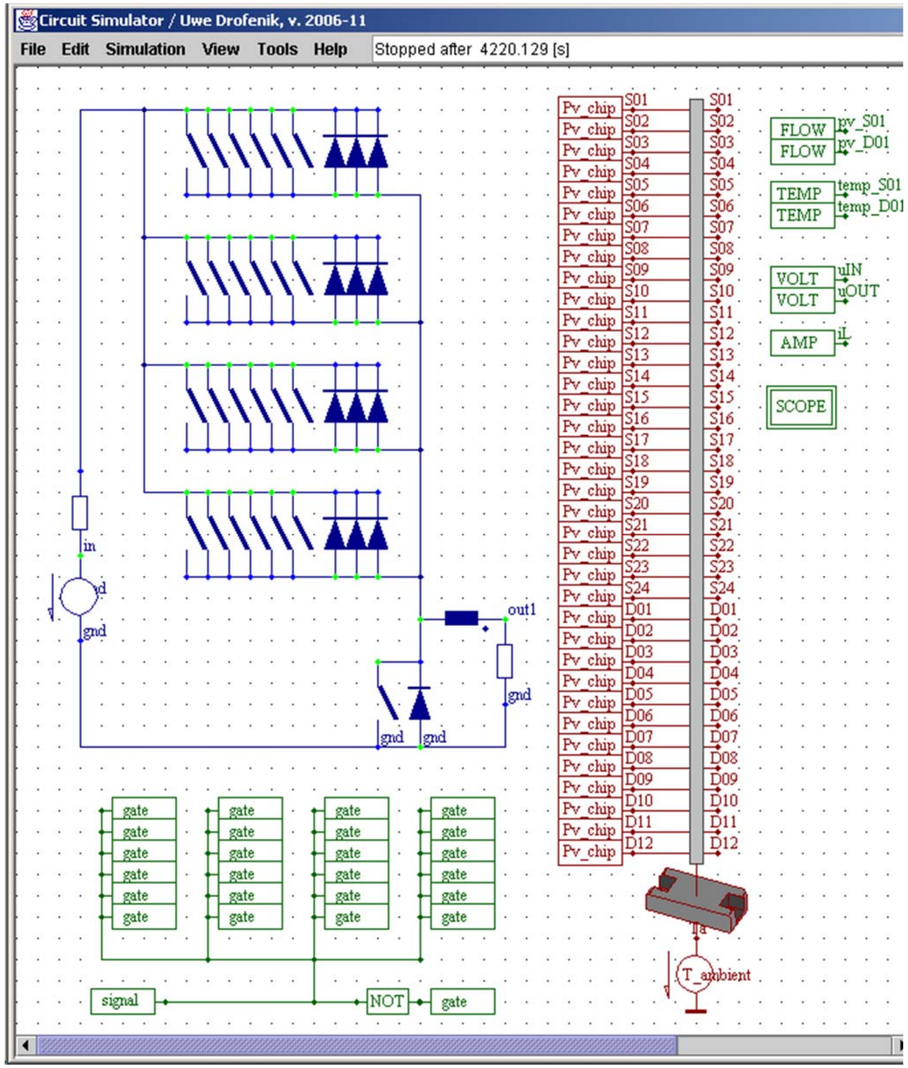
IGBT *s32* is heated by a thermal power of 168W giving transient temperatures at the centers of all 36 dies

$$
\begin{pmatrix} T_{junc,(1)}(t) \\ T_{junc,(2)}(t) \\ \vdots \\ T_{junc,(35)}(t) \\ T_{junc,(36)}(t) \end{pmatrix} = \begin{pmatrix} z_{1,1} & z_{1,2} & \cdots & z_{1,35} & z_{1,36} \\ z_{2,1} & z_{2,2} & \cdots & z_{2,35} & z_{2,36} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ z_{35,1} & z_{35,2} & \cdots & z_{35,35} & z_{35,36} \\ z_{36,1} & z_{36,2} & \cdots & z_{35,36} & z_{36,36} \end{pmatrix} \cdot \begin{pmatrix} p_{V,(1)}(t) \\ p_{V,(2)}(t) \\ \vdots \\ p_{V,(35)}(t) \\ p_{V,(36)}(t) \end{pmatrix} + T_{ambient}
$$

Thermal Model of Multi-Chip Power Modules (6)

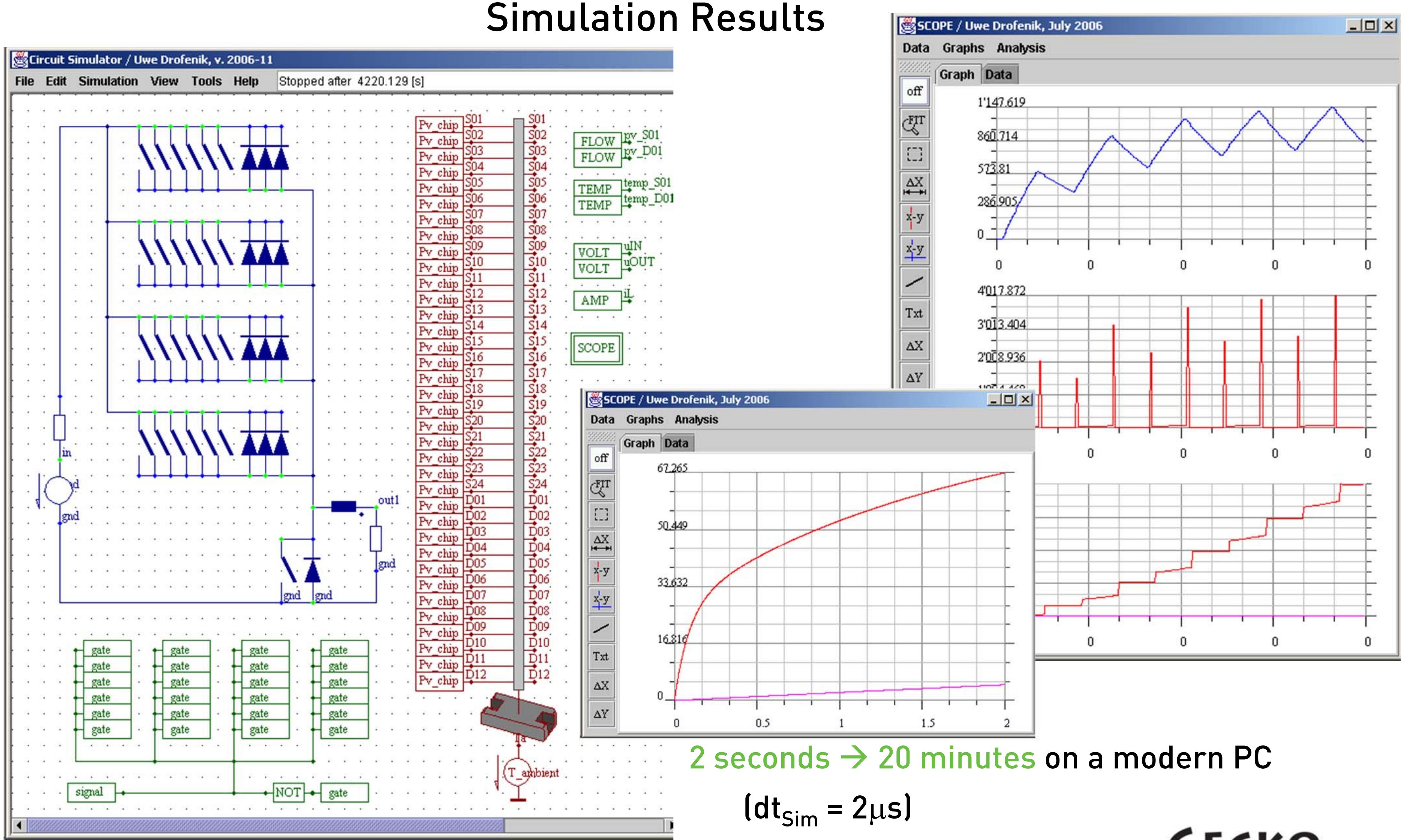
Software-Implementation of
transient thermal simulation

- Virtual Design Platform for Power Electronics PES / ETH Zurich
- Thermal Impedance Model automatically generated from 3D-Model of Power Module (3D-FEM)
- Temperature-dependent Conduction- and Switching Losses
- Losses available for thermal circuits



Thermal Model of Multi-Chip Power Modules (6)

Simulation Results



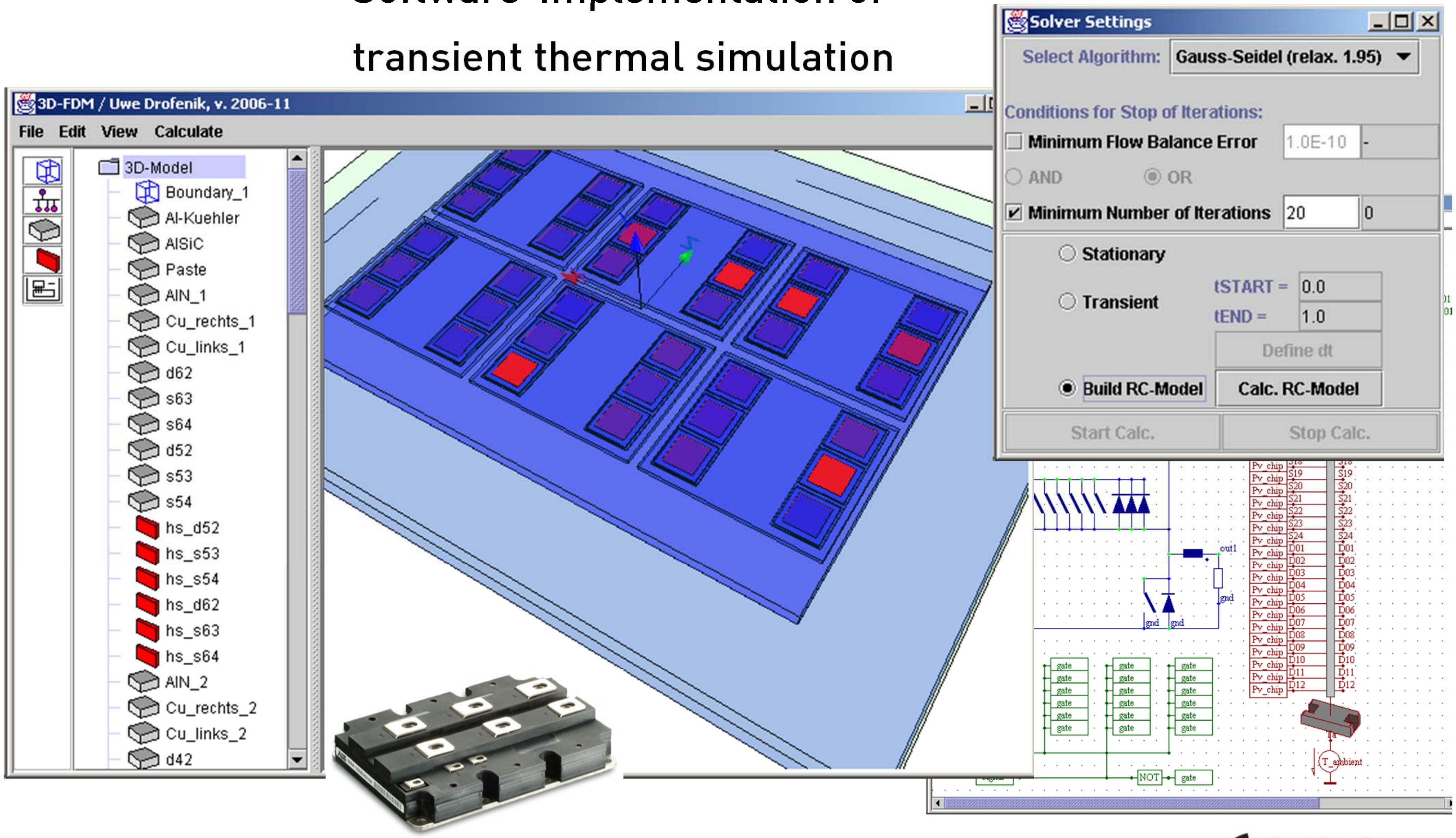
2 seconds → 20 minutes on a modern PC

($dt_{Sim} = 2\mu s$)

Thermal Model of Multi-Chip Power Modules (7)

Software-Implementation of

transient thermal simulation



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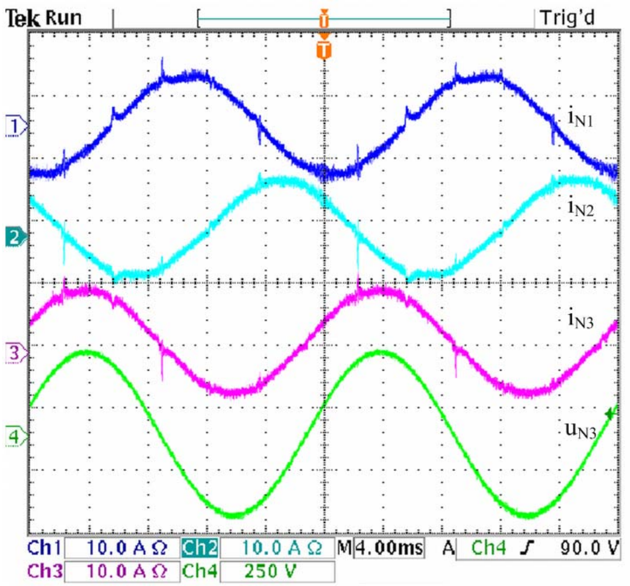
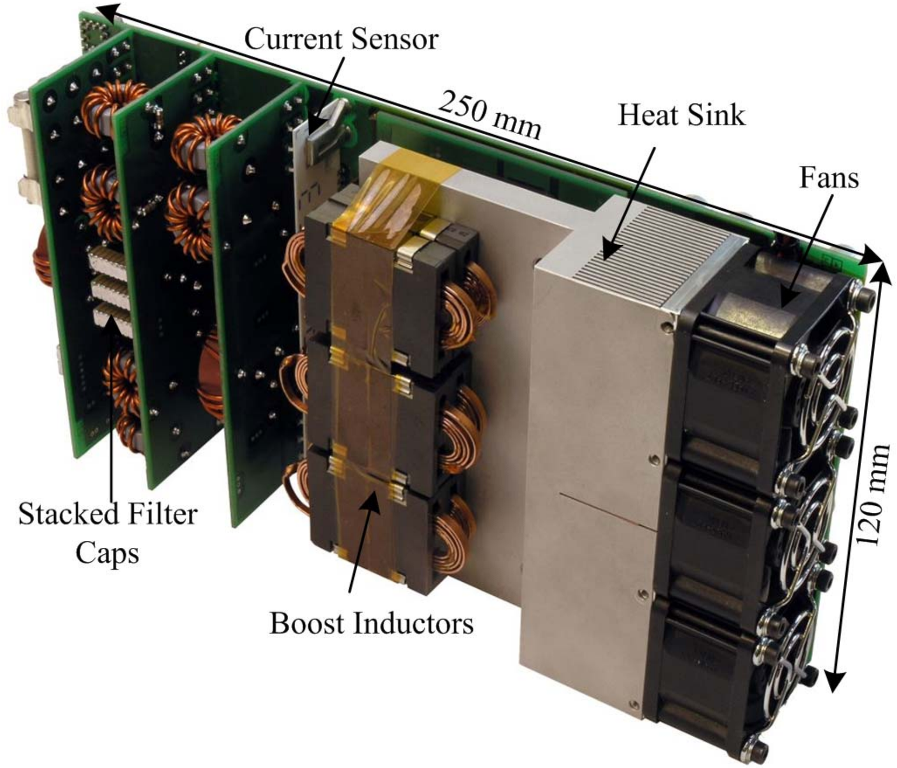
Air-Cooling for a 10kW/500 kHz Vienna Rectifier 1

- 10kW Rectifier with Power Density of 8.5kW/liter
- Power PCB, dedicated Ceramic Capacitor PCB, EMI filter on 3 daughter boards

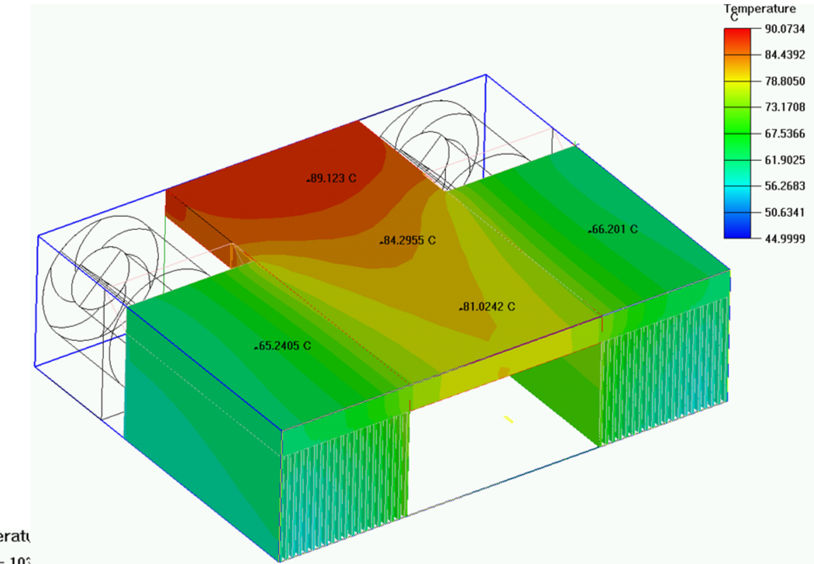




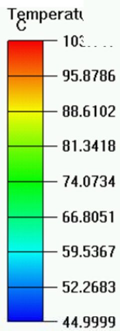
- U_{phase}=230V_{rms}, I_{phase}=5.8A_{rms}
- U_{out}=680V, P_{out}=4kW
- THD=4.75%

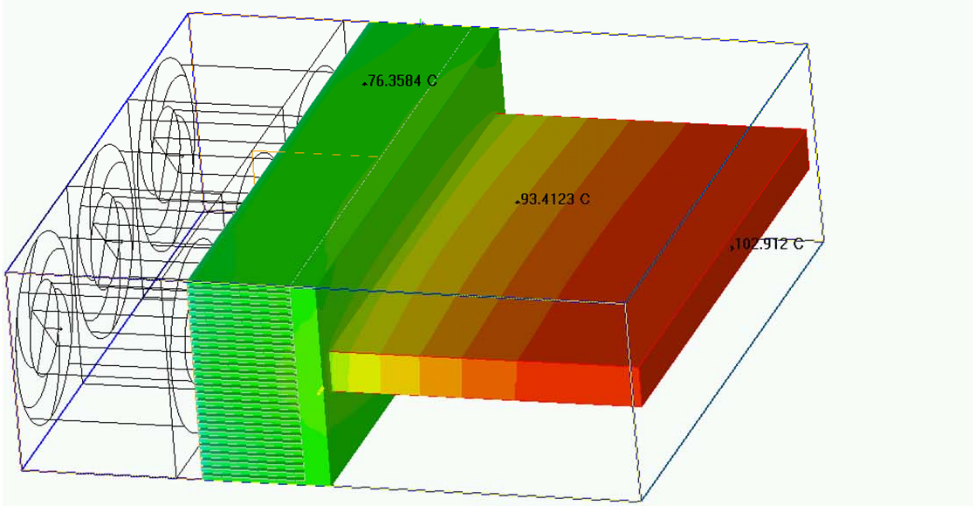
Air-Cooling for a 10kW/500 kHz Vienna Rectifier 1

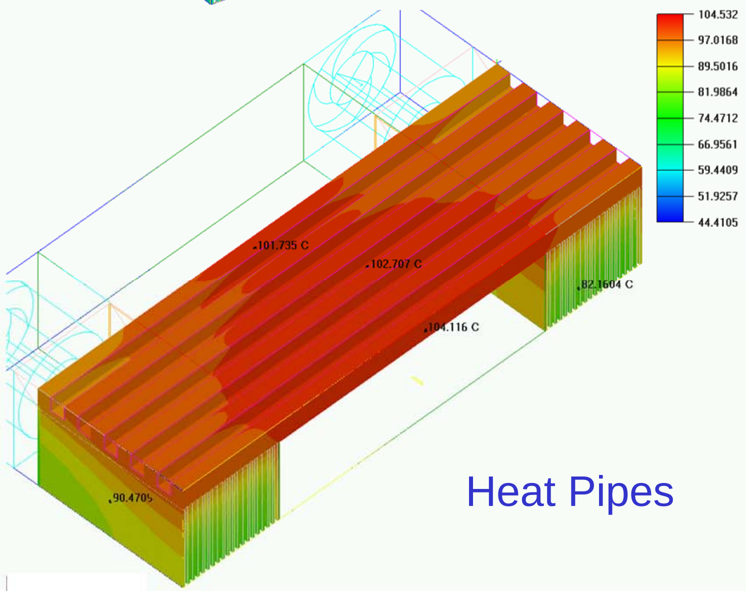
- Heat sink structures can be calculated **analytically!**
- Systematic optimization possible without 3D-CFD FEM



Thermal Design for 10kW 3ph Vienna Rectifier employing air-cooling / light-weight / 1U-heigth: **Calculate heat sink surface, avoid semiconductor model**



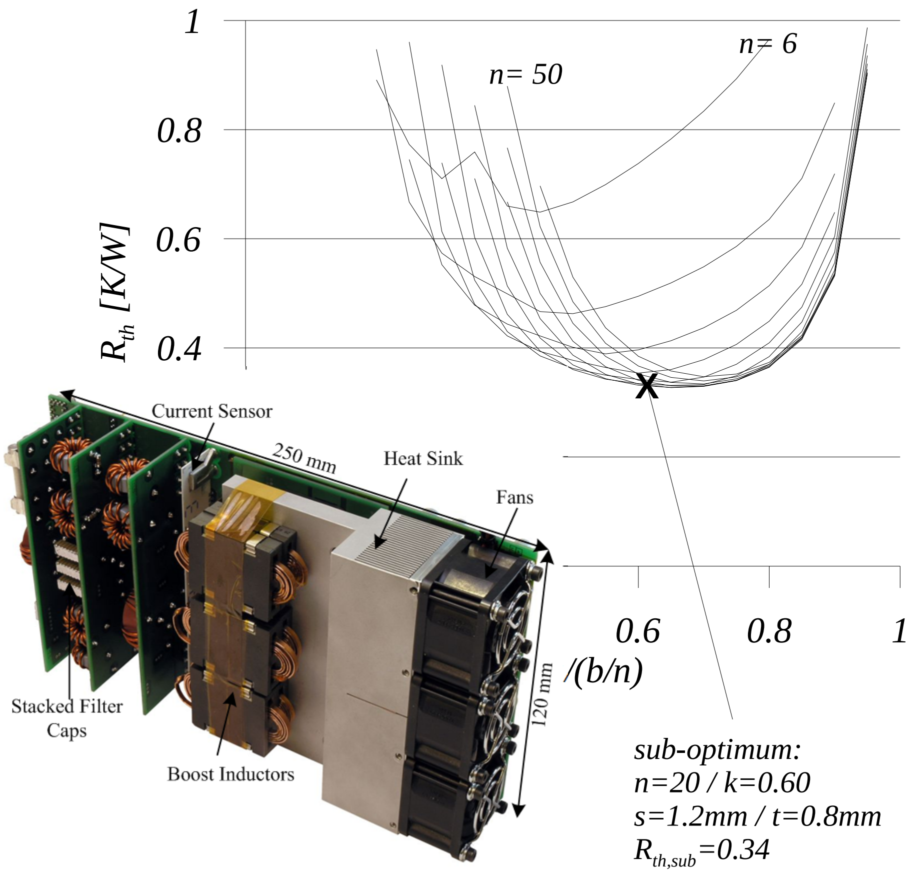




Air-Cooling for a 10kW/500 kHz Vienna Rectifier 1

SanAce 40x40x28/50dB
heat sink: L=60mm, b=c=40mm
Al** with λ_{th}= **210W/Km

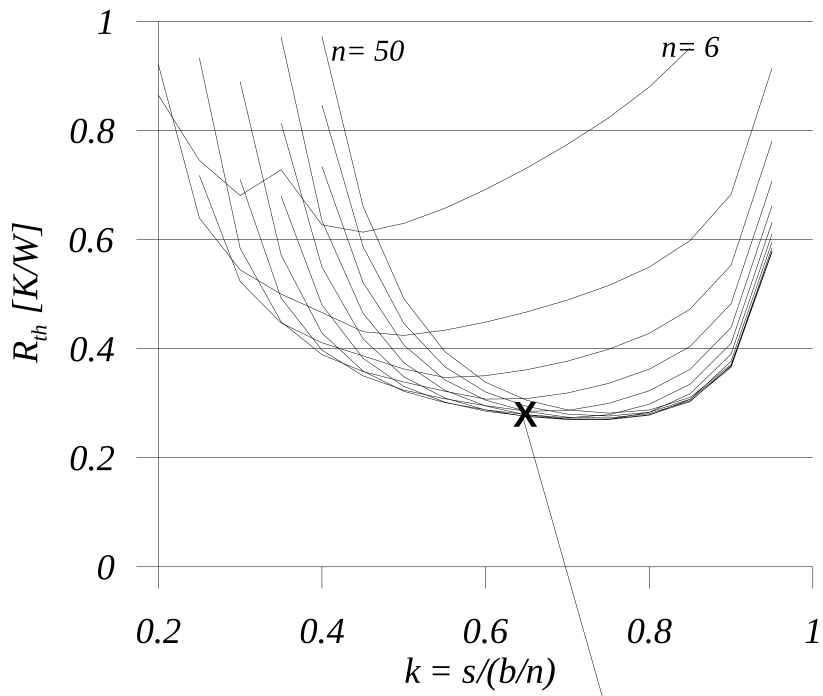
n = [6, 10, 14, ..., 42, 46, 50]



sub-optimum:
n=20 / k=0.60
s=1.2mm / t=0.8mm
$R_{th,sub}$=0.34

SanAce 40x40x28/50dB
heat sink: L=60mm, b=c=40mm
Cu** with λ_{th}= **380W/Km

n = [6, 10, 14, ..., 42, 46, 50]



sub-optimum:
n=20 / k=0.65
s=1.3mm / t=0.7mm
$R_{th,sub}$=0.30

Systematic optimization of the heat sink via **analytical equations**

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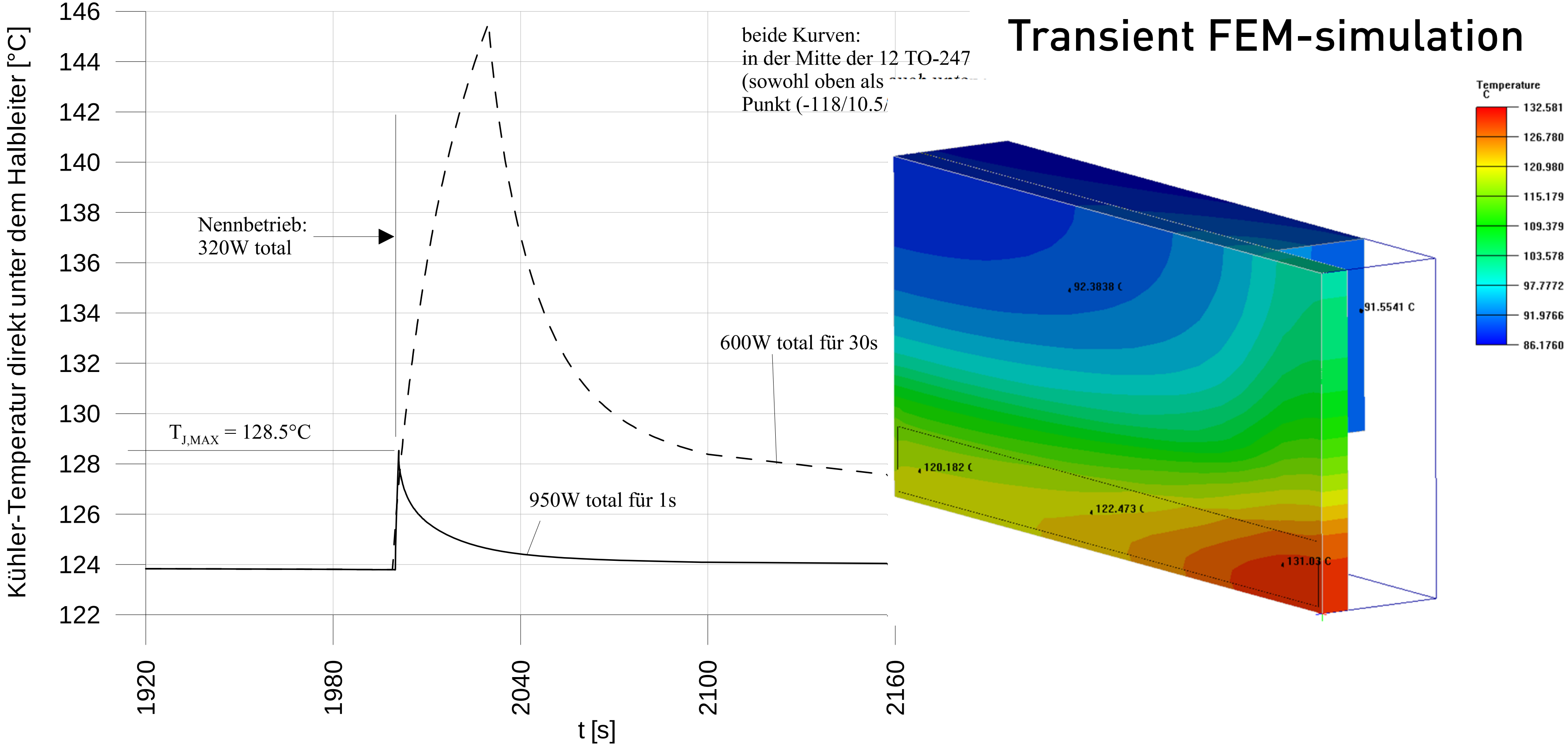
10kW/500 kHz Vienna Rectifier – Transient Overload



Losses at rated operating point: **320W total**

600W (180%) for 30s → +20°C at sink / 950W (300%) for 1s → +4°C at sink

→ $R_{th,JS\_TO\text{-}247} = R_{th,JC} + R_{th,Paste} = 0.7 + 0.15 = 0.85$

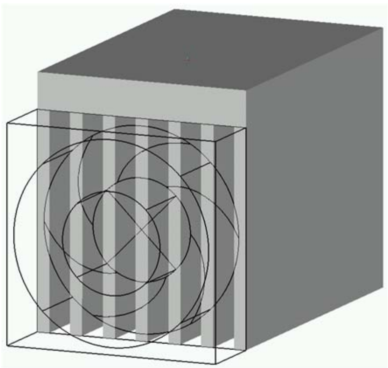
Worst Case: T_J = 155 +600/24*0.85 = 155 +21 = **176°C**

Thermal Modeling – Literature

- Drofenik, U., Cottet, D., Müsing, A., Meyer, J.-M., Kolar, J. W., "Modelling the Thermal Coupling between Internal Power Semiconductor Dies of a Water-Cooled 3300V/1200A HiPak IGBT Module", Proceedings of the International PCIM Europe 2007 Conference, Nuremberg, Germany, May 22 - 24, (2007).
- Drofenik, U., Cottet, D., Müsing, A., Meyer, J.-M., Kolar, J. W., "Computationally Efficient Integration of Complex Thermal Multi-Chip Power Module Models into Circuit Simulators", Proceedings of the 4th Power Conversion Conference (PCC'07), Nagoya, Japan, April 2 - 5, CD-ROM, ISBN: 1-4244-0844-X, (2007).
- Kolar, J. W., Drofenik, U., Biela, J., Heldwein, M. L., Ertl, H., Friedli, T., Round, S. D., "PWM Converter Power Density Barriers", Proceedings of the 4th Power Conversion Conference (PCC'07), Nagoya, Japan, April 2 - 5.
- Drofenik, U., Kolar, J.W., "A General Scheme for Calculating Switching- and Conduction-Losses of Power Semiconductors in Numerical Circuit Simulations of Power Electronic Systems", Proceedings of the 2005 International Power Electronics Conference (IPEC'05), Niigata, Japan, April 4 - 8, CD-ROM, ISBN: 4-88686-065-6 (2005).
- J. E. Ramos Torres, J. J. Connors, D. A. Murdock, R. D. Lorenz, "Active Thermal Tj and DTj Control and Thermal Modelling of Power Modules", Proceedings of the 2003 CPES Power Electronics Seminar, Blacksburg (VA), USA, April 27 - 29, pp. 113 – 119 (2003).
- S. D. Round, P. Karutz, M. L. Heldwein, J. W. Kolar, "Towards a 30 kW/liter, Three-Phase Unity Power Factor Rectifier", Proceedings of the 4th Power Conversion Conference (PCC'07), Nagoya, Japan, April 2 - 5, CD-ROM, ISBN: 1-4244-0844-X, (2007).
- P. Karutz, S. D. Round, M. L. Heldwein, J. W. Kolar, "Ultra Compact Three-phase PWM Rectifier", Proceedings of the 22nd IEEE Applied Power Electronics Conference, Anaheim (California), USA, Feb. 25 - March 1, Vol. 1, pp. 816 - 822 (2007).

Heat-Sink Modeling

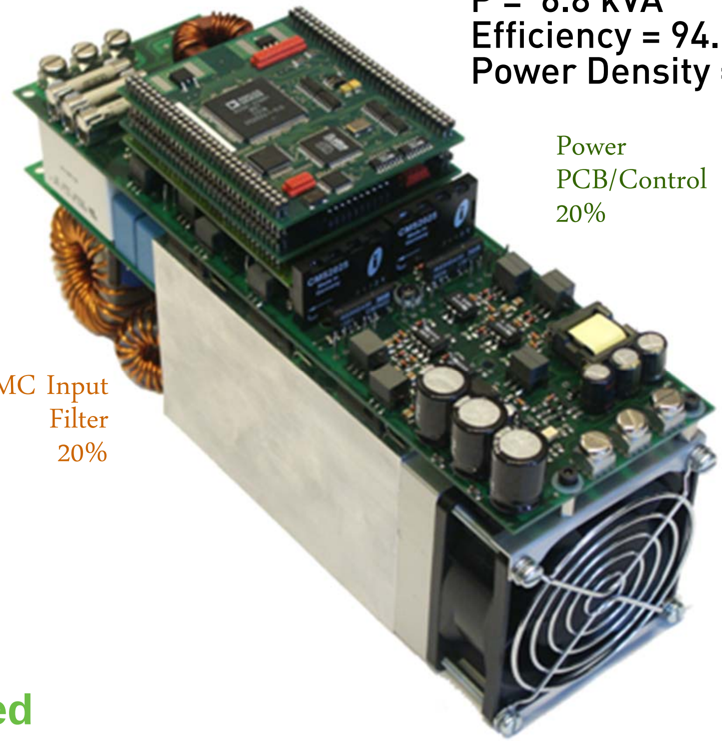
- Forced Air-Cooled Heat-Sinks
- Calculation of R_{th} based on
  - Geometry
  - Material Constants
  - Fan characteristics
- Optimal design, Cooling System Performance Index (CSPI)
- Manufacturing Limitations?
- A Practical Software Tool



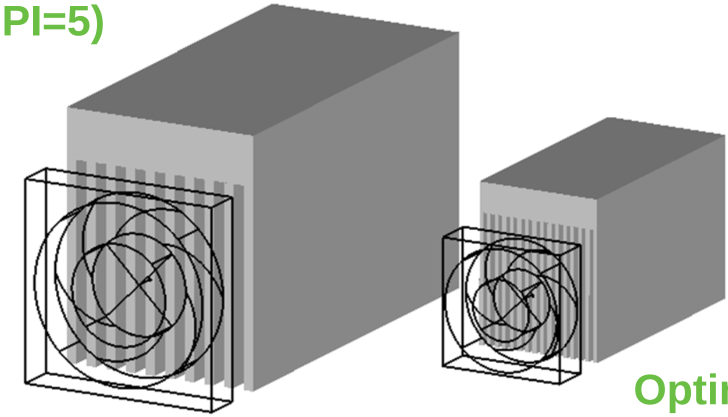
Motivation

- Increasing the converter power density [kW/dm^3]
- Where are the theoretical limits for the heat-sink performance (Rth)?
- What about manufacturing limitations?

Sparse Matrix Converter
P = 6.8 kVA
Efficiency = 94.5%
Power Density = 3kW/dm3



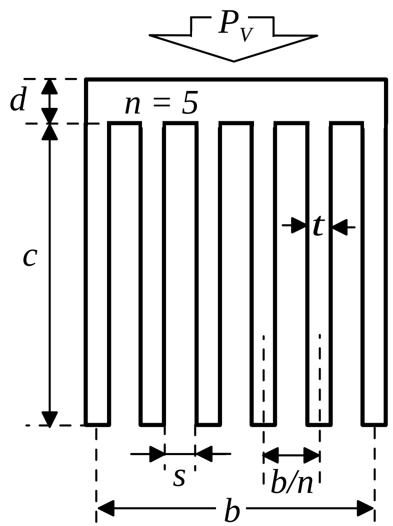
Typical (CSPI=5)

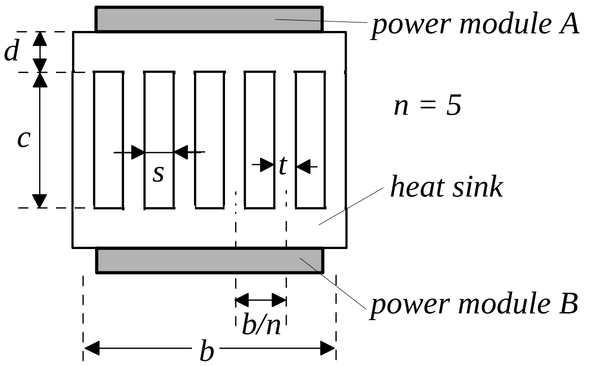


Optimized (CSPI=20)

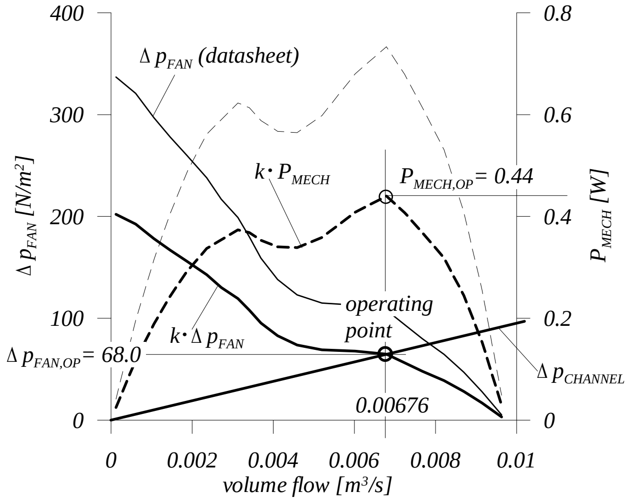
Heat-Sink Parameters to consider

- Geometry:
  - Number of Fins (n+1)
  - Length/Width (b,c)
  - Baseplate thickness d
  - Fin spacing
  - One-sided/two-sided





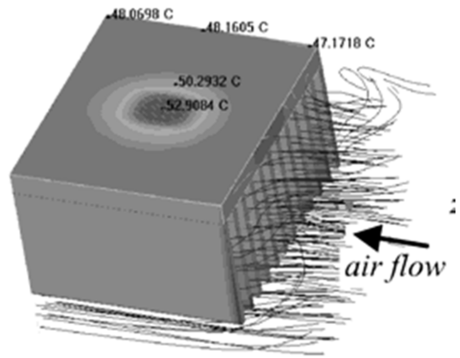
- Fan characteristics
  - Input/Output power
  - Volume flow / pressure drop curve



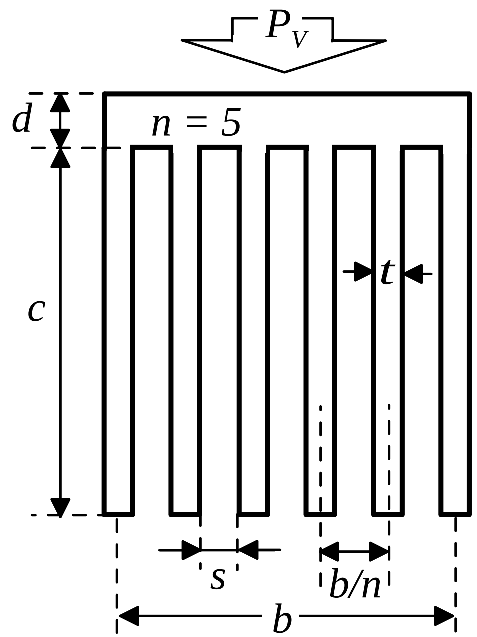
- Material: Copper and Aluminum

Material	Thermal Conduct. [W/mK]	In-plane CTE [ppm/K]	Specific weight [kg/m³]
Aluminum	210 (isotr.)	23	2700
Copper	380 (isotr.)	17	8930
Diamond	2200 (isotr.)	2	3500

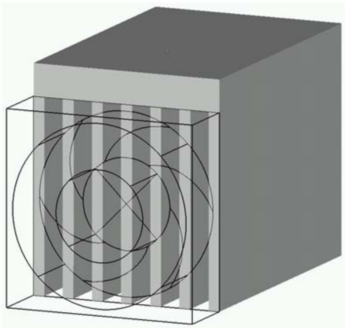
Changing Heatsink Parameters - Optimization

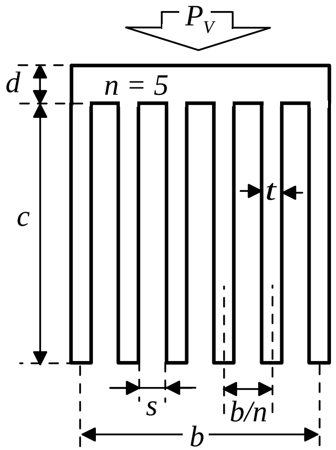


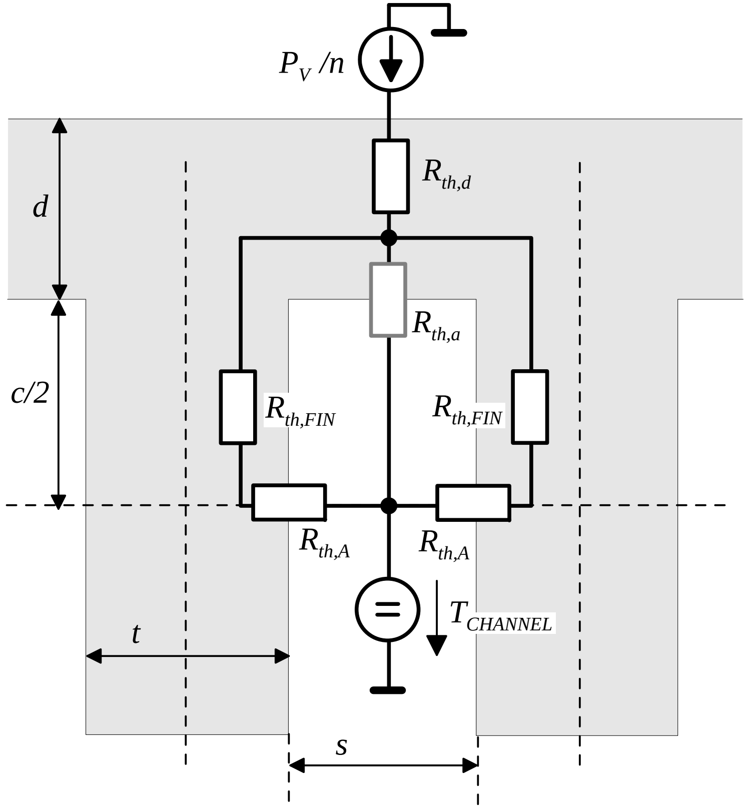
- Heatsink baseplate thickness (b)
  - Heat-spreader to avoid hot spots
  - larger *b* increases thermal resistance
- Fin length *L*
  - Increasing L → lower R_{th}
  - *L* too large: Fan pressure drop not optimal
- Fin spacing ratio k = s * n / b
  - k → 1: no air flow possible (pressure drop)
  - k → 0: fins too thin, no heat conduction
  - n larger: total surface increases
  - k + Fan determines operation point
- Material with better thermal conductivity



A Heatsink Model (1)







$$R_{th,A} = \frac{1}{h \cdot L \cdot c}$$

$$R_{th,d} = \frac{d}{\frac{1}{n} A_{HS} \lambda_{HS}}$$

$$R_{th,FIN} = \frac{\frac{1}{2} c}{\frac{1}{2} t \cdot L \cdot \lambda_{HS}}$$

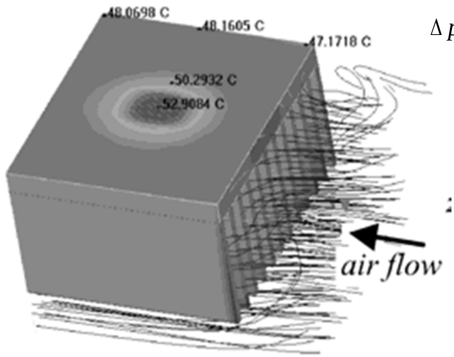
$$R_{th,S-a}^{(HS)} = \tfrac{1}{n}\left(R_{th,d} + \tfrac{1}{2}\left(R_{th,FIN} + R_{th,A}\right)\right) + \frac{0.5}{\rho_{AIR}\, c_{P,AIR}\, V}$$

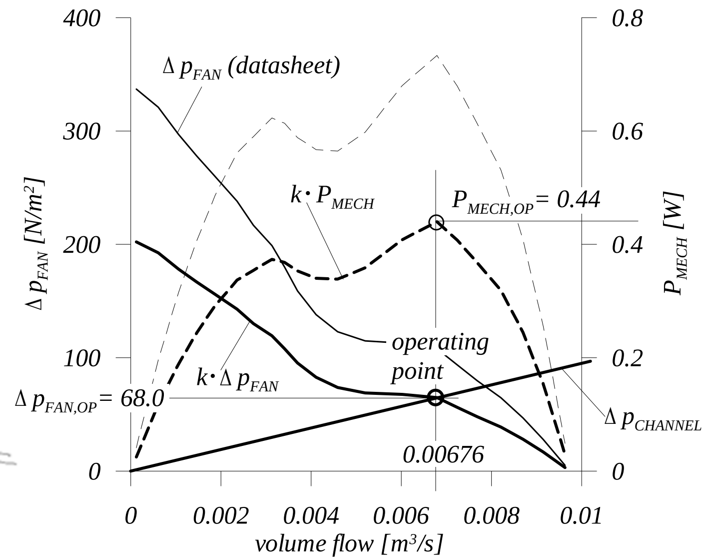
A Heatsink Model (2): Air-Flow

- Air-Flow equations: distinguish between laminar and turbulent flow (Reynolds number)
- Empirical equations: calculation of the air pressure drop in the fin channel

$$\Delta p_{lam}(V) = \frac{48\,\rho_{AIR}\,\nu_{AIR}\,L}{n\,(s\cdot c)\,d_h^2}\;V$$

$$\Delta p_{turb}(V) = \frac{L\,\frac{s+c}{2s\cdot c}\,\rho_{AIR}\,\frac{1}{2}\left(\frac{V}{n\,(s\cdot c)}\right)^2}{\left(0.79\cdot\ln\left(\frac{2V}{n\,(s+c)\,\nu_{AIR}}\right)-1.64\right)^2}$$



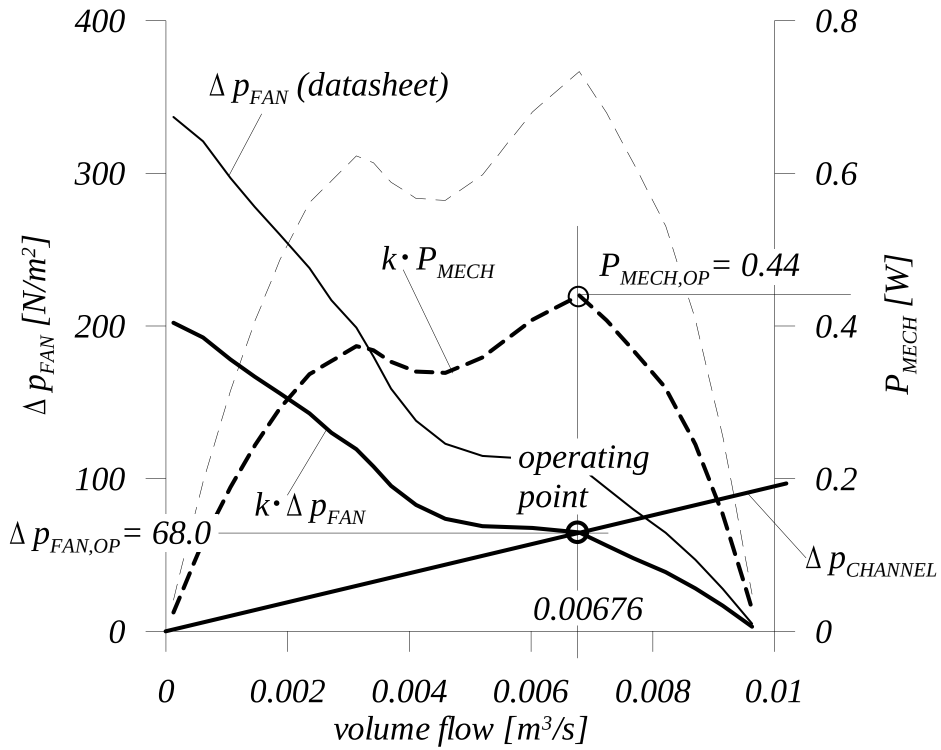


$$k\cdot\Delta p_{FAN}\,(V) = \Delta p_{lam}(V_{lam}) \;\rightarrow V_{lam} \;\rightarrow Re_{m,lam} < 2300\;?$$

$$Re_m = \frac{2V}{n\,(s+c)\,\nu_{AIR}}$$

A Heatsink Model (3): Fan Characteristics

- Fan Datasheet:
  pressure-drop / volume flow
- Dependent on fin spacing ratio
  k = (s n) / b
- Operating point: intersection of channel pressure drop curve and fan pressure drop characteristics
- Operating point typically close to the maximum of air flow mechanical power curve
- Empirical equations for turbulent flow channel pressure drop:

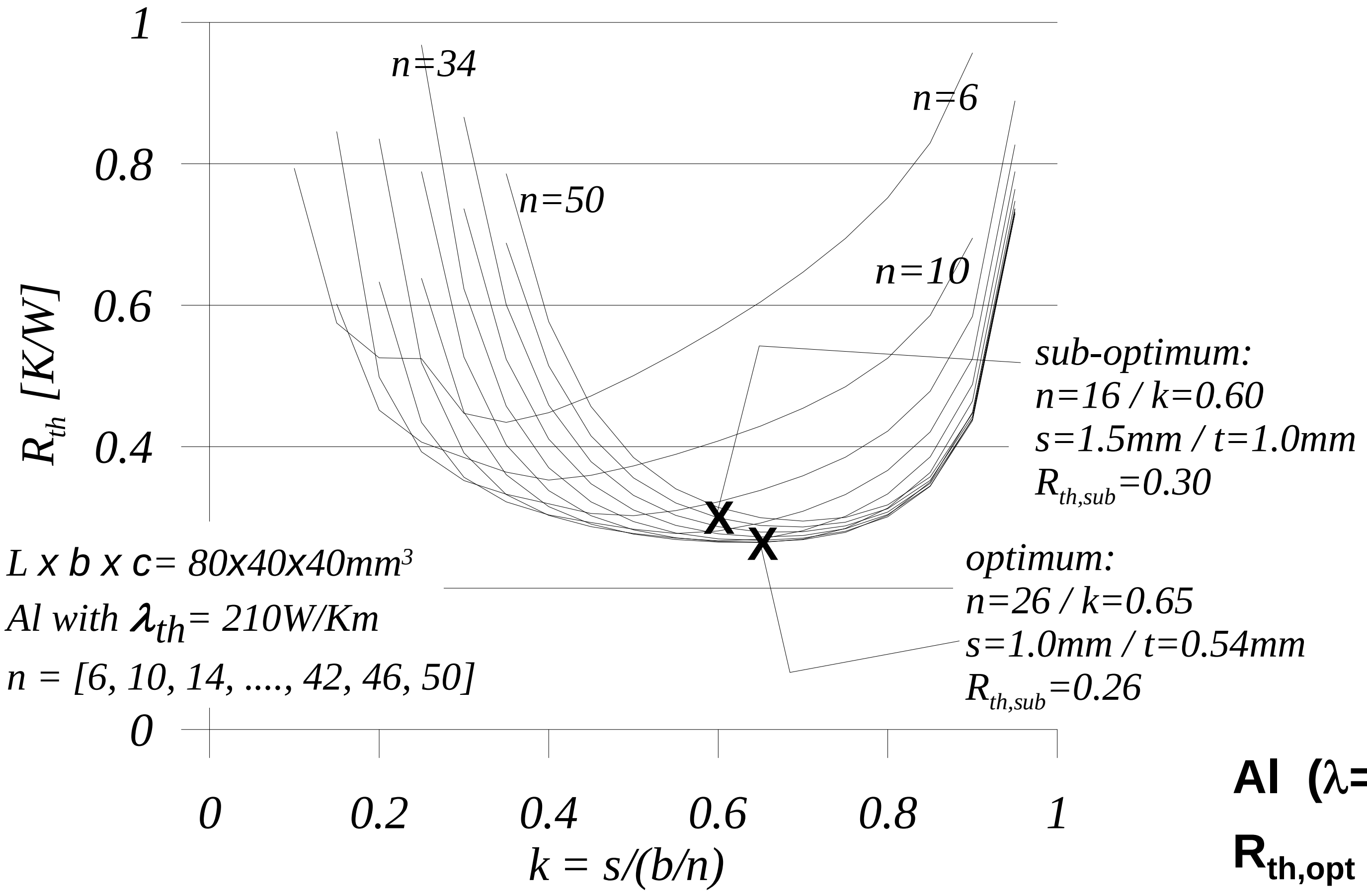


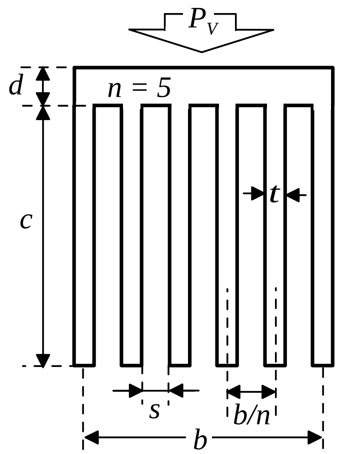
$$\Delta p_{turb}(V) = \frac{L\,\frac{s+c}{2s\cdot c}\,\rho_{AIR}\,\frac{1}{2}\left(\frac{V}{n(s\cdot c)}\right)^2}{\left(0.79\cdot\ln\left(\frac{2V}{n\,(s+c)\nu_{AIR}}\right)-1.64\right)^2}$$

$$h = \frac{Nu_m\cdot\lambda_{AIR}}{d_h}$$

$$Nu_{m,turb} = \frac{\{8\cdot(0.79\cdot\ln(Re_m)-1.64)^2)\}^{-1}\,(Re_m-1000)\;Pr}{1+12.7\sqrt{\{8\cdot(0.79\cdot\ln(Re_m)-1.64)^2)\}^{-1}}\;(Pr^{2/3}-1)}\cdot\left(1+\left(\frac{d_h}{L}\right)^{2/3}\right)$$

Example: Aluminum-Heatsink

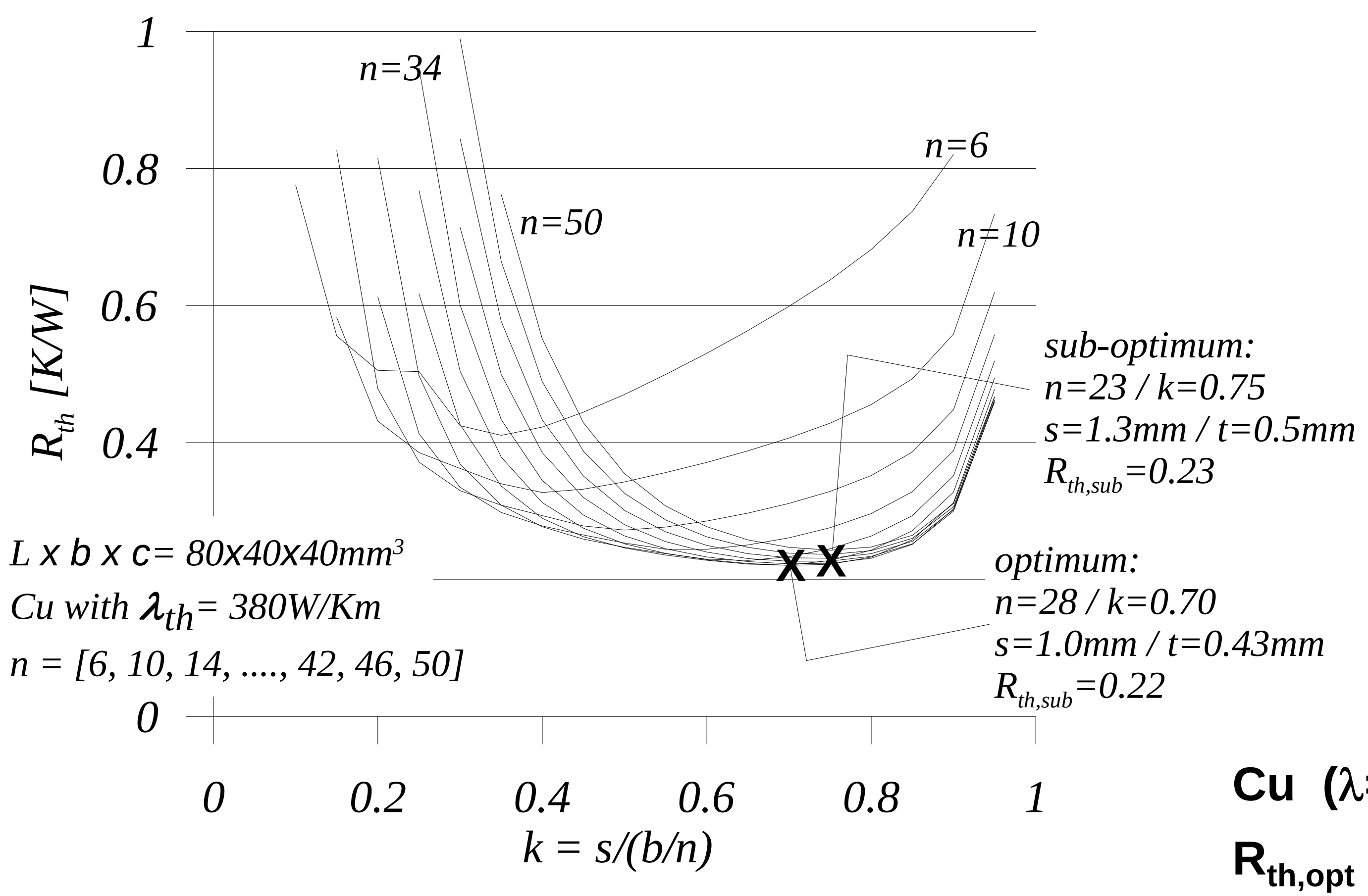


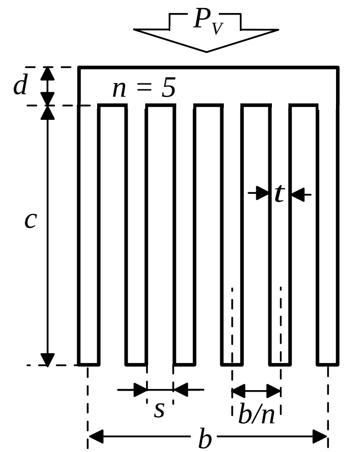


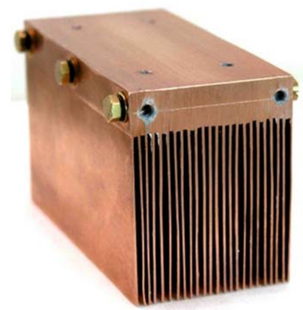
Al (λ=210W/Km)

$R_{th,opt}$ = 0.26K/W

Example: Copper-Heatsink



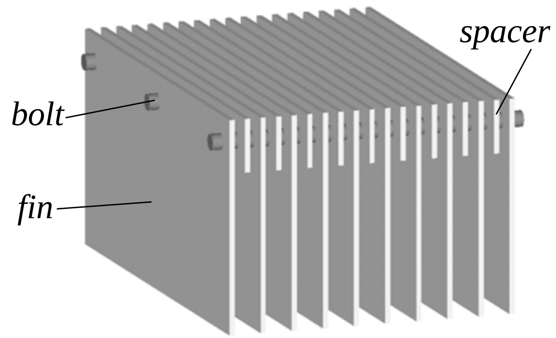




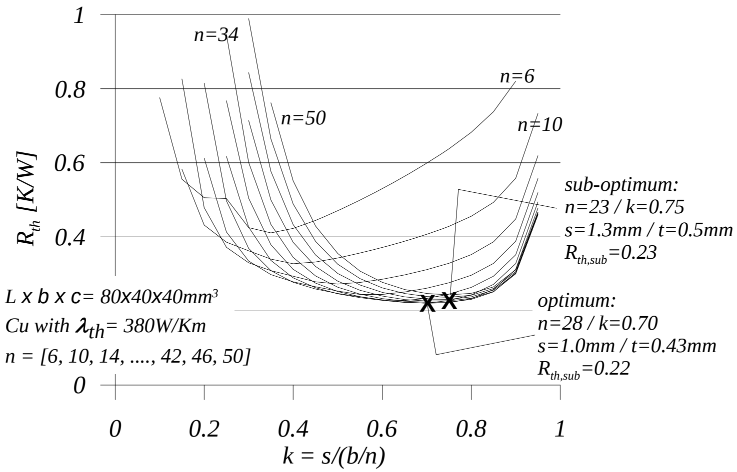
Cu (λ=380W/Km)

$R_{th,opt}$ = 0.22K/W

Practical Considerations



- Material cost: Copper (10\$/kg), Aluminum(2.5\$/kg)
- Weight: Copper (8.9 g/cm^3) Aluminum (2.7 g/cm^3)
- Manufacturing procedure and costs
- Availability of different thickness metal plates
- Consider sub-optimum design
- Example:



Fan: SanAce 40x40x28mm/50dB, b=c=40mm,
Heatsink: L=80mm, A_{CHIP}= 32cm^2, Vol_{CS} = 0.22dm^3

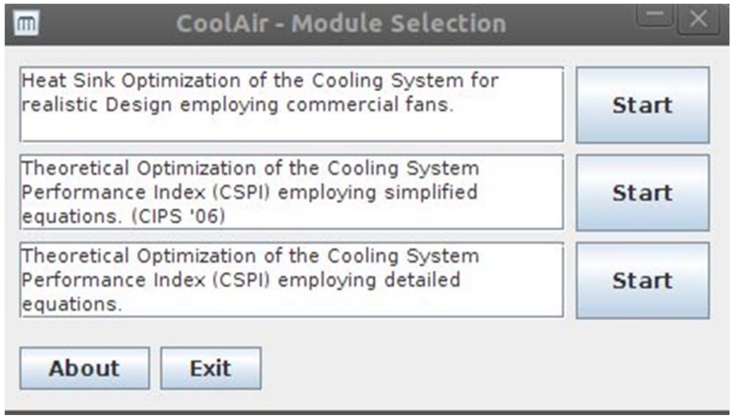
Al with n=16, s=1.5mm, t=1.0mm $R_{th,exp}$= 0.260 ($R_{th,theory}$ = 0.254)

Cu with n=23, s=1.3mm, t=0.5mm $R_{th,exp}$= 0.22 ($R_{th,theory}$ = 0.240)

«CoolAir» - a Heatsink Design Software Tool

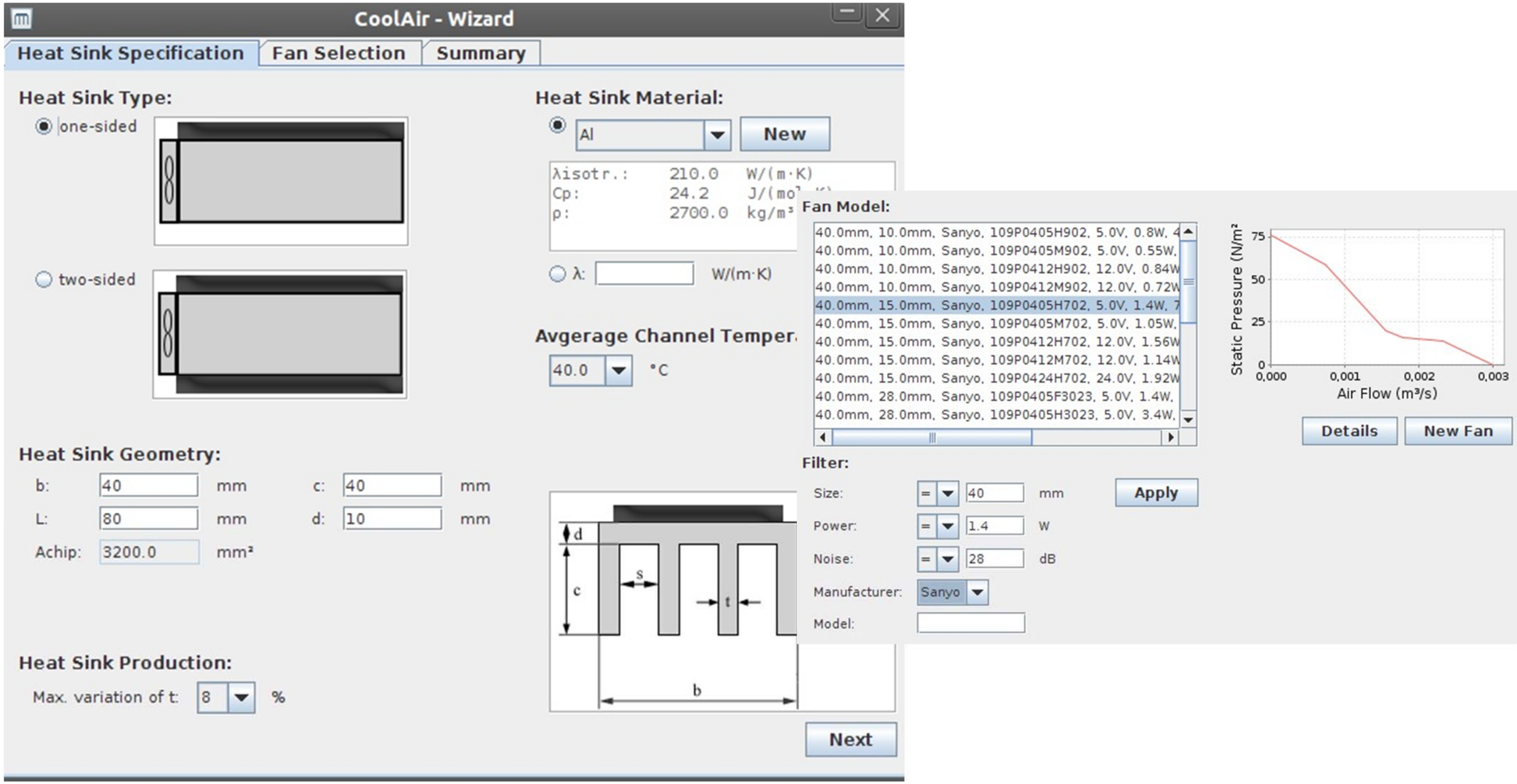
You can find the tool at the Minicourse CD-Rom

- All previously discussed equations implemented in a software tool
- Very easy to use, Wizard-based specification of heatsink geometry, materials, Fan, etc.
- Calculation of equivalent thermal resistance R_{th}
- Optimization of heatsink parameters (number of fins, channel-width, ...)
- Practial considerations included: Fan database, Material database



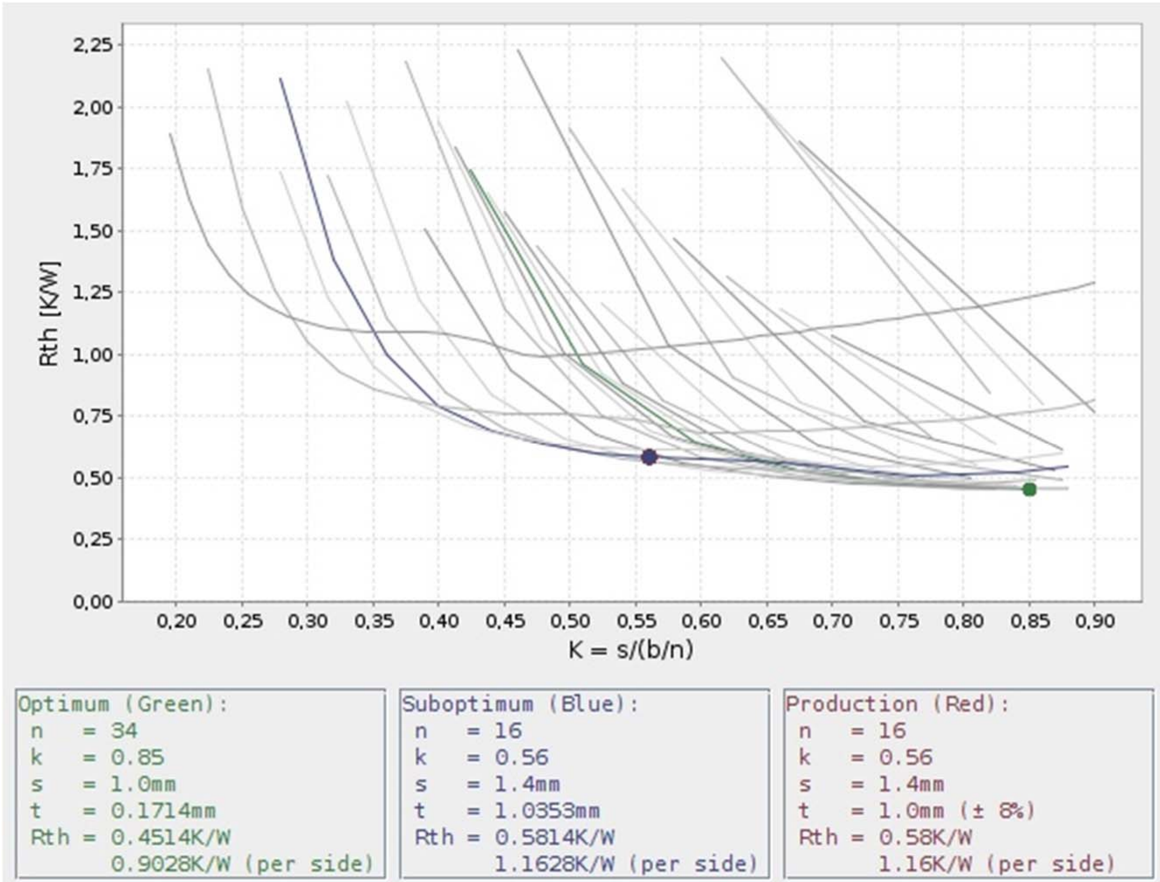
GECKO RESEARCH

«CoolAir» - Design Wizard



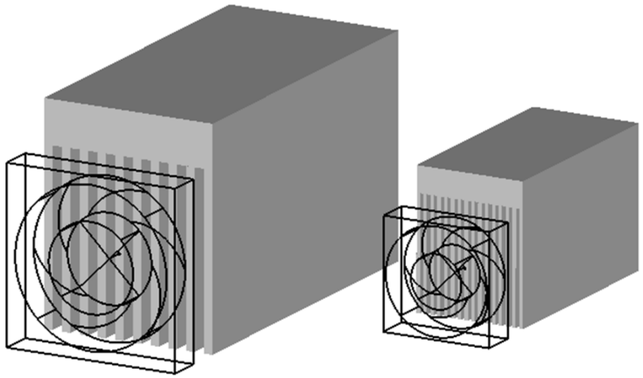
«CoolAir» - Optimization Results

- Fast and easy calculation of R_{th}
- Optimization of fin geometry
- Easy selection/characterization of sub-optimum designs



Heatsink design: Summary

- Set of empirical equations describes forced air-cooled heatsinks quite accurate
- Gecko-Research offers a practical software tool for the design of custom heatsinks
- Optimization might reduce volume by factor of 4 or more (theoretical minimum)
- Optimum-Design often diffcult to manufacture
  → Sub-Optimum design might be sufficient



Heatsink Modeling Modeling – Literature

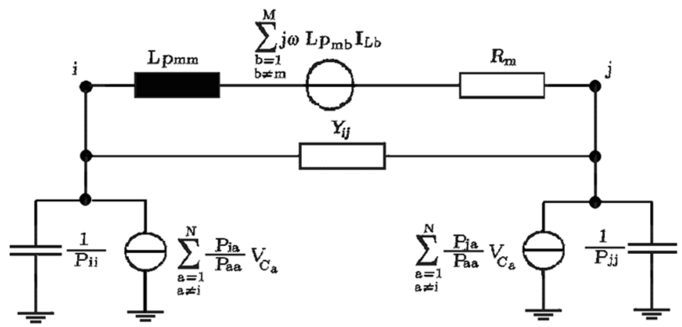
- Drofenik, U. Kolar, J.W., "Analyzing the Theoretical Limits of Forced Air-Cooling by Employing Advanced Composite Materials with Thermal Conductivities > 400W/mK", Proceedings of the 4th International Conference on Integrated Power Systems (CIPS'06), Naples , Italy, June 7 - 9, pp. 323 - 328, (2006).
- Drofenik, U., Kolar, J. W., "A Thermal Model of a Forced-Cooled Heat Sink for Transient Temperature Calculations Employing a Circuit Simulator", IEEJ Transactions of the Institute of Electrical Engineers of Japan, Volume 126-D, Number 7, July 2006, pp. 841 - 851
- Drofenik, U., Laimer, G., Kolar, J. W., "Theoretical Converter Power Density Limits for Forced Convection Cooling", Proceedings of the International PCIM Europe 2005 Conference, Nuremberg, Germany, June 7 - 9, pp. 608 - 619 (2005).
- Drofenik, U, Kolar, J.W., "Sub-Optimum Design of a Forced Air Cooled Heat Sink For Simple Manufacturing, Proceedings of the 4th Power Conversion Conference (PCC'07), Nagoya, Japan, April 2 – 5 (2007).
- Holahan, M.F., "Fins, Fans, and Form: Volumetric Limits to Air-Side Heatsink Performance", IEEE Trans. on Components and Packaging Technologies, vol. 28, Issue 2, June 2005, pp. 255-262.

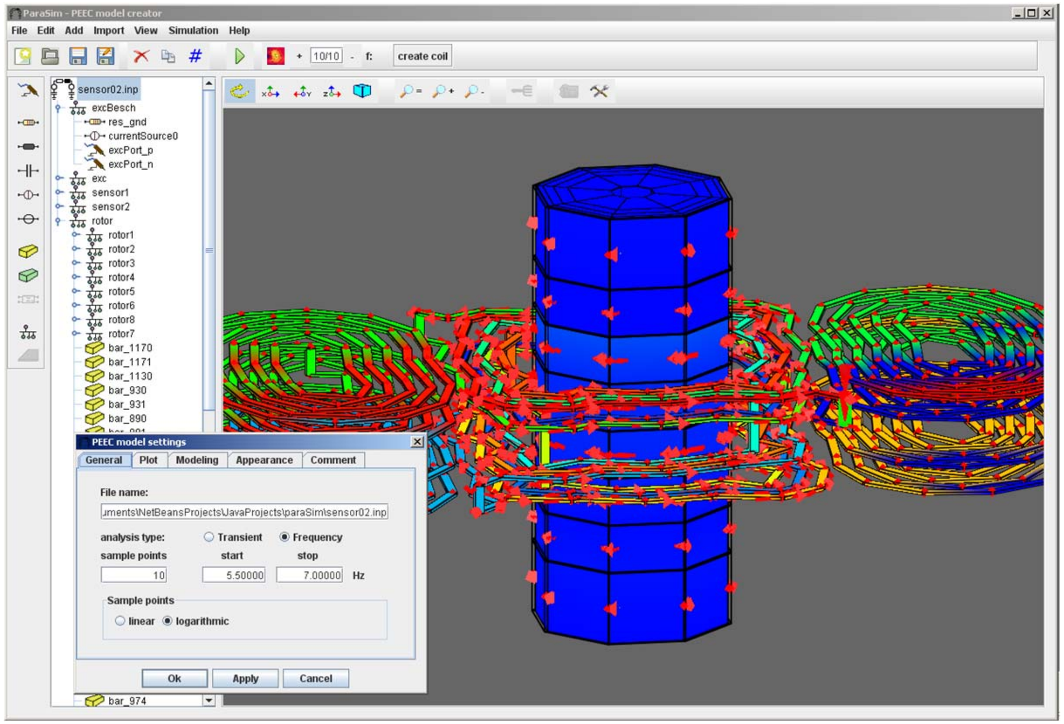
Electromagnetics Simulation using the PEEC Method

GeckoEMC

GeckoEMC – Partial Equivalent Element Circuit Method

- Electromagnetics of Layout (PCB, Busbars, IGBT modules represented as huge circuit: resistances, (mutual) inductances, capacitances
- Very intuitive approach for EE
- Fast, robust, easy-to-use





$$\begin{pmatrix} \mathbf{P}^{-1}\frac{d}{dt}+\mathbf{Y} & -\mathbf{A}^T \\ -\mathbf{A} & -(\mathbf{R}+\mathbf{L}\frac{d}{dt}) \end{pmatrix} \begin{pmatrix} I \\ V \end{pmatrix} = \begin{pmatrix} I_S \\ V_S \end{pmatrix}$$

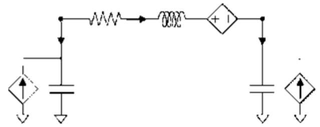
Modified Nodal Analysis (MNA) formulation of EM problem

GeckoEMC – Comparison to Finite Element (FEM)

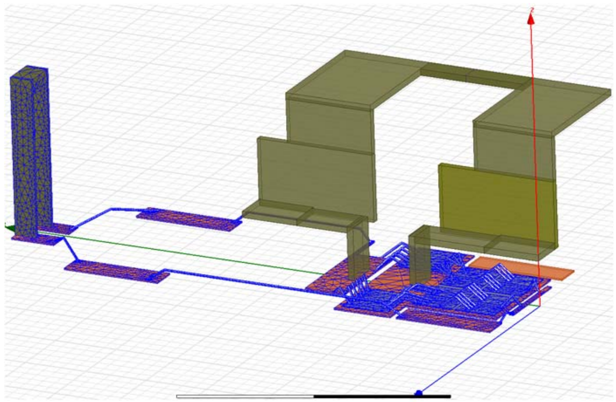
FEM, FDM

- Easy material modeling (μ, ε)
- Fine tetrahedral mesh required
- «Vacuum meshing» (huge matrices)
- Boundary conditions required
- Connection to circuit solver?

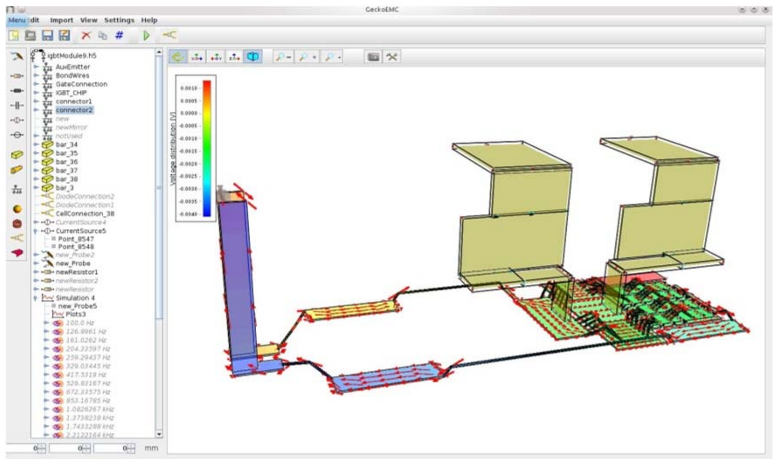
PEEC



- Circuit representation of EM
- Coarse mesh possible (dependent only on skin-depth)
- FD and TD simulation
- «Natural» connection to circuit solver



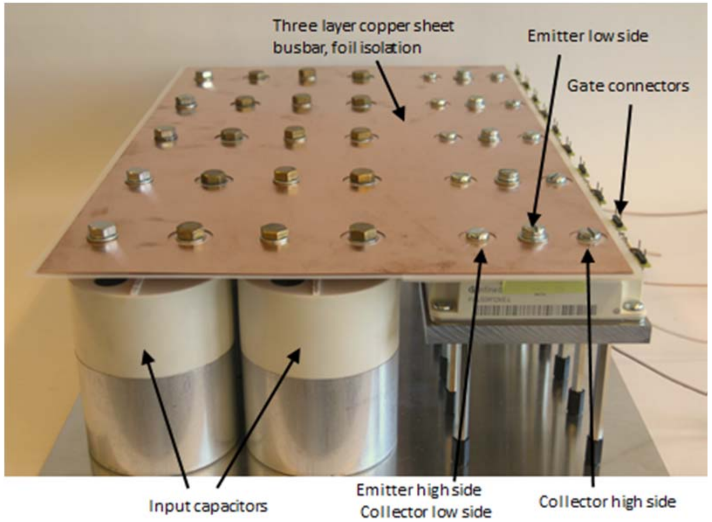
Maxwell3D: 1 h 20 min



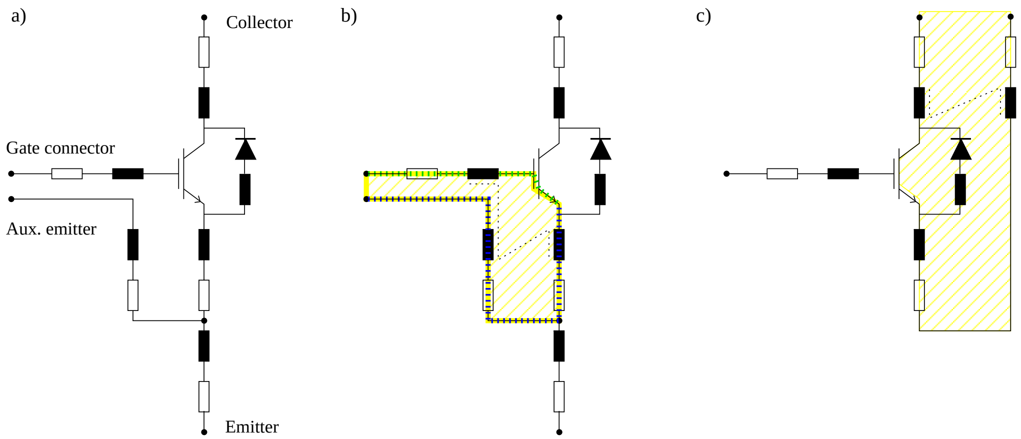
GeckoEMC: 30 sec

Interconnection Modeling

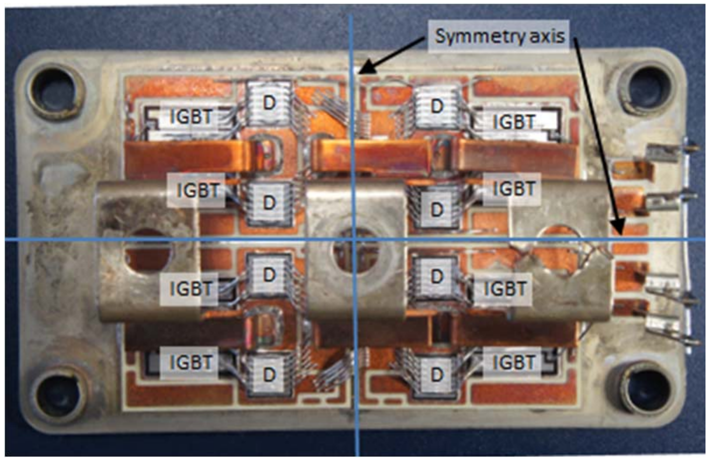
- Performance Evaluation of Simulation Methods and Tools for Analyzing Electromagnetic Effects in Power Electronics Interconnection Systems: Bus Bars, PCBs, and Power Modules
- Comparison of different electromagnetic solvers (FEM, PEEC)
  - Simulation performance (CPU, memory)
  - Result accuracy vs. measurement results
  - Usability issues

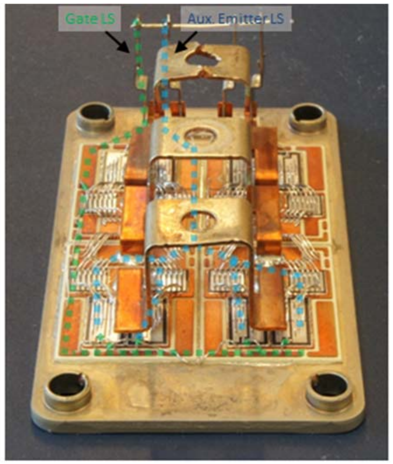


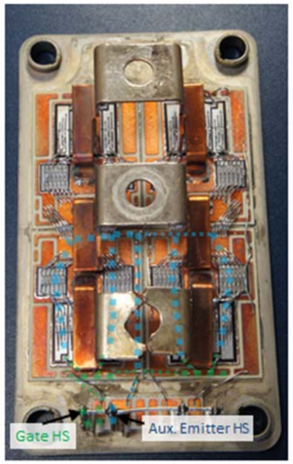
Interconnection Modeling



- Extraction of relevant parasitic inductances
- Frequency-dependency
- Mutual (coupling) inductances
- Which depth of modeling level is required?

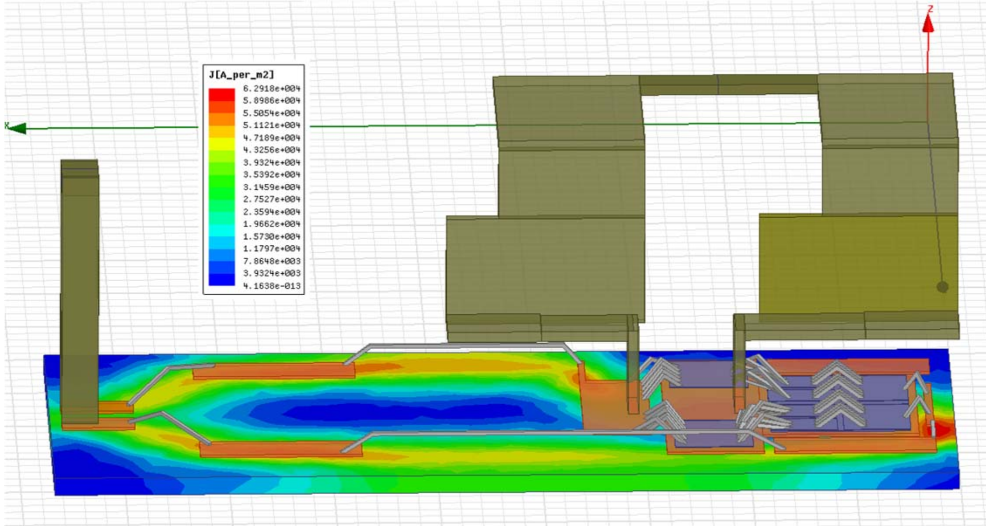




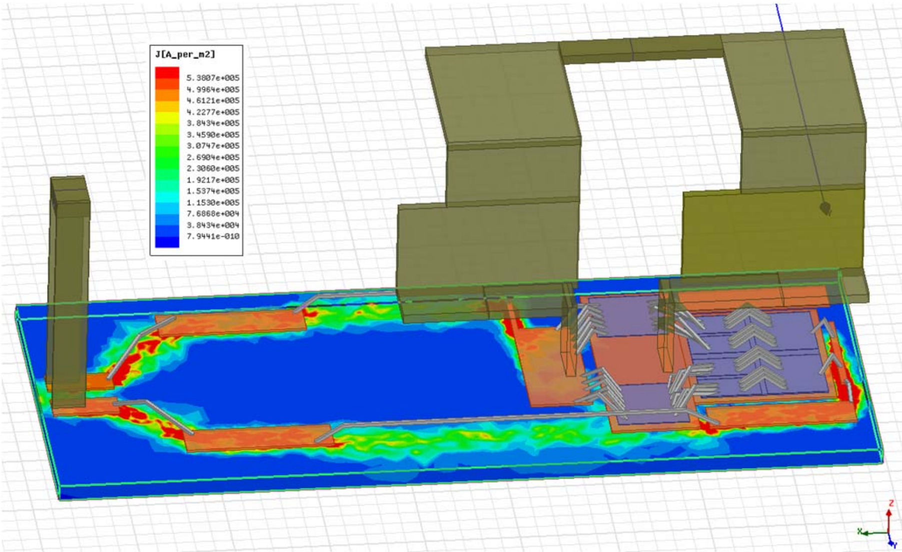


FEM model of IGBT Power Module

- Parasitic gate-auxilliary emitter inductance (L_{LS} ~ 90 nH)
- Base-plate reduces inductance significantly (40 nH at 1 MHz)
- Consider Skin-depth in baseplate
- Asymmetry high side / low side switch

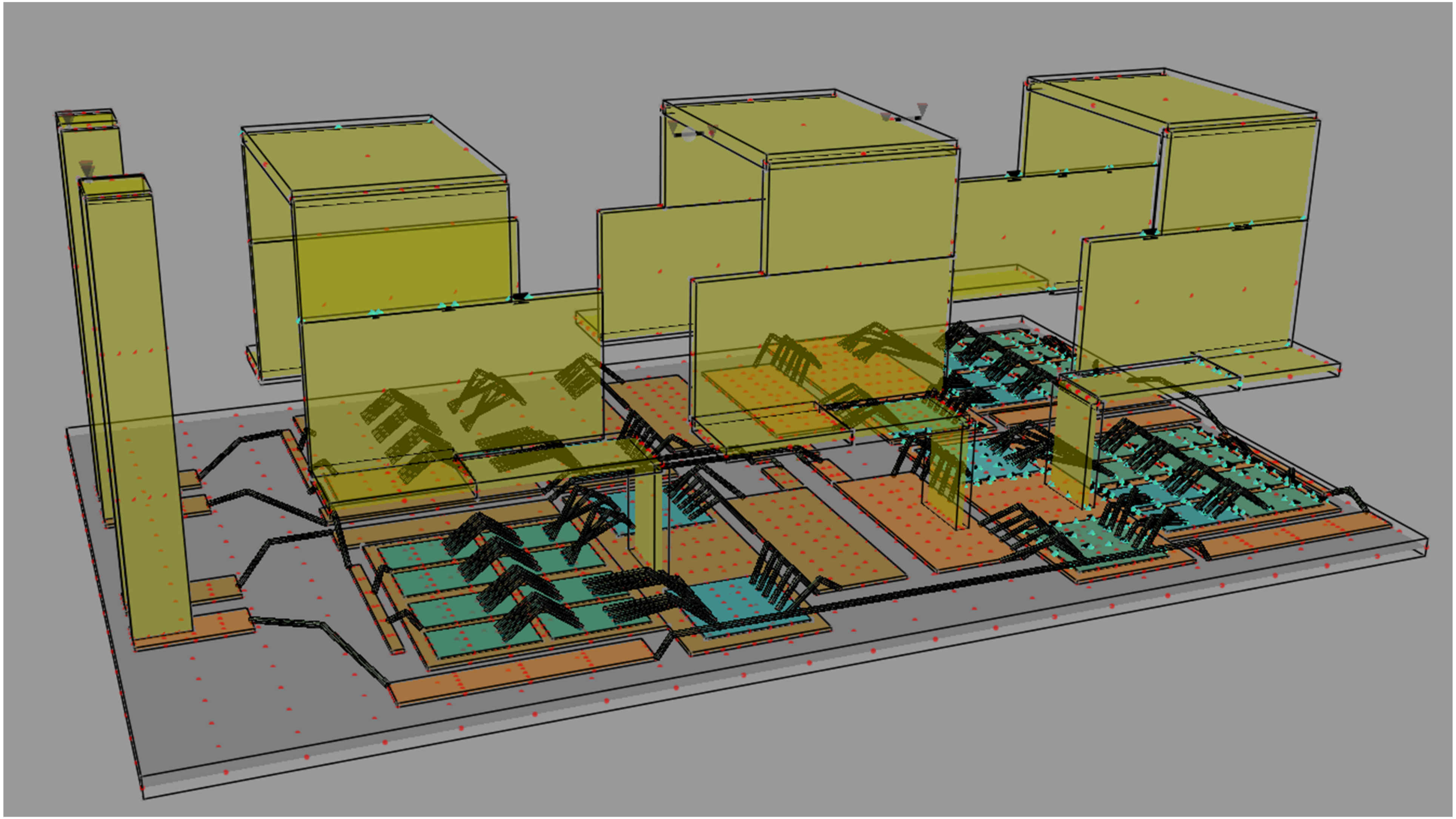


current distribution at f = 10 kHz



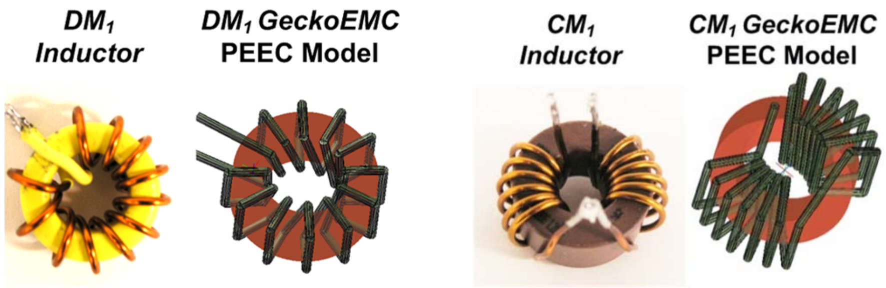
f = 1 MHz

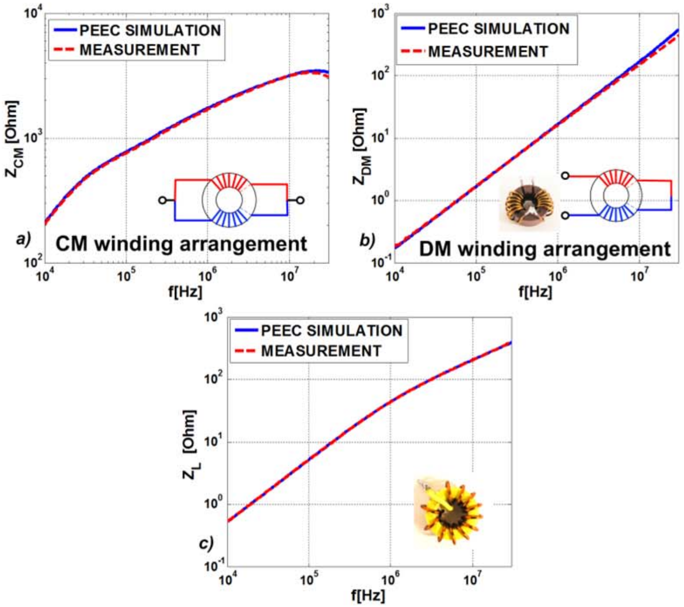
GeckoEMC – Complete Model of Infineon IGBT module

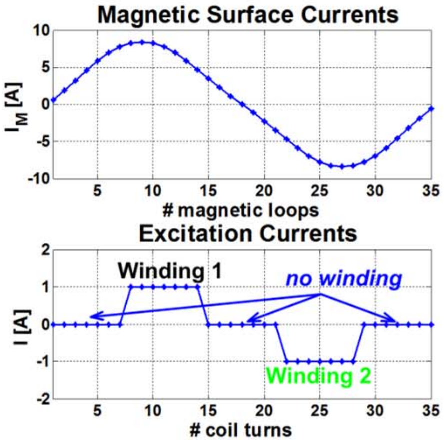


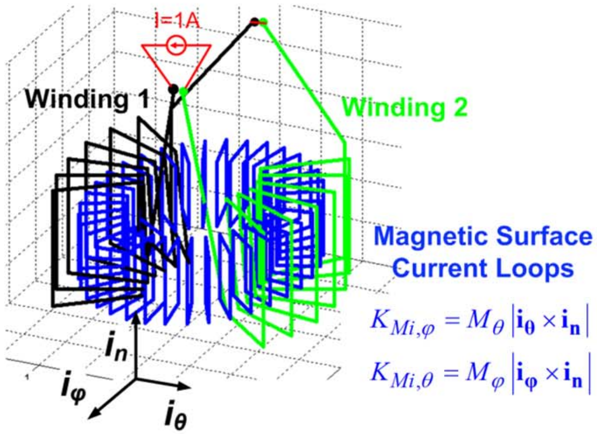
GeckoEMC model of EMI filter - Toroidal Inductors

- Difficulty: permeable material modeling was not available for PEEC method
- Solution: PEEC – boundary integral coupled method
- Very intuitive approach

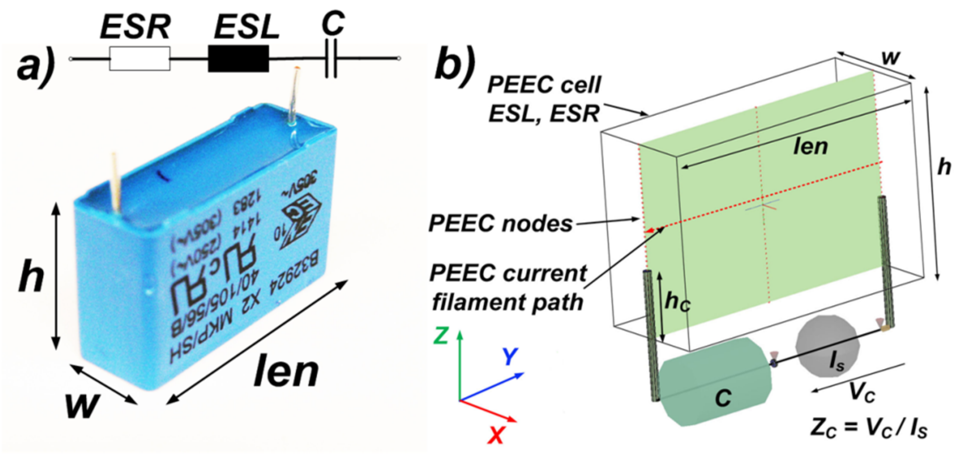


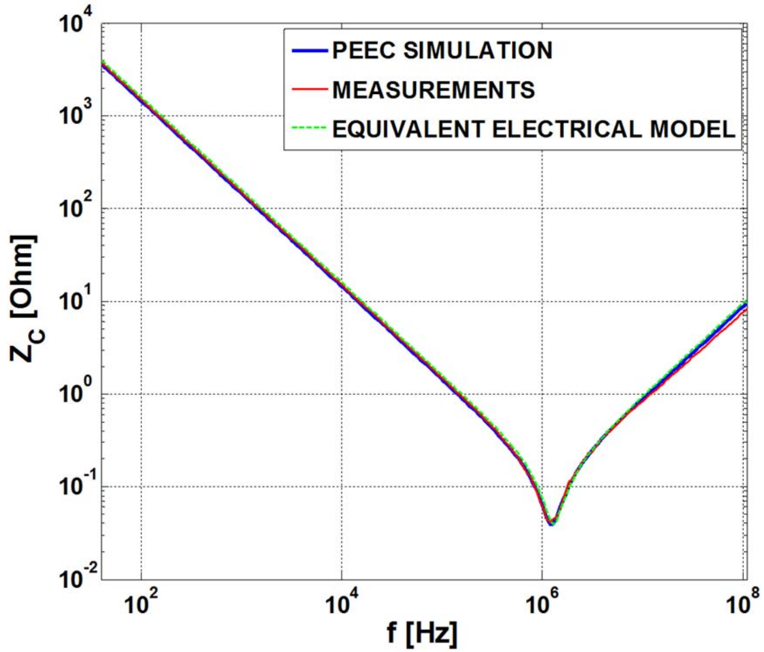


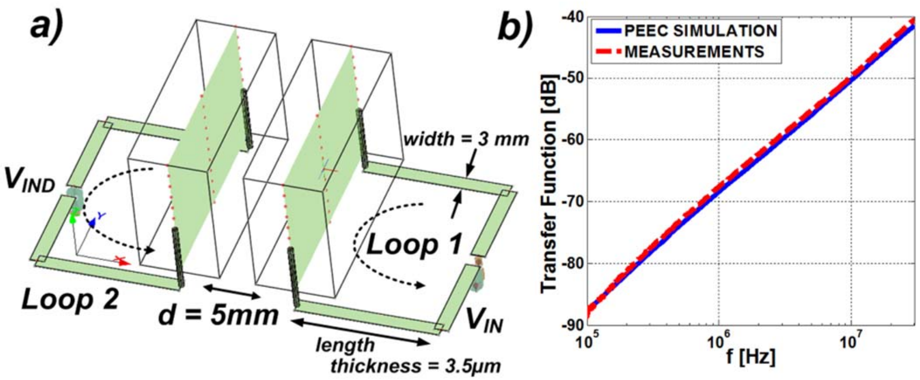




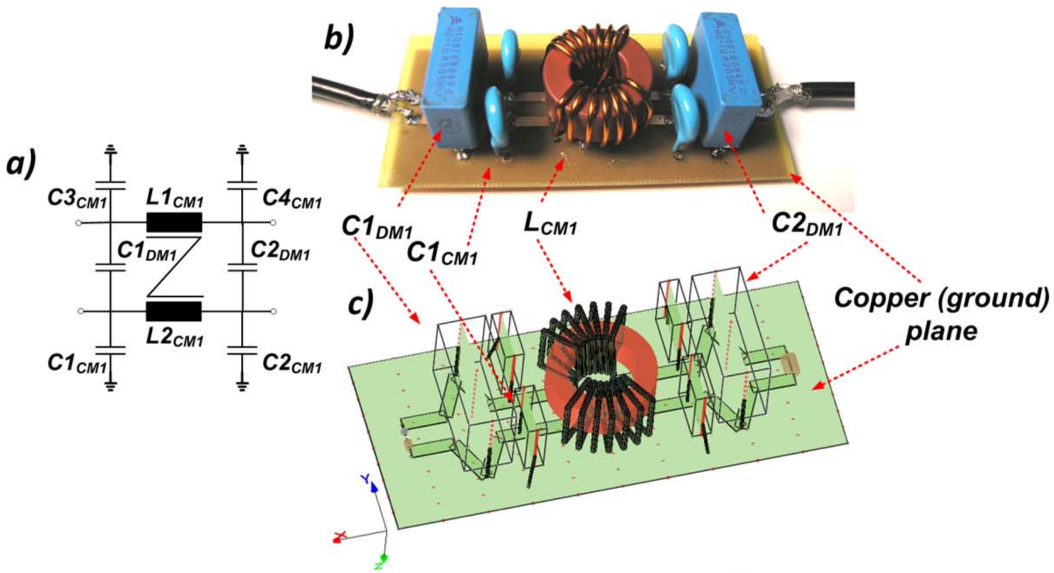
GeckoEMC model of EMI filters - Capacitors

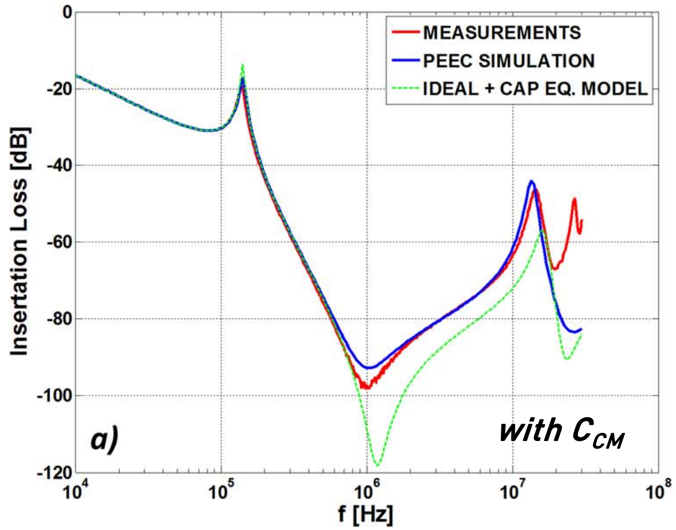




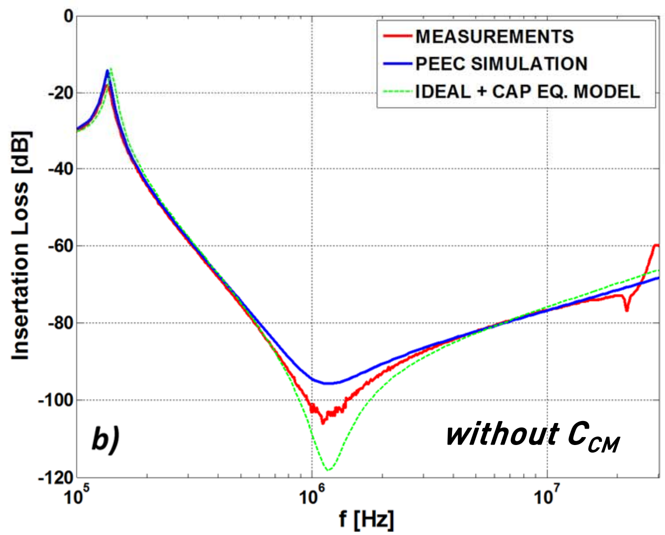


GeckoEMC model of EMI filter (1)

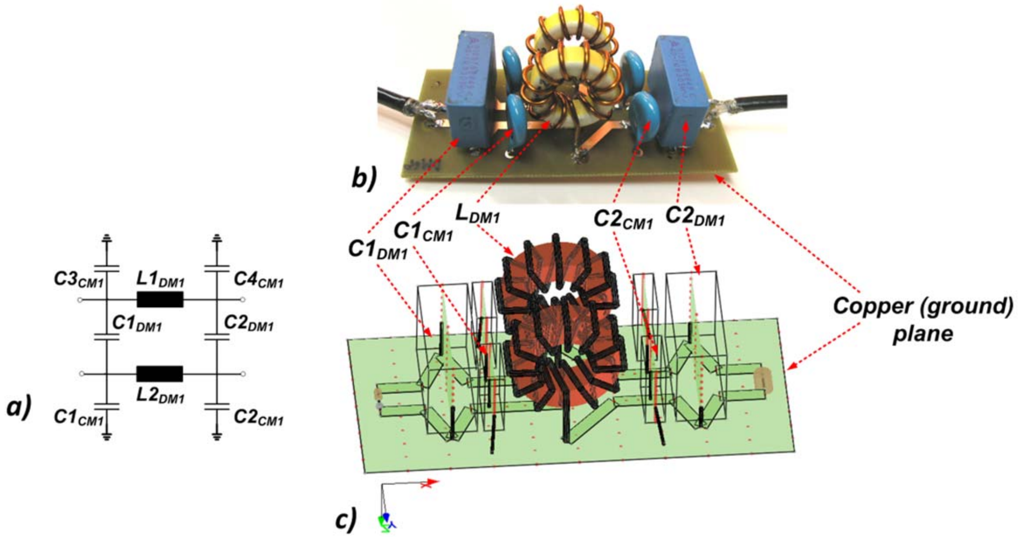


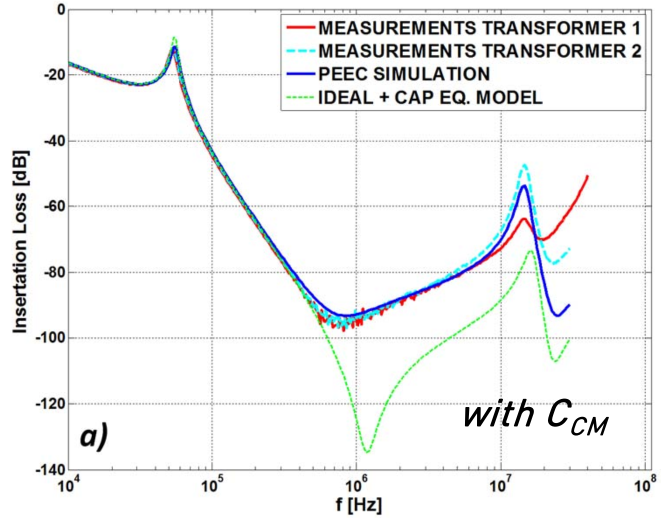


Single-stage single-phase EMI filter, **CM Inductor**

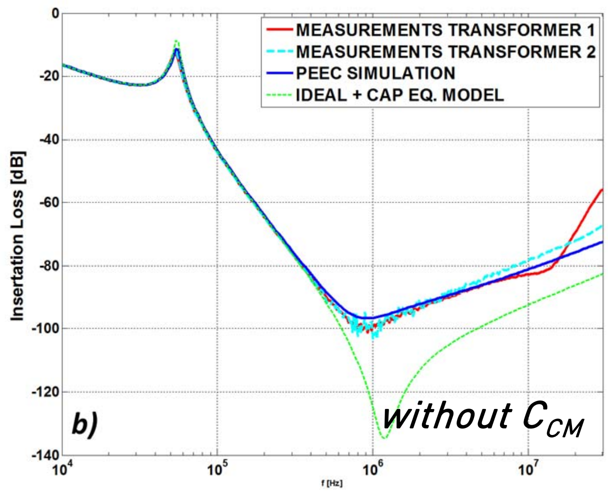


GeckoEMC model of EMI filter (2)



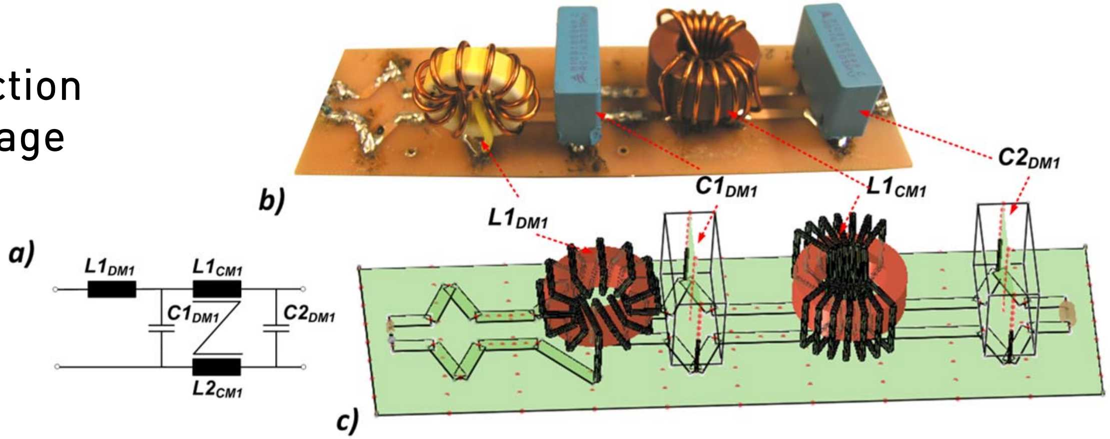


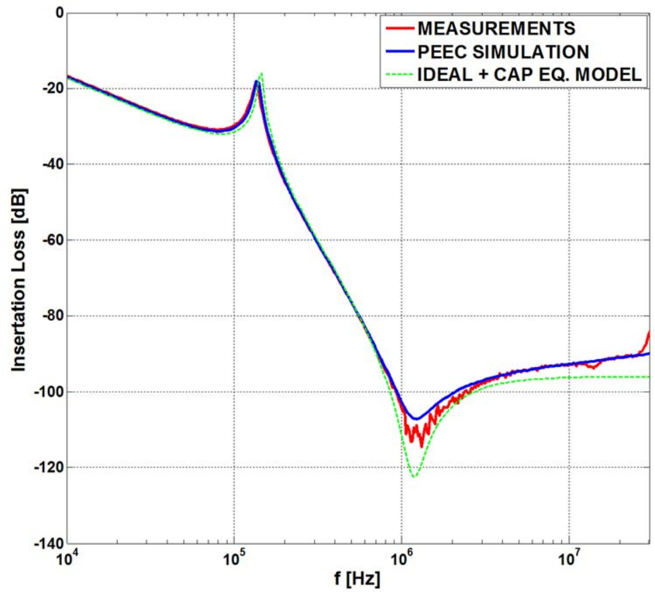
Single-stage single- phase EMI filter, **DM Inductors**



GeckoEMC model of EMI filter (3)

Power factor correction
(PFC) input filter stage





Model Order Reduction

How to combine different Simulation Domains?

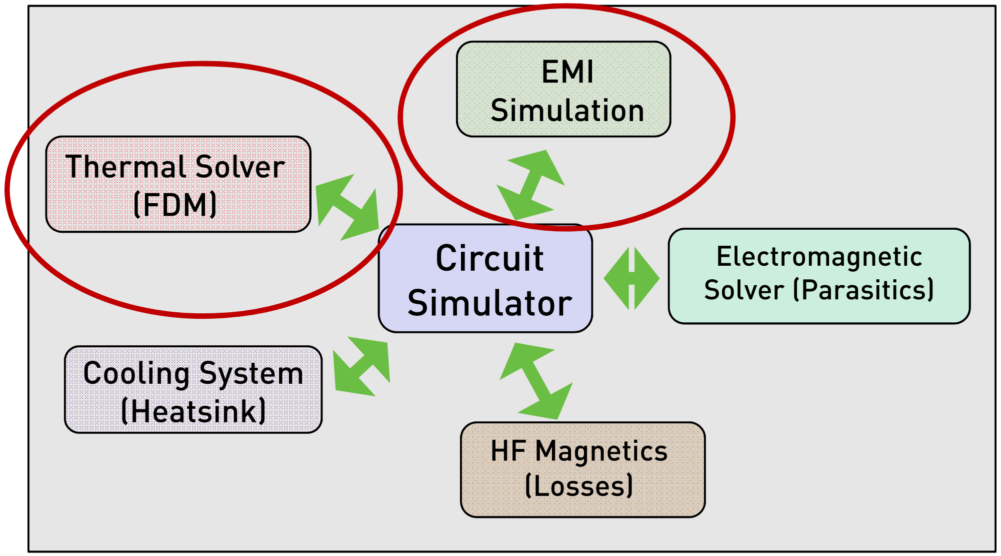
Model Order Reduction

Motivation: Finally, we want to include thermal models and electromagnetic models (parasitics) into a circuit simulation

- Model complexity is a computation performance issue!
- Typical: Thermal or EM solver contains > 10000 cells
- Circuit simulation: dt = 100 nsec, T = 1 sec

→ This is impossible to solve together

- Our future solution approach: Model Order Reduction (MOR)



MOR: Construct a simplified system to approximate the original system with reasonable accuracy.

The Basics of Model Order Reduction (1)

Original linear dynamic system:

$$\mathbf{C}\frac{d\mathbf{x}(t)}{dt} = -\mathbf{G}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)$$

$$\mathbf{y}(t) = L^T\mathbf{x}(t)$$

Example thermal FDM model:

C = Capacitance matrix
G = Conductance Matrix
Bu *(t)* = Excitation (power input, boundary conditions)
y *(t)* = output function
x *(t)* = internal model states (temperatures)

Goal: find a smaller linear system

$$\tilde{\mathbf{C}}\frac{d\tilde{x}(t)}{dt} = -\tilde{\mathbf{G}}\tilde{\mathbf{x}}(t) + \tilde{\mathbf{B}}\mathbf{u}(t)$$

$$\tilde{\mathbf{y}}(t) = L^T\tilde{\mathbf{x}}(t)$$

$$\underbrace{\mathbf{A}}_{10000 \times 10000}\vec{x} = \vec{b}$$

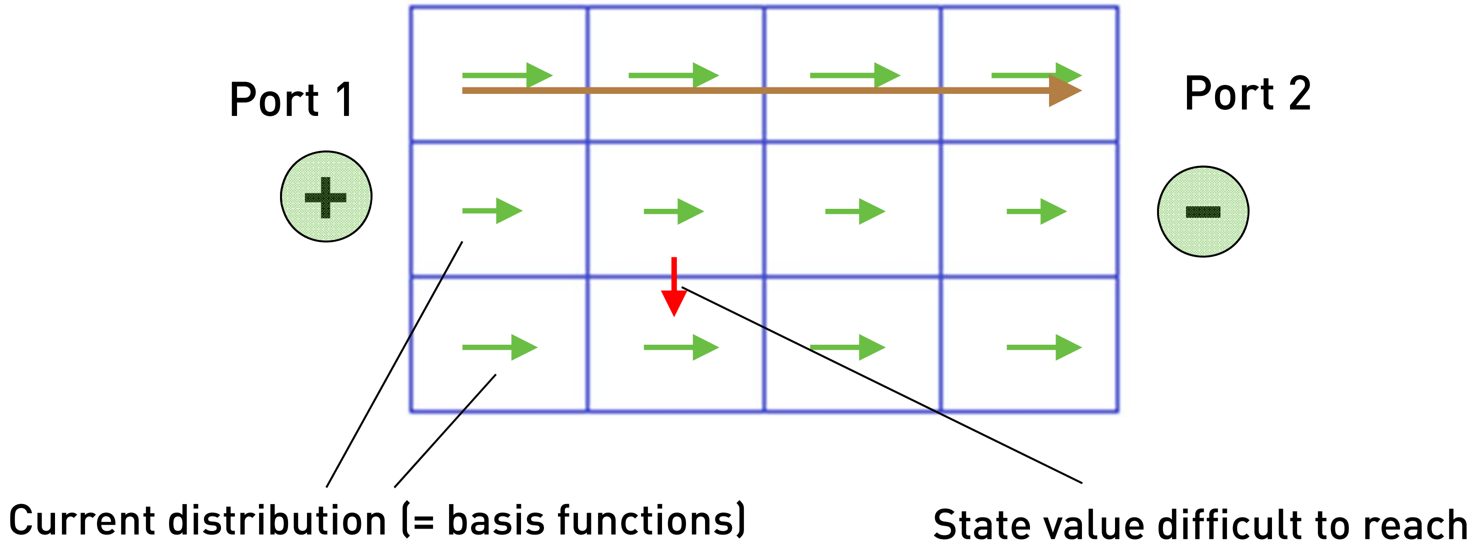
$$\underbrace{\mathbf{A}^{red}}_{100 \times 100}\vec{x} = \vec{b}$$

With the following properties:

- Number of internal states: m >> n
- Reduced system is a good approximation to original system
- Passivity of models must be preserved!

The Basics of Model Order Reduction (2)

- MOR strongly related to eigenvalue computations
- MOR is about projection of the states **x** to a better basis:
  Remove all unnecessary information from the model, example:



Two basic principles for MOR:

- „Krylov-Subspace“ methods (from iterative matrix solver theory)
- Truncated Balanced Realization (TBR, from control theory)

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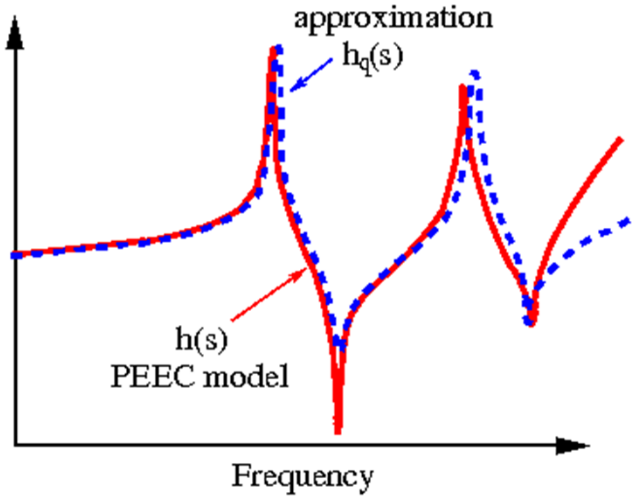
MOR – Krylov Subspace Methods

- Pade-Approximation of transfer function $$H(s) \approx H_q(s) = \frac{P(s)}{Q(s)} = \frac{a_0 + a_1 s + a_2 s^2 + \ldots + a_{q-1} s^{q-1}}{1 + b_1 s + b_2 s^2 + \ldots + b_q s^q}$$
- Why Pade?
  - Approximation methods: Taylor, Lagrange Polynomials, ...
  - Pade: approximate *H(s)* by order-limited rationale function



$$\underbrace{\mathbf{A}}_{10000 \times 10000}\vec{x} = \vec{b}$$

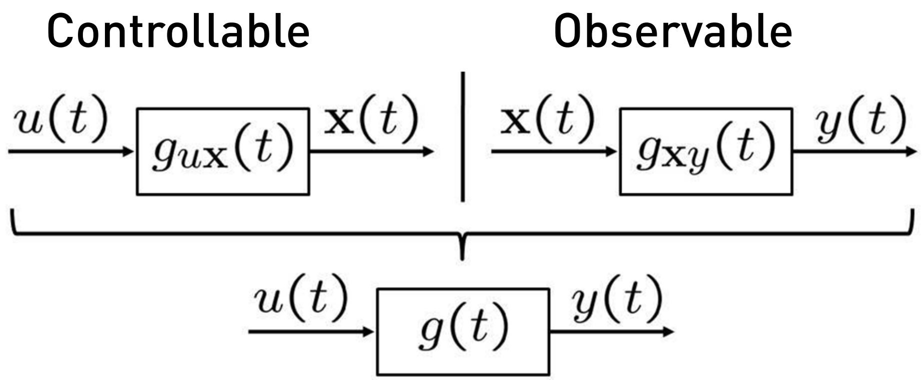
$$\Downarrow$$

$$\underbrace{\mathbf{A}^{red}}_{100 \times 100}\vec{x} = \vec{b}$$

- Krylov-subspace: calculate new basis in $K_r(\mathbf{A},\mathbf{b}) = \text{span}\{\mathbf{b}, \mathbf{Ab}, \mathbf{A}^2\mathbf{b}, \ldots, \mathbf{A}^m\mathbf{b}\}$
- Advantages: Very efficient, also for huge matrices
- Disadvantage: Passivity of approximation?
- Not the very best approximation, no error bound available!

Truncated Balanced Realization (TBR)

- Method well-known in control Theory
- Method based on „Singular Value Decomposition“ (SVD) $M = U\Sigma V^*$
- Idea: States not easy to reach or easy to measure can be neglected



- Disadvantage: numerical complexity of N^3 : $\widetilde{\mathrm{P}}^{-1}\mathrm{A}^T + \mathrm{A}\widetilde{\mathrm{P}}^{-1} + \mathrm{bb}^T = 0$

  → not efficiently applicable for large systems!
- Advantages: very compact reduced models, error bound available

Truncated Balanced Realization (TBR)

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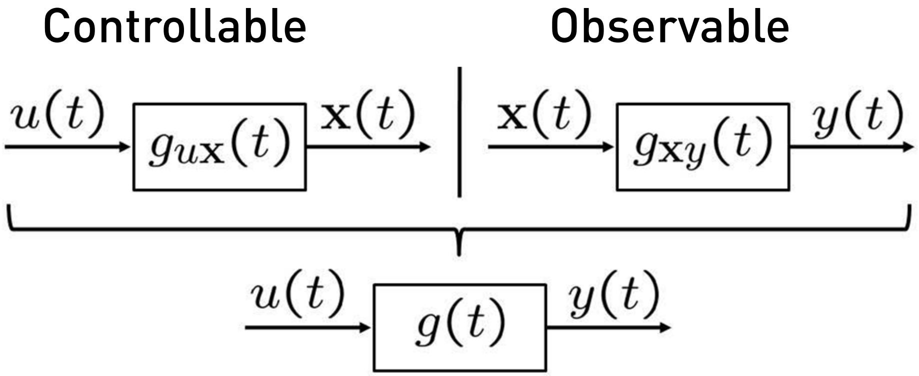

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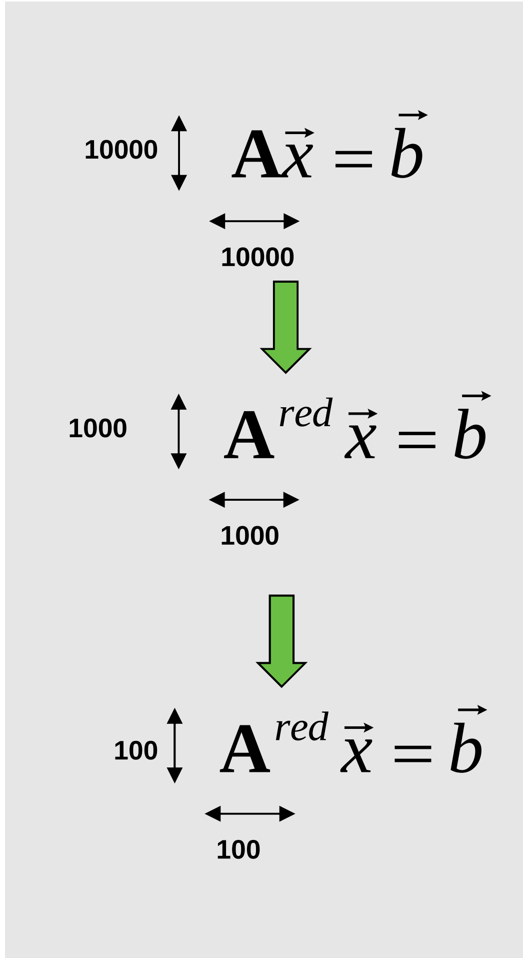
  → not efficiently applicable for large systems!

- Advantages: very compact reduced models, error bound available

MOR: Krylov → TBR

- Krylov: fast, but not optimal solution
- TBR: slow, but optimal solution
- Idea:
  - Combination of both methods
  - Reduce model size with Krylov approach
  - Execute TBR method on reduced model, to obtain a further (optimal) reduction



Model Order Reduction – Literature

- Sheldon Tan, “Advanced Model Order Reduction Techniques in VLSI Design”, Online ISBN: 9780511541117, 2007
- A. Odabasioglu, M. Celik, and L.T. Pileggi, "PRIMA: passive reduced-order interconnect macromodeling algorithm", presented at IEEE Trans. on CAD of Integrated Circuits and Systems, 1998, pp.645-654.

Losses in Inductive Components

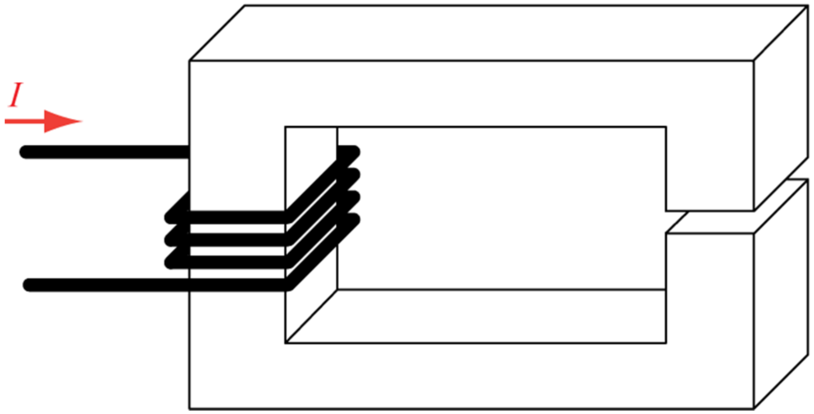
Inductor losses - Overview

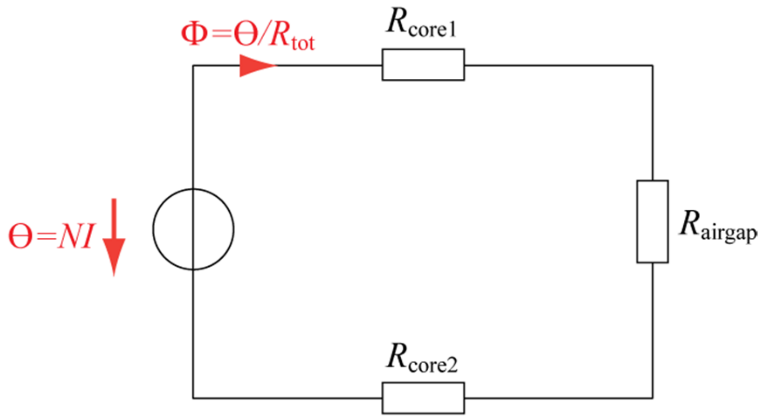
Losses in High Frequency and High Power Inductive components,

Basic strategy:

- Inductance calculation (E-type cores) via Reluctance models
- Core loss calculation: impact of peak-to-peak flux density B, frequency f, DC premagnetization H_{DC}, temperature T, core shape, minor and major loops, flux waveform, and material
- Winding loss calculation: including formulas for round conductors and litz wires, each considering skin- and proximity effects (influence of an air-gap fringing field)

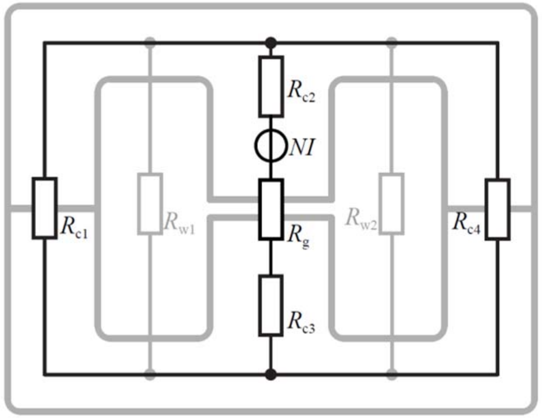
Inductors and the Reluctance model





	Electric Network	Magnetic Network
Conductivity	κ	μ
Resistance	$R = l / \kappa A$	$R_m = l / \mu A$
Voltage	$V = \int_{P_1}^{P_2} \vec{E}\, d\vec{s}$	$V_m = \int_{P_1}^{P_2} \vec{H}\, d\vec{s}$
Current / Flux	$I = \iint_A \vec{J}\, d\vec{A}$	$\Phi = \iint_A \vec{B}\, d\vec{A}$

E-Core Reluctance model



Core losses – Modeling Approaches (1)

- Steinmetz Equation SE

$$P = k\, f^{\alpha}\, B^{\beta}$$

  - Only sinusoidal waveforms (→ iGSE).

- iGSE (improved generalized Steinmetz equation)

$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} \left(\Delta B\right)^{\beta-\alpha}\, \mathrm{d}t$$

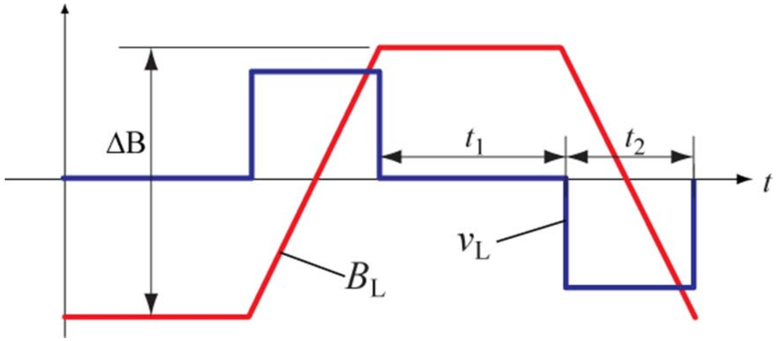
- DC bias not considered

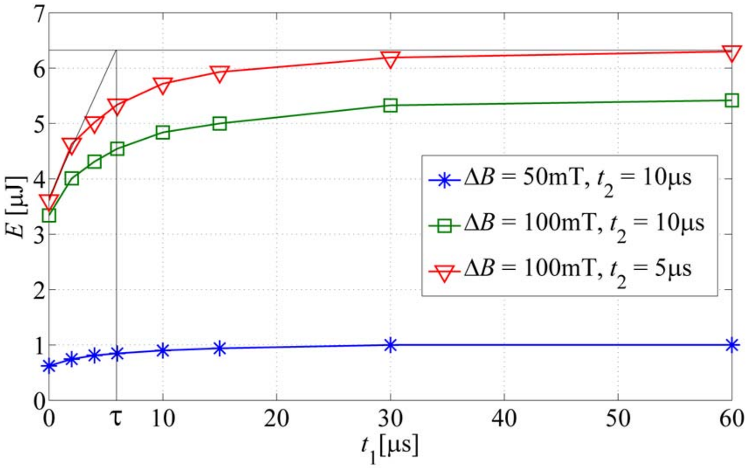
- Relaxation effect not considered

- Steinmetz parameters are valid only in a limited flux density and frequency range

Core losses – Modeling Approaches (2)

Relaxation Losses





Loss increase in the zero voltage phases (where dB/dt = 0)!

iGSE

$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t$$

i²GSE

$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} Q_{\mathrm{r}l} P_{\mathrm{r}l}$$

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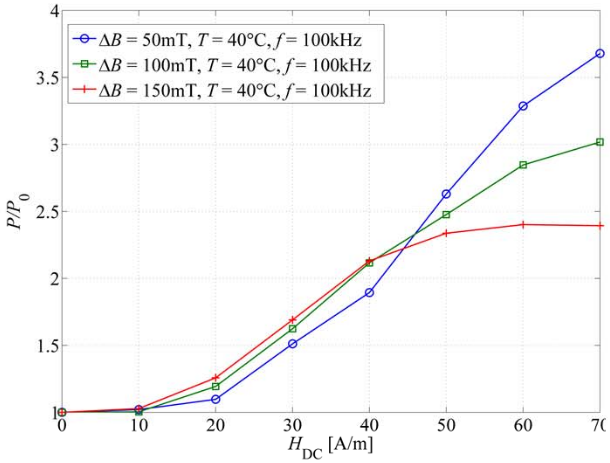
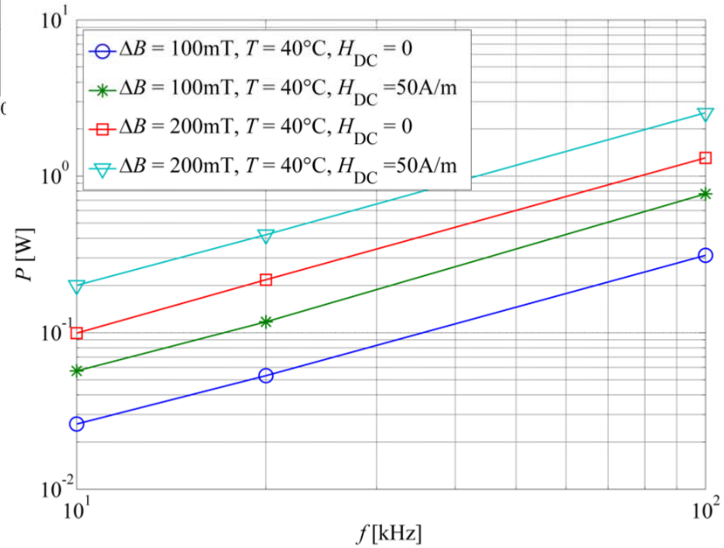
Core losses – Modeling Approaches (3)





- Is the i2GSE the best model we can apply?

$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} Q_{\mathrm{r}l} P_{\mathrm{r}l}$$

- Remaining problems:
  - Limited flux density and frequency range
  - DC bias
  - Modeling relaxation and DC bias effects need additional parameters (not supplied by core manufacturer)

- Measuring core losses is indispensable!

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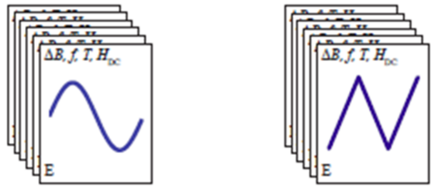
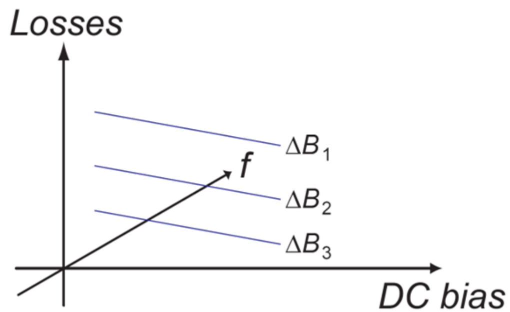
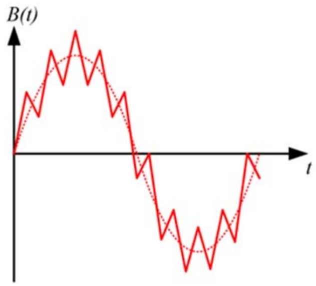
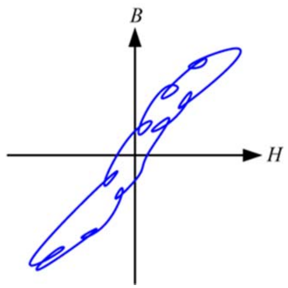
Core losses – Modeling Approaches (4)

Loss Map (Loss Material Database)







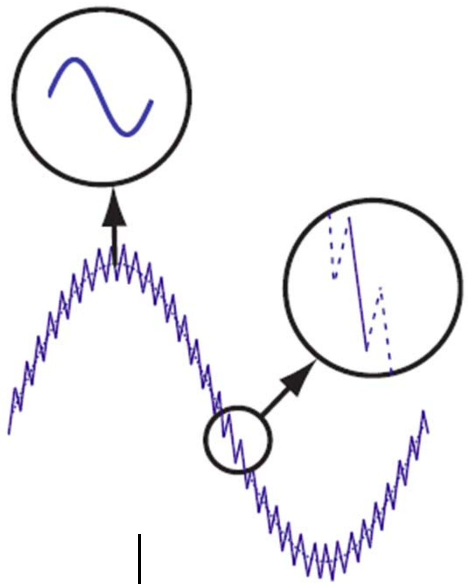


4th dimension: temperature.

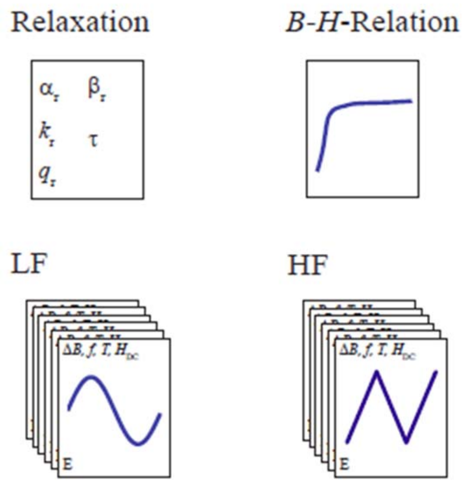
Question What loss map structure is needed to take all loss effects into consideration?

Core losses – Needed Loss Map Structure

Typical flux waveform



Content of Loss Map



$$k, k_i, \alpha, \beta, \alpha_r, \beta_r, q_r, \tau$$

$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\, dt + \sum_{l=1}^{n} Q_{rl} P_{rl} \longrightarrow \frac{P}{V}$$

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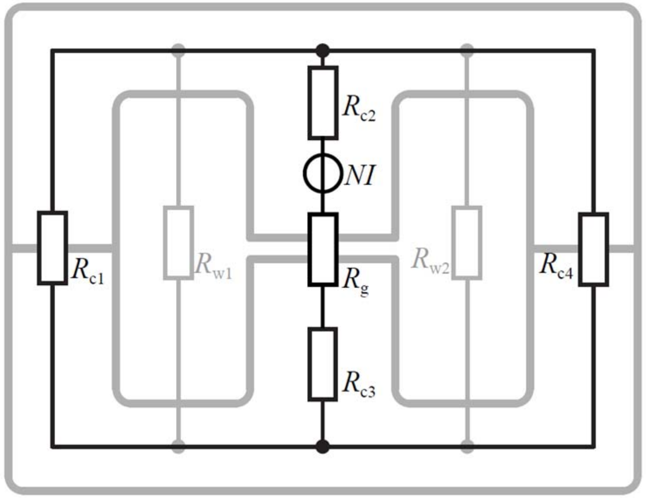
Core losses – Calculation Procedure

1) The flux density in every core section of (approximately) homogenous flux density is calculated.

2) The losses of each section are calculated.

3) The core losses of each section are then summed-up to obtain the total core losses.

Reluctance Model



Combining i²GSE and Loss Map Approach

Advantages

- Relaxation effects are considered (i2GSE).
- A good interpolation and extrapolation between premeasured operating points is achieved
- Loss map provides accurate i2GSE parameters for a wide frequency and flux density range
- A DC bias is considered as the loss map stores premeasured operating points at different DC bias levels
- Finally, a software tool performs all necessary calculations (inductance/flux calculation, loss map interpolation, conductor loss calculation

Winding Losses

- DC operation: simple ohmic loss calculation
- High-Frequency: consider additional losses due to
  - Skin effect (internal H-Field)
  - Proximity effect (external H-Field)
    - effect of neighbouring conductors
    - Magnetic flux leakage from air-gaps
- „High-Frequency" is defined via the skin-depth

$$\delta = \frac{1}{\sqrt{\pi \mu_0 \sigma f}}$$

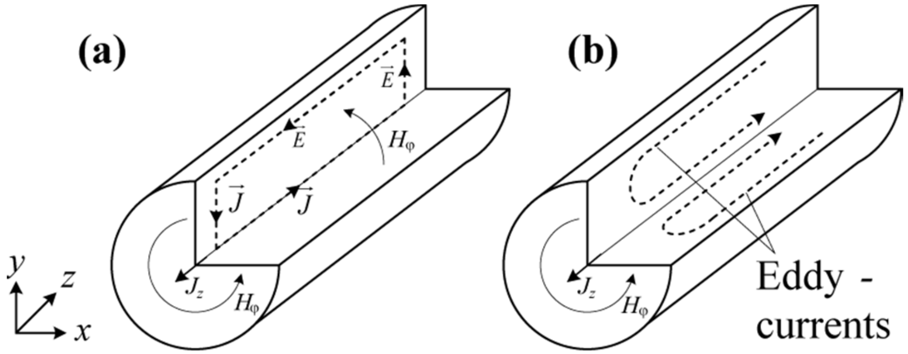
- Foil conductors / Litz wire: Analytic equations existing, here, we consider only round conductors

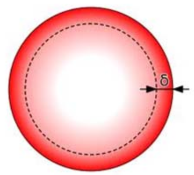
Winding Losses – Skin Effect

Solid Round Conductors,
Loss calculation formula:

(Loss per unit length)

$$P_S = F_R(f) \cdot R_{DC} \cdot \hat{I}^2$$





with

$$R_{DC} = \frac{4}{\sigma \pi d^2}$$

$$\xi = \frac{d}{\sqrt{2}\delta}$$

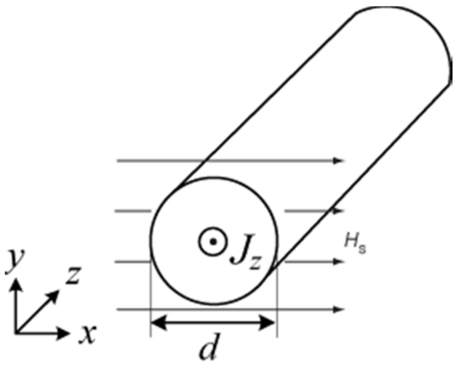
$$\delta = \frac{1}{\sqrt{\pi \mu_0 \sigma f}}$$

$$F_R = \frac{\xi}{4\sqrt{2}} \left[\frac{\mathrm{ber}_0(\xi)\mathrm{bei}_1(\xi) - \mathrm{ber}_0(\xi)\mathrm{ber}_1(\xi)}{\mathrm{ber}_1(\xi)^2 + \mathrm{bei}_1(\xi)^2} - \frac{\mathrm{bei}_0(\xi)\mathrm{ber}_1(\xi) - \mathrm{bei}_0(\xi)\mathrm{bei}_1(\xi)}{\mathrm{ber}_1(\xi)^2 + \mathrm{bei}_1(\xi)^2} \right]$$

Winding Losses – Proximity Effect

Solid Round Conductors,
Loss calculation formula:

$$P_{\mathrm{P}} = G_{\mathrm{R}}(f) \cdot R_{\mathrm{DC}} \cdot \hat{H}_{\mathrm{e}}^{2}$$

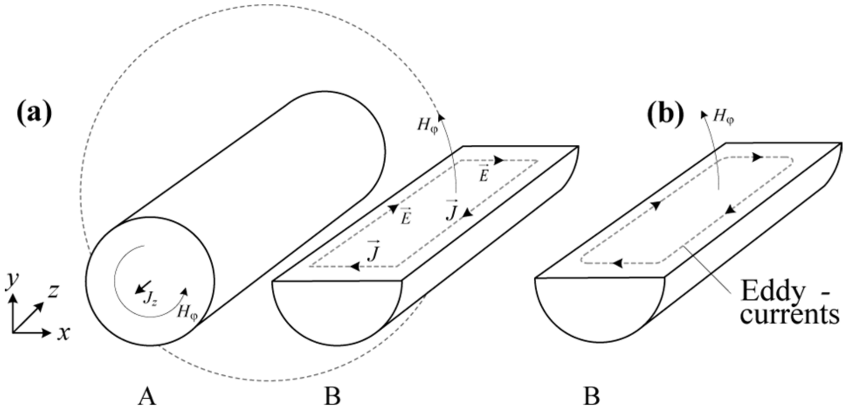


with

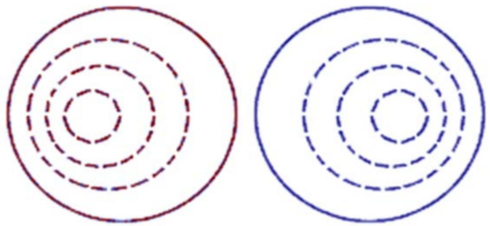
$$R_{\mathrm{DC}} = \frac{4}{\sigma \pi d^2}$$

$$\xi = \frac{d}{\sqrt{2}\delta}$$

$$\delta = \frac{1}{\sqrt{\pi \mu_0 \sigma f}}$$



Proximity Effect
Current distribution
in two conductors

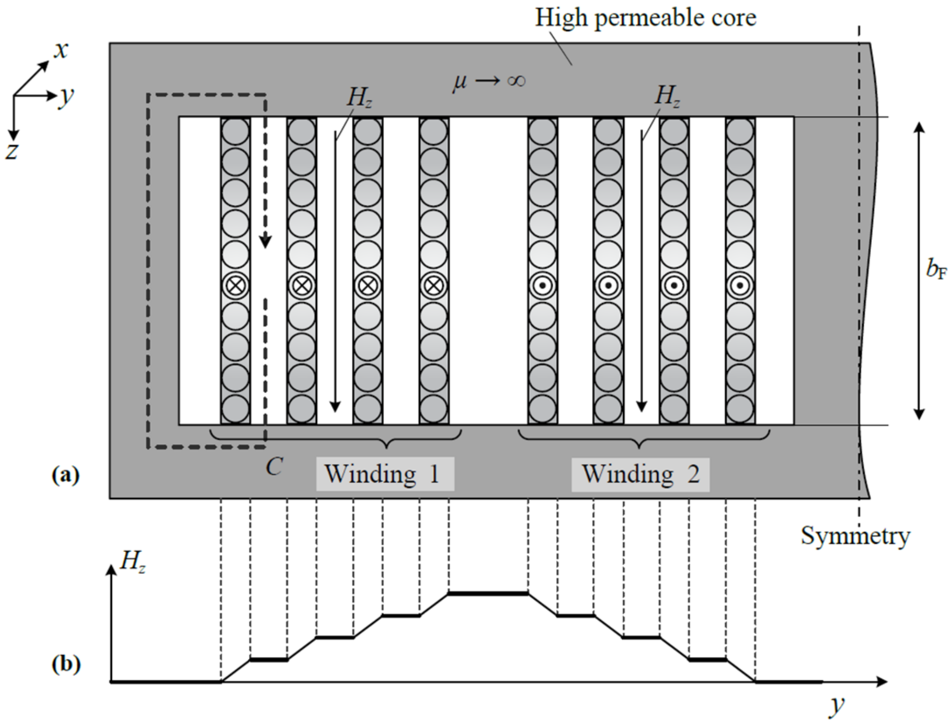


$$G_{\mathrm{R}} = -\frac{\xi \pi^2 d^2}{2\sqrt{2}} \left[\frac{\mathrm{ber}_2(\xi)\mathrm{ber}_1(\xi) + \mathrm{ber}_2(\xi)\mathrm{bei}_1(\xi)}{\mathrm{ber}_0(\xi)^2 + \mathrm{bei}_0(\xi)^2} + \frac{\mathrm{bei}_2(\xi)\mathrm{bei}_1(\xi) - \mathrm{bei}_2(\xi)\mathrm{ber}_1(\xi)}{\mathrm{ber}_0(\xi)^2 + \mathrm{bei}_0(\xi)^2} \right]$$

Winding Losses – Calculation of External Field H_e

1D - approach

Un-gapped cores (e.g. in transformers)



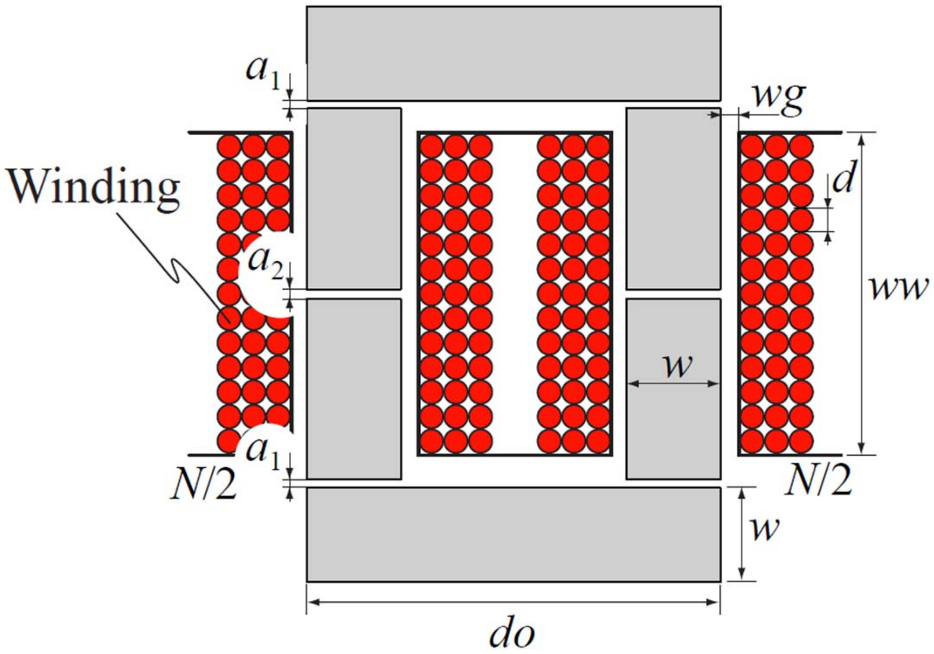
$$P = R_{DC}\left(F_R \hat{I}^2 NM + N G_R \sum_{m=1}^{M} \hat{H}^2_{avg,m} \right) l_m$$

with

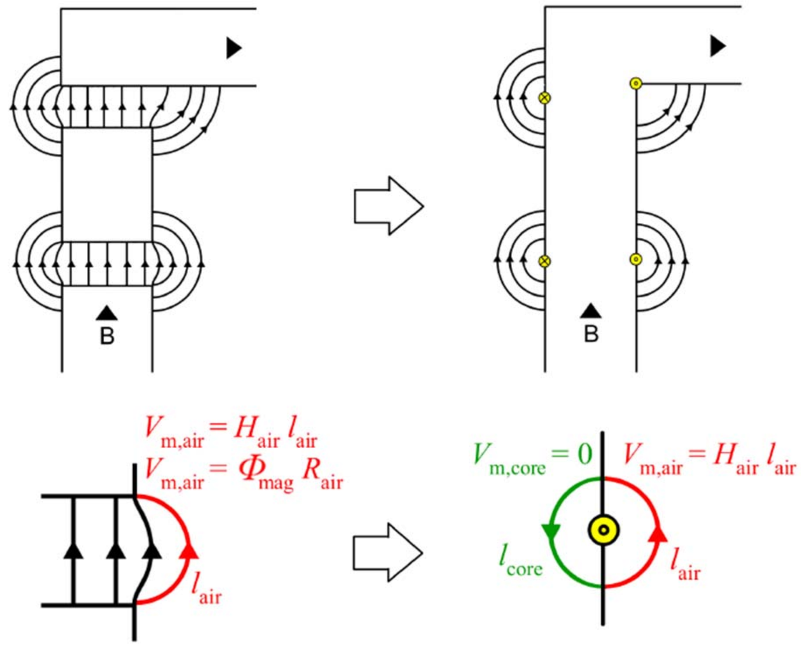
$$H_{avg} = \frac{1}{2}\left(H_{left} + H_{right} \right)$$

Winding Losses – Calculation of External Field H_e

Gapped cores: 2D – approach necessary!



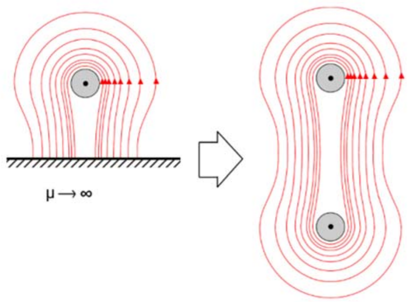
Effect of the air-gap fringing field



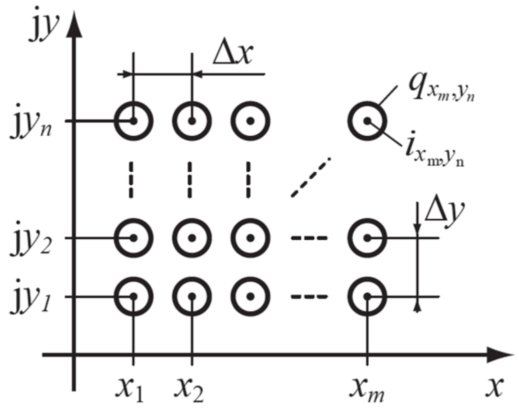
Air gap can be replaced by a fictitious current, with the value equal to the magneto-motive force (mmf) across the air gap.

Winding Losses – Effect of the Core Material

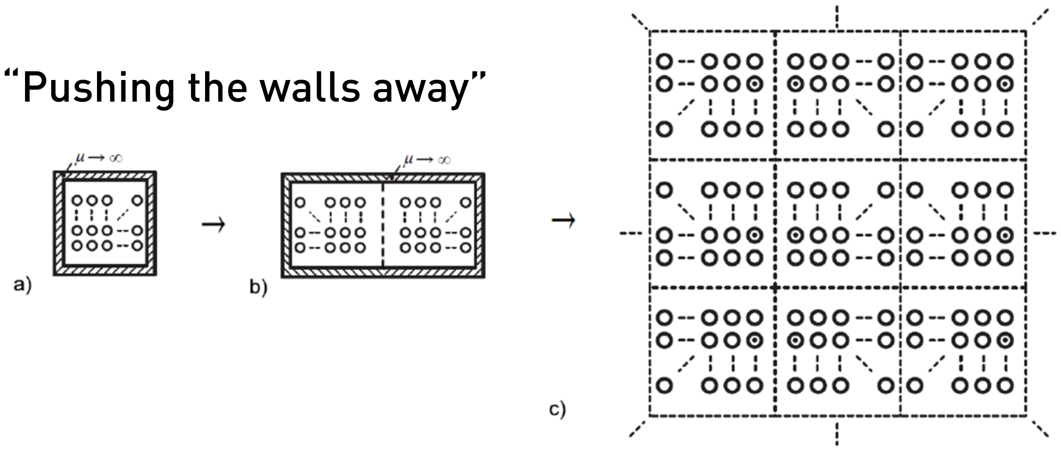
The method of images (mirroring)



Winding Arrangement



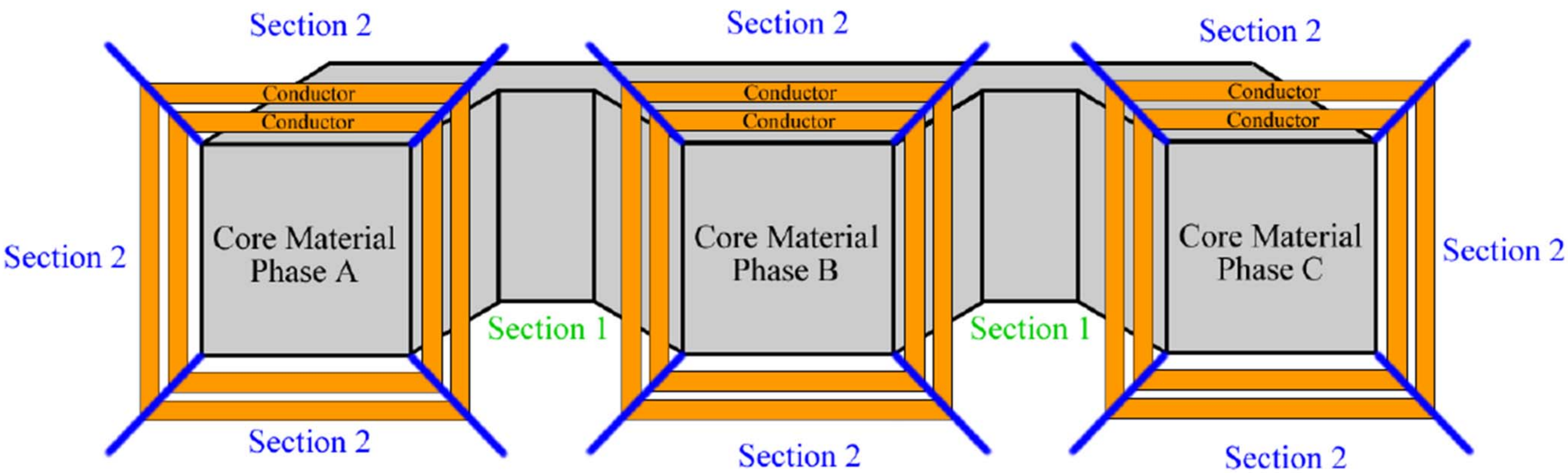
"Pushing the walls away"



External field vector across conductor $q_{xi;yk}$

$$\hat{H}_\mathrm{e} = \left| \sum_{u=1}^{m} \sum_{l=1}^{n} \epsilon(u,l) \frac{\hat{i}_{x_u,y_l} \left((y_l - y_k) - \mathrm{j}(x_u - x_i) \right)}{2\pi \left((x_u - x_i)^2 + (y_l - y_k)^2 \right)} \right|$$

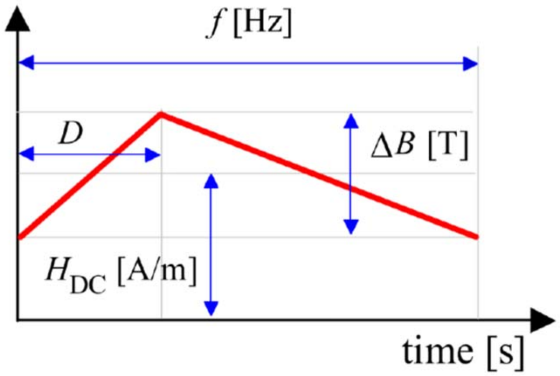
Winding Losses – Different Winding Sections



Section 1: Core window - many mirrorings
Section 2: Not core window - one mirroring

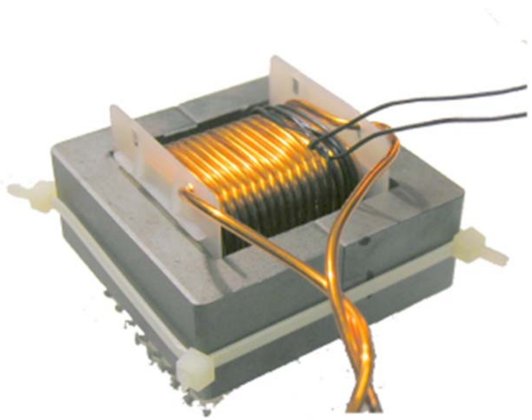
Experimental Results ←→ Calculation

Flux Waveform



Inductor

EPCOS E55/28/21, N = 18,
d = 1.7 mm, l_g = 1 mm

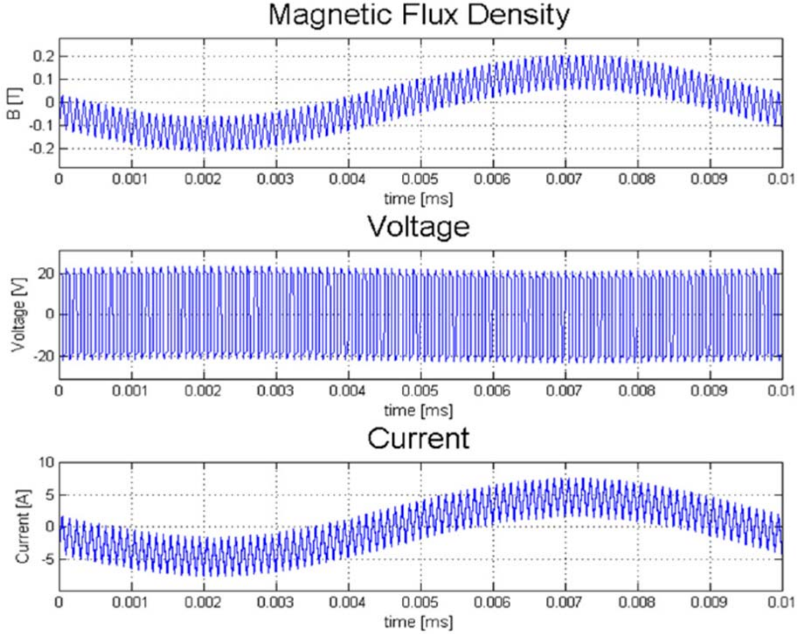


Results (measured with power analyzer Yokogawa WT3000)

Operating Points				Calculated Losses			Measured Losses	Comparison
ΔB [T]	f [kHz]	Duty-Cycle	H_{DC} [A/m]	Core Losses [W]	Winding Losses [W]	Total Losses [W]	Total Losses [W]	Rel. Error [%]
0.25	1	0.5	0	0.06	0.11	0.17	0.18	-5.56
0.5	1	0.5	0	0.32	0.42	0.74	0.77	-3.90
0.25	2	0.5	0	0.14	0.12	0.26	0.27	-3.70
0.5	2	0.5	0	0.72	0.49	1.21	1.21	0.00
0.25	5	0.5	0	0.4	0.23	0.63	0.61	3.28
0.5	5	0.5	0	2.04	0.92	2.96	2.70	9.63

Experimental Results ←→ Calculation

Flux Waveform



Inductor

EPCOS E55/28/21, *N* = 18,
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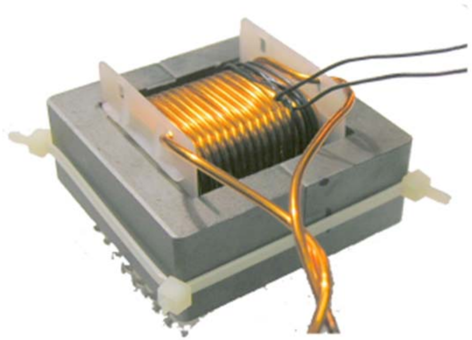


f_{LF} = 100 Hz
f_{HF} = 10 kHz

Results (measured with power analyzer Yokogawa WT3000)

Operating Points			Calculated Losses			Measured Losses	Comparison
$\hat{I}_{LF}$ [A]	ΔB_{LF} [T]	ΔB_{HF} [T]	Core Losses [W]	Winding Losses [W]	Total Losses [W]	Total Losses [W]	Rel. Error [%]
5	0.25	0.15	0.44	0.35	0.79	0.76	3.95
10	0.5	0.3	1.83	1.51	3.35	3.6	-6.94

GeckoMAGNETICS: 3D Tool for Inductor Loss Calculations

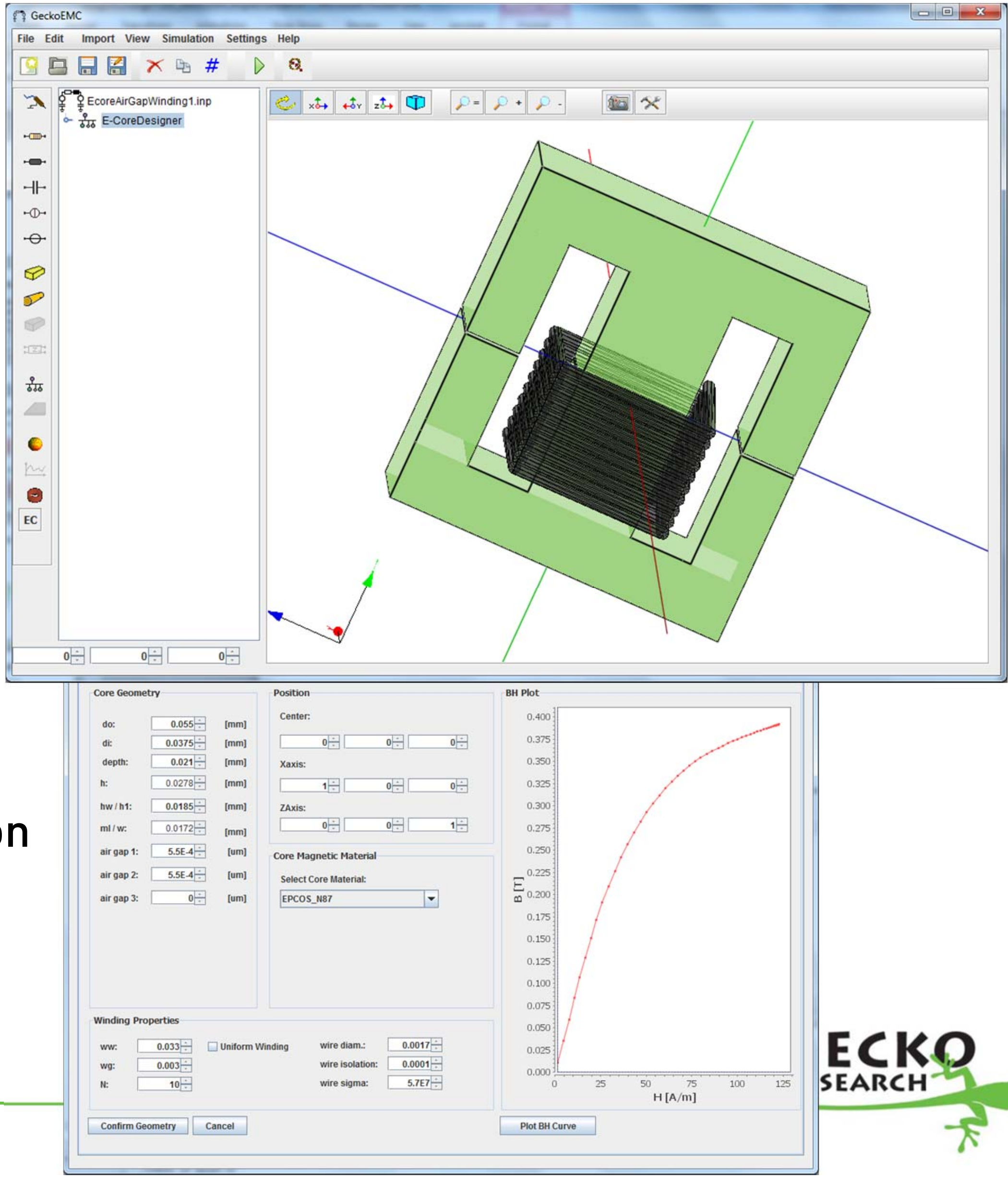
Currently in Development

Inputs:

- Core Dimensions
- Winding properties (round conductor, Litz Wire, Foil Conductors & arragement)
- Material Database (B-H curve, Steinmetz paramters, loss map)
- Current/Flux waveforms (e.g. from GeckoCIRCUITS, FFT)

Output:

- Total losses & loss distribution
- Inductances
- Field distribution



Inductor Loss Modeling – Conclusion & Outlook

A high accuracy in modeling inductive components has been achieved.

The following effects have been considered:

Reluctance model:

- Air gap stray field.
- Non-linearity of core material considered.

Core Losses:

- DC Bias (Loss Map)
- Relaxation Effects (i^2GSE)
- Different flux waveforms (iGSE / i^2GSE)
- Wide range of flux density and frequencies (Loss Map)

Winding Losses:

- Skin and proximity effect
- Stray field proximity effect
- Effect of core material

Software tool for the practical application of discussed models is in development

Next steps: Including thermal models into software framework

Inductors Loss Modeling – Literature

- J. Mühlethaler. Loss Modeling of Inductive Components Employed in Power Electronic Systems. Proceedings of the 8th International Conference on Power Electronics - ECCE Asia, May 30-June 3, 2011, The Shilla Jeju, Korea.
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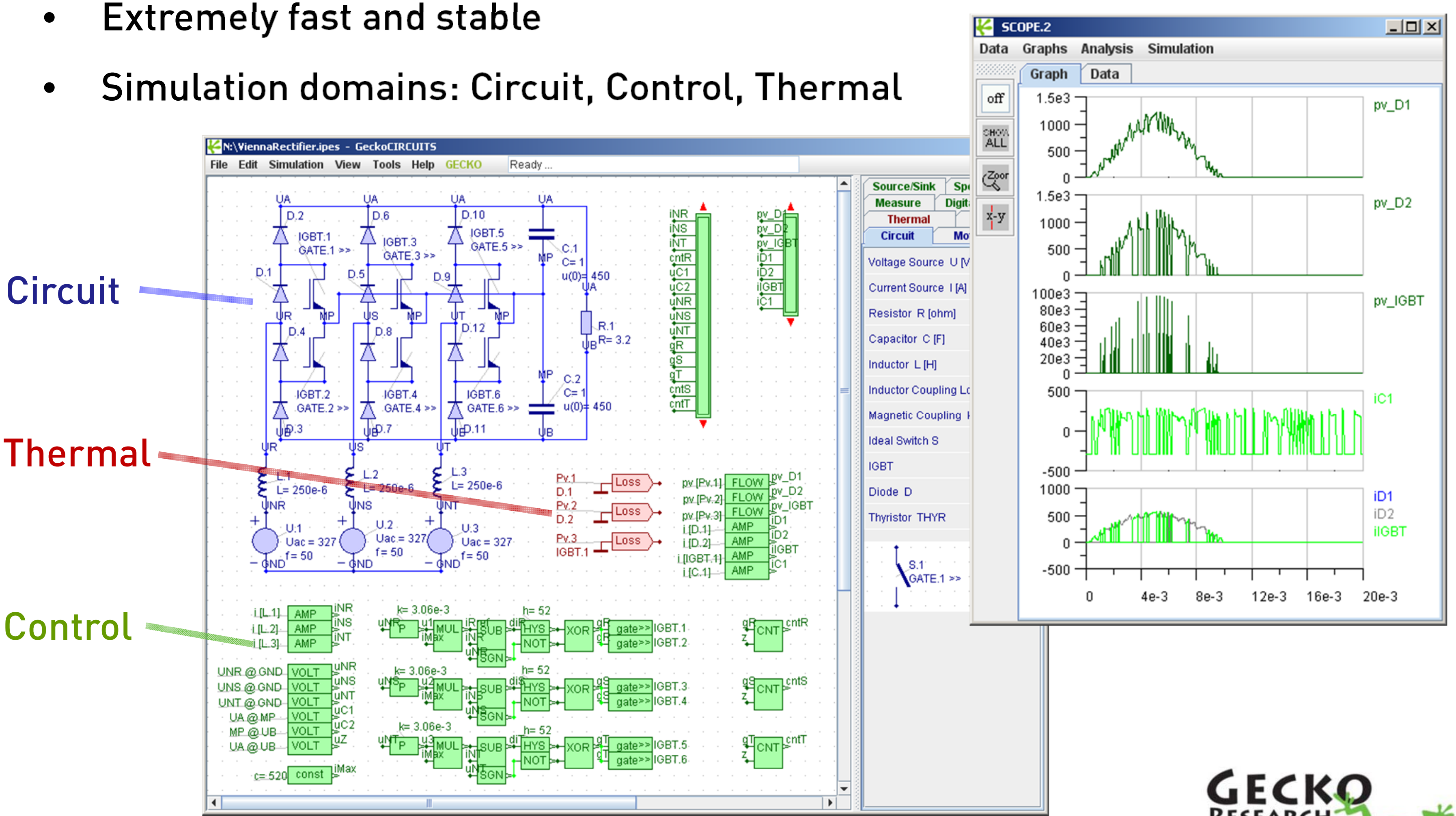
- S. Iyasu, T. Shimizu, and K. Ishii, “A novel iron loss calculation method on power converters based on dynamic minor loop,” in Proc. Of European Conference on Power Electronics and Applications, pp. 2016–2022, 2005.

GeckoCIRCUITS

Hands-on Training after the Presentation

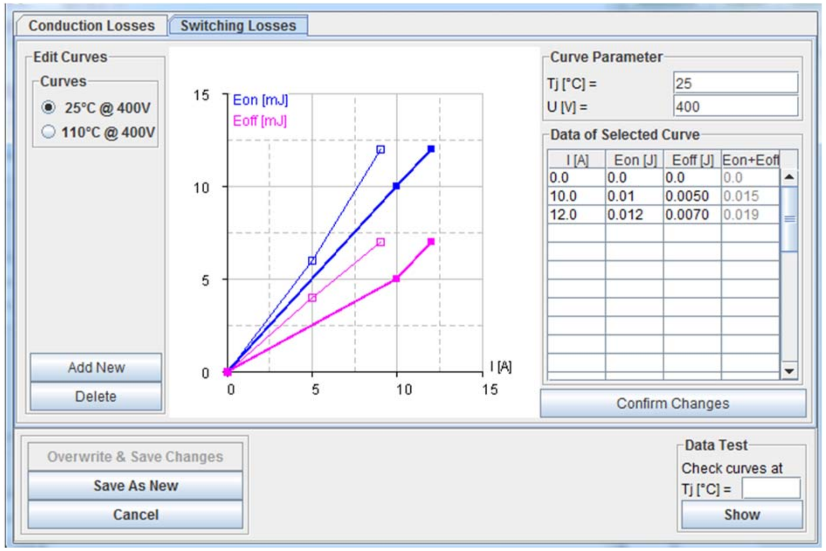
GeckoCIRCUITS - Strengths

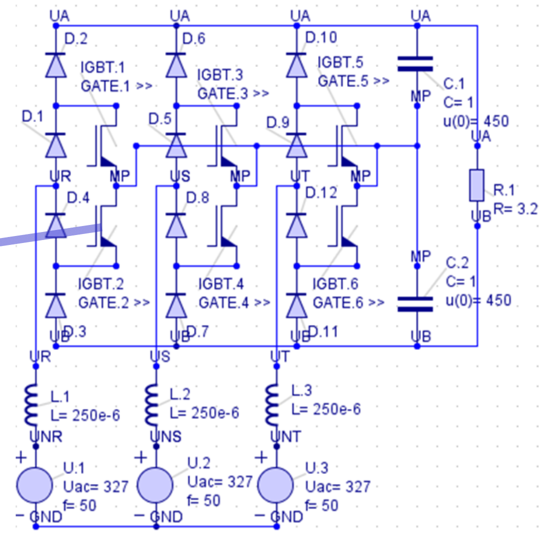
- Easy-to-learn system simulation
- Extremely fast and stable
- Simulation domains: Circuit, Control, Thermal



GeckoCIRCUITS – Circuit Simulation Features

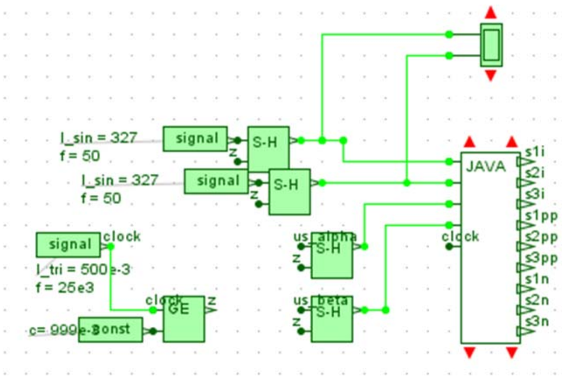
- Available switch models: Ideal switch, thyristor, IGBT, Diode
- Signal-controlled sources, non-linear capacitors and inductors
- Operational amplifier
- Machine models: PMSM, DC machine, ...
- Easy specification of thermal losses including temperature-dependent loss calculation:





GeckoCIRCUITS – Control Simulation Features

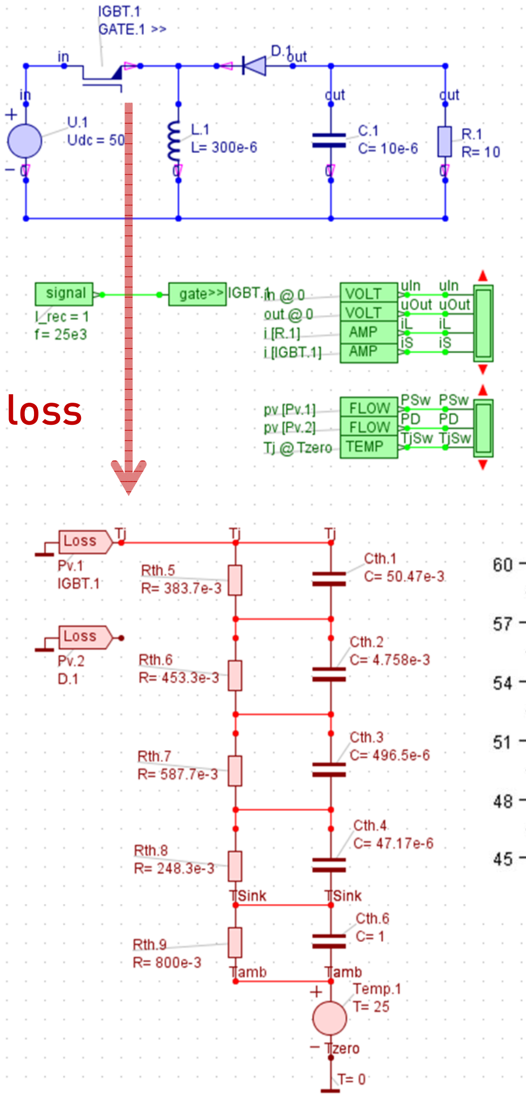
- Large repertoire of control building blocks:
  - digital functions
  - analog control blocks, e.g. integrators, PDI-Elements, ...
- JAVA-interface: write powerful control functions, e.g. state machines in the JAVA programming language

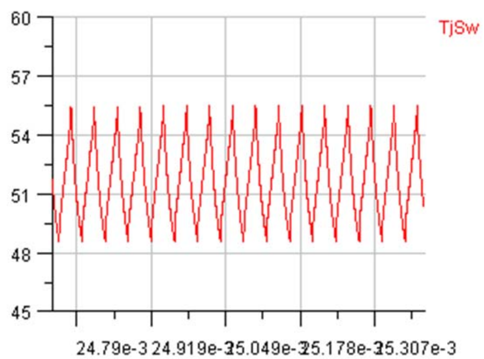



```java
//  Sparse Matrix modulator
//in[0]= Voltage fase A, main source
//in[1]= Voltage fase B, main source
//in[2]= Voltage alpha for output reference
//in[3]= Voltage beta for output reference
//in[4]= time, triangle for modulation stage
//========rectifier variables========

int sector_r=0,k;
double ang_r,  aux_r=0, out_r;
double is_alpha_r, is_beta_r,d_vec_0,d_vec_1, s0_r, s1_r,s1p,s2p,s3p,s1n,s2n,s3n,
double [][] u1_vector_sequence= {{0,1},{1,2},{2,3},{3,4},{4,5},{5,0}};
double [][] u1_vector_table ={{1,0,0,0,1,0},{1,0,0,0,0,1},{0,1,0,0,0,1},{0,1,0,1,
double cs_r, Ts_r, T_samp=1/25000,T;
double u1_vect_tau;

//========inverter variables========

int sector_i=0;
double ang_i,  aux_i=0,  M_u, t1 ,t2, t3, t4, t0, t1f, t2f, t3f, t4f, vec0, vec1,
double is_alpha_i, is_beta_i,d_vec_0i,d_vec_1i, mag_i;
double [][] u2_vector_sequence= {{0,1,7},{1,2,6},{2,3,7},{3,4,6},{4,5,7},{5,0,6}}
double [][] u2_vector_table ={{1,0,0},{1,1,0},{0,1,0},{0,1,1},{0,0,1},{1,0,1},{0,



//========alpha-beta transform========

is_alpha_r=xIN[0];
is_beta_r=2*((Math.sqrt(3)/2)*xIN[1]-(Math.sqrt(3)/2)*(-xIN[0]-xIN[1]))/3;
ang_r=Math.atan2(is_beta_r,is_alpha_r);
```

GeckoCIRCUITS – Thermal Simulation Features

power loss

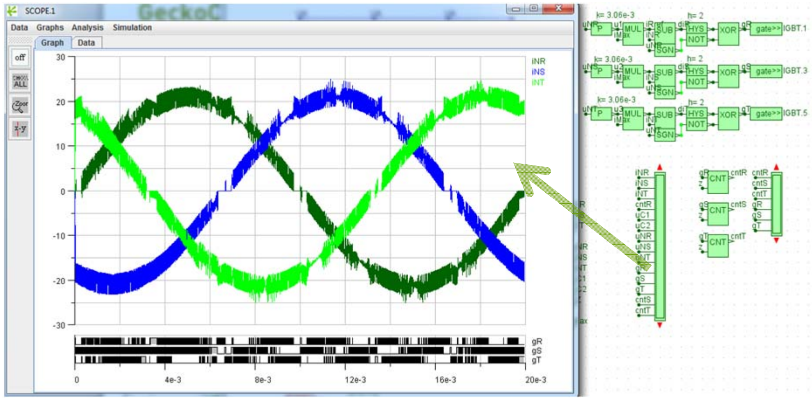


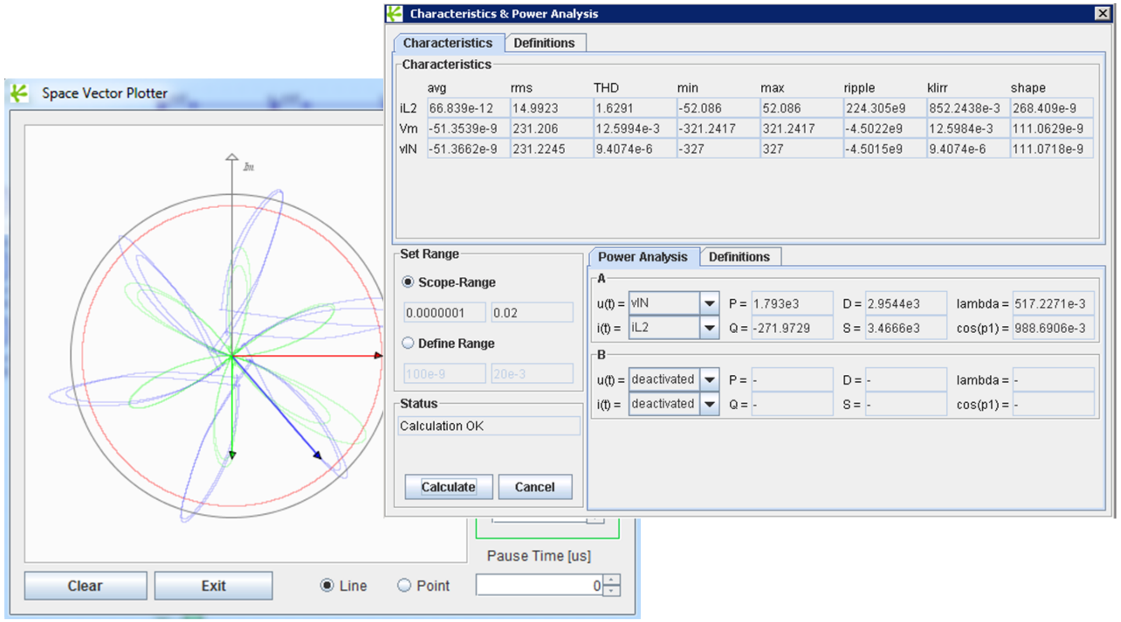


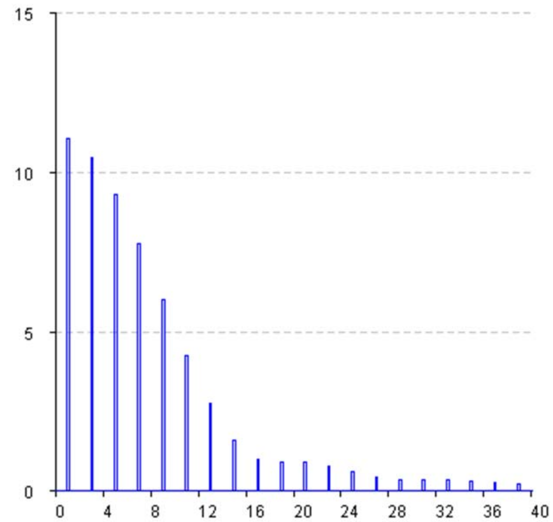
- Fast and accurate simulation of thermal networks
- Temperature dependent semiconductor loss calculation

GeckoCIRCUITS – Data Visualization, Postprocessing

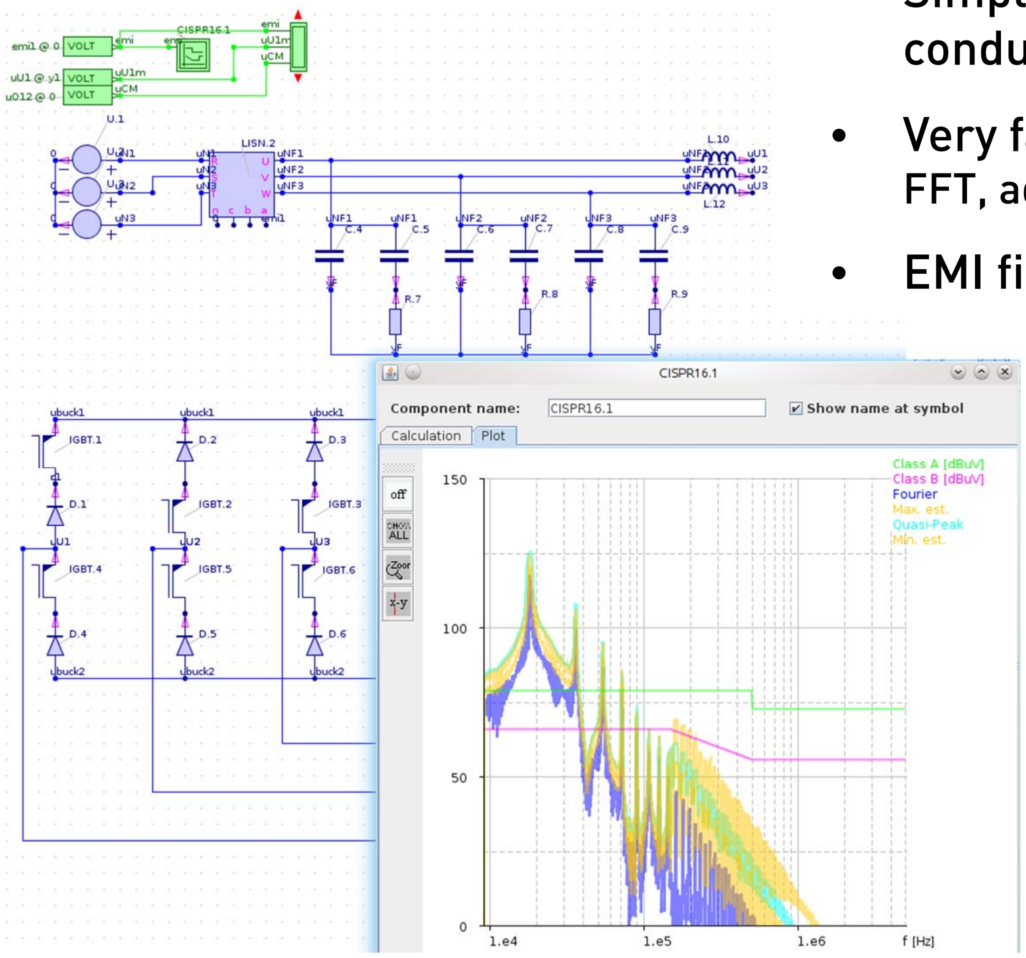
- Powerful «Scope» block for data visualization
- Waveform characterisitics calculation:
  - mean values, THD, ripple, power analysis
- Calculation of Fourier-transforms





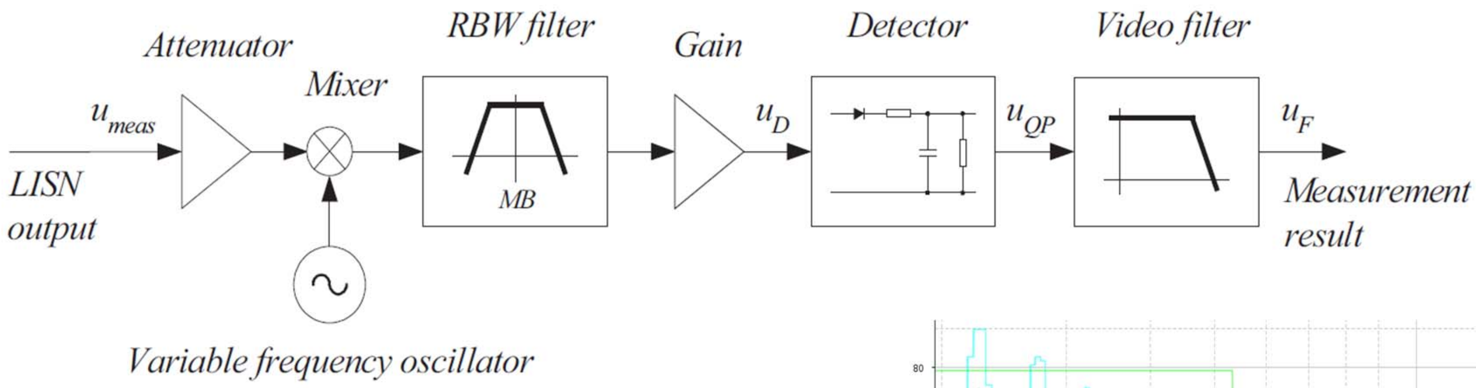


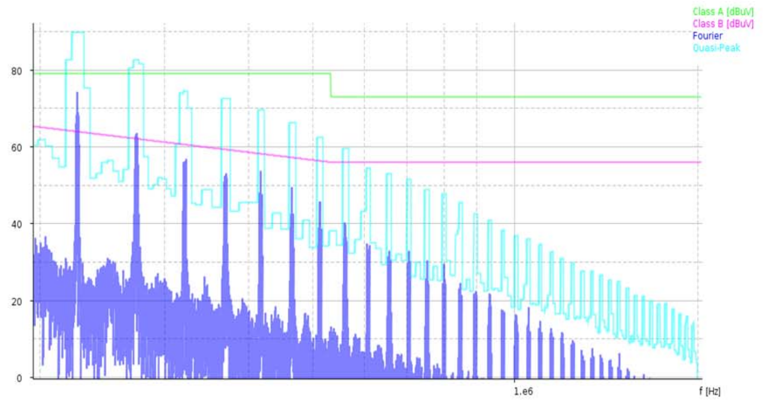
Feature: GeckoCIRCUITS – EMI calculation block



- EMI norm CISPR 16 (class A/B)
- Simple calculation / estimation of conducted noise emission
- Very fast algorithm required:
  FFT, advanced Quasi-Peak calculation
- EMI filter dimensioning «made easy»

Feature: GeckoCIRCUITS – EMI calculation block

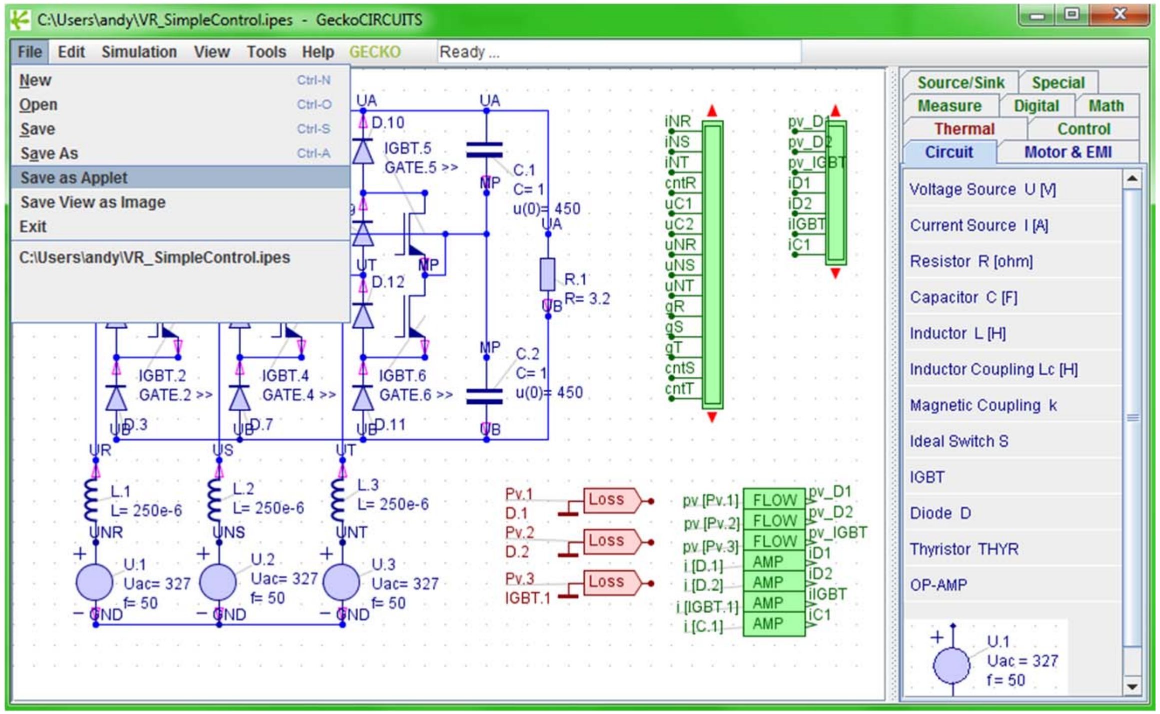




- Emulation of EMI test-receiver:
  Procedure is NOT just a Fourier transform!
- Proper weighting of frequencies within 9 kHz bandwidth filter («annoyance factor»)
- TD → FD → TD → FD domain conversions
- Numerical problems: EMI filter has strong attenuation (very bad S/N-Ratio)
- Fast algorithmic solution in GeckoCIRCUITS!

Feature: «Save-as-Applet»

- Easy distribution of your simulation models, e.g. for project reports
- Generate Java-applet including GeckoCIRCUITS & simulation model
- No software license for applet required
- You could even put the applet online and run in the browser!

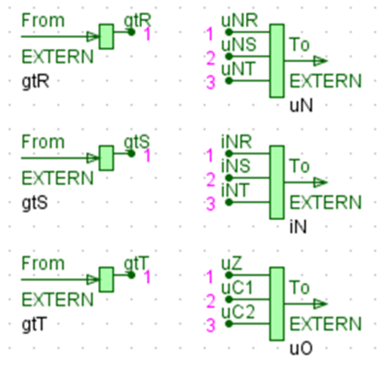


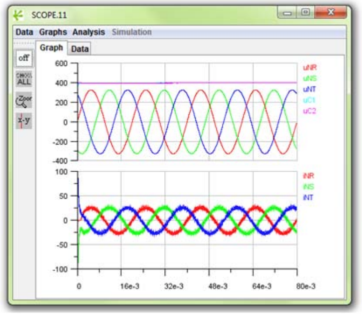
Java

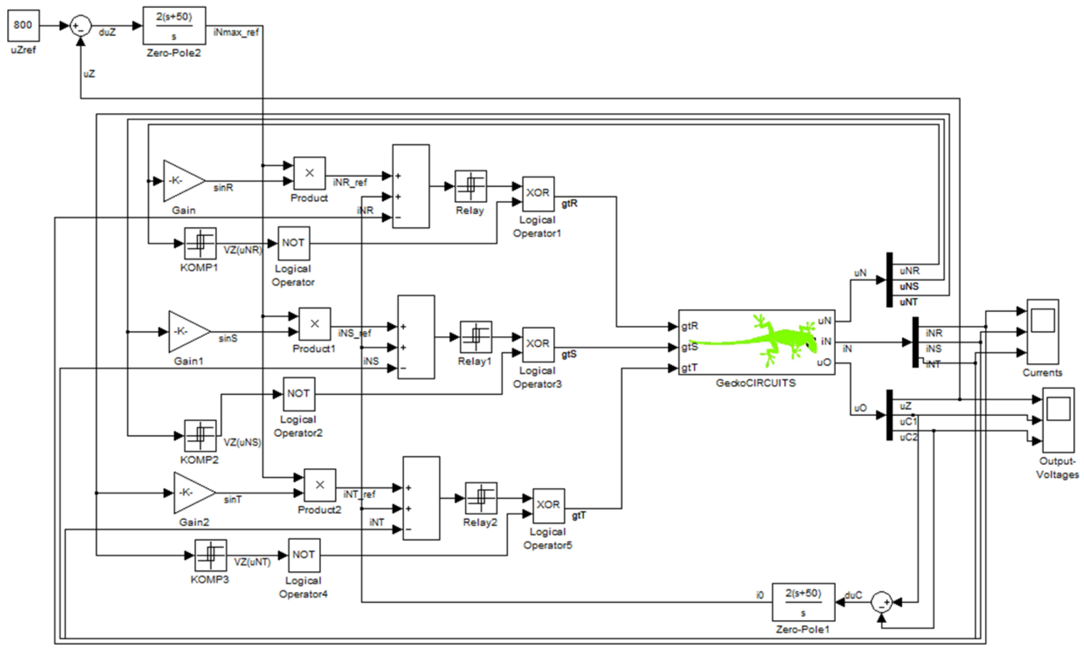
GECKO RESEARCH

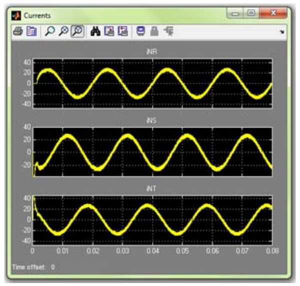
Feature: GeckoCIRCUITS – Simulink Coupling

- Existing control models in Simulink can easily be coupled to GeckoCIRCUITS
- GeckoCIRCUITS can «talk» to Simulink via S-Functions
- Fast and efficient, full functionality in Gecko

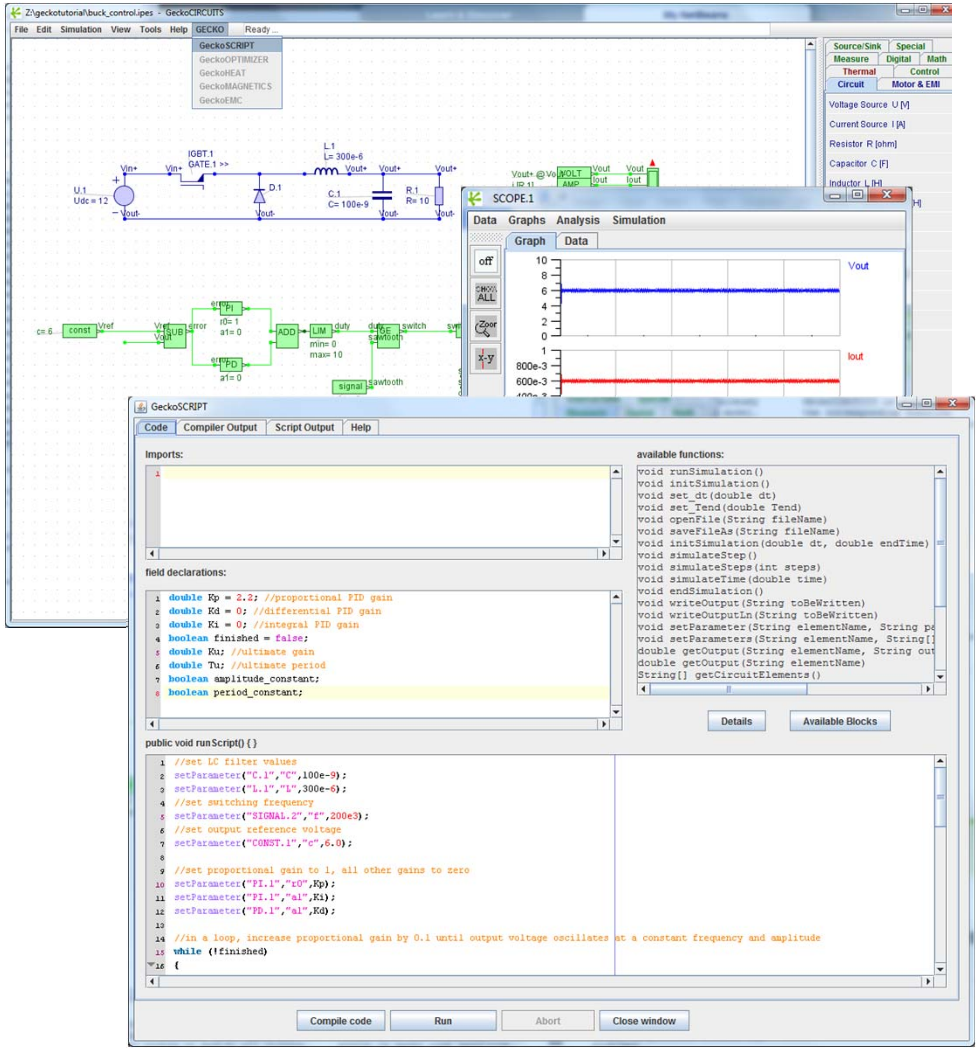








Feature: Simulation Control with GeckoSCRIPT

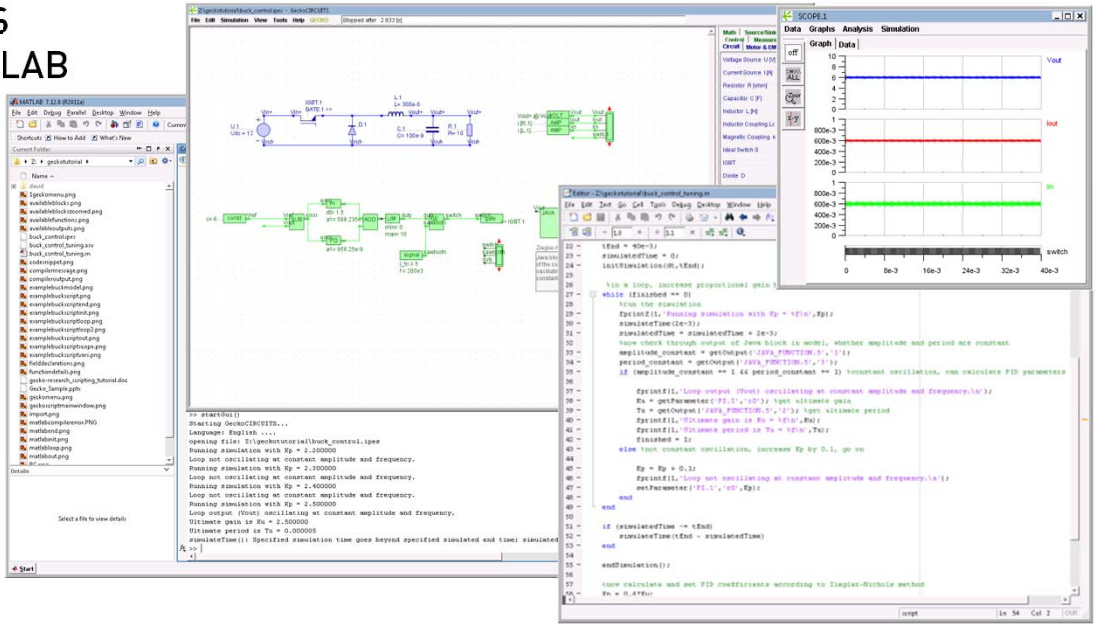


- New tool called GeckoSCRIPT included in GeckoCIRCUITS
- Script-based model and simulation control
- Using Java programming language
- Write scripts to:
  - modify model parameters
  - run simulations
  - examine results using functions provided by GeckoCIRCUITS
- Useful for automating:
  - Parameter sweep simulations
  - Optimizations of power converters

Feature: Control GeckoCIRCUITS from MATLAB

- All GeckoSCRIPT functions accessible in MATLAB
- Couple GeckoCIRCUITS with MATLAB:
  - Calculate and set Gecko model parameters in MATLAB
  - Run GeckoCIRCUITS simulations from MATLAB
  - Record and plot results for several simulations

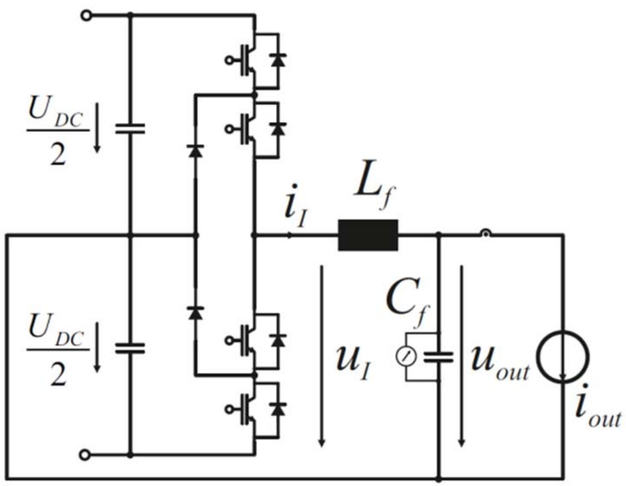
GeckoCIRCUITS running in MATLAB environment

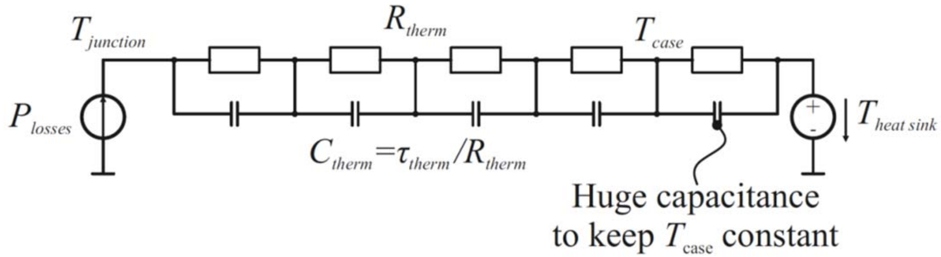


M-file control s GeckoCIRCUITS simulation

GeckoSCRIPT Example: Inverter Optimization

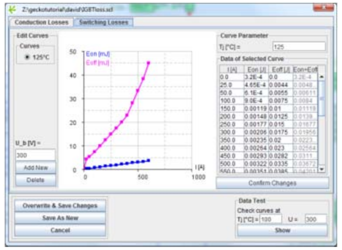
- NPC inverter – output stage of AC grid simulator
- Junction to ambient thermal model of IGBT module as Foster network
- Task: determine:
  - **Maximum RMS output current** at a given output frequency for a given switching frequency
  - Must not exceed max junction temperature (130 °C)



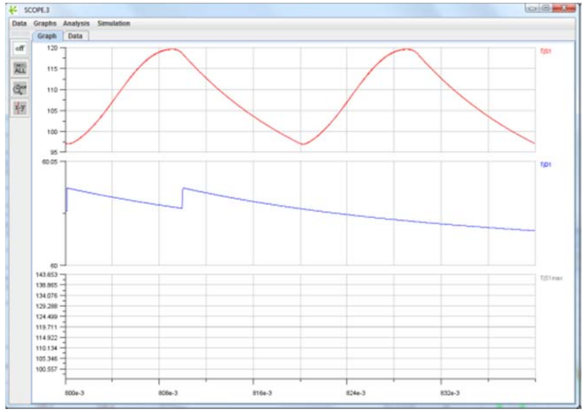


GeckoSCRIPT Example: Inverter Optimization

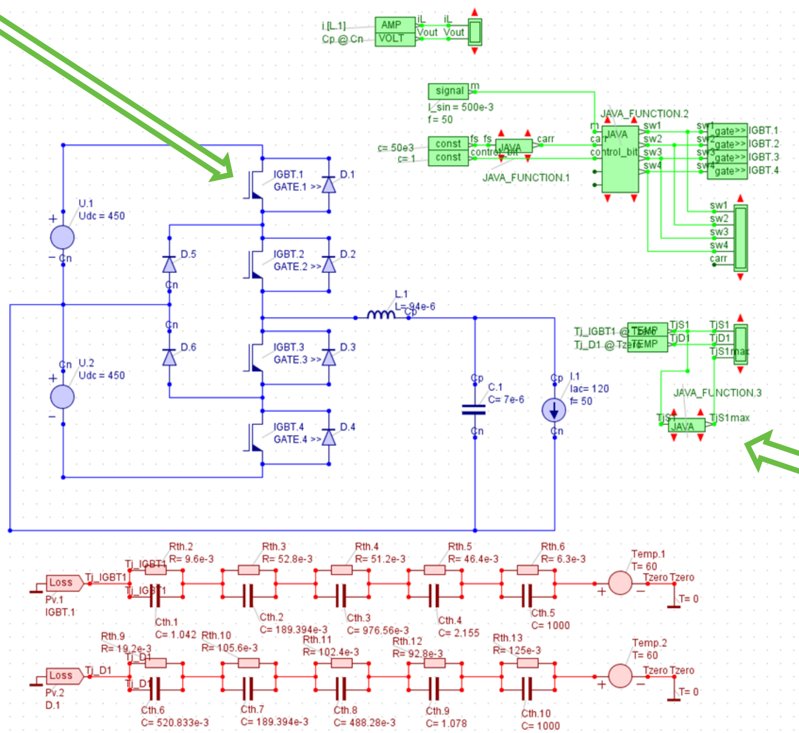
- First step: create detailed model in GeckoCIRCUITS



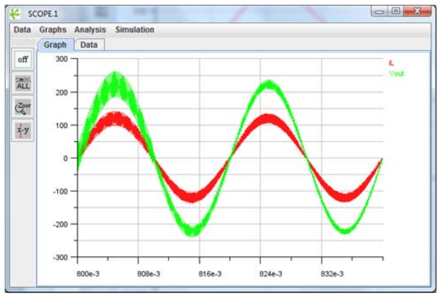
Conduction / switching losses for IGBTs / diodes



Junction temperature



Java-function to keep track of $T_{j,max}$



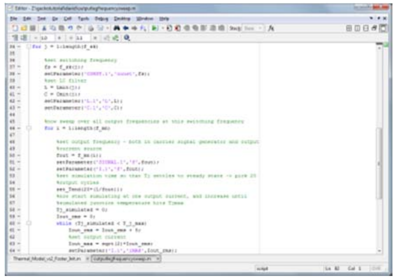
Output voltage and current

Thermal model

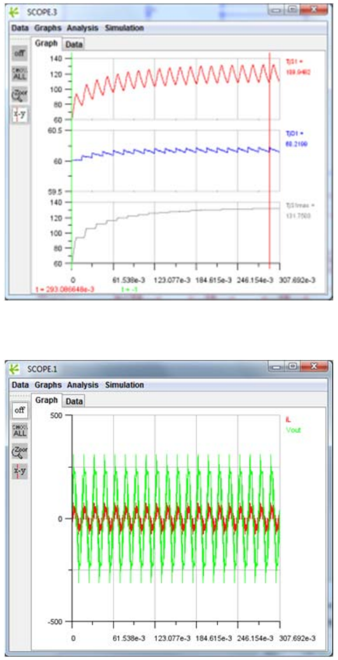
GeckoSCRIPT Example: Inverter Optimization

- Next step: simulations in MATLAB:
- For each switching frequency:
  Simulate at different output frequencies with different output currents until $T_{j,max}$ is reached

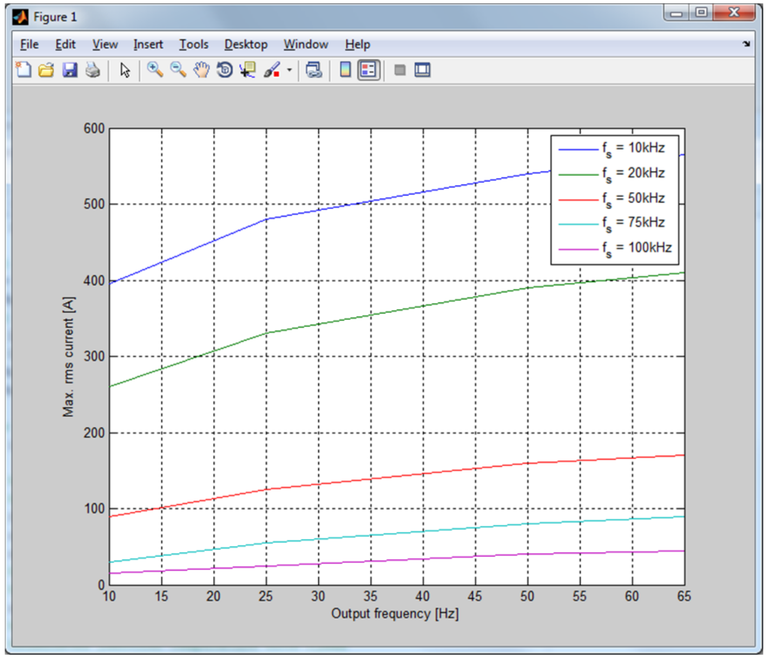
Results: Max. RMS I_{out} versus f_{out} for a given f_{sw}



MATLAB script

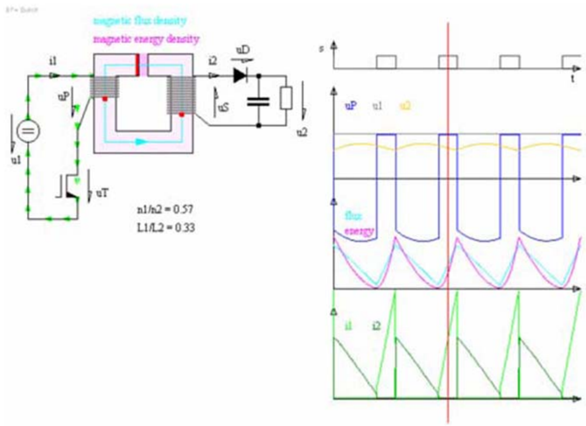


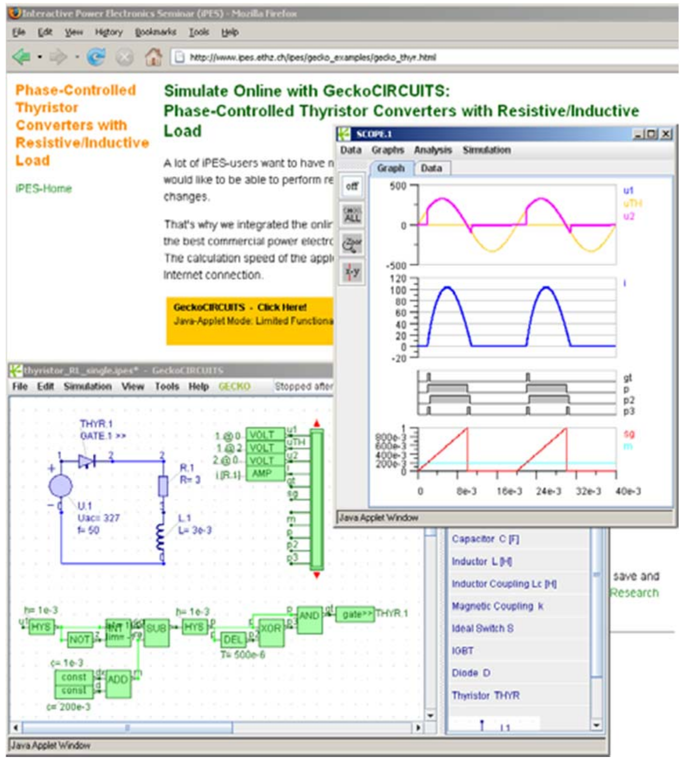
GeckoCIRCUITS simulations



GeckoCIRCUITS – Education at ETH Zürich

- Dedicated simulation / computer exercises in the power electronics courses
- iPES – online seminar with Java applets
  www.ipes.ethz.ch
- GeckoCIRCUITS also as online applet
  www.gecko-research.com
- ETH Zürich: power electronics exercises combined with online applets
  http://www.pes.ee.ethz.ch → education





Future Development of GeckoCIRCUITS (Version 2.0)

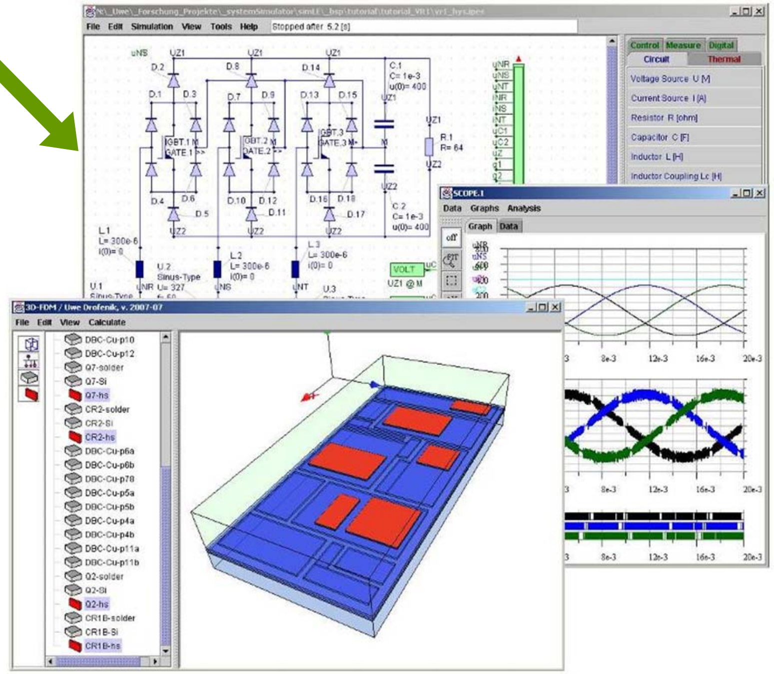
- Variable / adaptive simulation step-width
- Fast steady state calculation
- Reluctance models for transformers / magnetic circuits
- Detailed transformer database
- More detailed switch models (MOSFETS, bipolar transistors, ...)
- Subcircuits
- Frequency-domain circuit solution
- Connection of GeckoCIRCUITS to 3D field solvers:
  - GeckoEMC: calculation of layout parasitics
  - GeckoHEAT: 3D finite element thermal simulation

Further increases calculation speed
→ Optimization!

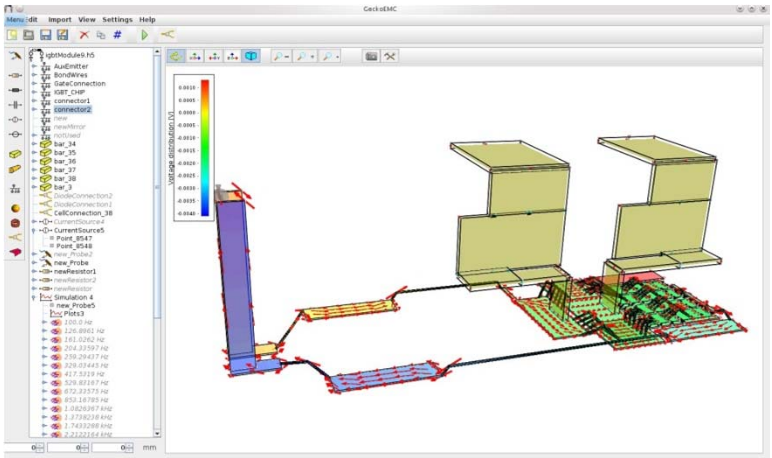
Putting all together – Model Order Reduction

Model Order Reduction

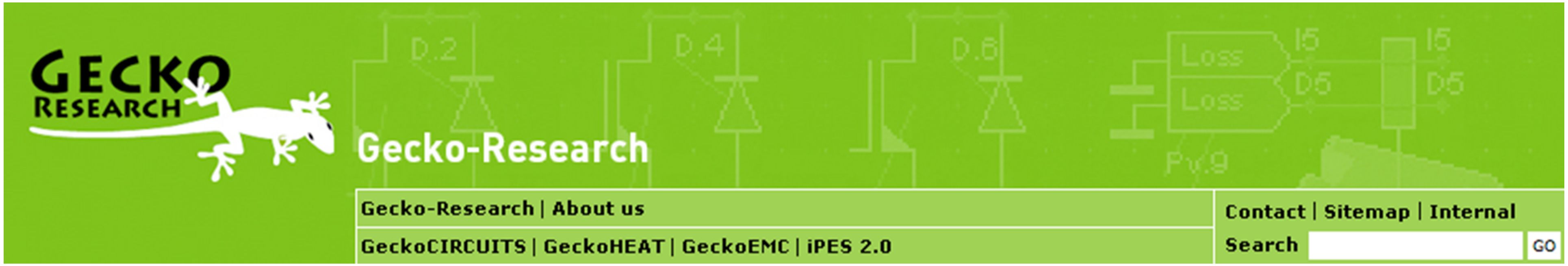
Circuit Simulator



PEEC Simulation Environment



3D FDM Thermal Solver



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