ETH zürich

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SS1 – Which Impact of SiC Technology?

Design and Experimental Analysis of a 10 kV SiC MOSFET Based 50 kHz Soft-Switching Single-Phase 3.8 kV AC / 400 V DC Solid-State Transformer

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Outline

- *Future Datacenters*
- *10kV SiC MOSFET Soft-Sw. Losses*
- *Highly-Compact Isolated Gate Drive*
- *3.8kV/7kV ZVS AC/DC Converter*
- *7kV/400V ZVS DC/DC Converter*
- *Conclusions*

Future Datacenters

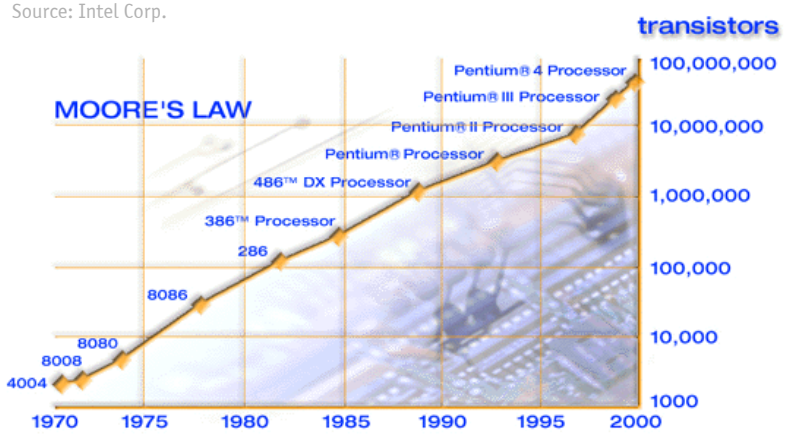
Digital Transformation
SST-Based MV Supply

Digital Transformation

- **Internet of Things (IoT) / Cognitive Computing**

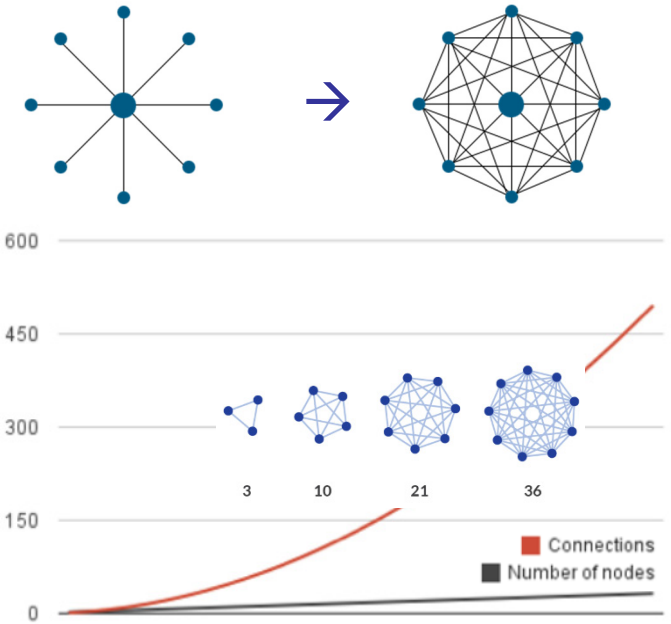
— Ubiquitous Computing / BIG DATA
— Fully Automated Manufacturing / Industry 4.0
— Autonomous Cars
— Etc.

Source: Intel Corp.



► Moore's Law

– Moving from Hub-Based to Community Concept Increases Potential Network Value Exponentially (~n(n-1) or ~n log(n))

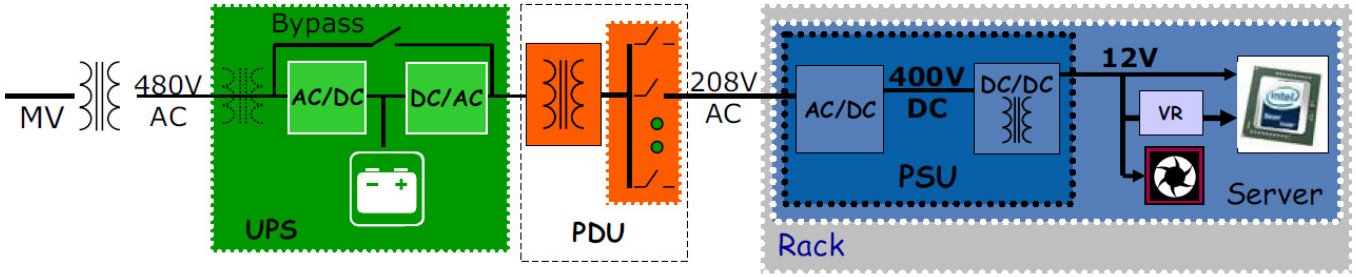


► Metcalfe's Law

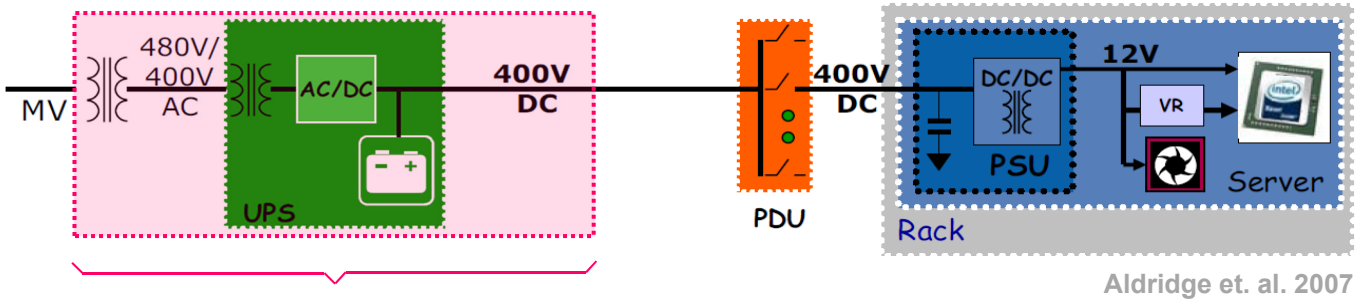
SST-Based Datacenter 400V DC Distribution System

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional



— Facility-Level 400 V_{DC} Distribution → Gain in Efficiency / Complexity

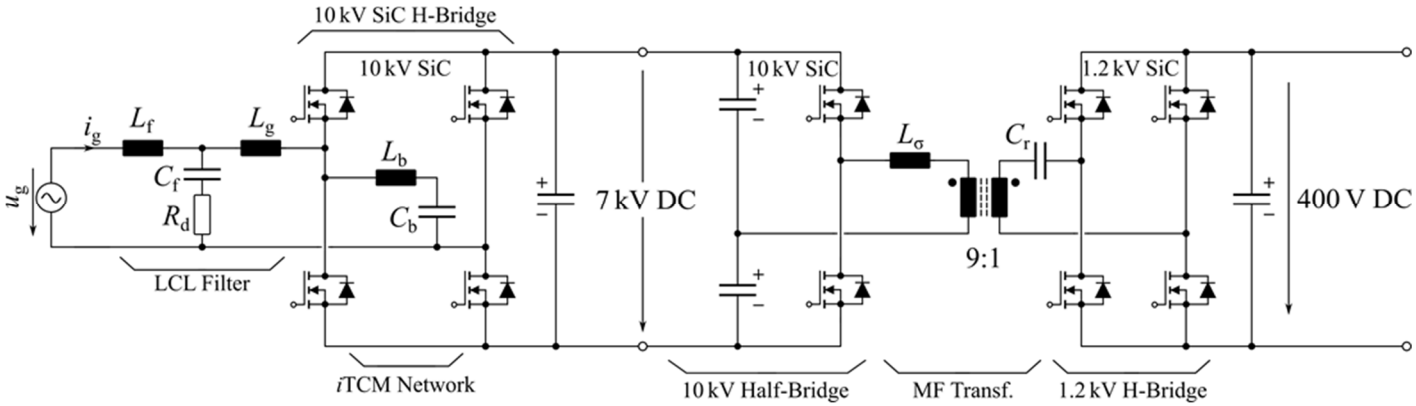


Aldridge et. al. 2007

- Direct 1-Φ 3.8kV AC → 400V DC Conversion / Unidirectional SST

25kW SwiSS-Transformer

- *Bidirectional 1-Φ 3.8 kV_{rms} AC → 400V DC Power Conversion*
- *Based on 10kV SiC MOSFETs*
- *Full Soft-Switching*



► *35...75kHz iTCM Input Stage*

► *48kHz DC-Transformer Output Stage*

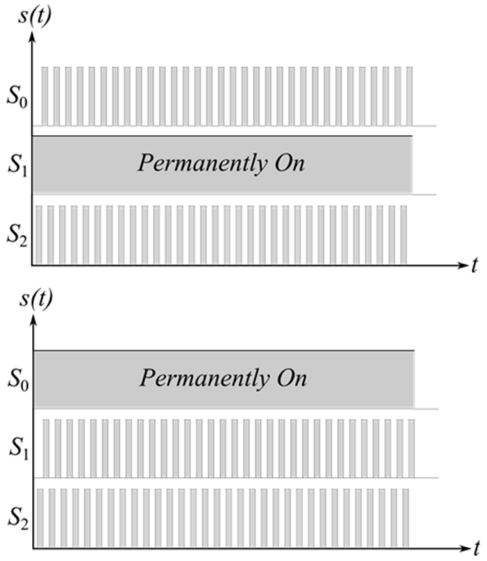
10kV SiC MOSFET Soft-Switching Losses

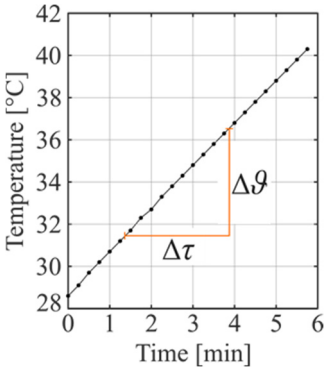
Transient Calorimetric Measurement
Measurement Results

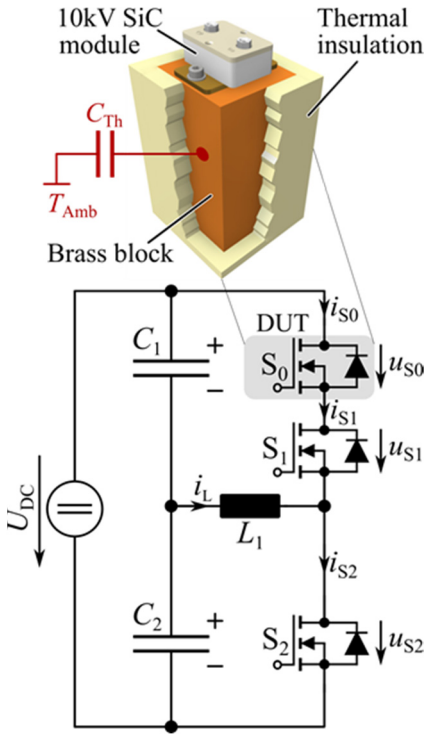
Trans. Calorimetric Measurement

Functional Principle

- DUT on Therm. Isolated Brass Block
- Temp. Gradient Indicates Total Power Loss
- Add. Switch S_0 for Separation of Cond. & Sw. Losses
- Measurement with S_0 Switching & Cont. Turn-On







- Measurement of Cond. Losses Mandatory as $R_{DS,on}$ Depends on Drain Current

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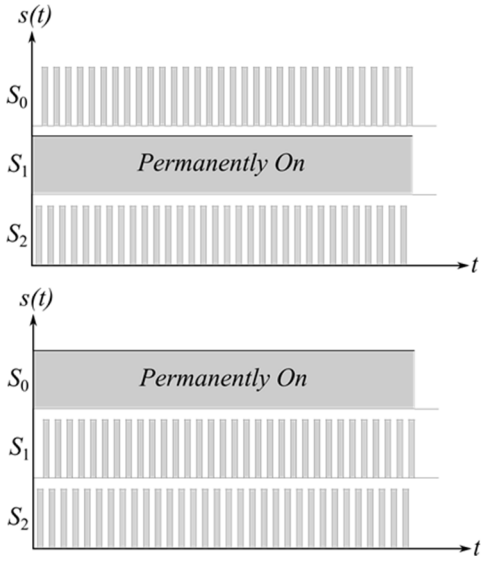
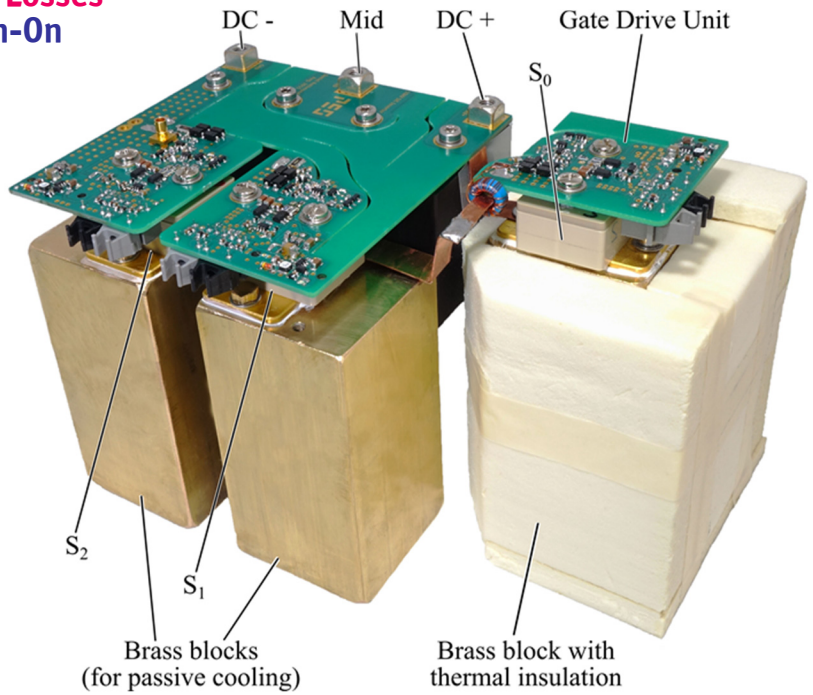
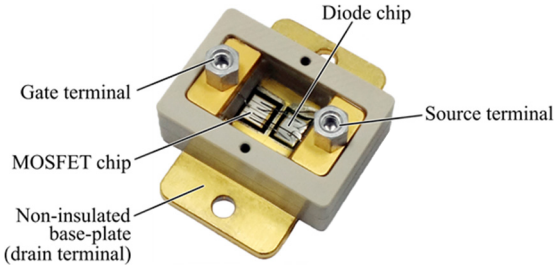


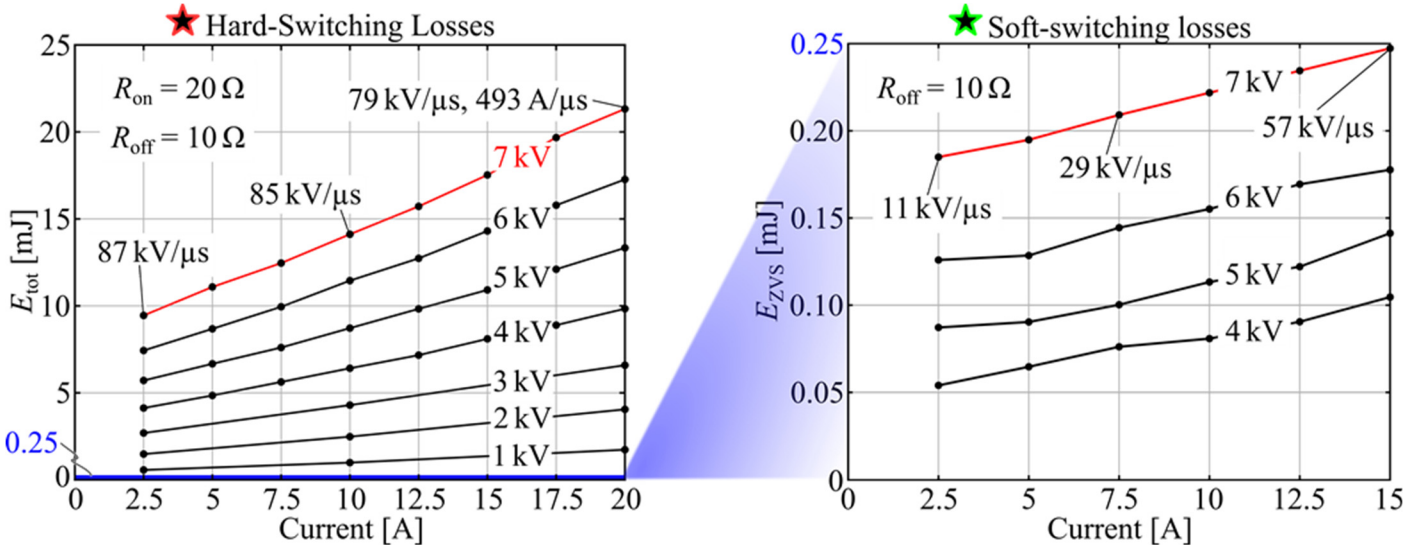


- Measurement of Cond. Losses Mandatory as $R_{DS,on}$ Depends on Drain Current

10kV SiC MOSFET Sw. Losses

- **Hard-Switching vs. Soft-Switching**
  - — Significant Hard Sw. Losses
  - — 30-Times Lower Soft-Sw. Losses / lower du/dt
  - — Soft-Sw. Losses Still in Range of Cond. Loss @ 50kHz





- ► **Losses Strongly Dependent on DC-Link Voltage / Less Dependent on Current**

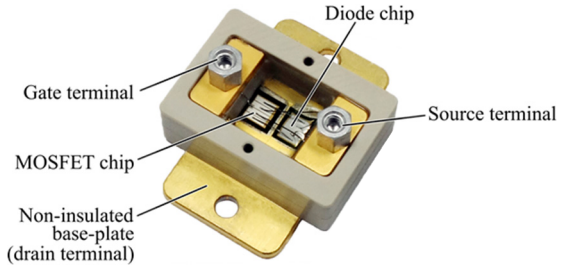
Highly-Compact Isolated Gate Drive

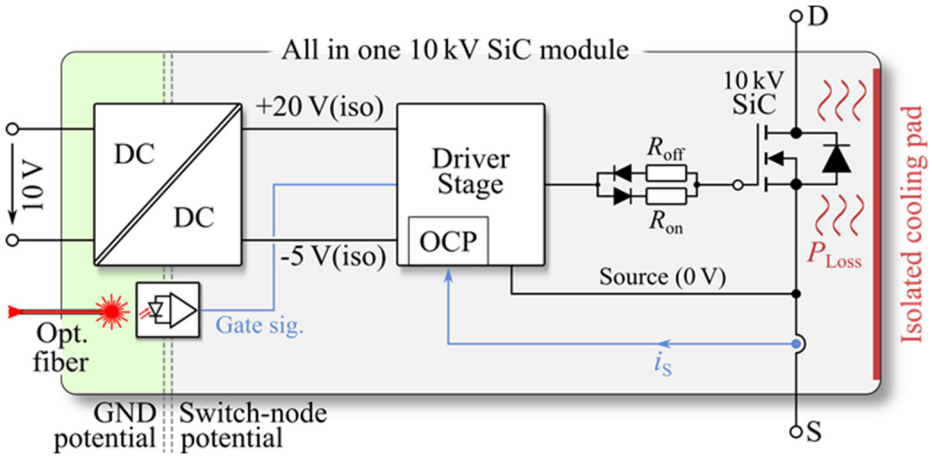
Isolated Power Supply
Ultra-Fast Overcurrent Protection

Future All-in-One SiC Module

- **Integrated Approach**

— Integrated Isol. Signal Transmission
— Integrated Isol. Power Supply
— Integrated Driver Stage
— Integrated Overcurrent Protection
— Isolated Cooling Pad



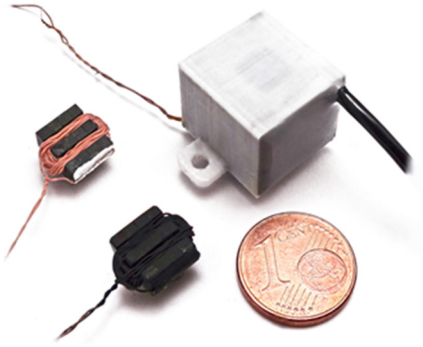


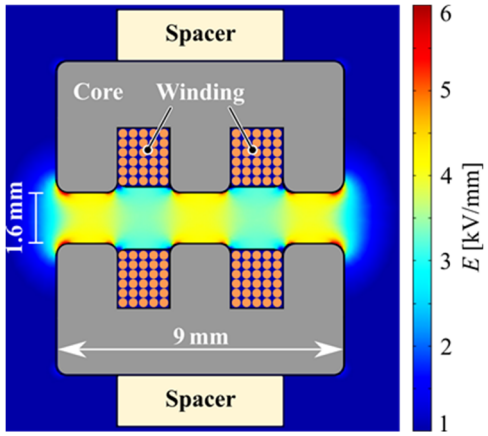
- **Large Dimensions of State-of-the-Art Isolation Transformers**

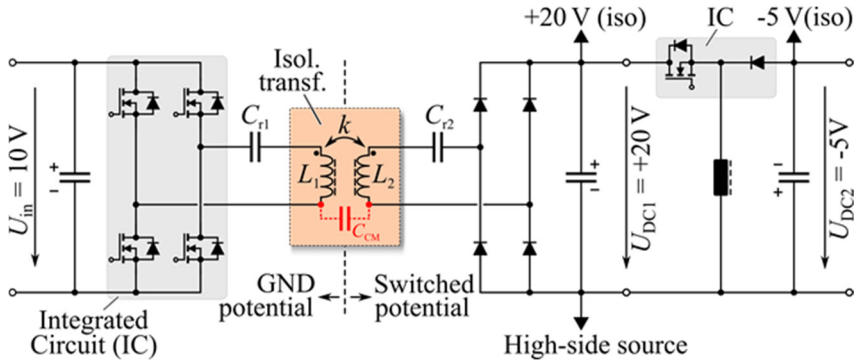
Highly-Compact Isolated Power Supply

- Two Core Halves Separated by Isol. Material

  — Each Core on Potential of Associated Wdg
  — Potted in Silicone
  — 2.6pF Coupling Cap.
  — Series-Resonant DC/DC Converter







- **Isolation Testing:** 20kVDC for 1 Hour -- 7kV / 50...200kHz for > 50 Hours

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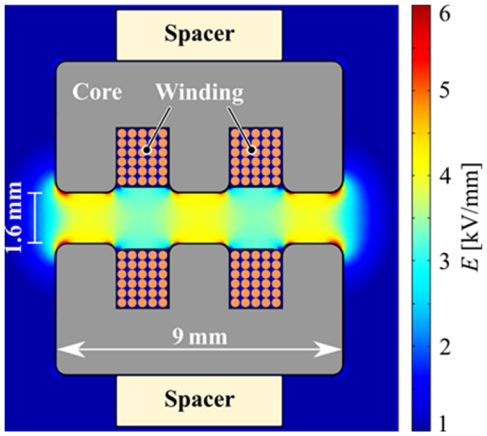

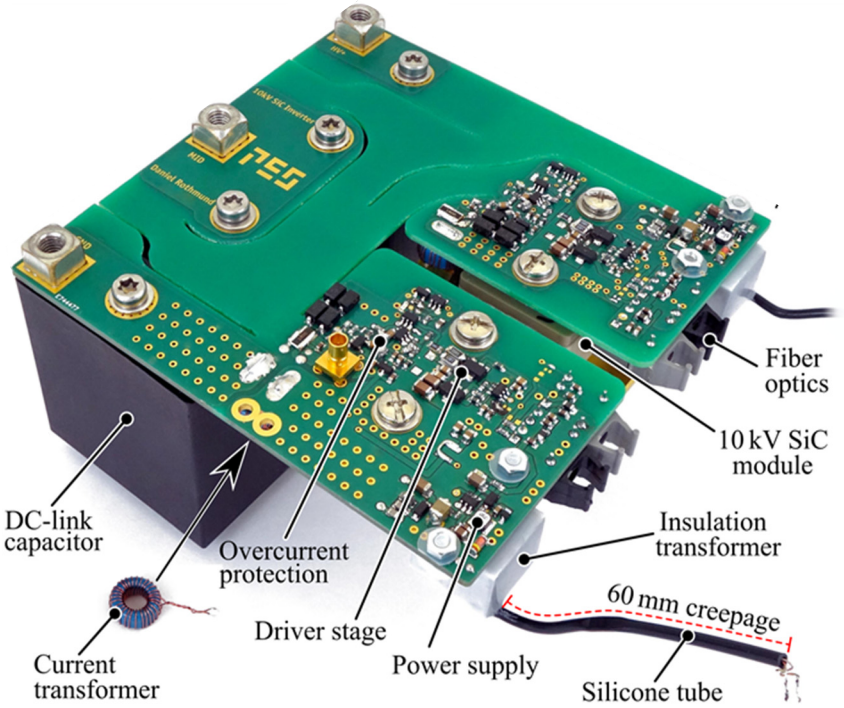

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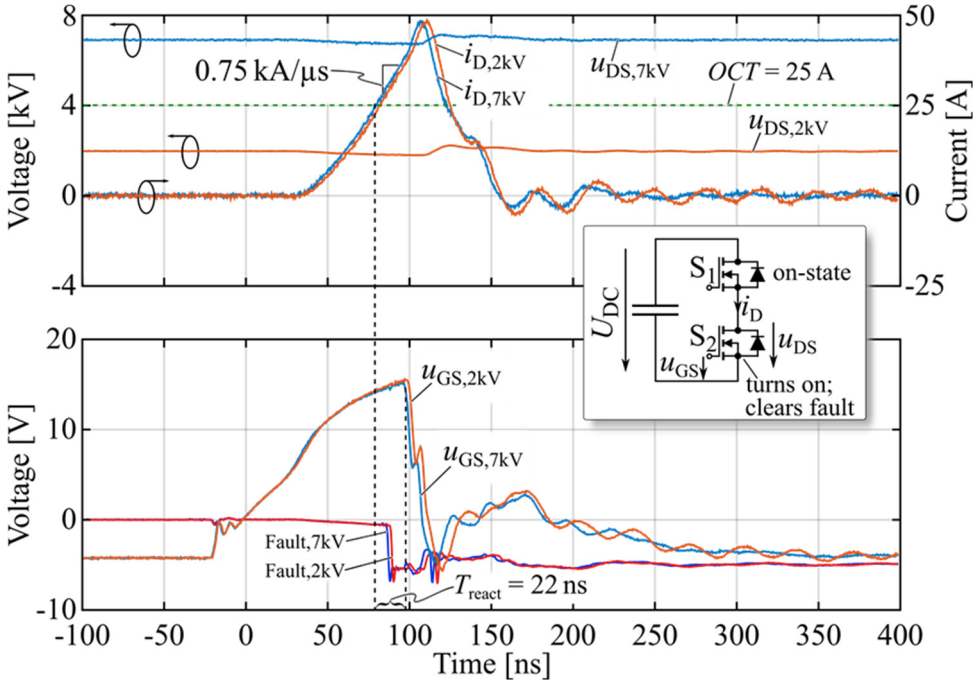
Ultra-Fast Overcurrent Protection

- Testing for Hard Sw. Fault & Flashover @ 7kVDC

— Current Transformer for Overcurrent Detection
— 22ns Delay from 30A Curr. Limit Crossing to Gate Voltage Reaction



▶ Hard Sw. → 50A Max. Curr. / 200ns for Turn-On of Low-Side Switch @ High-Side ON

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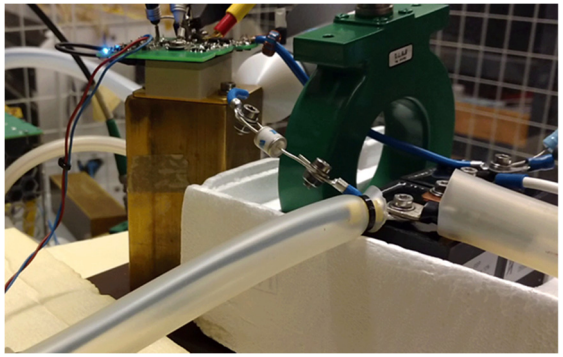
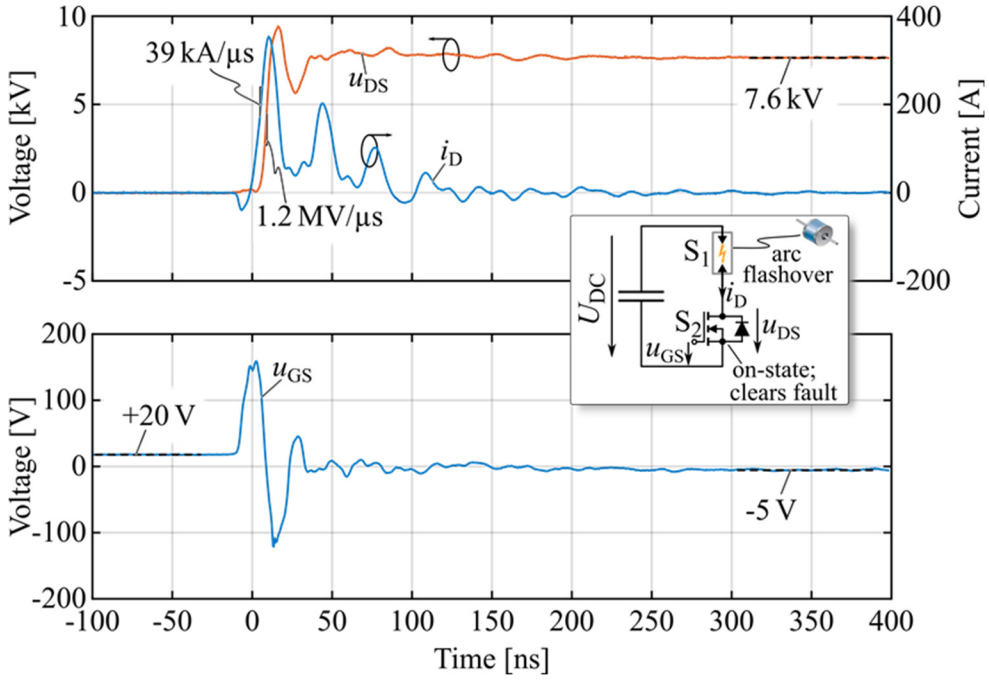




▶ Flashover (Gas Discharge Tube) → du/dt = 1.2 MV/us - Switching 7.2kV in 6.0 ns (!)

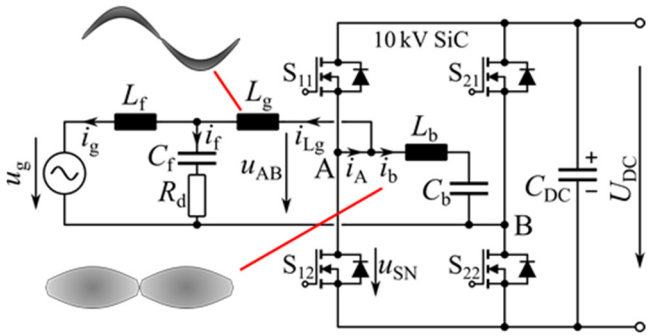
3.8kV→7kV ZVS AC/DC Converter

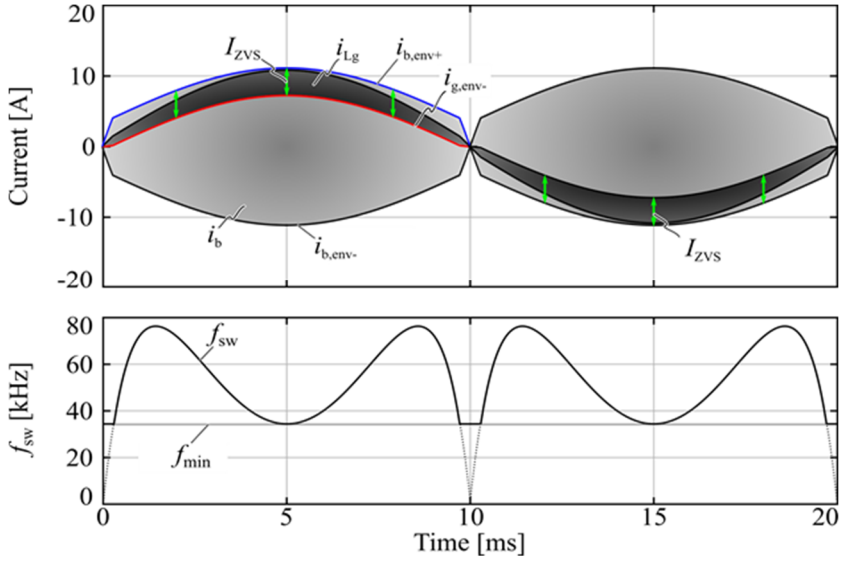
iTCM Operation
EMI Filter / Cable Resonances
Efficiency Measurement

iTCM – integrated Triang. Current Mode

■ *Full-Bridge iTCM Operation Enables ZVS*

— ZVS Requires Change of Sw. Current Direction in Each Sw. Period
— Open-Loop Variation of Sw. Frequency for Const. ZVS Current (35...75kHz)
— Separate Optim. of ZVS and Input Inductor Possible
— No Large Ripple Input Current





► Smooth Zero-Crossing of the Grid Current

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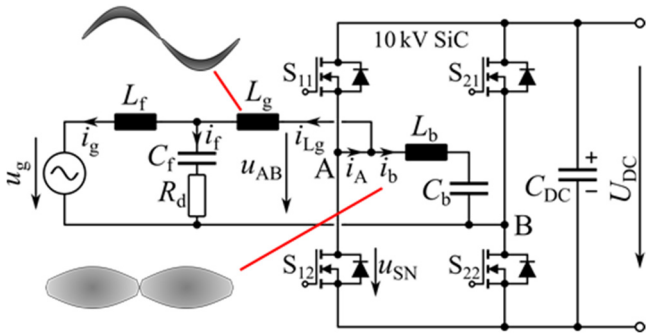

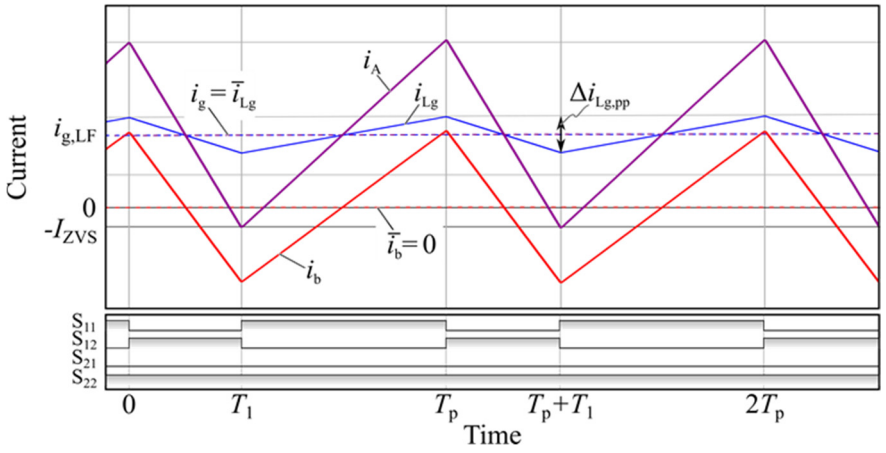

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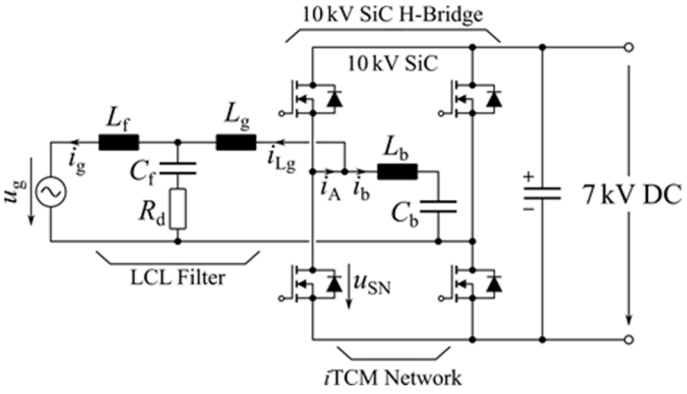
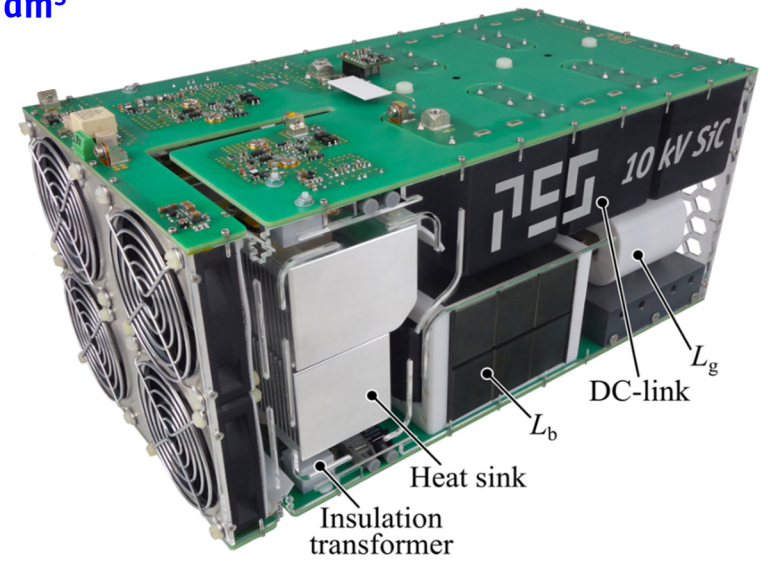
★ 3.3 kW/dm³





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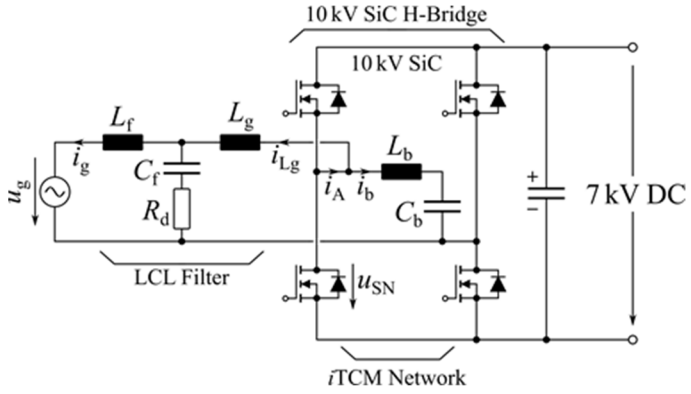
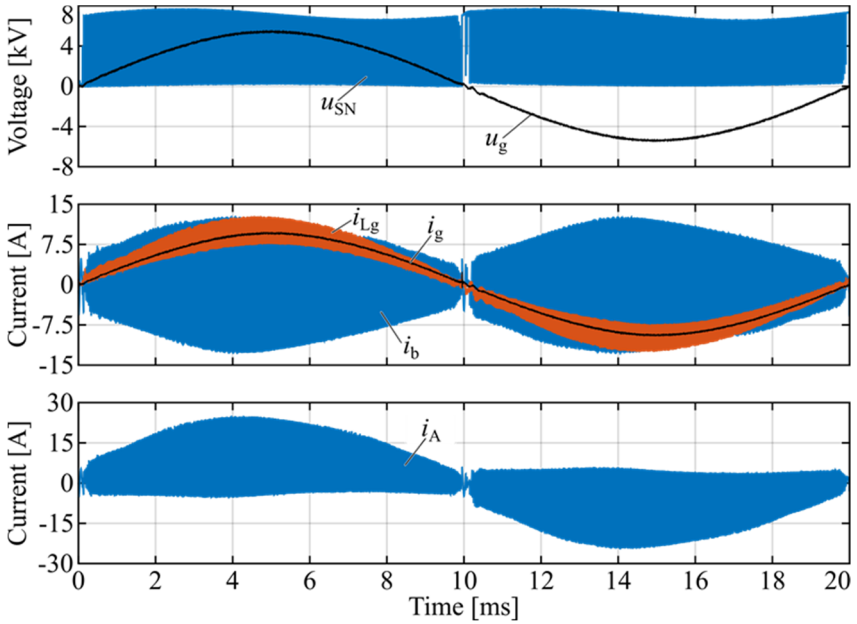


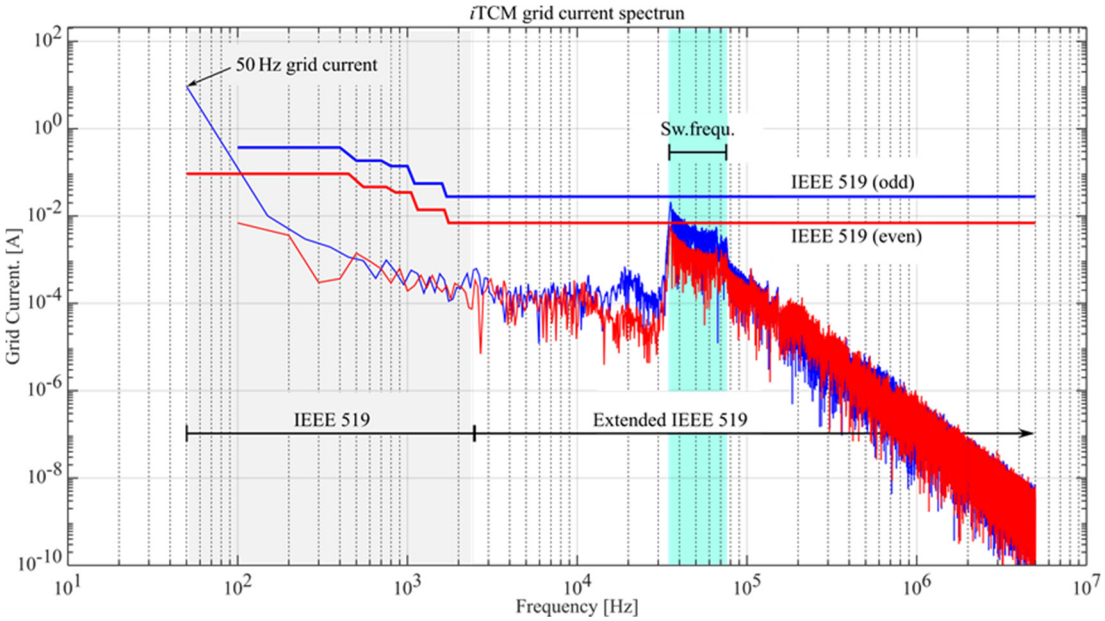


► Full-Load Measurement (25kW @ 3.8kVrms AC, 7kV DC) - ZVS Over Full AC Cycle (!)

EMI Input Filter

- *LCL-Filter & Damping of Supply Cable Resonances*

— IEEE 519 and BDEW Harmonic Standards
— No Standards Above 9kHz → Extension of IEEE 519 to Higher Frequ.
— Design for Mains Current THD < 1%
— Low Losses of Damping Branch



▶ iTCM Grid Current Spectrum

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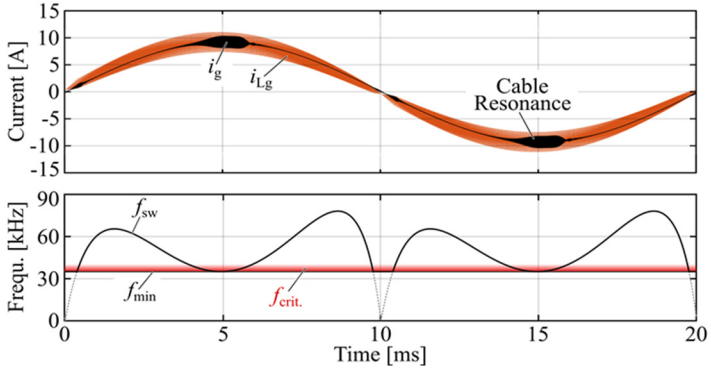

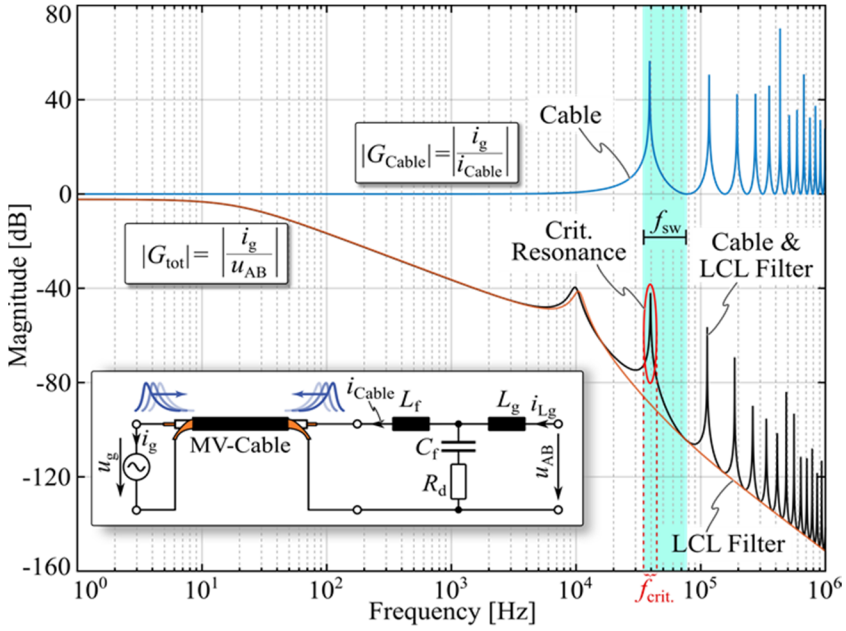

- *Undamped Operation*

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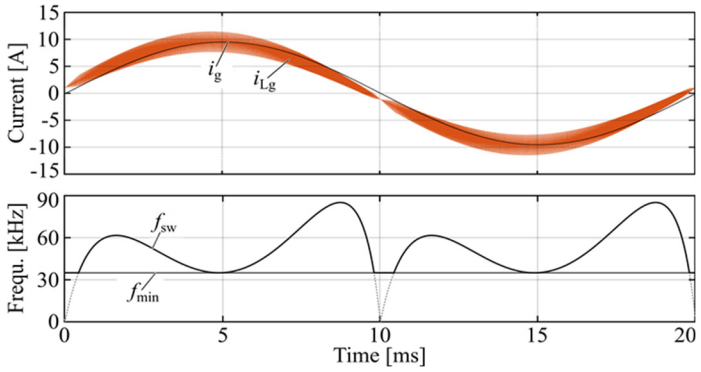
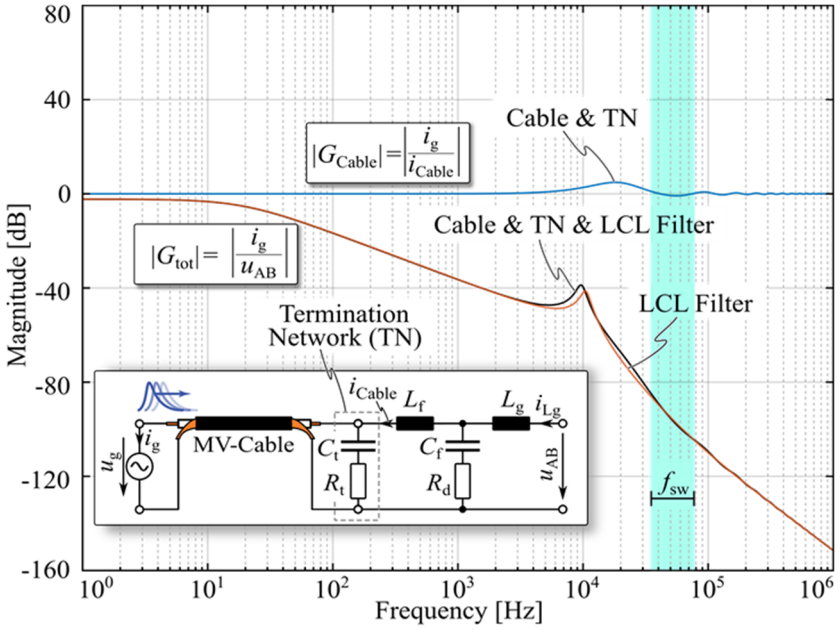


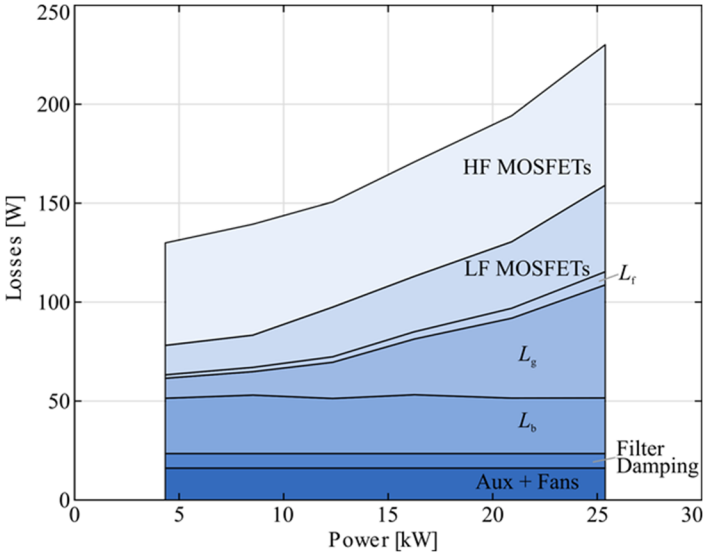


► Operation with Damping Branch → Clean Grid Current

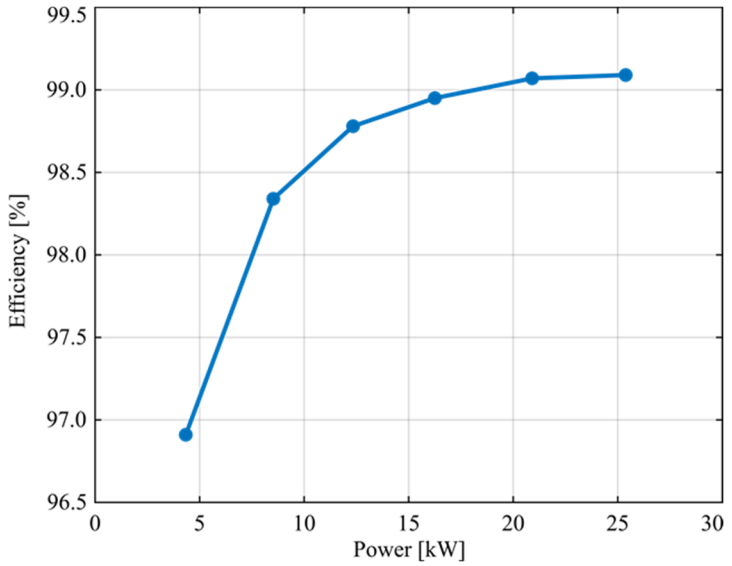
Efficiency & Loss Distribution

- **99.1% Efficiency @ 25kW**

— Low Sw. Losses Despite 35...75kHz Sw. Frequency
— Efficiency >98.75% Above 50% Rated Power



► *Loss Distribution*



► *Efficiency*

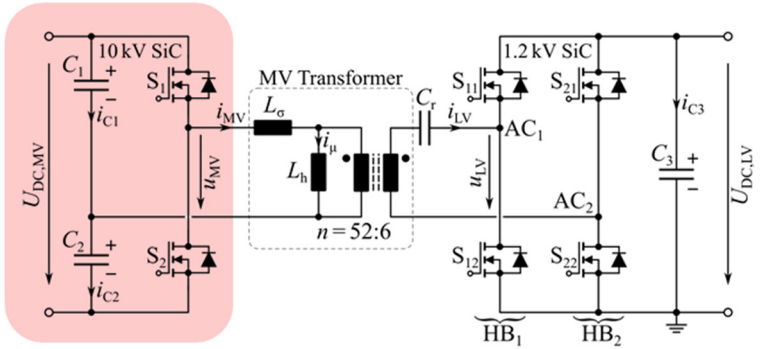
7kV → 400V ZVS Isolated DC/DC Converter

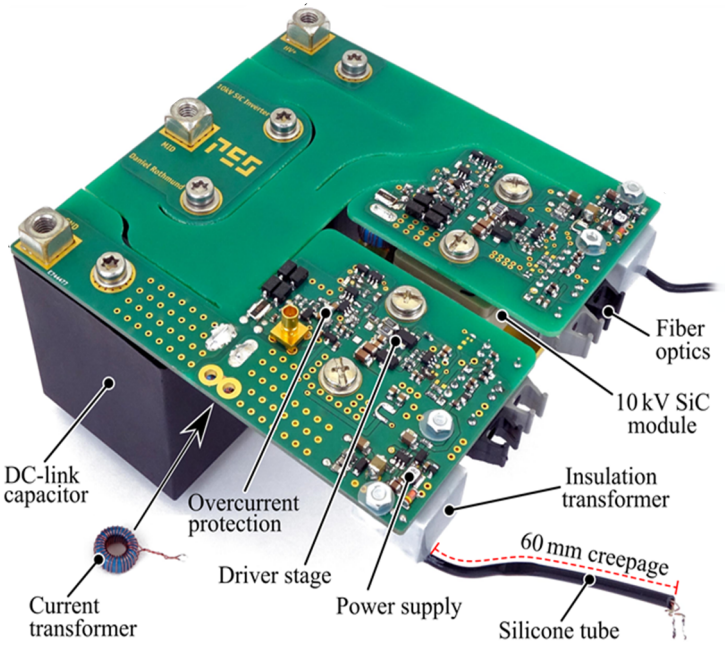
MV-Side 10kV SiC Half-Bridge
LV-Side 1.2kV SiC Full-Bridge
MF-Transformer
Waveforms & Efficiency

10kV SiC-Based DC/DC Converter

- *MV-Side Half-Bridge*

— 48kHz Sw. Frequency, ZVS
— Cooling of Power Semicond. by Floating Heatsinks (Not Shown)
— Creepage Distances Ensured by PCB Slots



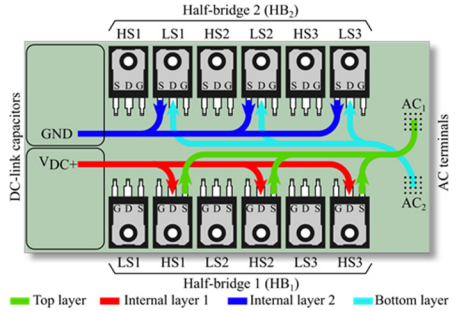


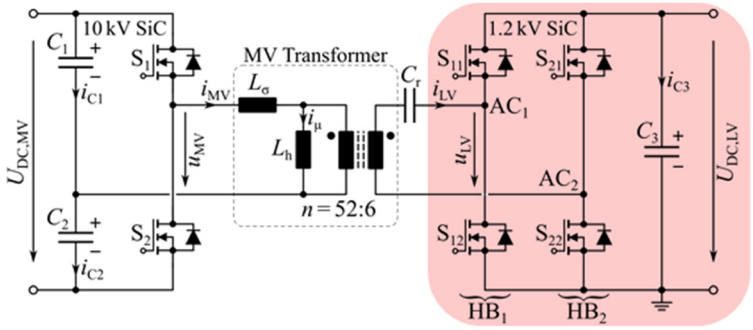
► Half-Bridge for Cutting Voltage in Half / Lower Switch Count

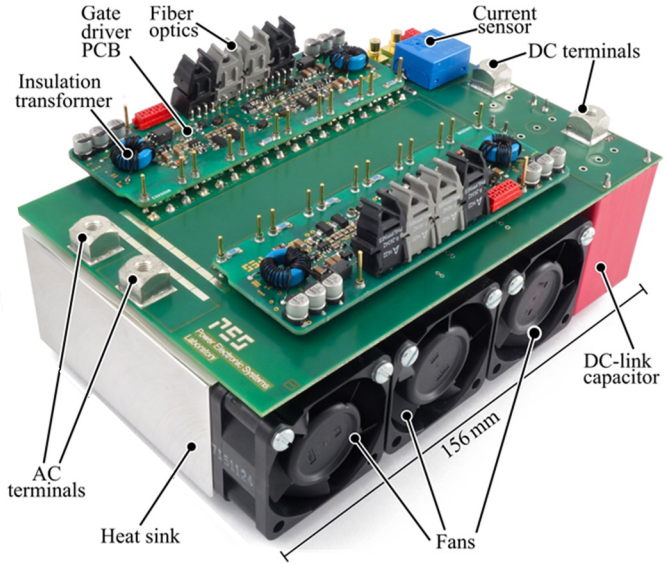
10kV SiC-Based DC/DC Converter

- *LV-Side Full-Bridge*

— 48kHz Sw. Frequency, ZVS
— 3x1.2kV 25mΩ MOSFETs in Parallel
— Layout Ensures Symm. Curr. Distribution





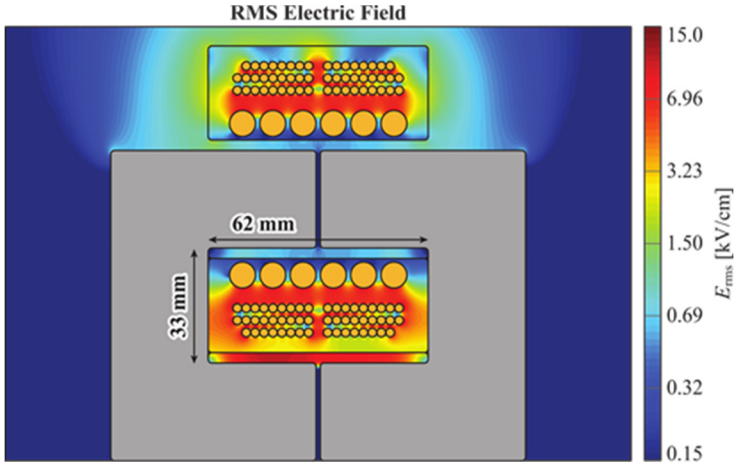


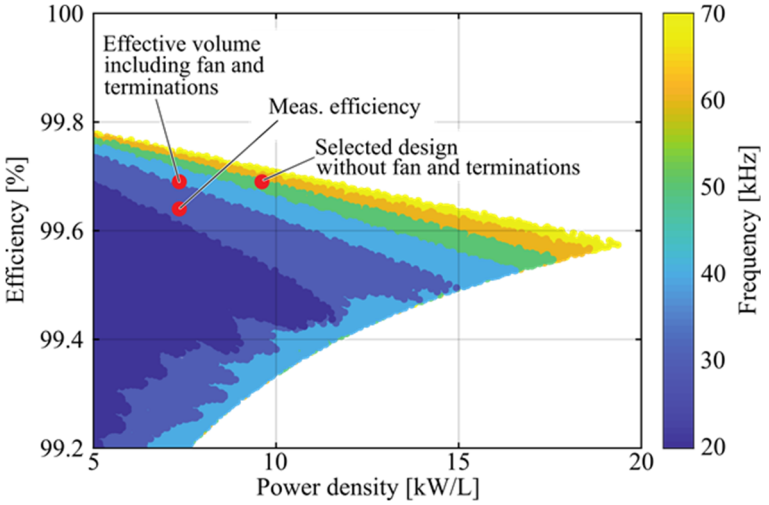
► 1.2kV Technology Used Due to Low On-Resistance

10kV SiC-Based DC/DC Converter

- *MF-Transformer*

— 25kW/31kVA @ 48kHz
— 15kV DM/CM Isolation
— Pareto-Optimization (# of Layers, # of Turns, E/U-Core, etc.)
— Ferrite U-Core, 71um/100um MV/LV Wdg
— 2-Chamber MV Wdg, 3 Layers



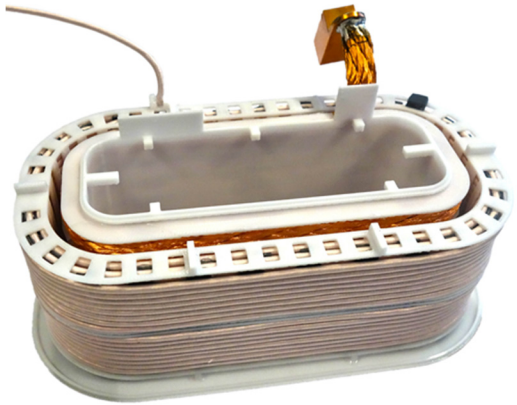


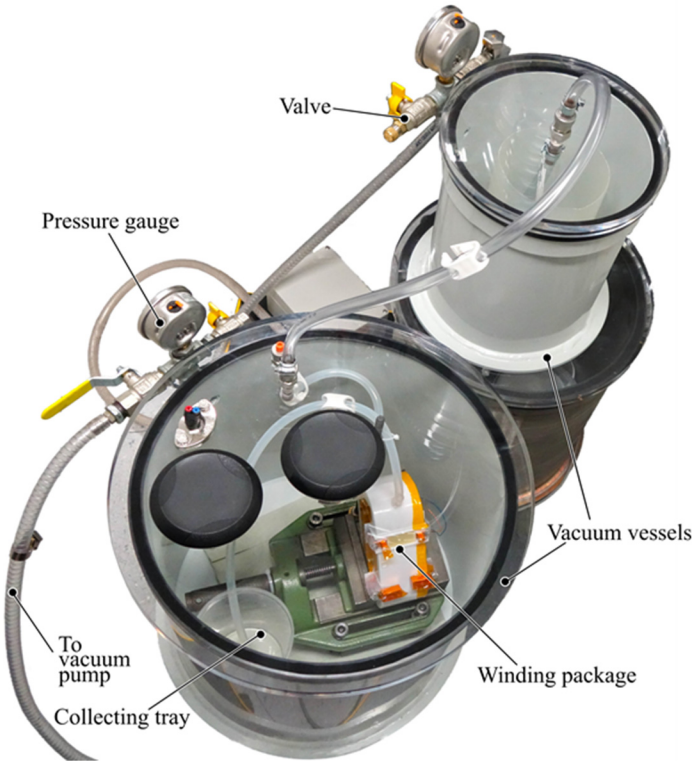
► Challenges: High El. Fields / Heat Transfer Through Insulation Material

10kV SiC-Based DC/DC Converter

- *MF-Transformer Construction*

— LV-Wdg Inside MV-Wdg
— Precise Positioning of Wdgs Mandatory
— Ensures MV/LV-Wdg Isolation



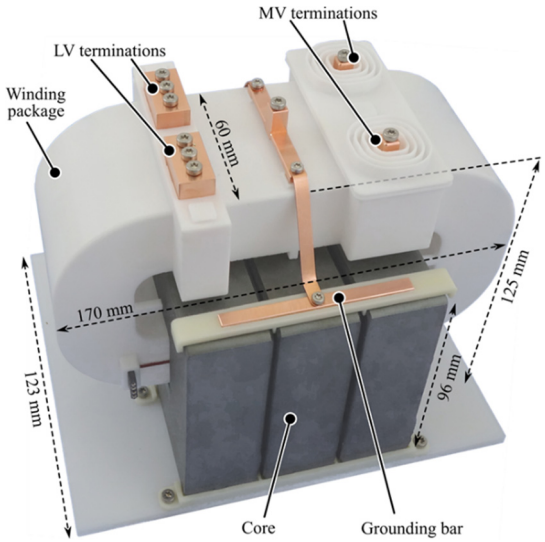


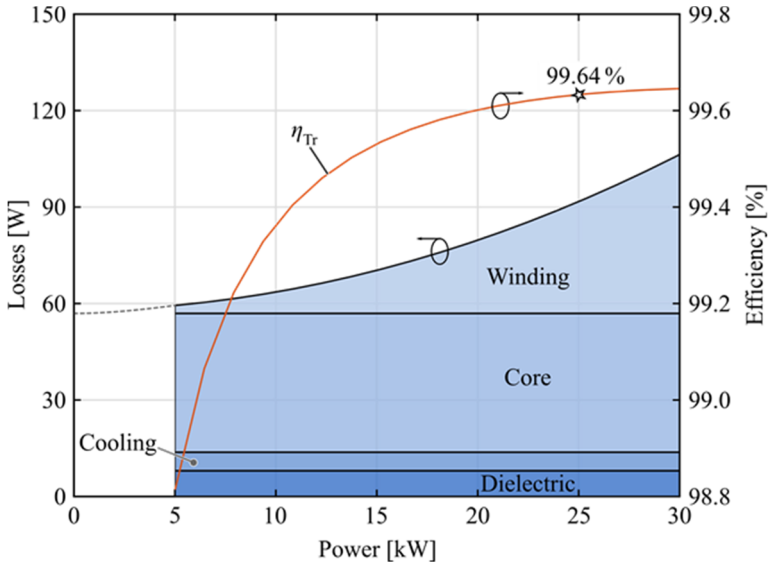
▶ Challenges: Processing Silicone Under Vacuum Avoiding Voids / Curing / etc.

10kV SiC-Based DC/DC Converter

- *MF-Transformer Measurement*

— Fully Tested @ 25kW / 7 kV
— Calorimetric Loss Measurement
— 99.64% Efficiency



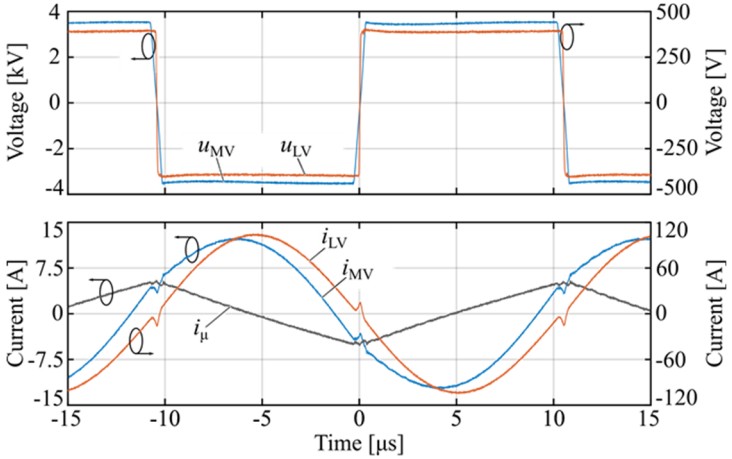


- *Transformer Prototype / Loss Distribution / Efficiency*

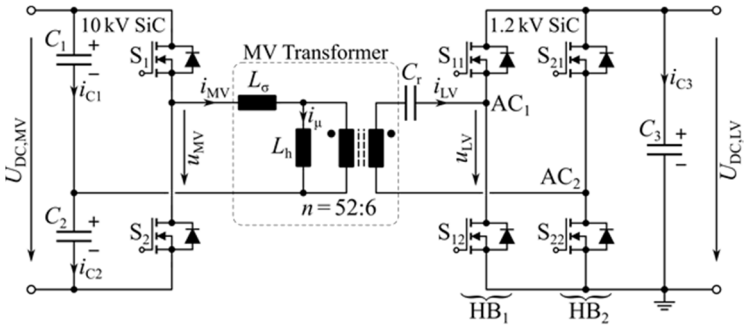
10kV SiC-Based DC/DC Converter

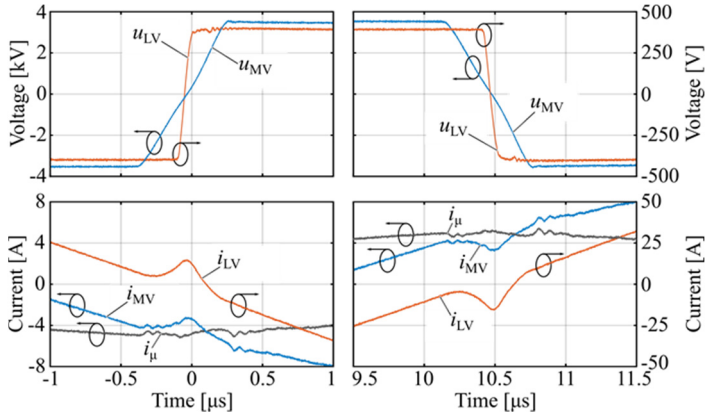
- *Experimental Results*

— 400V → 7kV Operation @ 25kW / 48 kHz
— ZVS of All MOSFETs Independent of Load



★ 3.8 kW/dm³



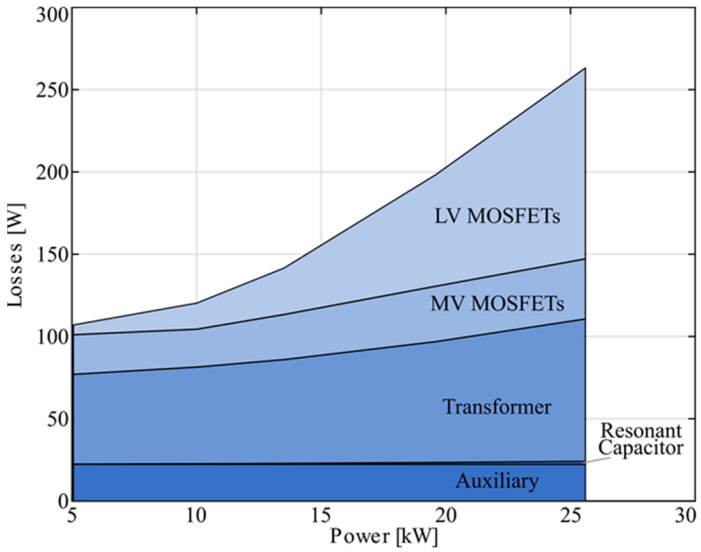


▶ Very Robust Concerning Changes in Sw. Frequ. or Component Values

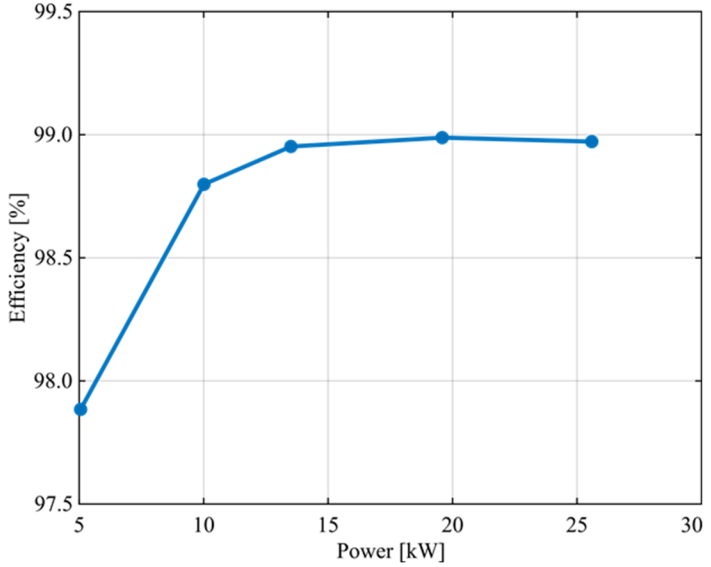
Efficiency & Loss Distribution

- 99% Efficiency for $P > 13$kW

— LV-MOSFETs Causing Substantial Losses @ Higher Power
— Efficiency Improvement for Larger SiC Area



► *Loss Distribution*



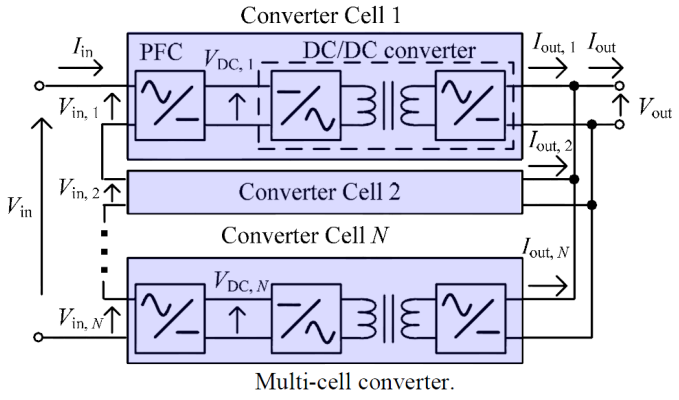
► *Efficiency*

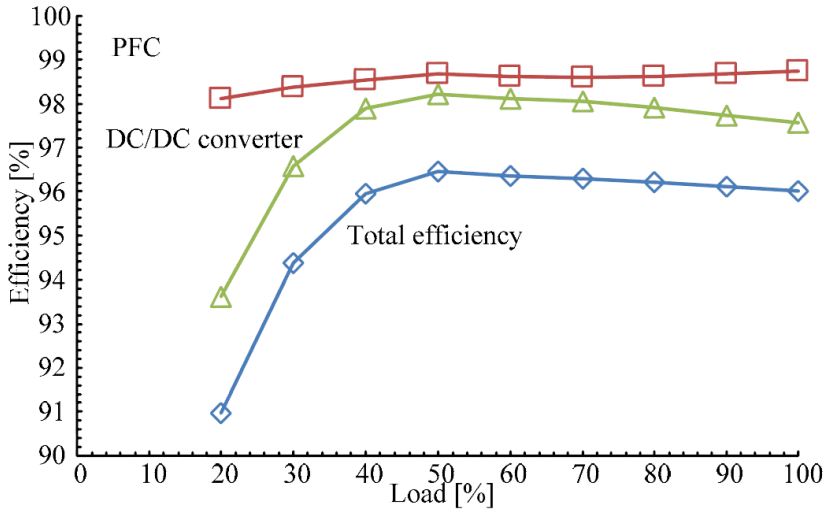
Conclusions

Remark 1-Φ 2.4 kV_{rms} AC → 54V DC

Fuji Electric

- *Published @ IEEE APEC 2017*
- *N=5 Series-Connected Cells @ MV-Side / Cost Optimum*
- *Module Input Stage → Boost PFC Half Contr. Thyr. Rect. / 1.2kV IGBTs & SiC Diodes*
- *Module Output Stage → 3-Level DC/DC Conv. - 600V SJ & 100V MOSFETs*



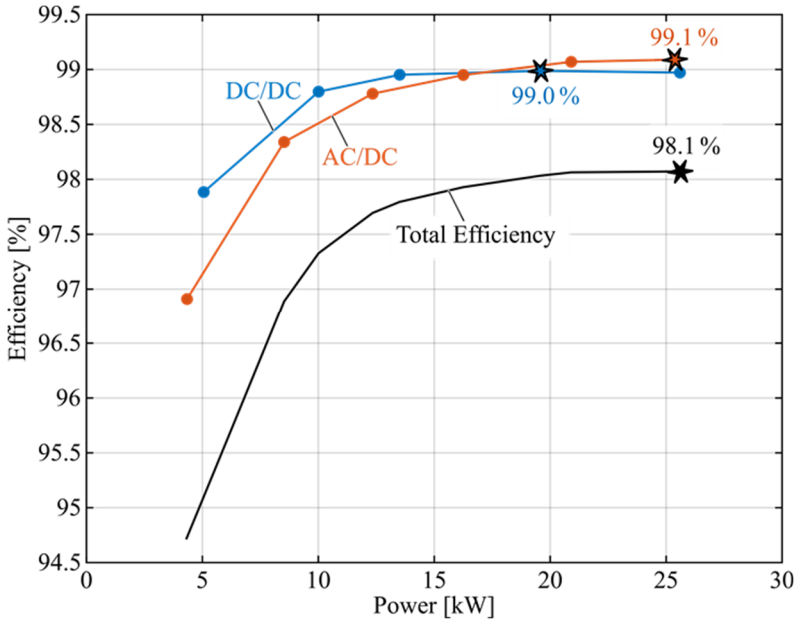


Efficiency of the prototype.

- *Power Density of 0.4kW/dm³ (6.6W/in³)*
- *96% Overall Efficiency @ 25kW*

Conclusions -- Overall Performance

- *Full Soft-Switching*
- *98.1% Overall Efficiency @ 25kW*
- *1.8 kW/dm³ (30W/in³)*



- *Red. of Losses & Volume by Factor of > 2 Comp. To Alternative Approaches (!)*
- *Significantly Simpler System Structure Compared to Multi-Module SST Approach*

■ End

Questions ?