Research Challenges and Future Perspectives of Solid-State Transformers

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Outline

► Smart Grid
► SST Functionalities
► 10 Key SST Realization/Application Challenges
► Future Perspectives
► Conclusions
Smart Grid Concept

- Borojevic (2010)

- Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids
  - Distr. Syst. of Contr. Conv. Interfaces
  - Source / Load / Power Distrib. Conv.
  - Picogrid-Nanogrid-Microgrid-Grid Structure
  - Subgrid Seen as Single Electr. Load/Source
  - ECCs provide Dyn. Decoupling
  - Subgrid Dispatchable by Grid Utility Operator
  - Integr. of Ren. Energy Sources

- ECC = Energy Control Center
  - Energy Routers
  - Continuous Bidir. Power Flow Control
  - Enable Hierarchical Distr. Grid Control
  - Load / Source / Data Aggregation
  - Up- and Downstream Commnic.
  - Intentional / Unintentional Islanding for Up- or Downstream Protection
  - etc.
Smart Grid Enablers / Drivers (1) ... besides CO₂ Reduction / Ren. Energy Integration etc.

- WBG Semiconductor Technology → Higher Efficiency, Lower Complexity
- Microelectronics → More Computing Power

► Advanced Packaging (!)

→ Moore's Law
Smart Grid Enablers / Drivers (2)

- **Metcalfe's Law**

  - Moving from Hub-Based Concept to Community Concept Increases Potential Network Value Exponentially (\(\sim n(n-1)\) or \(\sim n \log(n)\) )
Smart Grid Enablers / Drivers (3)

- Battery Technology

- TESLA Announces „The Beginning of the End For Fossil Fuels“
- Plans to Invest US$ 4-5 Billion in US Gigafactory until 2020
- Scalable up to Several MWh’s

≈ US$ 300 / kWh
Future Renewable Electric Energy Delivery & Management (FREEDM) Syst.

- Huang et al. (2008)

- Solid State Transformer (SST) as Enabling Technology for the “Energy Internet”
  - Full Control of Active/Reactive/Harmonic Power Flow
  - Integr. of Distributed Energy Resources
  - Integr. of Distributed E-Storage + Intellig. Loads
  - Protects Power System From Load Disturbances
  - Protects Load from Power Syst. Disturbances
  - Enables Distrib. Intellig. through COMM
  - etc.
  - etc.

- Medium Frequency Isolation → Low Weight / Volume


**Terminology (1)**

**United States Patent** [19]  
Brooks et al.  

**Terminology (1)**

United States Patent [19]  
Brooks et al.  

- **SOLID STATE REGULATED POWER TRANSFORMER WITH WAVEFORM CONDITIONING CAPABILITY**
- **Inventors:** James L. Brooks, Oxnard; Roger L. Staab, Camarillo, both of Calif.; James C. Bowers; Harry A. Nienhaus, both of Tampa, Fla.
- **Assignee:** The United States of America as represented by the Secretary of the Navy, Washington, D.C.

- **Appl. No.:** 188,419  
- **Filed:** Sep. 18, 1980

- **1980!**

**OTHER PUBLICATIONS**

Bowers et al, "A Solid State Transformer", PESC '80

- **No Isolation (!)**
- **"Transformer" with Dyn. Adjustable Turns Ratio**

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**Fig. 1.**
Terminology (2)

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

etc.
SST vs. Uninterruptible Power Supply

- Same Basic Functionalities of SST and Double-Conversion UPS
  - High Quality of Load Power Supply
  - Possible Ext. to Input Side Active Filtering
  - Possible Ext. to Input Reactive Power Comp.

- Input Side MV Voltage Connection of SST as Main Difference / Challenge
- Numerous Topological Options
Challenge #1/10

Creation of MV→LV SST Topologies
Basic SST Structures (1)

- 1st Degree of Freedom of Topology Selection → Partitioning of the AC/AC Power Conversion

  * DC-Link Based Topologies
  * Direct/Indirect Matrix Converters
  * Hybrid Combinations

- 1-Stage Matrix-Type Topologies
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 2-Stage with MV DC Link (Connection to HVDC System)
- 3-Stage Power Conversion with MV and LV DC Link

- Only Concepts Featuring MF Isolation Considered
Basic SST Structures (1)

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  Partitioning of the AC/AC Power Conversion

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  - Mohan (2009)

- Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
- LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency
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- Mohan (2009)

- Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
- LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency
**Basic SST Structures (2)**

- **2nd Degree of Freedom of Topology Selection → Partial or Full Phase Modularity**
  
  * Phase-Modularity of Electric Circuit
  * Phase-Modularity of Magnetic Circuit

* Phase-Integrated SST

* Possibility of Cross-Coupling of Input and Output Phases (UNIFLEX)
Basic SST Structures (2)

- 2nd Degree of Freedom of Topology Selection → Partial or Full Phase Modularity

- Enjeti (1997)

- Steimel (2002)

- Example of Three-Phase Integrated (Matrix) Converter & Magn. Phase-Modular Transf.

- Example of Partly Phase-Modular SST
Basic SST Structures (3)

- 3rd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage

- Multi-Cell and Multi-Level Approaches

- Two-Level Topology

- Multi-Cell and Multi-Level Topologies

- Akagi (1981)

- McMurray (1969)

- Alesina/Venturini (1981)
Basic SST Structures (3)

- 3rd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage

- Multi-Cell and Multi-Level Approaches
- Low Blocking Voltage Requirement
- Low Input Voltage / Output Current Harmonics
- Low Input/Output Filter Requirement

* Single-Cell / Two-Level Topology

ISOP = Input Series / Output Parallel Topologies
Basic SST Structures (3)

- Bhattacharya (2012)

- 13.8kV $\rightarrow$ 480V
- 15kV Si-IGBTs, 1200V SiC MOSFETs
- Scaled Prototype
Basic SST Structures (3)

- Akagi (2005)

\[ \bar{V}_{oa} = \frac{1}{3}(V_{oa1} + V_{oa2} + V_{oa3}) \]

- Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs
- Combination of Clustered Balancing Control with Individual Balancing Control
Classification of SST Topologies

- Very (!) Large Number of Possible Topologies
  - Partitioning of Power Conversion
  - Splitting of 3ph. System into Individual Phases
  - Splitting of Medium Operating Voltage into Lower Partial Voltages
  - Matrix & DC-Link Topologies
  - Phase Modularity
  - Multi-Level/Cell Approaches
Challenge #2/10

Availability / Selection of Power Semiconductors
Available Si Power Semiconductors

- **1200V/1700V Si-IGBTs Most Frequently Used in Industry Applications**

- **Derating Requirement due to Cosmic Radiation**
  
  1700V Si-IGBTs $\rightarrow$ 1000V max. DC Voltage

Multi-Level Converters for High Grid Voltages / High Reactive Power Injection
Available SiC Power Semiconductors

- 10kV / 10A SiC MOSFET and Antiparallel SiC Schottky Diode
- 15kV / 80A Low-Ind. High-Temp. Package

High Current 3.3kV / 1.7kV / 1.2 kV Power Modules Available (Mitsubishi, ROHM, etc.)
Vertical (!) Power Semiconductors on Bulk GaN Substrates

- GaN-on-GaN Means Less Chip Area

For a given on-resistance ($R_{on}$) of 10mΩ:

- Vertical FET Structure

<table>
<thead>
<tr>
<th>Breakdown Voltage (V)</th>
<th>Doping (cm⁻³)</th>
<th>Drift Length (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>4.8x10¹⁶</td>
<td>3.7</td>
</tr>
<tr>
<td>1200</td>
<td>2.4x10¹⁶</td>
<td>7.3</td>
</tr>
<tr>
<td>1800</td>
<td>1.6x10¹⁶</td>
<td>10.9</td>
</tr>
<tr>
<td>2400</td>
<td>1.2x10¹⁶</td>
<td>14.6</td>
</tr>
<tr>
<td>3200</td>
<td>0.9x10¹⁶</td>
<td>19.4</td>
</tr>
<tr>
<td>4800</td>
<td>0.6x10¹⁶</td>
<td>29.1</td>
</tr>
<tr>
<td>5600</td>
<td>0.5x10¹⁶</td>
<td>34.0</td>
</tr>
</tbody>
</table>

GaN-on-GaN lowers die cost while improving $R_{on} \times C_{eff}$ switching characteristic
Semiconductor Cooling and Isolation

- 1.7kV IGBTs $\rightarrow$ Semiconductor Modules on Coldplates/Heatsinks Connected to Different Potentials (CM Voltage Problems)
- 3.3kV or 6.5kV IGBTs $\rightarrow$ Isolation Provided by the Modules’ Substrate, No Splitting of the Cooling System Necessary.

$\bullet$ Hoffmann (2009)
SiC-Enabled Solid-State Power Substation

- 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 \((13.8kV_{\Delta}, 4 \text{ Modules in Series})\)
- LV Y-Connection \((465V/\sqrt{3}, \text{ Modules in Parallel})\)

- SiC Enabled 20kHz/1MVA “Solid State Power Substation”
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)
SiC-Enabled Solid-State Power Substation

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Challenge #3/10

*Single-Cell vs. Multi-Cell Converter Concepts*

- Losses
- Reliability
Scaling of Multi-Cell Converters

- Interleaved Series Connection Dramatically Reduces Switching Losses

Converter Cells Could Operate at VERY Low Switching Frequency (e.g. 5kHz)

Harmonics Cancellation instead of Filtering → Minimization of Filter Components

\[ P_{S,N} \approx P_{S,N=1} \cdot \left( \frac{1}{2N^2} \cdots \frac{1}{N^3} \right) \]
MEGALink @ ETH Zürich

- \( S_N = 630 \text{kVA} \)
- \( U_{LV} = 400 \text{ V} \)
- \( U_{MV} = 10 \text{kV} \)

- 2-Level Inverter on LV Side / HC-DCM-SRC DC-DC Conversion / Cascaded H-Bridge MV Structure
166kW / 20kHz DC-DC Converter Cell

- Half-Cycle DCM Series Resonant DC-DC Converter
- Medium-Voltage Side: 2kV
- Low-Voltage Side: 400V

80kW Operation
Optimum Number of Converter Cells

- Trade-Off: High Number of Levels → High Conduction Losses / Low Cell Switching Frequency / Losses (also because of Device Characteristic)

- Optimal Device Voltage Rating for Given MV Level
- η-Optimal Pareto (Compliance to IEEE 519)

1200V ... 1700V Power Semiconductors best suited for 10kV Mains → No Advantage of SiC (!)
Optimum Number of Converter Cells

- Trade-Off → Mean-Time-to-Failure vs. Efficiency / Power Density

- Influence of
  - FIT Rate (Voltage Utilization)
  - Junction Temperature
  - Number of Redundant Cells

■ High MTBF also for Large Number of Cells (Repairable) / Lower Total Spare Cell Power Rating
Challenge #4/10

Medium-Frequency Transformer Design

- Heat Management
- Isolation
MF Transformer Design – Cold Plates/ Water Cooling

- Nanocrystalline 160kW/20kHz Transformer (ETH, Ortiz 2013)

- Combination of Heat Conducting Plates and Top/Bottom Water-cooled Cold Plates
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core
Water-Cooled 20kHz Transformer

- **Power Rating**: 166 kW
- **Efficiency**: 99.5%
- **Power Density**: 32 kW/dm³

- Nanocrystalline Cores with 0.1mm Airgaps between Parallel Cores for Equal Flux Partitioning
- Litz Wire (10 Bundles) with CM Chokes for Equal Current Partitioning
Transformed Core Flux Density Measurement

- "Magnetic Ear"
  - Auxiliary Core Inductance Related to Main Core Magnetization State
  - Enables Closed Loop Transformer Flux Balancing
Voltage and E-Field Stresses in SSTs

- Mixed-Frequency (LF + Switching Frequency) Voltage Stress on Isolation
- Unequal Dynamic Voltage Distribution
- Potentially Accelerated Aging (!)
- Neglectable Dielectric Losses
- Specific Test Setup Required for Insulation Material Testing
Challenge #5/10

SST Noise Emissions /EMI
Common-Mode Currents of Cascaded H-Bridge SSTs

- Switching Actions of a Cell $i$ Changes the Ground Potential of Cells $i$, $i+1$, ..., $N$
- CM Currents through Ground Capacitances

- Example
  - 1MVA
  - 10kV Input
  - 400V Output
  - 1kHz/Cell
  - $C_{eq} \approx 650\mu F$

- 6.2mH at the Input of Each Cell for Limiting $i_{CM}$

$dv/dt=15kV/\mu s$
Grid Harmonics and EMI Standards

- Medium Voltage Grid Considered Standards (Burkart, 2012)
  - IEEE 519/1547
  - BDEW
  - CISPR

- Requirements on Switching Frequency and EMI Filtering
Challenge #6/10

Mains ← SST → Load Protection / Grid Codes
Potential Faults of MV/LV Distribution-Type SSTs

- Extreme Overvoltage Stresses on the MV Side for Conv. Distr. Grids
- SST more Appropriate for Local Industrial MV Grids

Conv. MV Grid Time-Voltage Characteristic

- Very fast front: Arcing transient, \( t_f = 3-100 \text{ ns} \), \( t_i = 1-3 \text{ ms} \)
- Fast front: Lightning surge, \( t_f = 0.1-20 \text{ µs} \), \( t_i = 100-300 \text{ µs} \)
- Slow front: Switching transient, \( t_f = 20-1000 \text{ µs} \), \( t_i = 1-20 \text{ ms} \)
Current Ratings – Overcurrent Requirements

- Low-Freq. XFRM must Provide Short-Circuit Currents of up to 40 Times Nominal Current for 1.5 Seconds (EWZ, 2009)
- Traction Transformers: 150% Nominal Power for 30 Seconds (Engel 2003)
- Power Electronics: Very Short Time Constants!

- SST is NOT (!) a 1:1 Replacement for a Conventional Low-Frequency XFRM
Protection of LF-XFRM vs. SST Protection

- Missing Analysis of SST Faults (Line-to-Line, Line-to-Gnd, S.C., etc.) and Protection Schemes

- Typical LF-XFRM Protection (Fuses, Surge Arresters)

- Proposed SST Protection Scheme with Minimum # of Protection Devices

- Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed /Safety /Reliability
Challenge #7/10

SST Efficiency / Size / Costs vs. Low-Frequency XFRM-Based Solution
Passive Transformer → SST

- **Efficiency Challenge**

- **Medium Freq. → Higher Transf. Efficiency Partly Compensates Converter Stage Losses**
- **Medium Freq. → Low Volume, High Control Dynamics**

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

**MF Isolation**
- Active Input & Output Stage (d)
Efficiency Advantage of Direct MV AC – LV DC Conversion

- Comparison to LF Transformer & Series Connected PFC Rectifier (1MVA)

MV AC/DC Stage Weight (Top) and Costs (Bottom) Breakdown

| Characteristic performance indices for 1000 kVA LFTs and SSTs in AC/AC or AC/DC applications. |
|---|---|---|---|---|
| AC/AC factor | AC/AC factor | AC/AC factor | AC/AC factor |
| LFT | SST | LFT | SST |
| losses [W/kVA] | 13.0 | ×2.75 | 35.7 | ×0.58 | 17.9 | 30.9 | ×0.58 | 17.9 |
| costs [USD/kVA] | 16.2 | ×4.75 | 77.0 | ×1.12 | 49.3 | 16.2 | ×4.75 | 77.0 | ×1.12 | 49.3 |
| volume [l/kVA] | 3.43 | ×0.57 | 1.96 | ×0.48 | 1.75 | 3.43 | ×0.57 | 1.96 | ×0.48 | 1.75 |
| weight [kg/kVA] | 2.59 | ×0.89 | 2.30 | ×0.35 | 1.26 | 2.59 | ×0.89 | 2.30 | ×0.35 | 1.26 |

Performance characteristics overview.

<table>
<thead>
<tr>
<th></th>
<th>SST MV</th>
<th>SST LV</th>
<th>SST</th>
<th>LFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>efficiency</td>
<td>98.2%</td>
<td>98.2%</td>
<td>96.5%</td>
<td>98.7%</td>
</tr>
<tr>
<td>volume</td>
<td>1.751 m³</td>
<td>0.211 m³</td>
<td>1.962 m³</td>
<td>3.427 m³</td>
</tr>
<tr>
<td>weight</td>
<td>1262 kg</td>
<td>1036 kg</td>
<td>2298 kg</td>
<td>2591 kg</td>
</tr>
<tr>
<td>cost</td>
<td>49.3 kUSD</td>
<td>27.7 kUSD</td>
<td>77.0 kUSD</td>
<td>16 kUSD</td>
</tr>
</tbody>
</table>
**SST vs. LF Transformer + AC/DC Converter**

- **Specifications**
  - 1MVA
  - 10kV Input
  - 400V Output
  - 1700V IGBTs (1kHz/8kHz/4kHz)

- **LF Transformer**
  - 98.7%
  - 16.2 kUSD
  - 2600kg (5700lb)

- **Clear Efficiency/Volume/Weight Advantage of SST for DC Output (98.2%)**
- **Weakness of AC/AC SST vs. Simple LF Transformer (98.7%) - 5 x Costs, 2.5 x Losses**
Challenge #8/10

**SST vs. FACTS**
Power Electronics for Flexible AC Transmission (FACTS)

- Improvement of Voltage Quality / Power Flow Control
- Hybrid SSTs as Compromise between FACTS & Full-SST

- Missing Contr. Concepts for Stable Operation of Low-Inertia Future Grids (for FACTS and SSTs)
- Performance/Cost/Reliability Adv./Disadv. of SST and FACTS Still to be Clarified (!)
Challenge #9/10

Multi-Disciplinary Education
Smart XXX = Power Electronics + Power Systems + ICT

Today: Gap in Mutual Understanding Between the Disciplines

Future:

\[ p(t) \rightarrow \int_{0}^{t} p(t) \, dt \]

- Power Conversion → Energy Management / Distribution
- Converter Stability → System Stability (Autonom. Cntrl of Distributed Converters)
- Cap. Filtering → Energy Storage & Demand Side Management
- Costs / Efficiency → Life Cycle Costs / Mission Efficiency / Supply Chain Efficiency
Example: US NSF/NAE-Sponsored Faculty/Industry Workshop

Organized by University of Minnesota / Ned Mohan — www.cusp.umn.edu
Reforming Electric Energy Systems Curric. in the USA — Emphasis on Sustainability

ETH Zürich — PowerENG 2015
Challenge #10/10

University Medium-Voltage Power Electronics
► MV Power Electronics — Test Facility

- Significant Planning and Realization Effort
- Power Supply / Cooling / Control / Simulation (integrated)

- Large Space Requirement / Considerable Investment (!)
MV Power Electronics – Safety Issues etc.

- Ph.D. Students are Missing Practical Experience / Underestimate the Risk
- High Power Density Power Electronics Differs from Conv. HV Equipment
- Very Careful Training / Remaining Question of Responsibility

... ESPECIALLY @ Medium Voltage (!)

- High Costs / Long Manufacturing Time of Test Setups
- Complicated Testing Due to Safety Procedures → Lower # of Publications / Time
Alternative – Scaled Demonstrator Systems

- Full Functionality at Relatively Safe Power and Voltage Levels

- E.g.: SST Demonstrator @ ETH Zurich
  $400V_{AC} - 800V_{DC} - 400V_{AC}$
  $15kVA$

- Allows Analysis of All Basic Functionalities / Testing of Control Hardware
- No Testing Concerning Parasitics / Isolation Stresses / Efficiency etc.
- Question of Full Simulation vs. Scaled Demonstration
Near Future SST Applications

Next Generation Locomotives
Direct $MV_{AC} \rightarrow LV_{DC}$ Power Supply
Classical Locomotives

- Catenary Voltage: 15kV or 25kV
- Frequency: $16\frac{2}{3}$ Hz or 50Hz
- Power Level: 1...10MW typ.

Transformer:
- Efficiency: 90...95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
- Current Density: 6 A/mm$^2$ (2A/mm$^2$ typ. Distribution Transformer)
- Power Density: 2...4 kg/kVA
Next Generation Locomotives

- **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

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**AC Catenary (15kV, 16%Hz or 25kV, 50Hz)**

- Conventional AC-DC conversion with a line frequency transformer (LFT).
- Rail
- AC$_{LF}$ → DC
- LFT

**AC Catenary (15kV, 16%Hz or 25kV, 50Hz)**

- AC-DC conversion with medium frequency transformer (MFT).
- Rail
- AC$_{LF}$ → AC$_{MF}$ → DC
- MFT

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- Replace LF Transformer by **Medium Frequency Power Electronics Transformer** → SST
- **Medium Frequency** Provides Degree of Freedom → Allows Loss Reduction **AND** Volume Reduction
Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives

- Medium Freq. Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction
1ph. AC/DC Power Electronic Transformer - PET

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

\[ P = 1.2\text{MVA}, 1.8\text{MVA pk} \]

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

- Cascaded H-Bridges – 9 Cells
- Resonant LLC DC/DC Converter Stages
1.2 MVA 1ph. AC/DC Power Electronic Transformer

- Cascaded H-Bridges – 9 Cells
- Resonant LLC DC/DC Converter Stages
Future Subsea Distribution Network – O&G Processing

- Devold (ABB 2012)

- Transmission Over DC, No Platforms/Floaters
- Longer Distances Possible
- Subsea O&G Processing
- Weight Optimized Power Electronics

ABB investing in subsea electrification & automation solutions to enable future subsea processing.
Unidirectional SST Topologies

- Direct Supply of 400V/48V DC System from 6.6kV AC
- Direct PV Energy Regeneration from 1kV DC into 6.6kV AC
- Even for Relatively Low Power (25...50kW) / Modular
- All-SiC Realization (50kHz XFMR)

Comparative Evaluation of SST Topologies based on Comp. Load Factors
AC vs. Facility-Level DC Systems for Datacenters

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

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Conventional US 480V\textsubscript{AC} Distribution

- Facility-Level 400 V\textsubscript{DC} Distribution

- Future Concept: Direct 6.6kV AC $\rightarrow$ 400V DC Conversion / Unidirectional SST
Unidirectional SST Topologies

- Direct Supply of 400V DC System from 6.6kV AC
- All-SiC Realization (50kHz XFMR)
- $P = 25$ kW

Comparative Evaluation based on Comp. Load Factors
Power-to-Gas


- High-Power @ Low DC Voltage (e.g. 220V)
- Very Well Suited for MV-Connected SST-Based Power Supply

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Hydrogenics 100 kW H₂-Generator (η=57%)
Future Hybrid or All-Electric Aircraft (1)

- Powered by Thermal Efficiency Optimized Gas Turbine and/or Future Batteries (1000 Wh/kg)
- Highly Efficient Superconducting Motors Driving Distributed Fans (E-Thrust)
- Until 2050: Cut CO₂ Emissions by 75%, NOₓ by 90%, Noise Level by 65%
Future Hybrid or All-Electric Aircraft (2)

- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- Electr. Power Transm. allows High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)
Airborne Wind Turbines

- Power Kite Equipped with Turbine / Generator / Power Electronics
- Power Transmitted to Ground Electrically
- Minimum of Mechanically Supporting Parts
100kW Airborne Wind Turbine

- Ultra-Light Weight Multi-Cell All-SiC Solid-State Transformer - $8kV_{DC} \rightarrow 700V_{DC}$
  - Medium Voltage Port: $1750 \ldots 2000 \, V_{DC}$
  - Switching Frequency: 100 kHz
  - Low Voltage Port: $650 \ldots 750 \, V_{DC}$
  - Cell Rated Power: 6.25 kW
  - Power Density: $5.2\, kW/dm^3$
  - Specific Weight: $4.4\, kW/kg$
Future Military Applications

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

Source: General Dynamics

- Bidirectional Power Flow for Advanced Weapon Load Demand
- Extreme Energy and Power Density Requirements
**MV → LV DCDC Conversion**

- **Rated Power**: 1MW (MEGA Cube)
- **Frequency**: 20kHz
- **Input Voltage**: 12kV\_DC
- **Output Voltage**: 1.2kV\_DC
- **Efficiency Goal**: 97%

**ISOP Topology** – 6/2x3 - Input / Output
MV – LV DCDC Conversion

- Rated Power: 1MW (MEGA Cube)
- Frequency: 20kHz
- Input Voltage: 12kV<sub>DC</sub>
- Output Voltage: 1.2kV<sub>DC</sub>
- Efficiency Goal: 97%

■ ISOP Topology – 6/2x3 - Input / Output
Conclusions

SST Evaluation / Application Areas
Future Research Areas
SST Ends the “War of Currents”

No “Revenge” of T.A. Edison but Future “Synergy” of AC and DC Systems!
SST Technology Hype Cycle

- Different States of Development of SSTs for
  - Traction Applications
  - Hybrid / Smart Grid Applications
SST for Grid Applications

- Huge Multi-Disciplinary Challenges / Opportunities (!)

Source: www.diamond-jewelry-pedia.com
SST Limitations – Application Areas

- **SST Limitations**
  - Efficiency (Rel. High Losses 2-6%)
  - High Costs (Cost-Performance Ratio still to be Clarified)
  - Limited Volume Reduction vs. Conv. Transf. (Factor 2-3)
  - Limited Overload Capability
  - (Reliability)

- **Potential Application Areas**
  - Traction Vehicles
  - UPS Functionality with MV Connection
  - Temporary Replacement of Conv. Distribution Transformer
  - Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)
  - Military Applications

 Applications for Volume/Weight Limited Systems where 2-4 % of Losses Could be Accepted
Overall Summary

- SST is **NOT** a 1:1 Replacement for Conv. Distribution Transformers
- SST will **NOT** Replace All Conv. Distribution Transformers (even in Mid Term Future)
- SST Offers High Functionality BUT shows also Several Weaknesses / Limitations

→ SST Requires a Certain Application Environment (until Smart Grid is Fully Realized)
→ SST Preferably Used in LOCAL Fully SMART EEnergy Systems

  @ Generation End (e.g. Nacelle of Windmills)
  @ Load End - Micro- or Nanogrids (incl. Locomotives, Ships etc.)

- Environments with Pervasive Power Electronics for Energy Flow Control (No Protection Relays etc.)
- Environments which Could be Designed for SST Application
- (Unidirectional) Medium Voltage Coupling of DC Distribution Systems
... One Last Comment

Electrification of the Developing World
Rural Electrification in the Developing World

- 2 Billion “Bottom-of-the-Pyramid People” are Lacking Access to Clean Energy

- Urgent Need for Village-Scale Solar DC Microgrids etc.
- 2 US$ for 2 LED Lights + Mobile-Phone Charging / Household / Month (!)
Thank You!
Questions?