ETH zürich

Power Electronic Systems Laboratory

Dielectric Losses in the Insulation of Dry-Type Medium-Frequency Transformers

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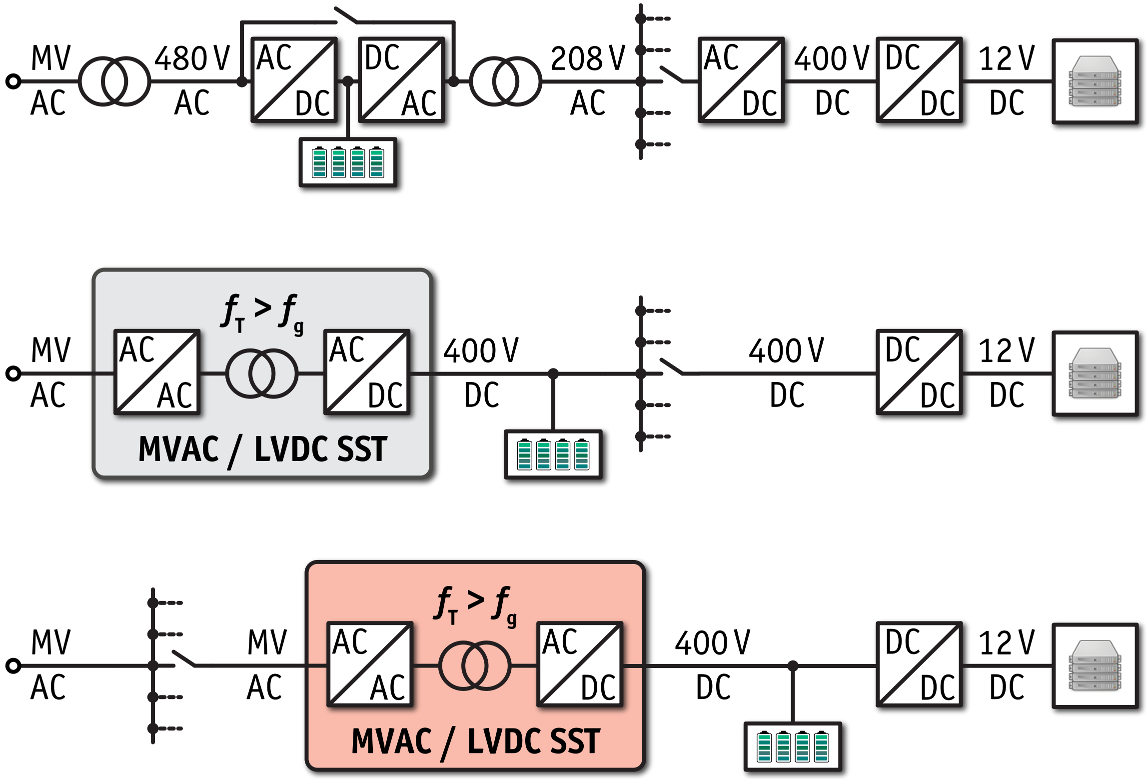
ECPE - New Technologies for Medium-Frequency Solid-State Transformers
Lausanne, Switzerland, February 15, 2019

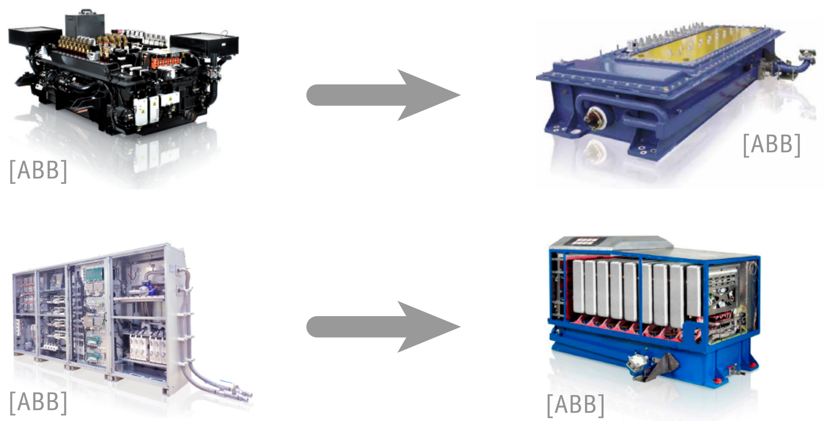
MV Solid-State Transformers (SSTs)

- ► Wind turbines / PV power plants
- ► Traction / more electric aircrafts
- ► Datacenters / EV fast chargers
- ► Building block for energy systems

▼ Future Datacenter Power Supply Chain



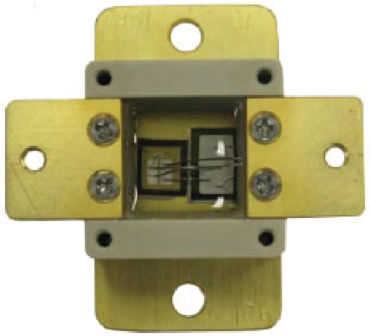
▼ Traction Power Supply Chain



Electrical Insulation for MV/MF Components

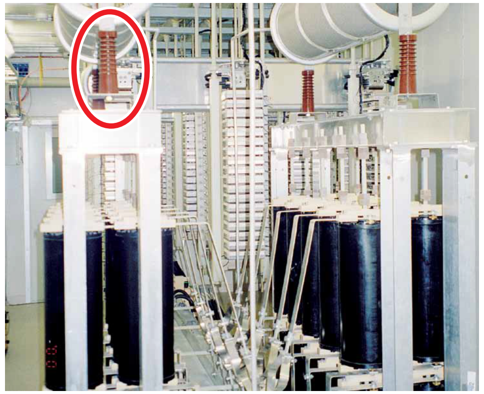
- New MV SiC devices
  - Voltages: 15 kV
  - Frequencies: 200 kHz
  - Switching speed: 150 kV/μs
- New topologies
  - Single-stage
  - Multi-cell
  - DC / LF / MF / HF
- Eagle Pass HVDC
  - MF harmonics
  - Losses in cable terminations
  - Time to failure: one week

▼ 10 kV SiC MOSFET



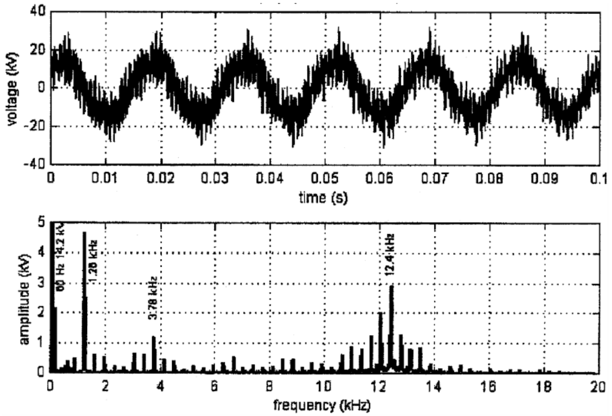
[Wolfspeed]

▼ Eagle Pass: Terminations



[ABB]

▼ Eagle Pass: Harmonics



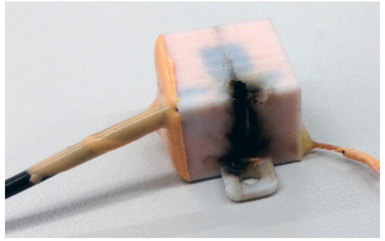
[Paulsson]

- Design and aging of electrical insulation of MV/MF converters is unclear

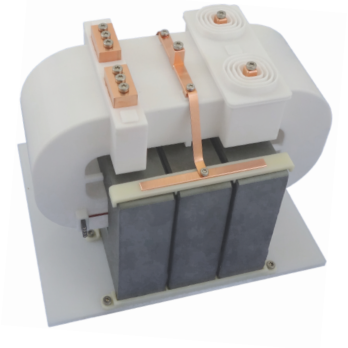
Dielectric Losses for MV/MF Components

- Electrical insulation
  - Electrical breakdown
  - Partial / surface discharges
  - Space charge migration
  - Shielding and grading
  - Dielectric losses
- Dielectric losses
  - Impact on the efficiency
  - Thermal breakdown
  - Thermal runaway
  - Diagnosis / aging
  - Quantitative computation
- Dielectric loss is an interesting figure of merit

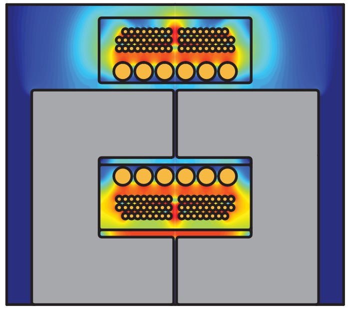
Breakdown



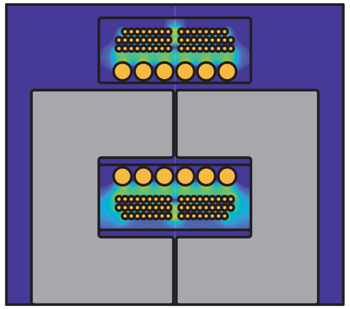
MV/MF Transformer



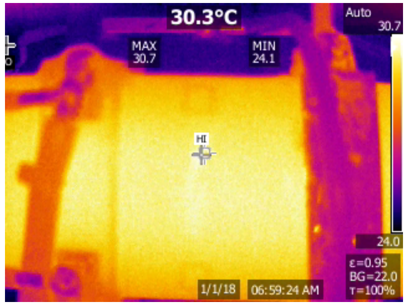
Electric Field



Dielectric Losses



Dielectric Heating



Outline

Theory of Dielectrics

Dielectrics with PWM

Case Study: SST

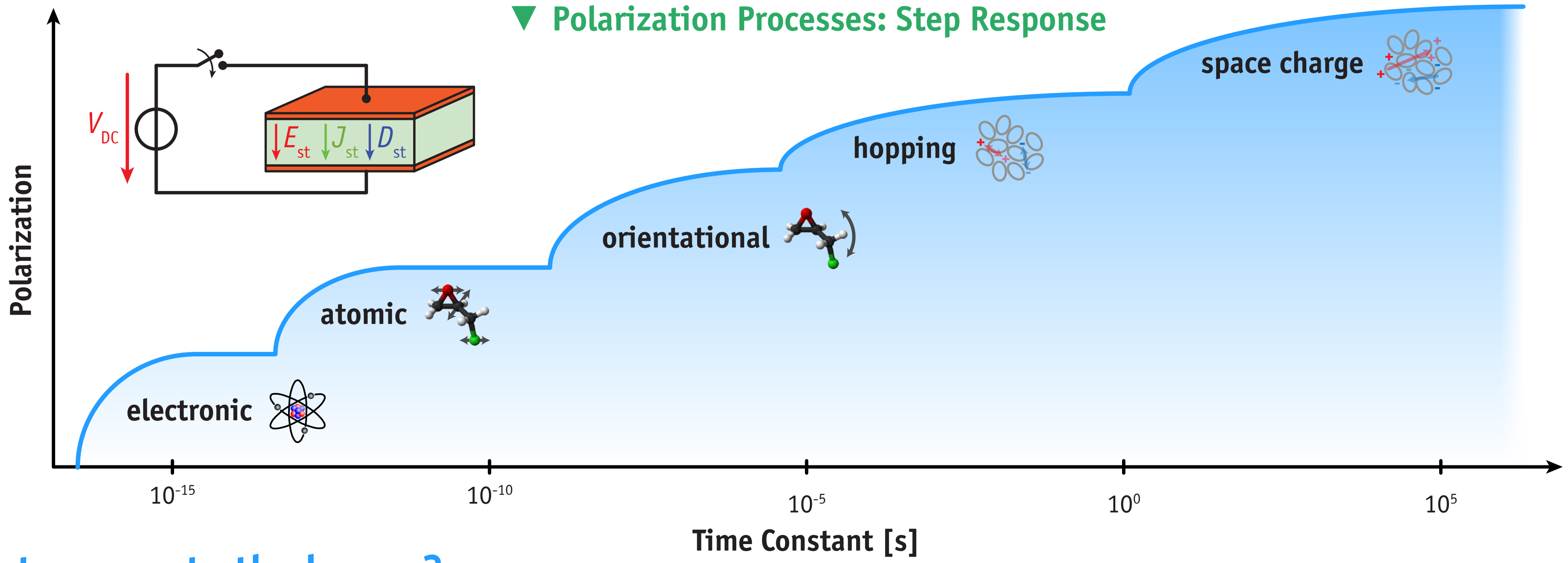
Conclusion

Theory of Dielectrics

Theory: Polarization in Dielectrics

- Polarization processes
  - Many micro-physical processes
  - Different time constants
- Polarization modeling
  - Polarization is mostly linear
  - Described with the step response

▼ Polarization Processes: Step Response



- How to compute the losses ?

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

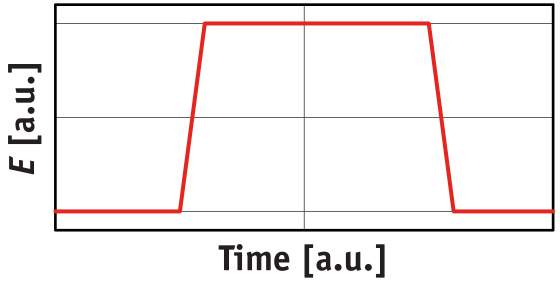
Theory: Dielectric in Time Domain

- ▶ PWM voltage
- ▶ Finite rise time

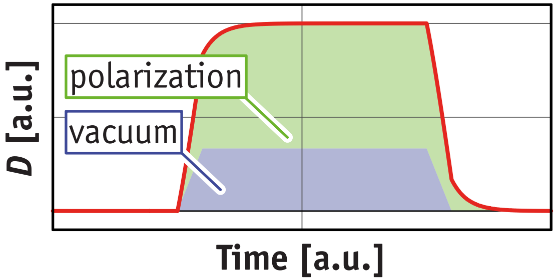
- ▶ Dielectric response
- ▶ Convolution integral

- ▶ Loss extraction
- ▶ Complex computation

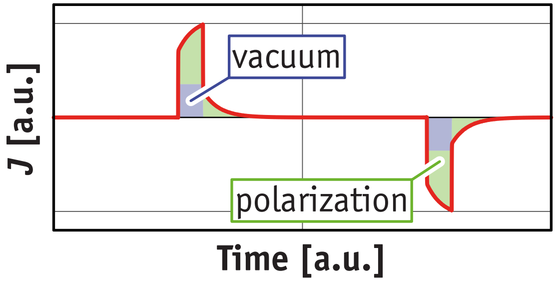
▼ Electric Field



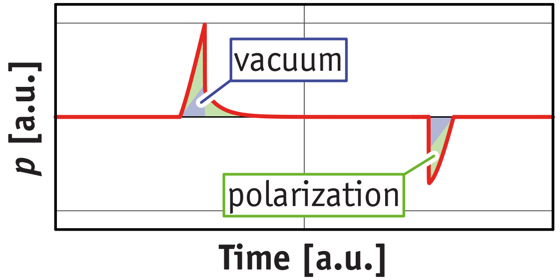
▼ Displacement Field



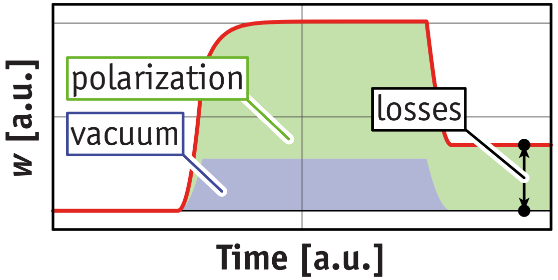
▼ Current Density



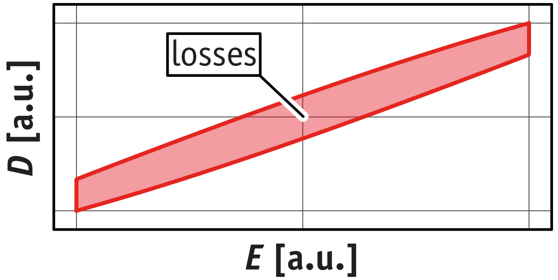
▼ Input Power



▼ Supplied Energy



▼ Hysteresis

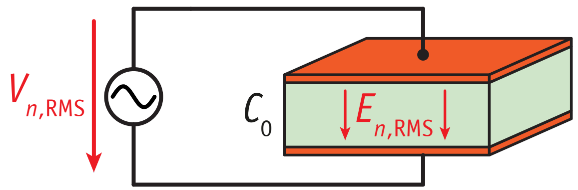


▶ Time domain → difficult computation → frequency domain

Theory: Dielectric in Frequency Domain

- **Physical processes**
  - DC conduction is negligible
  - Polarization is frequency-dependent
  - Polarization response is linear
- **Permittivity**
  - Fourier transformation
  - $\varepsilon(f) = \varepsilon_0 \left(\varepsilon_\mathrm{r}' - \mathrm{j}\varepsilon_\mathrm{r}''\right)$
  - $\tan\delta(f) = \varepsilon_\mathrm{r}'' / \varepsilon_\mathrm{r}'$
- **Dielectric losses**
  - $P = \iiint_\mathrm{V} \left(\sum_{n=1}^{\infty} \varepsilon_0 \varepsilon_\mathrm{r}'' \left(2\pi n f\right) E_{n,\mathrm{RMS}}^2 \right) \mathrm{dV} = \underline{C_0} \sum_{n=1}^{\infty} \underline{\varepsilon_\mathrm{r}''} \, \underline{\left(2\pi n f\right) V_{n,\mathrm{RMS}}^2}$
  - Geometry / capacitance → C_0
  - Material / temperature → ε_r''
  - Voltage / frequency → $\left(2\pi n f\right) V_{n,\mathrm{RMS}}^2$

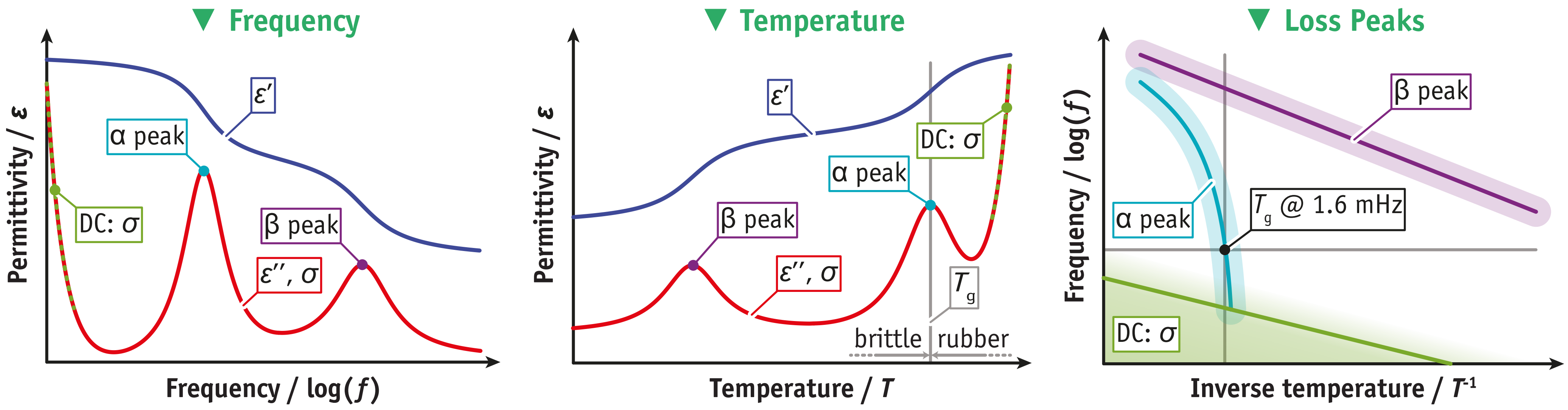
Setup



- **Dielectric losses depend on many parameters**

Theory: Frequency / Temperature

- **Permittivity**
  - $\varepsilon' / \varepsilon''$ for typical polymeric dry-type materials
  - Loss peaks between polarization mechanisms
- **Kramers-Kronig relations**
  - Causality condition
  - $\varepsilon_r''(f) \propto -\partial\varepsilon_r'(f) / \partial \ln(f)$

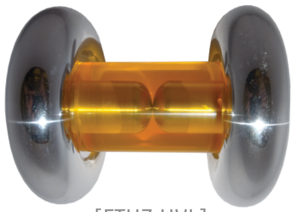


- **Frequency and temperature dependencies are critical**

Example: Epoxy VonRoll Damisol 3418

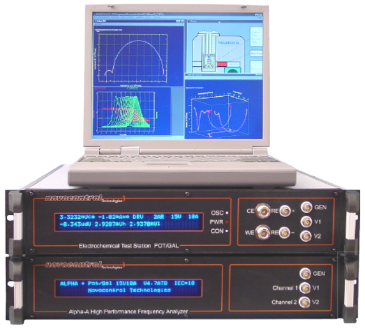
- Measured for a typical epoxy resin
  - Damisol 3418 (unfilled epoxy resin)
  - Frequency and temperature dependences
- Loss peaks
  - α peak @ T_g = 136°C
  - ß peak is less critical

Epoxy Sample



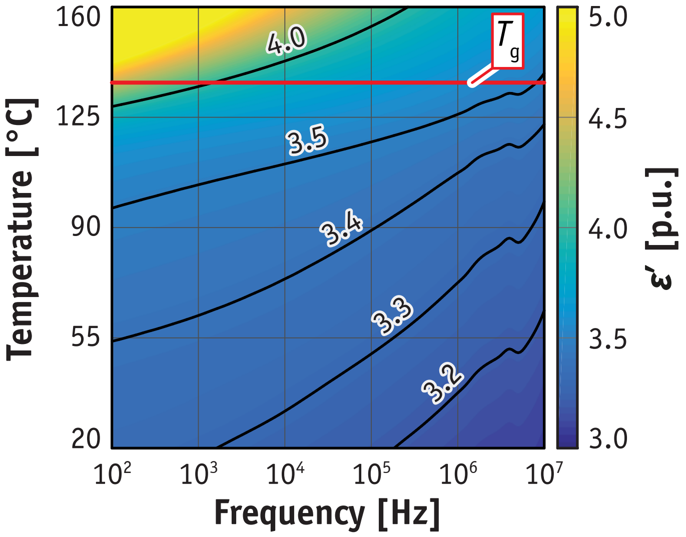
[ETHZ HVL]

Spectroscopy Setup

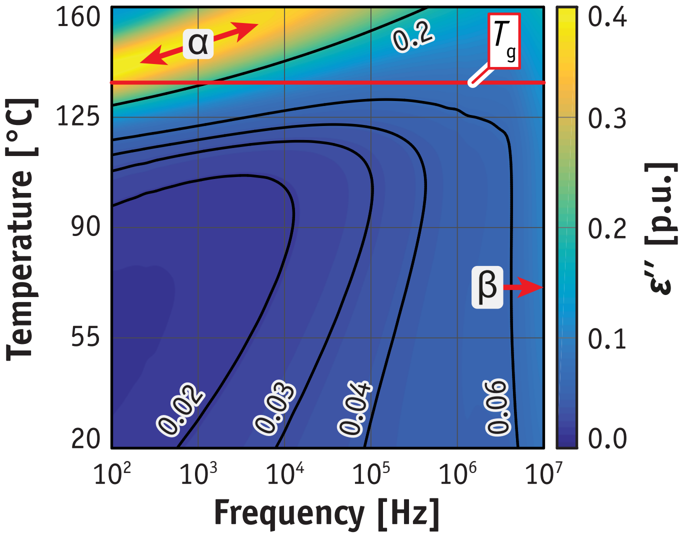


[Novocontrol]

Meas. of ε'



Meas. of ε''

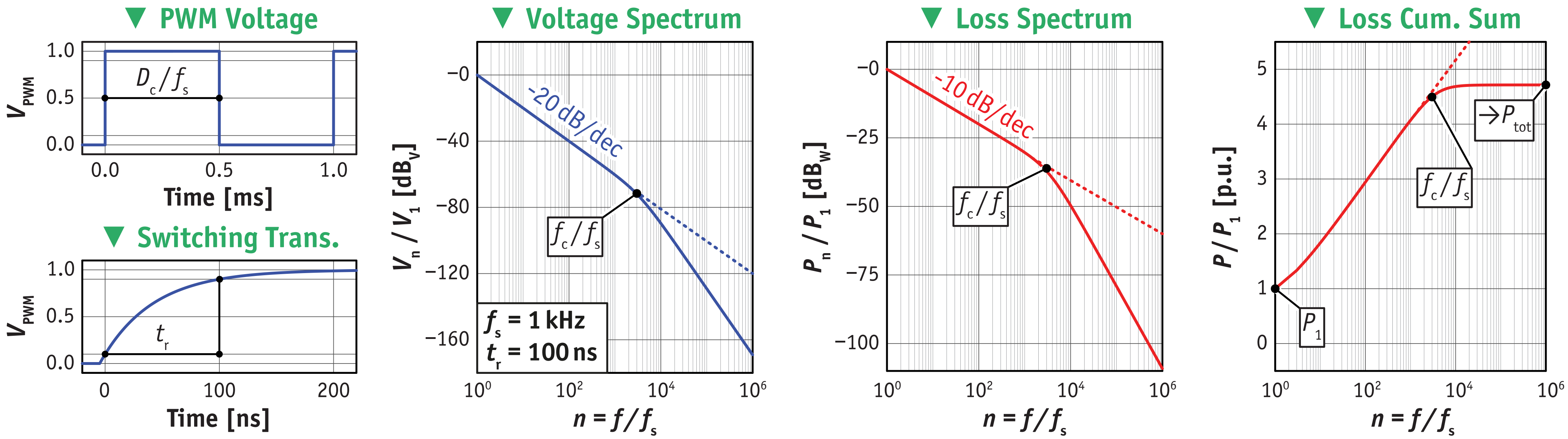


- How to compute the losses ?

Dielectrics with PWM

PWM: Spectral Losses

- **Hypothesis**
  - $\varepsilon(f)$ is constant
  - Temperature is constant
- **PWM signal**
  - Constant duty cycle
  - Many harmonics
- **Dielectric losses**
  - Fund. frequency analysis is incorrect
  - Switching transition model is required



- **Summation of harmonics is complex → simple computation method is required**

PWM: Constant Duty Cycle

- PWM with constant duty cycle
  - $\varepsilon(f)$ is constant
  - Typical for DC-DC converter
- Closed-form solution
  - Partial sum / residual
  - 4.0% accuracy

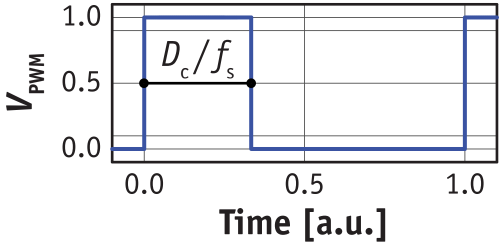
Closed-form Solution

$$P \approx \lambda P_1$$

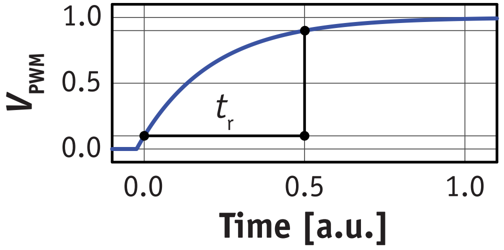
$$P_1 = (\varepsilon_r'' C_0)\,(2\pi f_s)\left(\frac{\sqrt{2}}{\pi} V_{DC}\right)^2$$

$$\lambda = \frac{1}{2}\ln\left(2e^{\gamma}\frac{f_c}{f_s}\sin(\pi D_c)\right)$$

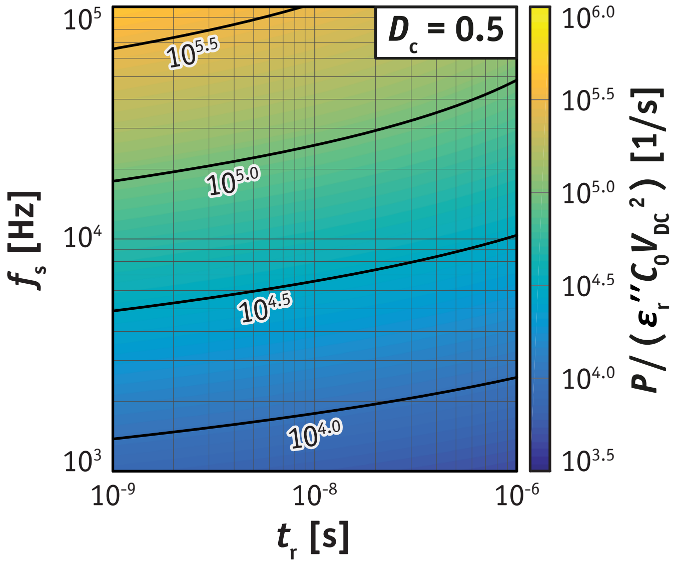
PWM Voltage



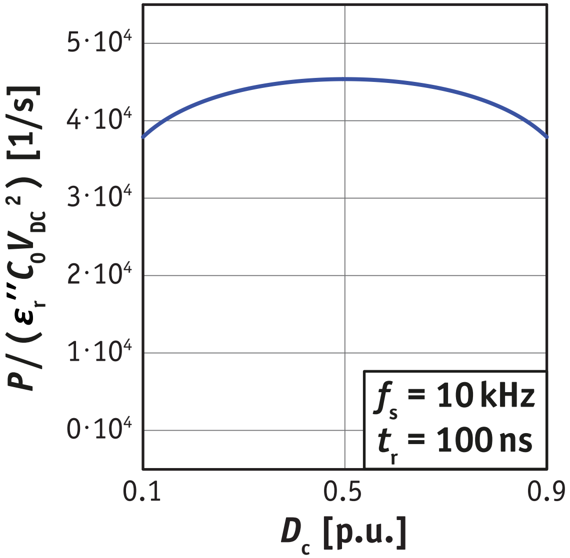
Switching Trans.



Freq. / Rise Time



Duty Cycle

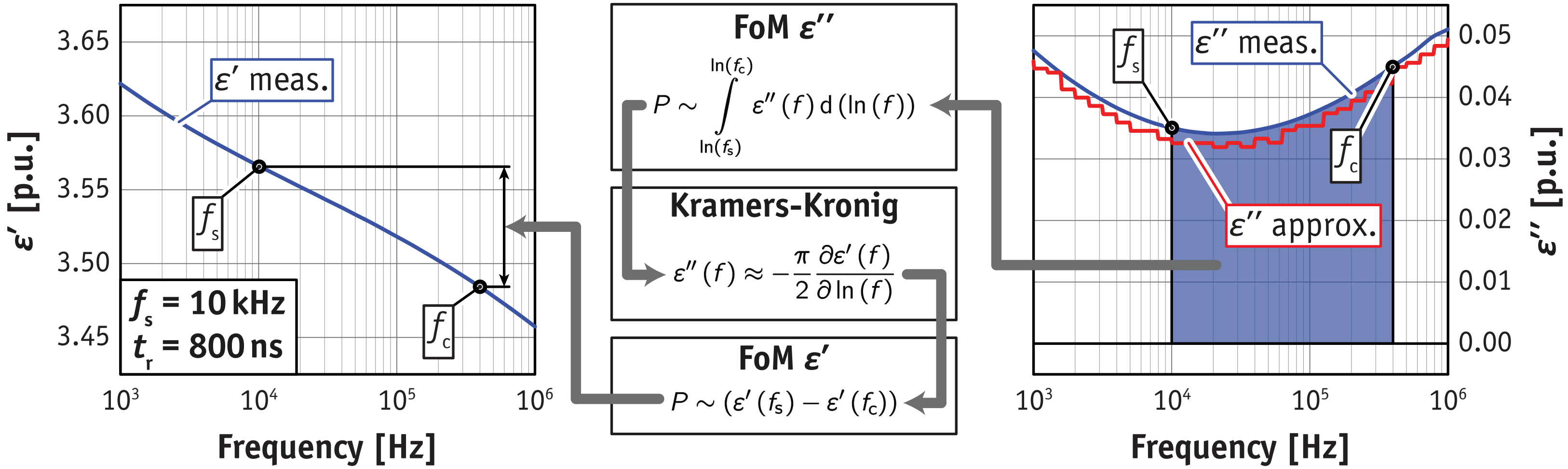


- Frequency dependency of the permittivity ?

PWM: Frequency-Dependent Material

- **Invalid simplifications**
  - Fund. freq. analysis → 100% error
  - No freq. dependency → 100% error
- **Closed-form approximation**
  - Approx. of the sum & Kramers-Kronig
  - 10% accuracy (Damisol 3418)

▼ Meas. of ε' ▼ Figures of Merit ▼ Meas. of ε''



▼ Epoxy Sample

[ETHZ HVL]

- **Simple figures of merit → guidelines for selecting materials**

Dielectric Losses: 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 level
ε''	$P \sim \varepsilon''$	permittivity ($\varepsilon(f)$ = const.)

Critical impact
Moderate impact
Small impact

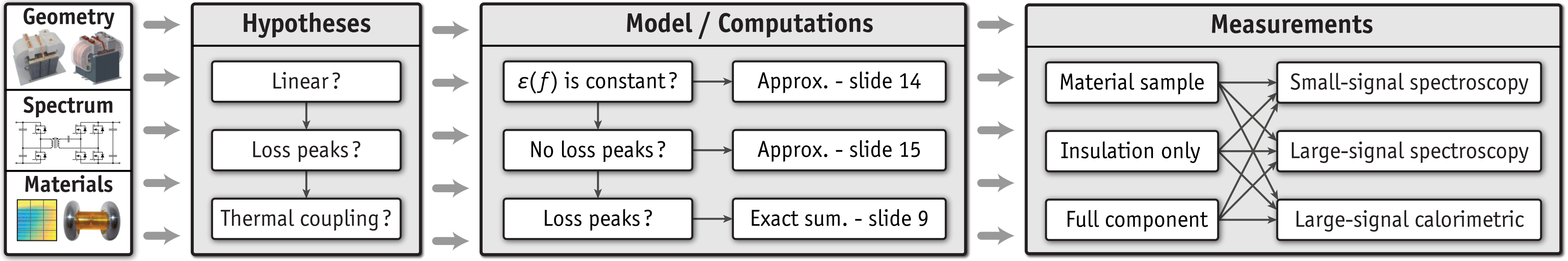
- **Summary**
  - Multi-cell IGBT-based SST: 2 kV / 5 kHz — 1x
  - Single-stage SiC-based SST: 7 kV / 50 kHz — 120x

- **Frequency and voltage are the critical parameters**

Dielectric Losses: Design Guidelines

- **Desired properties**
  - Low ε' and ε''
  - No massive loss peaks
  - High thermal conductivity
- **Electrical parameters**
  - Breakdown voltage
  - Partial discharges
  - DC conductivity
- **Other effects**
  - Chemical compatibility
  - Aging resistance
  - Potting and/or processing

▼ Workflow for Dielectric Losses



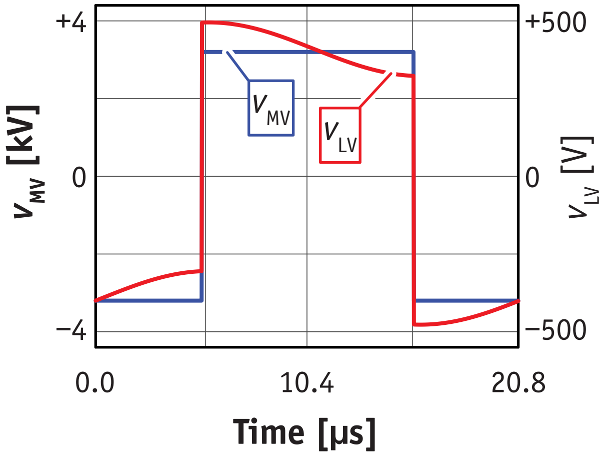
- **Many trade-offs → insulation design is a challenging task**

Case Study: SST

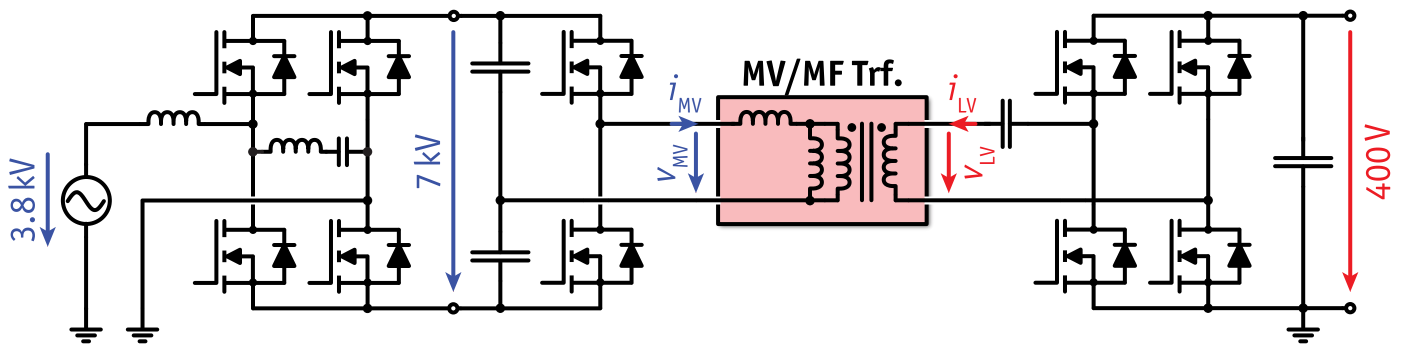
System: 10 kV SiC-based SST for Datacenters

- 25 kW: MV AC ↔ LV DC
  - 10 kV SiC FETs
  - AC-DC: 3.8 kV AC ↔ 7 kV DC
  - DC-DC: 7 kV DC ↔ 400 V DC
- DC-DC: 7 kV ↔ 400 V
  - Series Res. Conv. (SRC)
  - 48 kHz with ZVS
  - 99.0% efficiency
- MV/MF Transformer → electrical insulation → critical

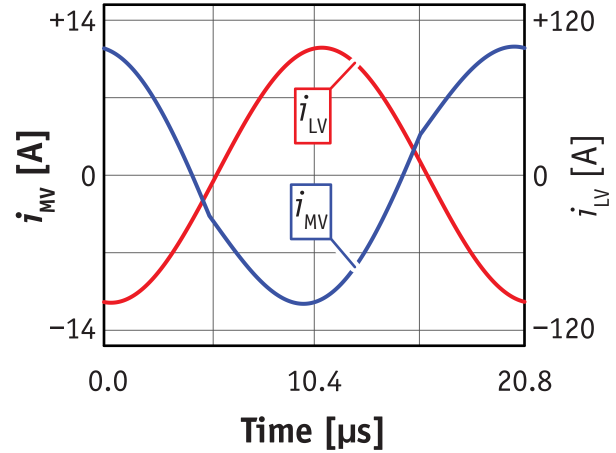
▼ SRC Voltages



▼ 25 kW SST: MVAC ↔ LVDC



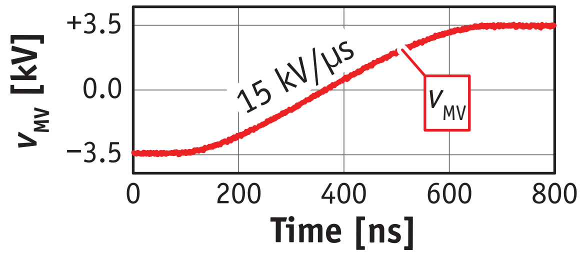
▼ SRC Currents



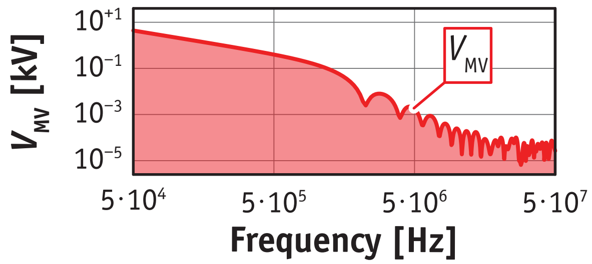
MV/MF Transformer: Voltage Stress

- **Voltage spectrum**
  - 7 kV DC bus
  - PWM DM voltage
  - PWM CM voltage
  - LF CM voltage
- **Switching**
  - No ringing, no overshoot
  - 15 - 75 kV/µs with ZVS
  - 100 kV/µs without ZVS
  - Relevant stress up to 1 MHz
- **Combines all the critical factors (single-stage, *f*, *V*, dv/dt)**

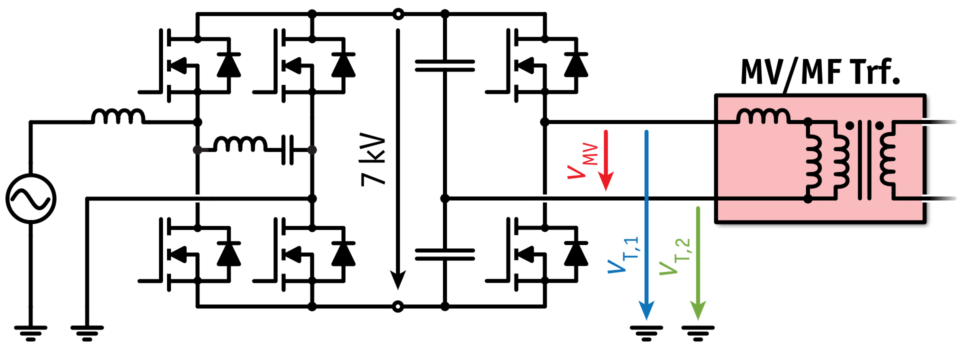
▼ Meas. MV Transient



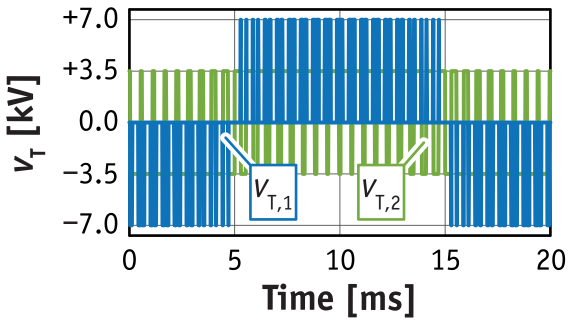
▼ Meas. MV Spectrum



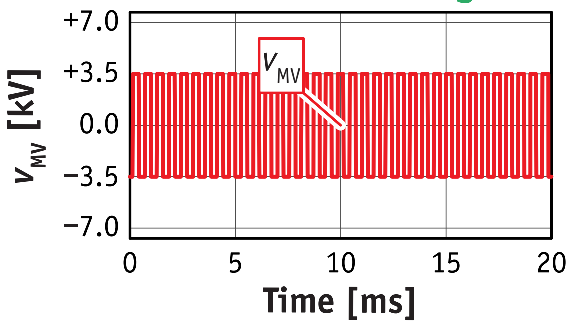
▼ 25 kW SST / MV Side



▼ MV Terminals



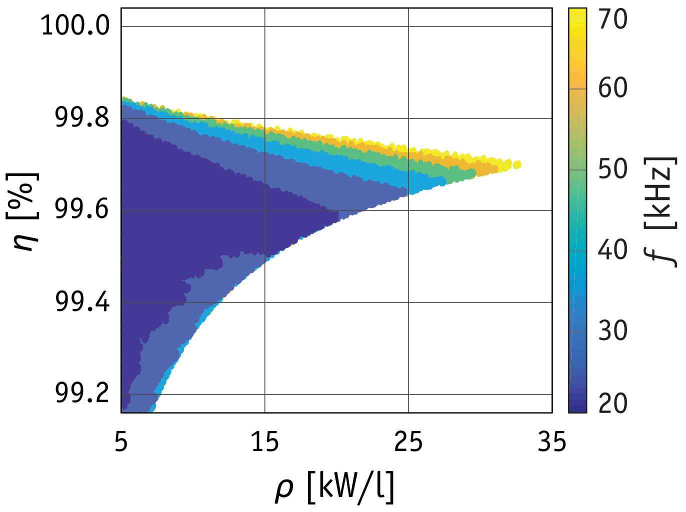
▼ MV DM Voltage



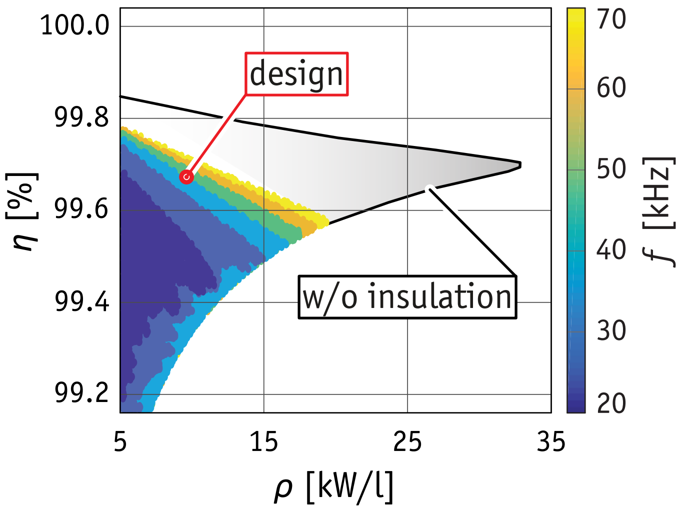
MV/MF Transformer: Optimization

- 25 kW / SRC DC-DC
  - ±3.5 kV ↔ ±400 V
  - 15 kV CM insulation
- Insulation requirements
  - Lower efficiency
  - Lower power density

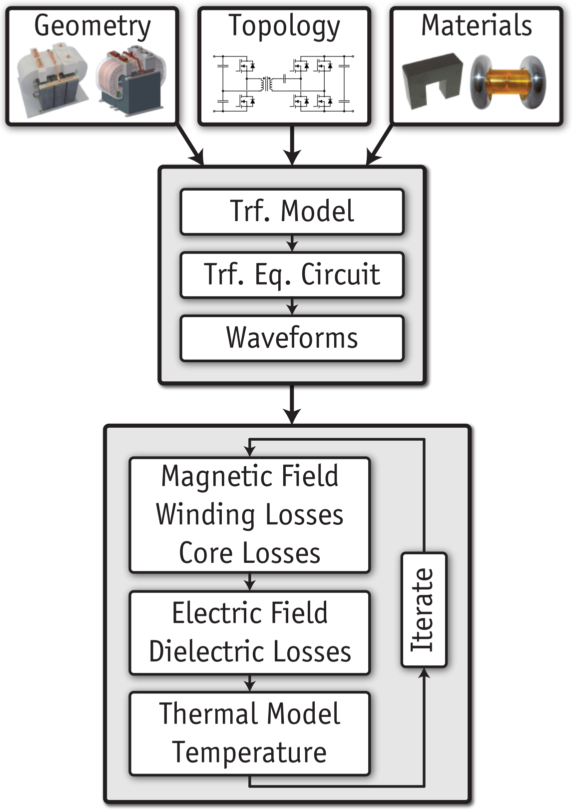
▼ Without Insulation



▼ With Insulation



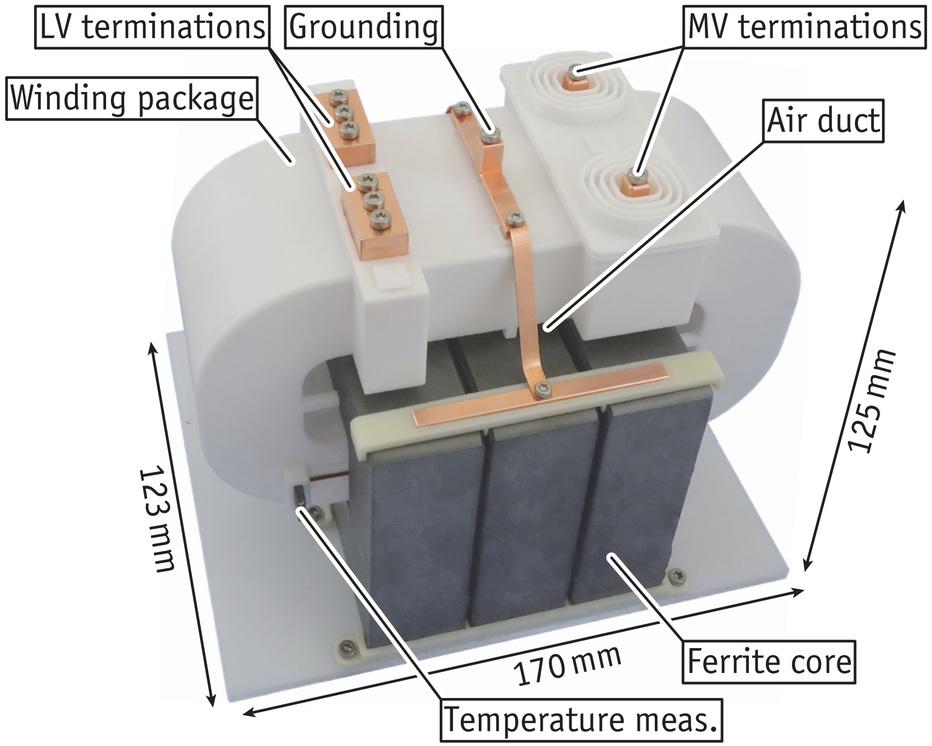
▼ Optim. Workflow



- Litz wires / ferrite core / air cooling / 48 kHz

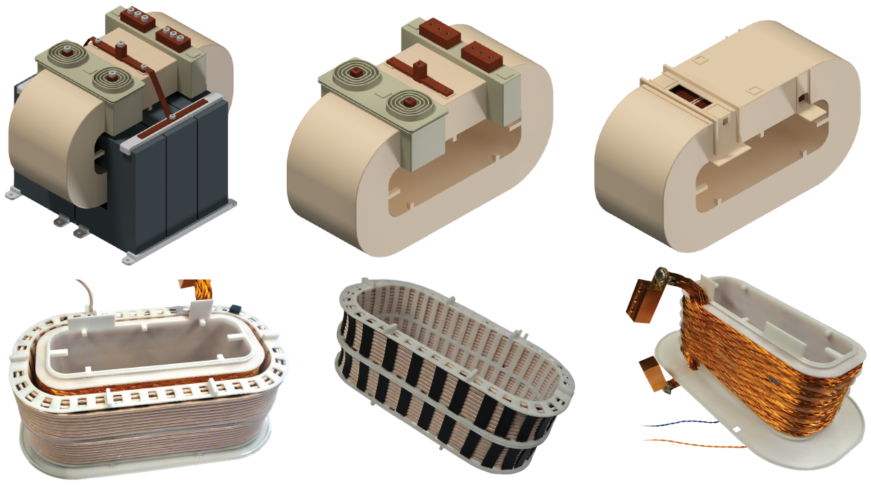
MV/MF Transformer: Construction

▼ MV/MF Transformer Prototype

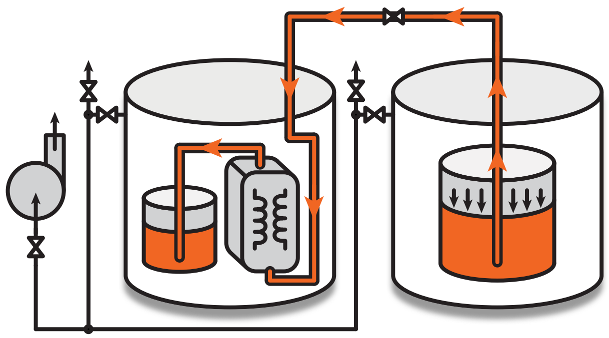


► **Vacuum potting process of the windings**

▼ Construction Process



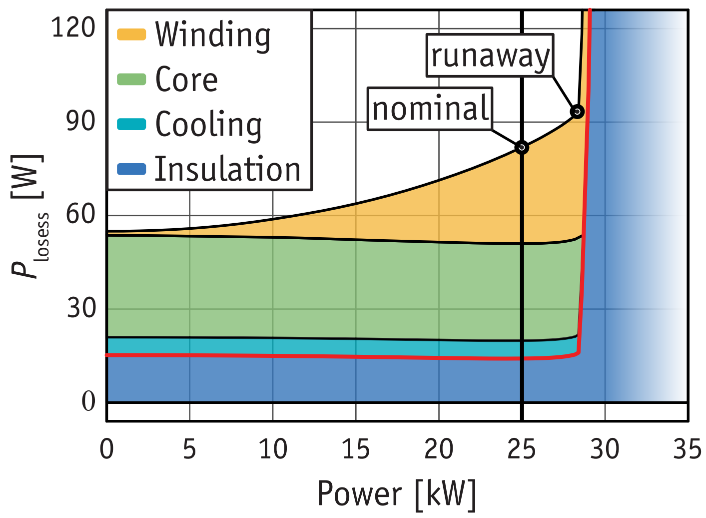
▼ Insulation Vacuum Potting



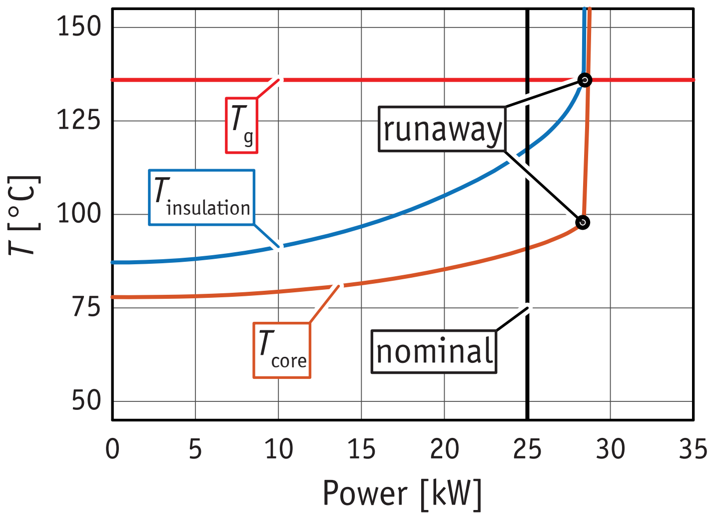
MV/MF Transformer: Epoxy VonRoll Damisol 3418

- **Insulation stress**
  - Reactive power: 1.0 kVA
  - Peak field: 2.2 kV/mm
- **Dielectric losses**
  - 27% at no-load
  - 17% at full-load
- **Thermal runaway**
  - Loss peak at α peak
  - At 12% overload

Loss Breakdown



Temperature



VonRoll Damisol 3418

Thermal properties (unfilled epoxy resin)

Conductivity	0.3 W/mK
Glass transition	136° C
Max. temperature	200° C

Electrical properties ($f > 50$ kHz and $T < 120$ °C)

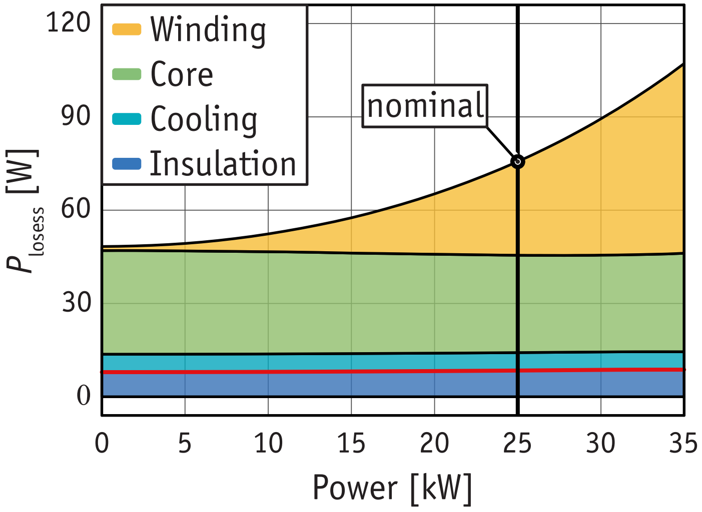
Permittivity	< 3.6
Dissipation factor	< 3.1%
Breakdown field	> 50 kV/mm

- **Dielectric losses are significant → thermal runaway → better materials required**

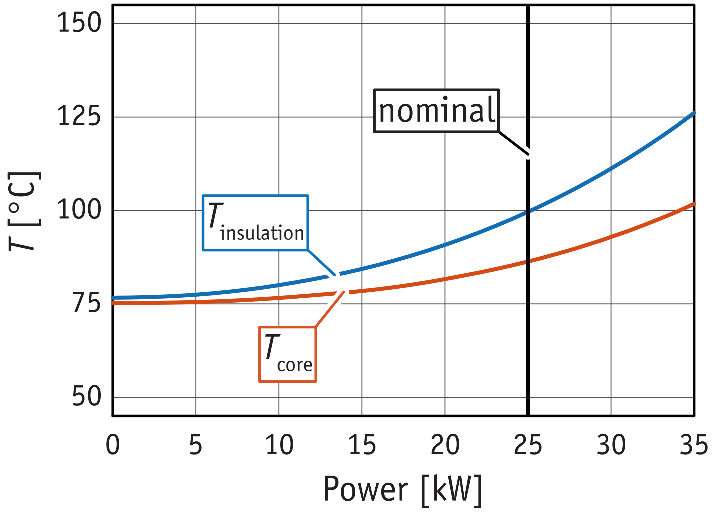
MV/MF Transformer: Silicone Dow TC4605 HLV

- **Insulation stress**
  - Reactive power: 1.2 kVA
  - Peak field: 2.3 kV/mm
- **Dielectric losses**
  - 16% at no-load
  - 11% at full-load
- **No loss peaks**
  - α peak at neg. temp.
  - No thermal runaway

Loss Breakdown



Temperature



Dow TC4605 HLV

Thermal properties (filled silicone elastomer)

Conductivity	1.0 W/mK
Glass transition	< 0° C
Max. temperature	200° C

Electrical properties (f > 50 kHz and T < 120 °C)

Permittivity	< 4.1
Dissipation factor	< 0.8%
Breakdown field	> 20 kV/mm

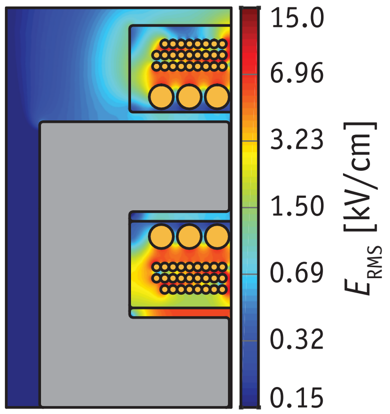
- **Sillicone elastomer → no loss peaks and high thermal performances**

[ECCE2016, JESTPE2018b]

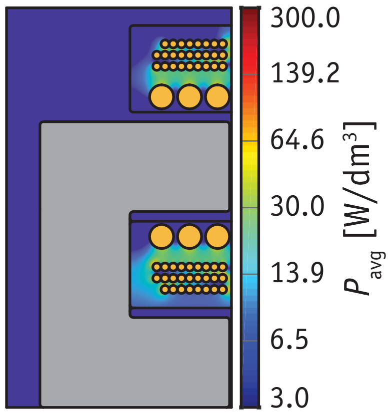
MV/MF Transformer: Dielectric Meas.

- Silicone elastomer
  - Dow TC4605 HLV
  - Loss computation
  - Good trade-off
- Small-signal measurements
  - Dielectric spectroscopy
  - Frequency sweep
  - 13% error vs. sim.
- Large-signal measurements
  - Calorimetric method
  - Sinus and PWM
  - 11% error vs. sim.

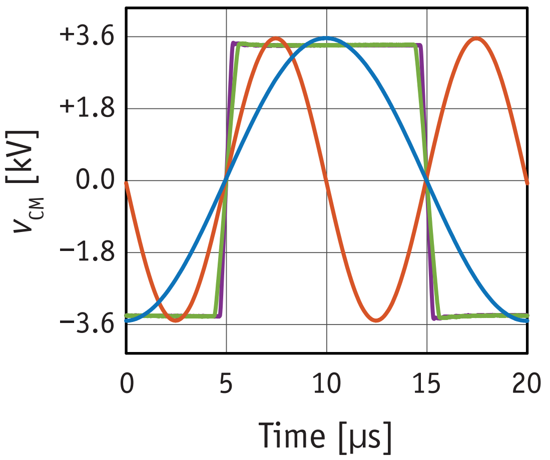
▼ El. Field



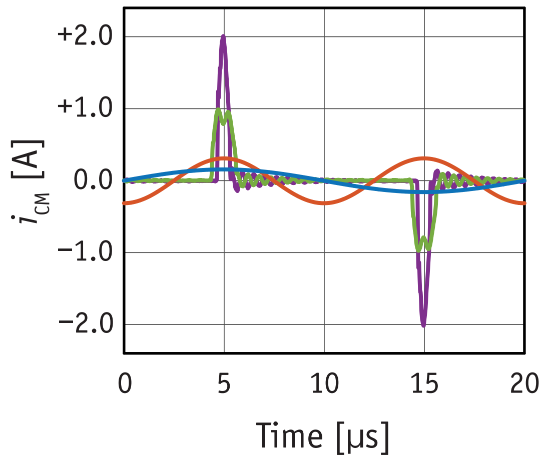
▼ Losses



▼ Applied Voltages



▼ Obtained Currents



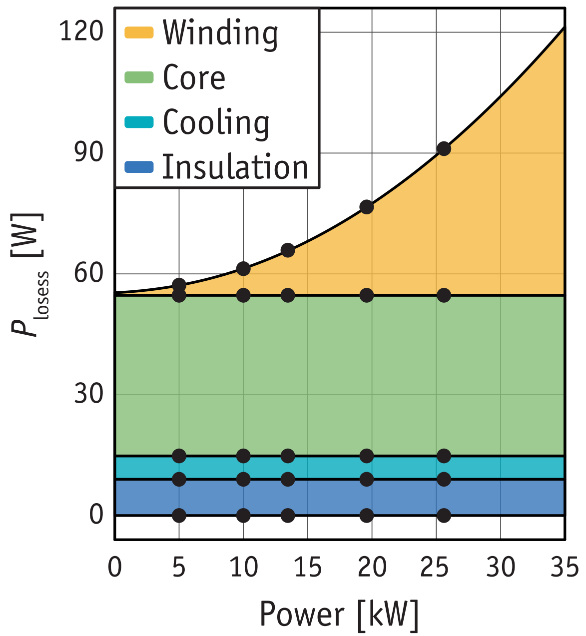
- LV spectroscopy and simulations are valid → prediction of the losses

[ECCE2016, JESTPE2018b]

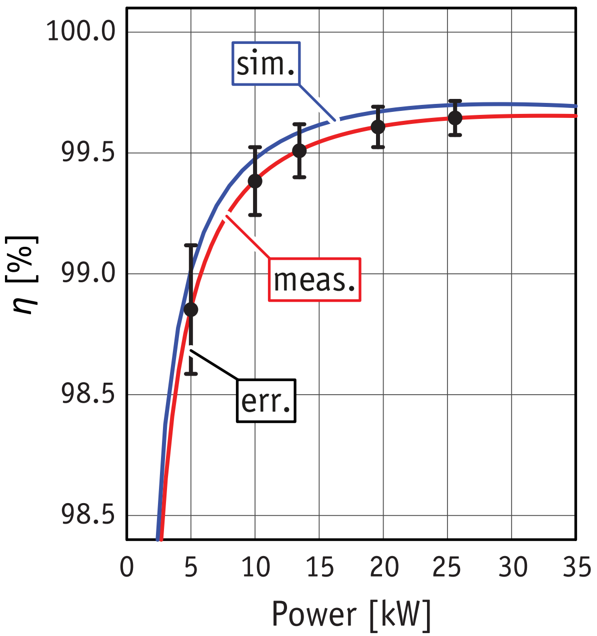
MV/MF Transformer: Losses

- Dielectric losses
  - Dielectric spectroscopy
  - Calorimeter
- Core losses
  - Resonant circuit
  - Calorimeter
- Winding losses
  - Impedance analyzer
  - Calorimeter

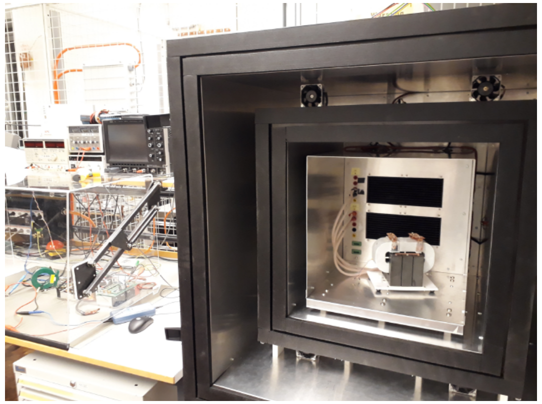
▼ Meas. Losses



▼ Efficiency



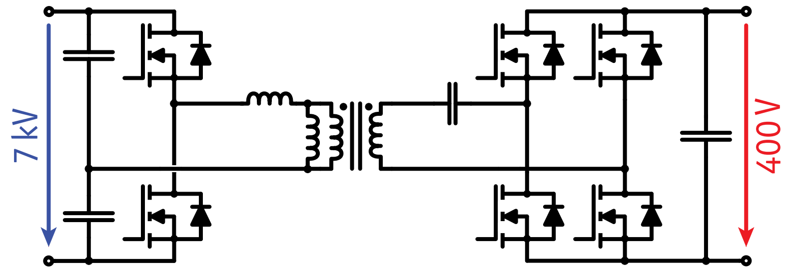
▼ Calorimeter



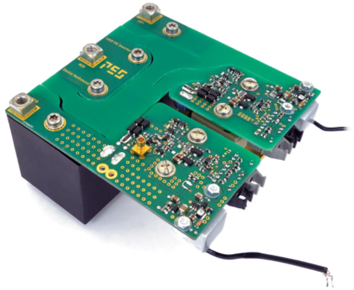
- 99.69% sim. efficiency
- 99.65% meas. efficiency
- 7.4 kW/l power density

DC-DC SRC: Measurements

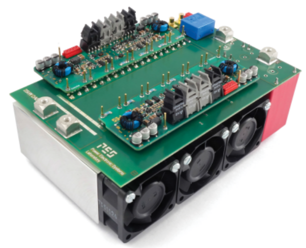
▼ SRC DC-DC Converter



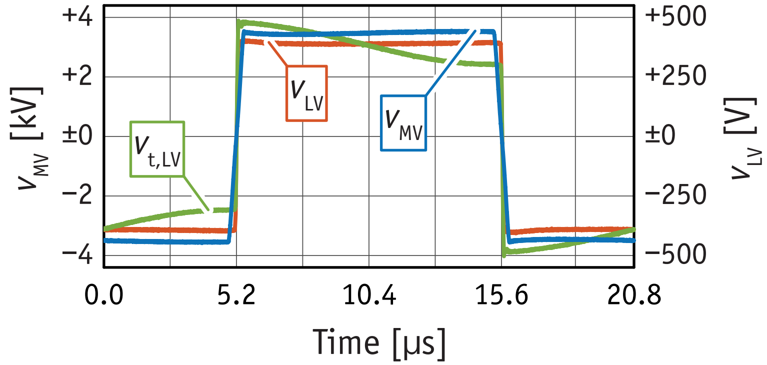
▼ MV Bridge



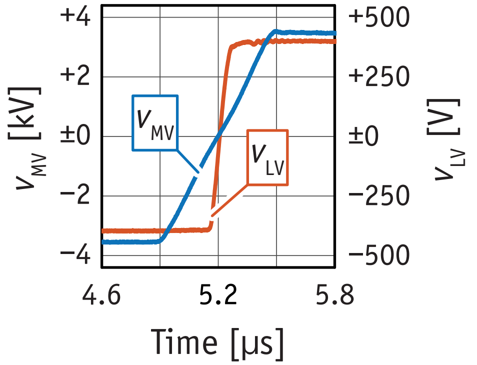
▼ LV Bridge



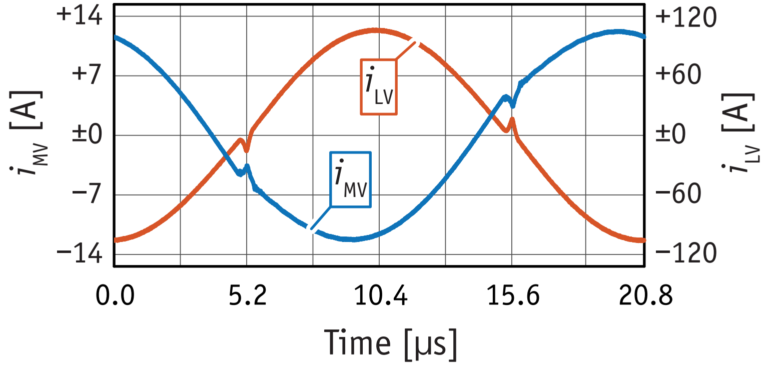
▼ DC-DC SRC: Voltages



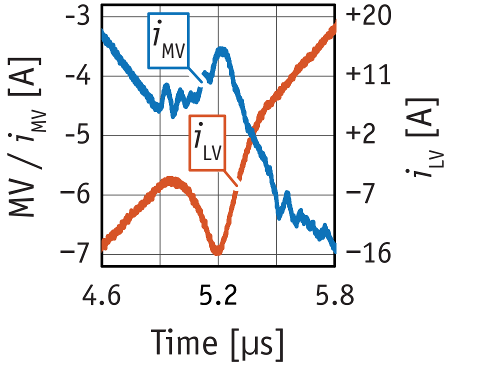
▼ ZVS



▼ DC-DC SRC: Currents



▼ ZVS

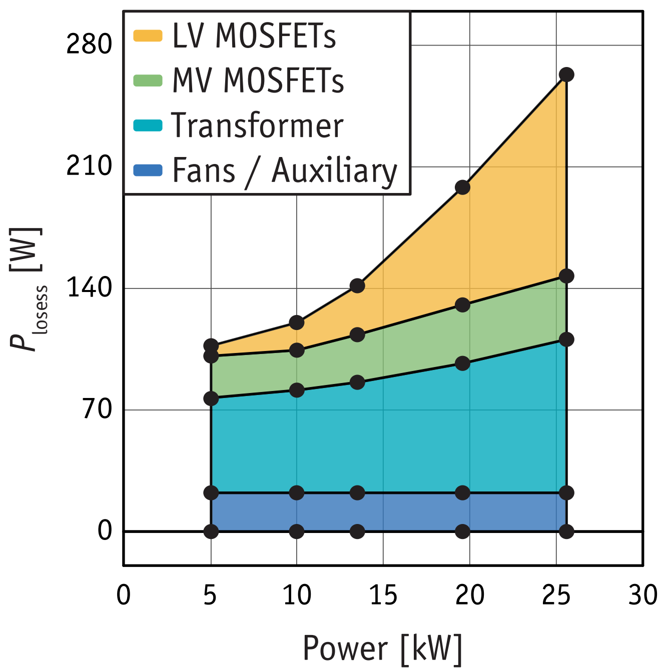


► **Tested at full power → measurements match the simulations**

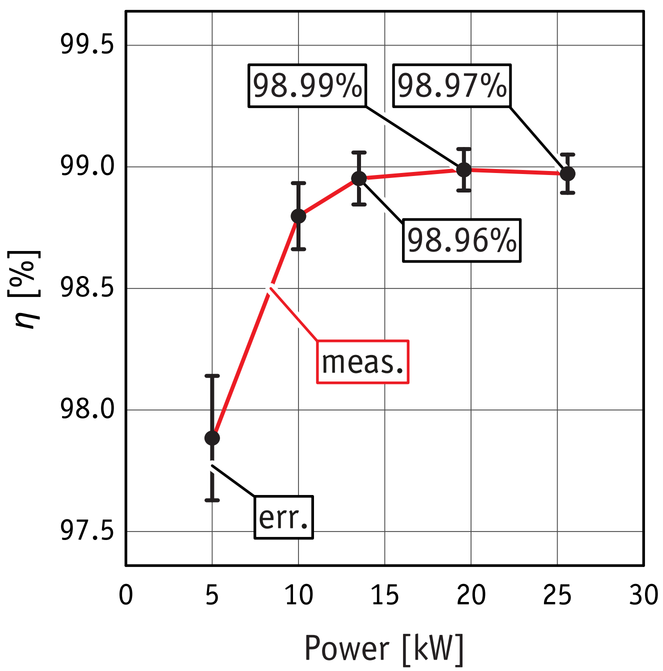
DC-DC SRC: Efficiency

- Calorimetric method
  - Carefully calibrated
  - 0.08% accuracy
- Loss breakdown
  - Transformer: 32%
  - LV MOSFETs: 44%
- Efficiency curve
  - Extremely flat curve
  - Overload is possible
- 99.0% meas. efficiency
- 3.8 kW/l power density

▼ Loss Breakdown



▼ Meas. Efficiency

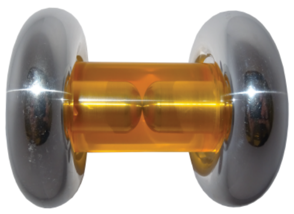


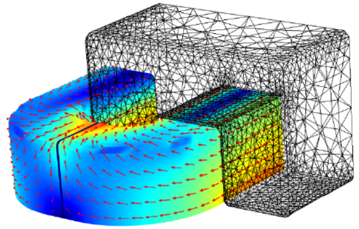
Conclusion

Conclusion & Outlook

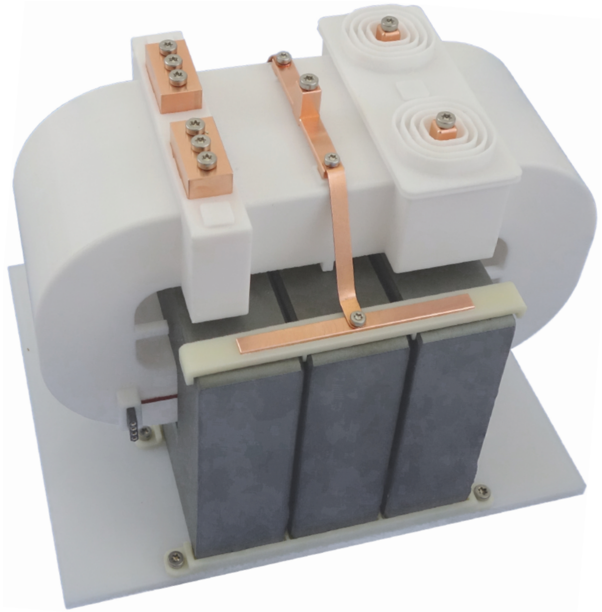
- Dielectric losses with PWM
  - Critical parameter for MV/MF designs
  - Materials exhibit dielectric loss peaks
  - Analytical expressions and guidelines
- 10 kV SiC SST demonstrator
  - Dielectric losses are not negligible
  - Transformer: 99.65% - 7.4 kW/l
  - DC-DC converter: 99.0% - 3.8 kW/l
- Outlook
  - Partial discharges / aging
  - Materials and/or datasheets for MF
- MV/MF transformers can take advantage of MV SiC MOSFETs
- Electrical insulation is critical for future SSTs

▼ MV/MF Transformer: Design and Construction





▼ MV/MF Transformer Prototype



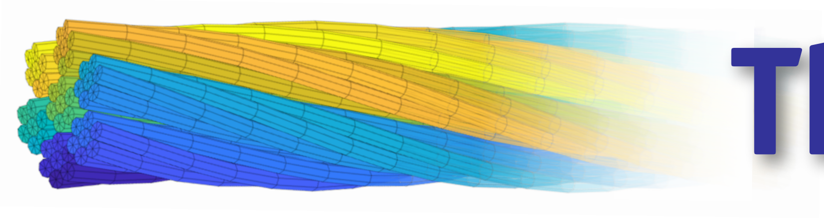
Detailed Results

[ECCE2016] **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

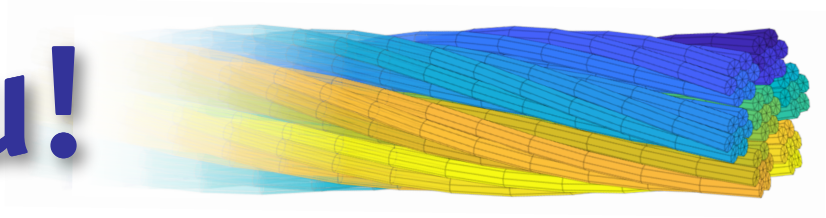
[APEC2017] **Electrical Shielding of MV/MF Transformers Subjected to High dv/dt PWM Voltages**
T. Guillod, F. Krismer, and J.W Kolar
IEEE APEC 2017, Tampa, USA
https://doi.org/10.1109/APEC.2017.7931050

[JESTPE2018a] **99.1% Efficient 10 kV SiC-Based Medium Voltage ZVS Bidirectional Single-Phase PFC AC/DC Stage**
D. Rothmund, T. Guillod, D. Bortis, and J. W. Kolar
IEEE Journal of Emerging and Selected Topics in Power Electronics, 2018
https://doi.org/10.1109/JESTPE.2018.2886140

[JESTPE2018b] **99% Efficient 10 kV SiC-Based 7 kV / 400 V DC-Transformer for Future Data Centers**
D. Rothmund, T. Guillod, D. Bortis, and J. W. Kolar
IEEE Journal of Emerging and Selected Topics in Power Electronics, 2018
https://doi.org/10.1109/JESTPE.2018.2886139



Thank You!



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