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

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The MEGA Cube Project

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PES Research Scope

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

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

Electromagnetic Actuators
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

\[ P_0 = 10 \text{ kW} \]
\[ U_N = 230V_{\text{AC}} \pm 10\% \]
\[ f_N = 50\text{Hz} \text{ or } 360...800\text{Hz} \]
\[ U_O = 800V_{\text{DC}} \]

\[ f_P = 250\text{kHz} \]

- Si CoolMOS
- SiC Diodes

\[ \eta = 96.2\% \text{ @ } P_0 \]
\[ THD_I = 1.6\% \text{ @ } P_0 \]
\[ \gamma = 3\text{kW/kg} \]

★ 10kW/dm³ Power Density
Mains Behavior @ 400 Hz/800 Hz

\[ P_O = 10\text{kW} \]
\[ U_N = 230\text{V} \]
\[ f_N = 400\text{Hz} \]
\[ U_O = 800\text{V} \]
\[ THD_i = 1.4\% \]

\[ P_O = 10\text{kW} \]
\[ U_N = 230\text{V} \]
\[ f_N = 800\text{Hz} \]
\[ U_O = 800\text{V} \]
\[ THD_i = 1.6\% \]
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

World Record!
100W @ 1’000’000 rpm

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

Performance Space

Design Space

Mapping of Design Space into System Performance Space
Technology Sensitivity Analysis
Based on $\eta$-$\rho$-Pareto Front

- Sensitivity to Technology Advancements
- Trade-off Analysis

![Diagram of Design Space and Performance Space](image)

Design Space  Performance Space
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]

100 times smaller
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

\[
P_{LV} = P_{LV} + P_{ES}
\]
\[
Q_{MV} = \frac{}{}
\]
\[
Q_{LV} = \frac{}{}
\]

▲ 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
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

![Graph showing energy reduction with saturable inductor](image_url)

- Power MV → LV
  - No sat. ind.: 50 [J]
  - 160 [μH] sat. ind.: 30% reduction

- Power LV → MV
  - No sat. ind.: 50 [J]
  - 160 [μH] sat. ind.: 72% reduction

![Diagram of power electronic system](image_url)
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 $\rightarrow$ IGBT
- Low Switching Losses $\rightarrow$ 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; $t_{ON,MOSFET} = 8\text{us}$ / $t_{OFF,IGBT} = 17\text{us}$
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; $t_{ON,MOSFET} = 8\, \mu s$ / $t_{OFF,IGBT} = 17\, \mu s$
Module-based vs. Interleaved Hybrid Switch

- Total Losses for a 166 kW Full-Bridge
- Mesh with Different $t_{\text{ON, MOSFET}}$ and $t_{\text{OFF, IGBT}}$ 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/dm³
Preventing Core Saturation

- **Flux Density Transducer – Magnetic Ear**

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

  ![Diagram](image)

  **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?