ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Intelligent Solid State Transformers (SSTs)
A Key Building Block of Future Smart Grid Systems

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ETH
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The MEGA Cube Project

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ETH Zurich - Power Electronic Systems Laboratory

Power Electronic Systems Laboratory
Johann W. Kolar

Industry Relations
R. Coccia / B. Seiler

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Pulsed Power	Multi-Domain Modeling	Mega-Speed Drives	Magnetic Levitation
F. Krismer		**B. Cougo**	**D. Bortis**				
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Electronics Laboratory
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29 Ph.D. Students
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ECPE Competence Centre

EPSMA

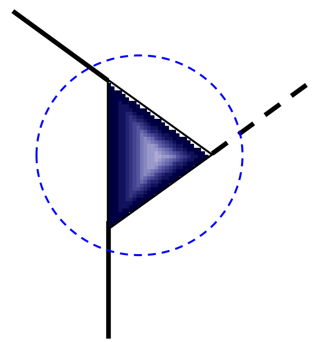
Leading Univ. in Europe

PES Research Scope

Cross-Departmental

Mechanical Eng., e.g. Turbomachinery, Robotics
Microsystems
Medical Systems
Economics / Society

Power Electronics

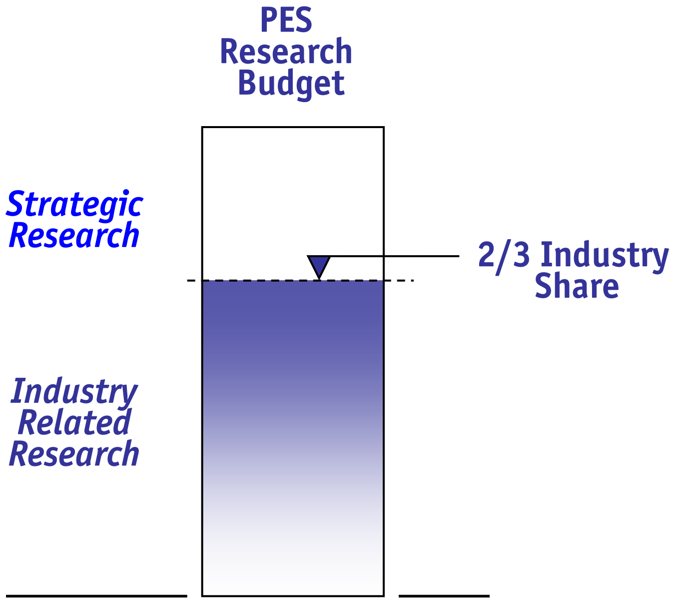


Electromagnetic Actuators

- *Micro-Scale Energy Systems*
- *Wearable Power*
- *Exoskeletons / Artificial Muscles*
- *Environmental Systems*
- *Pulsed Power*

Industry Collaboration

- Core Application Areas
  - IT Power Supply
  - Renewable Energy
  - Industry Automation
  - Automotive Systems
  - More-Electric Aircraft
  - Semiconductor Process Technology
  - Medical Systems
  - Etc.
- *16 International Industry Partners*



Examples of
Research Results

Ultra-Compact Systems
Super-Efficient Systems
MEGA Speed Drives

3-Φ Boost-Type PFC Rectifier

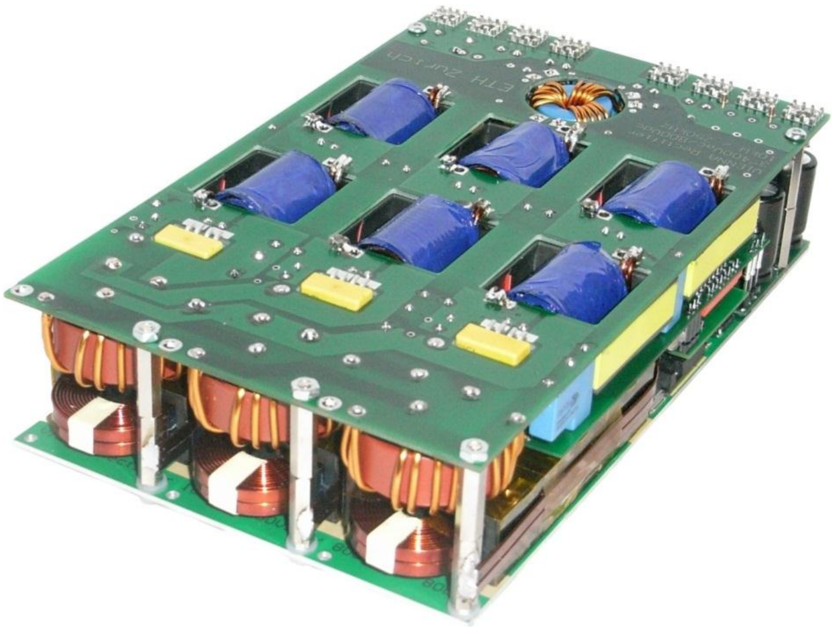
P_0= 10 kW
U_N= 230V_{AC}±10%
f_N= 50Hz or 360…800Hz
U_0= 800V_{DC}

f_P= 250kHz

▶ Si CoolMOS
▶ SiC Diodes

η = 96.2% @ P_0
THD_I = 1.6% @ P_0
γ = 3kW/kg

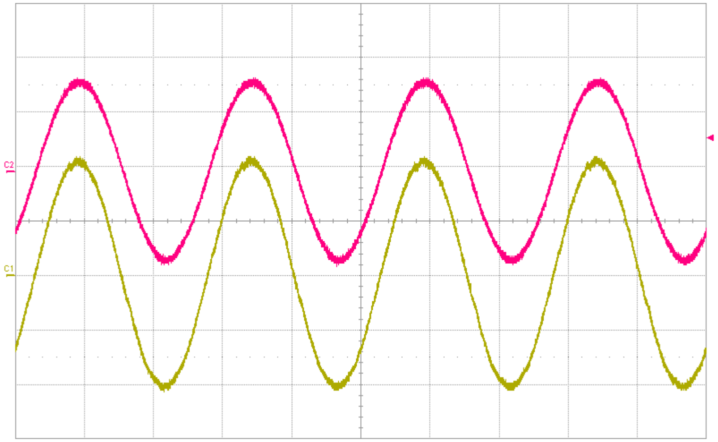
★ 10kW/dm³ Power Density



Mains Behavior @ 400 Hz/800 Hz

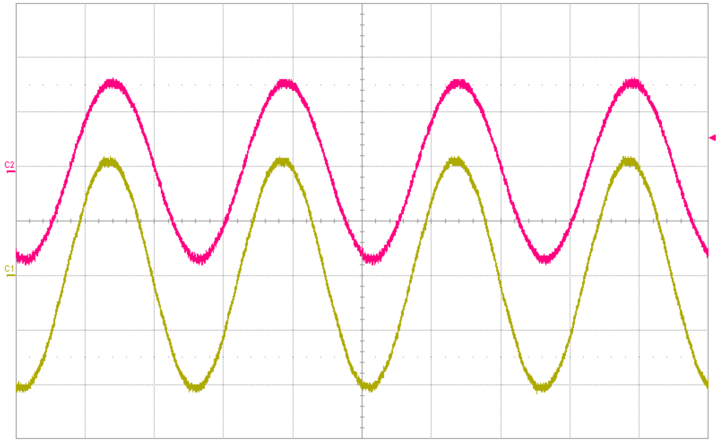
P_0 = 10kW
U_N = 230V
f_N = 400Hz
U_0 = 800V
THD_i = 1.4%

10A/Div
200V/Div
1ms/Div



P_0 = 10kW
U_N = 230V
f_N = 800Hz
U_0 = 800V
THD_i = 1.6%

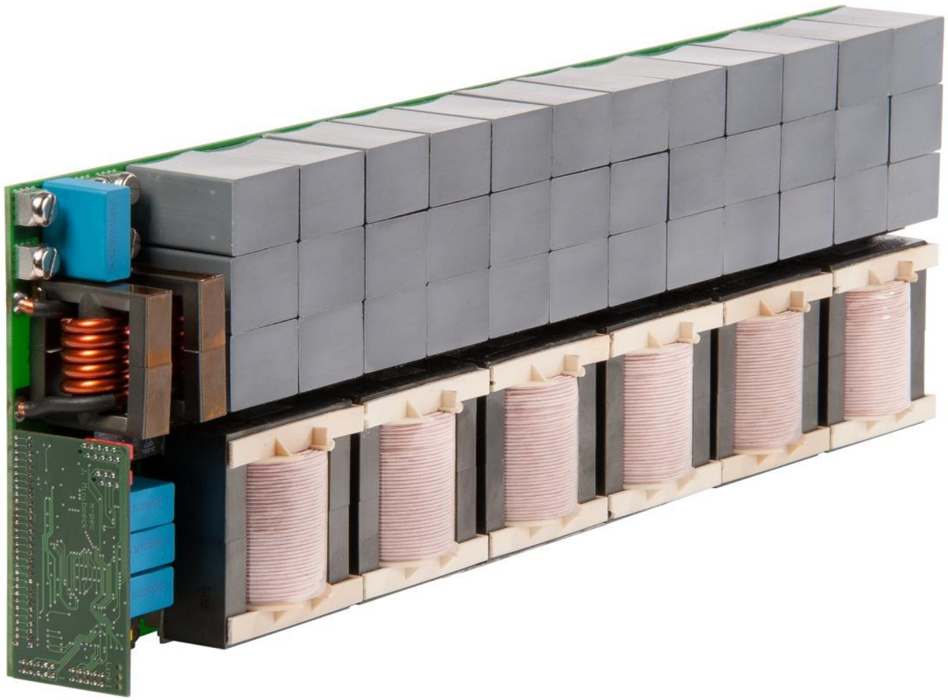
10A/Div
200V/Div
0.5ms/Div



Bidirectional Super-Efficient
1-Φ PFC Mains Interface

★ **99.3% @ 1.2kW/dm³**

Hardware Testing to be finalized in November 2011



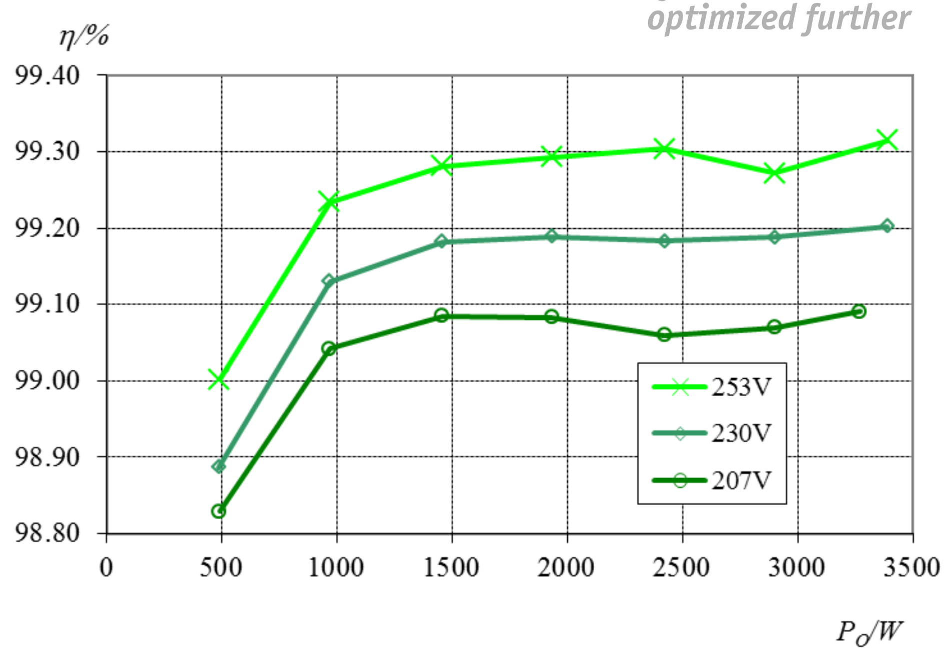
► **Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only**

Bidirectional Super-Efficient
1-Φ PFC Mains Interface

★ **99.3% @ 1.2kW/dm³**

Hardware Testing to be finalized in November 2011

Results of first testing; System still to be optimized further



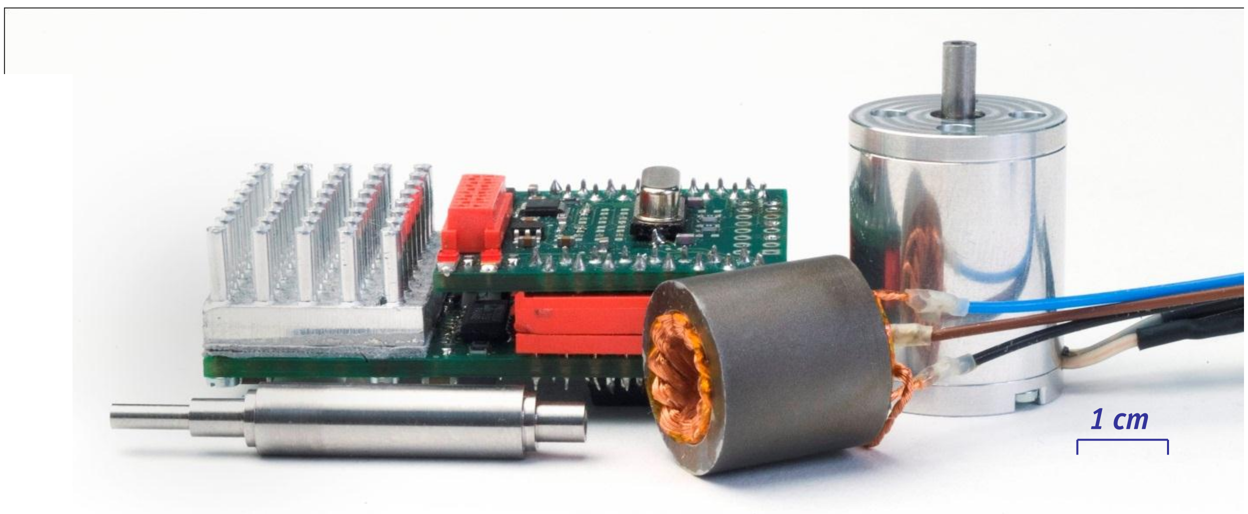
► **Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only**

MEGA Speed Drive Systems

- µm-Scale PCB Drilling
- Dental Technology
- Laser Measurement Technology
- Turbo-Compressor Systems
- Air-to-Power
- Artificial Muscles
- Mega Gravity Science

World Record !

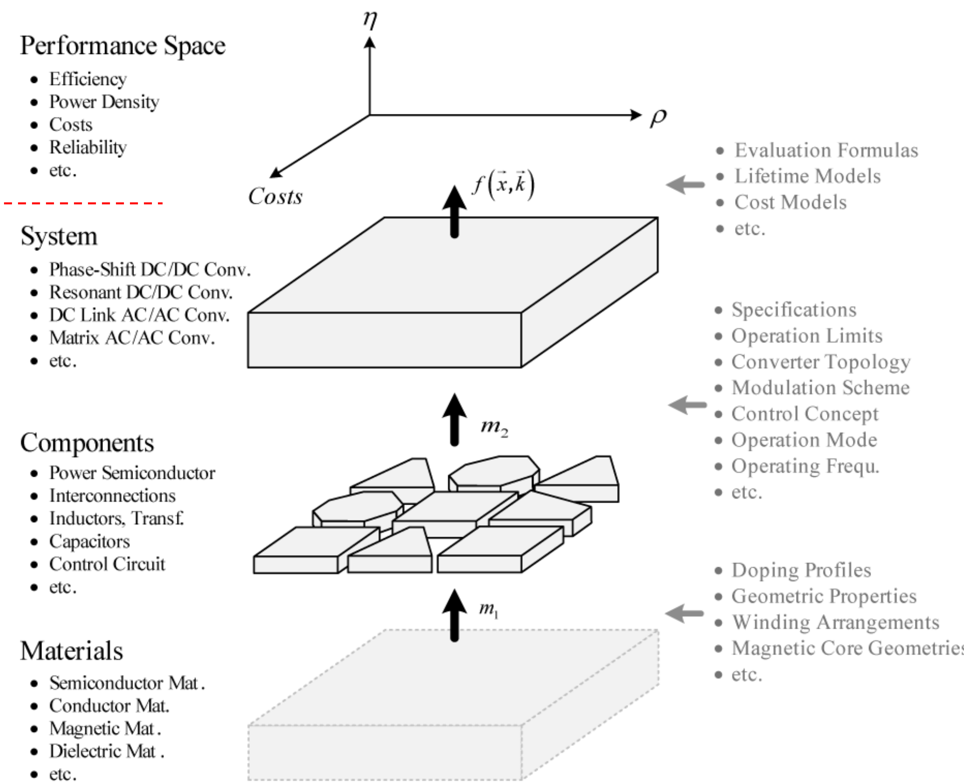
100W @ 1'000'000 rpm



Abstraction of Power Converter Design

Performance Space

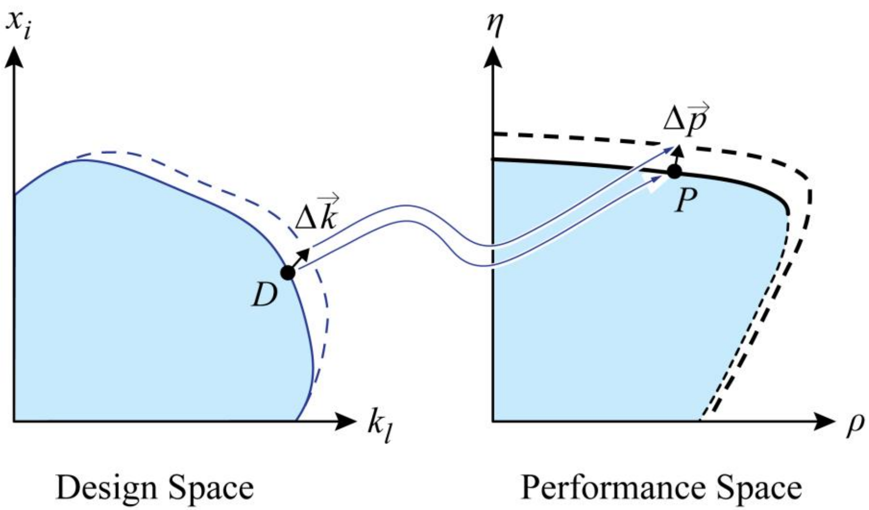
Design Space

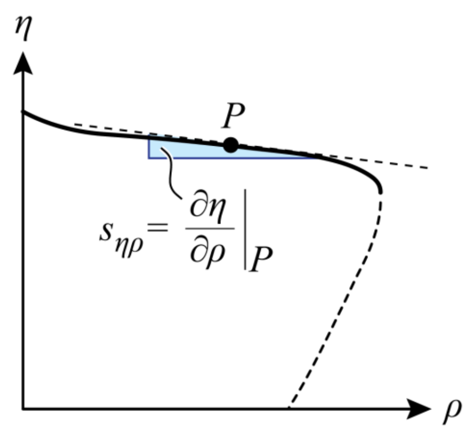


▶ **Mapping of *Design Space* into System *Performance Space***

Technology Sensitivity Analysis Based on η-ρ-Pareto Front

- ▶ Sensitivity to Technology Advancements
- ▶ Trade-off Analysis





Outline

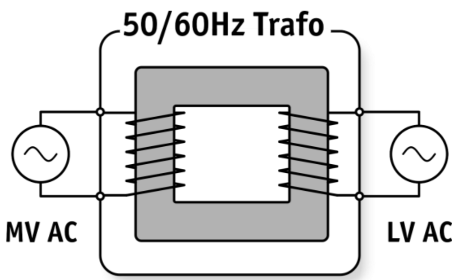
- Introduction to SST Concept
- Applications of SSTs
- Overview of SST Research since 2001
- Details on the MEGA Cube
- Conclusions / Outlook

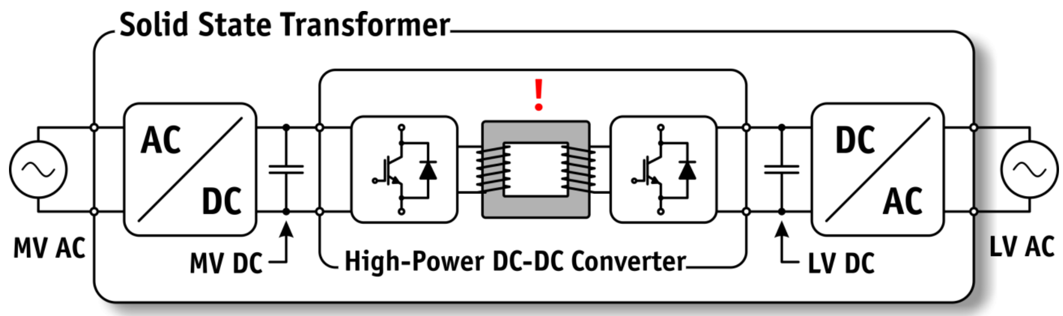
Introduction to

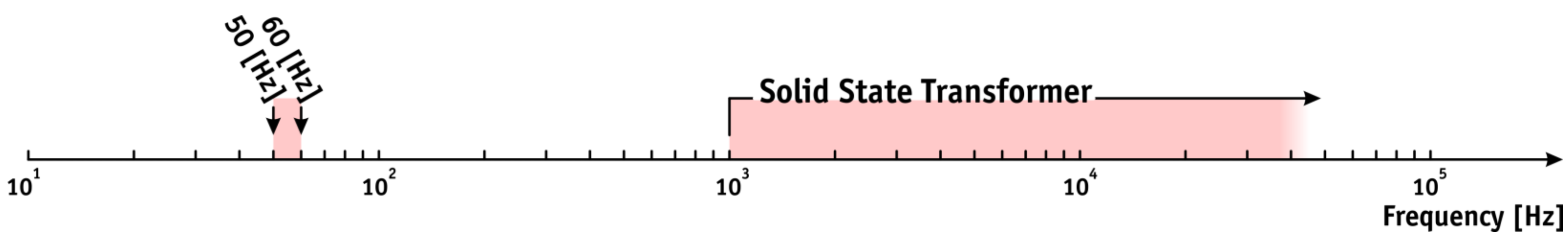
Solid State Transformer Concept

50/60 Hz Transformer

Solid State Transformer





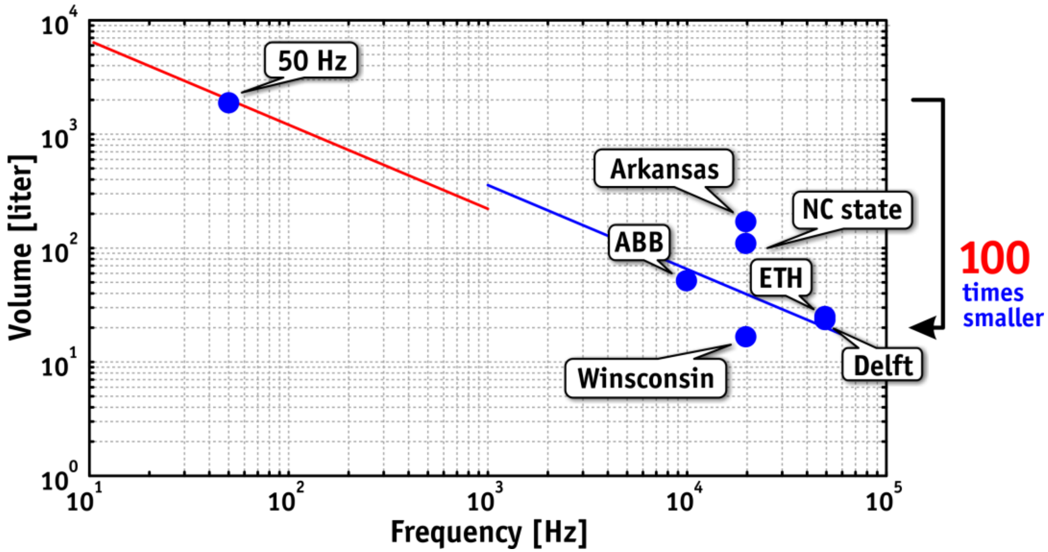


▲ 50/60Hz vs. SST Operating Frequencies in the kHz Range

Size/Weight Reduction

- Higher Operating Frequency Reduces Transformer Size/Weight

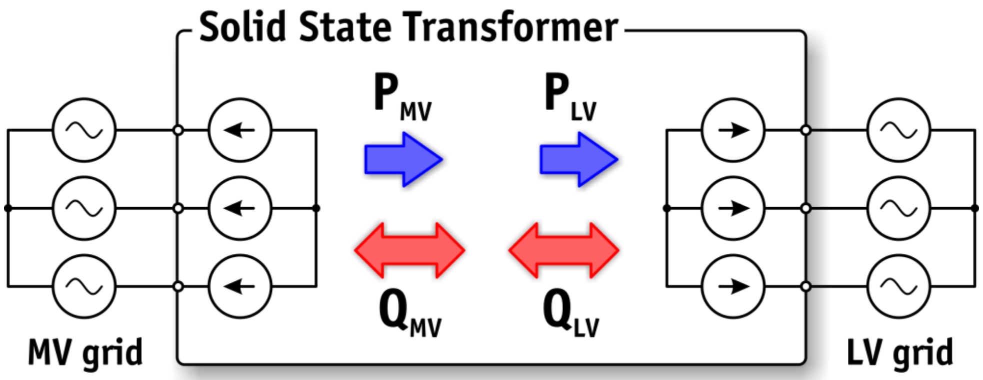
$$V_T \propto \frac{1}{\hat{B}} \cdot \frac{1}{f}$$



▲ Volume vs. Frequency of Transformers Realized in Previous Research Scaled to 1 [MW]

Reactive Power Control

- **Power Factor Correction**
  - VAr Compensation
  - Active Filtering

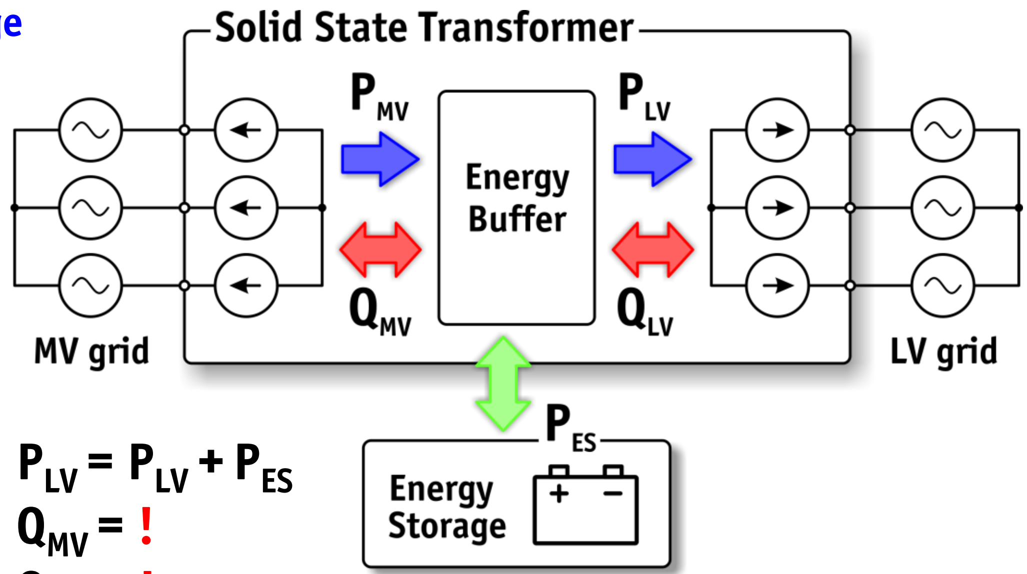


$P_{MV} = P_{LV}$
$Q_{MV} = !$
$Q_{LV} = !$

▲ SST providing Reactive Power Compensation

UPS Operation

- Linked to Energy Storage
  - Ability to Source/ Sink Active Power in Both Directions



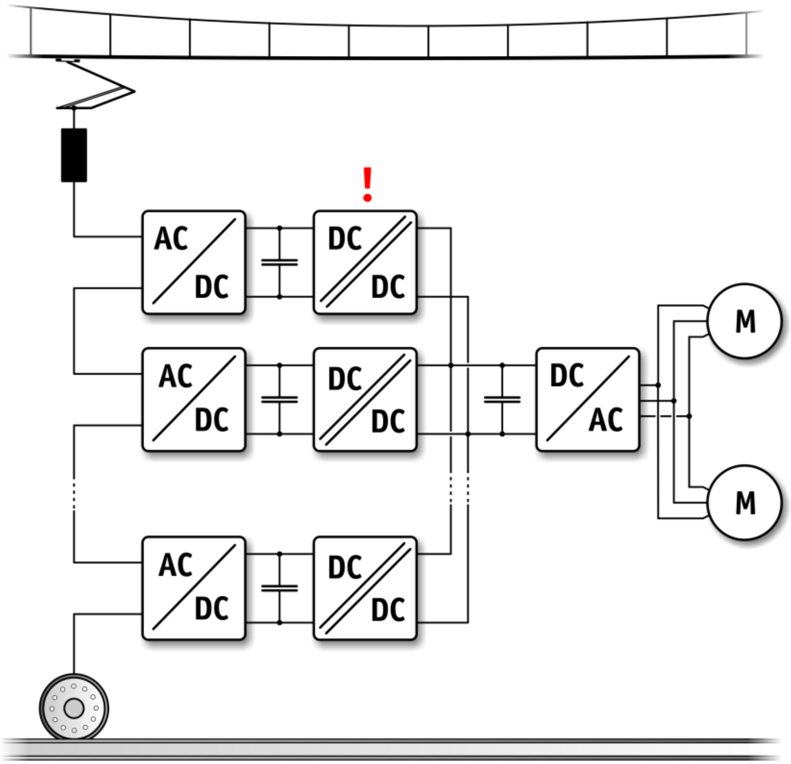
$$P_{LV} = P_{LV} + P_{ES}$$
$$Q_{MV} = !$$
$$Q_{LV} = !$$

▲ SST Linked to Energy Storage System - providing UPS

Applications
of the Solid State Transformers

Traction / Locomotives

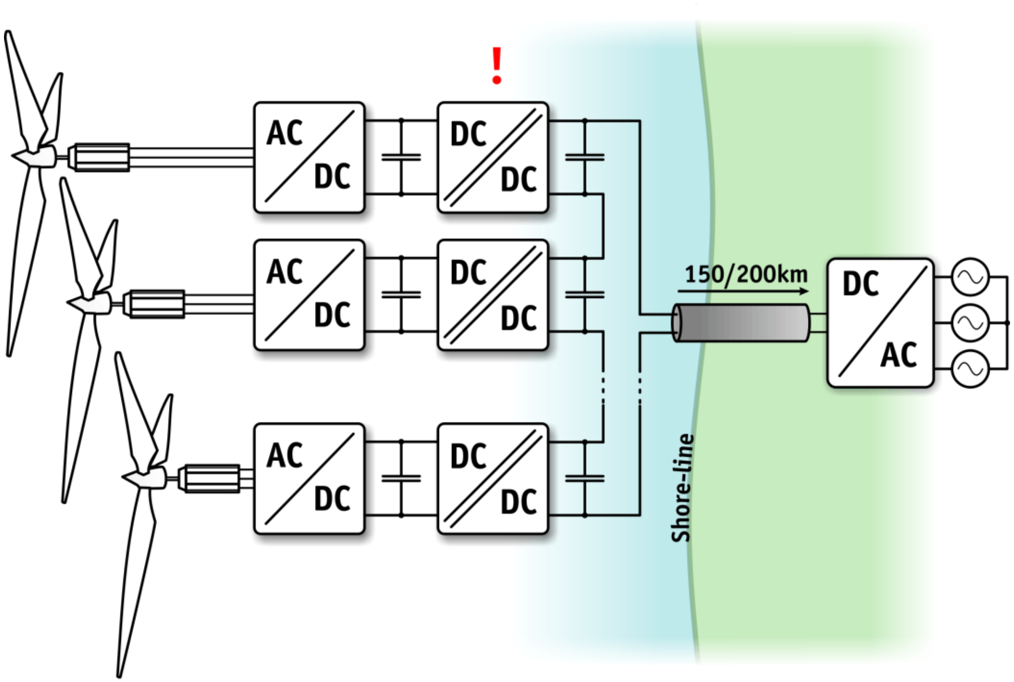
- Reduced Weight/Size
- Increased Efficiency
- Reduced Line Filtering



▲ SST Replacing the Input Transformer of a Locomotive

Wind Power

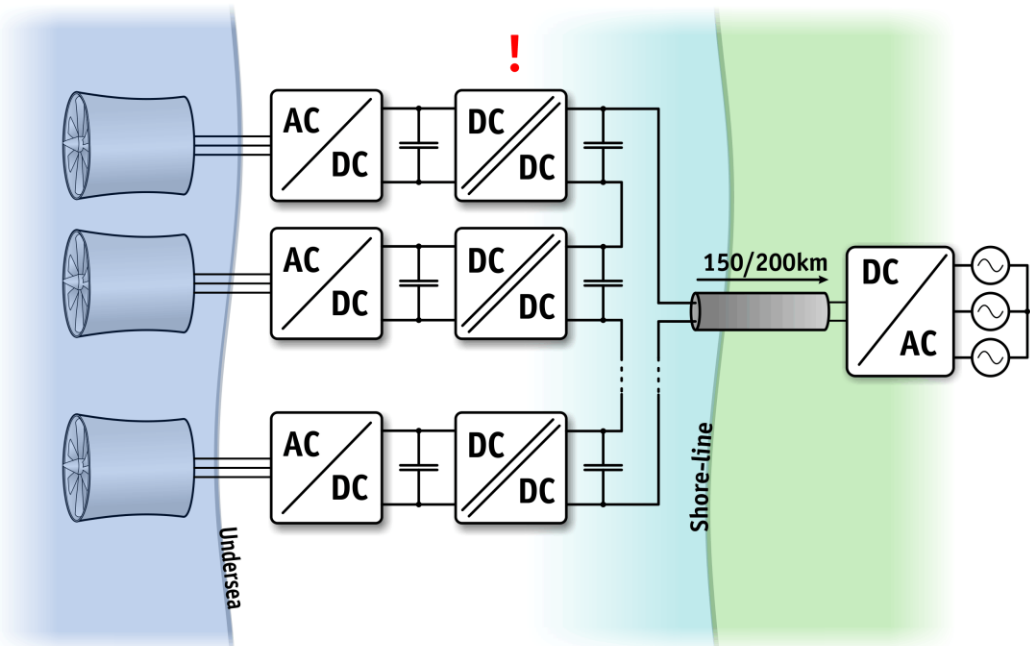
- Reduced Weight/Size
- Increased Efficiency of Power Transmission



▲ SST in Off-Shore Wind Farms

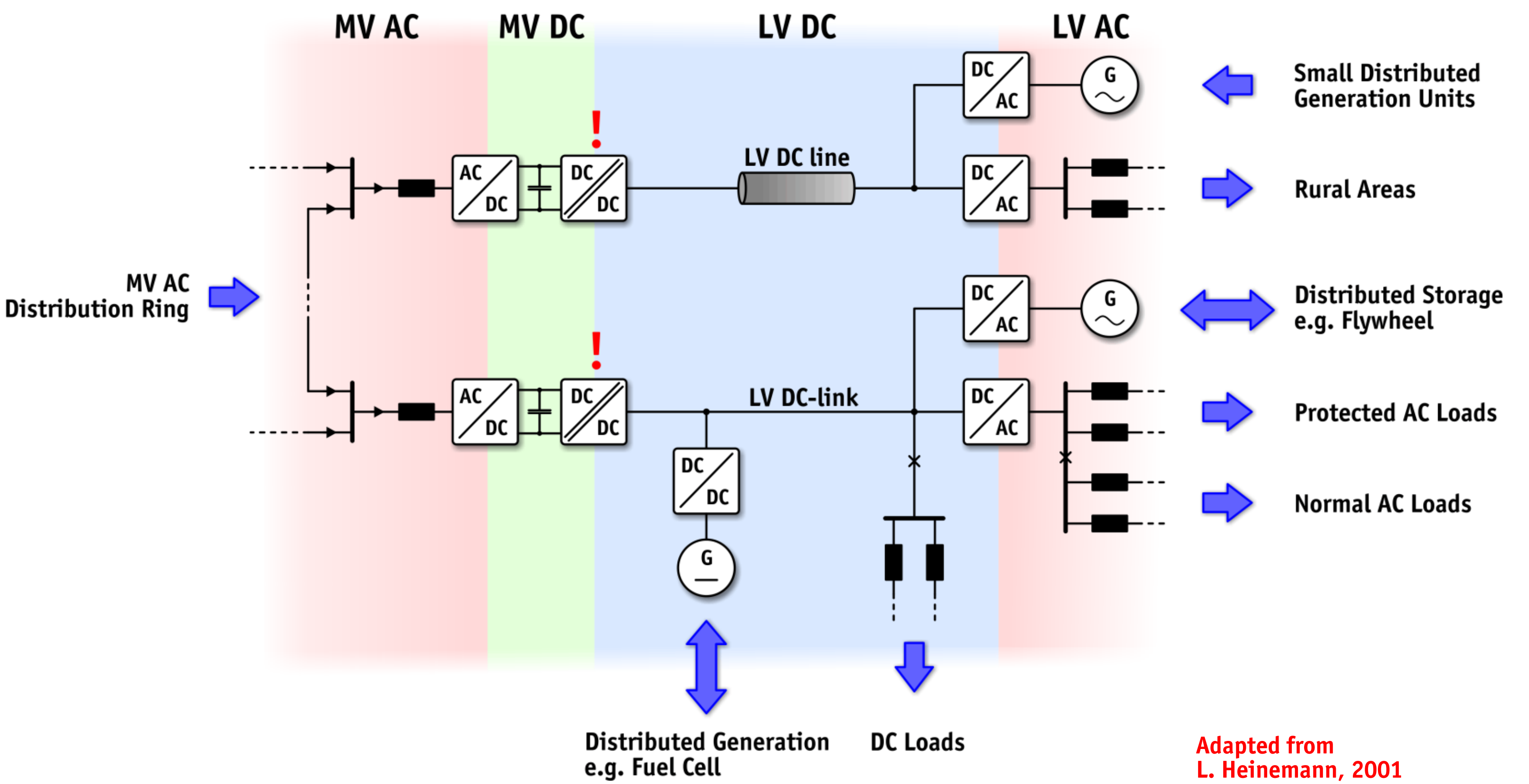
Tidal Power

- Reduced Weight/Size
- Increased Efficiency of Power Transmission



▲ SST in Tidal Power Plants

Smart Grid Scheme



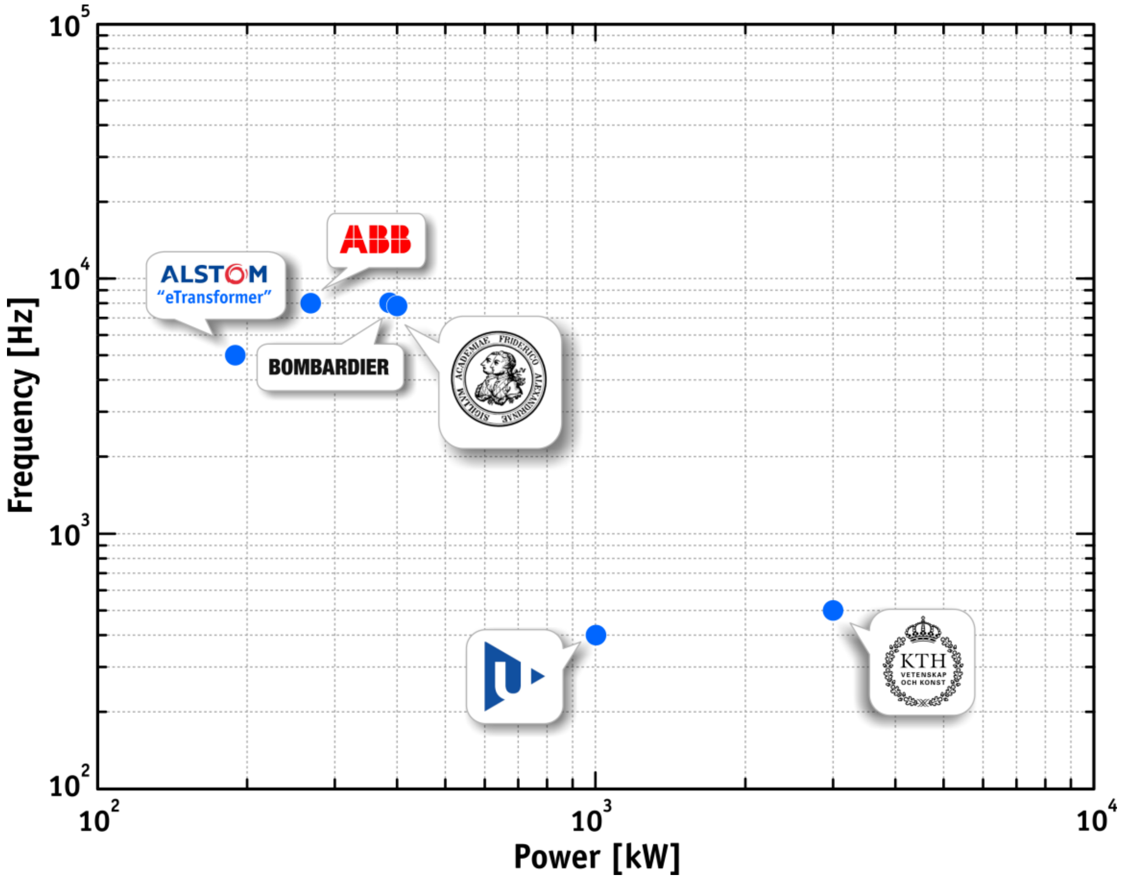
Adapted from
L. Heinemann, 2001

Overview of SST Research
over the last 10 years

Introduction to
The MEGA Cube

Traction Applications

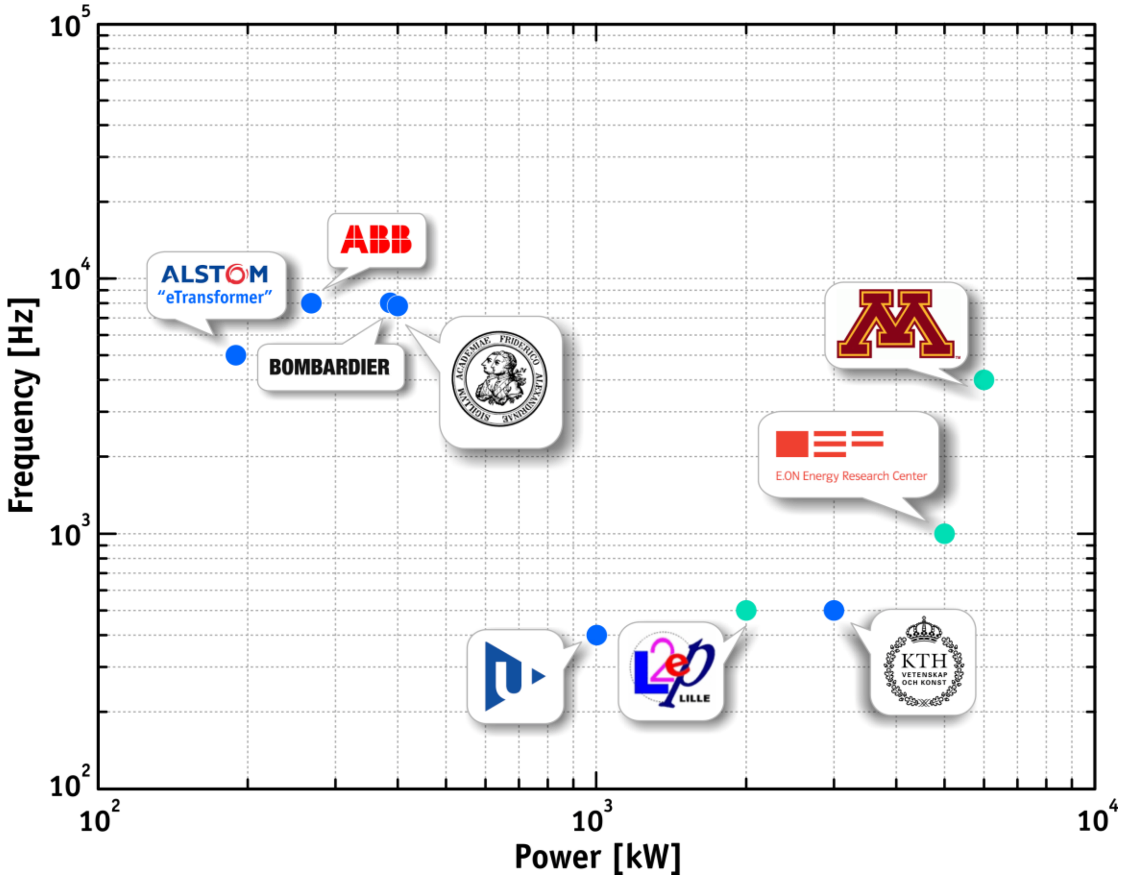
- 2001 ABB (ETH)
- 2007 Alstom
- 2007 Bombardier
- 2009 KTH
- 2010 Erlangen
- 2010 West Bohemia



SST Research over the
Last 10 Years

Wind / Tidal Power

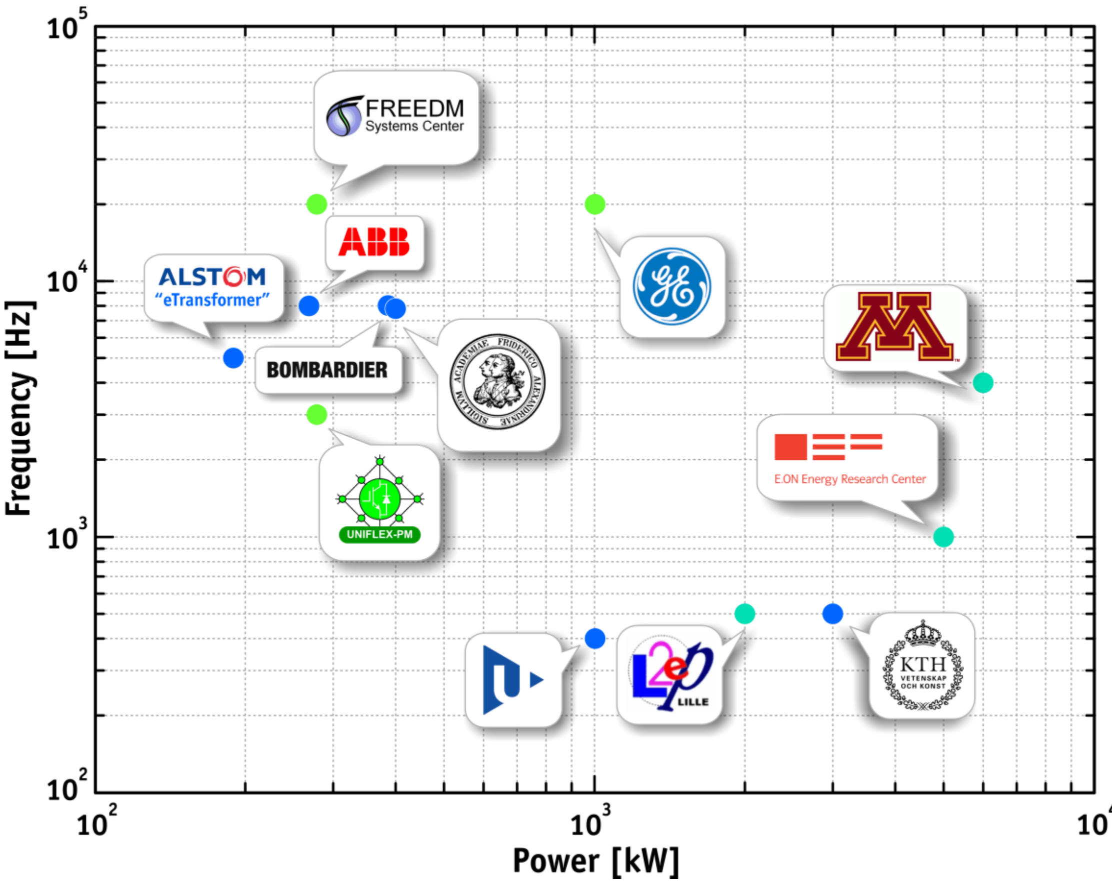
- 2009 E ON
- 2009 Minnesota
- 2011 L.2.E.P.



SST Research over the
Last 10 Years

Smart Grids

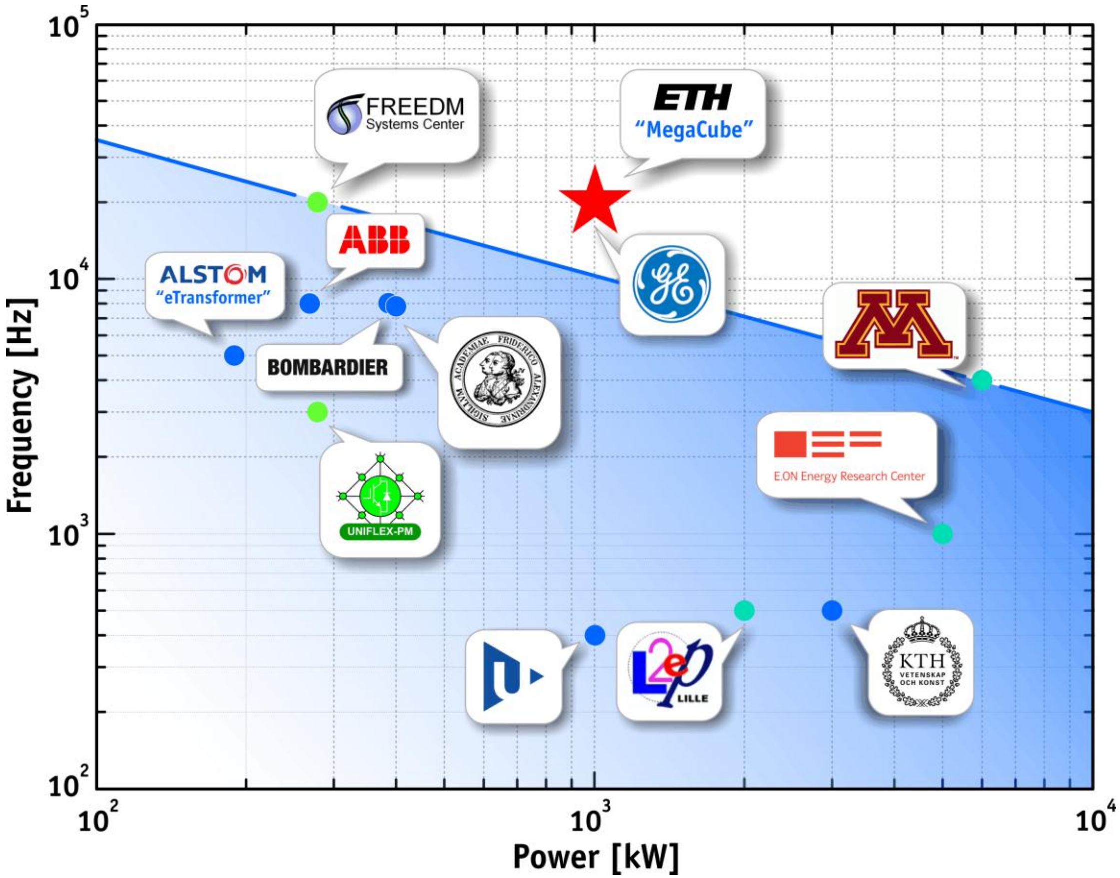
- 2006 UNIFLEX
- 2007 FREEDM
- 2011 GE



SST Research over the Last 10 Years

The MEGA Cube @ ETH Zurich

- 1MW
- 20 kHz
- 12kV MV → 1.2kV LV



SST Research over the Last 10 Years... plus MEGA Cube

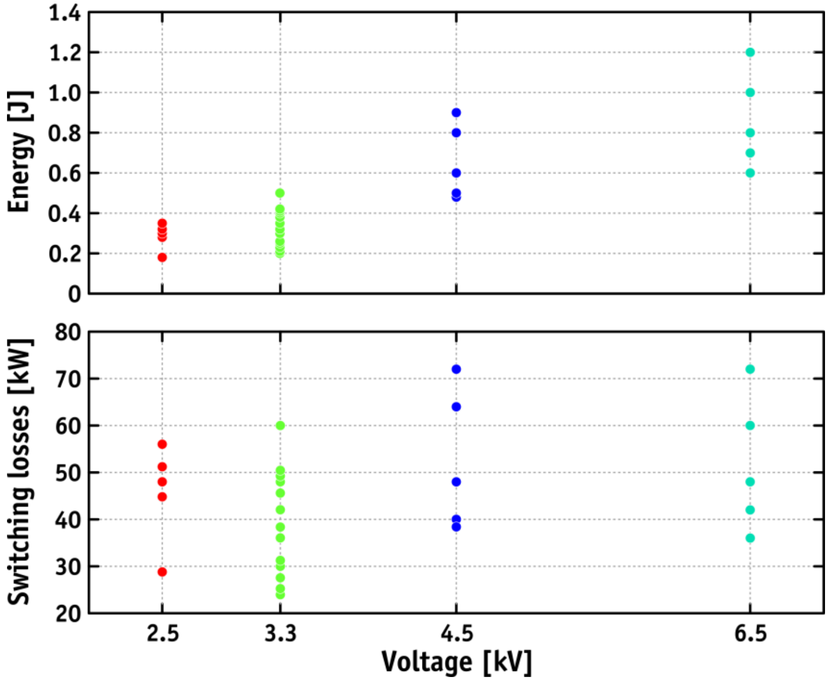
Details on
The MEGA Cube

Medium-Voltage Side
12kV - 20kHz

High-Voltage IGBTs

- Not Designed for Medium-Frequency Operation
- Zero-Current-Switching Schemes Required

◀ 4.5 kV/150 A
ABB IGBT Module

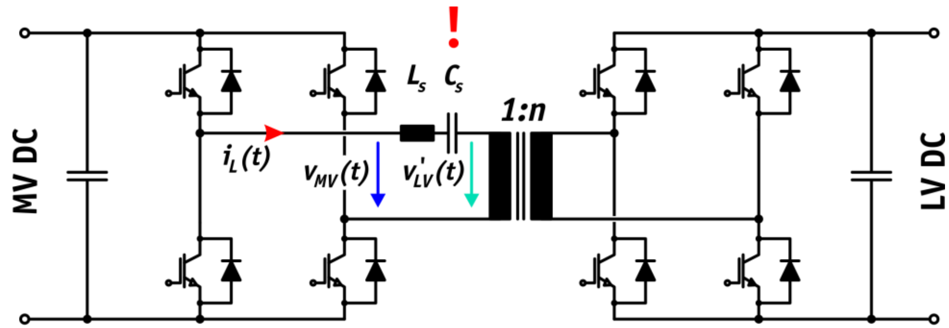


▲ 100 A Turn-Off Energies
▲ 100 A/20 kHz Switching Losses

Dual Active Bridge DC/DC Converter

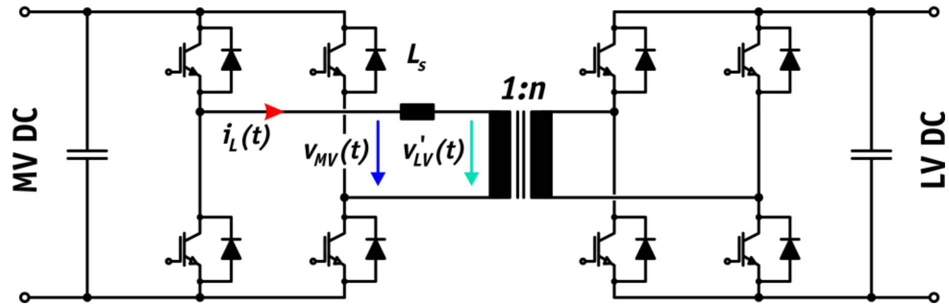
▶ **Resonant**

- Capacitor and Inductor in Series with Transformer
- Low Switching Losses in MV and LV Bridges



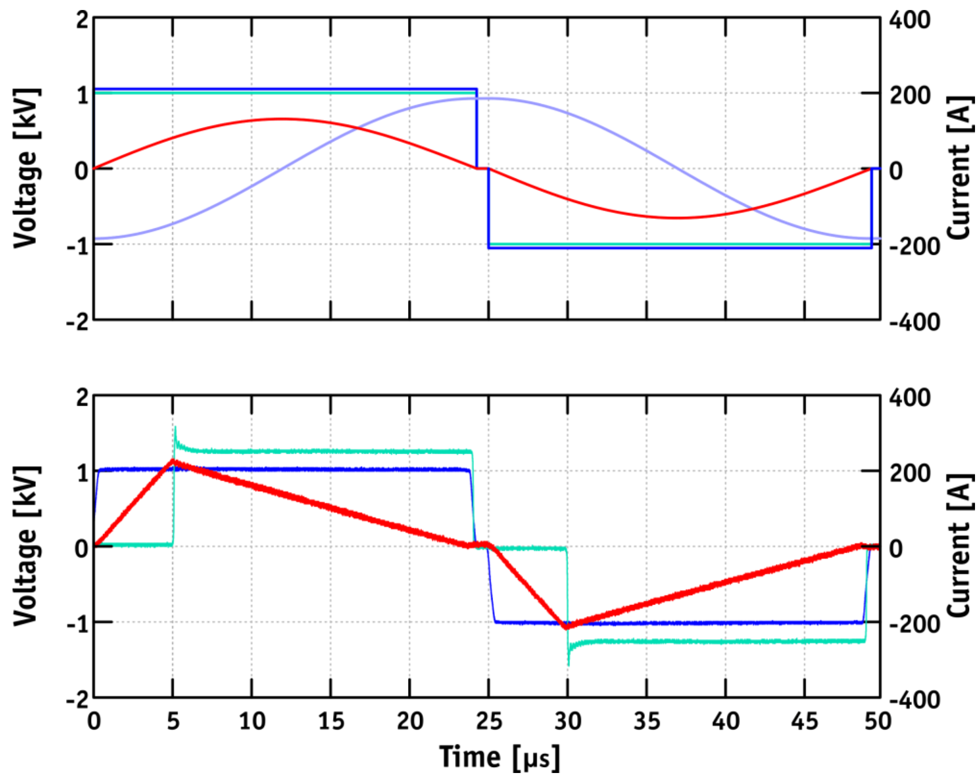
▶ **Triangular Current**

- Only Inductor in Series with Transformer
- High Switched Currents on LV Side



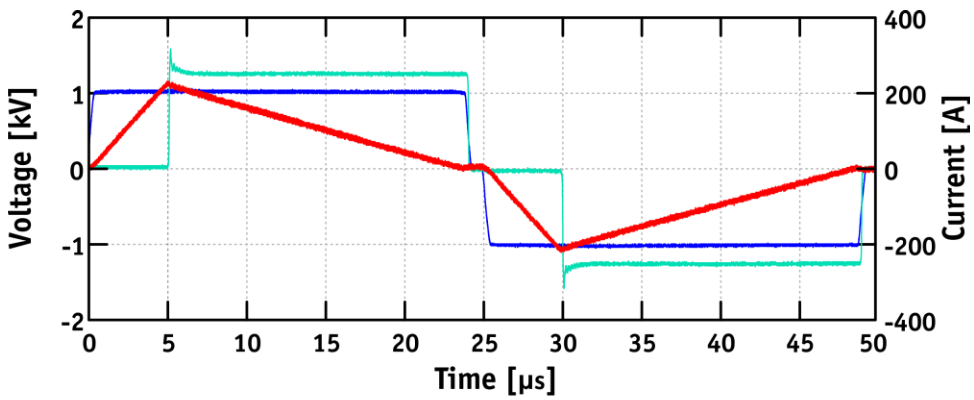
Resonant vs. Triangular Current DAB

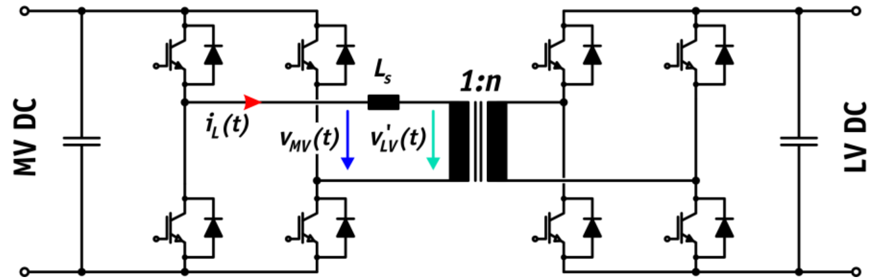
- **Resonant**
  - ZCS on LV and MV Sides
  - Low Controllability of Transferred Power
- **Triangular Current**
  - ZCS only on MV Side
  - Duty Cycle Power Flow Control



Triangular Current DAB

- Enables ZCS Only on MV Side
- All Current Turn-Off Events Shifted to LV Side

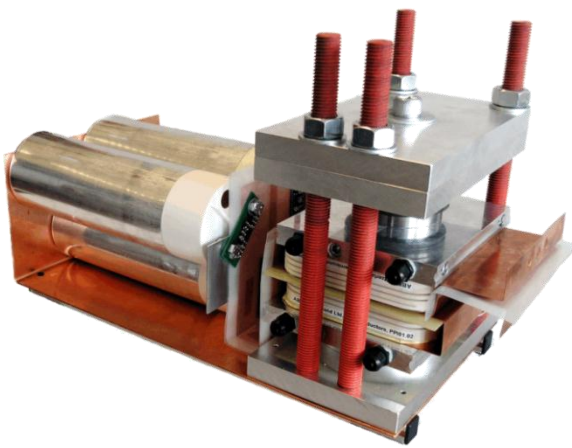


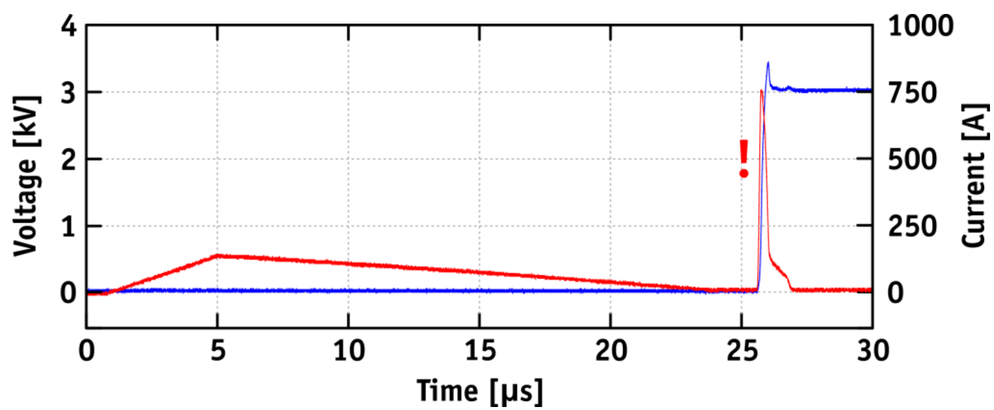


Shown for Power
Transfer from MV to LV Side

MV Switch Realization - 4.5 kV IGBT

► **Large Tail Current Despite ZCS**



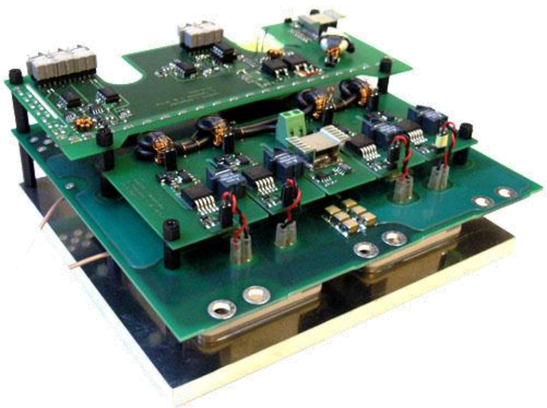


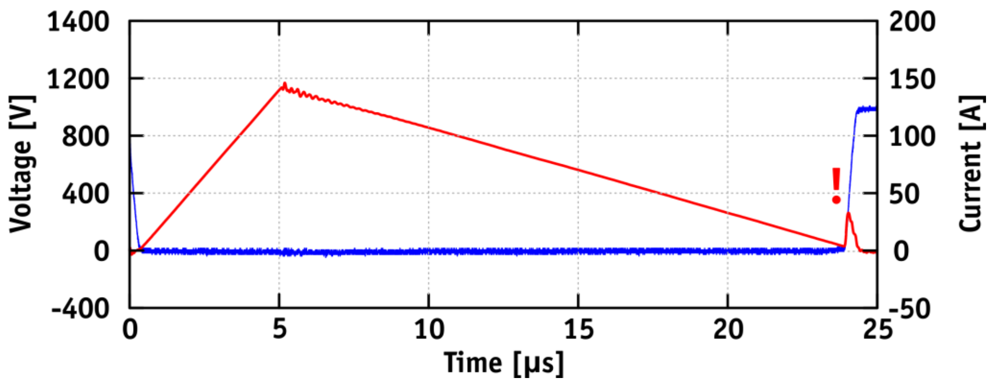
▲ **4.5kV Press-Pack IGBT Testbench**

▲ **ZCS Testing @ 3kV DC-Link 150A Peak**

MV Switch Realization - 1.7 kV IGBT

- ▶ Testbenches for NPT and PT 1.7kV IGBTs
- ▶ Massive ZCS Loss Reduction



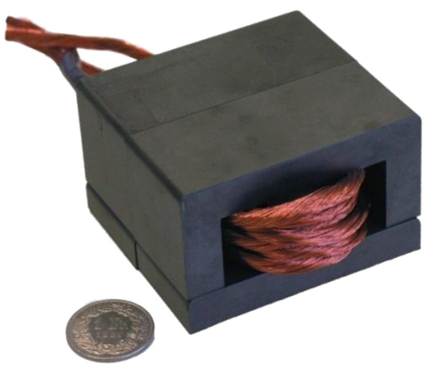


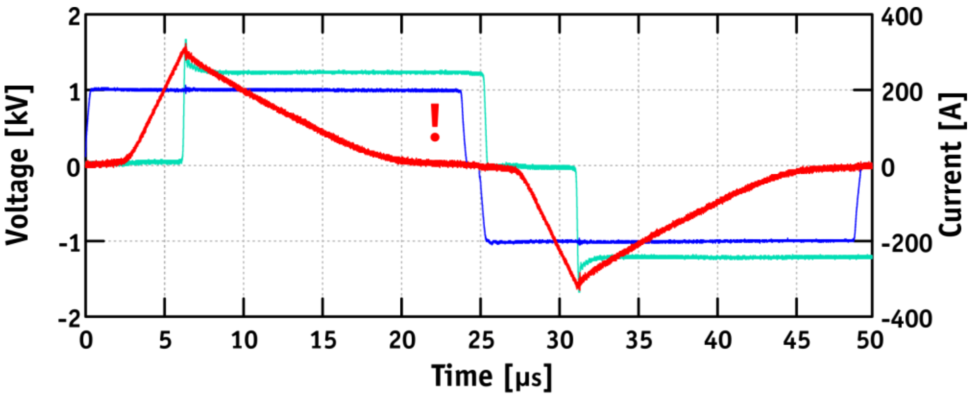
▲ 1.7kV PT IGBT NPC Module

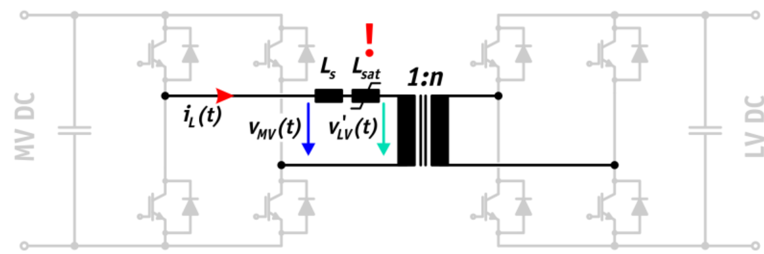
▲ ZCS Testing @ 1kV DC-Link 150A Peak

Enhancement - Saturable Inductor

- **Provides Time for Charge Carrier Recombination**

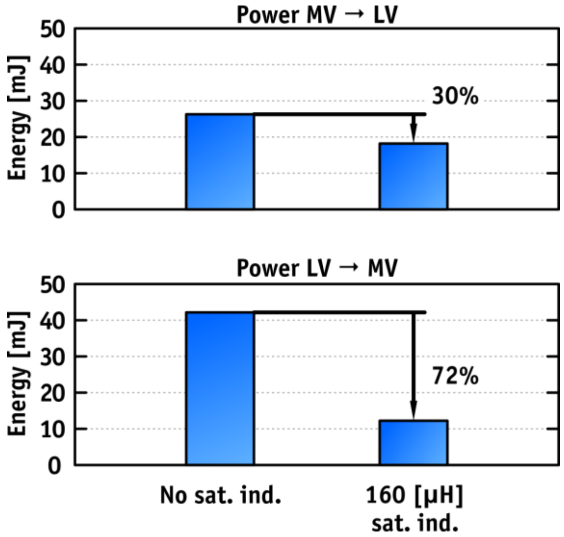


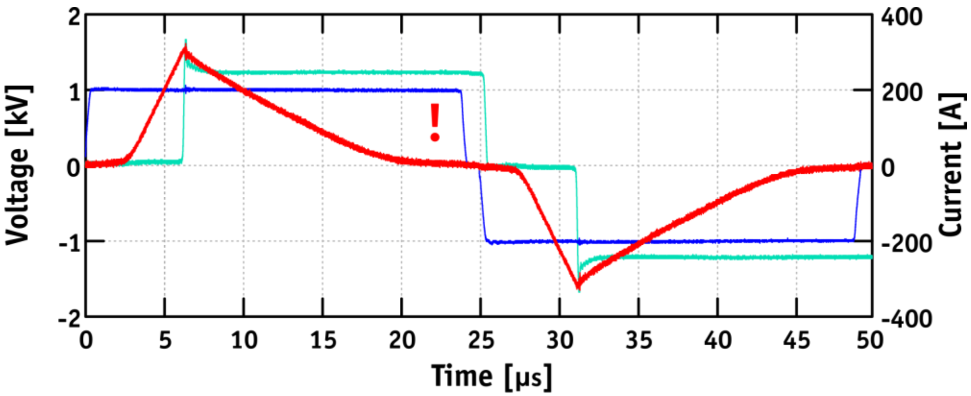


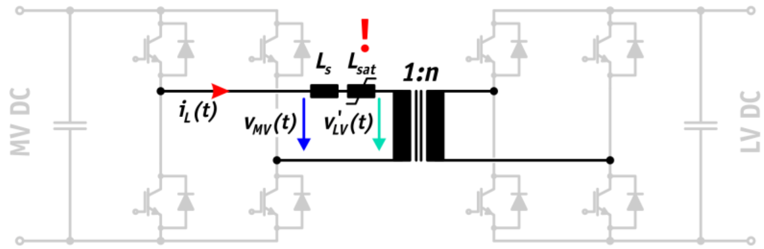


Enhancement - Saturable Inductor

- **Loss Reduction for Both Directions of Power Flow**

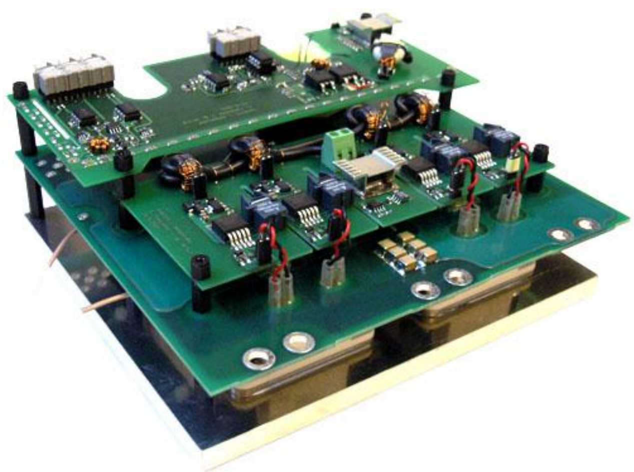




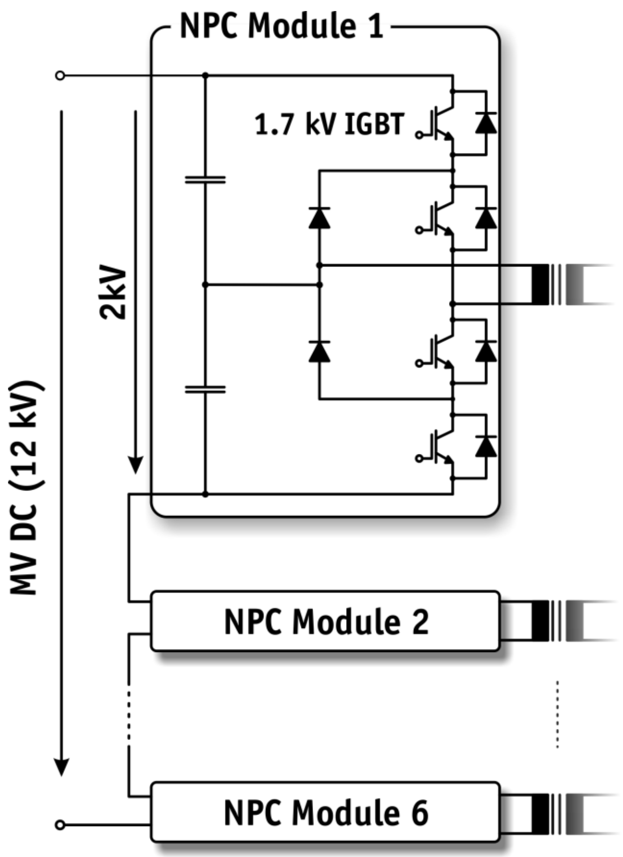


Modular MV Side

- Modular Construction due to MF + MV
- 1.7 kV IGBT Used in NPC Structure



▲ 1.7kV PT IGBT NPC Module



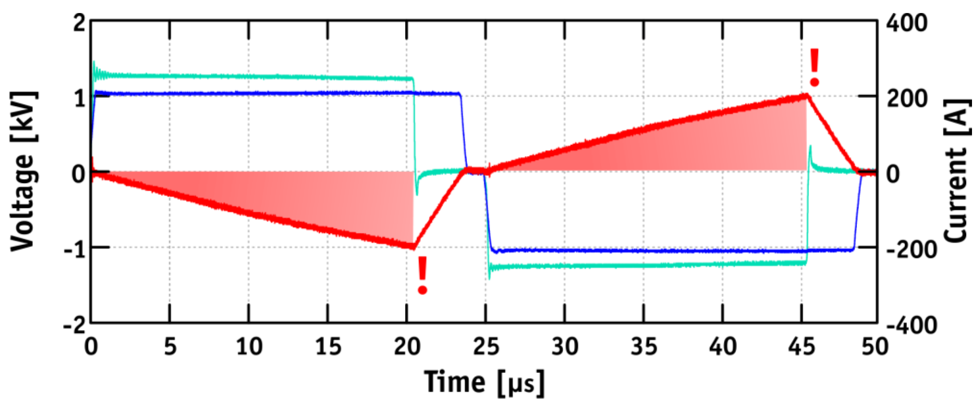
▲ Stacked MV side NPC Modules

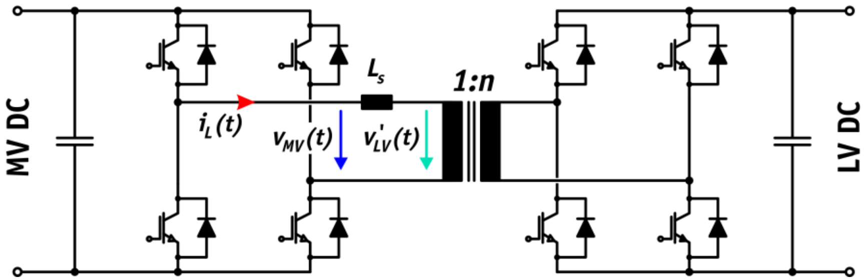
Details on
The MEGA Cube

Low-Voltage Side
1.2kV - 20kHz

DAB with Triangular Current

- **High Currents Switched / Conducted on LV side**
- **ZCS on MV Side**

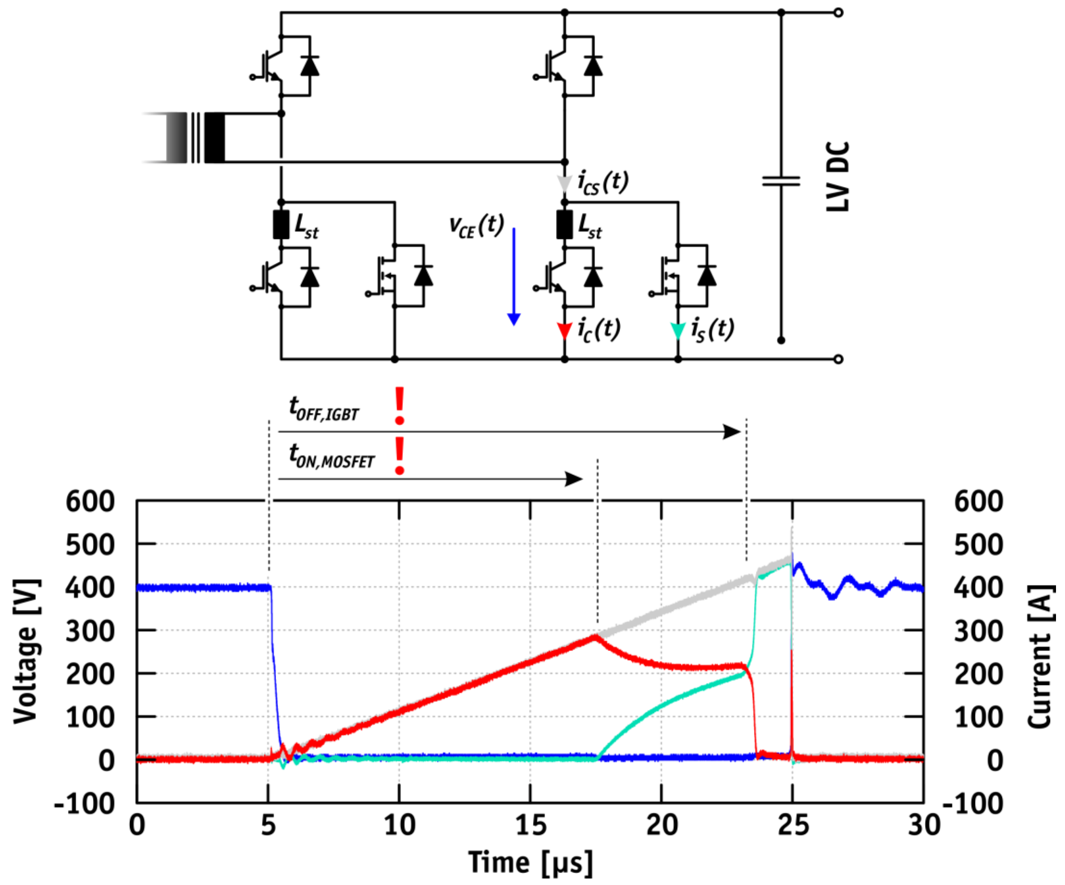




Shown for Power Transfer from MV to LV Side

Hybrid LV Switch

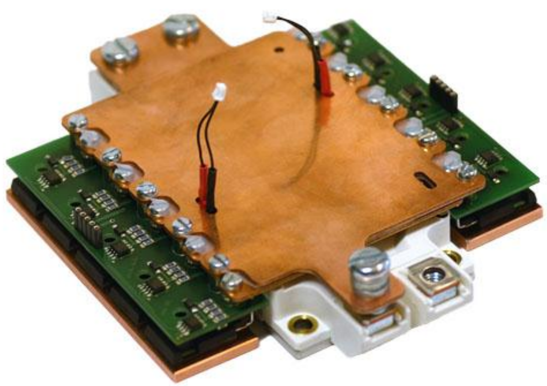
- Low Conduction Losses → IGBT
- Low Switching Losses → MOSFET



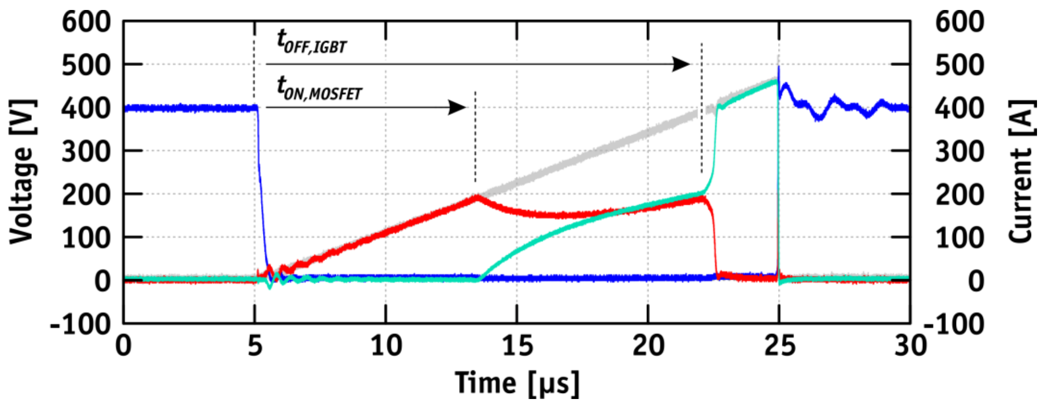
Circuit Schematic and Waveforms of LV Side Hybrid MOSFET/ IGBT Full-Bridge

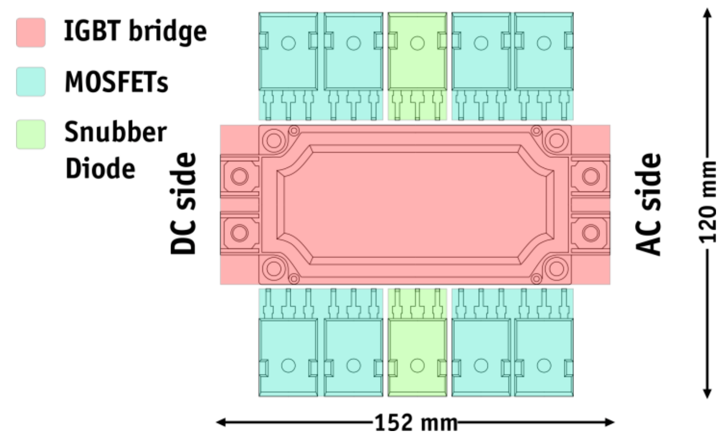
Module-Based Hybrid Switch

- IGBT Module: Infineon 600V/600A Econopack
- MOSFET: Infineon 600V/70A “CoolMOS”



▲ Hybrid Switch Based on IGBT Bridge Leg Module

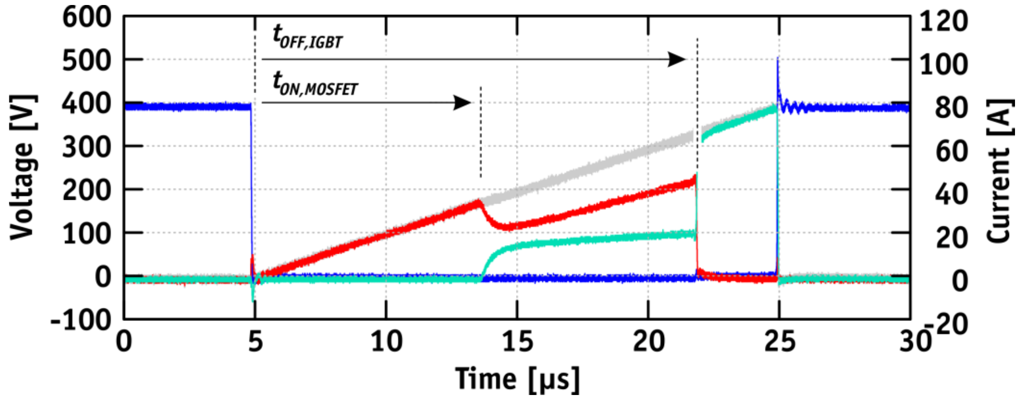


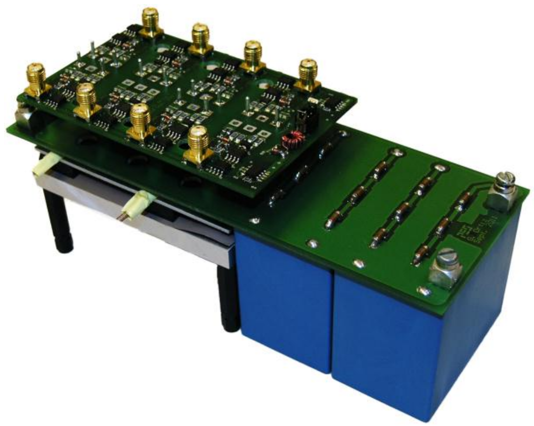


▲ Hybrid Switch Layout and Waveforms; $t_{ON,MOSFET}$ = 8us / $t_{OFF,IGBT}$ = 17us

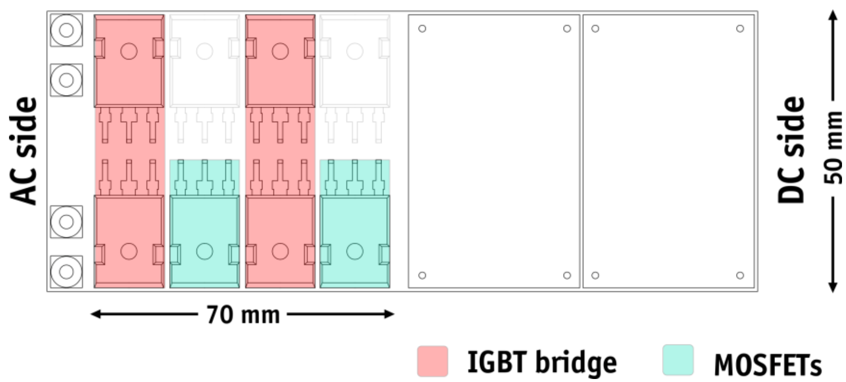
Interleaved Hybrid Switch

- IGBT : Infineon 600V/75A Trench Field-Stop
- MOSFET: Infineon 600V/70A "CoolMOS"





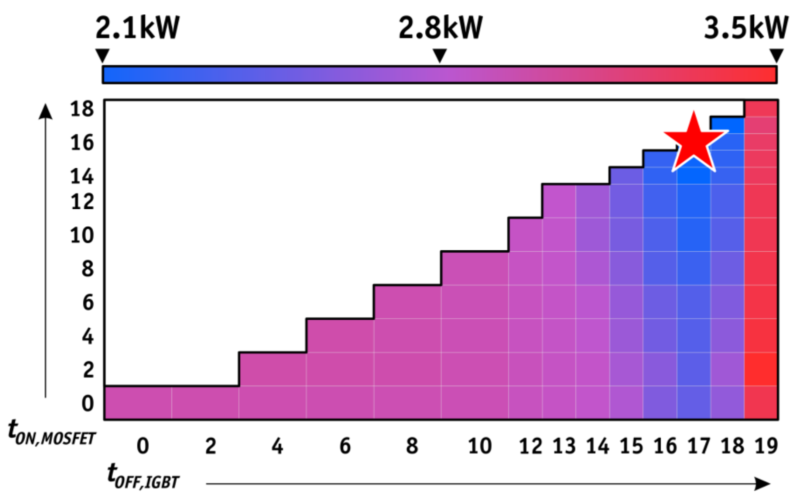
▲ Testbench for Interleaved Hybrid Switch



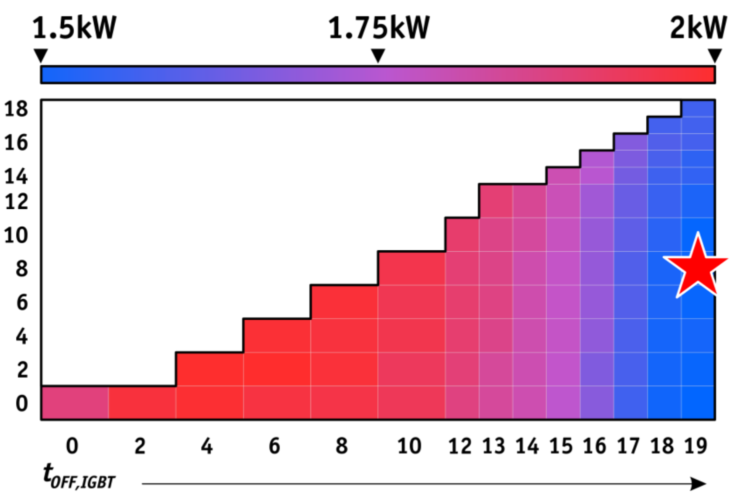
▲ Hybrid Switch Layout and Waveforms; $t_{ON,MOSFET}$ = 8us / $t_{OFF,IGBT}$ = 17us

Module-based vs. Interleaved Hybrid Switch

- Total Losses for a 166 kW Full-Bridge
- Mesh with Different $t_{ON,MOSFET}$ and $t_{OFF,IGBT}$ Showing Optimal Selection



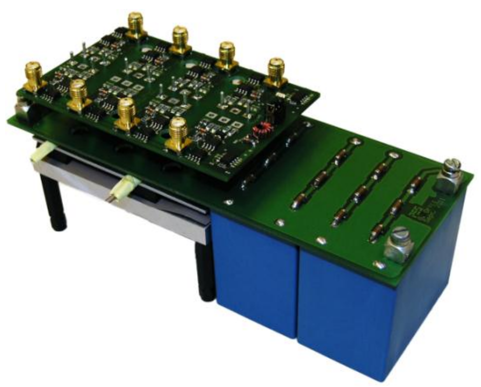
▲ Module-Based Full-Bridge Total Losses (Conduction and Switching)



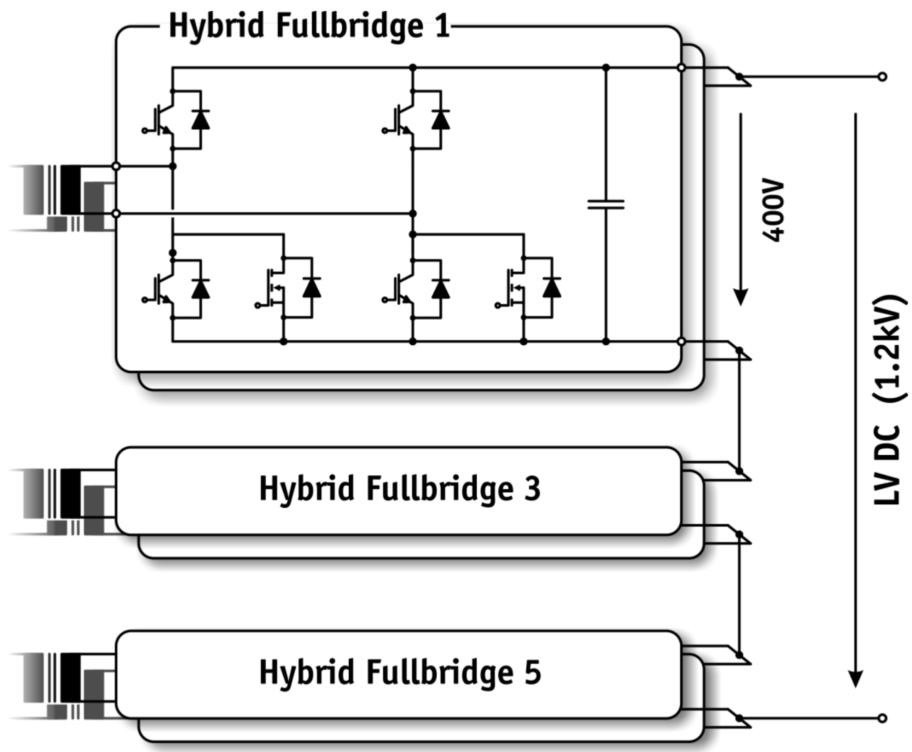
▲ Interleaved Full-Bridge Total Losses (Conduction and Switching)

Modular LV-Side Full-Bridge

- 6 Modules – 6 x 166 kW
- Hybrid Switch for Low Conduction/Switching Losses



▲ Testbench for Interleaved Hybrid Switch



▲ Structure of the Modular LV Side Comprising Hybrid Switch

MEGACube
The Big Picture

- 6 Modules

- LV Side

  Parallel/Series Connection of 400V Full Bridges

- MV Side

  Series Connection of NPC Bridges

Module 1

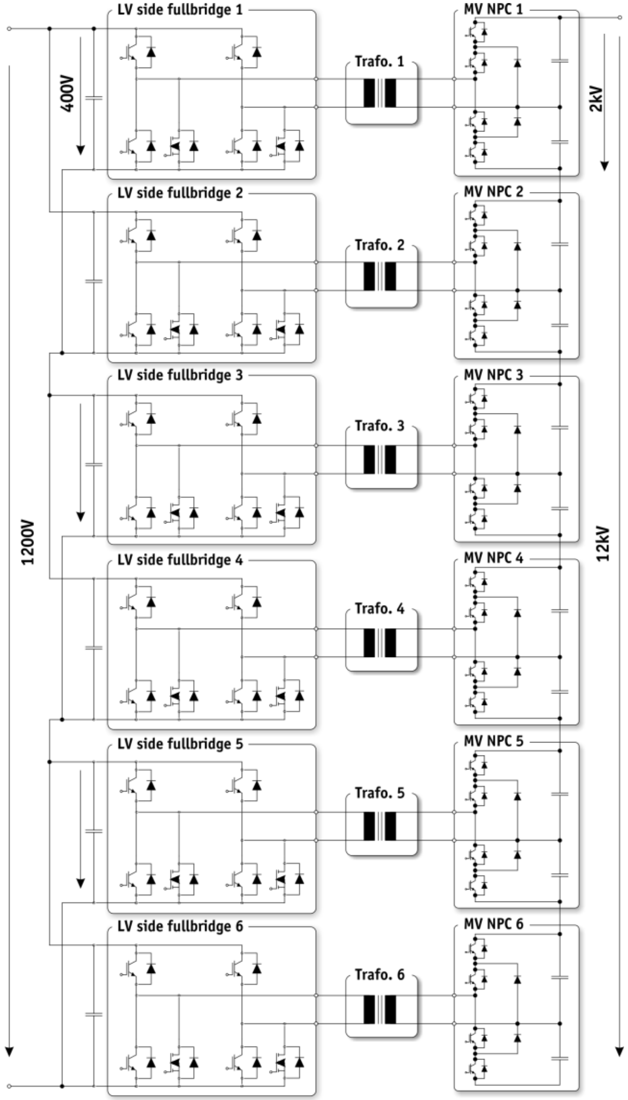
Module 2

Module 3

Module 4

Module 5

Module 6

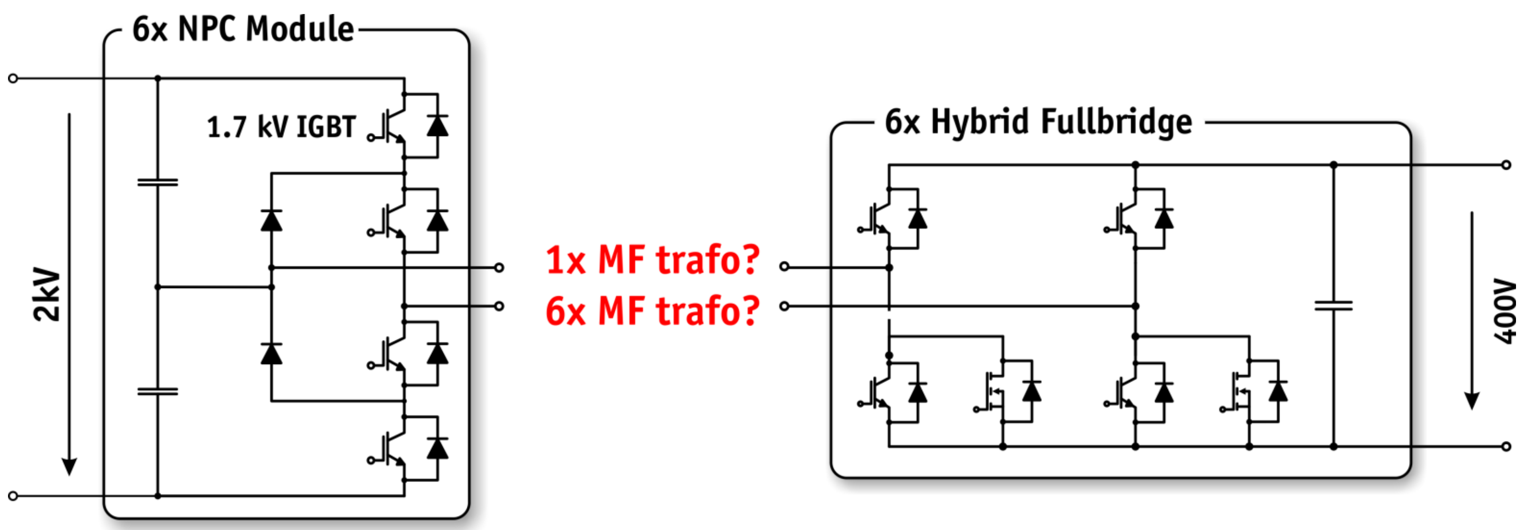


Details on
The MEGA Cube

Transformer
20kHz

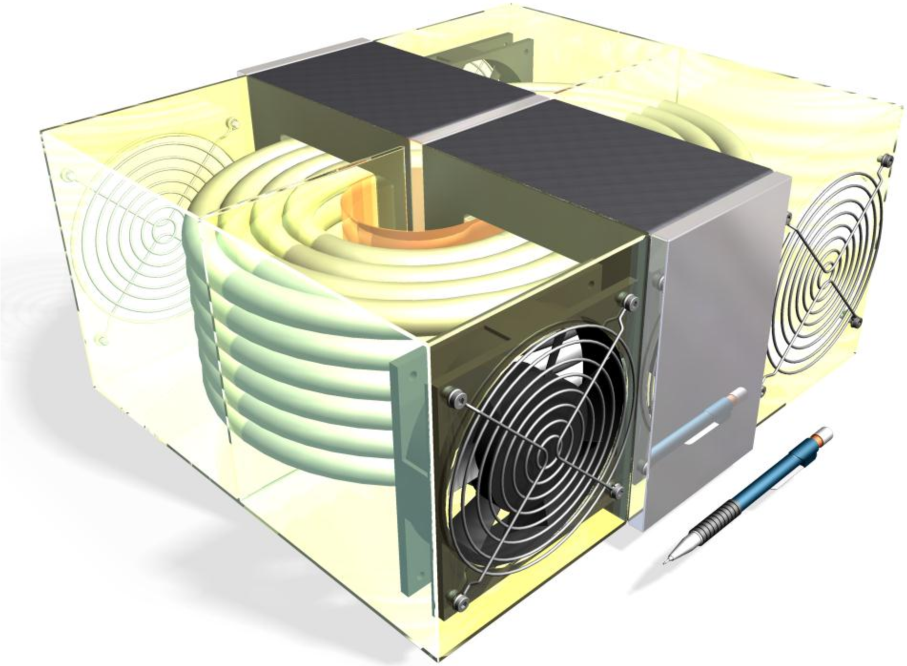
How Many MF Transformers?

▶ Six Transformers (One per Module) **OR** One Transformer with 6 LV/MV Windings?



▲ MF Transformer - Link of MV NPC Module and LV Hybrid Switch Full-Bridge

Option 1: Shell-Type

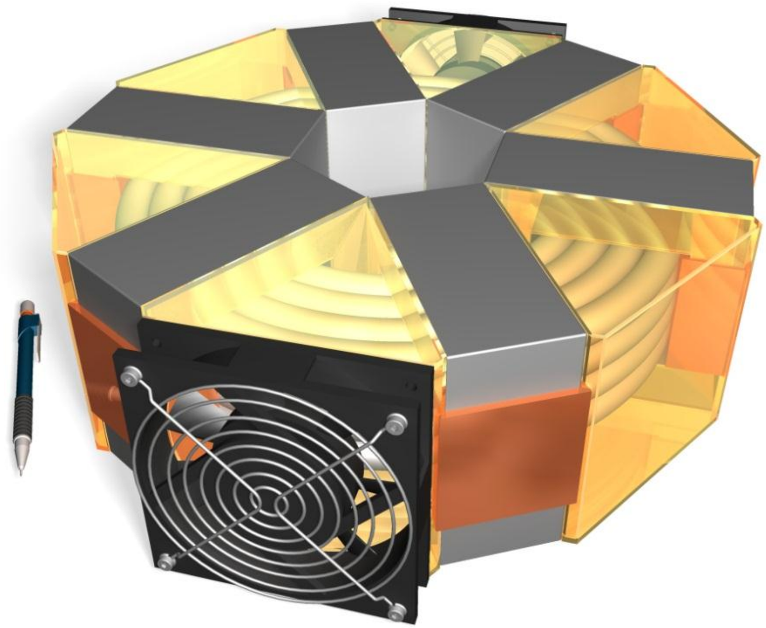


- E-Shape Based on Magnetic Core

- Vitroperm 500F / Heatsinks
- HV Litz Cable /
- LV Foil
- Air-Cooled

▲ Shell-Type Transformer with
HV Cable Winding Designed for 1MW/20kHz

Option 2: Matrix-Type



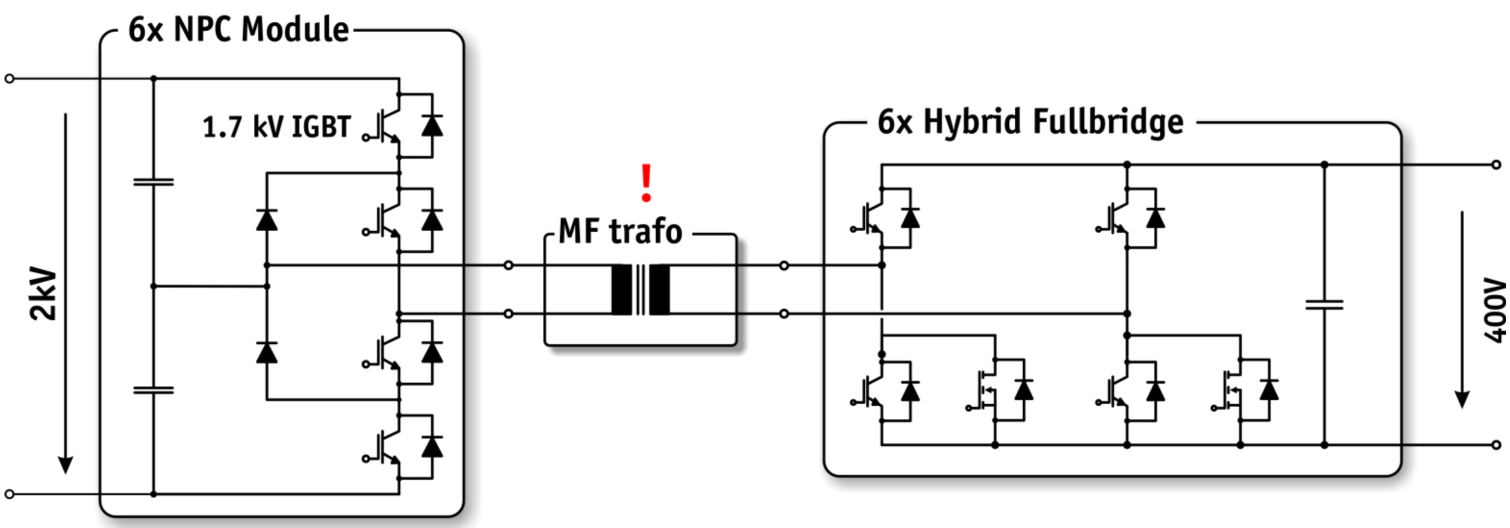
- Several Cores / Each Realizing a Transformer
- Realization of the Turns Ratio Through Parallel/ Series Connection

- Vitroperm 500F / Heatsinks
- HV Litz Cable /
- LV Foil
- Air-Cooled

▲ Matrix-Type Transformer with HV Cable Winding Designed for 1MW/20kHz

MF Transformer Split up to 6 Modules

- Linking MV NPC Module and LV Hybrid-Switch Full-Bridge Modules
- Isolation + Voltage Adaptation



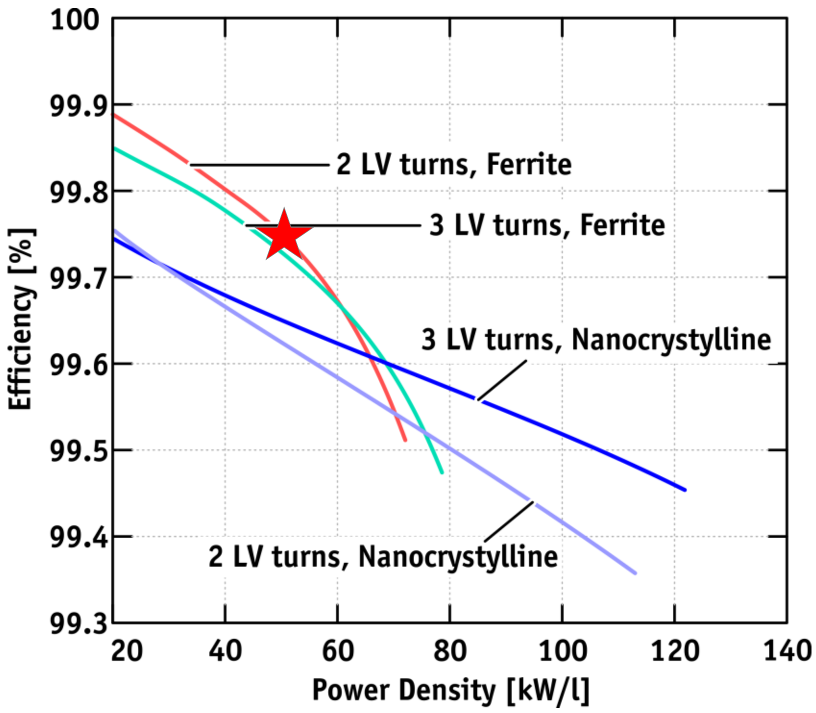
▲ Block Diagram of High-Power DC-DC Converter Utilizing Modular LV and MV Converters

Transformer Optimization

- Parameter 1: Core Material
- Parameter 2: LV Winding Number of Turns

- Selected Design:

- 2 Turns LV Winding
- Stacked Ferrite Cores

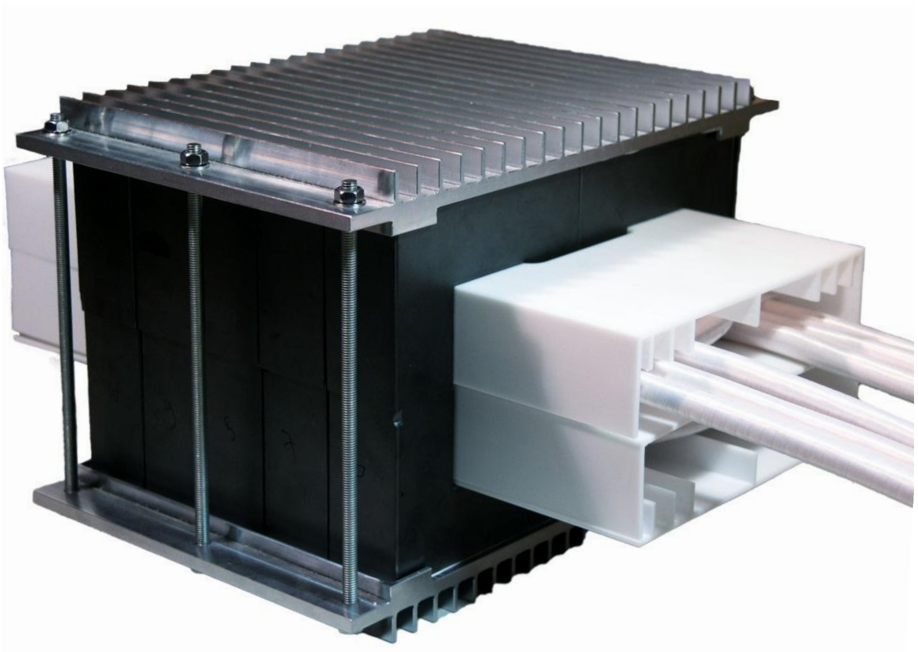


Power Density vs. Efficiency Pareto Front of the 166kW Transformer

Assembled Transformer

- 166kW / 20kHz
- Ferrite N87
- 9500 Strands Litz Wire
- PTFE Isolation Bobbin
- Forced Air Cooled

- Efficiency: 99.75%
- Power Density: 31kW/dm^3

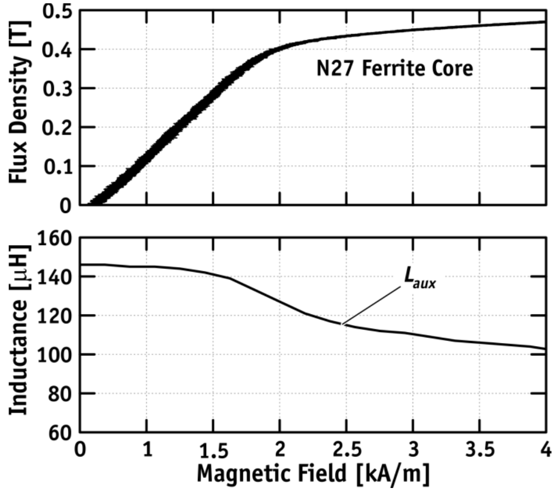


166kW / 20kHz Transformer

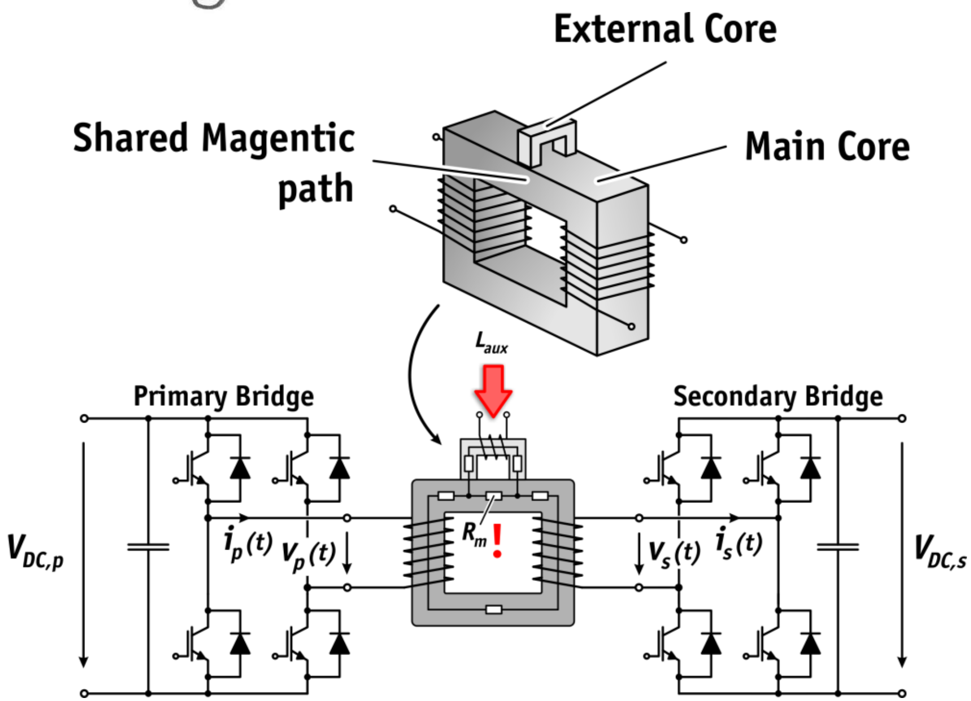
Preventing Core Saturation

▸ **Flux Density Transducer – Magnetic Ear**

Shared Magnetic Path between Main and Auxiliary core



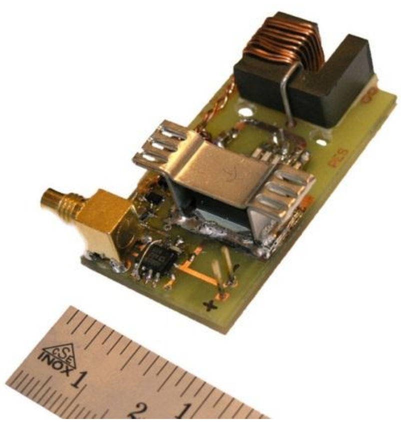
▲ Measured External Core Inductance

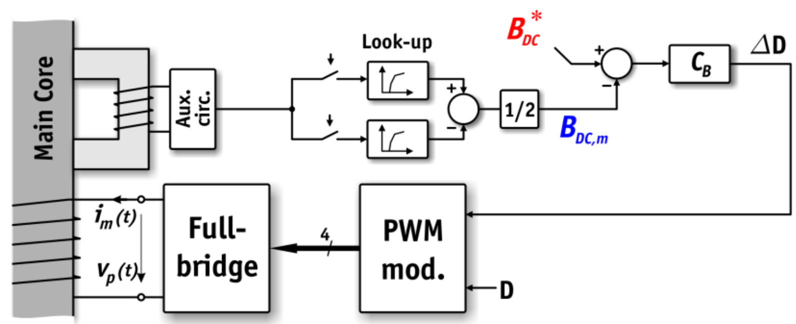


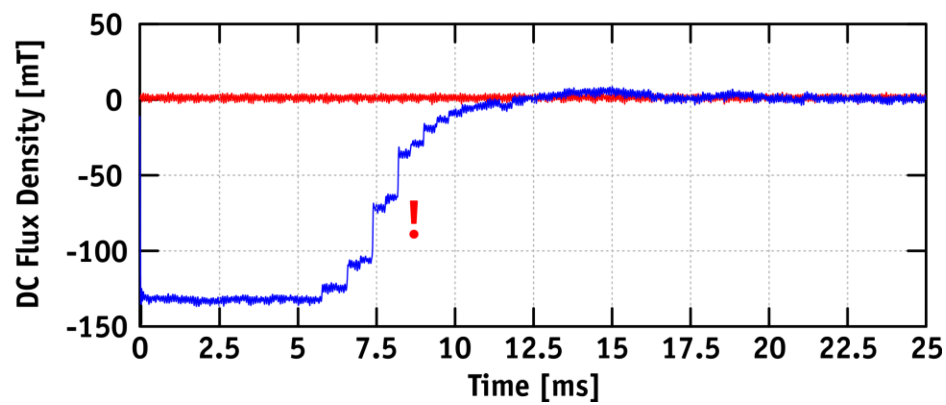
▲ Magnetic Ear Concept

Magnetic Ear

- **Closed-Loop Control of the Flux Density in the Main Core**
- **Eliminate Problems of DC Magnetization**







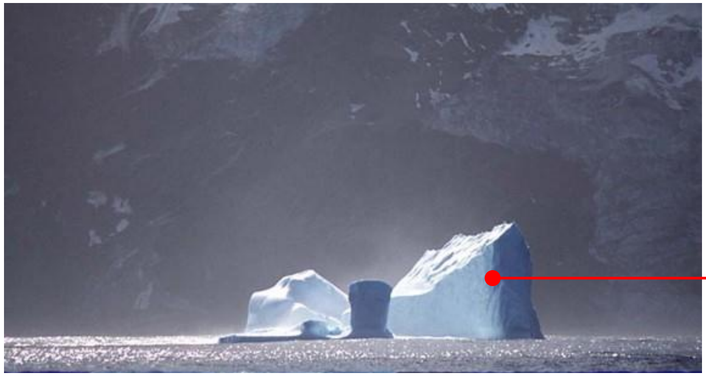
Conclusions / Outlook

Conclusions

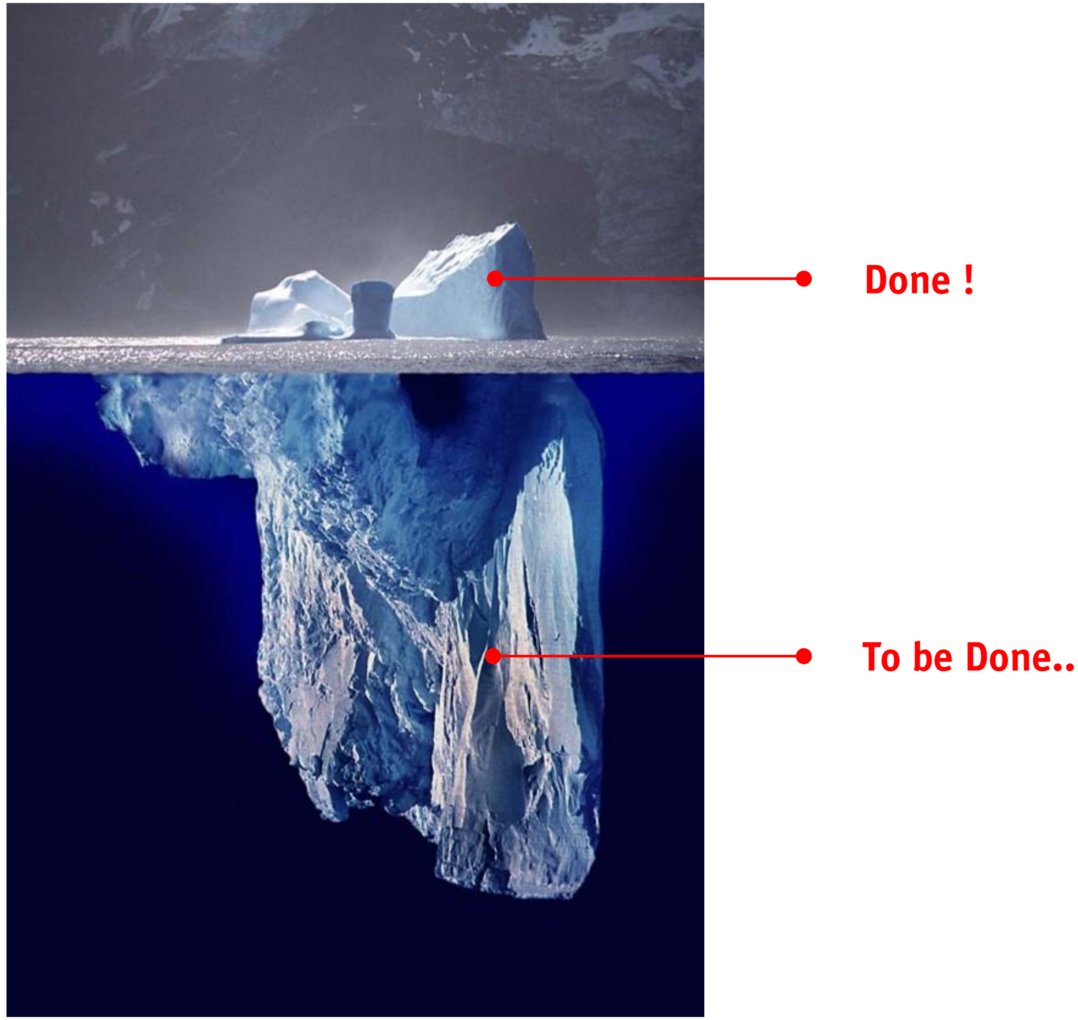
- SST Technology Attractive for Traction / Renewable Energy / Smart Grids
- High-Power MF DC-DC Converters are a Key Component for SSTs

- 1MW / 20kHz MV to LV MEGA Cube under Construction @ ETH Zurich
- With Available Semiconductors → ZCS required on MV side
- Medium Voltage + Medium Frequency → Modular Arrangement

- Major Opportunities for WBG Power Semiconductors



Done !


Done !
To be Done...

Outlook

- Modeling/Simulation of ZCS Behavior
- High Performance Cooling Systems
- Magnetics Thermal Management
- High RMS Currents of Capacitors
- Partial Discharge Testing
- Common Mode Voltages of Stacked MV Modules
- Alternative Core Materials
- Winding Resonances
- High-Current Medium-Frequency Test Setup
- ...

Thank You!

Questions?