ETH zürich

Power Electronic Systems Laboratory

Dielectric Losses
MV/MF Converter Insulation

SCCER FURIES Technical Workshop
September 20, 2017

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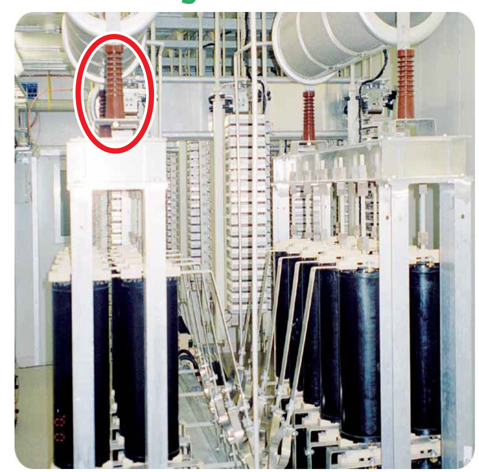
Insulation in MV/MF Converters

- New **SiC MV** devices
  - Higher voltages: **15 kV**
  - Higher switching frequency: **100 kHz**
  - Higher commutation speed: **150 kV/µs**
- New **topologies**
  - **Single-stage** or **multi-cell** converters
  - Voltages at DC/low/medium **frequencies**
  - High **power densities**
  - High operating **temperatures**
- **Proven to be critical**
  - Eagle Pass **HVDC**
  - Large **harmonics** content
  - **Cable termination** lifetime: **one week**
  - **Losses** in the field grading
- **Insulation coordination of MV/MF converters is unclear**

▼ **MV AC-DC Converter**

[ETHZ PES MEGAlink]

▼ **Eagle Pass HVDC**



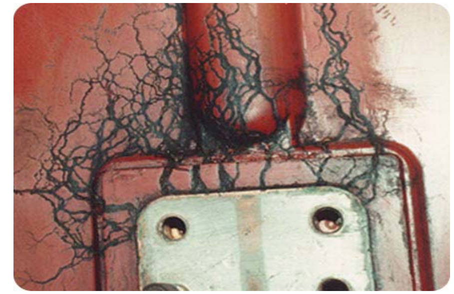
[ABB]

Paulsson, L., High-Frequency Impacts in a Converter-Based Back-to-Back Tie: the Eagle Pass Installation, 2003

MV/MF Electric Field

- **Insulation coordination**
  - **Dielectric losses**
  - Thermal **breakdown**
  - **Space charge** migration
  - **Partial / surface discharges**
  - Parasitic **resonances / shielding**
  - etc.
- **Electromagnetic compatibility**
- **Dielectric losses**
  - **Efficiency** impact
  - Thermal **runaway**
  - Thermal **breakdown**
  - **Diagnosis** (production and aging)
  - **Computation** is possible
- **Dielectric loss is an interesting figure of merit**

▼ **Partial Discharges**



[RMS Energy]

▼ **7 kV / 100 kHz EMI**

[ETHZ PES SwiSS SST]

Outline

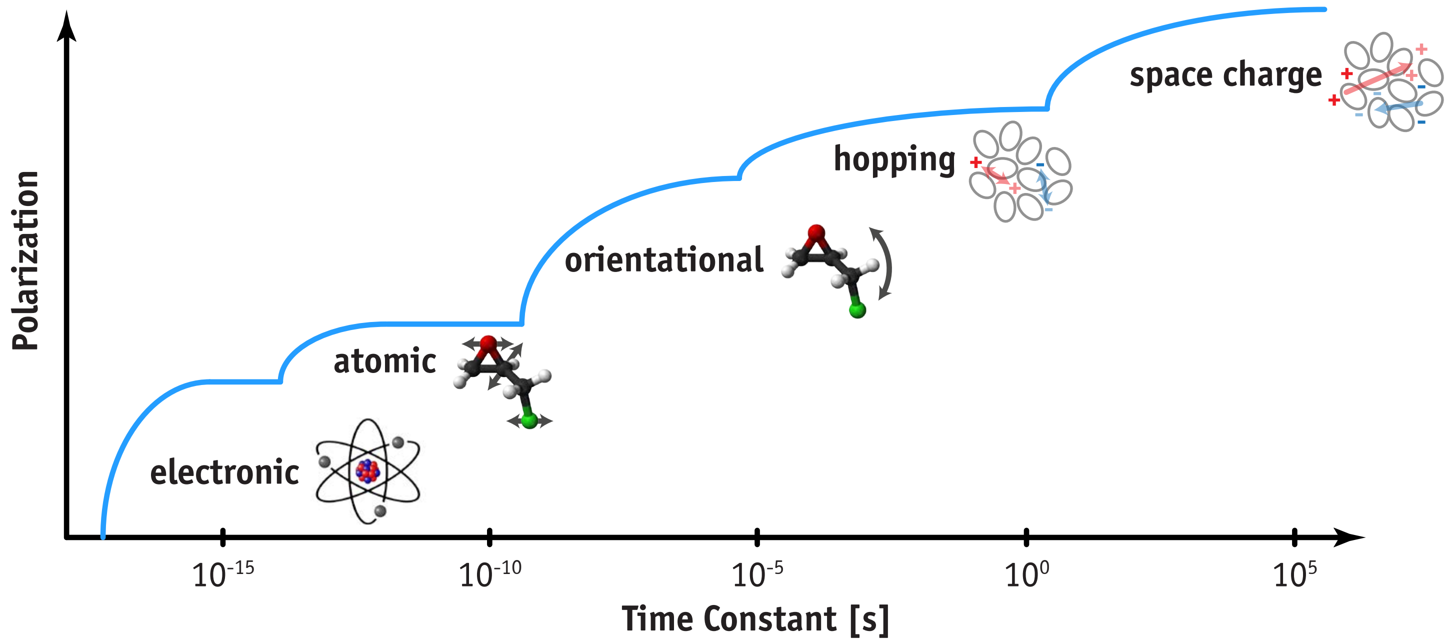
- Dielectric Material Parameters
- Dielectric Losses Computation
- Case Study: Solid-State Transformer
- Conclusion

Outline

Material: Polarization Types

- ε depends on many **micro-physical processes**
- **Conduction** is usually **negligible**
- **Polarization** is mostly **linear**

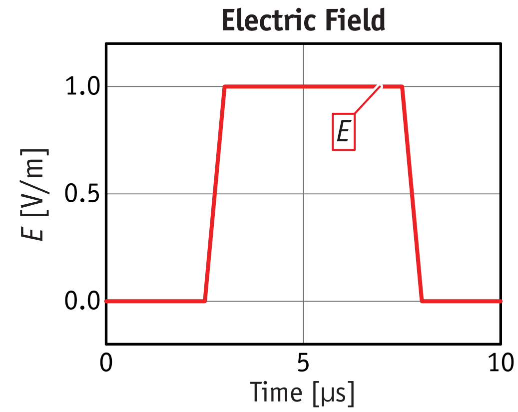
- How to compute the losses?

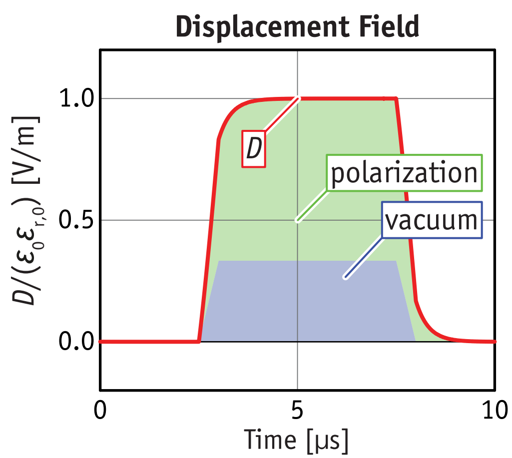


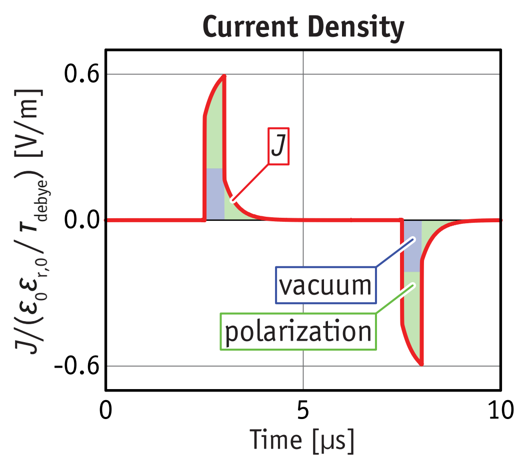
Adapted from Kao, K., Dielectric Phenomena in Solids, 2004

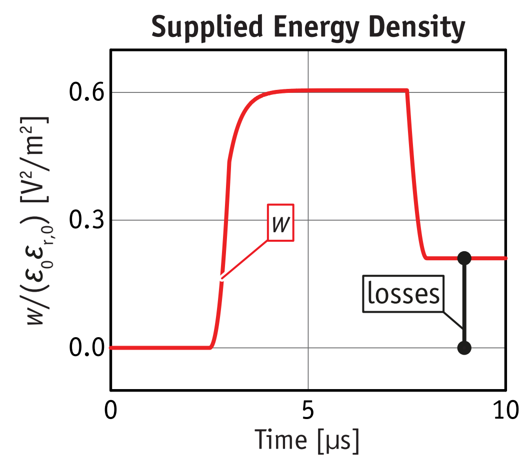
Dielectric Losses: Time Domain

- **PWM voltage** applied to the insulation
  - **Periodic** rectangular **pulses**
  - Finite **rise time**
- **Time domain**
  - **Convolution integrals** (step response)
  - **Loss computation** is **difficult**
- **Frequency domain modeling**









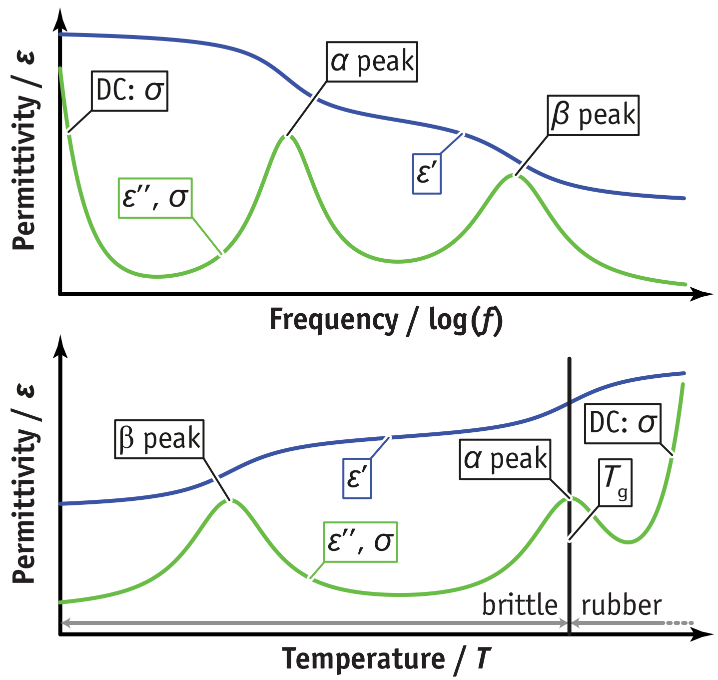
f_s = 100.0 kHz / t_r = 500 ns / Debye relaxation / $\varepsilon_{r,0}''$ = 3.0 / $\varepsilon_{r,inf}''$ = 2.0 / τ_{debye} = 320 ns

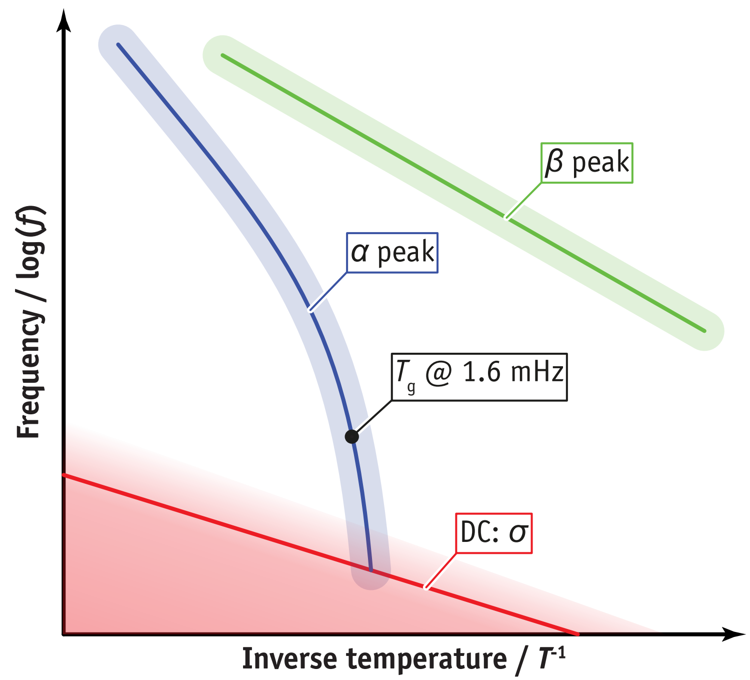
Dielectric Losses: Frequency Domain

- **Polarization**
  - **DC conduction** is **negligible**
  - **Polarization** is **linear**
  - **Frequency/temperature** dependence
  - $\varepsilon\left(f,T\right) = \varepsilon_0\left(\varepsilon' - \mathrm{j}\varepsilon''\right), \quad \tan\delta = \varepsilon''/\varepsilon'$
  - **Permittivity** should be **low**
- **Losses** (dielectric between two electrodes)
  - $P = \iiint\limits_{\mathrm{V}} \left(\sum_{n=1}^{\infty} \varepsilon_0 \varepsilon'' \left(2\pi f n\right) E_{n,\mathrm{RMS}}^2 \right) \mathrm{dV} = \underline{C_0} \sum_{n=1}^{\infty} \underline{\varepsilon''} \, \underline{\left(2\pi f n\right) V_{n,\mathrm{RMS}}^2}$
  - **Geometry/Capacitance** → C_0
  - **Material/Temperature** → ε''
  - **Voltage/Frequency** → $\left(2\pi f n\right) V_{n,\mathrm{RMS}}^2$
- **Dielectric losses depend on many parameters**

Material: Frequency / Temperature

- ***ε′* / *ε′′*** for typical polymeric **dry-type insulation** materials
- **Loss peaks** between polarization mechanisms
- **Frequency and temperature dependencies are critical**

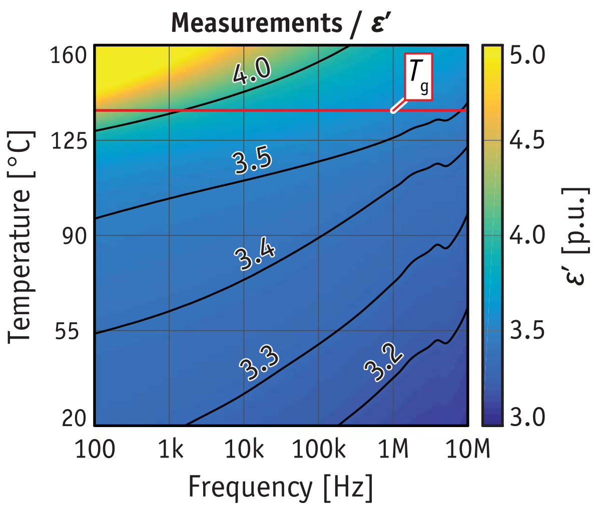


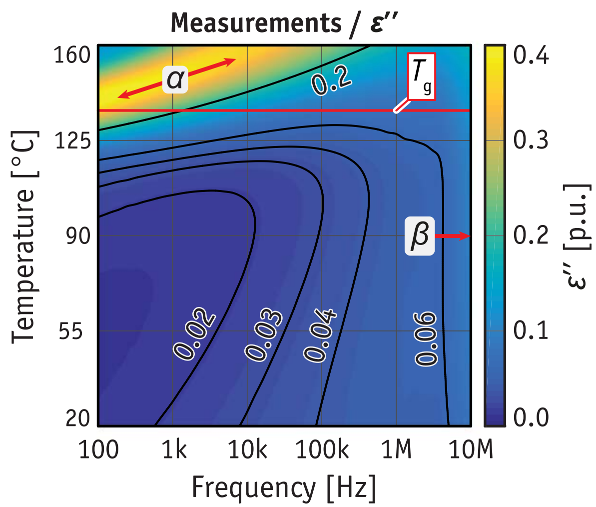


Adapted from Menczel, J., Thermal Analysis of Polymers: Fundamentals and Applications, 2008

Material: Measured Parameters

- **Measured for a typical HV epoxy resin**
  - **Damisol 3418** unfilled resin
  - T_g **= 136°C**
  - **Frequency** and **temperature dependence**
  - T_g is a **critical parameter** (α peak @ 1.6 mHz)
- **How to compute the losses?**





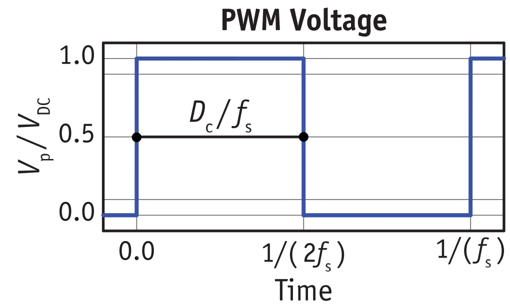
▼ Epoxy Sample

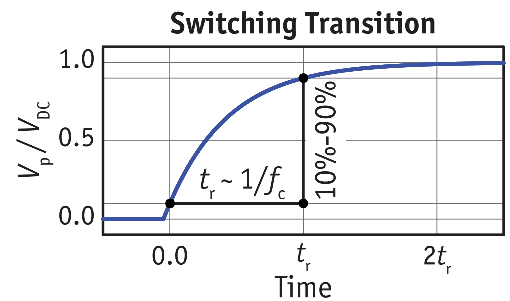
Outline

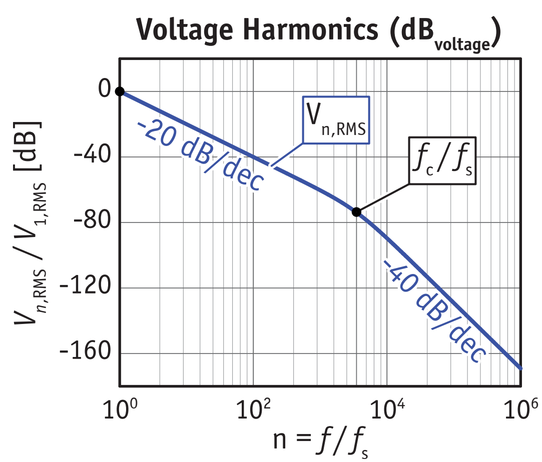
- Dielectric Material Parameters
- **Dielectric Losses Computation**
- Case Study: Solid-State Transformer
- Conclusion

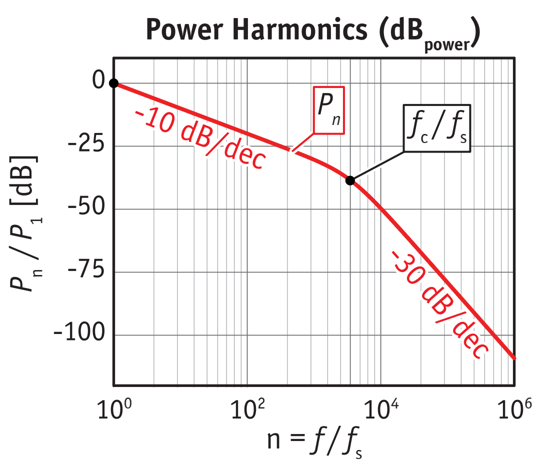
PWM: Spectral Losses

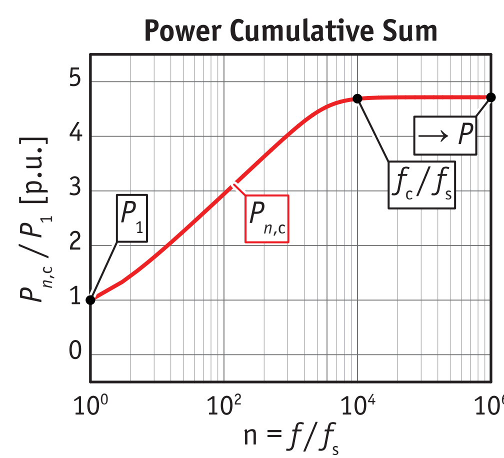
- Hypothesis: $\varepsilon''(f)$ is **constant**
- **PWM signal**
  - **Switching** frequency/speed
  - Many **harmonics**
  - **Fast transitions** lead to **large losses**
  - **Switching transition** model is required
  - **Fundamental frequency analysis** is **incorrect**
- **Simple computation method is required**









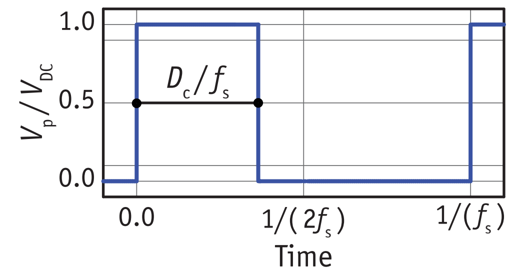


f_s = 1.0 kHz / t_r = 100 ns / D_c = 0.5

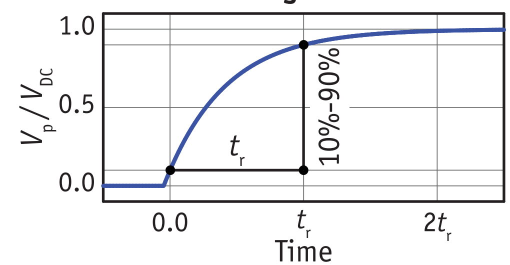
PWM: Constant Duty Cycle

- **PWM with constant duty cycle**
  - Typical for **DC-DC converter**
  - Finite **switching speed**
- **Closed-form solution**
  - Approximation of **partial sum/residual**
  - **2.5%** accuracy
  - Formula and derivation in [Gui16]
- **Frequency and voltage are critical**

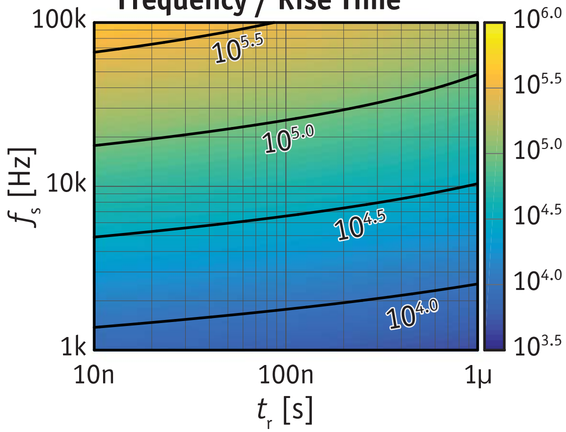
PWM Voltage



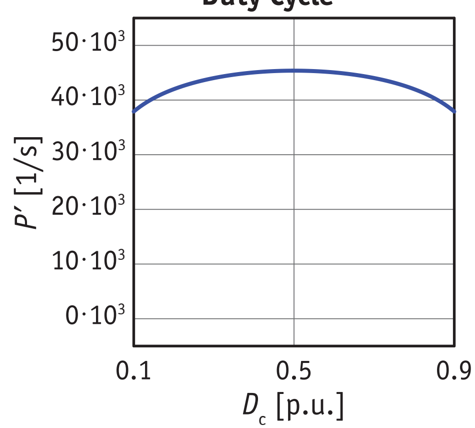
Switching Transition



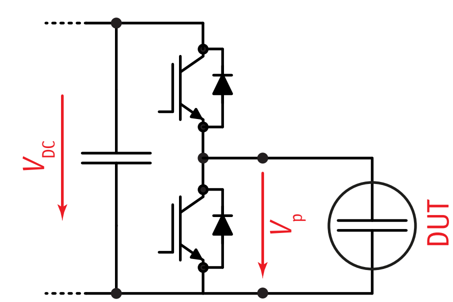
Frequency / Rise Time



Duty Cycle



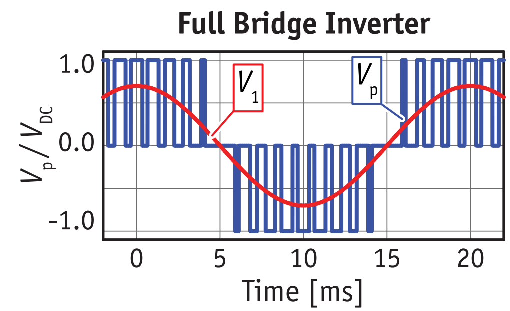
Circuit Topology

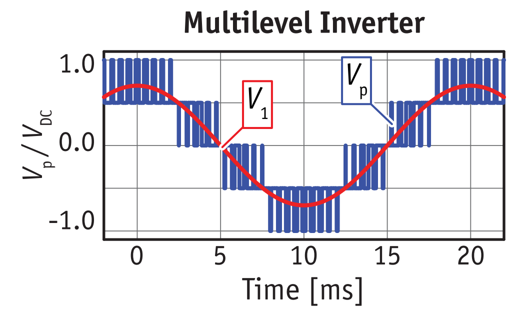


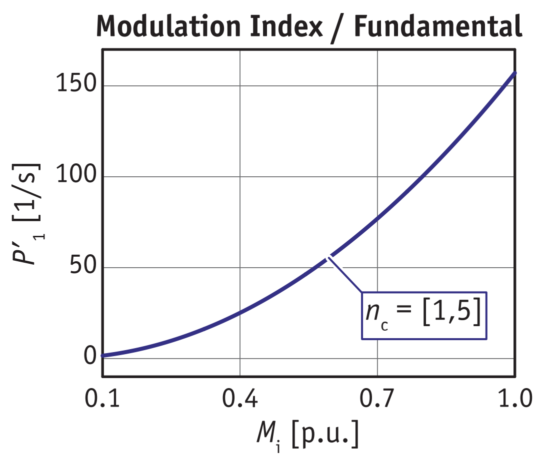
f_s = 10.0 kHz / t_r = 100 ns / D_c = 0.5 / $P' = P/(\varepsilon'' \cdot C_0 \cdot V_{DC}^2)$

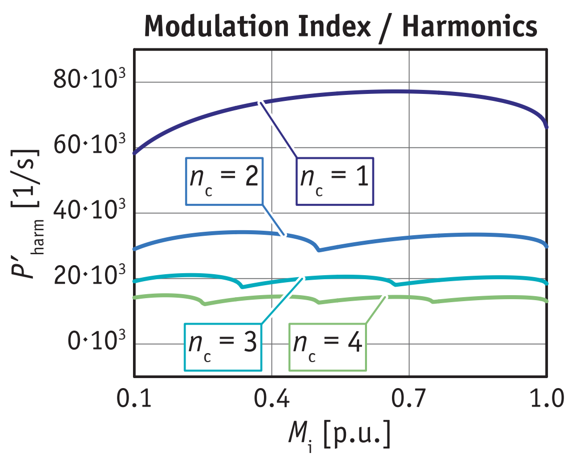
PWM: Sinusoidal Modulation

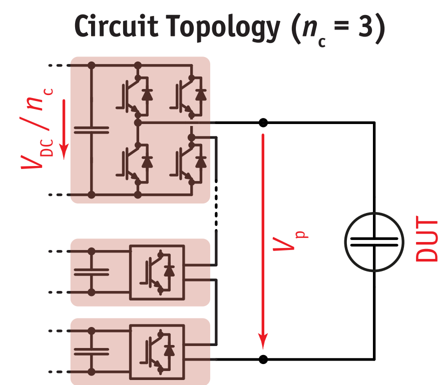
- **PWM with sinusoidal duty cycle**
  - Typical for **AC-DC converter**
  - **Multilevel inverters**
- **Closed-form solution**
  - **Local averaging** of PWM with constant D_c
  - **3.4%** accuracy
  - Formula and derivation in [Gui16]
- **Single-stage inverters are critical**











f_g = 50 Hz / f_s = 10.0 kHz / t_r = 100 ns / $P' = P/(\varepsilon'' \cdot C_0 \cdot V_{DC}^2) = P'_1 + P'_{harm}$

PWM: Scaling Laws

- **PWM with constant D_c**

f_s	$P \sim f_s \cdot \log(\text{const.}/f_s)$	switching frequency
t_r	$P \sim \log(\text{const.}/t_r)$	switching speed
D_c	$P \sim \text{const.}$	duty cycle
V_{DC}	$P \sim V_{DC}^2$	voltage
ε''	$P \sim \varepsilon''$	material loss parameter

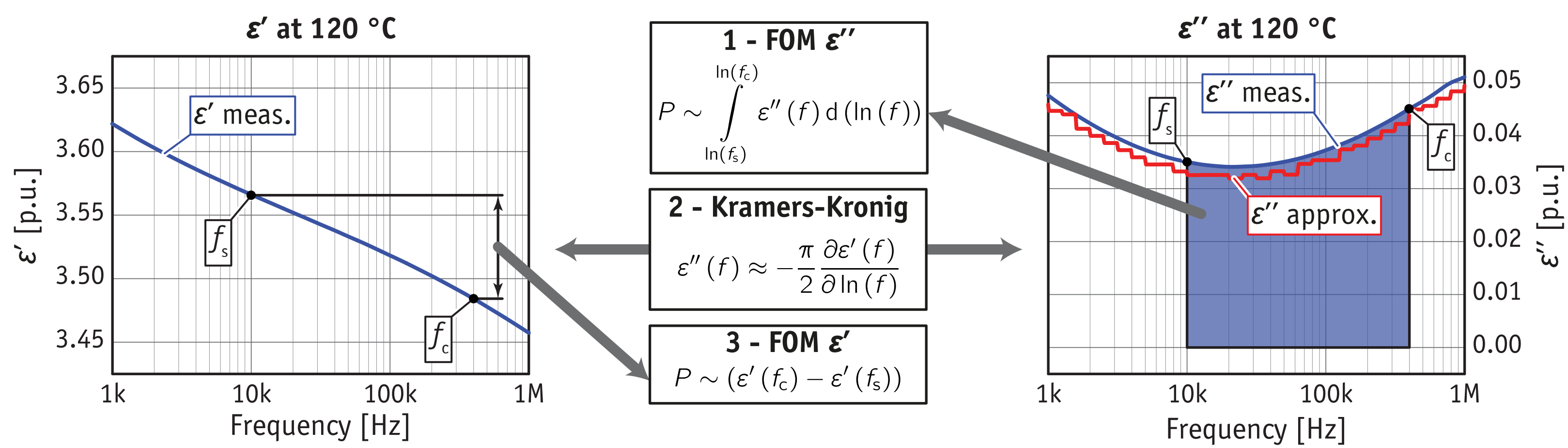
- **PWM with sinusoidal M_i**

f_s	$P_1 \sim \text{const.}$	$P_{harm} \sim f_s \cdot \log(\text{const.}/f_s)$	switching frequency
f_g	$P_1 \sim f_g$	$P_{harm} \sim \text{const.}$	grid frequency
t_r	$P_1 \sim \text{const.}$	$P_{harm} \sim \log(\text{const.}/t_r)$	switching speed
M_i	$P_1 \sim M_i^2$	$P_{harm} \sim \text{const.}$	modulation index
n_c	$P_1 \sim \text{const.}$	$P_{harm} \sim 1/n_c^2$	multilevel stages
V_{DC}	$P_1 \sim V_{DC}^2$	$P_{harm} \sim V_{DC}^2$	voltage
ε''	$P_1 \sim \varepsilon''$	$P_{harm} \sim \varepsilon''$	material loss parameter

- **Impact of frequency dependency of ε''?**

PWM: Frequency-Dependent Material

- **PWM signal**
  - **Frequency dependent** permittivity
  - **Constant ε''** assumption is **inaccurate** (50% error)
- **Closed-form solution**
  - Approximation of **sum with integral** & **Kramers-Kronig**
  - **7%** accuracy (Damisol 3418)
  - Formula and derivation in [Gui16]
- **Simple figures of merit for the losses**



f_s = 10.0 kHz / t_r = 800 ns / D_c = 0.5/ T = 120 °C / Damisol 3418

Outline

- Dielectric Material Parameters
- Dielectric Losses Computation
- Case Study: Solid-State Transformer
- Conclusion

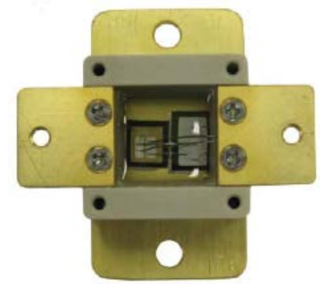
Converter: Solid-State Transformer

- **MV AC-DC converter**
  - **25 kW**
  - **6.6 kV AC**
  - **400 V DC**
  - **Full ZVS** (AC-DC and DC-DC)
- **Applications**
  - **Renewable** collecting **grid**
  - **Datacenter** supply
- **Important stresses for the DC-DC stage**

▼ Partner

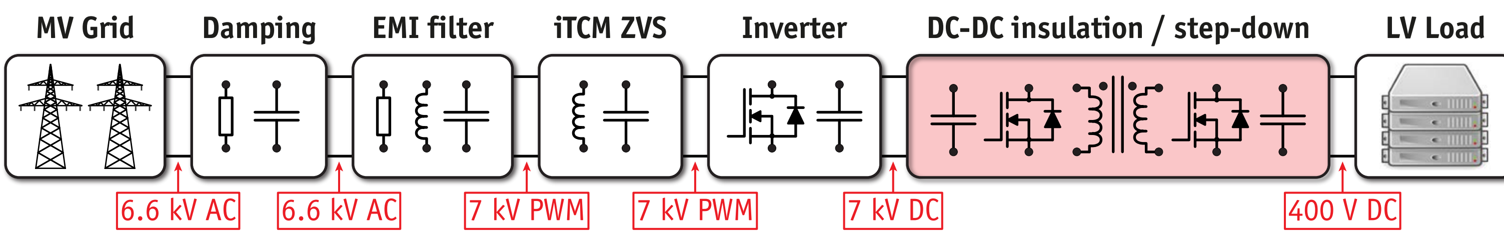
Energy Turnaround
National Research Programme NRP 70

▼ 10 kV SiC MOSFET



[Wolfspeed]

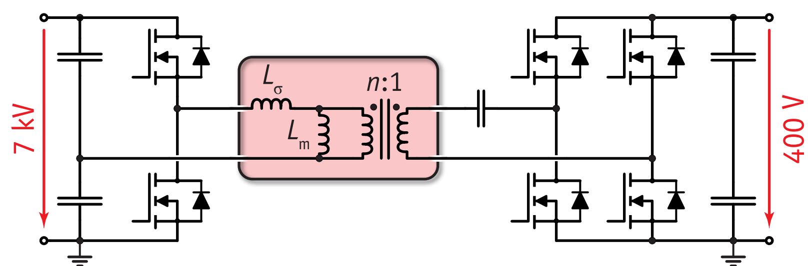
▼ Considered SST (SwiSS SST)



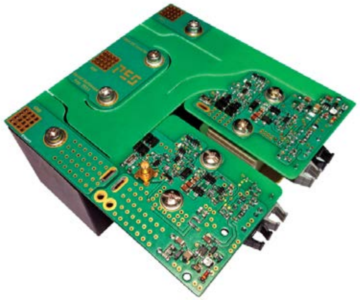
Converter: MV/MF DC-DC

- **MV DC-DC converter** (single stage)
  - **Dual-active bridge**
  - **Series-resonant converter**
- **Ratings**
  - **25 kW / 50 kHz**
  - **7 kV** to **400 V**
  - **15 kV** CM insulation
  - **10 kV / 900 V SiC MOSFETs**
- **Important stresses for the MF transformer**

▼ Converter

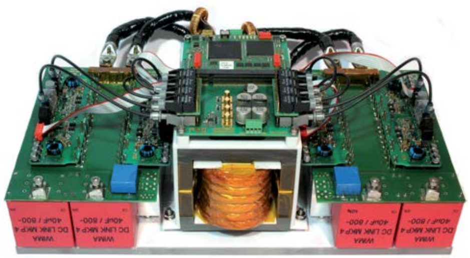


▼ 10 kV SiC Inverter



▼ Transformer Prototype

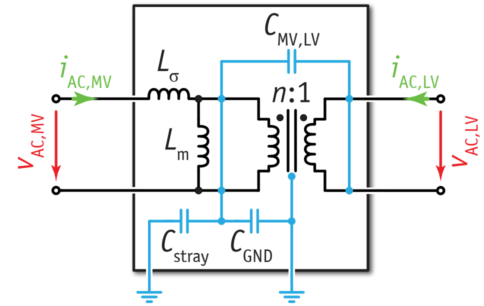
▼ 400 V SiC Test Converter



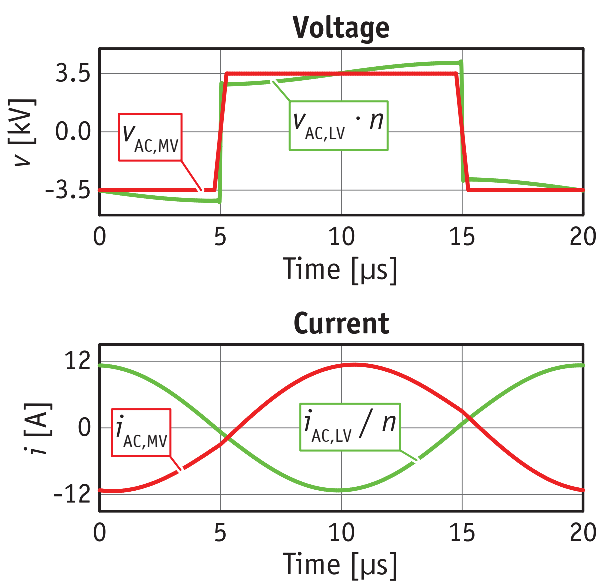
Converter: Transformer Stress

- **Switching**
  - **ZVS** achieved with magnetizing current
  - **15 kV/µs** with ZVS (**100 kV/µs** without ZVS)
  - **Relevant stress up to 1 MHz**
- **Combines all the critical factors (*f*, *V*, d*v*/d*t*)**

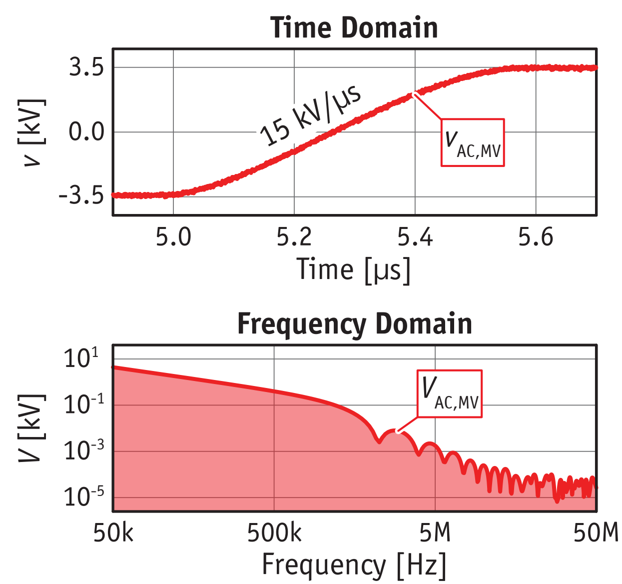
Transformer



Simulated Waveform



Measured MV Transient

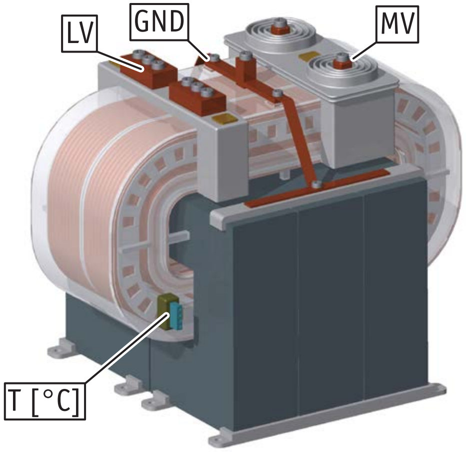


Waveforms shown for SRC DC-DC converter

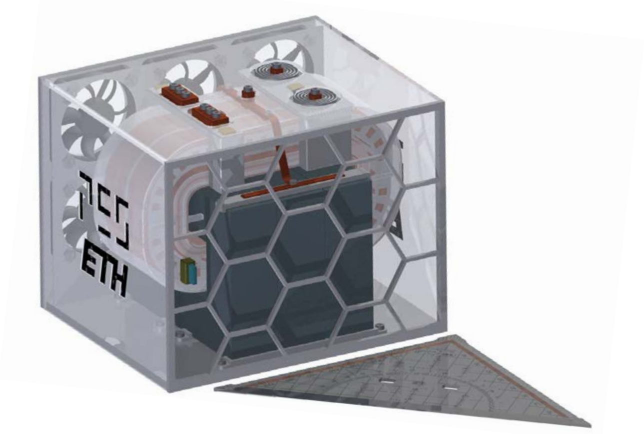
Transformer: Prototype

- **Ratings**
  - **25 kW / 31 kVA**
  - **50 kHz**
  - **±3.5 kV / ±400 V**
  - **15 kV** DM/CM **insulation**
  - 2.8 dm^3 / 170 x 120 x 135 mm
  - **99.55% / 9 kW/dm^3**
- **Construction**
  - **Ferrite** core (U-cores)
  - **Two air gaps** (for ZVS)
  - **Litz** wire (54:6 turns)
  - **MV chamber winding**
  - **Dry-type** insulation (Damisol 3418)
  - Forced **convection** cooling
- **Insulation coordination ?**

▼ Transformer



▼ Cooling System

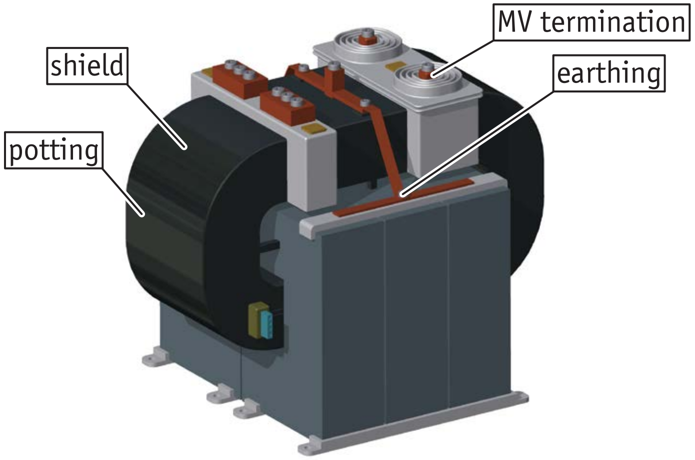


Final prototype is insulated with silicone elastomer (instead of Damisol 3418)

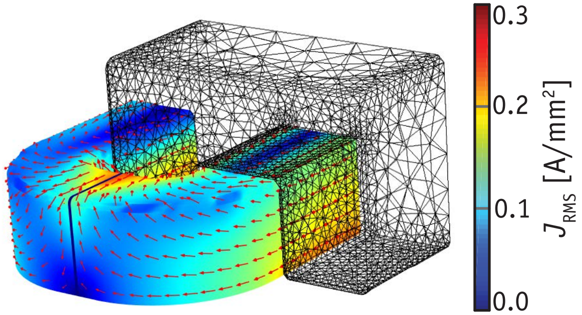
Transformer: Insulation Coordination

- **Insulation coordination**
  - **Terminations** with creepage extenders
  - **Vacuum potting** of the windings
  - **Earthing** of the cores
- **Shielding of the windings**
  - **Resistive coating** at the **surface**
  - **No additional losses**
  - Complete analysis in [Gui17]
- **Electric field is confined inside the windings**

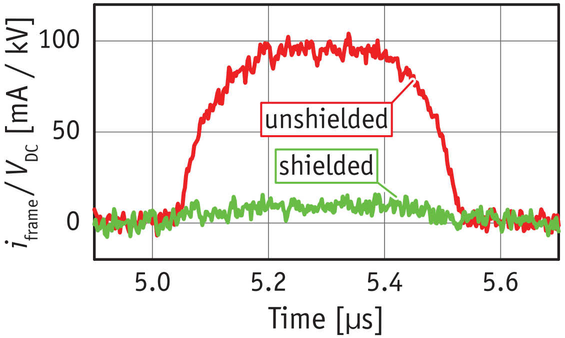
▼ **Insulation coordination**



▼ **Eddy current in the shield**

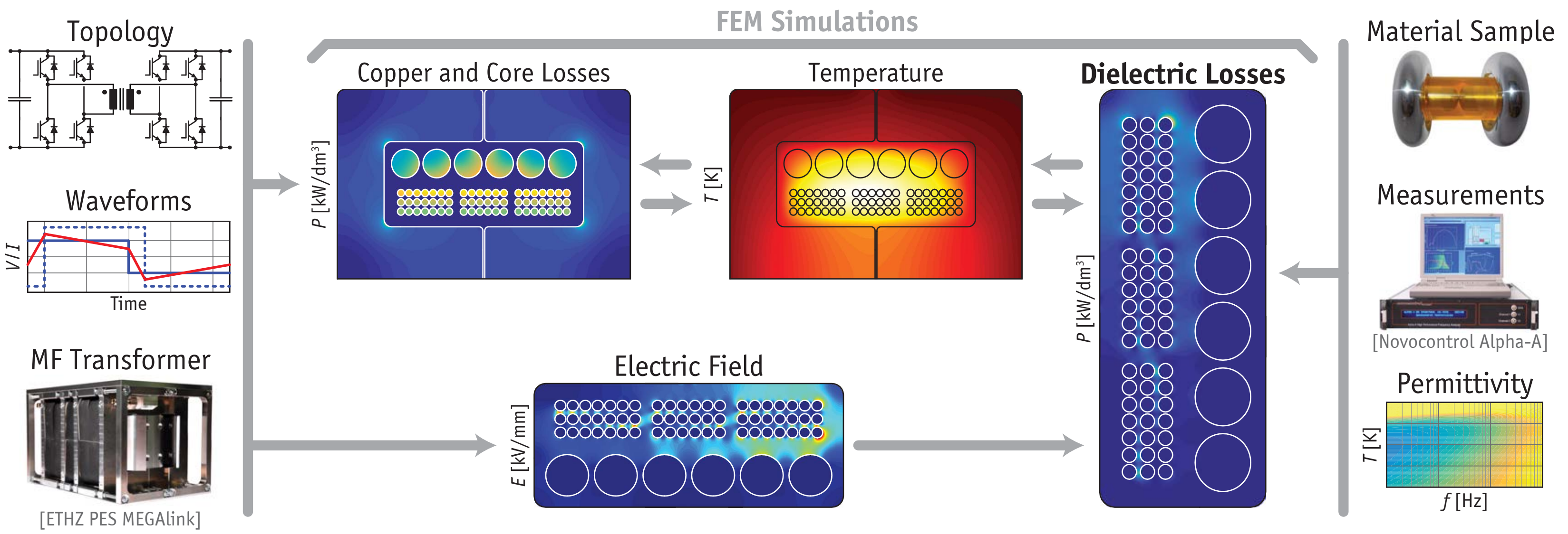


▼ **CM currents (EMI)**



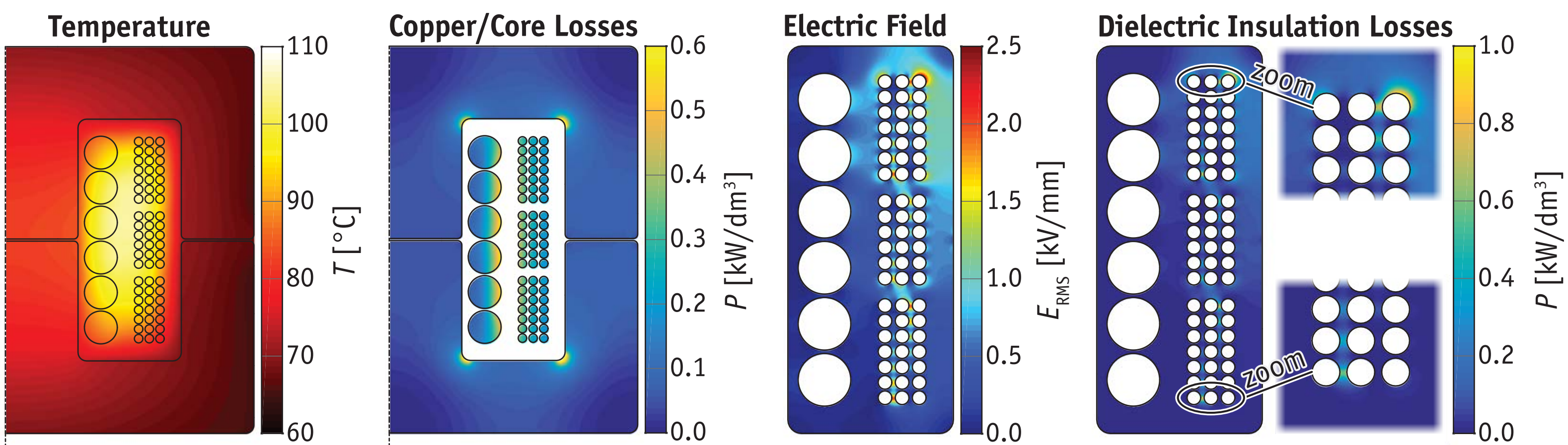
Transformer: Computational Workflow

- Simulation of dielectric losses
  - Voltage/frequency
  - Electric Field
  - Temperature
  - Material Parameters
- Simulation of insulation losses requires a multiphysics framework



Transformer: Loss Densities

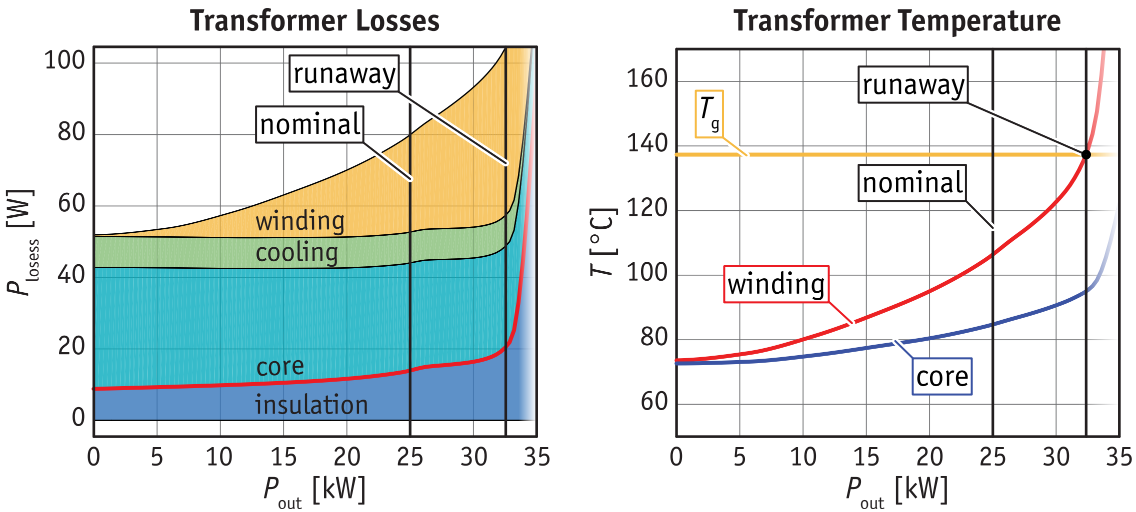
- **Dielectric losses**
  - **110 °C** hotspot **temperature**
  - **0.6 kW/dm³** peak **copper/core** loss density
  - **2.5 kV/mm** RMS **electric field**
  - **1.0 kW/dm³** peak **dielectric** loss density
  - Mostly **near the MV winding**
- **Dielectric loss density is large and very localized**



Losses simulated for DAB DC-DC converter

Transformer: Losses Breakdown

- **Dielectric losses**
  - **17%** of the **transformer losses**
  - **Frequency/temperature** dependence are important
  - Thermal **runaway** at the **glass transition temperature**
- **Dielectric losses are not negligible**
- **Alternative materials with higher or much lower T_g**



Losses simulated for DAB DC-DC converter

Outline

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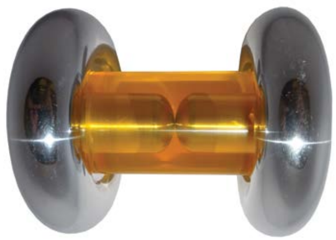
Conclusion

- **Dielectric losses with PWM**
  - **Frequency** and **voltage** are **critical**
  - Materials exhibit **dielectric loss peaks**
  - Simple **analytical expressions** for the losses
- **Insulation coordination** with **MV/MF electric fields**
  - **Insulation material** (e.g. losses, breakdown)
  - **Terminations / creepage**
  - **Shielding / grading**
  - **Electromagnetic compatibility**
- **MV/MF transformer**
  - **Resistive shielding**
  - **Dielectric losses** are **not negligible** (17%)
  - Typical insulation **epoxy resins** are **not adapted**
  - **Other materials are promising** (e.g. elastomers)
- **MV/MF electric fields are critical**

▼ Epoxy Sample



▼ Transformer Prototype

Detailed Results

[Gui16] Computation and Analysis of Dielectric Losses in MV Power Electronic Converter Insulation
T. Guillod, R. Färber, F. Krismer, C.M. Franck, and J.W Kolar
IEEE ECCE 2016, Milwaukee, USA
https://doi.org/10.1109/ECCE.2016.7854952

[Gui17] Electrical Shielding of MV/MF Transformers Subjected to High dv/dt PWM Voltages
T. Guillod, F. Krismer, and J.W Kolar
IEEE APEC 2017, Tampa, USA
https://doi.org/10.1109/APEC.2017.7931050

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R. Färber et al., “Modular Arbitrary Waveform Dielectric Spectrometer for Aging Diagnostics of Recessed Specimens”, CEIDP 2016
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Thank You! Questions?

Acknowledgements

Raphael Färber
Prof. Christian M. Franck
High Voltage Laboratory

Daniel Rothmund
Michael Leibl
Dr. Jonas Huber
Dr. Gabriel Ortiz
Power Electronic Systems Laboratory

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