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

Johann W. Kolar ...
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The MEGA Cube Project

Johann W. Kolar & Gabriel Ortiz
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

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 M. Hartmann Ch. Marxgut J. Mühlethaler	T. Friedli M. Schweizer A. Korn	**B. Cougo** D. Boillat T. Andersen U. Badstübner R. Friedemann M. Kasper G. Ortiz St. Waffler	**D. Bortis** Y. Lobsiger B. Wrzecionko R. Burkart	T. Soeiro	F. Giezendanner I. Kovacevic A. Müsing A. Stupar	T. Baumgartner P. Imoberdorf A. Looser A. Tüysüz	T. Reichert B. Warberger C. Zingerli F. Zürcher

Secretariat
M. Kohn

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

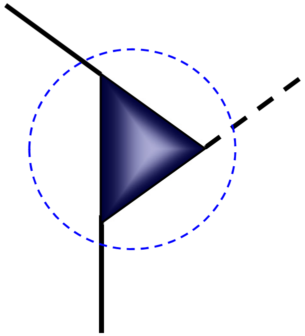
29 Ph.D. Students
3 Post Docs

ECPE Competence Centre

EPSMA

Leading Univ. in Europe

PES Research Scope



Cross-Departmental

Mechanical Eng., e.g.
Turbomachinery, Robotics

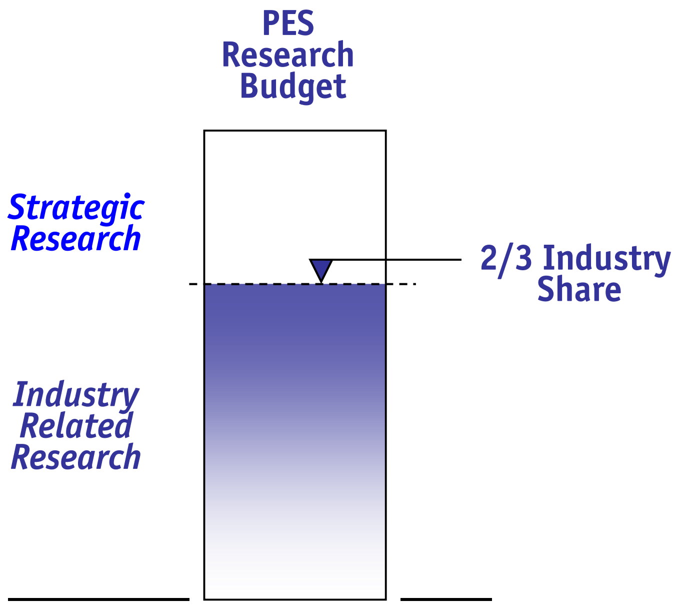
Microsystems
Medical Systems

Economics / Society

- *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

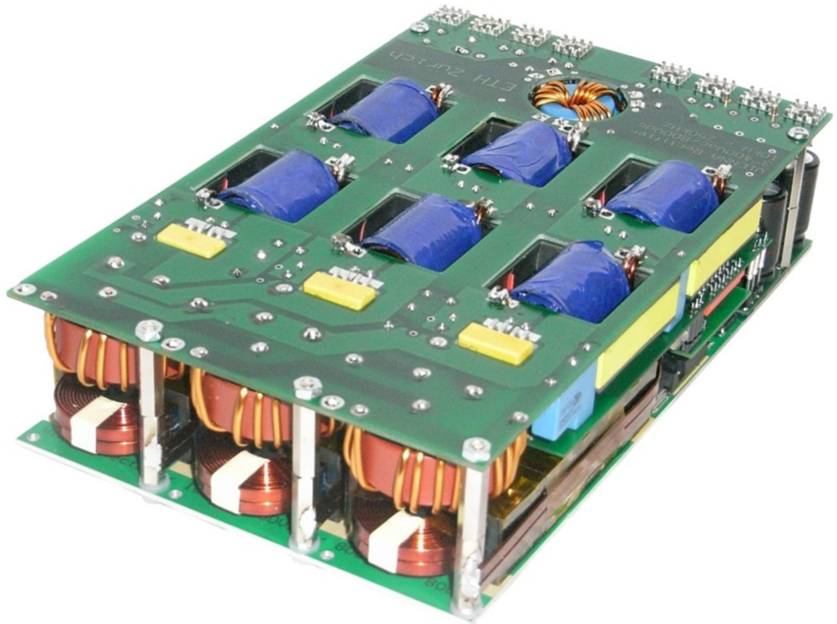
3-Φ Boost-Type PFC Rectifier

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

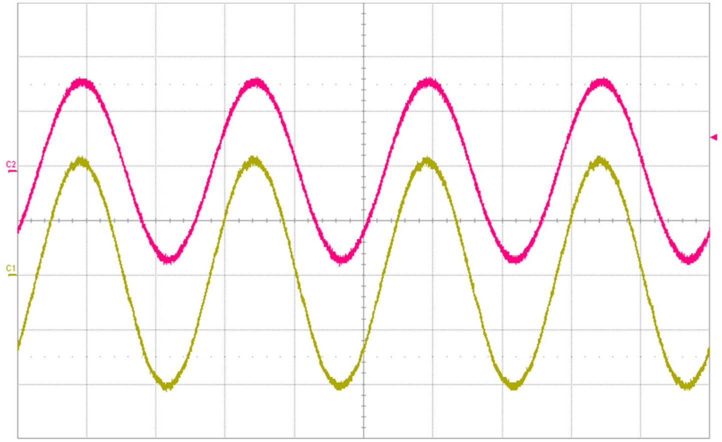


★ 10kW/dm³ Power Density

Mains Behavior @ 400 Hz/800 Hz

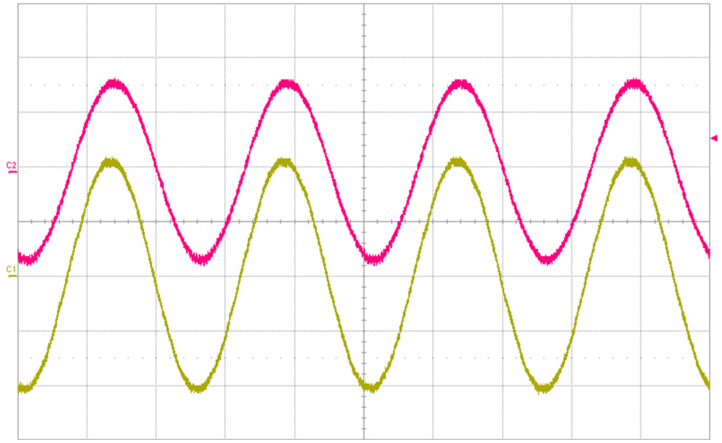
P_0 = 10kW
U_N = 230V
f_N = 400Hz
U_0 = 800V
THD_i = 1.4%

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



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

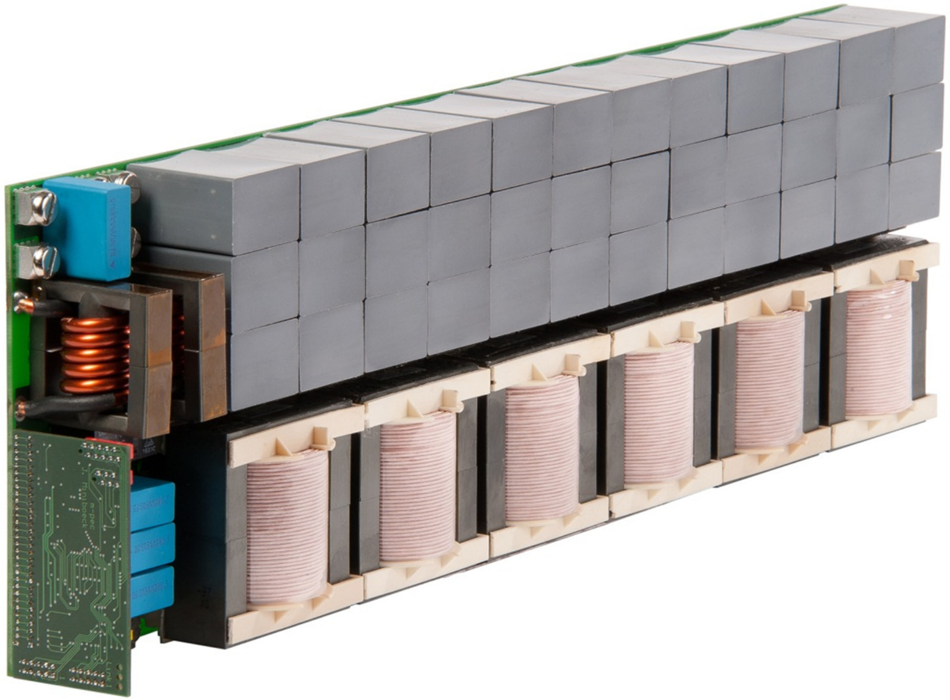
10A/Div
200V/Div
0.5ms/Div



Bidirectional Super-Efficient
1-Φ PFC Mains Interface

★ **99.3% @ 1.2kW/dm³**

Hardware Testing to be finalized in November 2011



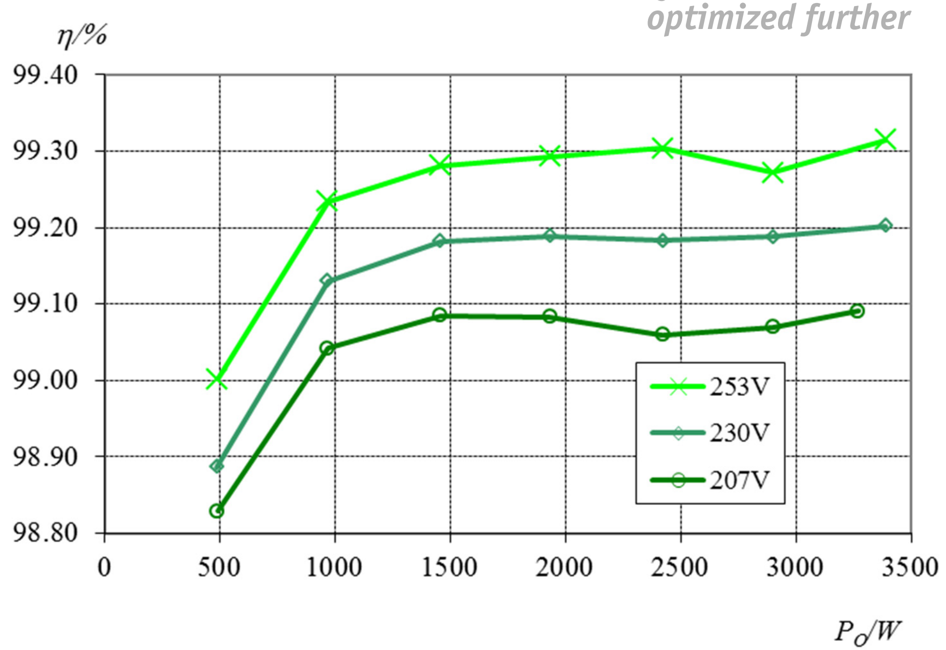
► **Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only**

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



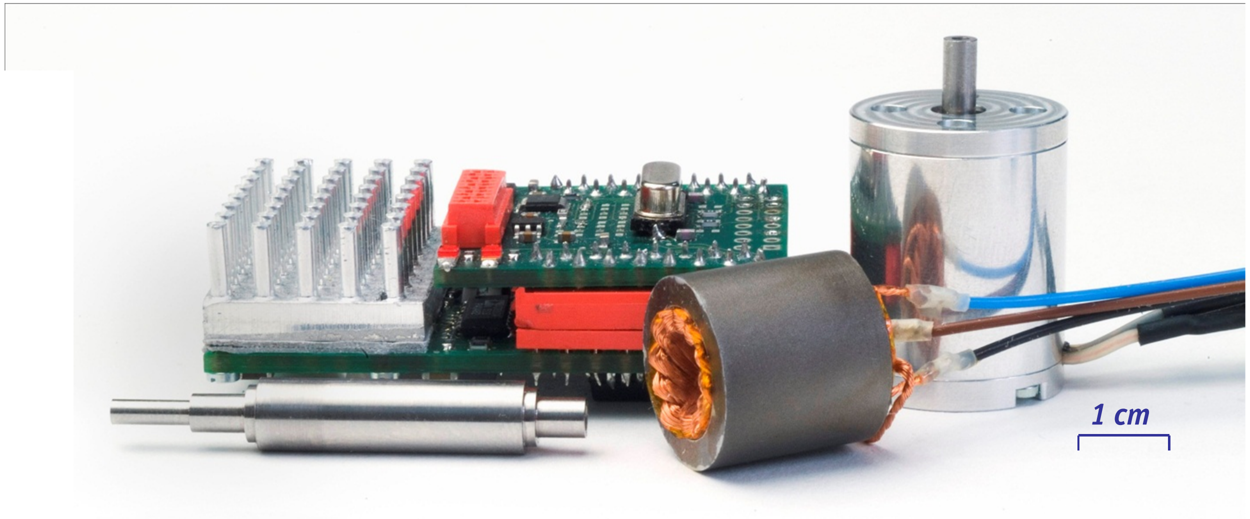
► **Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only**

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 !

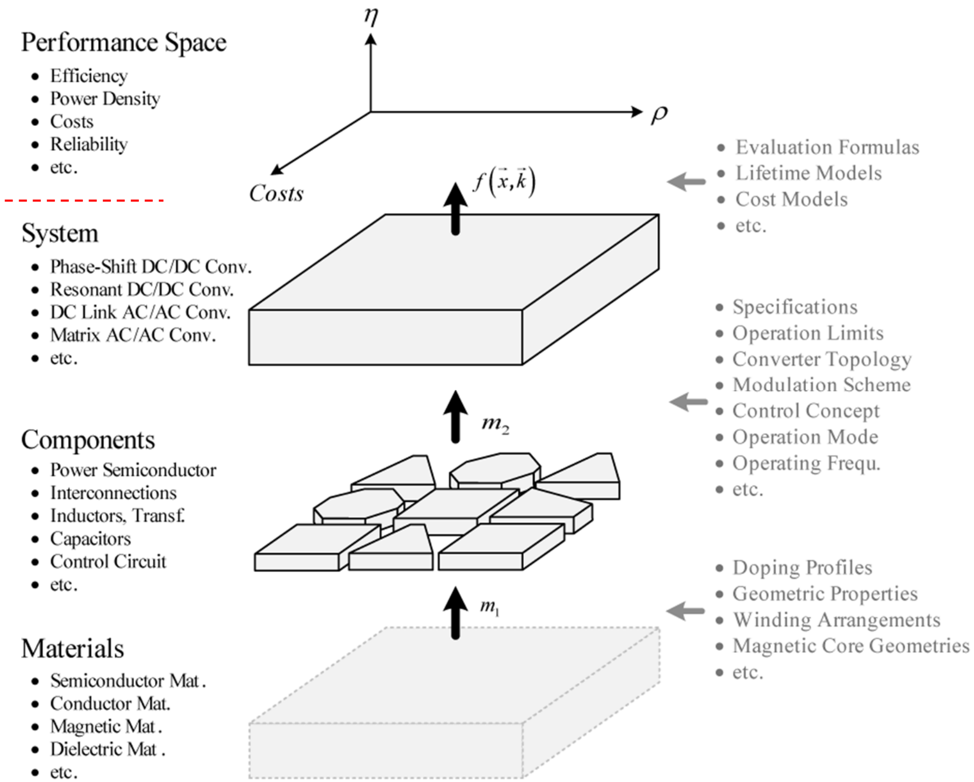
100W @ 1‘000‘000 rpm



Abstraction of Power Converter Design

Performance Space

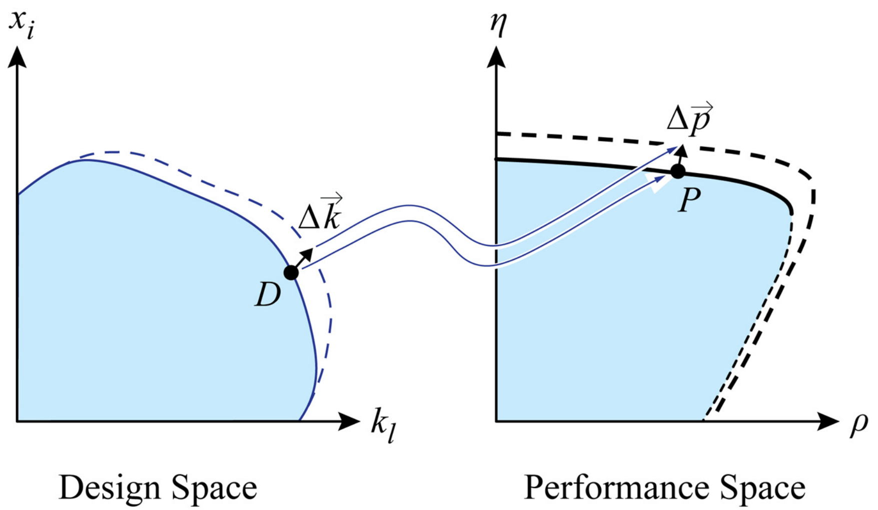
Design Space

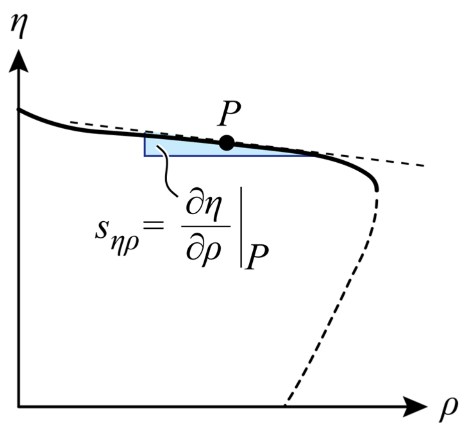


► Mapping of *Design Space* into System *Performance Space*

Technology Sensitivity Analysis Based on η-ρ-Pareto Front

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





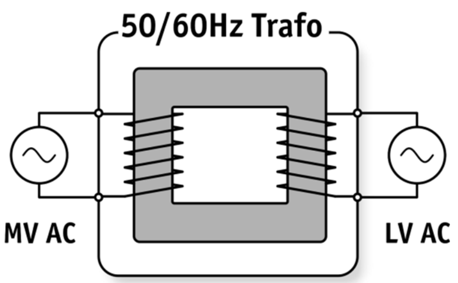
Outline

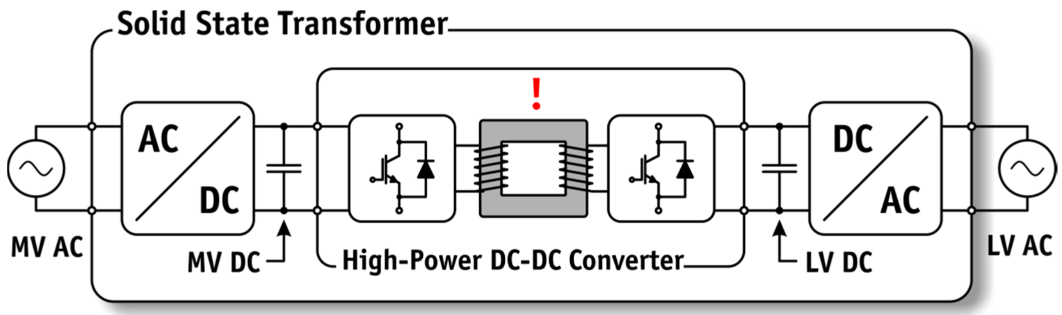
- Introduction to SST Concept
- Applications of SSTs
- Overview of SST Research since 2001
- Details on the MEGA Cube
- Conclusions / Outlook

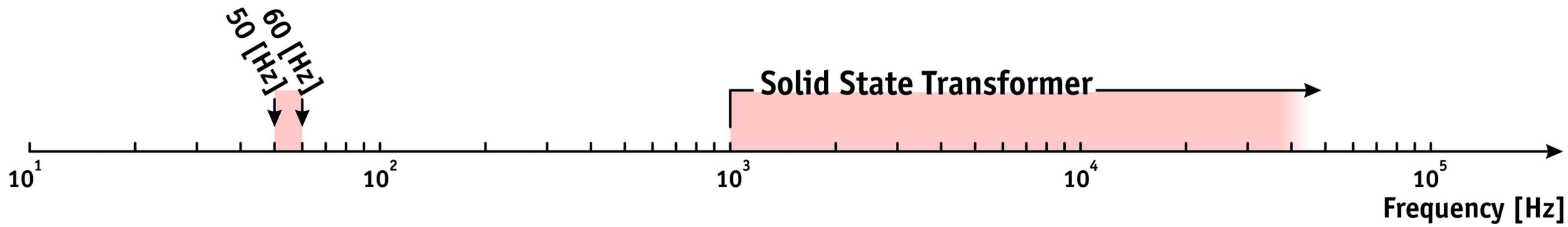
Introduction to
Solid State Transformer Concept

50/60 Hz Transformer

Solid State Transformer





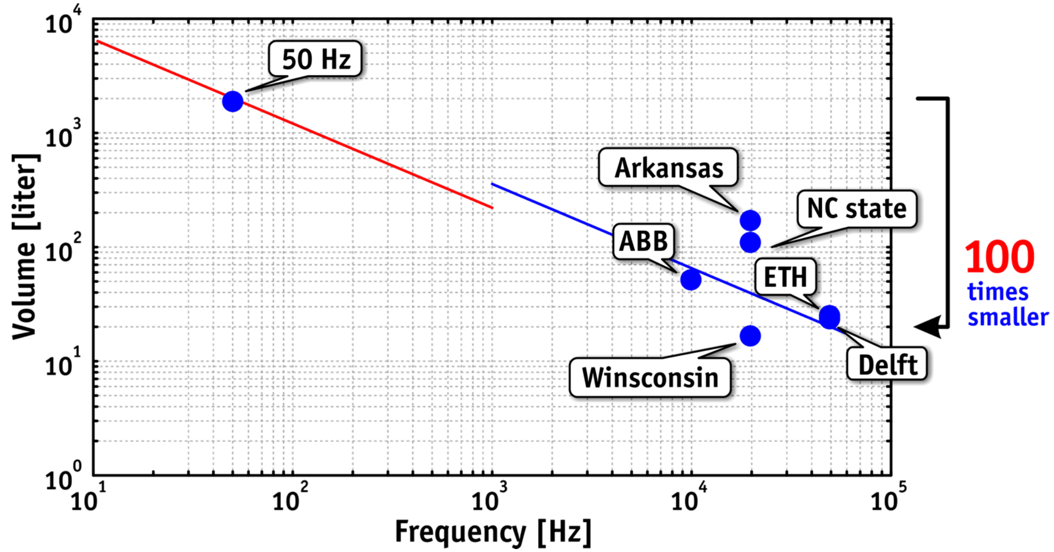


▲ 50/60Hz vs. SST Operating Frequencies in the kHz Range

Size/Weight Reduction

- ▶ Higher Operating Frequency Reduces Transformer Size/Weight

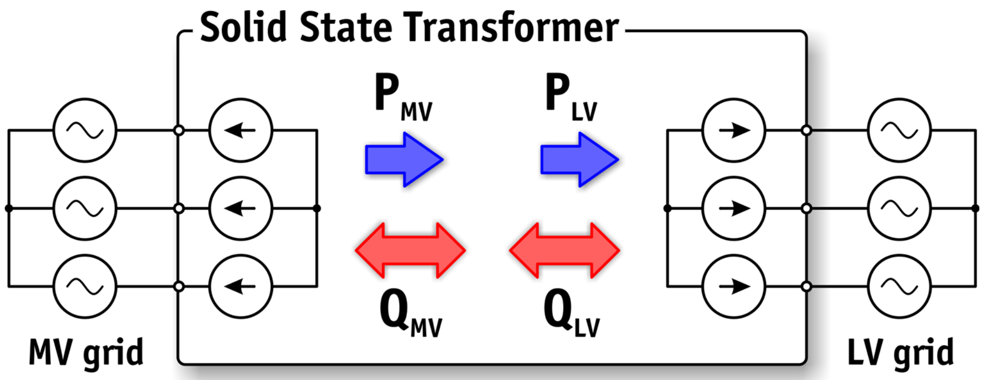
$$V_T \propto \frac{1}{\hat{B}} \cdot \frac{1}{f}$$



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

Reactive Power Control

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

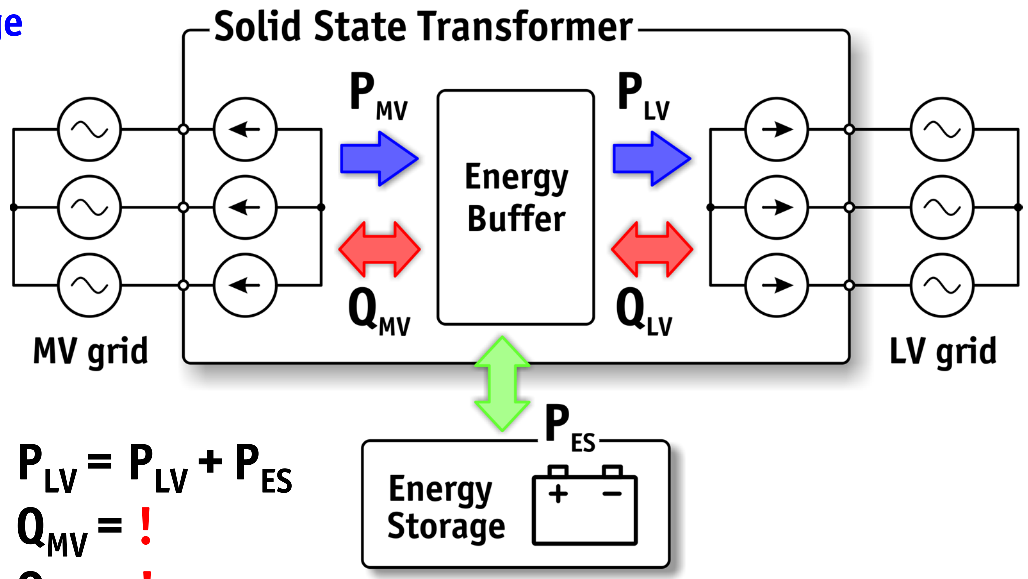


$P_{MV} = P_{LV}$
$Q_{MV} =$!
$Q_{LV} =$!

▲ SST providing Reactive Power Compensation

UPS Operation

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



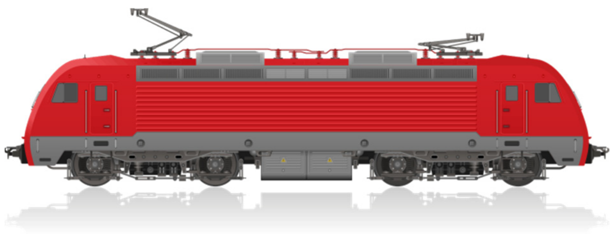
$P_{LV} = P_{LV} + P_{ES}$
$Q_{MV} = !$
$Q_{LV} = !$

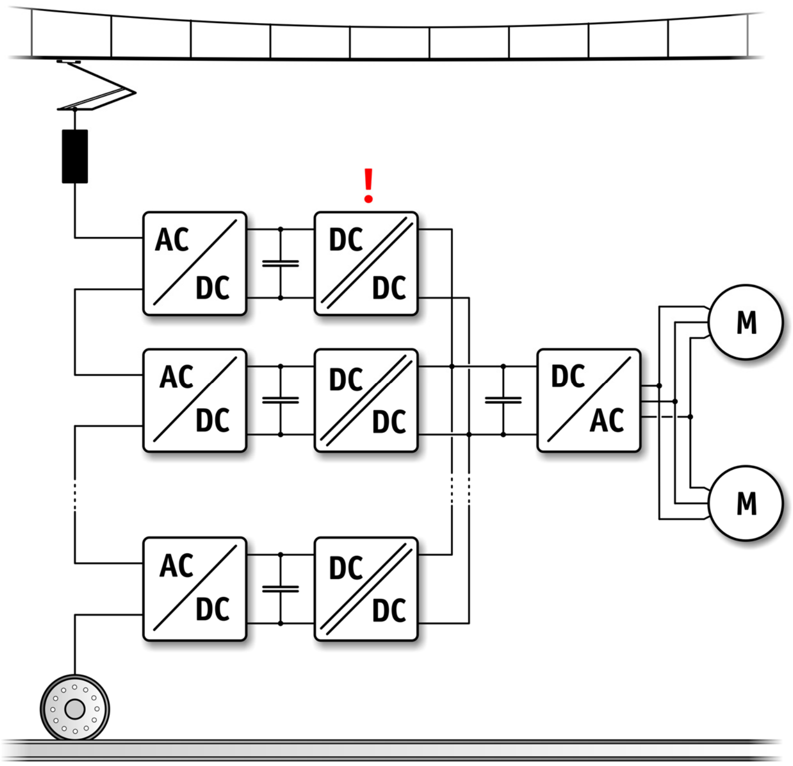
▲ SST Linked to Energy Storage System - providing UPS

Applications
of the Solid State Transformers

Traction / Locomotives

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

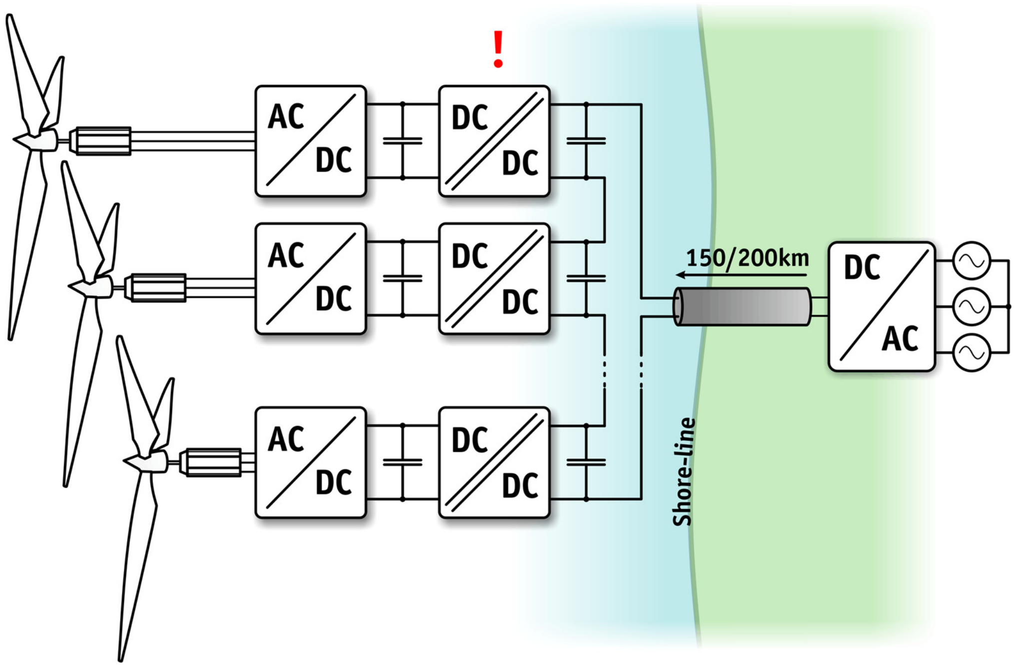




▲ SST Replacing the Input Transformer of a Locomotive

Wind Power

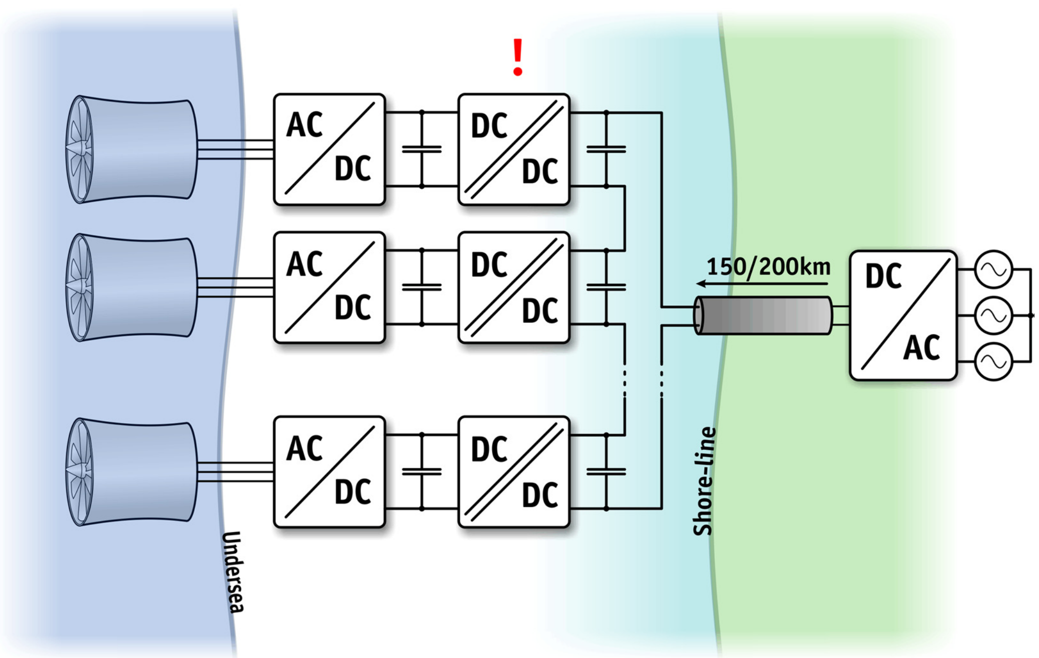
- Reduced Weight/Size
- Increased Efficiency of Power Transmission



▲ SST in Off-Shore Wind Farms

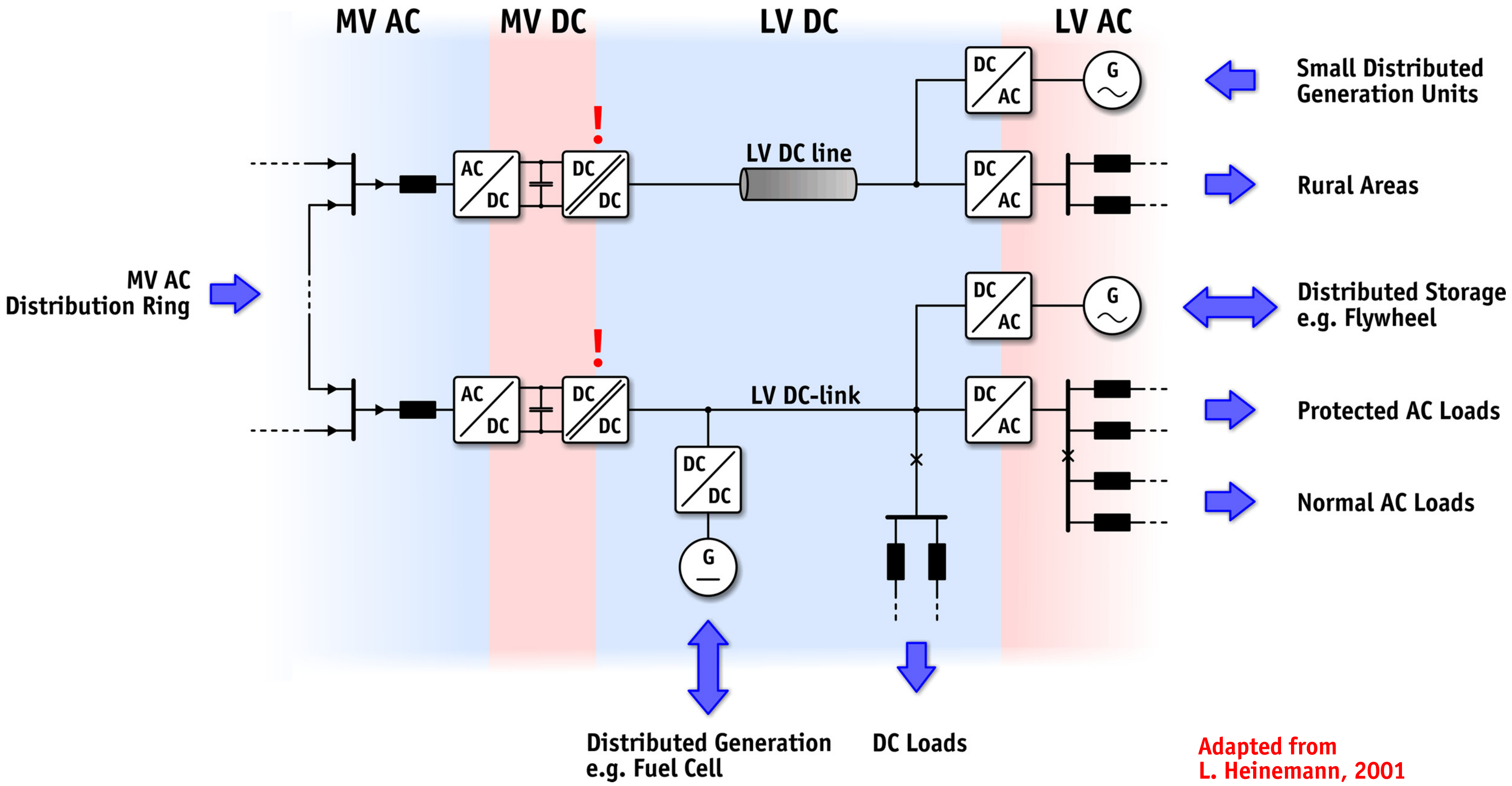
Tidal Power

- Reduced Weight/Size
- Increased Efficiency of Power Transmission



▲ SST in Tidal Power Plants

Smart Grid Scheme



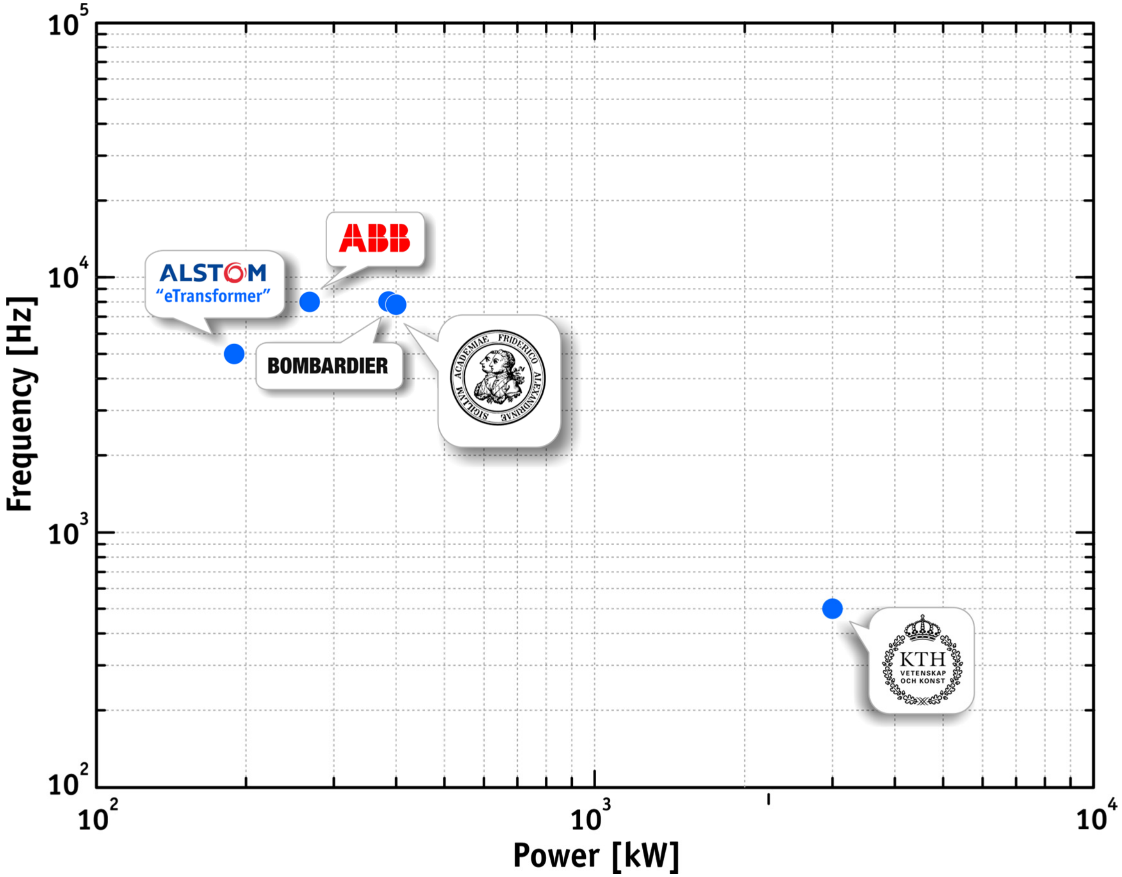
Adapted from
L. Heinemann, 2001

Overview of SST Research
over the last 10 years

Introduction to
The MEGA Cube

Traction Applications

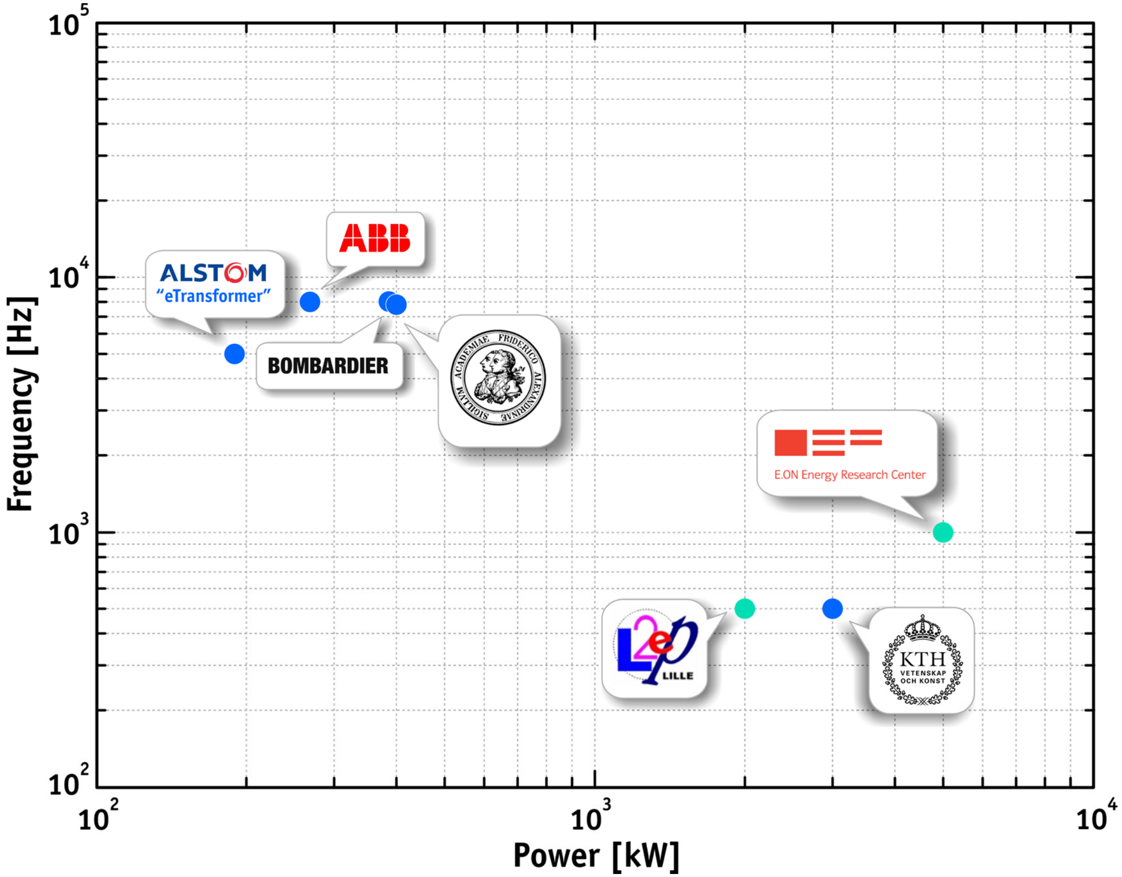
- 2001 ABB (ETH)
- 2007 Alstom
- 2007 Bombardier
- 2009 KTH
- 2010 Erlangen



SST Research over the Last 10 Years

Wind / Tidal Power

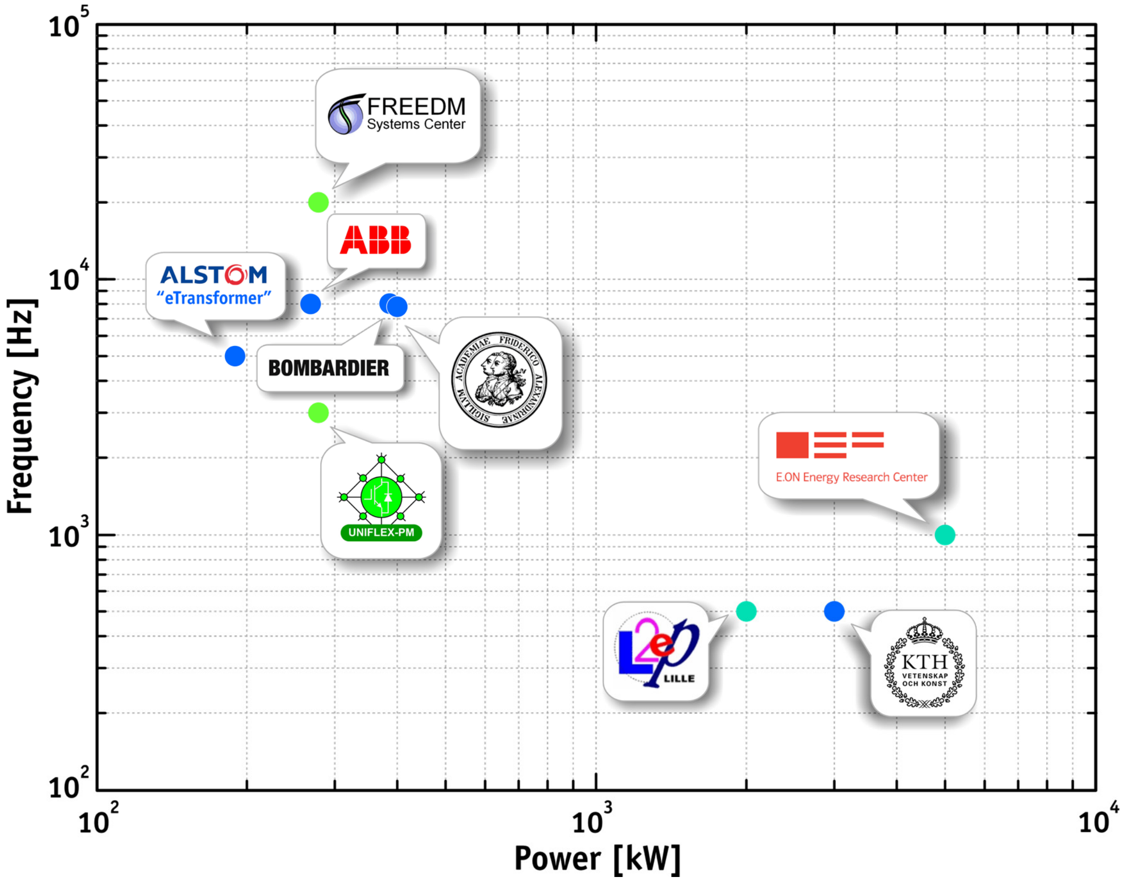
- 2009 Eon
- 2011 L.2.E.P.



SST Research over the
Last 10 Years

Smart Grids

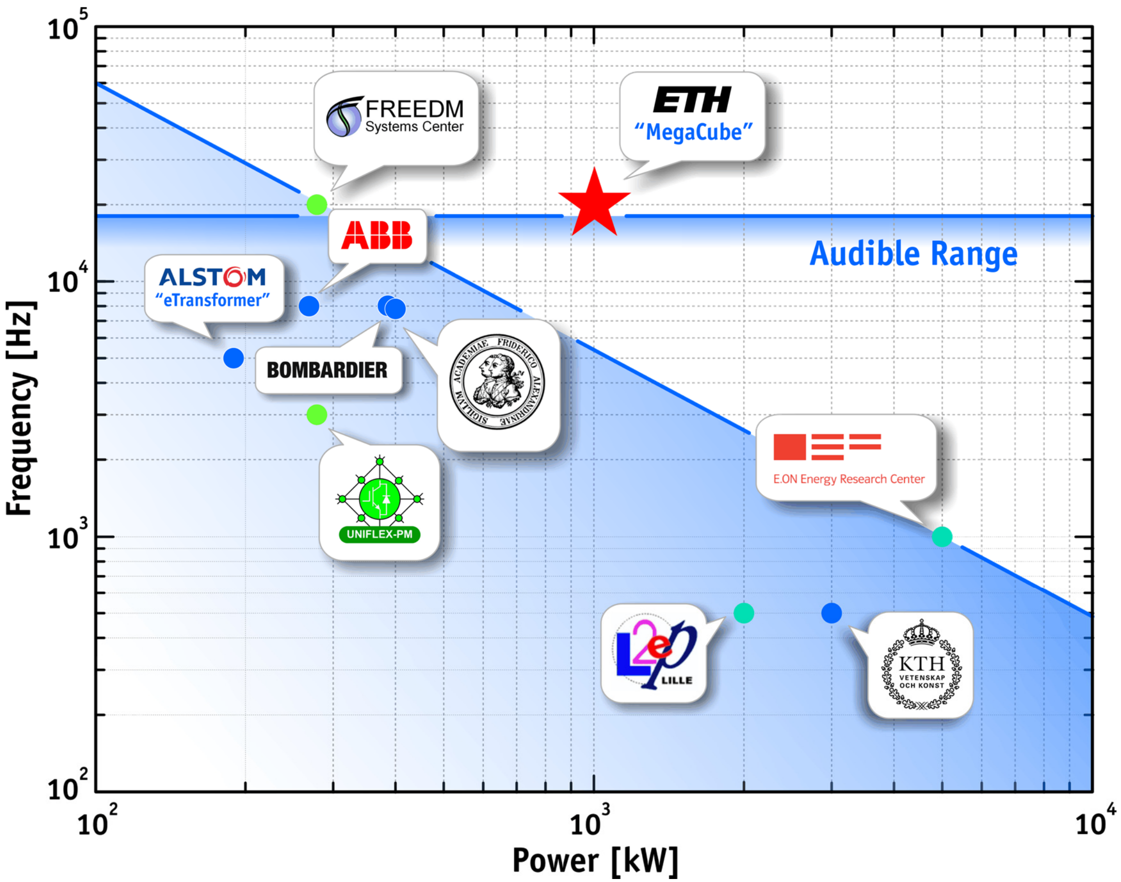
- ▶ 2006 UNIFLEX
- ▶ 2007 FREEDM



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

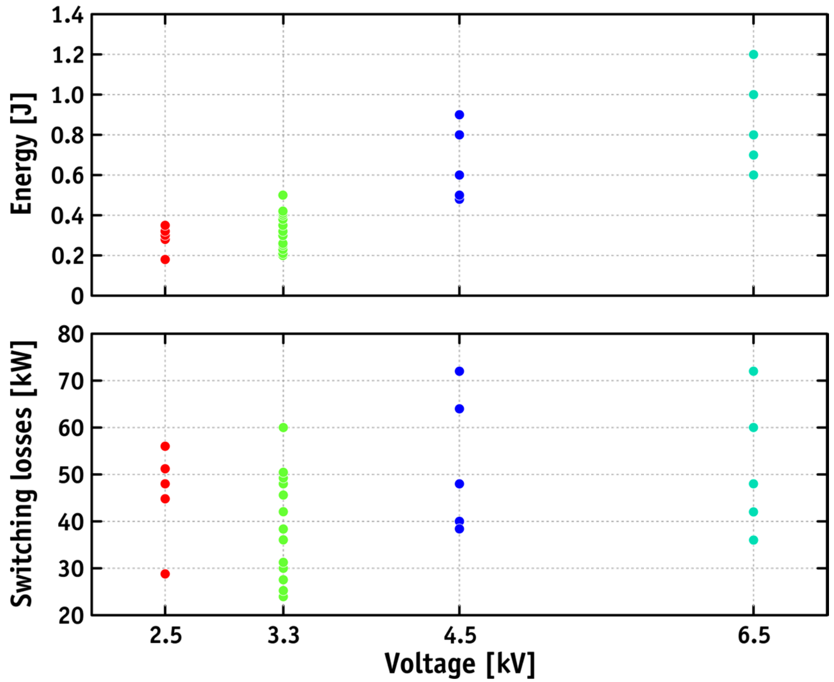
Details on
The MEGA Cube

Medium-Voltage Side
12kV - 20kHz

High-Voltage IGBTs

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

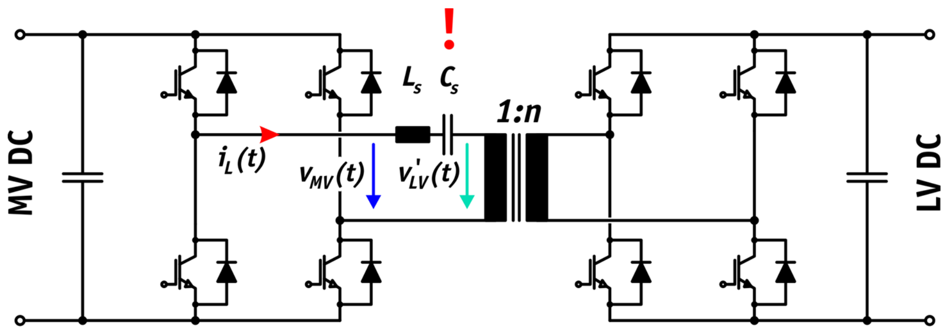
◀ 4.5 kV/150 A
ABB IGBT Module



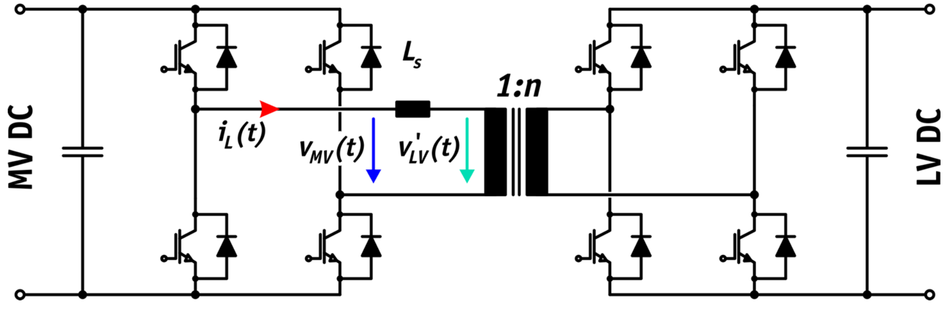
▲ 100 A Turn-Off Energies
▲ 100 A/20 kHz Switching Losses

Dual Active Bridge DC/DC Converter

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



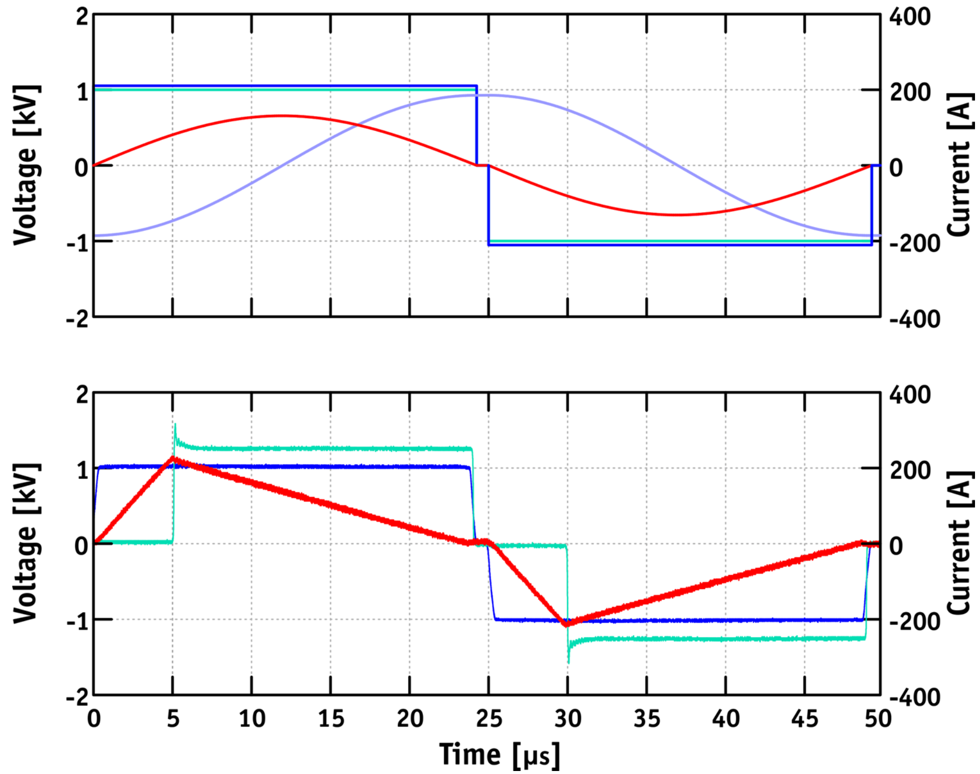
- **Triangular Current**
  - Only Inductor in Series with Transformer
  - High Switched Currents on LV Side



Resonant vs. Triangular Current DAB

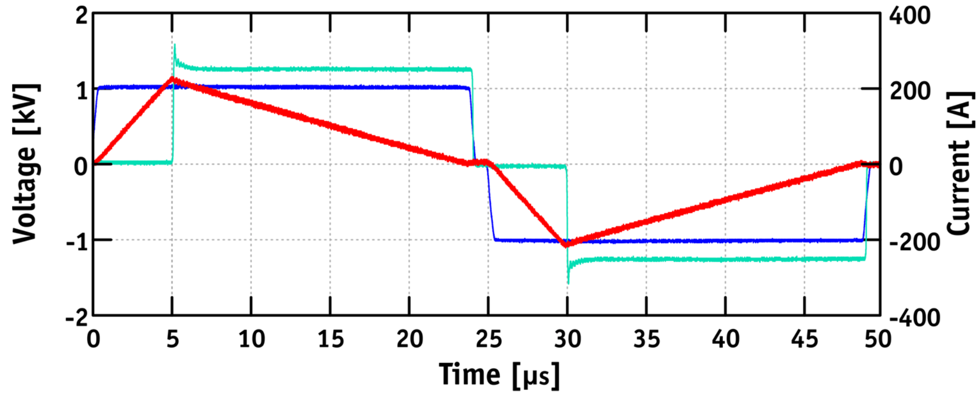
- **Resonant**
  - ZCS on LV and MV Sides
  - Low Controllability of Transferred Power

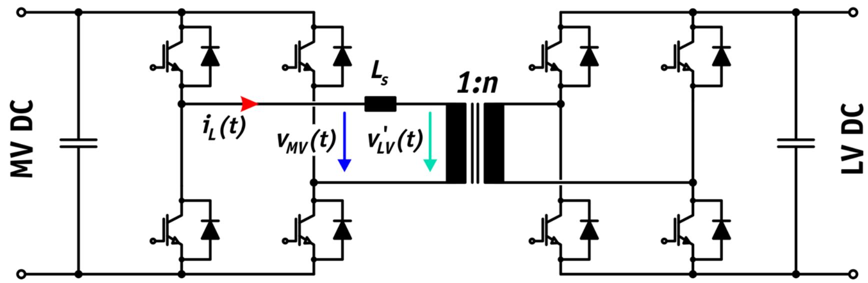
- **Triangular Current**
  - ZCS only on MV Side
  - Duty Cycle Power Flow Control



Triangular Current DAB

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

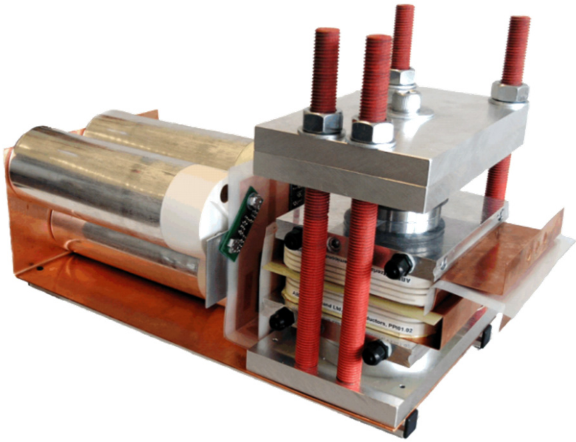


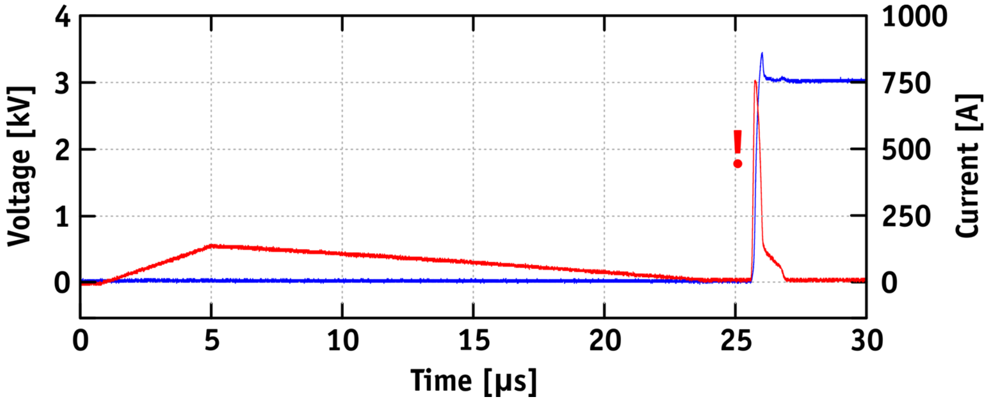


Shown for Power Transfer from MV to LV Side

MV Switch Realization - 4.5 kV IGBT

▶ Large Tail Current Despite ZCS



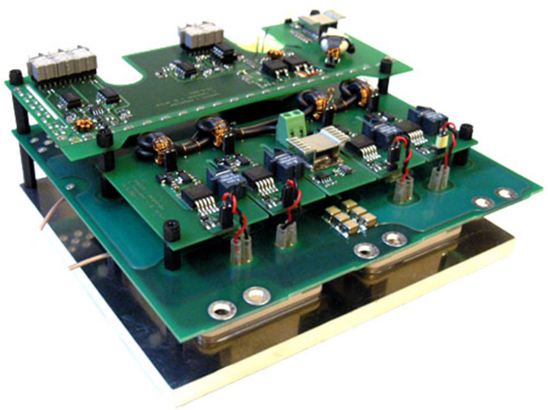


▲ 4.5kV Press-Pack IGBT Testbench

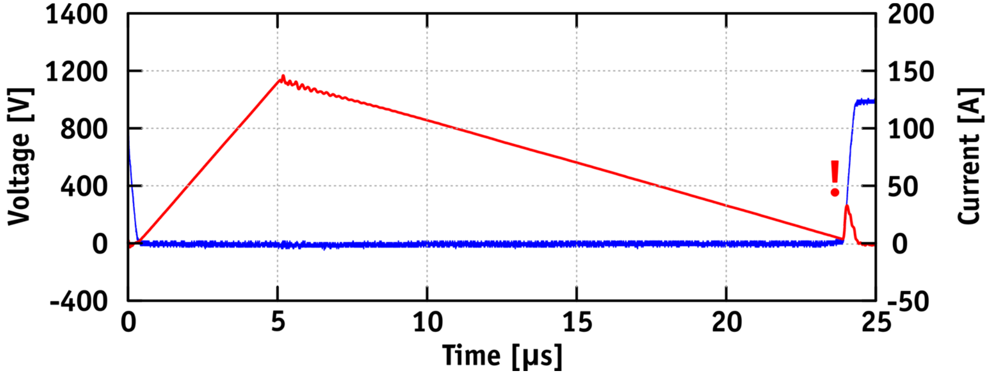
▲ ZCS Testing @ 3kV DC-Link 150A Peak

MV Switch Realization - 1.7 kV IGBT

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



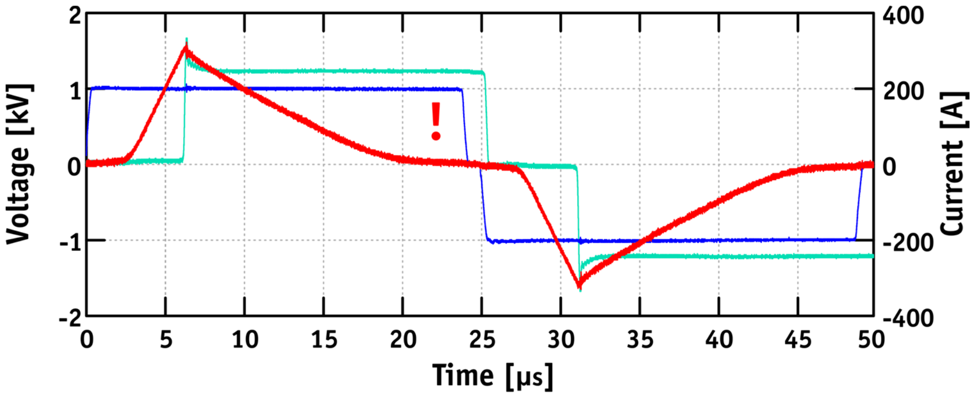
▲ 1.7kV PT IGBT NPC Module

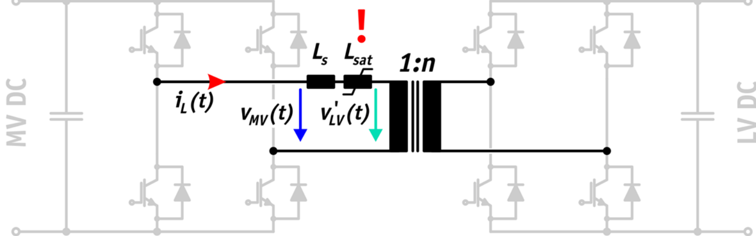


▲ ZCS Testing @ 1kV DC-Link 150A Peak

Enhancement - Saturable Inductor

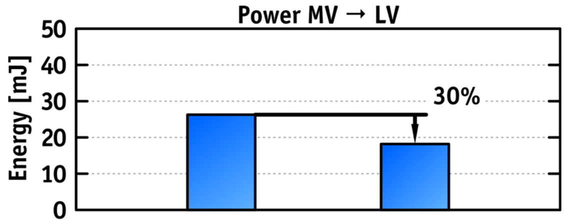
- Provides Time for Charge Carrier Recombination

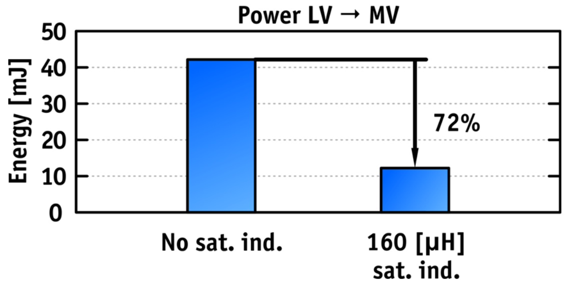


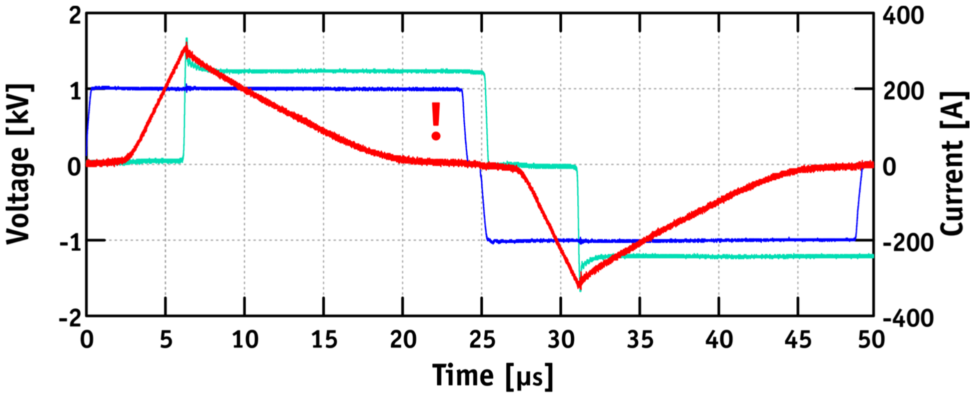


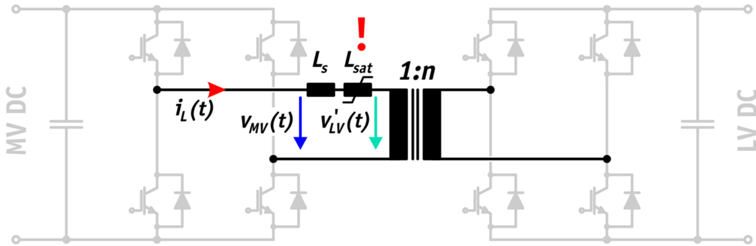
Enhancement - Saturable Inductor

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



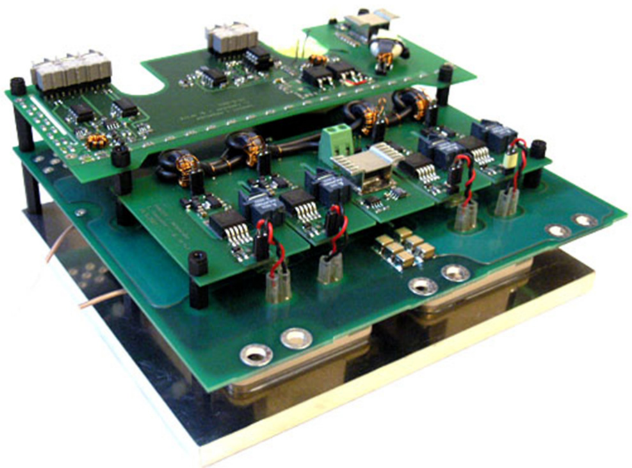




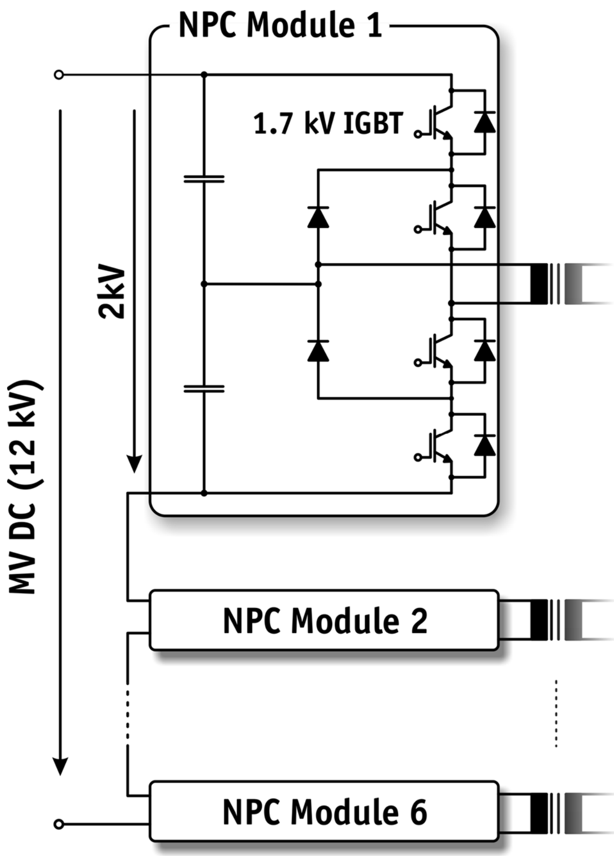


Modular MV Side

- 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

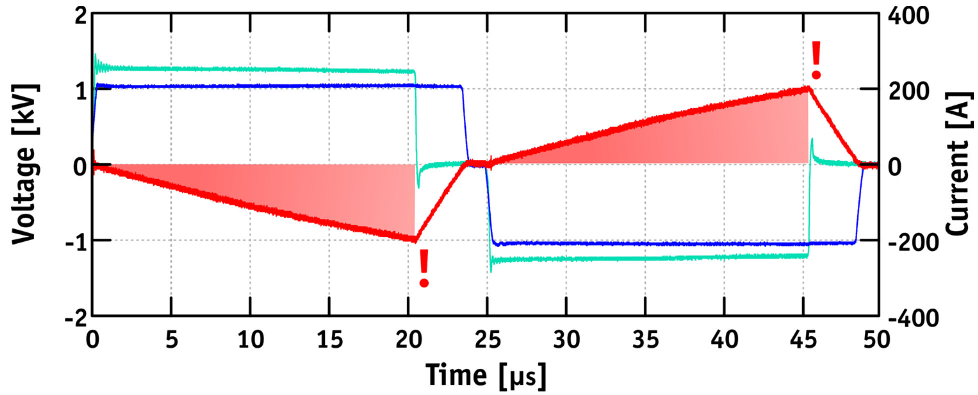
Details on

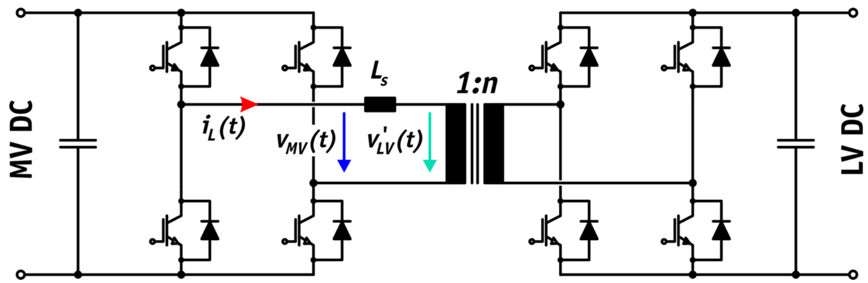
The MEGA Cube

Low-Voltage Side
1.2kV - 20kHz

DAB with Triangular Current

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

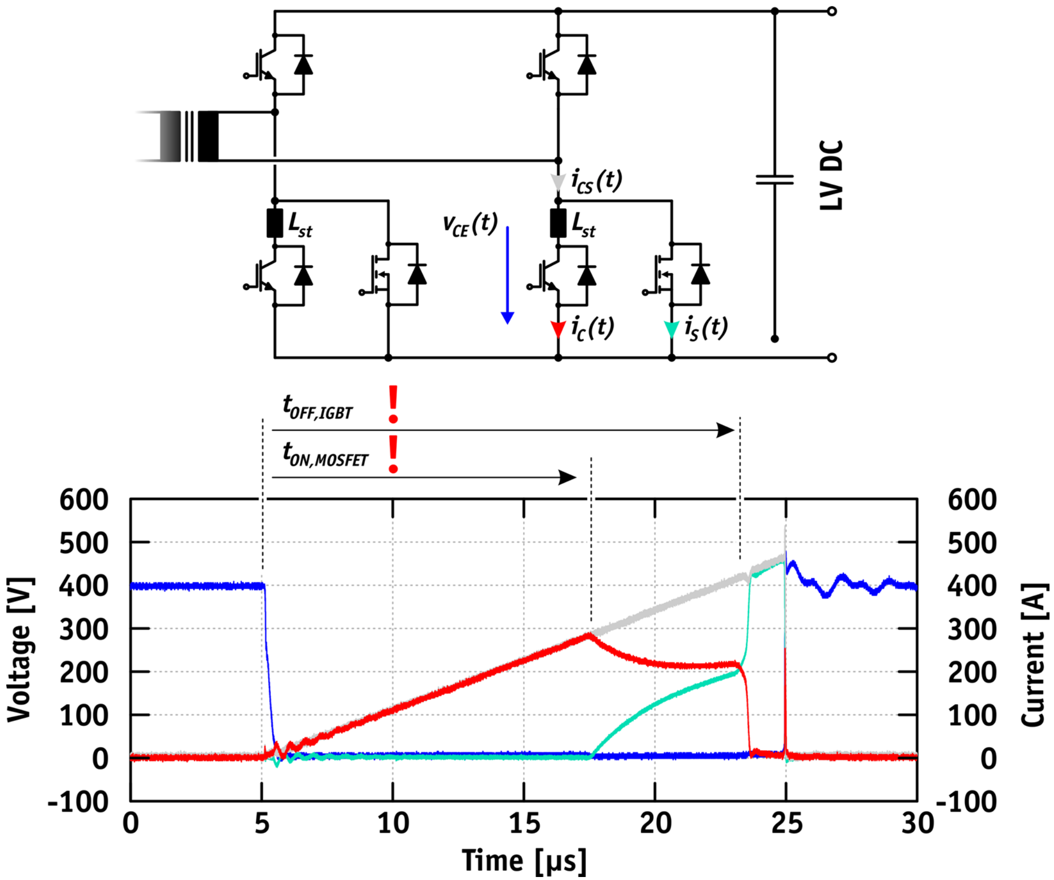




Shown for Power
Transfer from MV to LV Side

Hybrid LV Switch

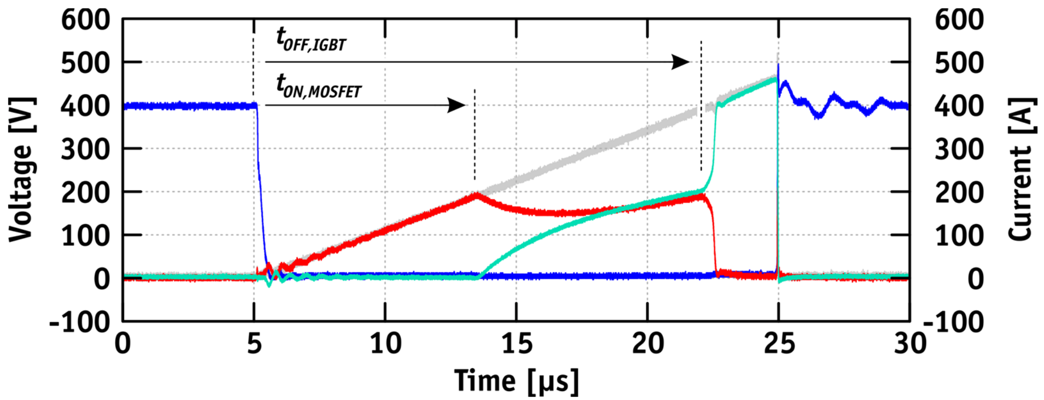
- **Low Conduction Losses → IGBT**
- **Low Switching Losses → MOSFET**

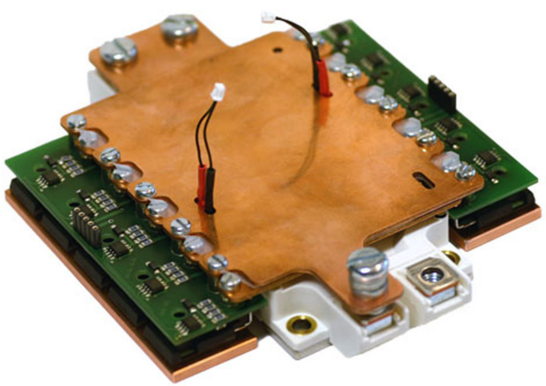


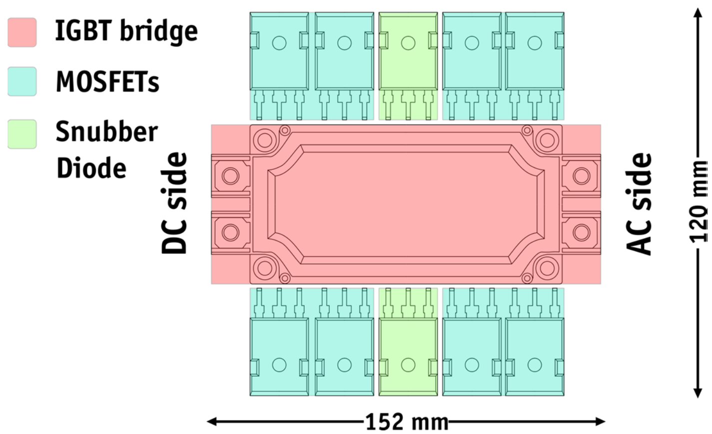
Circuit Schematic and Waveforms of LV Side Hybrid MOSFET/ IGBT Full-Bridge

Module-Based Hybrid Switch

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





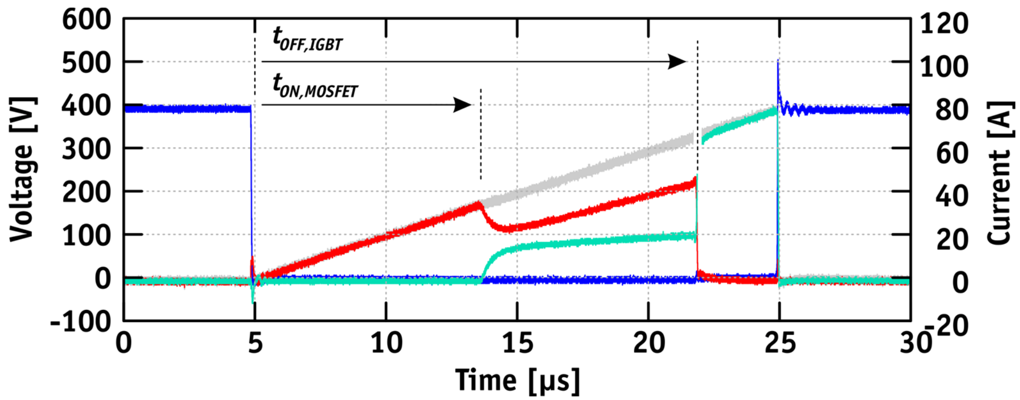


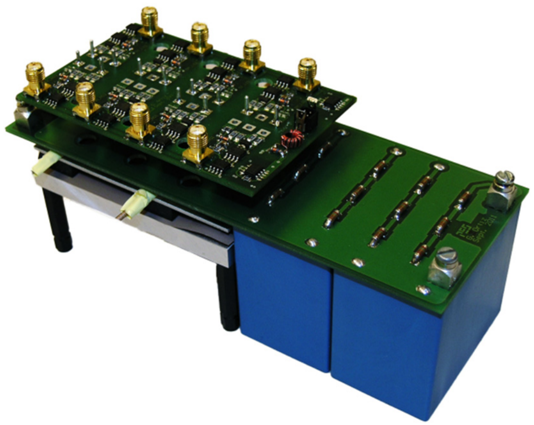
▲ Hybrid Switch Based on IGBT Bridge Leg Module

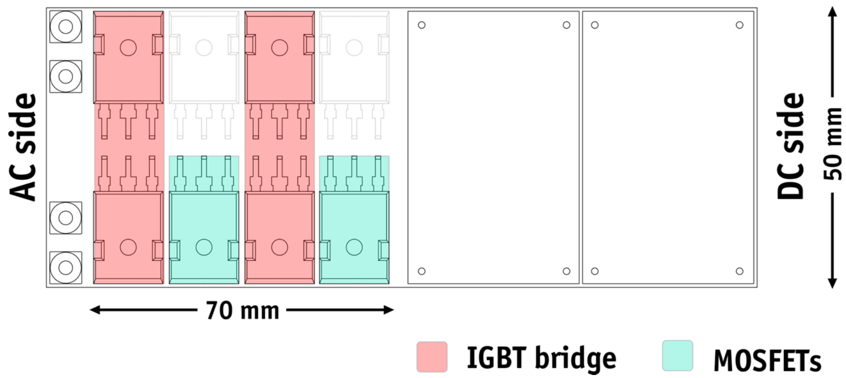
▲ Hybrid Switch Layout and Waveforms; $t_{ON,MOSFET}$ = 8us / $t_{OFF,IGBT}$ = 17us

Interleaved Hybrid Switch

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





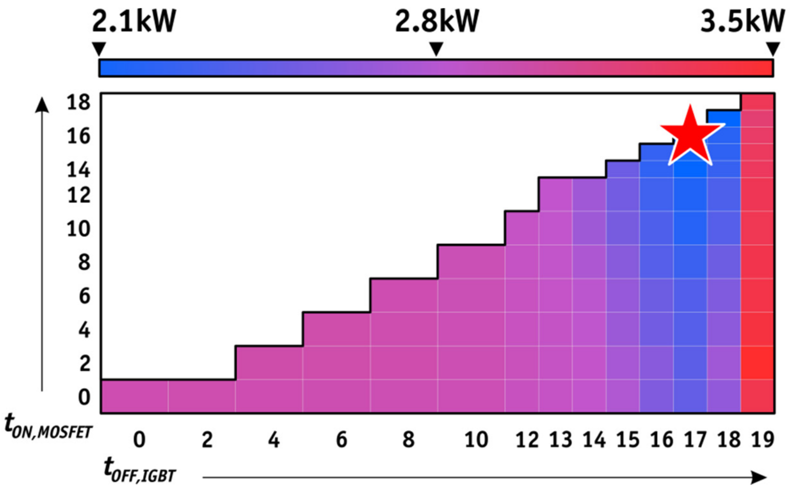


▲ Testbench for Interleaved Hybrid Switch

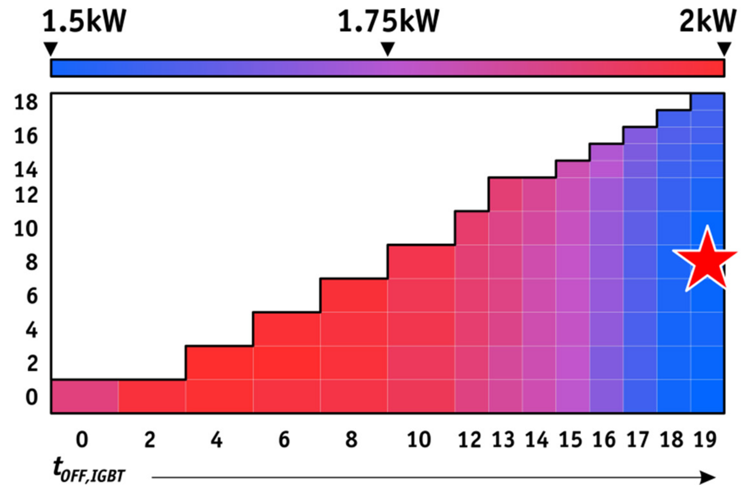
▲ Hybrid Switch Layout and Waveforms; $t_{ON,MOSFET}$ = 8us / $t_{OFF,IGBT}$ = 17us

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



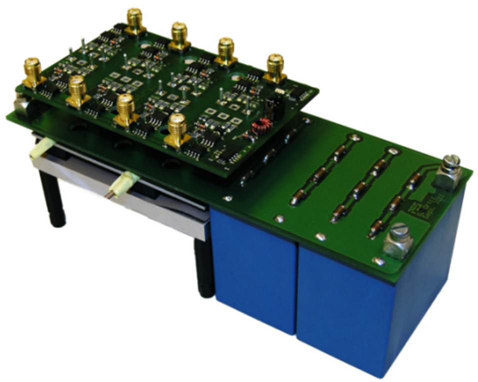
▲ Module-Based Full-Bridge Total Losses (Conduction and Switching)



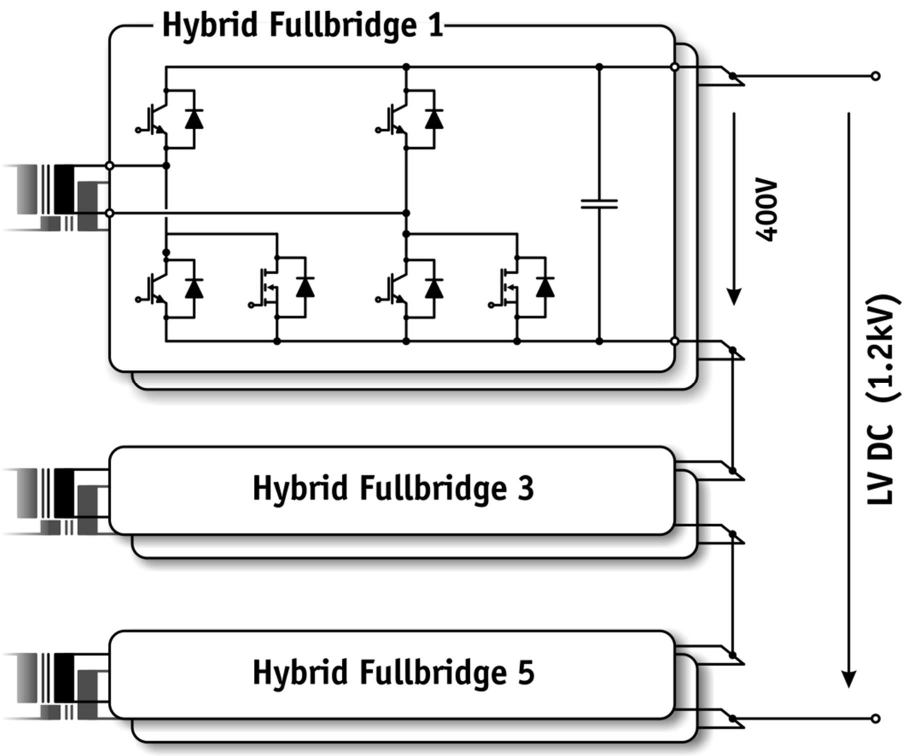
▲ Interleaved Full-Bridge Total Losses (Conduction and Switching)

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

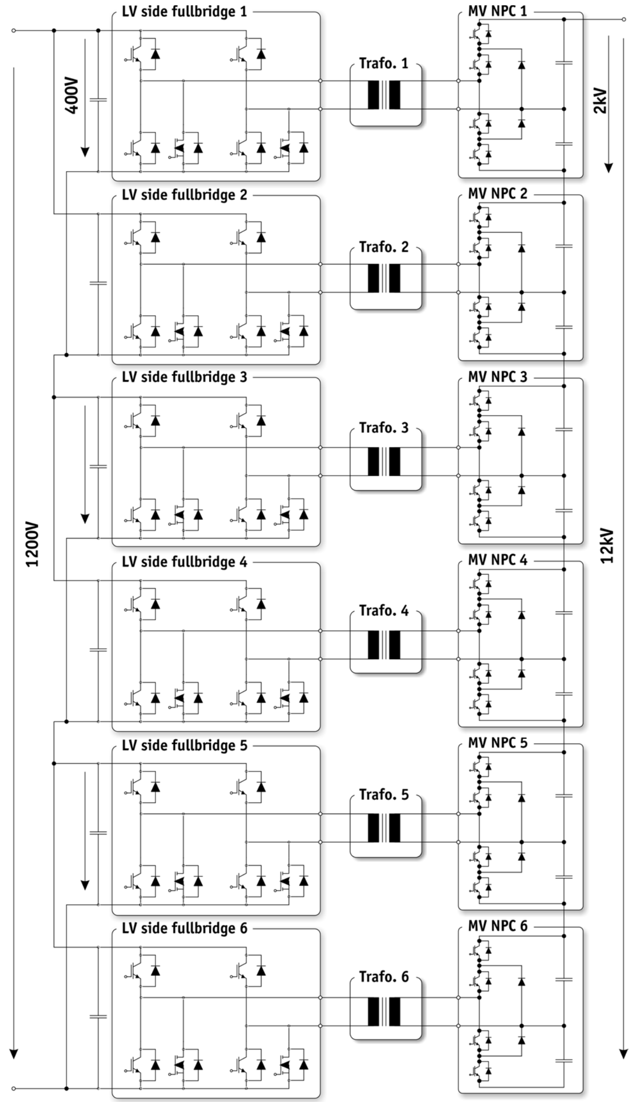
Module 2

Module 3

Module 4

Module 5

Module 6

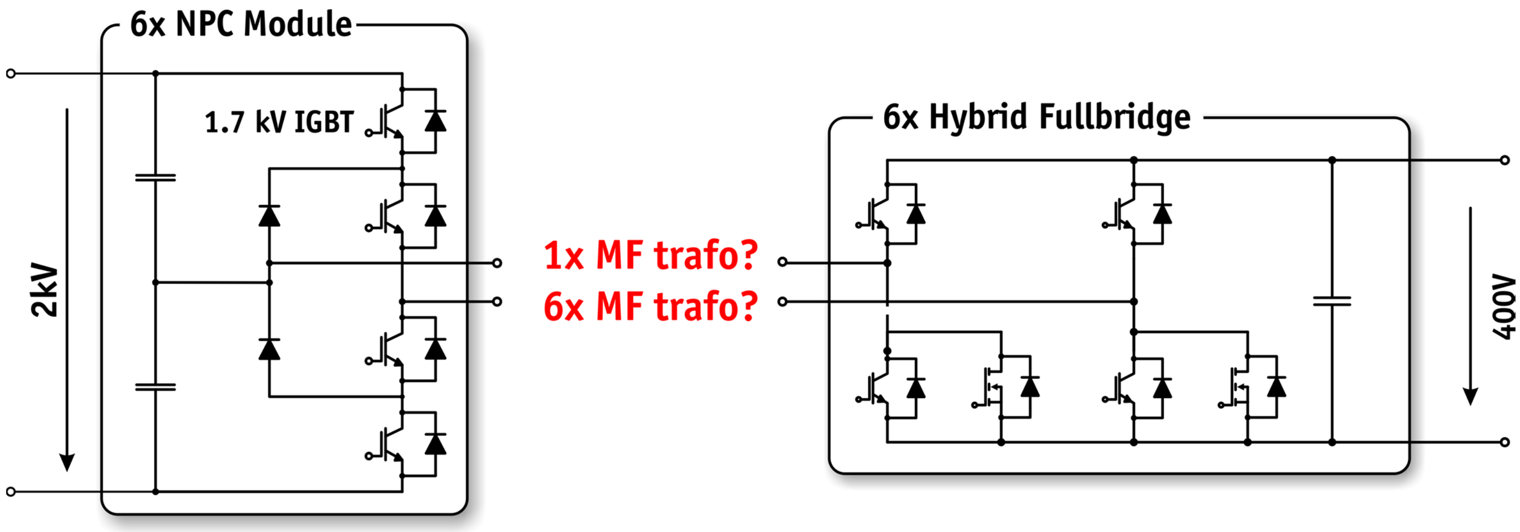


Details on
The MEGA Cube

Transformer
20kHz

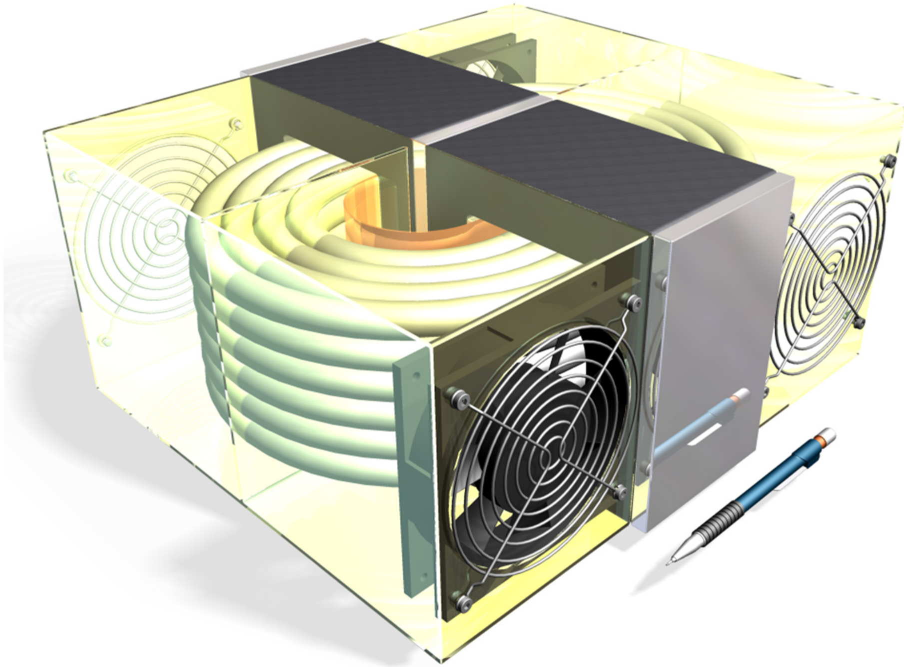
How Many MF Transformers?

▶ 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

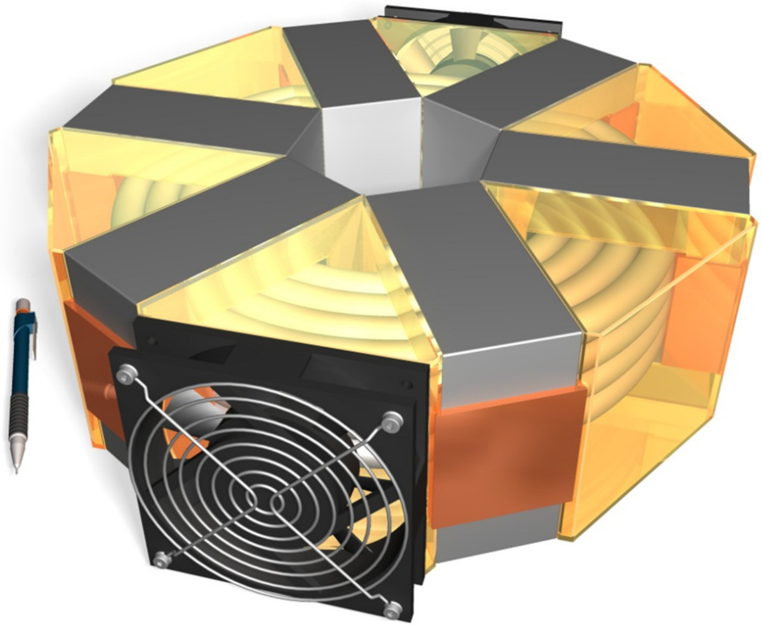


- **E-Shape Based on Magnetic Core**

- 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



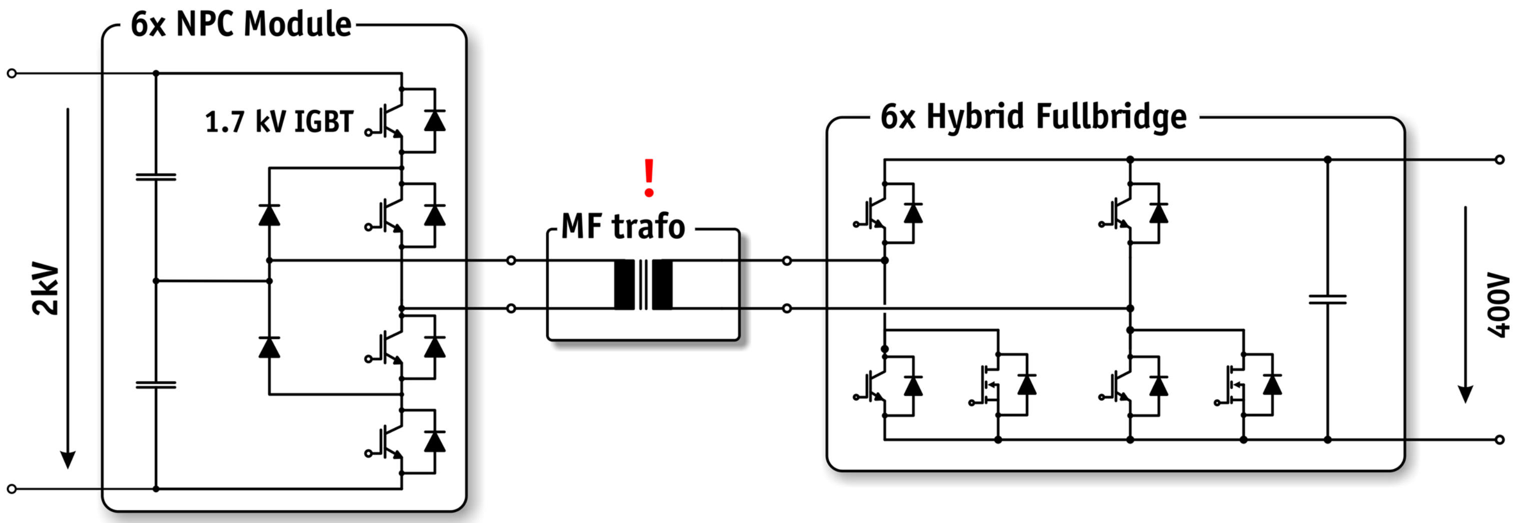
- Several Cores / Each Realizing a Transformer
- Realization of the Turns Ratio Through Parallel/ Series Connection

- 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



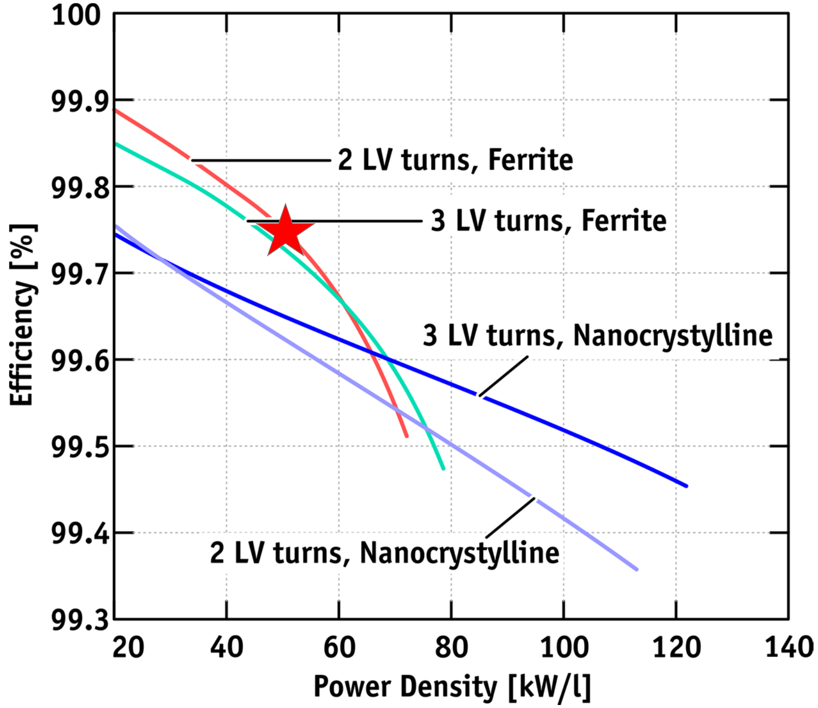
▲ Block Diagram of High-Power DC-DC Converter Utilizing Modular LV and MV Converters

Transformer Optimization

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

- Selected Design:

- 2 Turns LV Winding
- Stacked Ferrite Cores

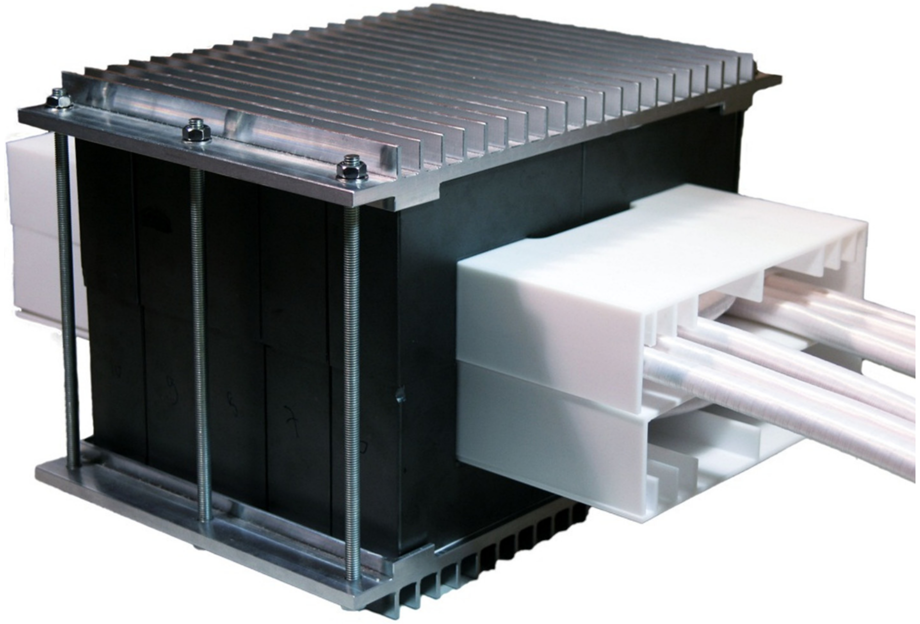


Power Density vs. Efficiency Pareto Front of the 166kW Transformer

Assembled Transformer

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

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

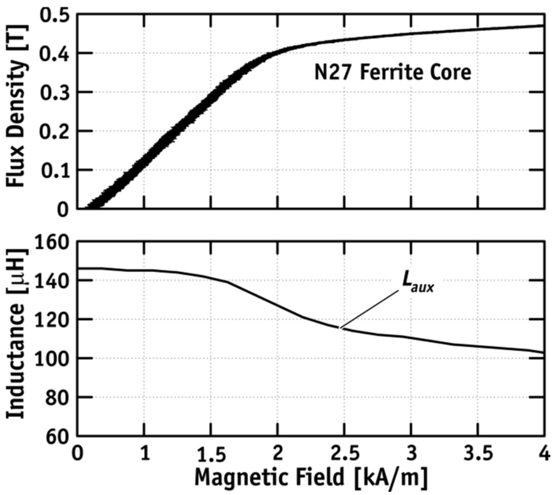


166kW / 20kHz Transformer

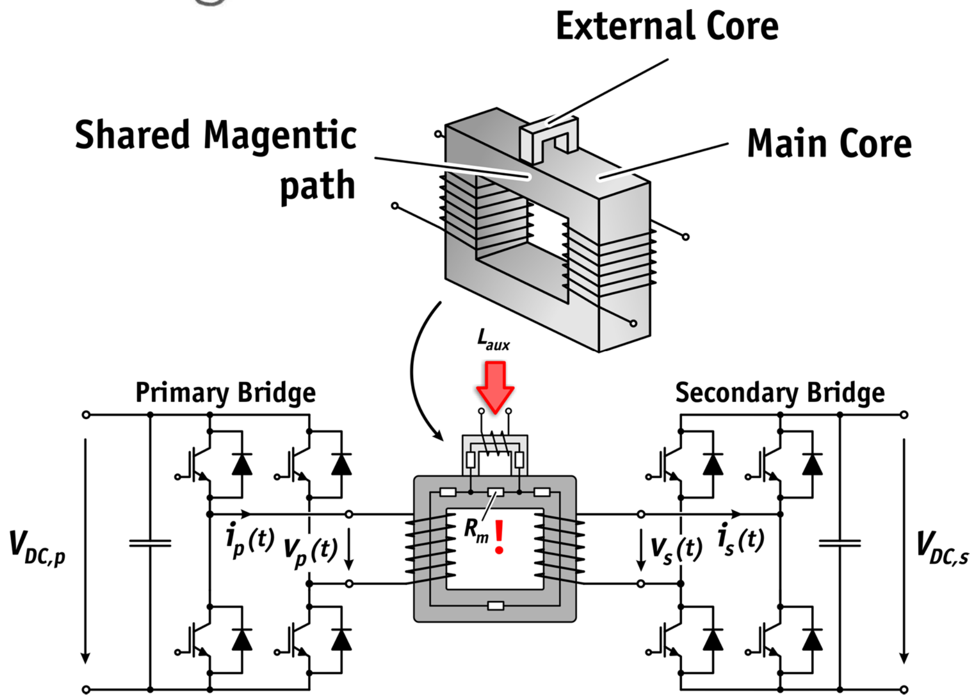
Preventing Core Saturation

- **Flux Density Transducer – Magnetic Ear**

**Shared Magnetic Path between
Main and Auxiliary core**



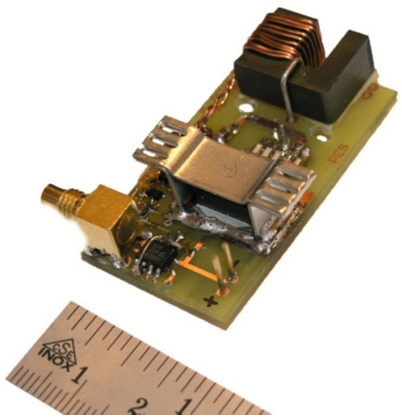
▲ Measured External Core Inductance

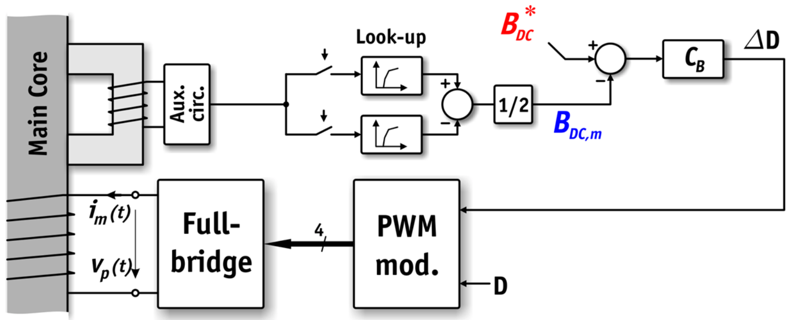


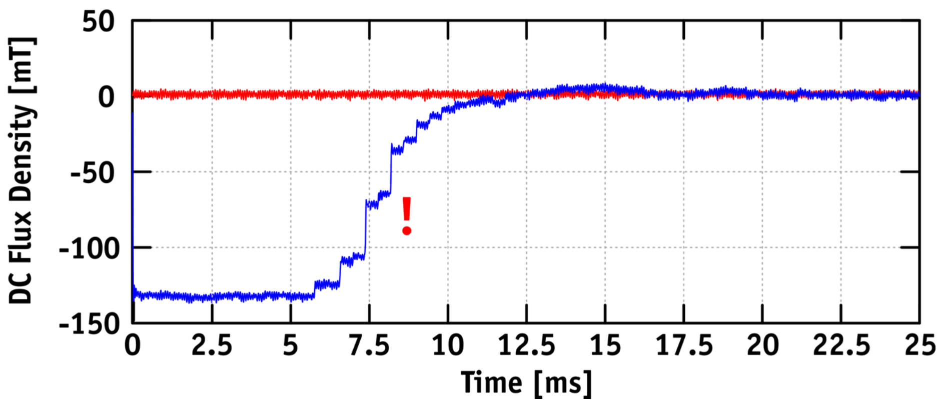
▲ Magnetic Ear Concept

Magnetic Ear

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







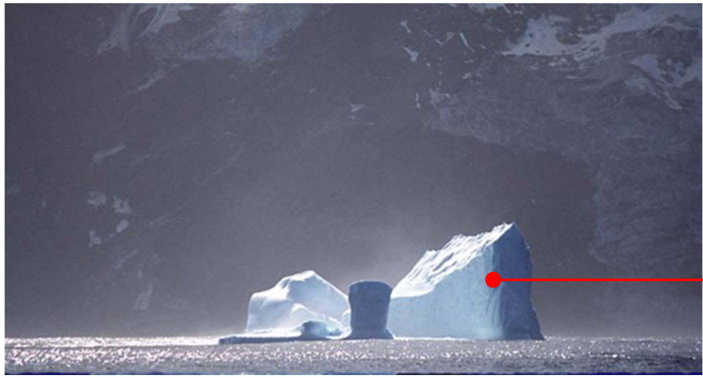
Conclusions / Outlook

Conclusions

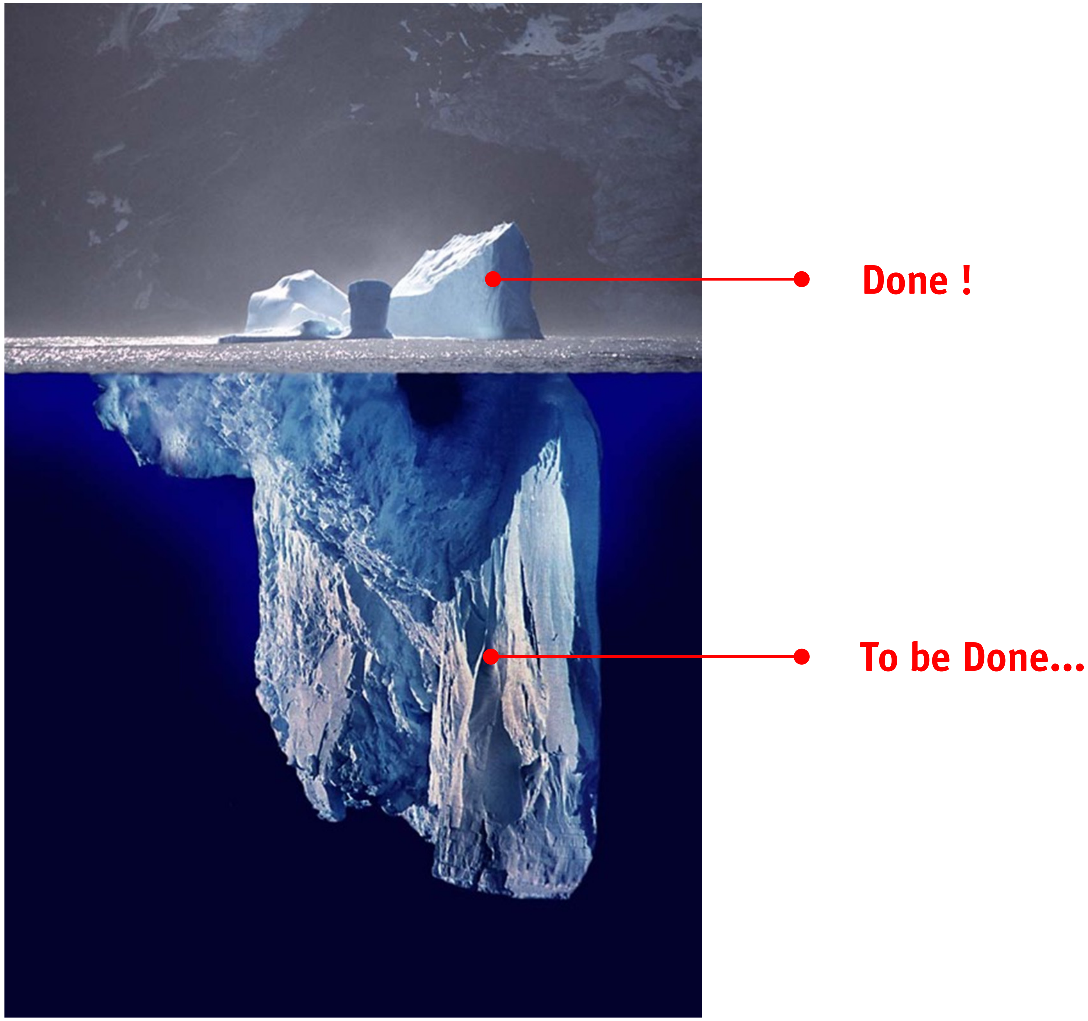
- SST Technology Attractive for Traction / Renewable Energy / Smart Grids
- High-Power MF DC-DC Converters are a Key Component for SSTs

- 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?