Solid-State-Transformer (SST) Applications - A Glimpse Into the Future

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Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

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ETH Zurich

Departments

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21 Nobel Prizes
530 Professors
6100 T&R Staff
2 Campuses
136 Labs
35% Int. Students
90 Nationalities
36 Languages
150th Anniv. in 2005

Students ETH in total

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ETH zürich
ITET – Research in E-Energy

- Power Systems
- Advanced Mechatronic Systems
- Power Semiconductors
- Power Electronic Systems
- High Power Electronics
- High Voltage Technology

► Balance of Fundamental and Application Oriented Research
Power Electronic Systems Laboratory

Industry Relations
R. Coccia / B. Seiler

Johann W. Kolar

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter
M. Heller
Y. Li
D. Menzi
D. Neumayr
D. Zhang

AC-AC Converter
J. Azurza
P. Czyz
M. Haider

DC-DC Converter
P. Bezerra
T. Guillod
G. Knabben
J. Schäfer

DC-AC Converter
D. Bortis
M. Antivachis
J. Böhler
M. Guacci

Multi-Domain Modeling
F. Krismer
P. Papamanolis

Measurement Technology
P. Niklaus

Advanced Mechatronics
D. Bortis

Magnetic Levitation
D. Bortis

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

22 Ph.D. Students
1 PostDoc
2 Sen. Researchers

Leading Univ. in Europe
Outline

► SST Origins
  ▪ Traction
  ▪ Smart Grids

► Key Characteristics

► MEGATRENDS → Future SST Application Areas
  ▪ Datacenter
  ▪ Smart Cities / Buildings
  ▪ High Power EV Charging
  ▪ More Electric/Hybrid Aircraft
  ▪ More Electric/Hybrid Ships
  ▪ Renewable Energy – Wind / Solar
  ▪ Deep Sea Exploration etc.

► Key Topologies

► Industry / ETH Demonstrators

► Conclusions

Acknowledgement: D. Rothmund
SST Origins

*Next Generation Traction Vehicles*
Classical Locomotives

- **Catenary Voltage**: 15kV or 25kV
- **Frequency**: 16²/₃Hz or 50Hz
- **Power Level**: 1…10MW typ.

Transformer:
- **Efficiency**: 90…95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
- **Current Density**: 6 A/mm² (2A/mm² typ. Distribution Transformer)
- **Power Density**: 2…4 kg/kVA (0.5…0.25 kVA/kg)

Source: www.abb.com
Passive Transformer

- **Magnetic Core Cross Section**
  \[ A_{\text{Core}} = \frac{1}{\sqrt{2\pi}} \frac{U_1}{\hat{B}_{\text{max}}} \frac{1}{f} N_1 \]

- **Winding Window**
  \[ A_{\text{Wdg}} = \frac{2I_1}{k_w J_{\text{rms}}} N_1 \]

- **Construction Volume**
  \[ A_{\text{Core}} A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_w J_{\text{rms}} \hat{B}_{\text{max}}} f \sim L^4 \]

- **Symbols**
  - \( P_t \): Rated Power
  - \( k_w \): Window Utilization Factor
  - \( \hat{B}_{\text{max}} \): Flux Density Amplitude
  - \( J_{\text{rms}} \): Winding Current Density
  - \( f \): Frequency

- **Trade-off**
  - Low Frequency \( \rightarrow \) Large Weight / Volume
  - Trade-off \( \rightarrow \) Volume vs. Efficiency
Next Generation Locomotives (1)

- Trends
  * Distributed Propulsion System → Volume Reduction (Decreases Efficiency)
  * Energy Efficient Rail Vehicles → Loss Reduction (Requires Higher Volume)
  * Red. of Mech. Stress on Track → Mass Reduction

AC Catenary (15kV, 16⅔Hz or 25kV, 50Hz)

![Conventional AC-DC conversion with a line frequency transformer (LFT).](image)

Replace LF Transformer with **MF Transformer & Power Electronics Interface** → SST

Medium-Frequency Allows **Reduction of Volume & Losses**

AC Catenary (15kV, 16⅔Hz or 25kV, 50Hz)

![AC-DC conversion with medium frequency transformer (MFT).](image)
Next Generation Locomotives (2)

- Loss Distribution of Conventional & Next Generation Locomotives

- MF Provides Degree of Freedom → Reduction of Volume & Losses (!)
SST Motivation

*Future Smart EE Distribution*

Source: TU Munich
**Advanced (High Power Quality) Grid Concept**

- Heinemann / ABB (2001)

- MV AC Distribution with DC Subsystems (LV and MV) and Distributed AC & DC Sources /Loads
- MF AC/AC Conv. with DC Link Coupled to Energy Storage provide High Power Qual. for Spec. Customers
Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

- Huang et al. (2008)

- SST as Enabling Technology for the “Energy Internet”
  - Full Control of the Power Flow
  - Integr. of DER (Distr. Energy Res.)
  - Integr. of DES (Distr. E-Storage) + Intellig. Loads
  - Protects Power Syst. From Load Disturbances
  - Protects Load from Power Syst. Disturbances
  - Enables Distrib. Intellig. through COMM
  - etc.
  - etc.

- Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonomous Cntrl
3-Φ AC vs. DC Power Systems

- DC Voltage Ensures Max. Utiliz. of Isol. Voltage → Highest Voltage RMS Value / Lowest Current (!)
- Quadratic Dependency of Losses on Voltage Level → Reduction of Conductor Cross Section

\[
P_{V,AC} = 3 \cdot \left( \frac{1}{3} \frac{P}{U_{AC}} \right)^2 \cdot R_L
\]

\[
P_{V,DC} = 2 \cdot \left( \frac{P}{2U_{DC}} \right)^2 \cdot R_L
\]

\[
\frac{P_{V,DC}}{P_{V,AC}} = \frac{3}{2} \cdot \left( \frac{U_{AC}}{U_{DC}} \right)^2 \quad \text{if} \quad U_{DC} = \sqrt{2} U_{AC} = 0.75
\]

- DC Voltage Level Transformation Requires Power Electronics Interfaces
- DC Fault Current Clearing is Challenging (Missing Regular Current Zero Crossing)
**AC vs. DC Power Transmission**

- **AC Cable** – Thermal Limit Due to Cap. Current @ $L = 0$

- **HVDC Transmission** – Advantageous for Long Distances

- **Low-Frequency AC (LFAC)** as Possible (Purely Passive) Solution for Medium Transmission Distances
**SST Key Characteristics**

- McMurray: Electronic Transformer (1968)
- Brooks: Solid-State Transformer (SST, 1980)
- EPRI: Intelligent Universal Transformer (IUT™)
- ABB: Power Electronics Transformer (PET)
- Wang: Energy Router
- etc.

- Interface to Medium-Voltage
- Medium-Frequency Isolation
- AC or DC Input and/or Output
Remark

Trade-Off - Controllability vs. Efficiency

**LF Isolation**
- Purely Passive (a)
- Series Voltage Comp. (b)
- Series AC Chopper (c)

**MF Isolation**
- Active Input & Output Stage (d)

- Lower Efficiency of SST Compared to “Grid-Type” Passive Transformer
- Medium Freq. $\rightarrow$ Higher Transf. Efficiency only Partly Compensates Converter Stage Losses
SST Development Cycles

1. Wave
   MF Transformer Concepts for Traction (Thyristors)

2. Wave
   Modular SST Concepts and Prototypes for Traction (Si IGBTs, LV-SiC)

3. Wave
   Advanced SST Concepts (HV-SiC)

4. Wave
   SST Applications & Products

- Grid
  Appl. in Datacenters
  Ultra-Fast Charging
  PV

- Traction
  Ultra-Fast Charging

Development Cycles Reaching Over Decades – Matched to “Product” Life Cycle
Global Megatrends

Digitalization
Urbanization
Sustainable Mobility
Renewable Energy
Etc.
Global Megatrends

Digitalization
Urbanization
Sustainable Mobility
Renewable Energy
Etc.
Deep Green/Zero Carbon Datacenters

- Ranging from Medium Voltage to Power-Supplies-on-Chip
- Short Power Supply Innovation Cycles
- Modularity / Scalability
- Higher Availability
- Higher Efficiency
- Higher Power Density
- Lower Costs

Server-Farms up to 450 MW
99.9999%/<30s/a
$1.0 Mio./Shutdown

Since 2006
Running Costs > Initial Costs

Source: REUTERS/Sigtryggur Ari
Future Modular SST-Based Power Distribution

- 5...7% Reduction in Losses & Smaller Footprint
- Improves Reliability & Power Quality

--- Conventional

--- Direct 3-Φ 6.6kV AC → 48V DC Conversion / Unidirectional SST

- MV → 48V → 1.2V - Only 2 Conversion Stages from MV to CPU-Level (!)
Urbanization

- 60% of World Population Exp. to Live in Urban Cities by 2025
- 30 MEGA Cities Globally by 2023

- Smart Buildings
- Smart Mobility
- Smart Energy / Grid
- Smart ICT, etc.

► Selected Current & Future MEGA Cities 2015 → 2030

Source: World Urbanization Prospects: The 2014 Revision
→ Smart Cities/Grids/Buildings (1)

- **Masdar = “Source”**
- Fully Sustainable Energy Generation
  * Zero CO₂
  * Zero Waste
- EV Transport / IPT Charging
- to be finished 2025
Smart Cities/Grids/Buildings (2)

- Masdar = “Source”
- Fully Sustainable Energy Generation
  * Zero CO₂
  * Zero Waste
- EV Transport / IPT Charging
- to be finished 2025
**DC Microgrids**

- Local DC Microgrid: Integrating Loads/Ren. Sources/Storage
- No Low-Voltage AC/DC Conversion → Higher Efficiency & Lower Realization Effort

---

**Conventional**

**Future SST-Based Concept**
Global Megatrends

- Digitalization
- Urbanization
- Sustainable Mobility
- Renewable Energy
- Etc.
Sustainable Mobility

- EU Mandatory 2020 CO\textsubscript{2} Emission Targets for New Cars
  - 147g CO\textsubscript{2}/km for Light-Commercial Vehicles
  - 95g CO\textsubscript{2}/km for Passenger Cars
  - 100% Compliance in 2021

Hybrid Vehicles
Electric Vehicles
Ultra-Fast / High-Power EV Charging

- Medium Voltage Connected Modular Charging Systems
- Very Wide Output Voltage Range (200...800V)

- E.g., Porsche FlexBox incl. Cooling
- Local Battery Buffer (140kWh)
- 320kW → 400km Range in 20min

Source: Porsche Mission-E Project
→ **Bidirectional SST-Based MV Interface**

- **Conventional**

- **Future SST-Based Concept**

- **On-Site Power / Energy Buffer** → „Energy-Hub“
- **Power / Energy Management** → Peak Load Shaving & Grid Support / Stabilization
Sustainable Air Transportation

■ Massive Steady Increase of Global Air Traffic Over the Next Decades
  — Need for 70’000 New Airliners over the Next 20 Years (Boeing & Airbus)
  — Stringent *Flightpath 2050 Goals* of ACARE → Reduction of CO₂/NOₓ/Noise Emissions

**GLOBAL AIR TRAFFIC (TRILLION REVENUE PASSENGER KILOMETRES)**

Traffic is expected to double in the next 15 years

Source: International Civil Aviation Organization (ICAO)/Airbus 2015
Future Distributed Propulsion Aircraft

- Cut Emissions Until 2050
  - CO₂ by 75%,
  - NOₓ by 90%,
  - Noise Level by 65%

- Wing-Tip Mounted Eff. Optimized Gas Turbines & Distributed E-Fans ("E-Thrust")
- MV or Superconducting Power Distribution Integr. 1000Wh/kg Batteries (EADS-Concept)
Future Aircraft Electric Power System

- MV or Superconducting Power Distribution Integr. 1000Wh/kg Batteries (EADS-Concept)

- Generators — 2 x 40.2MW (NASA)
- E-Fans — 14 x 5.7 MW (1.3m Diameter)
**Sustainable Maritime Transportation**

- 80% of All Globally Traded Goods **Transported by Ships**
  - Crude Oil → New Fuel Types (LNG)
  - Fully-Electric Port Infrastructure

**Worldwide Seaborne Trade in Billions of Cargo Ton-Miles**

*Source: UNCTAD 2018*
**Hybrid Diesel-Electric Propulsion**

- No Mech. Coupling of Propulsion & Prime Movers (DGs) → Eff. Optim. Load Distrib. to the DGs
- Energy Storage (Batt., Fuel Cell, etc.)
  - Peak Shaving
  - High Dyn. Performance

- Conv. AC Power Distrib. Network → Disadvantage of Const. Prime Mover / Generator Speed
Shipboard DC Power Distribution

- Future DC/AC-SST Interface to Low-Voltage AC & DC Grid
- Future DC/DC-SST Interface to Energy Storage (ES)

DC Distribution →
Up to 20% Fuel Eff.
Improvement / Smaller Footprint / Easier ES Integr.

1kV/< 20MW or 1…35kV/20…100MW DC Distribution (Radial or Ring, Central. or Distrib.)
Future Combat Ships (1)

- MV Cellular DC Power Distribution on Future Combat Ships etc.

- Bidirectional Power Flow for Advanced Weapon Load Demand
- Extreme Energy and Power Density Requirements
Future Combat Ships (2)

- MV Cellular DC Power Distribution on Future Combat Ships etc.

- Bidirectional Power Flow for Advanced Weapon Load Demand
- Extreme Energy and Power Density Requirements
Global Megatrends

- Digitalization
- Urbanization
- Sustainable Mobility
- Renewable Energy
- Etc.
Wind Energy

- Power prop. $D^2 \rightarrow \text{“Bigger is Better” / Lower Relative Costs}$
- 50kW ($D = 15m$) in 1980 $\rightarrow$ Up to 20MW ($D = 250m$) in Future

12MW
Under Development

Source: gwec.net / Blaabjerg
→ **Wind Turbine Electrical System**

- Current 690V Electrical System → Significant Cabling Weight/Costs & Space Requirement
- Future Local Medium-Frequency Conv. to Medium-Voltage AC or DC

![Diagram of Wind Turbine Electrical System]

▶ **On-Shore Wind Power System**
▶ **Future Off-Shore System**
→ **Off-Shore Collector-Grid Concepts**

- **Conventional AC Collector-Grid**

- **DC/DC-SST Interface** — Wind Turbine DC Link to MVDC Collector Grid → Lower Losses (1%) & Volume
- **DC/DC-SST Interface** — MVDC Grid to HVDC Transmission → Lower Losses (1%) & Volume
Utility-Scale Solar Power Plants

- Medium-Voltage Power Collection and Transmission

Globally Installed PV Capacity Forecasted to 2.7 Terawatt by 2030 (IEA)

Source: REUTERS/Stringer
→ **Future DC Collector Grid**

- DC/DC SST for MPPT & Direct Interfacing of PV Strings to MV Collector Grid
- 1.5% Efficiency Gain Compared to Conv. AC Technology

![Diagram showing conventional and future DC collector grid setups]
Power-to-Gas

- Electrolysis for Conversion of Excess Wind/Solar Electric Energy into Hydrogen
- Fuel-Cell Powered Cars
- Heating

- High-Power @ Low DC Voltage (e.g. 220V)
- Very Well Suited for MV-Connected SST-Based Power Supply
- SST Allows Direct Interfacing to DC Collector Grid

Hydrogenics 100 kW H₂-Generator (η=57%)

Medium-Voltage Distribution System

Conventional ▶ Future
Global Megatrends

Digitalization
Urbanization
Sustainable Mobility
Renewable Energy
Etc.
Future Deep Sea Mining

- “Subsea Factories” / Subsea Power Grid → Long-Distance MV Power Supply from Shore
- Subsea Mining Machines / ROVs / Pumps / Compressors etc.

Demand for Highly Compact / Efficient / Reliable Systems

Source: SMD - Specialist Machine Developments
Future Power Supply of Subsea Systems

- DC Transmission from Shore
- No Platforms/Floaters

Source: Devold (ABB 2012)

Today ➤ Ongoing ➤ Future

O&G processing

Platform/floaters based ➤ Subsea

Power supply

Platform based power generation or power from shore ➤ Long distance power from shore

ABB investing in subsea electrification & automation solutions to enable future subsea processing
→ Cutting Emissions & Noise in Airports / Harbours

- SST Medium-Voltage Interfaces
  - Voltage Level / Frequ. Adaption
  - Low Space Requirement

- Ground Power Supply of Aircraft → APU Turned Off

- MV-Level Shore-Side Power to Docked Ships ("Cold-Ironing") → Diesel Aux. Engines Turned Off

Source: iecetech.org
SST Concept Implementation
Creation of MV → LV SST Topologies
Classification of SST Topologies (1)

- Number of Levels
  Series/Parallel Cells

- Degree of Power
  Conversion Partitioning

- Degree of Phase
  Modularity

3-Dimensional Topology Selection Space
Classification of SST Topologies (2)

- Very (!) Large Number of Possible Topologies
  - Partitioning of Power Conversion  ➔ Matrix & DC-Link Topologies
  - Splitting of 3ph. System into Individual Phases  ➔ Phase Modularity
  - Splitting of Medium Operating Voltage into Lower Partial Voltages  ➔ Multi-Level/Cell Approaches

Degree of Power Conversion Partitioning

Degree of Phase Modularity

Number of Levels Series/Parallel Cells

Combining the Basic Concepts I

Single-Phase AC-DC Conversion / Traction Applications
Cascaded H-Bridges w. Isolated Back End

- Multi-Cell Concept (AC/DC Front End & Soft-Switching Resonant DC/DC Converter)
- Input Series / Output Parallel Connection – Self Symmetrizing (!)
- Highly Modular / Scalable
- Allows for Redundancy
- High Power Demonstrators: ABB, Bombardier, Alstom, etc.

Source: Zhao / Dujic (ABB / 2011)
DCX — “DC Transformer”

- $f_S \approx$ Resonant Frequency $\rightarrow$ “Unity Gain” $(U_2/U_1=N_2/N_1)$
- Fixed Voltage Transfer Ratio Independent of Transferred Power (!)
- Power Flow Level & Direction Self-Adjusting
- No Controllability / No Need for Control
- ZCS of All Devices

Diodes $\rightarrow$ IGBTs for Bidirectional Power Flow

Operating Frequency

Relative voltage $U_{R_{L}}/U_{0}$

Relative Frequency $\frac{\omega}{\omega_0}$

$Q = \frac{\sqrt{L}}{R_L}$

$Q = 1$
$Q = 2$
$Q = 5$
$Q = 10$

Diode $\rightarrow$ IGBT

Currents $i_1, i_2$

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Current Shaping & Isolation → Isolation & Current Shaping

- Isolated DC/DC Back End
- Isolated AC/AC Front End

- Typical Multi-Cell SST Topology
  - Two-Stage Multi-Cell Concept
  - Direct Input Current Control
  - Indirect Output Voltage Control
  - High Complexity at MV Side

- Swiss SST (S3T)
  - Two-Stage Multi-Cell Concept
  - Indirect Input Current Control
  - Direct Output Voltage Control
  - Low Complexity on MV Side
Modular Multilevel Converter

- Single Transformer Isolation
- Highly Modular / Scalable
- Allows for Redundancy
- Challenge of Balancing the Cell DC Voltages

Source: Zhao / Dujic (ABB / 2011)

Source: Marquardt/Glinka (2003)
Combining the Basic Concepts II

Three-Phase AC-AC Conversion /
Smart Grid Applications

Source: EPRI | ELECTRIC POWER RESEARCH INSTITUTE
MEGALink @ ETH Zurich

- 2-Level Inverter on LV Side
- HC-DCM-SRC DC//DC Conversion
- Cascaded H-Bridge MV Structure – ISOP Topology

- $S_N = 630$ kVA
- $U_{LV} = 400$ V
- $U_{MV} = 10$ kV

MEGALink

Power Electronic Systems Laboratory

ETH Zürich

MegaLink

SN = 630 kVA
ULV = 400 V
UMV = 10 kV

Diagram showing power electronic components and connections:
- LV converter
- MV phase stack
- Converter cell
- Transformer $L_F$

ETH Zürich
Non-Cascaded Structure (SiC)

- 13.8kV → 480V
- Scaled Prototype
- 15kV SiC-IGBTs, 1200V SiC MOSFETs

Redundancy Only for Series-Connection of Power Semiconductors (!)
SST Demonstrator Systems

Future Locomotives
Smart Grid Applications
1ph. AC/DC Power Electronic Transformer - PET

- Dujic et al. (2011)
- Heinemann (2002)
- Steiner/Stemmler (1997)
- Schibli/Rufer (1996)

\[ P = 1.2 \text{MVA}, \ 1.8 \text{MVA pk} \]
9 Cells (Modular)

- 54 x (6.5kV, 400A IGBTs)
- 18 x (6.5kV, 200A IGBTs)
- 18 x (3.3kV, 800A IGBTs)

- 9 x MF Transf. (150kVA, 1.8kHz)
- 1 x Input Choke
1.2 MVA 1ph. AC/DC Power Electronic Transformer (1)

- Cascaded H-Bridges – 9 Cells
- Resonant LLC DC/DC Converter Stages

- Same Overall Volume as Conventional System
- Future Development Targets Half Volume
1.2 MVA 1ph. AC/DC Power Electronic Transformer (2)

- Cascaded H-Bridges – 9 Cells
- Resonant LLC DC/DC Converter Stages

Efficiency

- Same Overall Volume as Conventional System
- Future Development Targets Half Volume
SiC-Enabled Solid-State Power Substation (1)

- Das et al. (2011)
- Lipo (2010)
- Weiss (1985 for Traction Appl.)

- Fully Phase Modular System
- Indirect Matrix Converter Modules ($f_1 = f_2$)
- MV Δ-Connection (13.8kV L-L, 4 Modules in Series)
- LV Y-Connection (265V, Modules in Parallel)

- SiC Enabled 20kHz/1MVA “Solid State Power Substation”
- 97% Efficiency @ Full Load / 1/3rd Weight / 50% Volume Reduction (Comp. to 60Hz)
SiC-Enabled Solid-State Power Substation (2)

- Das et al. (2011)

- Fully Phase Modular System
- Indirect Matrix Converter Modules \( f_1 = f_2 \)
- MV Δ-Connection (13.8kV-l, 4 Modules in Series)
- LV Y-Connection (265V, Modules in Parallel)

- SiC Enabled 20kHz/1MVA “Solid State Power Substation”
- 97% Efficiency @ Full Load / 1/3rd Weight / 50% Volume Reduction (Comp. to 60Hz)
25kW SwiSS-Transformer @ ETH Zurich

- Bidirectional 1-Φ 3.8 kV\textsubscript{rms} AC $\rightarrow$ 400V DC Power Conversion
- Based on 10kV SiC MOSFETs
- Full Soft-Switching

$\star$ 3.3 kW/dm\textsuperscript{3}

$\star$ 3.8 kW/dm\textsuperscript{3}

$\triangleright$ 35...75kHz $i$TCM Input Stage

$\triangleright$ 48kHz DC-Transformer Output Stage
► **3.8kV → 7kV ZVS AC/DC Stage**

- **Full-Bridge iTM – integrated Triang. Current Mode 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

★ **3.3 kW/dm³**

► **Full-Load Measurement (25kW @ 3.8kVrms AC, 7kV DC) - ZVS Over Full AC Cycle (!)**
7kV → 400V DC/DC Stage (1)

- **MV-Side Half-Bridge**
  - 48kHz Sw. Frequency, ZVS
  - Cooling of Power Semicond. by Floating Heatsinks (Not Shown)
  - Creepage Distances Ensured by PCB Slots

![ schematics and image showing technical details of the converter stage with a 3.8 kW/dm³ output power and labeled components like Fiber optics, 10 kV SiC module, Insulation transformer, 60 mm creepage, and Silicone tube.]

**Half-Bridge for Cutting Voltage in Half / Lower Switch Count**
7kV $\rightarrow$ 400V DC/DC Stage (2)

- **MF-Transformer Measurement**
  - Fully Tested @ 25kW / 7 kV
  - Calorimetric Loss Measurement
  - 99.64% Efficiency

Transformer Prototype / Loss Distribution / Efficiency
**Overall Performance**

- Full Soft-Switching
- 98.1% Overall Efficiency @ 25kW
- 1.8 kW/dm$^3$ (30W/in$^3$)

**Red. of Losses & Volume by Factor of >2 Comp. to Alternative Approaches (!)**

**Significantly Simpler Compared to Multi-Module SST Approach**
**Remark**

1-Φ 2.4 kV\textsubscript{rms} AC $\rightarrow$ 54V DC

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

- Power Density of 0.4 kW/dm\(^3\) (6.6W/in\(^3\))
- 96% Overall Efficiency @ 25kW

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**Abbreviations:**
- PFC: Power Factor Correction
- MV: Medium Voltage
- DC/DC: Direct Current/Direct Current
- IGBT: Insulated Gate Bipolar Transistor
- SiC: Silicon Carbide
- MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor

**Graphs:**
- Efficiency vs. Load (%)
- Total efficiency curve
40kV SiC Super-Switch @ ETH Zurich

- Cascaded 10kV SiC MOSFETs
- Quasi-X-Level (Staggered) Switching
- Intellig. Power Module — Two-Level Bridge-Leg Appearance

- Integrated Gate Drive / Voltage Balancing / Protection / Isol. Cooling Surface etc.
► **SST — Air-Core vs. Magnetic-Core XFRM (1)**

- Rated Power: **166kW**
- DC/DC Conversion: **7kV / 7kV**

► **Clarify Weight / Efficiency Trade-Off**
**SST — Air-Core vs. Magnetic-Core XFRM (2)**

- **Gravimetric Power Density of the Transformers**
  - Efficiency (%) vs. Gravimetric Power Density (kW/kg)
  - Two plots showing efficiency and power density with different frequencies (20, 40, 60, 80, 100 kHz).

- **Volumetric Power Density of the Transformers**
  - Efficiency (%) vs. Volumetric Power Density (kW/dm³)
  - Two plots showing efficiency and power density with different frequencies (20, 40, 60, 80, 100 kHz).

- **Gravimetric Power Density of the Converters**
  - Efficiency (%) vs. Gravimetric Power Density (kW/kg)
  - Two plots showing efficiency and power density with different frequencies (20, 40, 60, 80, 100 kHz).

- **Volumetric Power Density of the Converters**
  - Efficiency (%) vs. Volumetric Power Density (kW/dm³)
  - Two plots showing efficiency and power density with different frequencies (20, 40, 60, 80, 100 kHz).

- **η-γ-ρ-Pareto Fronts of Transformers & Converters**
► **SST — Air-Core vs. Magnetic-Core XFRM (3)**

- **Air Core SST** → 98.9% / 12.8kg (77kHz)
- **Mag. Core SST** → 99.2% / 27.2kg (40kHz)

**Weight / Efficiency Trade-Off**

- **Mass**:
  - Air-core: 13.0 kg, 6.1 kW/kg
  - Magnetic-core: 12.8 kg, 27.5 kg

- **Losses**:
  - Cooling System: 80 W | 80 W
  - Resonant Capacitors: 83 W | 18 W
  - Transformer: 879 W | 601 W
  - DC Capacitors: 2 W | 6 W
  - MOSFETs Switch: 212 W | 89 W
  - MOSFETs Cond: 561 W | 519 W

- **η (%)**:
  - Air-core: 98.9%
  - Magnetic-core: 99.2%

**Star** 13 kW/kg

**24 kW/kg**

- Aluminum Shielding (0.5mm)
Conclusions

SST Limitations / Concepts
Research Areas
The Solid-State Transformer Hype

- Large # of Publications!
- Research on Main Application Challenges Currently Largely Missing

Protection (?)
Control in Active Grids (?)
System Level Adv. (?)

Source:
And Update My Website
And Update My Website.com
SST Applications → The Road Ahead

- **NOT (!) Weight / Space Limited**
- **Smart Grid, Stationary Applications**

### AC/AC
- Efficiency Challenge
- More Eff. Voltage Control by
  - Tap Changers
  - Series Regulators (Partial Power)
- Not Compatible w. Existing Infrastr.
- Cost / Robustness / Reliability

### AC/DC
- Efficiency Challenge more Balanced
- “Local” Applic. (Datacenters, DC Distr.)
- Cost / Robustness / Reliability

### DC/DC
- No Other Option (!)
- MV DC Collection Grids (Wind, PV)
- Sw. Frequ. as DOF of Design

- **Weight / Space Limited**
- **Traction Applic. etc.**

### DC/AC
- **Sw. Frequ. as DOF of Design**
- Low Weight/Volume @ High Eff.
- Local Applic. (Load/Source Integr.)
Remark: "Hybrid" Transformers

- Combination of Mains-Frequ. Transformer & SST
- Fractional Power Processing → High Efficiency
- Low Blocking Voltage Requirement
- Simplified Protection

➤ Shunt Connection
  — Reactive Current Inj.

➤ Series Connection
  — Reactive Voltage Inj.
  — Phase Shiftg / Volt. Cntrl

➤ Combined Connection
  — Volt. Cntrl / Phase Shiftg
Current SST Research Status

Huge Multi-Disciplinary Challenges / Opportunities (!) are Still Ahead
Thank You!
Questions

www.pes.ee.ethz.ch/publications.html
Electronic Transformer - History

- System Using Mech. Switches *Patented Already in 1913 (!)*
- Mechanical Sw. → Tubes → Mercury Arc Valves → Solid State Switches

1,206,662.

1913 — P.M.J. Boucherot
1944 — E.F.W. Alexanderson et al.

1928 — D.C. Prince
1968 — W. McMurray

● “Transformer of Cont. Current” / “DC Transformer” / “Electronic Transformer”
ABSTRACT OF THE DISCLOSURE

Several single phase solid state power converter circuits have a high frequency transformer link whose windings are connected respectively to the load and to a D-C or low frequency A-C source through inverter configuration switching circuits employing inverse-parallel pairs of controlled turn-off switches (such as transistors or gate turn-off SCR's) as the switching devices. Filter means are connected across the input and output terminals. By synchronously rendering conductive one switching device in each of the primary and secondary side circuits, and alternately rendering conductive another device in each switching circuit, the input potential is converted to a high frequency wave, transformed, and reconstructed at the output terminals. Wide range output voltage control is obtained by phase shifting the turn-on of the switching devices on one side with respect to those on the other side by 0° to 180°, and is used to effect current limiting, current interruption, current regulation, and voltage regulation.

- Transistor/Diode-Based "Electronic Transformer"
- AC or DC Voltage Regulation & Current Regulation/Limitation/ Interruption