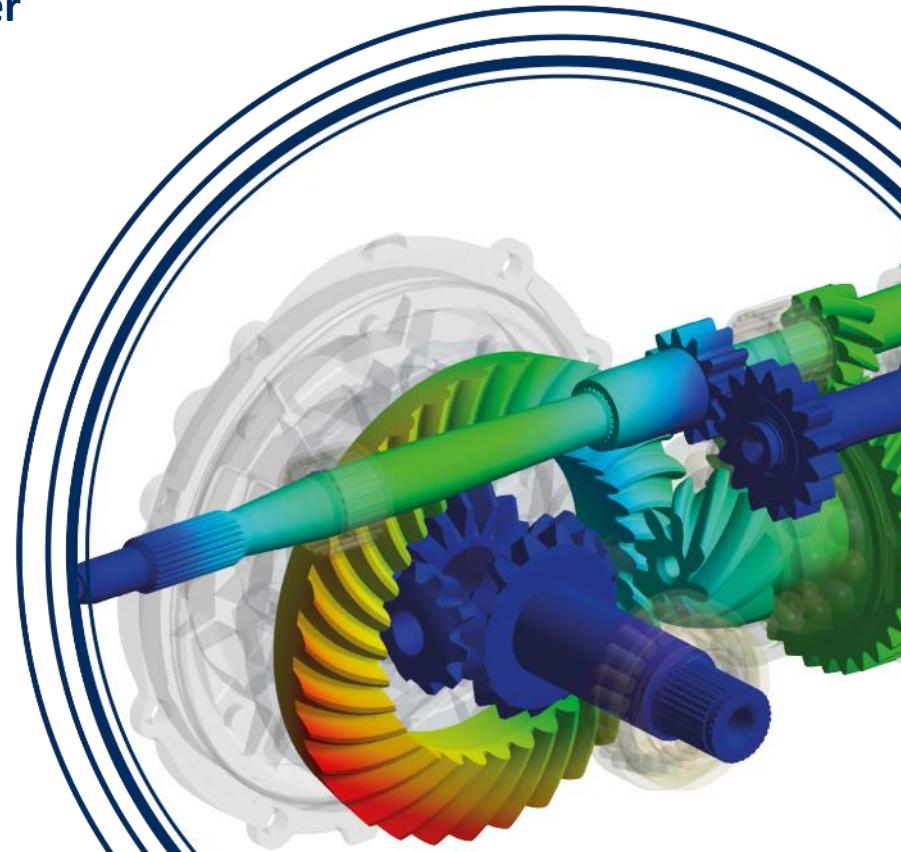


# Neue Möglichkeiten in Maxwell zur Simulation von Leistungselektronik

New possibilities in Maxwell for the simulation of power  
electronics

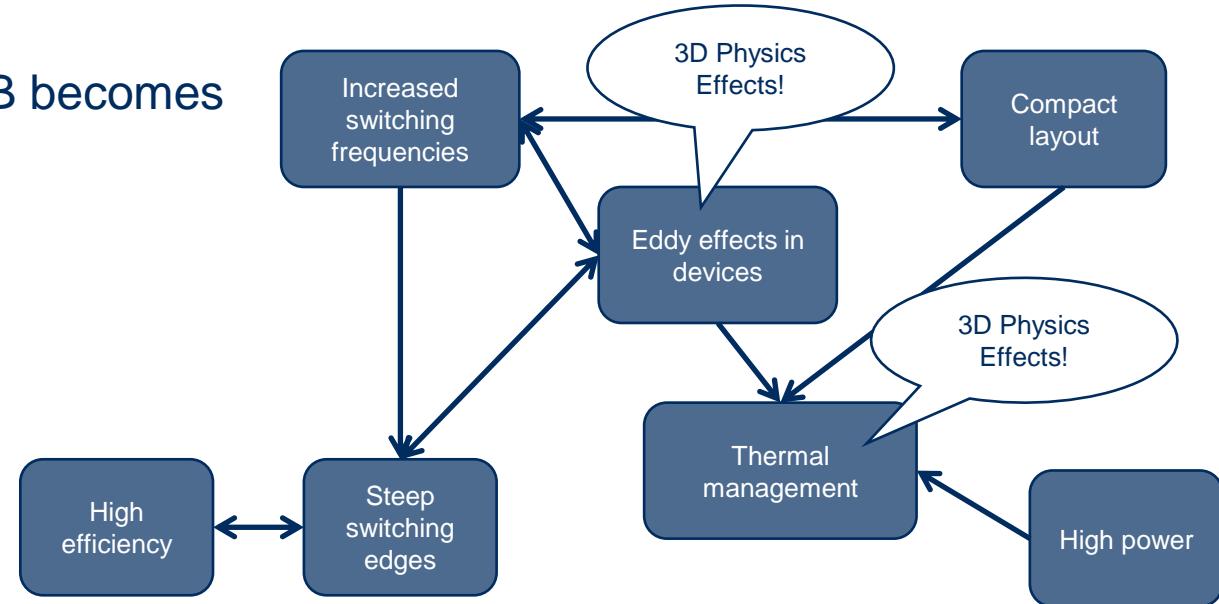
CADFEM Elektromagnetik Technologietage 2021  
Leistungselektronik  
18. Juni 2021

Rene Fuger, CADFEM (Austria) GmbH



# Challenges for Power Electronics Applications

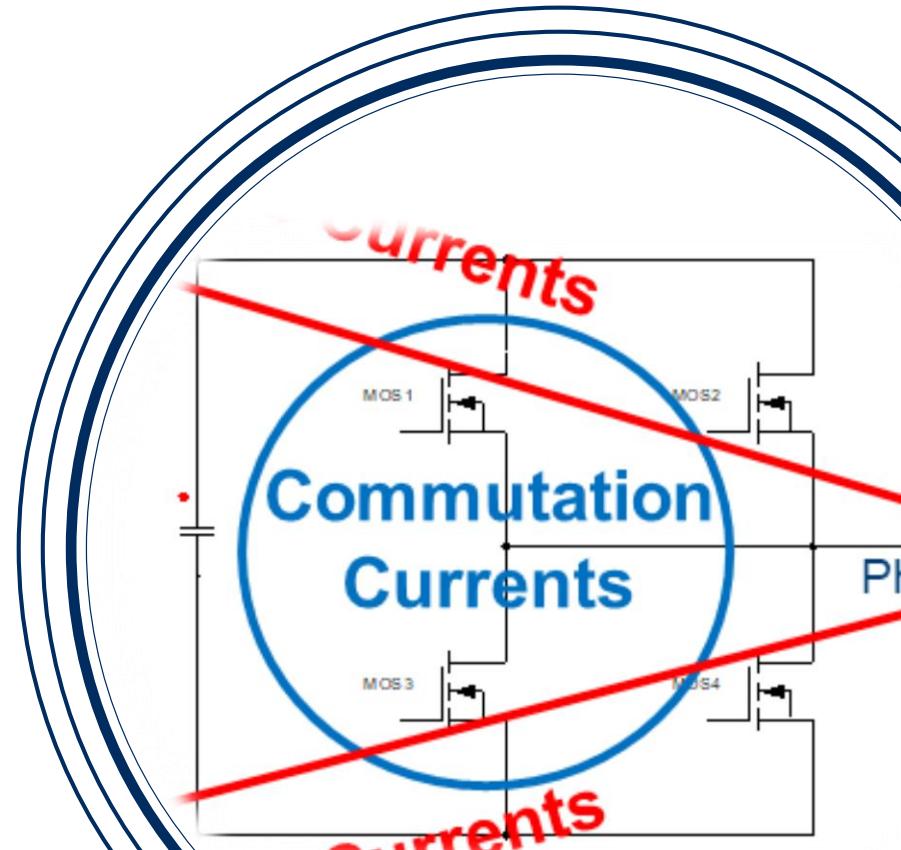
- With *decreasing size* and *increasing power* hardware design gets more difficult.
- Understanding and determining *local behavior* is becoming increasingly important.
- Local *loss distributions* on the PCB becomes more significant.



# Agenda

- Efficient calculation of solid losses in a half bridge circuit
  - Local loss distribution
  - Using harmonic solver to calculate the frequency dependent loss contributions
  - Using transient solver to calculate the local time dependent loss distribution
- Local current distribution in busbars
  - Unbalanced loads for capacitors
- First resonance of an inductor
  - Eddy current analysis to determine the inductance
  - AC conduction analysis to determine the capacity

# Local Loss Distribution



CADFEM®

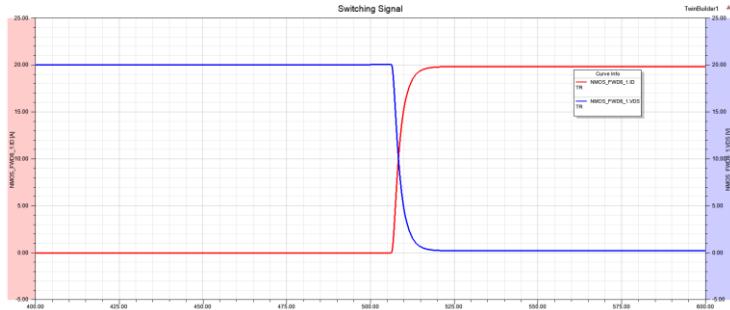
Ansys

CERTIFIED  
ELITE CHANNEL  
PARTNER

# Switching vs Ohmic Losses

## Switching losses in semiconductor

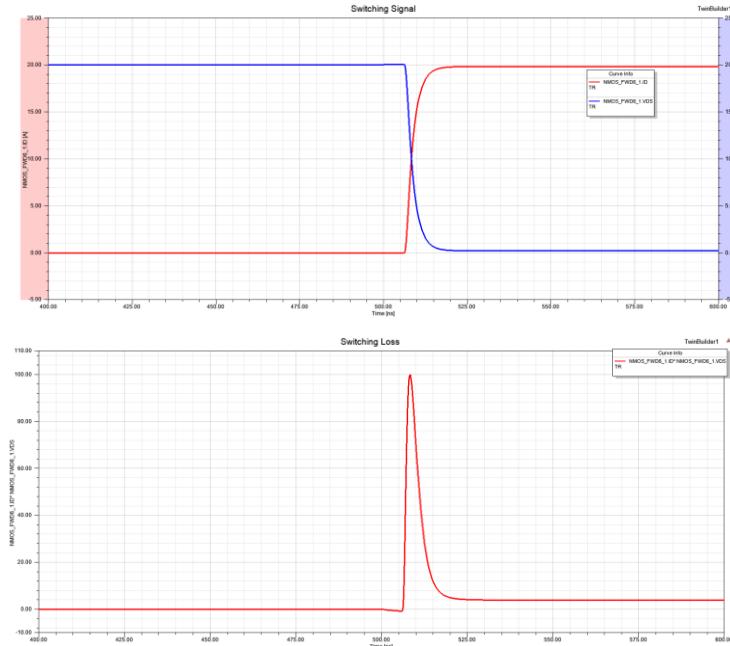
- Frequency content very high according to Nyquist criterium ( $>> f_{\text{PWM}}$ )
- The switching time is significant



# Switching vs Ohmic Losses

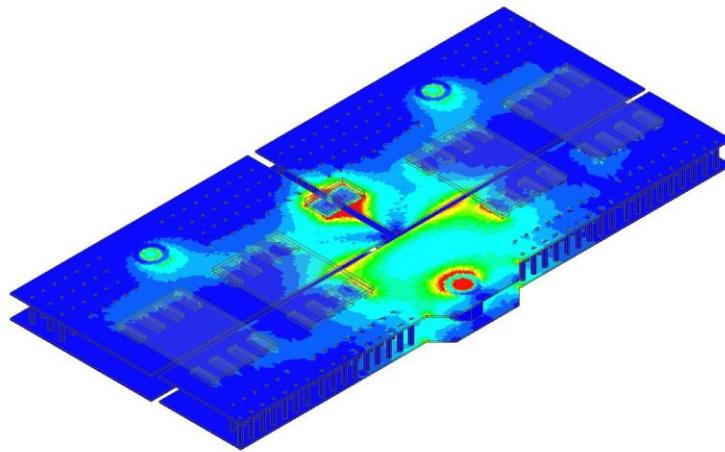
## Switching losses in semiconductor

- Frequency content very high according to Nyquist criterium ( $>> f_{\text{PWM}}$ )
- The switching time is significant



## Ohmic losses in copper

- Losses at phase frequency and harmonics of PWM frequency ( $f_{\text{PWM}}$ )
- Eddy effects significant at  $f_{\text{PWM}}$



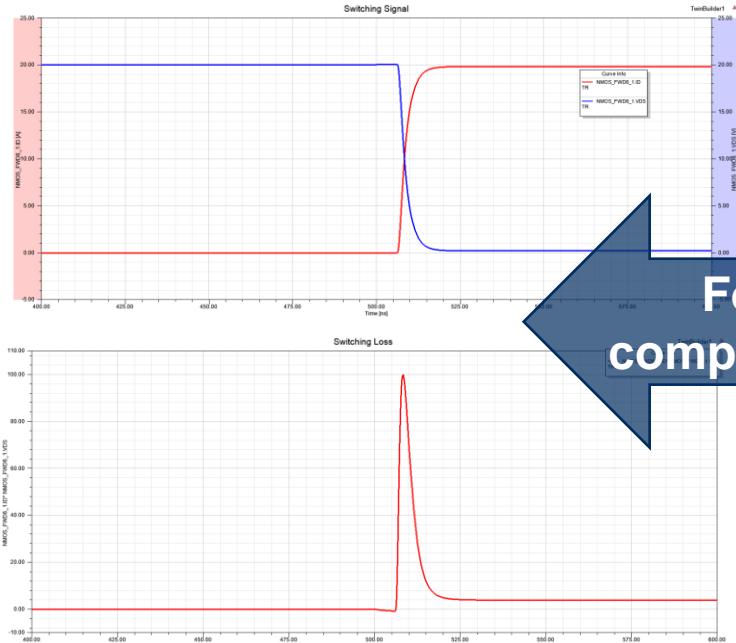
# Switching vs Ohmic Losses

## Switching losses in semiconductor

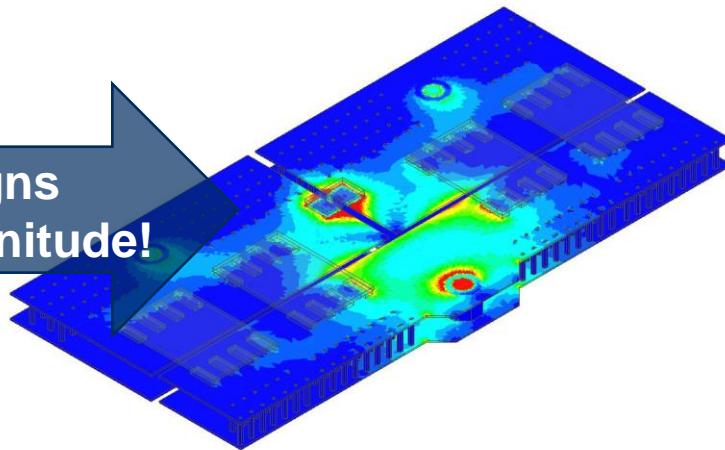
- Frequency content very high according to Nyquist criterium ( $>> f_{\text{PWM}}$ )
- The switching time is significant

## Ohmic losses in copper

- Losses at phase frequency and harmonics of PWM frequency ( $f_{\text{PWM}}$ )
- Eddy effects significant at  $f_{\text{PWM}}$



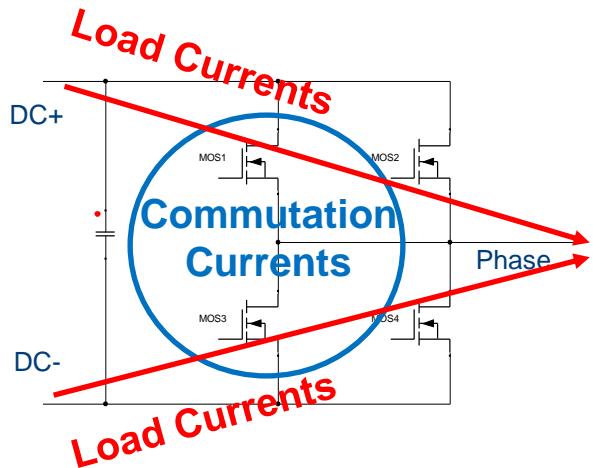
For many designs  
comparable in magnitude!



# Distribution of Ohmic Losses (Joule Heat)

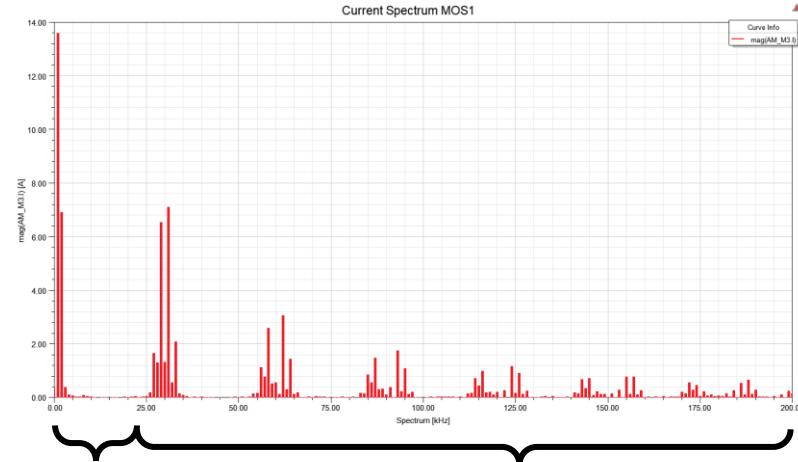
## Current path

- The current path is not straight forward, and loops exists on the circuit board.
- Eddy and coupling effects leads to inhomogeneous current distribution.



## Current pattern

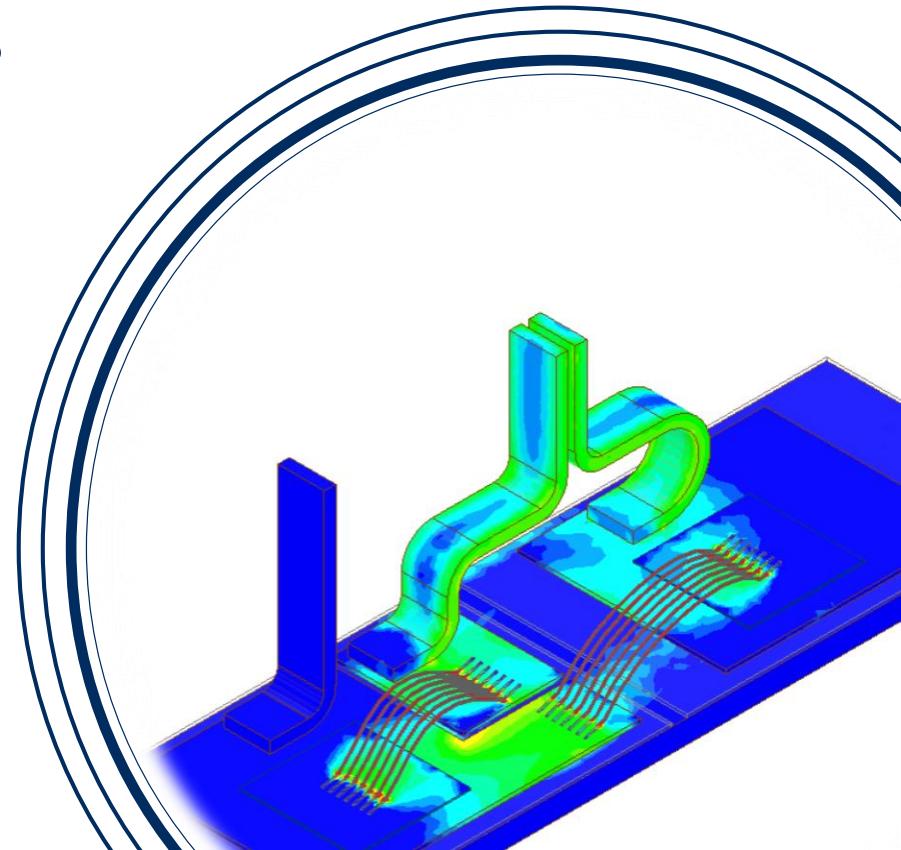
- Spatial current density distribution are frequency dependent.
- The current is separated into different harmonic contributions.



Load Currents

Commutation Currents

# Using Harmonic Solver to Calculate the Frequency dependent Loss Contributions



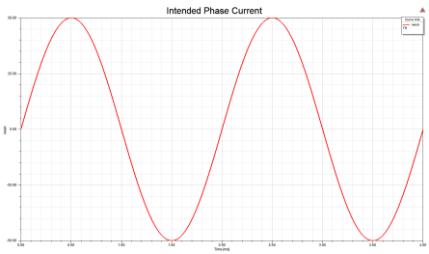
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Ansys

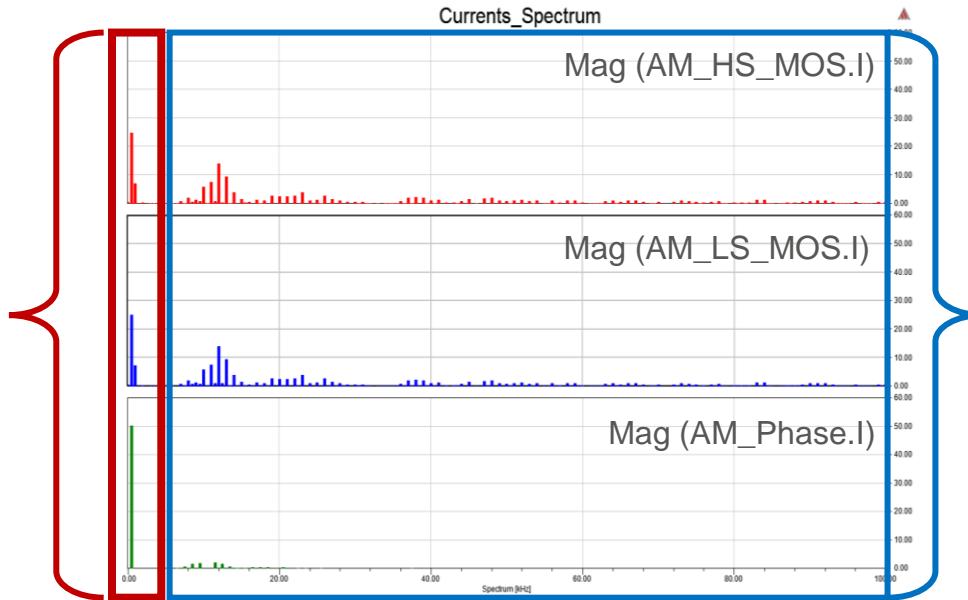
CERTIFIED  
ELITE CHANNEL  
PARTNER

# Currents in Phase Net of First Half Bridge

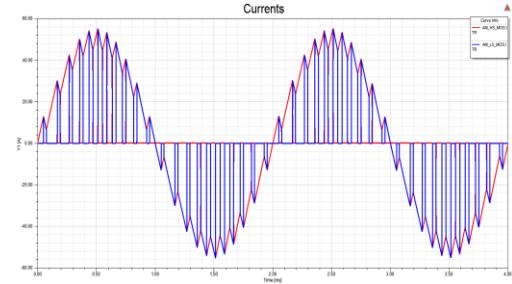
Contribution from base signal  
(Sine Wave)



Contribution from commutation currents  
(higher spectral content due to modulation effects and rectangular signals)



Sine (500Hz)

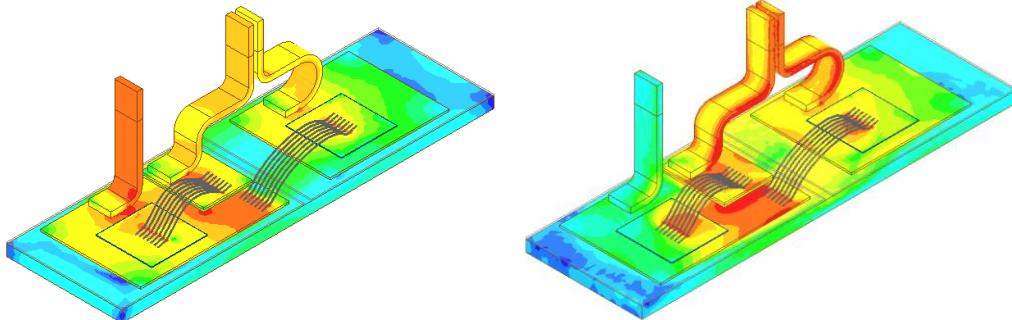


PWM Frequency (120kHz)

# Reduction to two Loss Distributions

## Pointwise Split of Losses into Spectral Contributions

- We are assuming a periodic mode of operation.
- PWM and sinusoidal load frequency are commensurable.
- Local ohmic loss distribution is given in terms of the electric field and the current density.
- Decompose time averaged loss distribution into frequency contributions



$$\bar{p}(\vec{r}) = \frac{1}{T} \int_0^T dt \vec{E}(\vec{r}, t) \cdot \vec{j}(\vec{r}, t)$$

Fourier–  
Orthonormal  
function system  
(in time)

$$\bar{p}(\vec{r}) = \vec{E}^{(0)}(\vec{r}) \cdot \vec{j}^{(0)}(\vec{r}) + \frac{1}{2} \sum_{k=1}^{\infty} \text{re} \left( \vec{E}^{(k)}(\vec{r}) \cdot \vec{j}^{(k)*}(\vec{r}) \right)$$

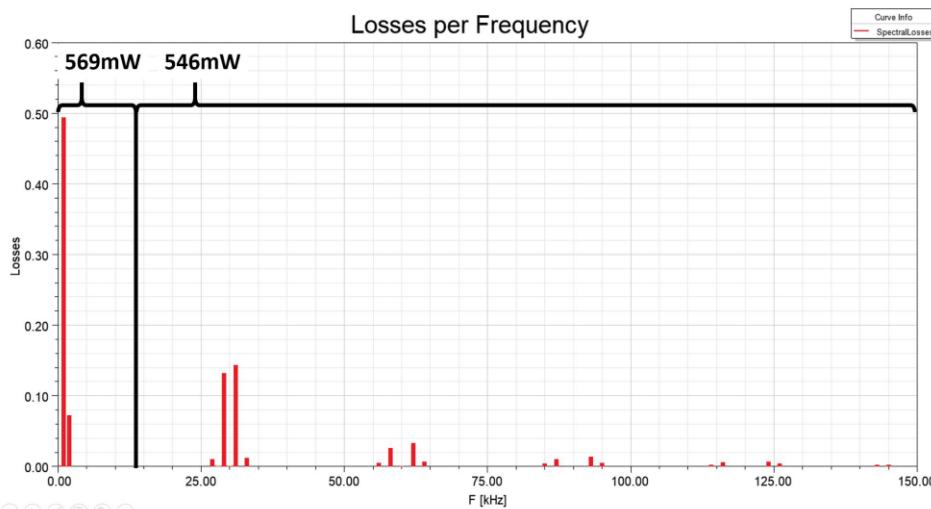
$$\vec{E}(\vec{r}, t) = \sum_{k=0}^{\infty} \text{re} \left( \vec{E}^{(k)}(\vec{r}) e^{2\pi i k \frac{t}{T}} \right)$$

$$\vec{j}(\vec{r}, t) = \sum_{k=0}^{\infty} \text{re} \left( \vec{j}^{(k)}(\vec{r}) e^{2\pi i k \frac{t}{T}} \right)$$

# Summing up the Losses

## Split of Losses into Spectral Contributions

- The currents and the voltages at the various terminals can be written as a Fourier series.
- In time direction currents and voltages are expanded in Fourier expansion
  - Orthogonal system of functions
  - Losses can be calculated in a Pythagorean way



Fourier–  
Orthonormal  
function system  
(in time)

$$\bar{P} = \frac{1}{T} \int_0^T dt \sum_m I_m(t) V_m(t)$$

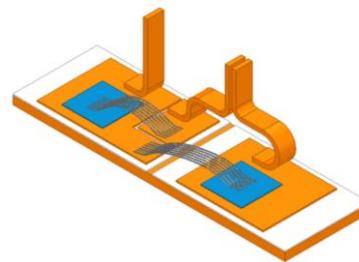
$$I_m(t) = \sum_{k=0}^{\infty} \operatorname{re} \left( I_m^{(k)} e^{2\pi i k \frac{t}{T}} \right)$$

$$V_m(t) = \sum_{k=0}^{\infty} \operatorname{re} \left( V_m^{(k)} e^{2\pi i k \frac{t}{T}} \right)$$

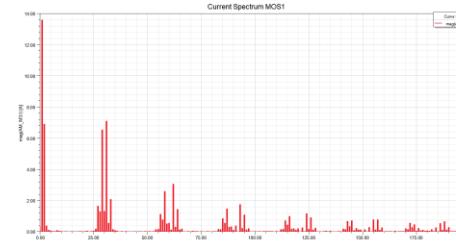
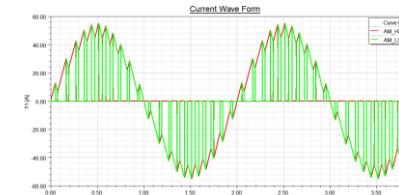
$$\bar{P} = \sum_m I_m^{(0)} V_m^{(0)} + \frac{1}{2} \sum_m \sum_{k=1}^{\infty} \operatorname{re} \left( I_m^{(k)} V_m^{(k)*} \right)$$

# Simulation Workflow

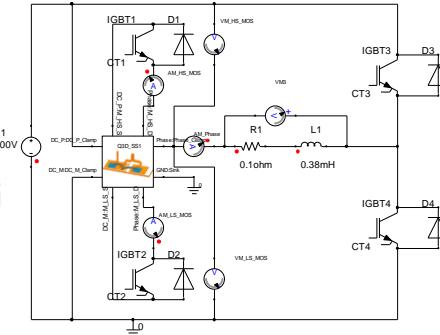
Parasitic extraction using ANSYS Q3D Extractor



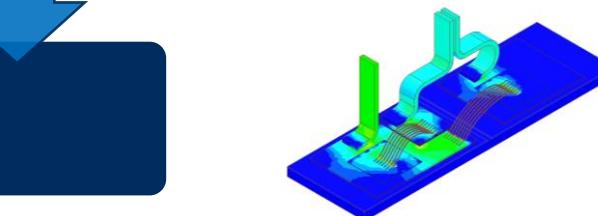
Determining the current wave forms using ANSYS Simplorer



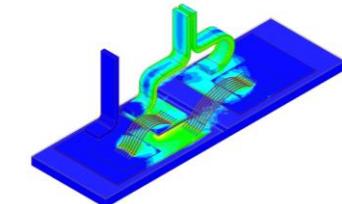
Calculating spectrum of the Ohmic Losses using ANSYS Circuit



Determining the actual current distribution using ANSYS Maxwell



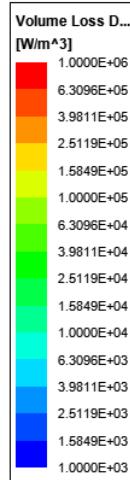
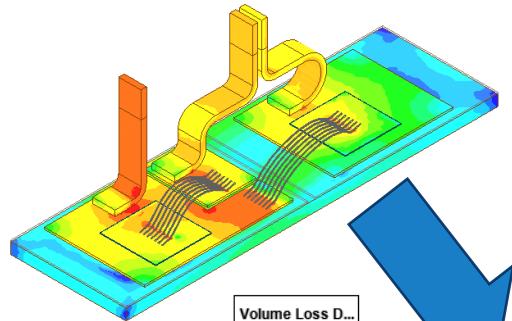
Losses from load current at 500Hz



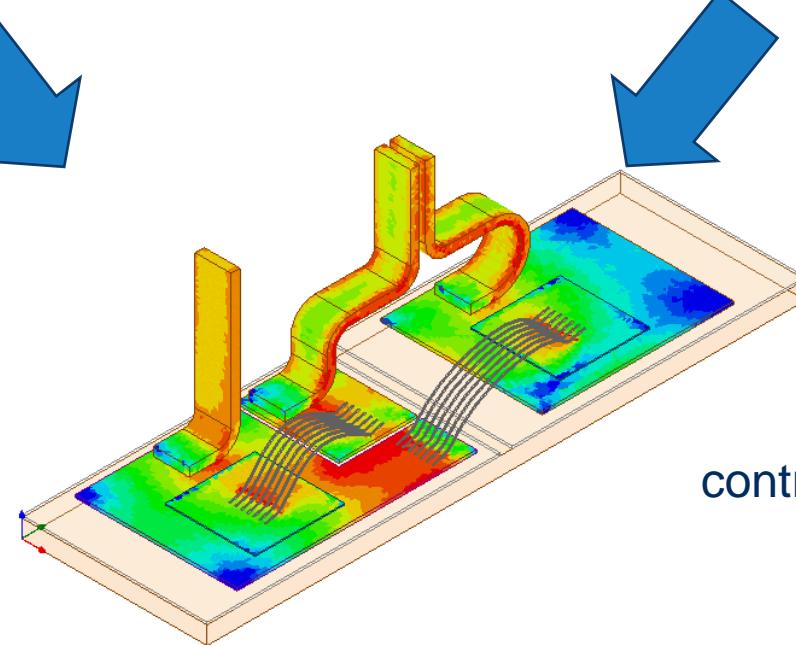
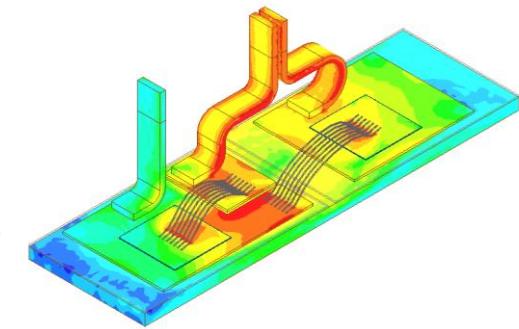
Losses from commutation current at 10kHz

# Average Losses Distribution

Losses from load  
current at 500Hz

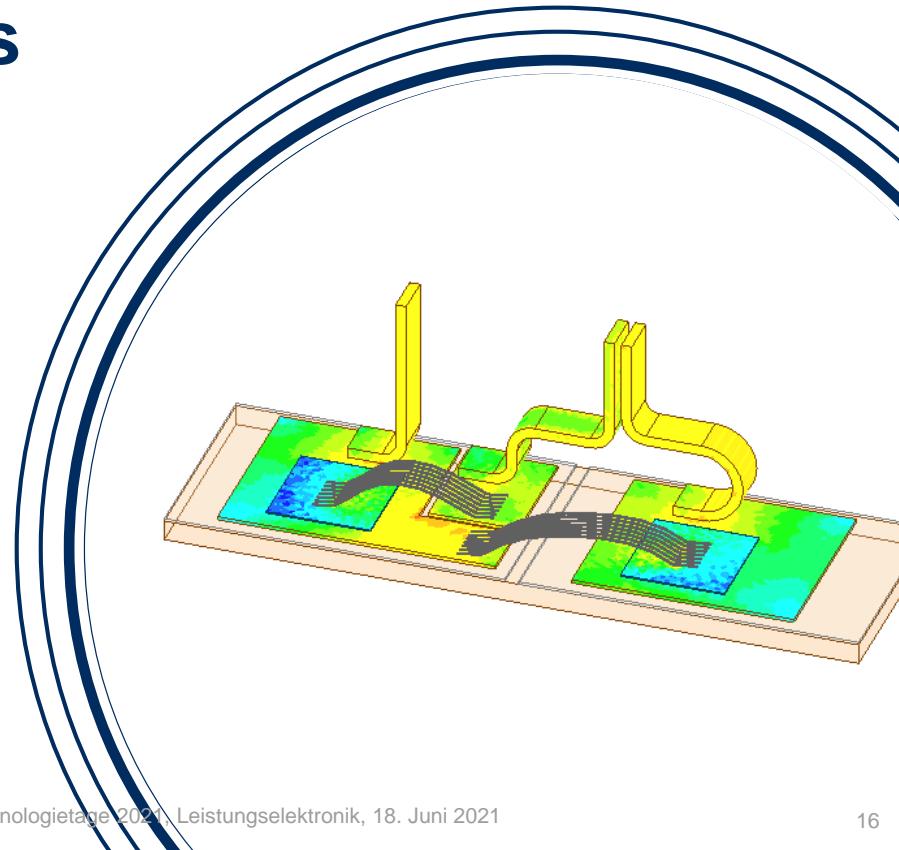


Losses from commutation  
current at 10kHz



Addition of the loss  
contributions for the thermal  
simulation

# Using Transient Solver to Calculate the Local Time Dependent Loss Distribution



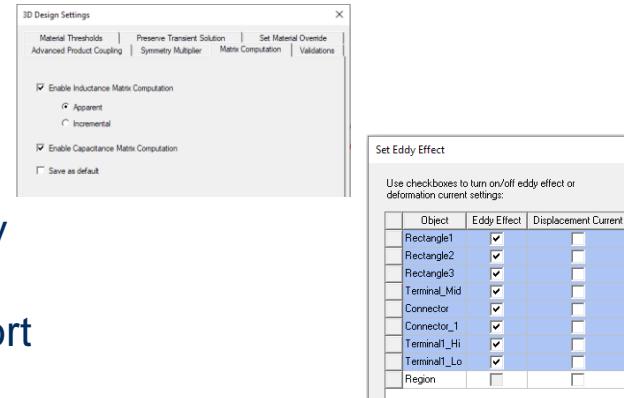
# Maxwell Transient A-Φ Solver

A new transient solver in Ansys Maxwell based on A-Φ Formulation (magnetic vector potential A and electric scalar potential Φ)

A (semi)full wave solver including displacement (capacitive) and eddy (inductive) effects

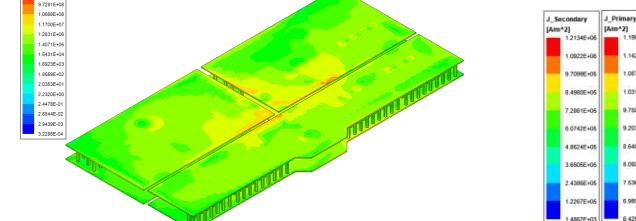
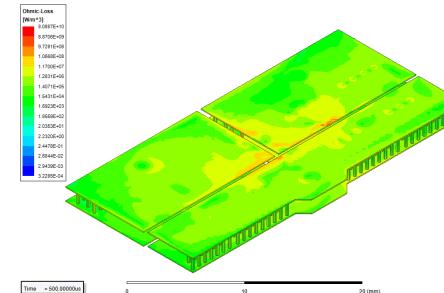
## Features

- Partial inductance calculation
- Capacitance Matrix
- J and E fields calculated directly
- Displacement effect
- Multi-terminal conductors support
- ...



## Applications

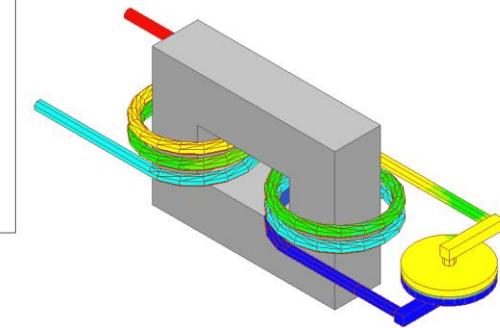
- Inverter
- Bus bars
- Electronic transformer
- High voltage/electric field devices
- ...



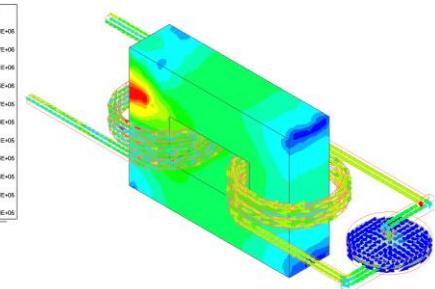
$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{E} = -\frac{d\mathbf{A}}{dt} - \nabla \varphi$$

## Voltage Conductor



## Current & B-Field



# Simple Half Bridge - Design Setup

## External Terminals

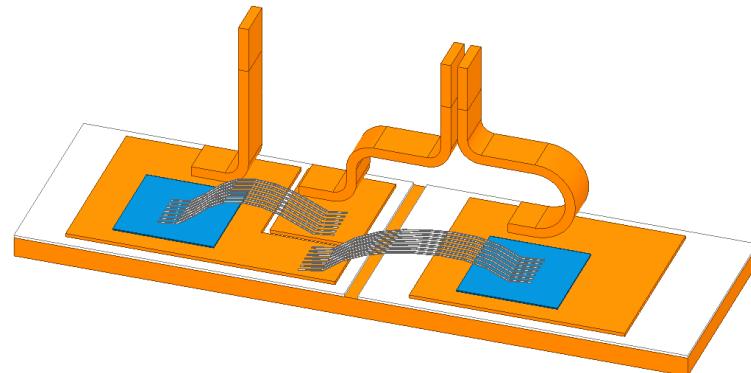
- DC+, DC- and Phase

## Internal Terminals

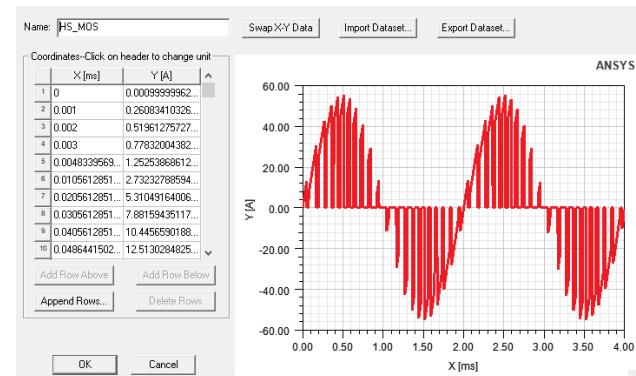
- High Side MOSFETS
- Low Side MOSFETS

## Nets

- DC\_M, DC\_P and Phase

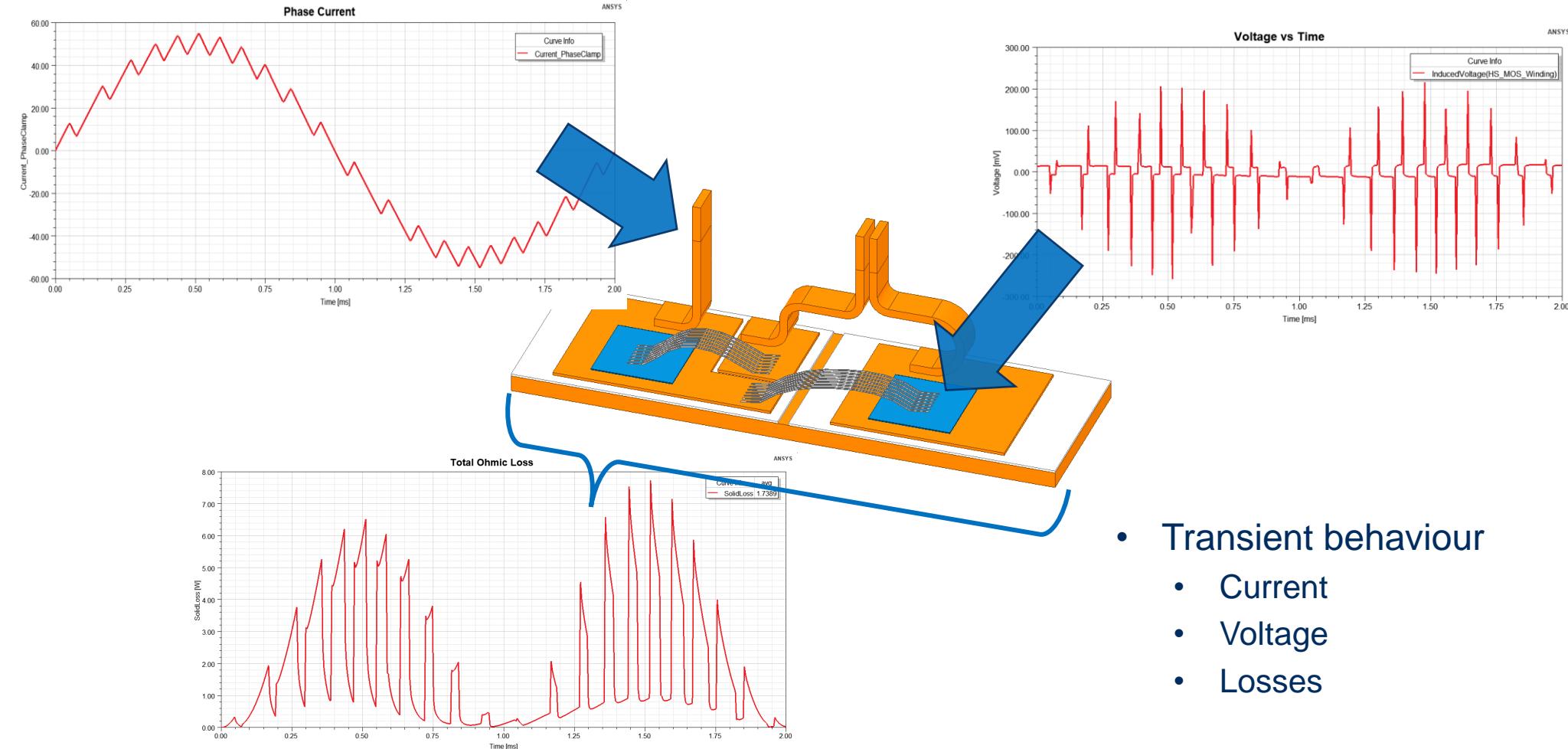


## Excitation



# Simple Half Bridge - Phase Current & Ohmic Loss

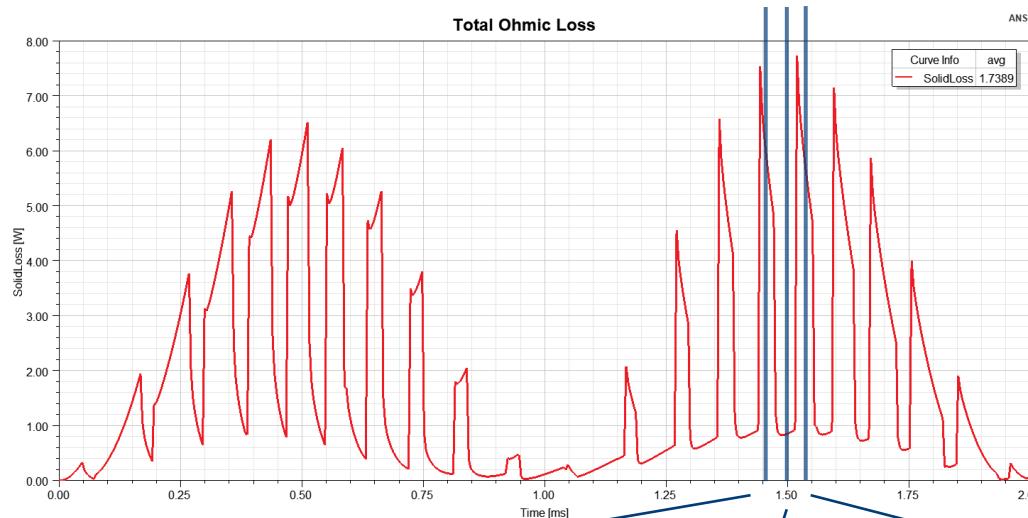
CADFEM®



- Transient behaviour
  - Current
  - Voltage
  - Losses

# Simple Half Bridge - Local Losses

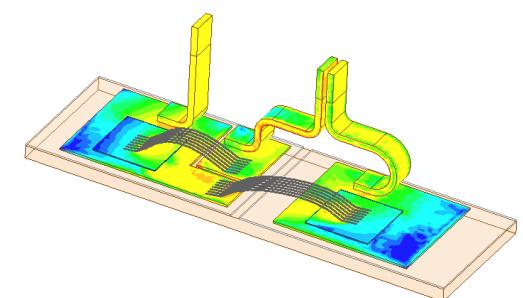
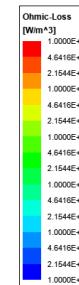
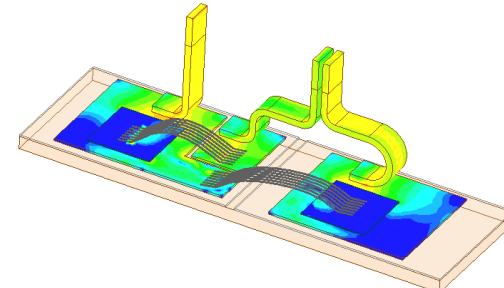
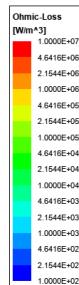
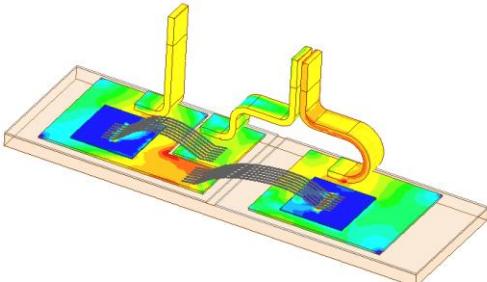
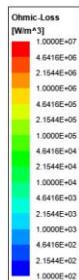
CADFEM®



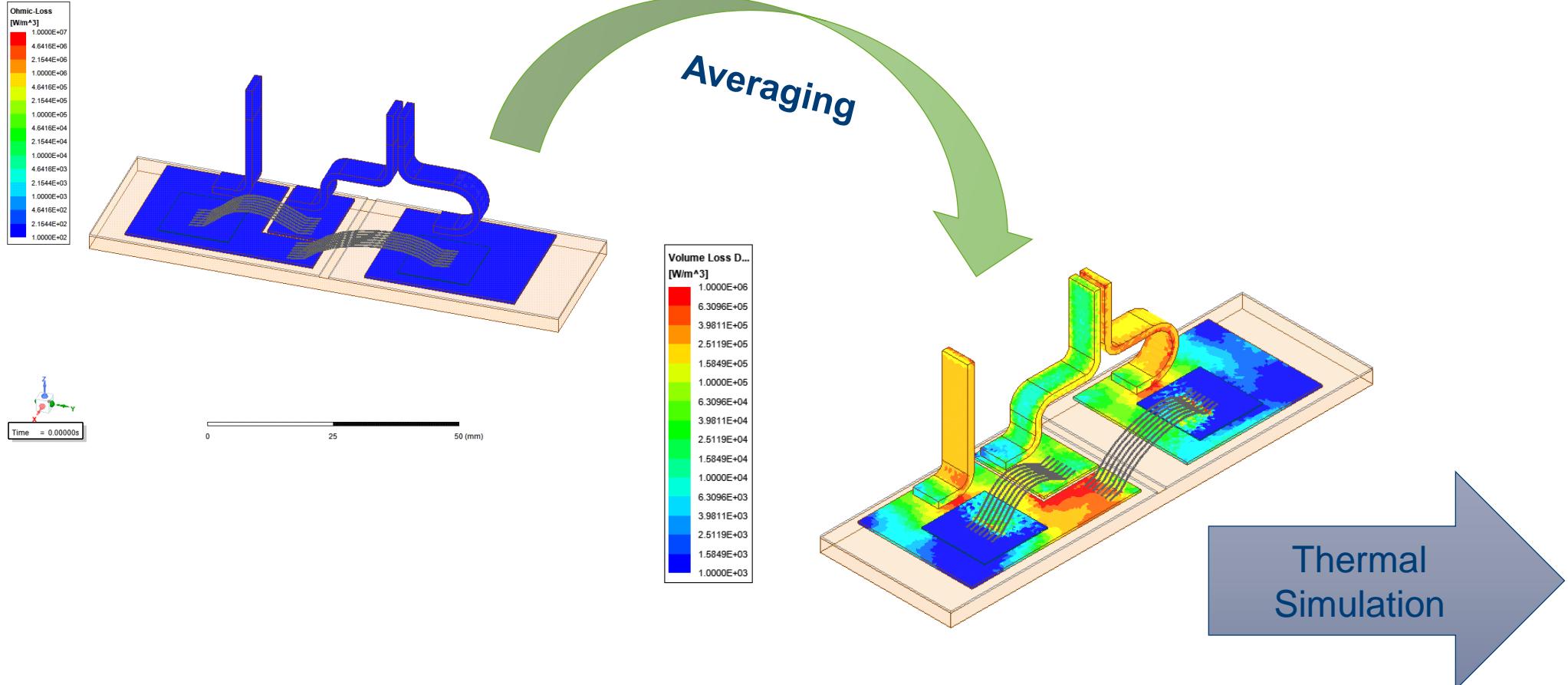
1.452 ms

1.5 ms

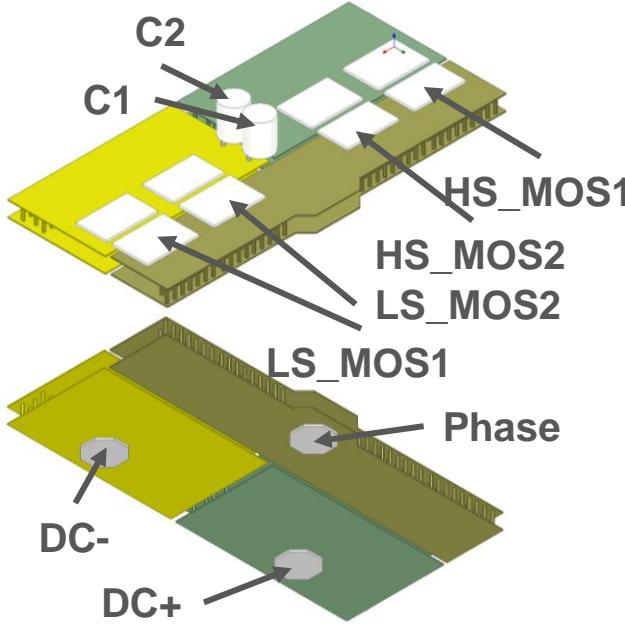
1.556 ms



# Simple Half Bridge - Average Losses



# Example: 2-Layer PCB with Parelle MOSFETS and 2 Capacitors



## External Terminals

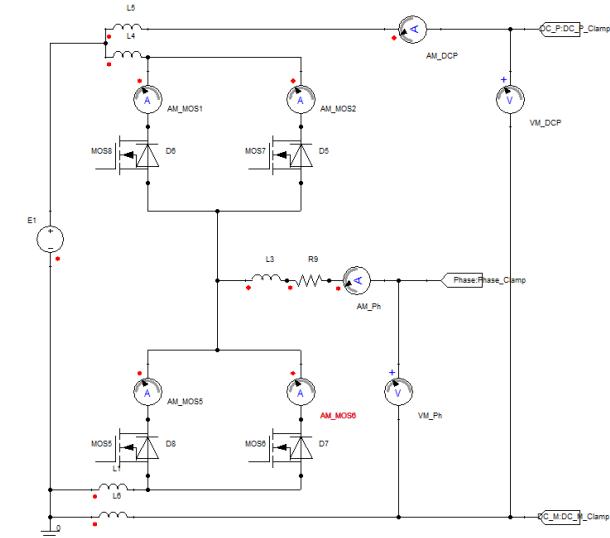
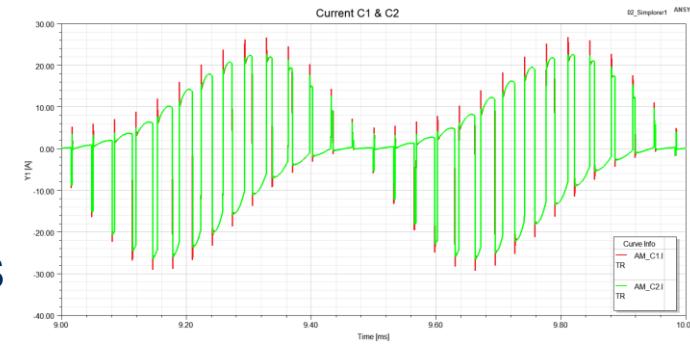
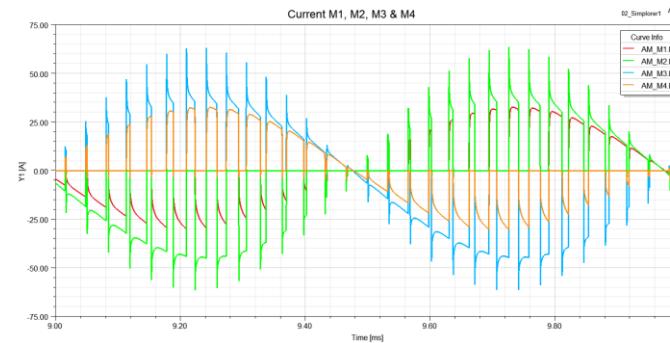
- DC+, DC- and Phase

## Internal Terminals

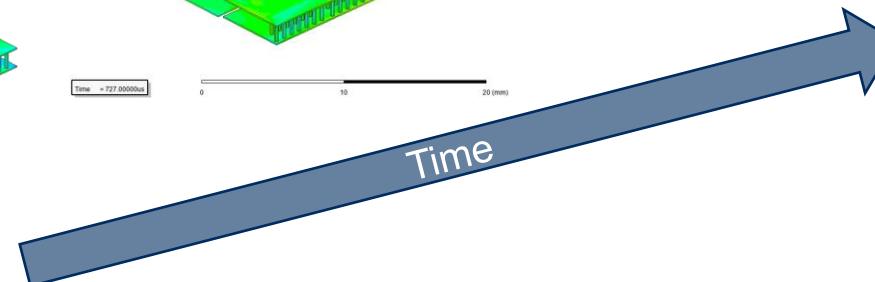
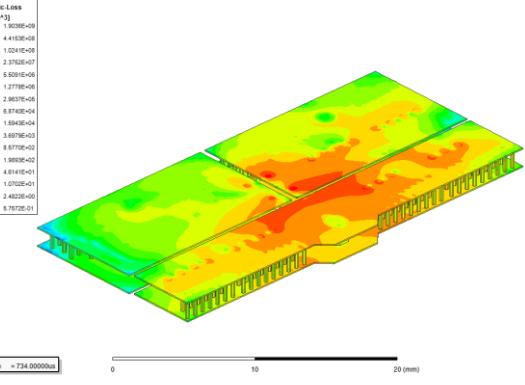
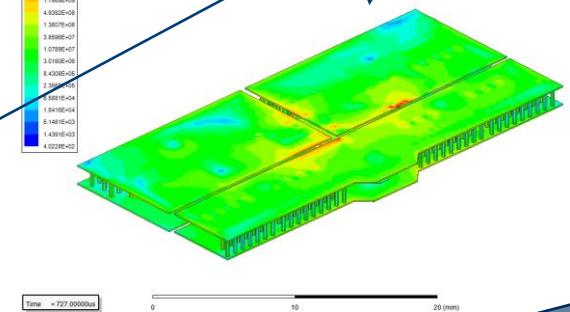
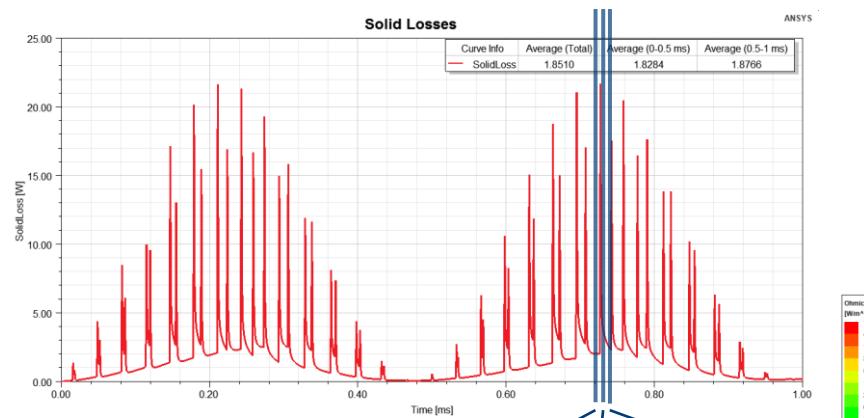
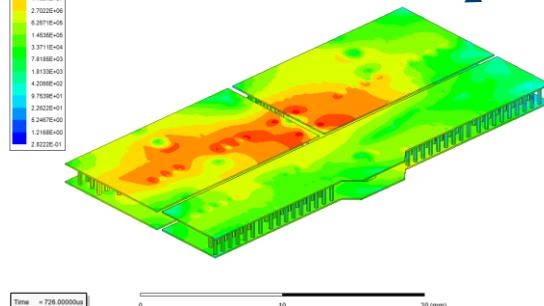
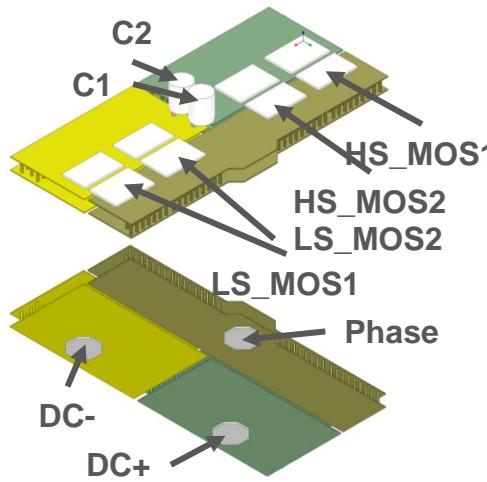
- Two parallel high side MOSFETS
- Two parallel low side MOSFETS
- Two DC-link capacitor

## Nets

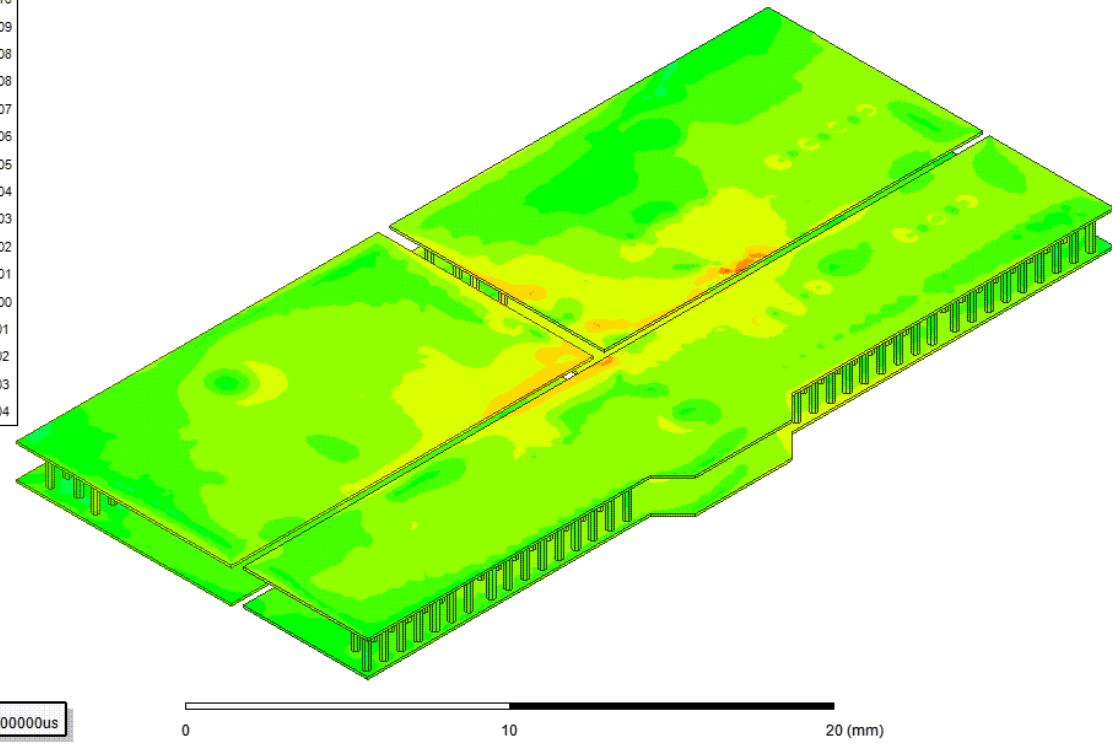
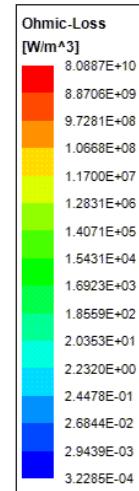
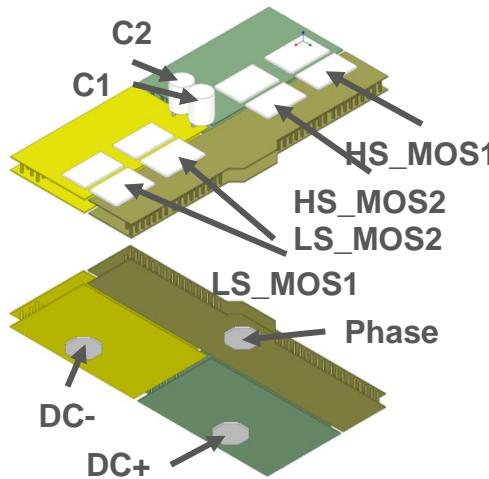
- DC\_M, DC\_P and Phase



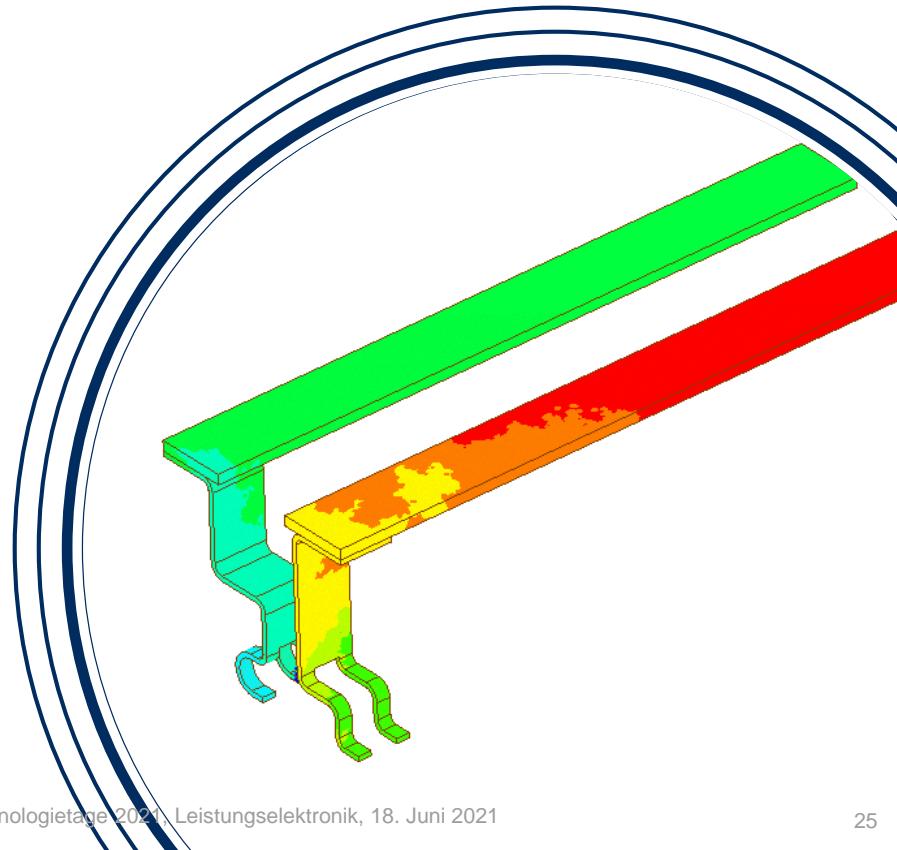
# Example: 2-Layer PCB with Parallel MOSFETS and 2 Capacitors



# Example: 2-Layer PCB with Parelle MOSFETS and 2 Capacitors



# Local current distribution in busbars



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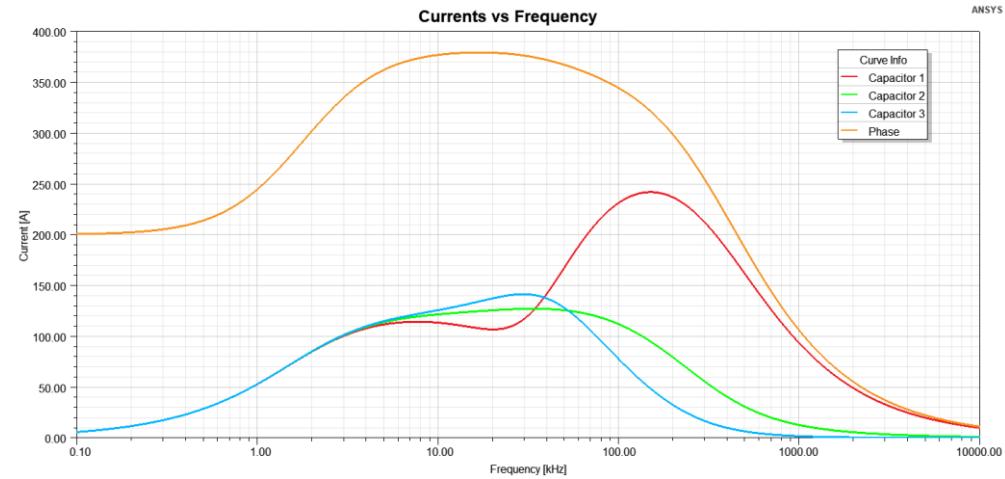
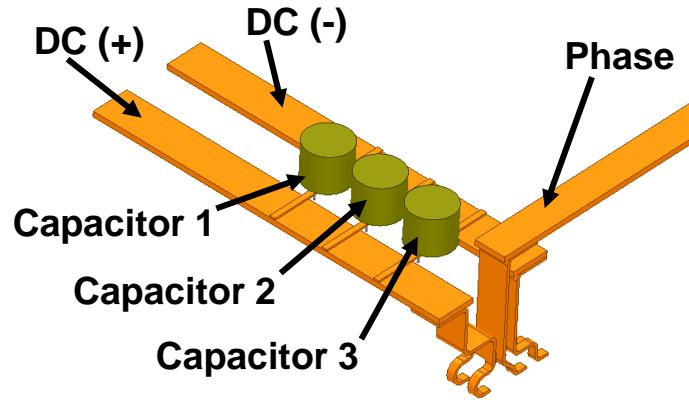
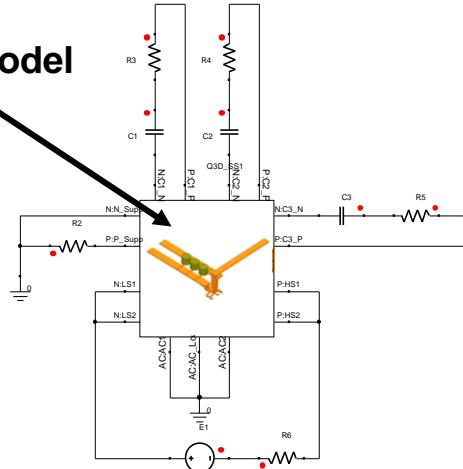
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# Unbalanced Loads for Capacitors

- Parasitic properties of components
- Parasitic properties of busbars
- Position of the capacitors
- Load on the capacitors are frequency dependent

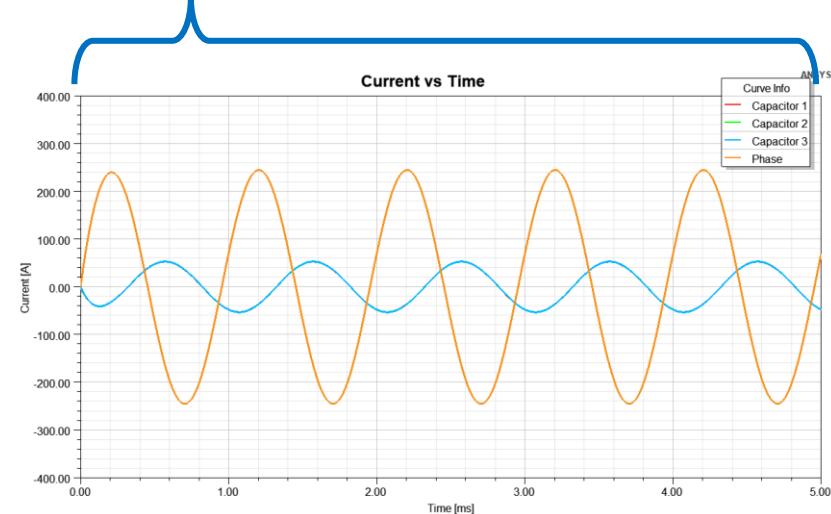
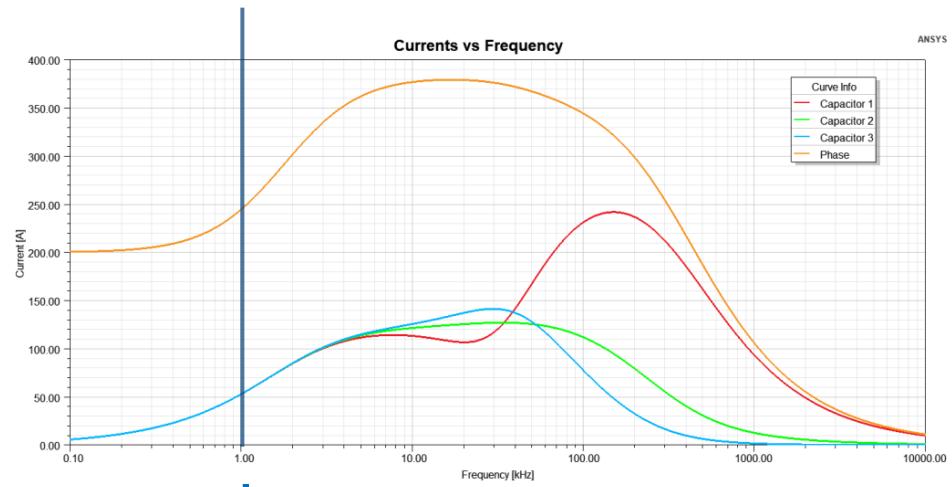
## Circuit Simulation

### Reduced Order Model Q3D



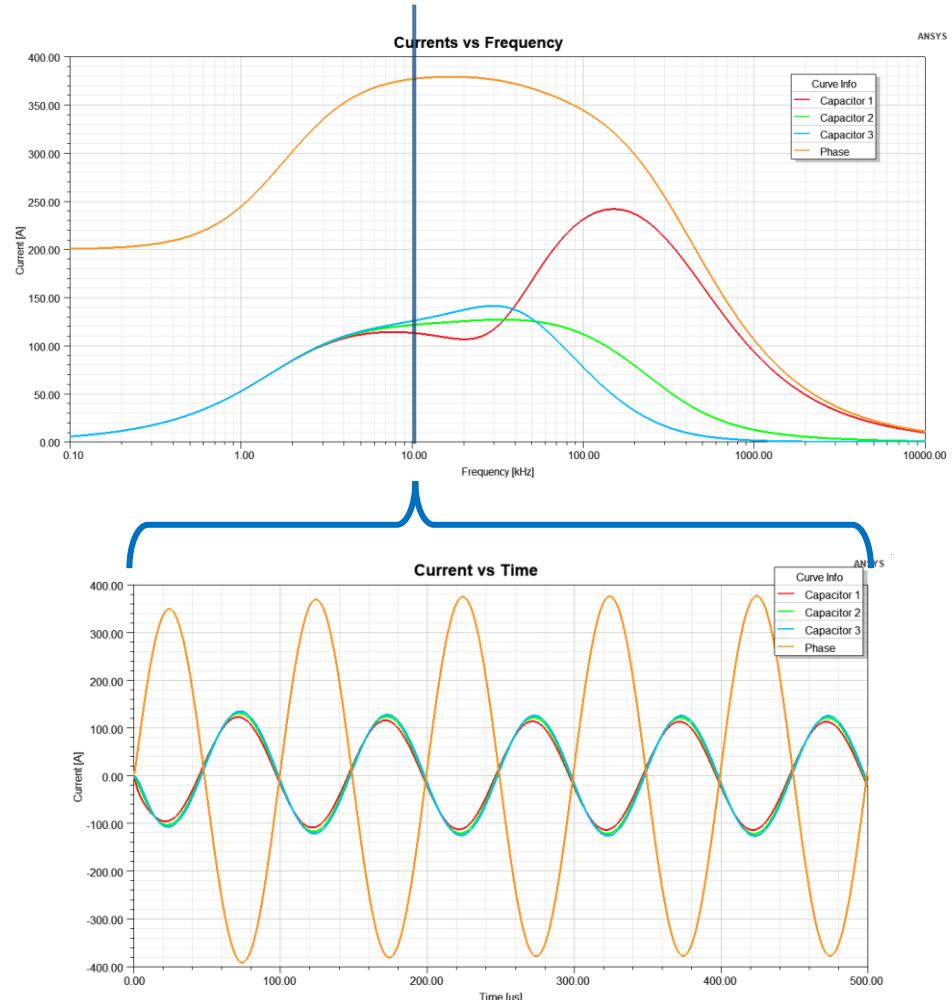
# Current Distribution on the Terminals

- Identifying the input currents for the different terminals.
- Due to parasitic properties of the components and busbars the current can be very different depending on the frequency.



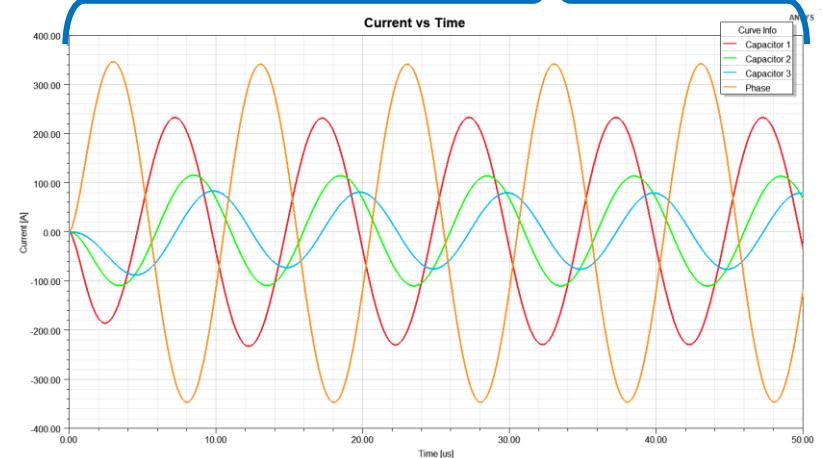
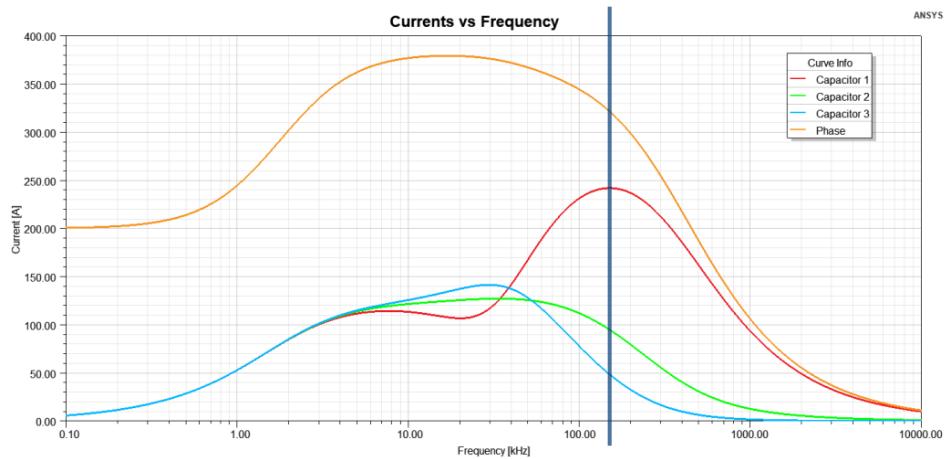
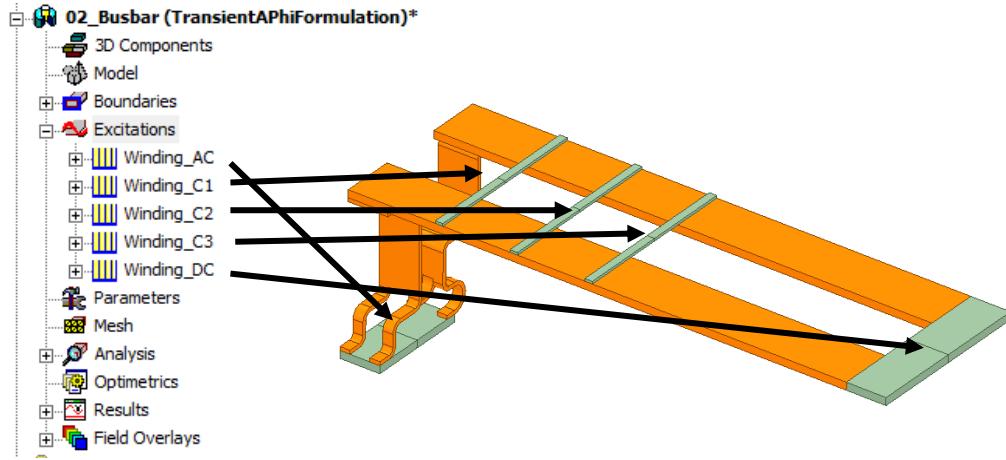
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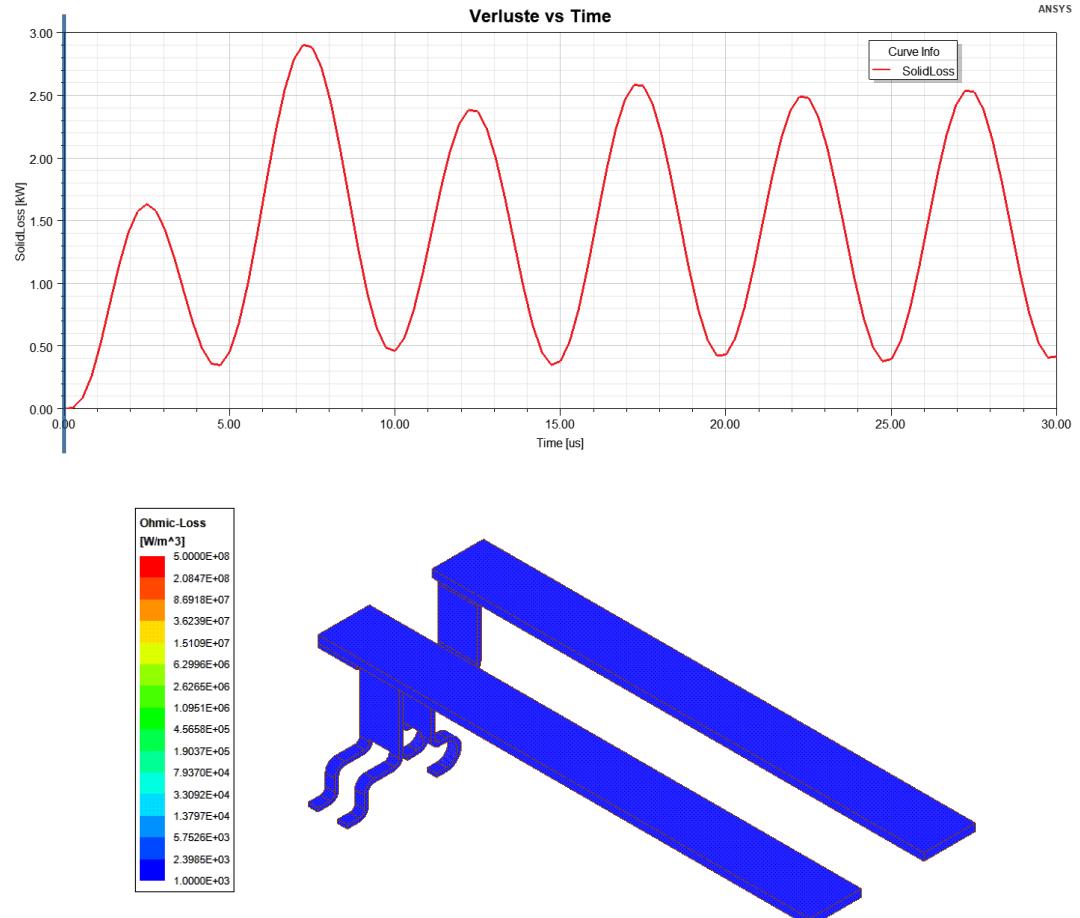
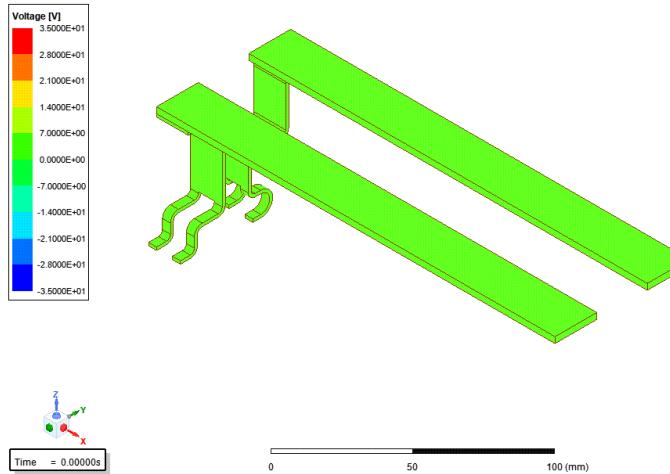
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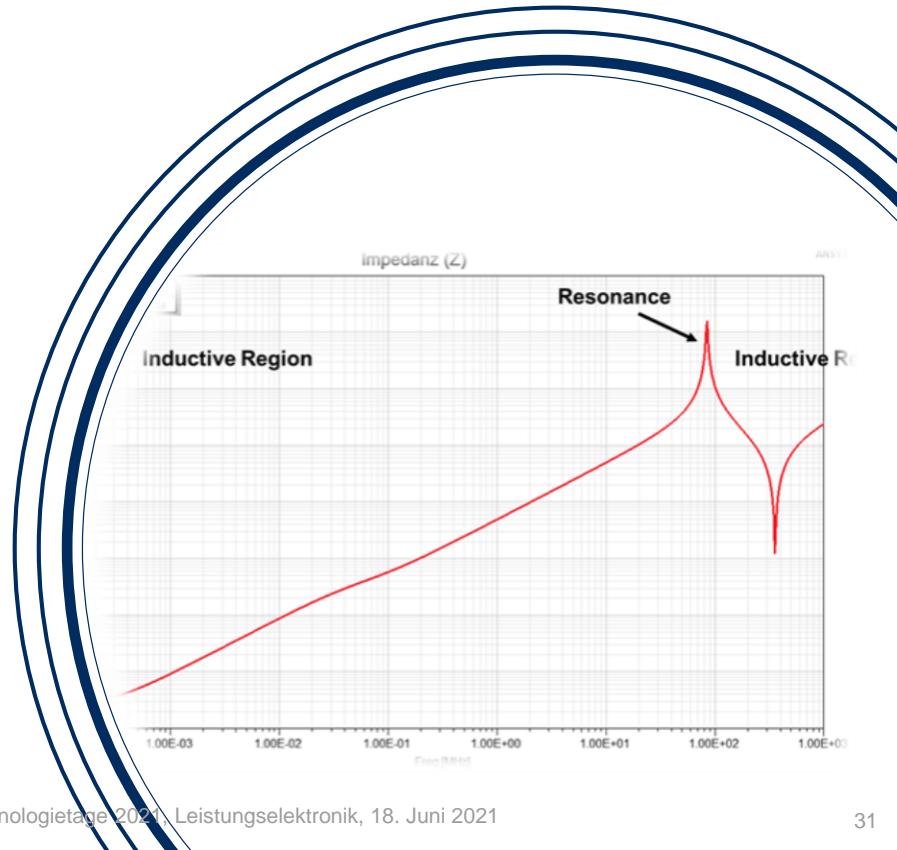


# Ohmic Losses

- Local losses indicates possible hotspots.
- Circulating currents increase losses near the capacitors.



# First resonance of an inductor



# New 3D AC Conduction Solutions (Beta)

CADFEM®

- Electric frequency domain solution
  - Mixed voltage and current excitation
  - Frequency dependent materials
  - GC matrix
  - Multi-physics coupling
- Applications:
  - PCB board
  - Circuit parameters extraction
  - High voltage application with lossy materials
  - Medical applications such as electrical impedance tomography

Formulation:

$$\mathbf{E} = -\nabla\varphi$$

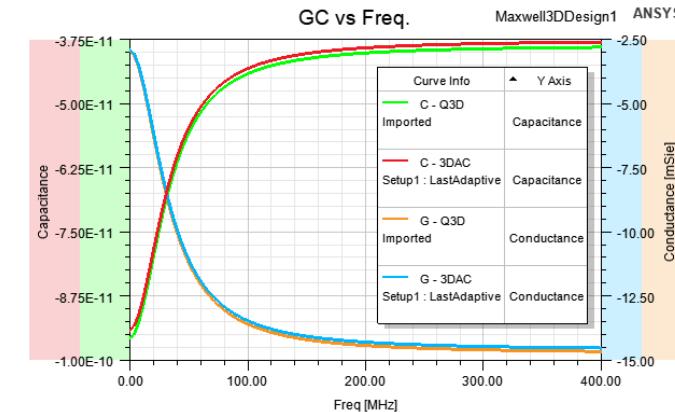
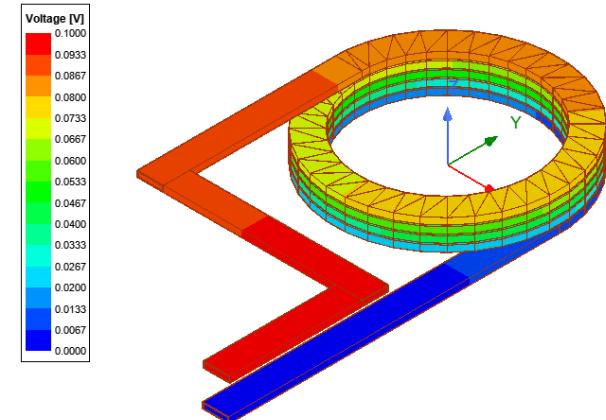
$$-\nabla \cdot [\nabla\varphi(\sigma_b + j\omega\epsilon)] = 0$$

Lossy materials:

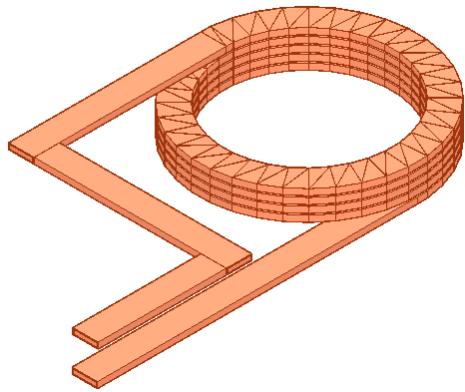
$$\epsilon = \epsilon' - j\epsilon''$$

$$-\nabla \cdot [(\sigma_b + \omega\epsilon'' + j\omega\epsilon')\nabla\varphi] = 0$$

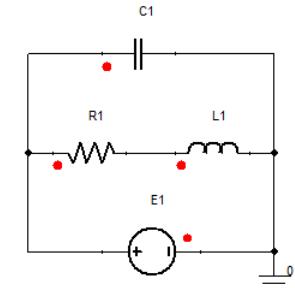
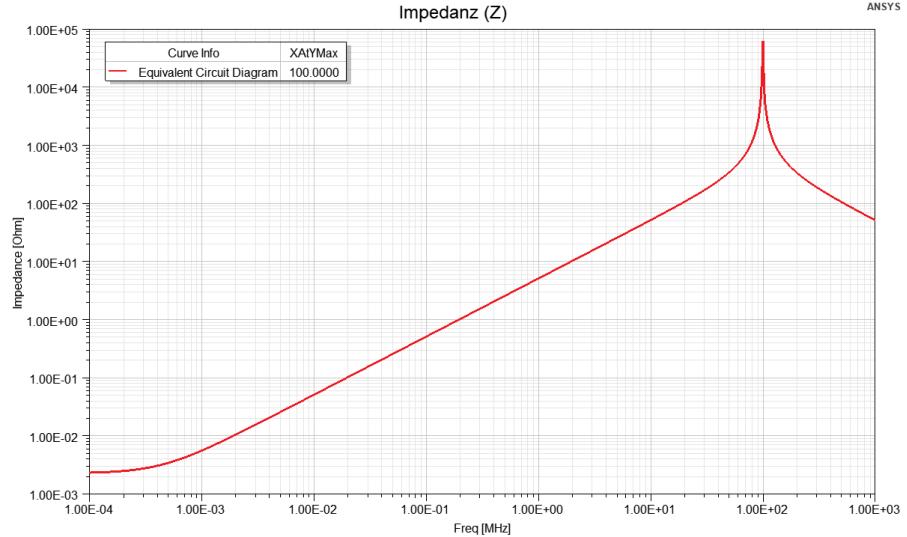
$$\tan\delta = \frac{\sigma_b + \omega\epsilon''}{\omega\epsilon'} \quad \tan\delta = \frac{\sigma}{\omega\epsilon}$$



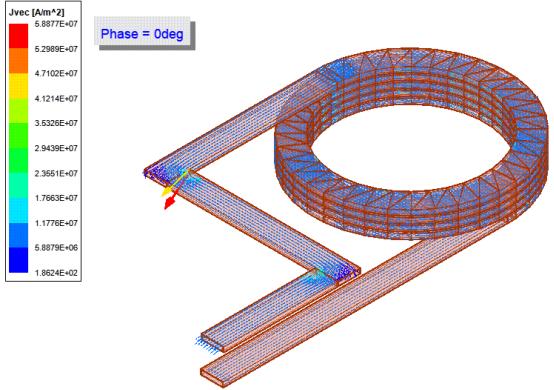
# Equivalent circuit diagram



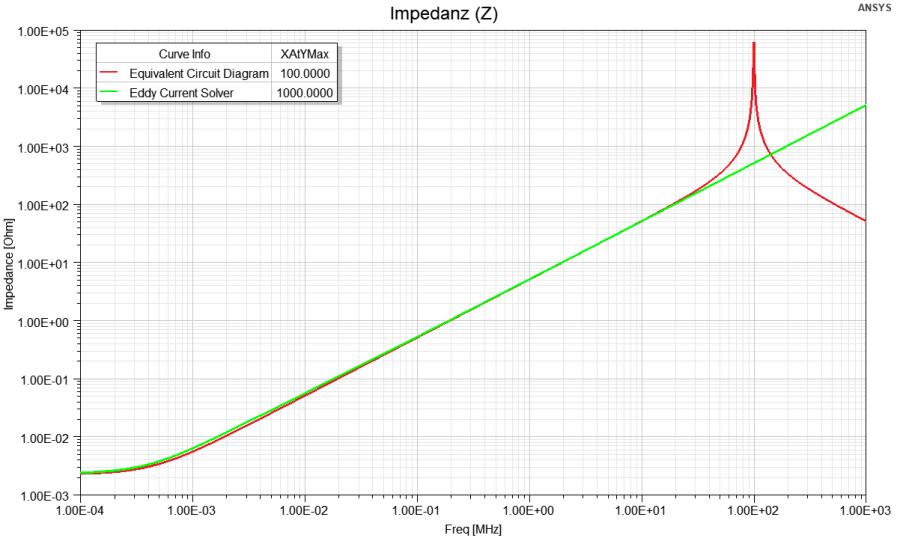
- The inductance and parasitic capacitance forms a resonant circuit
- The resistance consist of an DC and AC component
- The components are frequency dependent



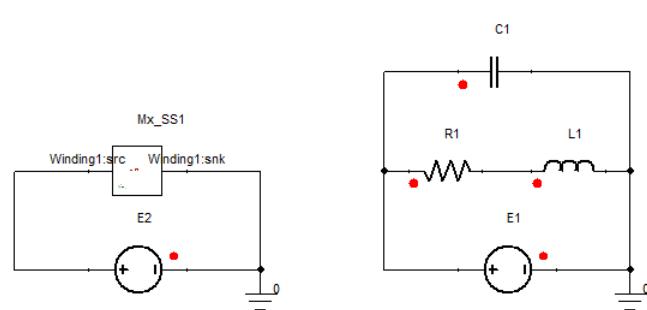
# Inductance – Eddy Current Solver



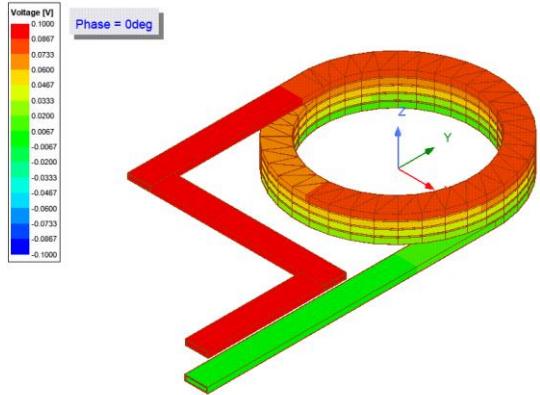
	Freq [MHz]	Matrix1 L(Winding1,Winding1) [nH] Setup1 : LastAdaptive
1	0.000100	944.499273
2	0.000215	944.366629
3	0.000464	943.765413
4	0.001000	941.248949
5	0.002154	933.211503
6	0.004642	917.587904
7	0.010000	896.824482
8	0.021544	875.275553
9	0.046416	854.678432
10	0.100000	840.243463
11	0.215443	831.561948
12	0.464159	825.952324
13	1.000000	821.990395
14	2.154435	819.390364
15	4.641589	817.818934
16	10.000000	816.989784
17	21.544347	816.680568
18	46.415888	816.586644
19	100.000000	816.561952
20	215.443469	816.556222
21	464.158883	816.554963
22	1000.000000	816.554691
23	2154.434690	816.554632



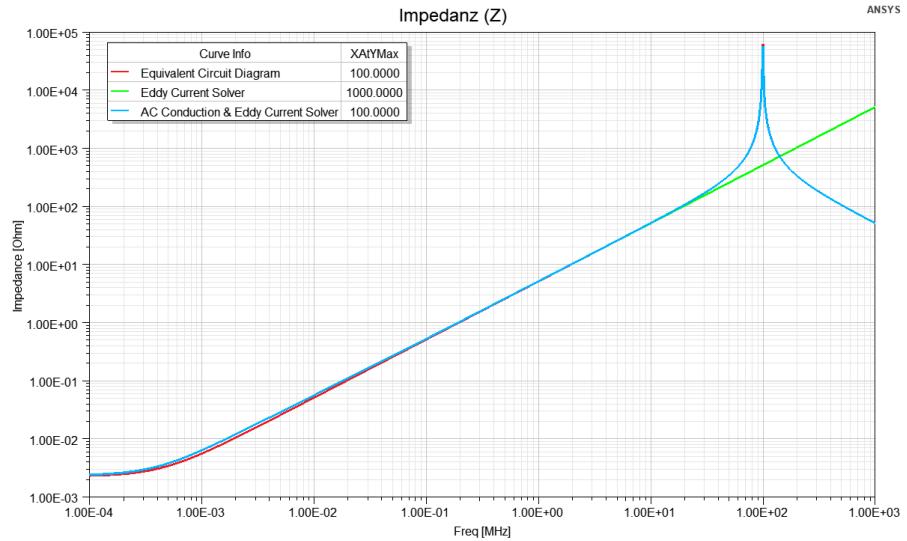
- Frequent dependent inductance due to changes in the current distribution in the conductor.
- AC and DC Resistance are evaluated.



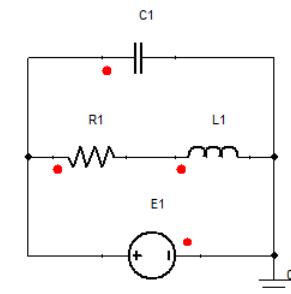
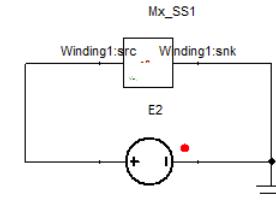
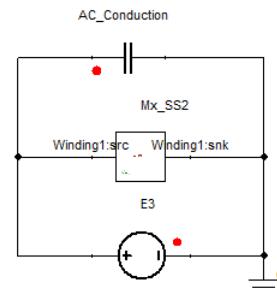
# Capacitance – AC Conduction Solver



Freq [MHz]	Matrix1.C(Voltage1,Voltage1) [pF] Setup1 : LastAdaptive
1	3.127308
2	3.127308
3	3.127308
4	3.127308
5	3.127308
6	3.127308
7	3.127308
8	3.127308
9	3.127308
10	3.127308
11	3.127308



- Determination the capacitance of the coils



# Summary

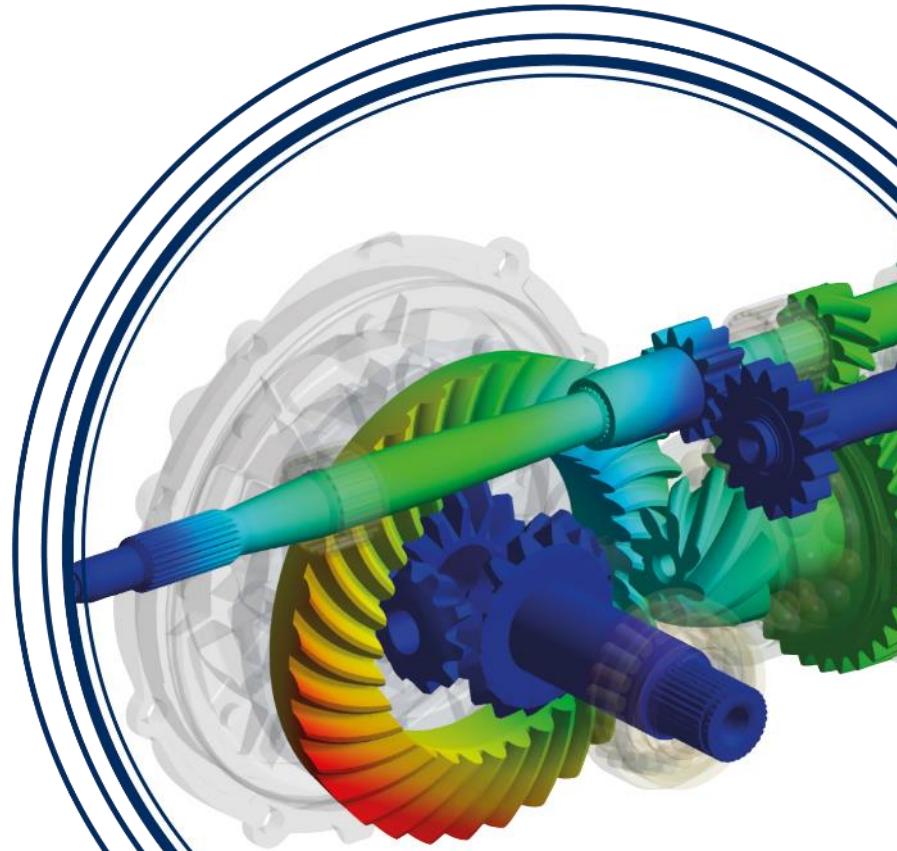
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- It is important to know the local loss distribution to identify critical regions. Two methods was presented to analyse the local loss distribution.
- The new A-Phi solver allows to calculate the transient behavior and plots the losses for each time step.
- Internal terminals can be used to apply current and voltage wave forms.
- The parasitic properties of busbars have to be taken into account for circuit simulations to understand the loads on the capacitors.
- Characterization of components regarding parasitic properties be performed with the new AC Conduction solver.

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## Simulation is more than Software



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