Solid-State Transformers
Key Design Challenges, Applicability, and Future Concepts

Johann W. Kolar, Jonas E. Huber
Power Electronic Systems Laboratory
ETH Zurich, Switzerland
What Is a SST?

Transformer History and Basics
SST Definition
### Classical Transformer — History (1)

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<td>Easy Manufact. XFMR (1st Full AC Distr. Syst.)</td>
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[Stanley1886]
Classical Transformer — History (2)

- 1889 Dobrovolsky → 3-Phase Transformer
- 1891 1st Complete AC System (Gen. + XFMR + Transm. + El. Motor + Lamps, 40Hz, 25kV, 175km)

[Dobrovolski1890]
Classical Transformer — Basics

- **Magnetic Core Material**
  - Silicon Steel / Nanocrystalline / Amorphous / Ferrite

- **Winding Material**
  - Copper or Aluminum

- **Insulation / Cooling**
  - Mineral Oil or Dry-type

- **Operating Frequency**
  - 50/60Hz (El. Grid, Traction) or $16^2/3$Hz (Traction)

- **Operating Voltage**
  - 10kV or 20kV (6…35kV)
  - 15kV or 20kV (Traction)
  - 400V

- **Voltage Transfer Ratio**
  - Fixed

- **Current Transfer Ratio**
  - Fixed

- **Active Power Transfer**
  - Fixed ($P_1 \approx P_2$)

- **Reactive Power Transfer**
  - Fixed ($Q_1 \approx Q_2$)

- **Frequency Ratio**
  - Fixed ($f_1 = f_2$)

- **Magnetic Core Cross Section**
  \[ A_{Core} = \frac{1}{\sqrt{2}\pi B_{max}} \frac{U_1}{f_1 N_1} \]

- **Winding Window**
  \[ A_{Wdg} = \frac{2I_1}{k_{WJ_{rms}}} N_1 \]
**Transformer Scaling Laws (1)**

- **Area Product:**
  \[
  A_{\text{Core}} = \frac{1}{\sqrt{2\pi}} \frac{U_1}{B_{\text{max}} f N_1}
  \]

- **Volume:**
  \[
  V \propto \left( A_{\text{Core}} A_{\text{Wdg}} \right)^{3/4} \propto \frac{1}{f^{3/4}}
  \]

**Caution:** Too Optimistic!
- Constant Isolation Material Thickness
- Lower Fill Factor \(k_W\) because of Litz Wires

**Gain of Frequency Increase Depends on Grid Frequency**
 Transformer Scaling Laws (2)

- Scaling of Core Losses
  \[ P_{\text{Core}} \propto f_P \left( \frac{\Phi}{A} \right)^2 V \]
  \[ P_{\text{Core}} \propto \left( \frac{1}{l^2} \right)^2 l^3 \propto \frac{1}{l} \]

- Scaling of Winding Losses
  \[ P_{\text{Wdg}} \propto I^2 R \propto \frac{I^2 l_{\text{Wdg}}}{\kappa A_{\text{Wdg}}} \]
  \[ P_{\text{Wdg}} \propto \frac{1}{l} \]

- Higher Relative Volumes (Lower kVA/m³) Allow to Achieve Higher Efficiencies

Increasing Size (l)
Classical Transformer — Summary (1)

**Advantages**

- Relatively Inexpensive
- **Highly Robust / Reliable**
- **Highly Efficient (98.5%...99.5% Dep. on Power Rating)**
- Short Circuit Current Limitation

**Weaknesses**

- Voltage Drop Under Load
- **Losses at No Load**
- Sensitivity to Harmonics
- Sensitivity to DC Offset Load Imbalances
- Provides No Overload Protection
- Possible Fire Hazard
- Environmental Concerns
- **Low Frequency → Large Weight / Volume**

Image: http://www.hieco-electric.com
Classical Transformer — Summary (2)

Advantages

- Relatively Inexpensive
- Highly Robust / Reliable
- Highly Efficient (98.5%...99.5% Dep. on Power Rating)
- Short Circuit Current Limitation

Source: http://www.africancrisis.org
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.

- Electronic Transformer ($f_1 = f_2$)
- AC or DC Voltage Regulation & Current Regulation / Limitation / Interruption
Electronic Transformer

- Inverse-Paralleled Pairs of Turn-off Switches
- 50% Duty Cycle of Input and Output Stage

- $f_1 = f_2 \rightarrow$ Not Controllable (!)
- Voltage Adjustment by Phase Shift Control (!)

[McMurray1968]
What is a Solid-State Transformer (SST)?

- **Power Electronics Interface**
- **Medium Voltage** Connection
- **Medium Frequency** Isolation Stage
- Communication Link

- **I/O Quantities**
  - DC/DC
  - AC/DC
  - $AC_{f1}/AC_{f1}$
  - $AC_{f1}/AC_{f2}$
  - 1ph, 3ph, var. $f$, etc.
  - MV/LV, MV/MV

- **Terminology**

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.

[Brooks1980]
Example SST System: ETH MEGAlink SST Concept

Specifications

- 1 MVA
- 10 kV AC to 800 V DC and 400 V AC
- 1700V IGBTs on MV Side

Commonly Envisioned Features

- Voltage Scaling & Galvanic Isol.
- Power Flow Control
- Reactive Power Compensation
- Fault Current Limiting
- DC Interface
- ...

MV Connection

MF Isolation
The Solid-State Transformer Hype

Evolution of # of SST Publications Per Year:

- Identify Origin and Evolution of Key Concepts
- Narrow Down Feasible Solutions by Identifying Core Requirements, e.g., Modularity

Google Scholar Hits for Query: ("solid-state transformer") OR ("electronic transformer") OR ("Intelligent Universal Transformer") OR ("Power Electronic Transformer") OR ("Power Electronics Transformer")

How To Keep An Overview?
SST Concept Motivations

Traction \rightarrow Weight & Volume
Smart Grid \rightarrow Controllability
DC-DC Conversion
Classical Locomotives (1)

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

- Isolated AC/DC Conversion (!)
- Volume & Weight Constraints

Main Transformer

Images: www.abb.com

Images: www.elprocus.com
Classical Locomotives (2)

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

- Isolated AC/DC Conversion (!)
- Volume & Weight Constraints

- Traction Transformer
  $$A_{\text{Core}}A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_W J_{\text{rms}} B_{\text{max}} f}$$

$\rightarrow$ Volume/Weight Reduction By Increasing $J_{\text{rms}}$

- Efficiency: 90...95% (99% Typ. for Distr. Transf.)
- Current Density: 6 A/mm$^2$ (2A/mm$^2$ Typ. for Distr. Transf.)
- Power Density: 2...4 kg/kVA
Next Generation Traction Systems

- **It’s Getting Tougher!**
  - Distributed Propulsion → Volume Constraints
  - Low-Floor Vehicles → Weight Constraints
  - High-Speed Trains → Weight Constraints
  - Impr. Energy Efficiency → Loss Constraints
    (Space for Add. Seats)
    (Roof Mounting)
    (Higher Power at Same Max. Axle Load Limit)
    (No Further Increase of $J_{rms}$, etc.)

- **What Degrees of Freedom Are Left?**

\[
A_{\text{Core}}A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_{WJ_{rms}}B_{max}f}
\]

\[
V \propto (A_{\text{Core}}A_{\text{Wdg}})^{\frac{3}{4}} \propto \frac{1}{f^{\frac{3}{4}}}
\]

→ Frequency as DOF to Reduce Weight & Volume!

1.74kg/kVA @ 16.6Hz

0.17kg/kVA @ 400Hz

Factor 1/10 (!)

[Victor2005]

[Hazeltine1923]
Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives

- Medium Freq. Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction
SST Concept Motivations

Traction → Weight & Volume

*Smart Grid* → *Controllability*

DC-DC Conversion
Advanced (High Power Quality) Grid Concept

- Heinemann (2001)

- MV AC Distribution with DC Subsystems (LV and MV) and Large Number of Distributed Resources
- MF AC/AC Conv. with DC Link Coupled to Energy Storage provide High Power Qual. for Spec. Customers

[Heinemann2001]
## Smart Grid Concept

- Boroyevich (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 Communic.
- Intentional / Unintentional Islanding for Up- or Downstream Protection
- etc.
Future Ren. Electric Energy Delivery & Management (FREEDM) System

- Huang et al. (2008)
- SST as Enabling Technology for the “Energy Internet”
  - Integr. of DER (Distr. Energy Res.)
  - Integr. of DES (Distr. E-Storage) + Intellig. Loads
  - Enables Distrib. Intellig. through COMM


[Huang2009, Huang2011], Figs.: [Falcones2010]
SST Functionalities

- **Protects Load from Power System Disturbance**
  - Voltage Harmonics / Sag Compensation
  - Outage Compensation
  - Load Voltage Regulation (Load Transients, Harmonics)

- **Protects Power System from Load Disturbance**
  - Unity Inp. Power Factor Under Reactive Load
  - Symmetrizes Load to the Mains
  - Protection against Overload & Output Short Circ.

- **Further Characteristics**
  - **Operates on Distribution Voltage Level (MV-LV)**
  - Integrates Energy Storage (Energy Buffer)
  - DC Port for DER Connection
  - **Medium Frequency Isolation → Low Weight / Volume**
  - Definable Output Frequency (1-ph. AC, 3-ph. AC, DC)
  - High Efficiency
  - No Fire Hazard / Contamination
  - Supervisory Control / Status Monitoring Interface
“Efficiency Challenge” (Qualitative)

- **SSTs in Grid Applications – A Skeptic’s View**
  - Efficiency of LFT for AC/AC Very Hard To Attain
  - Weight/Volume Typically Not an Issue In Stationary Grid Applications
  - Robustness, Reliability?
  - Cost?
SST Concept Motivations

Traction → Weight & Volume
Smart Grid → Controllability
DC-DC Conversion
**Isolated DC-DC Applications**

- **Examples**
  - In-Building DC Microgrids
  - DC Collection Grids (Wind, PV)
  - Future DC Grids in General

- DC Systems With Galvanic Separation Requirements → **Isolated DC-DC Conversion = SST!**
- Not Limited to MV Connection (Overlap With PSUs)

- **Transformer Operating Frequency Can Be Freely Chosen!**
11 Key Challenges of SST Design

1. Handling of Medium Voltage
2. Topology Selection
3. Reliability
4. MF Isolated Power Converters
5. MF Transformer Design
6. Isolation Coordination
7. EMI
8. Protection
9. Control
10. Construction of Modular Conv.
11. Testing of MV Converters
Challenge #1/11

Handling of Medium Voltage

Multi-Cell Approaches
Optimum Blocking Voltage
Single-Cell Approaches
Outlook
**Interfacing Medium Voltage With Power Electronics**

- Limited Blocking Voltages of Available Semiconductors
  - 6.5kV for Si IGBTs
  - 10-15kV for SiC FETs (Prototype Devices Only)

- Feasible Blocking Voltage Utilization: Only 50-70% (Cosmic Ray Induced Failures)

![Diagram showing series devices and grid voltage](Image)

- A Single Device Is Often Not Sufficient!

![Graph with series devices and grid voltage](Image)

- Mod. Index.: 0.8
- Blocking Voltage Utilization: 0.66
United States Patent

[54] FAST RESPONSE STEPPED-WAVE SWITCHING POWER CONVERTER CIRCUIT

[72] Inventor    William McMurray
                Schenectady, N.Y.

[22] Filed       July 31, 1969
[45] Patented    May 25, 1971
[73] Assignee    General Electric Company

1969!

- Cascading of Converter Cells
- Multilevel Output Voltage

Fig. 1

[McMurray1969]
Cascaded Converter Cells Instead of Direct Series Connection

- **Direct Series Connection is Suboptimal**
  - Voltage Sharing (Static and Dynamic)
  - Switching Synchronization
  - No Add. Benefit of Multiple Switches

- **Added Value: Multiple Converter Cells**
  - Modularity, Redundancy
  - Multilevel Output Voltage Waveform
    \[ f_s \propto \frac{1}{N_{\text{Cell}}}^2 \] for Same Filter Inductor
Challenge #1/11
Handling of Medium Voltage

Multi-Cell Approaches
Optimum Blocking Voltage
Single-Cell Approaches
Outlook
Basic Trade-Offs: Conduction Losses

- **More Cells, More Series Voltage Drops (IGBTs):**

\[ P_{\text{cond}} \propto n \]

- **Reality:** Voltage Drop Increases with Blocking Voltage Due to Larger Drift Region
Basic Trade-Offs: Switching Losses

- For Equal Current Ripple in Equal Filter Inductors
  - Switching Frequency (per Cell): $f_S \propto 1/n^2$
  - Cell DC Voltage: $V_{DC} \propto 1/n$
  - But: Number of Cells: $\propto n$

Switching Loss Modeling (Qualitative)

- Assumed
  - $P_{SW} \propto 1/n^2$

- Reality
  - $P_{SW} \propto 1/n^{2...3}$

Switching Losses

$P_{SW} \propto 1/n^2$ (❗)

Normalized IGBT Turn-Off Energies
Loss-Optimal Blocking Voltage Choice

- For Equal Current Ripple in Equal Filter Inductors
  
  - 10kV Grid Voltage  ▶ There Is an Optimum Blocking Voltage
  
  ![Graph showing total losses, switched losses, and conduction losses with optimum blocking voltage at 1200V and 1700V]

- Other Grid Voltages
  
  ![Graph showing optimum grid voltage for different grid voltages: 600V, 1200V, 1700V, 2.5kV, 3.3kV, 4.5kV, 6.5kV]
Optimal (Efficiency & Power Density!) Blocking Voltage (1)

- Volume as 2nd Dimension: Varying Also the Filter Inductance!

- Modeling of Component Losses and Volumes (Inductor, Heatsinks, Capacitors, IGBTs, etc.)
Optimal (Efficiency & Power Density!) Blocking Voltage (2)

- Volume as 2\textsuperscript{nd} Dimension: Varying Also the Filter Inductance!

- Component Losses and Volumes (Inductor, Heatsinks, Capacitors, IGBTs, etc.)

- Caution: Minimum Filter Inductance Might be Defined By Application-Dependent Protection Considerations

Further Reading: ETH / [Huber2016b]
Enter Silicon Carbide: Si vs. WBG (SiC/GaN) Semiconductors

\[ W_D = \frac{2BV}{E_{\text{crit}}} \]

Amount of semiconductor material needed to isolate 10,000V

Specific On-State Resistance

\[ R_{\text{on,sp}} = \frac{4BV^2}{\varepsilon \mu n E_c^3} \]

Blocking Voltage

Critical Electric Field

- \( E_c \) in SiC ca. 9x Larger Than in Si
- Lower \( R_{\text{on,sp}} \) For Given Blocking Voltage

Unipolar Si Limit

Unipolar 4H-SiC Limit

Bipolar Si (!) Limit

But: Bipolar \( \rightarrow \) Sw. Losses!
Example: All-SiC Traction Inverter

- Mitsubishi All-SiC Traction Inverter (2014)

- **3.3kV/1.5kA** SiC Modules in All-SiC Traction Inverter

- **65%** Reduction of Size and Weight
- **55%** Loss Reduction

![Image of Mitsubishi All-SiC Traction Inverter](image)

![Graph showing rated voltage for power device](graph)
Optimal (Efficiency & Power Density!) Blocking Voltage with SiC

1200V and 1700V SiC FET Power Modules for Comparison

Caution: Minimum Filter Inductance Might be Defined By Application-Dependent Protection Considerations

Si IGBT → SiC Transition Yields Significant Benefits!

Further Reading: ETH / [Huber2016b]
Challenge #1/11
Handling of Medium Voltage

Multi-Cell Approaches
Optimum Blocking Voltage
Single-Cell Approaches
Outlook
Enter HV SiC Power Semiconductors

- $E_c$ in SiC ca. 9x Larger Than in Si
- Lower $R_{on,sp}$ For Given Blocking Voltage
- Or: Higher Blocking Voltage for Given $R_{on,sp}$

- 10…15kV Prototype Devices Are Available

- Challenging HV Packaging

10kV SiC MOSFET (Wolfspeed)

15kV/80A Package (Wolfspeed)
**Single-Cell Approach: The Positive Aspects**

- Standard Inverter Topologies Can Be Employed (Two-Level, Three-Level)
- Comparably **Low System Complexity**

- **Three-Phase Inverter Stage**
  - Constant Power Flow In Isolation Stage (!)

- Max. Feasible Grid Voltages Limited By Blocking Voltages

---

**Graphical Representation:**

- **22kV DC Bus**
- **DC-DC Isolation Stage**
- **800V**

**Assumptions:**

\[ u = 0.7, \quad M = 0.9 \]

**Graph:**

- Three-Level
- Two-Level

**Equation:**

\[ 2L + 10kV \text{ SiC} \]

\[ \rightarrow 4.16kV \text{ Max.} \]
Single-Cell Approach: The Challenging Aspects

- Low Number of Levels → Remember: $f_s \propto 1/n^2$
- High Switching Frequency and/or Large Filter Inductor

- “Virtual” Devices By Adapting $t_s$ (and thus $di/dt$ and $dv/dt$)
- Pareto Optimization for Two-Level, Single-Phase (!) System

- Very Fast Switching Transitions Required
  - High $dv/dt$ → CM Disturbances
  - High $di/dt$ → Overvoltages

Further Reading: ETH / [Huber2016b]

- Implementation of Redundancy?
Challenge #1/11
Handling of Medium Voltage

Multi-Cell Approaches
Optimum Blocking Voltage
Single-Cell Approaches
Outlook
Outlook: Single-Cell vs. Multi-Cell

Strategies for Handling Medium Voltage Connection

- Multi-Cell Approach
  - LV Devices, Multilevel Waveforms, Redundancy, “Divide et Impera”
  - Complexity, Phase-Modular Topologies

- Single-Cell Approach
  - Simplification of Converter Structure, Three-Phase Topologies

The Best of Both Worlds?

- FEWER-Cells Approach
  - Higher DC Voltage per Cell
  - Less Cells, Lower Complexity
  - Multilevel Waveforms
  - Redundancy

Suitable Choice Depends on Application Voltage and Power Levels

Careful Choice/Optimization of Blocking Voltage for Multi-Cell Systems

Img: [Passmore2015]
Challenge #2/11
Topology Selection

Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity
Classification of SST Topologies

Conclusion: Main SST Topologies
Partitioning of the AC/AC Power Conversion

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
Partitioning of the AC/AC Power Conversion

1st Degree of Freedom of Topology Selection

- 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)

- 3-Stage Power Conversion with MV and LV DC Link
  → Requires HV Devices (!)
Challenge #2/11

Topology Selection

Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity
Classification of SST Topologies

Conclusion: Main SST Topologies
Partial or Full Phase Modularity

- 2\textsuperscript{nd} Degree of Freedom of Topology Selection
  → Partial or Full Phase Modularity

  - Phase-Modularity of Electric Circuit
  - Phase-Modularity of Magnetic Circuit
Partial or Full Phase Modularity: Examples

- **2\textsuperscript{nd} Degree of Freedom of Topology Selection** → Partial or Full Phase Modularity


  - Example of **Partly Phase-Modular SST**

- **Enjeti (1997)**
  [Kang1999]

- **Steimel (2002)**
  [Wrede2002]
Partitioning of Single-Phase AC/DC PFC Functionality

- **Required Functionality**
  - **F**: Folding of the AC Voltage into a $|AC|$ Voltage
  - **CS**: Input Current Shaping
  - **I**: Galvanic Isolation & Voltage Scaling
  - **VR**: Output Voltage Regulation

- **Isolated PFC Task Partitioning Variants**

  **Isolated Back End (IBE)** ➤
  - Broadly Analyzed and Employed in SSTs

  **Fully Integrated** ➤

  **Isolated Front End (IFE)** ➤
  - Less Common Alternative

One Phase of Phase-Modular 3ph-SST ➔ Single-Phase System!
Examples of Multi-Cell AC/DC SST Topologies

- **Isolated Back End (IBE)**

  ![Diagram of Isolated Back End (IBE)]

  [Steiner1998], [Steiner2000], [Dujic2013], [Zhao2014]

- **Isolated Front End (IFE)**

  ![Diagram of Isolated Front End (IFE)]

  [Weiss1985], [Han2014], [Kolar2016], [Huber2016a]
Challenge #2/11

Topology Selection

Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity

Classification of SST Topologies

Conclusion: Main SST Topologies
Classification of SST Topologies

- **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 Voltage into Lower Partial Voltages → Multi-Level/Cell Approaches
**Side Note: Unidirectional SSTs**

- Simplification of Topologies for Unidirectional Power Flow
- SST As **MV-Connected Power Supply**

![Example Topology: Unidirectional Multi-Cell Boost Topology](image)

**Example Applications**

- Direct Supply of 400V/48V DC System from 6.6kV AC
- Direct PV Energy Regeneration from 1kV DC into 6.6kV AC

[VanDerMerwe2009a]
[VanDerMerwe2009b]
ETH / [Rothmund2014]
Challenge #2/11

Topology Selection

Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity
Classification of SST Topologies

Conclusion: Main SST Topologies
Main SST Topologies (1)

- Multi-Cell Topologies
  - Isolated Back End
  - Isolated Front End
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)

- Single-Cell Topologies

Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, AC/AC Conversion, NPC Cells, DC-DC Converter Type, Unidirectionality, etc.)

[Steiner1998]
[Steiner2000]
[Dujic2013]
[Zhao2014]
Main SST Topologies (2)

- Multi-Cell Topologies
  - Isolated Back End
  - **Isolated Front End**
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)

- Single-Cell Topologies

Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, AC/AC Conversion, NPC Cells, Unidirectionality, etc.)
Main SST Topologies (3)

- Multi-Cell Topologies
  - Isolated Back End
  - Isolated Front End
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)

- Single-Cell Topologies

Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, NPC Cells, Unidirectionality, etc.)
Main SST Topologies (4)

- **Multi-Cell Topologies**
  - Isolated Back End
  - Isolated Front End
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)

- **Single-Cell Topologies**

- **Note**: Specific Realizations May Vary (e.g., 3-Phase Configurations, AC/AC Conversion, Bidirectionality, etc.)

[Glinka2003], Img.: ETH / [Rothmund2014]
Main SST Topologies (5)

- Multi-Cell Topologies
  - Isolated Back End
  - Isolated Front End
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)

- Single-Cell Topologies

Note: Specific Realizations May Vary
(e.g., DC-DC Converter Type, Unidirectionality, etc.)
SST Topologies Summary & Outlook

- High Number of Possible SST Topologies
  → **Optimum Topology Choice Depends on Specific Application Requirements!**

- **Trends And Outlook**
  - LV SiC Devices
  - **HV SiC Devices / Single-Stage SSTs**
  - Reliability Considerations Are Highly Important
Challenge #3/11

Reliability

Basics of Reliability Modeling
Cell-Level Redundancy
“Reliability Bottlenecks”
Example System: ETH MEGAlink Distribution SST

Specifications

- 1 MVA
- 10 kV AC to 800 V DC and 400 V AC
- 1700V IGBTs on MV Side

Modular System → MANY Components!

→ Can Such a System Still Be Reliable?
Reliability Considerations for SST Design

Remember:

Conventional Transformers are Highly Reliable and Robust

- Copper, Iron and Oil

VS.

- High # of Semiconductors, Gate Drives, Measurement and Control Electronics, Cooling Systems, ... (!)

Very High Reliability Requirements for Grid and Traction Equipment

Include Reliability Considerations Early in the SST Design Process

- Reliability Block Diagrams
- Design for Reliability Approach [Wang2013]
- Etc.

Textbook: [Birolini1997]

Source: http://www.africancrisis.org
Modeling Reliability: The Failure Rate

- In General, the **Failure Rate** $\lambda(t)$ is a Function of Time

- Here, Only **Useful Life** is Considered
  - Dominated by Random Failure Distribution
  - Constant Failure Rate $\lambda$
  - $[\lambda] = 1$ FIT (1 Fail. in $10^9$ h) – Typ. Value for an IGBT Mod.: 100 FIT

- Example Sources for Empirical Component Failure Rate Data
  - Stds. Define Base Failure Rates for Comp. and Factors to Account for Stress Levels (e.g., Temperature)
Modeling Reliability: The Reliability Function

- **Expresses** Probability of System Being Operational After \( t \) Hours

- **General Definition:**

\[
R(t) = e^{-\int_0^t \lambda(x)\,dx}
\]

- **During Useful Life:** \( \lambda(t) = \text{const.} = \lambda \):

\[
R(t) = e^{-\lambda t}
\]

- **Mean Time Between Failures**

\[
MTBF = \int_0^{\infty} R(t)\,dt = \int_0^{\infty} e^{-\lambda t}\,dt = \frac{1}{\lambda}
\]

**Caution:** MTBF is **Not** the Time Before Which No Failure Occurs – It’s All Statistics!

- **Average Availability:**

\[
A = \frac{MTBF}{MTBF + MTTR}
\]

Textbook: [Birolini1997]
Modeling Reliability: Basic Multi-Element Considerations

**Series Structure**
(e.g. Components of a Single Converter Cell)

\[ \lambda_S = \sum_{i=1}^{n_{\text{comp.}}} \lambda_i \]

(General Assumption: Independent Elements with Equal Failure Rate.)

**k-out-of-n Redundancy**
(e.g., Redundancy of Cells in a Phase Stack)

- System is Operational as Long as At Least \( k \) out of \( n \) Subsystems (Cells) Are Operational

Effect of \( q \) Additional Redundant Cells

Textbook: [Birolini1997]
The “Power of Redundancy” (1)

- Remember: \[ MTBF = \int_0^\infty R(t) \, dt \]
  - Area Below Reliability Function!

- Redundancy Can Significantly Improve System Level Reliability
  - 10 Elements + 2 Redundant: Reliability Higher than for 5 Elements!
The “Power of Redundancy” (2)

- **Value of Reliability Function at** $t = 25$ **Years**
  (Probability That System Is Operational After 25 Years)

  - $N$ Elements
  - $q$ Additional Redundant Elements

  ![Diagram showing reliability function for different values of $q$](image)

- **Redundancy Can Significantly Improve System Level Reliability**

  - E.g., for $N = 40$: from 40% to > 90% with 2 Additional Redundant Cells
Example System: Cell Redundancy

Modular System → Simple Implementation of Cell Redundancy!

Redundancy Concepts
- Standby Redundancy
- Active Redundancy with Load Sharing

Basic Assumptions
- Failure Rate of a Cell: $\lambda_{cell}$
- Failure Rate of Stack: $\lambda_{cell}^{n_{cell}}$ (w/o Redundancy)
Example System: Cell Redundancy and Reparability

- **Reparability**: Faulty Cell Can Be Replaced On-Site; Possibly Even In a Hot-Swap Operation
  - Example: **Mean Time To Repair (MTTR)** of One Week Assumed

**Graph:**
- 29 Required Cells + 2 Redundant Cells
- 15 Required Cells + 1 Redundant Cells

**Note 1:** 50% Of Cell FIT Rate Is Assumed To Be Proportional To Blocking Voltage
**Note 2:** Absolute MTBFS Values Depend on FIT Rate Assumptions; Relative Results Stay The Same

- **Multi-Cell Designs Can Be Made Highly Reliable By Adding Redundancy!**
- Preventive Maintenance Can Further Improve System Availability

Further Reading:
ETH / [Huber2016b]
Reliability “Bottlenecks”

- Reliability Improvement by Means of Cell-Level Redundancy Is
  - Very Effective

  - But Limited by Other Parts of the Converter System
    - Control
    - Auxiliary Supplies
    - Communication
    - Bypass Devices
    - ...

[Grinberg2013]
Redundancy In Single-Cell Systems

- Example: MV Motor Drive

Redundant Series Devices

- Press-Pack NPC Phase Module (Converteam GmbH)

- **Fail-To-Short Behavior Required!**
- Only Feasible With IGBT Press Pack Modules

[Image: powerguru.org]

[Image: M. Hiller, KIT]

[Image: StakPak Subunit (Submodule)]

[Image: StakPak Module]

[Image: powerguru.org]

[Hiller2016]
Challenge #4/11

MF Isolated Power Converters

- Dual Active Bridge
- HC-DCM Series Resonant Converter
Example System: ETH MEGAlink Distribution SST

Specifications

- 1 MVA
- 10 kV AC to 800 V DC and 400 V AC
- 1700V IGBTs on MV Side

Each Converter Cell Contains

- Active Rectification Unit (ARU)
- Isolated DC/DC w. Fixed Voltage Transfer Ratio
**Power Flows in Phase-Modular Solid-State Transformers**

- **MV:** 100 Hz Power Fluctuation in Single-Phase Systems

- **DC/DC Converter Power Flow**
  How To Handle The Single-Phase Power Fluctuation?

- **Buffering ↔ Transmission**
  Capacitor Vol. ↔ RMS Currents

- **MV DC Voltage Ripple**

- **LV:** Constant Power Behavior of Three-Phase Systems

10kV MV AC Grid

\[ P_{out} = \bar{P}_R + \bar{P}_S + \bar{P}_T \]

800V DC Bus

- **1kV MV AC Grid**
Challenge #4/11
MF Isolated Power Converters

Dual Active Bridge
HC-DCM Series Resonant Converter
■ Soft Switching in a Certain Load Range
■ **Power Flow Control by Phase Shift between Primary & Secondary Voltage**
Common Bridge Configurations

- **Full-Bridge**

  ![Full-Bridge Diagram]

  - Three Voltage Levels on Each Side

- **NPC / Full-Bridge Configuration**

  ![NPC Full-Bridge Diagram]

  - Suitable for Higher MV/LV Ratios

- Other Configurations Possible (Half-Bridge / Half-Bridge, etc.)
Phased-Shift Modulation (1)

- **Power Transfer Controlled** Through Phase Shift Between MV and LV Bridges

![Diagram of power transfer controlled through phase shift between MV and LV bridges.]

Fundamental model of the dual bridge dc/dc converter.

Comparison of the output power versus $\phi$, at $d = 1$, from the fundamental model and actual model.

$$P_0 (\text{pu}) = \frac{V_{fi}^2}{\omega L} d \sin (\phi)$$

[DeDoncker1989]
Phase-Shift Modulation (2)

- All Switching Transitions done in ZVS Conditions (within a Certain Operating Range)
**Phase-Shift / Duty Cycle Modulation**

- **Additional Degrees of Freedom** Can Be Utilized for Optimization
- For Example: Minimization of the RMS Currents through the Transformer

![Graph showing phase-shifted duty cycle modulation](Image)

- Not Possible in Half-Bridge Configurations (No Zero Voltage Intervals)

[Ref. Krismer2012]
Duty Cycles and Phase Shift Utilized to Perform **Zero Current Switching (ZCS)**

- **Triangular Current Modulation**

  - ZCS on MV Side (!)
  - ZCS on MV and LV Sides
  - HV IGBT Switching Loss Reduction

![Diagram of power electronic system with descriptions and waveforms showing voltage and current relationships for ZCS on MV and LV sides.](image-url)
Challenge #4/11
MF Isolated Power Converters

Dual Active Bridge
HC-DCM Series Resonant Converter
A Method of Resonant Current Pulse Modulation for Power Converters

FRANCIS C. SCHWARZ, SENIOR MEMBER, IEEE

Fig. 4. Alternative simplified schematic of a controllable and load-insensitive series capacitor dc converter with transfer of inductive energy to the load.

[Schwarz1970]
[McMurray1971]
**Half-Cycle Discont.-Cond.-Mode Series-Res.-Conv. (HC-DCM SRC)**

- **Operating Principle:** Resonance Frequency $\approx$ Switching Frequency $\rightarrow$ Unity Gain

- The Input/Output Voltage Ratio is Close to Unity, Independent of Power Transfer

- ZCS of All Devices

*Img.: [Zhao2014]*
**HC-DCM SRC Switching Transitions**

- **Zero Current Switching (ZCS) For All Transitions**

- **Load-Independent Zero Voltage Switching (ZVS)**
  Using The Magnetizing Current

- **Loss Optimization With Magnetizing Current and Interlock Time**

- **Example:** 1700V IGBT

Further Reading: ETH / [Huber2013a]  
ETH / [Ortiz2013a]
**HC-DCM SRC: “DC Transformer” Behavior**

- **Ideal** (Lossless Components)
  - Steady State: \( V_{\text{out}} = V_{\text{in}} \)

- **Real**
  - Steady State: \( V_{\text{out}} \approx V_{\text{in}} \)
    - (Deviation Due to Losses)
  - Tight Coupling of DC Input and Output Voltages

- Acts as “DC Transformer” with Certain Dynamics!

- **No Control Possible/Required!**

- **Disturbance**
  - \( V_{\text{out}} \neq V_{\text{in}} \)

- **Steady State 1**
  - \( i_{T,1} = \frac{\hat{V}_{\text{Cr},0,1}}{Z_0} \)
  - \( V_{\text{out}} = V_{\text{in}} \)

- **Steady State 2**
  - \( i_{T,2} = \frac{\hat{V}_{\text{Cr},0,2}}{Z_0} \)
  - \( V_{\text{out}} = V_{\text{in}} \)

- Source Bridge \( \rightarrow \) Actively Switched Only
- Sink Bridge \( \rightarrow \) Passive Operation (Diodes)
HC-DCM SRC Dynamic Modeling of Terminal Behavior

How to Choose Eq. Circ. Element Values?

- \( R_{dc} \) (Equal RMS Losses):
  \[
  \frac{i_R^2}{R_{dc}} = \frac{i_R^2}{R_{total}} \quad \Rightarrow \quad R_{dc} = \frac{i_R^2}{i_R^2} R_{total} = \beta^2 R_{total}
  \]

- \( L_{dc} \) (Equal Stored Energy):
  \[
  \frac{i_R^2}{L_{dc}} = \frac{i_R^2}{L_{\sigma}} \quad \Rightarrow \quad L_{dc} = \frac{i_R^2}{i_R^2} L_{\sigma} = \alpha^2 L_{\sigma}
  \]

Dynamic Equivalent Circuit
- Modeling of Terminal Behavior
- Based on Local Average Current, \( \tilde{i}_R \)

Further Reading: [Esser1991], [Steiner2000], ETH / [Huber2015]
Again: Power Flows in Phase-Modular SSTs

- MV: 100 Hz (120 Hz) **Power Fluctuation** in Single-Phase Systems

10kV MV AC Grid

- 100 Hz (120 Hz) Power Fluctuation in Single-Phase Systems
- Higher RMS Current (23%) in Transformer and DC-DC Switches
- Appropriate Dimensioning

- HC-DCM SRC **Dynamics**
  - MV DC Volt.: 100 Hz Fluct.
  - LV DC Volt.: Constant

→ **Transmission of Full Single-Phase Power Fluctuation!**
  - Higher RMS Current (23%) in Transformer and DC-DC Switches
  - Appropriate Dimensioning

- **LV: Constant Power** Behavior of Three-Phase Systems

Further Reading: ETH / [Huber2015]
Realization Options for DC/DC Converters in SST Cells

- **Dual Active Bridge (DAB)**
  - Can (Must!) Be Fully Controlled
  - Arbitrary Choice in Losses ↔ Capacitor Volume Trade-Off
  - Potentially Lower RMS Currents

- **Half-Cycle Discont.-Conduction-Mode SRC (HC-DCM SRC)**
  - Does Not Have To (Can Not!) Be Controlled (!)
  - Reduces Complexity in Multi-Cell Systems
  - Ensures MV Side Voltage Balancing

► Predominant Solution in Multi-Cell SSTs!
Challenge #5/11
MF Transformer Design

Transformer Types
Litz Wire Issues
General Challenge of MF Transformers

- Higher Operating Frequency
- Lower Unit Power Rating

\[ A_{\text{Core}} A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_{WJ_{\text{rms}}B_{\text{max}}f}} \]

- Smaller Active Volume
- Same Isolation Voltage (!)

Isolation vs. Cooling Trade-Off

- Solid Isolators → Bad Thermal Conductors

Oil = Coolant And Isolator (!)
**MF Transformer Design – Transformer Types**

- **Main Transformer Types as Found in Literature**

  - **Coaxial Cable**
  - **Shell-Type**
  - **Core-Type**

- **Transformer Construction Types**
  - Very Limited by Available Core Shapes in this Dimension Range
  - Shell-Type has Been Favored Given Its Construction Flexibility and Reduced Parasitic Components
**MF Transformer Examples (1)**

- **Coaxial Cable Winding**
  - Extremely Low Leakage Inductance
  - Reliable Isolation due to Homog. E-Field
  - Low Flexibility on Turns Ratio (1:1)
  - Complex Terminations

- Heinemann (ABB, 2002)  
  [Heinemann2002]
MF Transformer Examples (2)

Coaxial Windings – Core Type

• Tunable Leakage Inductance
• More Complex Isolation
• Total Flexibility on Turns Ratio
• Simple Terminations

Hoffmann (2011)
[Hoffmann2011]
MF Transformer Examples (3)

Coaxial Windings – Shell Type

- Tunable Leakage Inductance
- More Complex Isolation
- Total Flexibility on Turns Ratio
- Simple Terminations

- 8kHz, 350kW
- Water Cooling (Hollow Conductors)
- Isolation for 33kV

- Steiner (2007)
  [Steiner2007]

- 8kHz, 450kW, 50kg
- Efficiency: 99.7%
- Dry-Type / Liquid Isol. (34.5kV)

- STS (2014)
  www.sts-trafo.com
**ETH MEGACube: Water-Cooled Nanocrystalline Core Transformer**

- **Power Rating**: 166 kW
- **Losses**: 0.88 kW
- **Efficiency**: 99.5 % (Meas.)
- **Power Density**: 32.7 kW/dm³

ETH / Ortiz, Leibl (2013)
ETH MEGACube: MF Transformer Design – Cold Plates / Water Cooling

- Nanocrystalline 166kW/20kHz Transformer

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

ETH / [Ortiz2013b]
ETH MEGACube: MF Transformer Design – Cold Plates / Water Cooling

- Nanocrystalline 166kW/20kHz Transformer

Windings
$\Delta P = 353 \text{ W}$

Inner Cooling Plates
$\Delta P = 57 \text{ W}$

Outer Cooling Plates
$\Delta P = 19 \text{ W}$

Inner C-Shaped Pieces
$\Delta P = 34 \text{ W}$

Outer C-Shaped Pieces
$\Delta P = 44 \text{ W}$

Heat Sinks
$\Delta P = 2.8 \text{ W}$

- Losses Generated in Internal Cooling System Amount to ca. 20% of Total Transformer Losses

ETH / [Ortiz2013b]
Anecdote: Litz Wire Issues

- Case Study: Litz Wire with 10 Sub Bundles and 9500 x 71µm Strands in Total

- Unequal Current Sharing Between Sub Bundles
  - Flawed Interchanging Strategy
  - Influence of Terminations

- Common-Mode Chokes for Forcing Equal Current Sharing

ETH / [Ortiz2013b]
Coffee Break
Challenge #6/11
Isolation Coordination

Isolation Barrier Positioning
Mixed-Frequency Stress
Cascaded Cells Are On **Floating Potentials**

- Isolation Voltage = Grid Voltage + Margin
  → I.e., Many kV!

**Isolation Required**
- Towards Ground
- Towards Adjacent Cells

**Typical Isolation Voltage**

(Qualitative)
Example: Isolation Coordination of Cascaded Cells’ MV Part

- Components on MV Potential (e.g., Heat Sink)
- Isolation Towards Cabinet Required
- Field Grading to Avoid Partial Discharges, etc.

[Steiner2007]
Challenge #6/11
Isolation Coordination

Isolation Barrier Positioning
Mixed-Frequency Stress
### Mixed-Frequency Electrical Field Stress

- **Combined Electrical Field Stress**
  - Large DC or Low-Frequency Component
  - Smaller Medium-Frequency Component

- **Known From Machine Isolation Systems**
- **Physical Breakdown & Ageing Mechanisms Are Unclear**

- **50Hz Stress** Common-Mode
- **MF Stress** Differential-Mode (Mostly)

→ **Degree of Freedom To Optimize Isolation System!**

**Further Reading:** ETH / [Guillod2014]
Mixed-Frequency Electrical Field Stress: Dielectric Losses

- Dielectric Losses Depend on the Frequency
  \[ P(\vec{x}) \propto f \cdot E(\vec{x})^2 \]

- Example: HV-SiC DC/DC Converter:
  - 25kW
  - 8kV
  - 50kHz

- Dielectric Losses In Epoxy Isolation: 16% of Total Transformer Losses
  → Reduced Efficiency
  → Increased Hot-Spot Temperature
  → Accelerated Aging (?)

- Careful Choice of Isolation Material is Essential (Field Strength/Thermal Cond./Dielectric Losses)

Further Reading: Upcoming ETH Pub. by T. Guillod.
Challenge #7/11

EMI

Common-Mode Ground Currents
EMI Limits
CM Ground Currents: Basic Problem Description

- Considering One Phase Stack Including the DC/DC Converters
- Parasitic Capacitances Between Cells and Ground
- Switching Action in One Cell Moves All Cells At Higher Stack Positions In Potential
- Charging Currents: \( i = C \frac{dv}{dt} \)
- CM Oscillations With Parasitic Inductances!
CM Ground Currents: Countermeasure

- Placing Common-Mode Chokes At Cells’ AC Inputs
  - Low Effort (Losses, Volume)

- Simulations With/Without CM Chokes

- Outlook: Higher $dv/dt$ With SiC!?
Challenge #7/11

Common-Mode Ground Currents

EMI Limits
Grid Harmonics and EMI Standards

- **Medium Voltage Grid Considered Standards**
  - IEEE 519/1547
  - BDEW
  - CISPR (?)

- **Requirements on Switching Frequency and EMI Filtering**
  - Limits for CM Ground Currents?
  - Limits for HF Noise?

**Unclear Limits!**

![Graph showing THD, IEEE 519, BDEW, etc. and CISPR 11, etc.](graph.png)

ETH / [Burkart2012]
Challenge #8/11
Protection

Protection of the SST
Possible Fault Situations

- Transformer / SST May Be Exposed To
  - Overvoltages
  - Overcurrents

- ETH / [Guillod2015]
Typical LFT Protection Scheme

- Overvoltage
- Overcurrent
- Earthing

MV Side
L1
L2
L3
Disconnector
Surge Arrester
Fuse

LV Side
L1
L2
L3
PEN
Disconnector
Surge Arrester
Breaker
Fuse

Trade-Off Betw. Overvoltages and Overcurrents

Surge Arresters
LV and MV Fuses

ETH / [Guillod2015]

Imgs.: http://www.openelectrical.org/

Imgs.: ABB
MV Side SST Protection (1)

- **Grid Short Circuit**

  - **Phase-To-Phase Voltage (!!) Must Be Blocked → DC Capacitor Volt. Ratings!**

- **SST Short circuit**

  - **Overvoltage Protection**
    - Overvoltage Surge (e.g., Lightning Strike)
    - Arrester Clamping Voltage Is Still High
    - Grounding Scheme: Lower Stress if Unearthed
    - Current Limiting → Filter Inductor > 8%
    - Energy Absorption in DC Link Capacitors → DC Capacitance Requirement

Further Reading: ETH / [Guillod2015]
MV Side SST Protection (2)

Protection Considerations Affect SST Design & Limit Performance

Example: Boost/Filter Inductor → Low Frequency Magnetic Component (!)

- Min. 8% pu (SCR > 8%)
  - Critical for Low Power SSTs: \[ L_F = 8\% \cdot \frac{V_B^2}{2\pi f \cdot P_N} \]
- Creation of “Safe” Environments to Protect Several SSTs at Once → “Swarm Protection”
  - Limits Control Bandwidth (e.g., Act. Filtering, etc.)
  - Volume Reductions Due to Higher Switching Frequencies Might be Limited By Protection Considerations

Outlook: Advanced Protection Concepts

- E. g., Solid-State Protection

\[ L_F = 8\% \cdot \frac{V_B^2}{2\pi f \cdot P_N} \]

Further Reading: ETH / [Guillod2015]
Challenge #9/11

Control

It’s Not Just Passives!
A SST is Not Just Passives!

High Complexity of SST Control System Compared to Passive Low Frequency Transformers

Source: http://www.africancrisis.org
**SST Control System Partitioning**

- Very Different Timing Requirements
  - IGBT Protection: \( \text{us} \)
  - Grid Transients: \( \text{ms to s} \)

- Feasible Approach: Several Hierarchical Layers

- How To Test?

---

The *miniLINK* Lab-Scale Full SST Demonstrator

15kVA, \( 400V_{\text{AC}} \leftrightarrow 800V_{\text{DC}} \leftrightarrow 400V_{\text{AC}} \)
Example of SST Control System Partitioning

Central Control Unit (DSP + FPGA)
- Overall Power Flow. Mgmt.
- Current Ref. Generation
- Aux. Units (Breakers, etc.)

Battery Management

Cascaded MV Inverter
- Time Sync.
- Redundancy Mgmt.

Cell Ctrl. (FPGA)
- Modulation
- Protection
- DC/DC Ctrl.

Real-Time Communication
- Ethernet-Based
- Fiber Optics
- Time Sync. (IEEE 1588)


Smart Grid Integration

SCADA Interface

LV Inverter (FPGA)
- Current Ctrl. & Mod.
- DC Cap. Balancing
- Protection
Challenge #10/11
Construction of Modular Converter Systems
From Conceptualization to Realization
From Conceptualization to Realization (1)

Actual Realization of a Modular MV Converter Systems → **Complex Task**

- Isolation Coordination
- Cooling
- Control & Communication
- Hot-Swap
- Auxiliary Supply
- Mechanical Assembly
- etc., etc.

Example: MV Modular Multilevel Converter Presented by **ABB** (2015)

2 Single-Phase MMC in Back-to-Back Configuration

- 1kV, 600A Cell
- 48 Cells

Imgs.: W. van der Merwe
From Conceptualization to Realization (2)

- Actual Realization of a Modular MV Converter Systems → Complex Task
  - Isolation Coordination
  - Cooling
  - Control & Communication
  - Hot-Swap
  - Auxiliary Supply
  - Mechanical Assembly
  - etc., etc.

- Example: MV Modular Multilevel Converter Presented by ABB (2015)

> 25 Authors (!)
[Cottet2015a]
[Cottet2015b]
Modularity: Hot-Swapping at 24kV

- Example: MV Modular Multilevel Converter Presented by ABB (2015) [Cottet2015a], [Cottet2015b]

- All Interfaces Must Support Modularity

- Power
- Auxiliary (IPT)
- Cooling (Air)

∨ Bypass Switch

∧ Lab Test ∧

24kV Sw. Arc

Power plugs

Ethernet

U_{test} = 24 kV

Graph:
- Cell voltage [V]
- Time [s]
- soft bypass
- release bypass
- natural re-balancing
- pull-out PEBB
- insert PEBB

ETH Zürich
Advanced Integration Technologies

- Example: MV Modular Multilevel Converter Presented by **ABB** (2015) [Cottet2015a], [Cottet2015b]

- IPT for Auxiliary Power Supply

- Two-Phase Cooling

- Wireless Optical EtherCAT Comm.

- Solid Isolation of PEBBs

→ Actually Building an SST is a Multi-Disciplinary, Highly Complex Task!
Challenge #11/11

Testing of MV Converters
**Infrastructure**

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

![Infrastructure Image](Image:Center for Advanced Power Systems / Florida State University)

- Large Space Requirement / Considerable Investment (!)
Infrastructure Examples

- Medium-Voltage and High-Voltage Testing Facilities & Experience
  - 60kV Flashover
  - Source/Sink for 100s of kW
  - Or Back-To-Back Testing Concepts → Complexity
Measurement Equipment

- E.g., Switching Loss Measurements of HV SiC Devices
  
  - Voltage Range vs. Accuracy/Resolution
  - Skew
  - Disturbances
  - ...

- Special High-Voltage Measurement Eq.

![Circuit: ETH / [Rothmund2015]](www.Tektronix.com)
11 Key Challenges

Core Competencies

1. Handling of Medium Voltage
2. Topology Selection
3. Reliability
4. MF Isolated Power Converters
5. MF Transformer Design
6. Isolation Coordination
7. EMI
8. Protection
9. Control
10. Construction of Modular Conv.
11. Testing of MV Converters
Core Competencies for SST Design

- The 11+ Challenges Need to be Addressed by a TEAM

  - MV and LV Power Electronics
  - Digital Control & Software
  - Transformers & Magnetics
  - Isolation Coordination
  - Mechanical Construction
  - ...

Developing and Actually Building an SST is a Multi-Disciplinary, Complex Task!
SST Applicability In Grid Applications

Grid SST Examples
Competing Approaches
Compatibility w. Existing Infrastructure
► UNIFLEX Project (1)

- EU Project (2009)

- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- Cellular 300kVA Demonstrator of 3-Port Topology for 3.3kV Distr. System & 415V LV Grid Connection

[Watson2009]
UNIFLEX Project (2)

- EU Project (2009)

- AC/DC-DC//DC-DC/AC Module (MF Isolation, 1350V DC Link) and Prototype @ Univ. of Nottingham

[Watson2009]
SiC-Enabled 1MVA/20kHz Solid State Power Substation (1)

- Das (2011)
- Fully Phase Modular System
- Indirect Matrix Converter Modules \( f_1 = f_2 \)
- MV Δ-Connection (13.8kV, 4 Modules in Series)
- LV Y-Connection (465V/√3, Modules in Parallel)

Comp. to 60Hz: 25% Weight / 50% Volume Reduction @ 97% Efficiency

[Das2011]
SiC-Enabled 1MVA/20kHz Solid State Power Substation (2)

- Das (2011)

- Fully Phase Modular System
- Indirect Matrix Converter Modules \( f_1 = f_2 \)
- MV Δ-Connection (13.8kV, 4 Modules in Series)
- LV Y-Connection (465V/√3, Modules in Parallel)

Comp. to 60Hz: 25% Weight / 50% Volume Reduction @ 97% Efficiency

[Das2011]
Applicability

Grid Applications

Grid SST Examples

Competing Approaches: Isolation
Compatibility w. Existing Infrastructure
Grid Application Task No. 1: Isolation & Voltage Scaling

Typical Grid Application: **MVAC // LVAC**

Low Frequency Transformer → SST

- No Significant Efficiency Gain of Magnetic Transformer
- Additional Conversion Stages Generate Additional Losses

\[ f_{g, MV} \quad f = f_g \quad f_{g, LV} = f_{g, MV} \]

\[ V_{MV} \quad \frac{V_{LV}}{n_{MV}} \]

\[ f_{g, MV} \quad f >> f_g \quad f_{g, LV} = f_{g, LV}^* \]

\[ V_{MV} \quad \frac{V_{LV}}{V_{LV}^*} \]

→ Remember “Efficiency Challenge”
Task: Isolation & Voltage Scaling

- The Competitor: **1000kVA LF Distribution Transformer**
  - Standard Off-the-Shelf Products
  - Typically Liquid Filled (Oil): Isolation, Cooling

### Averaged Data from Different Manufacturers

<table>
<thead>
<tr>
<th></th>
<th>LFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>98.7%</td>
</tr>
<tr>
<td>Volume</td>
<td>3.43 m³</td>
</tr>
<tr>
<td>Weight</td>
<td>2590 kg</td>
</tr>
<tr>
<td>Material Cost</td>
<td>11.3 kUSD</td>
</tr>
</tbody>
</table>
**SST vs. LFT Quantified – MV Side Modeling**

- Fully Rated 80kW Converter Cell Prototype

- Filter Inductor Pareto Optimization

- Cabinet Modeling Based on Empirical Data

SST vs. LFT Quantified – LV Side Modeling

- Pareto Optimization of Standard 500kVA Inverter/Rectifier

- Calculated Results (Losses, Volumes)

- Good Agreement with Specs of Commercially Available Active Frontend Converter
**SST vs. LFT Quantified – AC/AC Conversion**

- **AC/AC SST** = SST MV + 2 SST LV

<table>
<thead>
<tr>
<th></th>
<th>LFT</th>
<th>AC/AC SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>98.7 %</td>
<td>96.3 %</td>
</tr>
<tr>
<td>Volume</td>
<td>3.4 m^3</td>
<td>2.6 m^3</td>
</tr>
<tr>
<td>Weight</td>
<td>2590 kg</td>
<td>2600 kg</td>
</tr>
<tr>
<td>Material Cost</td>
<td>11.3 kUSD</td>
<td>&gt; 52.7 kUSD</td>
</tr>
</tbody>
</table>

**Efficiency Challenge** Confirmed by Quantitative Analysis
**SST vs. LFT Quantified – AC/AC and AC/DC Conversion**

- **AC/AC Application**
- **AC/DC Application**

Further Reading: ETH / [Huber2014b]
Applicability
Grid Applications

Grid SST Examples

Competing Approaches: Control
Compatibility w. Existing Infrastructure
Controllability As Unique SST Selling Point?

- SST Is Not Competitive If Only Isolation & Voltage Scaling Are Required!

- Added Value: Commonly Envisioned SST Features
  - Reactive Power Compensation
  - Voltage Regulation
  - Active Filtering
  - Power Flow Control
  - Fault Current Limiting
  - DC Interface (e.g., Energy Storage)
  - …

- Alternative Approaches To Provide These Features? → Several Examples In The Following!

- Is It Necessary To Process The Full Power Flow With The Controllable (Less Efficient) Stage?
Voltage Band Violations in the Distribution System

- Voltage Band Specified by EN 50160: ±10%

- **Limits** Renewable Power Infeed on LV and MV Level
  - Max. 3% Voltage Increase on LV Level
  - Max. 2% Voltage Increase on LV Level

Grid Expansion Becomes Necessary Even Though Equipment Capacities Are Not Exhausted

- SST Can Control Voltages – But So Can Voltage Regulation Distribution Transformer (VRDT), etc.
**Voltage Regulation Distribution Transformer**

- LFT Extended By A **Controlled Automatic On-Load Tap Changer**
  - Up to 9 Positions, e.g., ±4 x 2.5%
  - Up to 700’000 Switching Transitions
  - LFT Efficiency & Robustness!

<table>
<thead>
<tr>
<th>Substation</th>
<th>Medium-voltage grid</th>
<th>Local grid station</th>
<th>Low-voltage grid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.4 kV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.4 kV</td>
</tr>
</tbody>
</table>

- Up to 9 Positions, e.g., ±4 x 2.5%
- Up to 700’000 Switching Transitions
- LFT Efficiency & Robustness!

Max. **11%** Voltage Increase on LV Level
Max. **13%** Voltage Increase on MV Level

![Diagram](Image: Maschinenfabrik Rheinhausen)

![Diagram](Image: ABB)
Distribution Voltage Regulators

- Available for MV or LV Systems
- Easy **Retrofit** (No Modification of Existing LFT)
- Typ. Regulation ±10% in 32 Steps of 0.625%
- Comparably **Slow** (Several Seconds)
- Voltage Symmetrization (Three 1ph-Units)

Mechanical Solution: **Auto-Transformer With Tap Changer**
Active Series Voltage Regulators

- Protection of Sensitive Industrial and Commercial Loads from Voltage Disturbances
- Power Electronic Solution: Converter With Injection Transformer
  
  - Continuous & Fast Voltage Regulation
  - Correction of Voltage Sags, Unbalances, Surges, and Phase Angle Errors
  - Harmonic Filtering
  - Reactive Power Compensation / Power Factor Correction

Typical Features Envisioned For SSTs (!)

But: Power Electronics Do Not Process The Full Power Flow
Reactive Power Compensation

- Static VAr Compensation
  Switched Capacitor or Reactor Banks

- STATCOM
  Power Electronic Converter

Additional Features
- Improved Power/Voltage Quality
- Voltage Regulation
- Compensation of Harmonics, Flicker, etc.
**SST vs. LFT + STATCOM**

- **SST's VAr Capability Depends on Active Power Flow!**
- Or: SST Max. Reactive Power Capability Is Limited By Active Power Demand

- SST Provides Complete Decoupling of Reactive Power Flow of MV and LV Grid
  - No Propagation of Disturbances
  - Different STATCOM OPs in MV and LV Grid
Hybrid Transformers: Combinations of LFT and SST

- **Shunt**
  - Reactive Current Injection
  - Power Factor Correction
  - Harmonic Filtering
  - Flicker Control

- **Series**
  - Reactive Voltage Injection
  - Phase Shifting
  - Voltage injection

- **Combined**
  - Power Factor Correction
  - Harmonic Filtering
  - Flicker Control
  - AC Regulation
  - Phase Shifting

- Isolated DC Port

- **Fractional Power Processing**
  - Power Electronics Processes Only A Fraction Of The Power And/Or Voltage

[Bala2012], [Burkard2015]
Applicability

Grid Applications

Grid SST Examples
Competing Approaches
Compatibility w. Existing Infrastructure
Grid Protection Schemes

- Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed / Safety / Reliability

- **Selectivity:** Only Closest Upstream Breaker/Fuse Should Trip to Isolate Faults Quickly
  - Different Trip Current Levels
  - Different Time Delays

**Certain Overcurrents Required To Trip Fuses And/Or Breakers**

Imgs.: ETH / [Guillod2015]
**Tripping of LV Side Fuses**

- **Example:** 400V Fuse for 630kVA Transformer

- **Very High Short-Circuit Currents Required** To Trip Fuses → No Problem for LFT!

- But Not Possible With Power Electronic Converter (Semiconductors!)
Alternative Protection Schemes

- **SST Can Limit Its Short-Circuit Current**
- **Load Switches (≠ Breakers!)** Could Be Used To Isolate Faults

- Integration of SST in Existing LV Distribution System Remains Challenging
- **Communication** Between (Protection) Devices Becomes Essential

- **SST Requires a “Smart Grid”** → Coordination of Protection Relays
SST Grid Integration

- SST Requires A **Controlled Environment** On Its LV Side
- SST Is Thus **Not a Direct Replacement** For A Distribution LFT!

- Novel Protection Schemes
- Micro Grid Can Act as a “Virtual Power Plant”
- DC Distribution
- Etc.

**Comparison: Traction Application**

→ Locomotive Is A **User-Controlled, Self-Contained** Environment!
Applicability

DC-DC Applications

No Alternatives!
Example: DC Collection Grids for Offshore Wind Parks

- $\pm 320\text{kV}_\text{DC}$ HVDC Transmission to Shore
- $\pm 50\text{kV}_\text{DC} / \pm 320\text{kV}_\text{DC}$ Offshore Substations with M2LC-Based MF Isolation and Step-Up Stage
- $50\text{kV}_\text{DC}$ Offshore Collection Grid

- Series Resonant Unidir. DC $\rightarrow$ MVDC Conversion in the Individual Wind Turbines
- Transformer Frequency Can Be Freely Chose

$\pm 2\text{kV}$

[Kjaer2016]
Example: MEGACube @ ETH Zurich (1)

- Total Power: 1 MW
- Frequency: 20 kHz
- Efficiency Goal: 97%

- MV Level: 12.0 kV
- LV Level: 1.2 kV

[Ortiz2010], [Ortiz2013c]
Example: MEGACube @ ETH Zurich (2)

- **Dual Active Bridge** DC-DC Converter Stage
- Module Power: 166 kW
- Frequency: 20 kHz
- Triangular Current Mode Modulation

![Diagram showing the structure of the 166kW Module and MV Side Waveforms](Ortiz2013c)

▲ 166kW / 20kHz TCM DC-DC Converter (Ortiz, 2013)

▲ Structure of the 166kW Module and MV Side Waveforms
Example: **MEGACube @ ETH Zurich** (3)

- **HC-DCM SRC** DC-DC Converter Stage
- Module Power: 166 kW
- Frequency: 20 kHz
- Medium Voltage Side: 2 kV
- Low Voltage Side: 400 V

![Diagram of HC-DCM SRC]

- **Operation at 80kW**

![Graph showing voltage and current waves at 80kW]

ETH / Ortiz, Leibl, Huber
SST Applicability In Traction Applications

Traction SST Example

Img.: www.futuretimeline.net
Cascaded H-Bridges and Resonant LLC DC-DC Stages (1)

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

P = 1.2MVA, 1.8MVA 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

[Dujic2013] & [Zhao2014]
Cascaded H-Bridges and Resonant LLC DC-DC Stages (2)

- 1.2MVA, 15kV, $16 \frac{2}{3}$ Hz, 1ph. AC/DC Power Electronic Transformer (PETT)
  - Cascaded H-Bridge – 9 Cells
  - Resonant LLC DC/DC Converter Stages

PET topology with cascaded H-bridges and resonant (LLC)DC-DC stages.

[Dujic2013] & [Zhao2014]

Img.: [Dujic2011]
Cascaded H-Bridges and Resonant LLC DC-DC Stages (3)

- 1.2MVA, 15kV, 16 \( \frac{2}{3} \) Hz, 1ph. AC/DC Power Electronic Transformer (PETT)
  - Cascaded H-Bridge – 9 Cells
  - Resonant LLC DC/DC Converter Stages

[Dujic2013] & [Zhao2014]
Cascaded H-Bridges and Resonant LLC DC-DC Stages (4)

- 1.2MVA, 15kV, $16^{2/3}$ Hz, 1ph. AC/DC Power Electronic Transformer (PETT)
  - Cascaded H-Bridge – 9 Cells
  - Resonant LLC DC/DC Converter Stages

Efficiency

[Dujic2013] & [Zhao2014]
SST Applicability

Summary
"Efficiency Challenge" (Qualitative)

- **No Weight/Volume Constraints**
  - Efficiency of LFT for AC/AC Very Hard To Attain
  - Weight/Volume Typically Not an Issue In Stationary Grid Applications
  - Robustness, Reliability?
  - Cost?

- **Weight/Volume Constraints**
  - SST Shows Efficiency Benefits for Applications with Volume/Weight Constraints!

SSTs in Grid Applications – A Skeptic’s View

- Typical Grid Application

SSTs in Traction Applications

- Typical Traction Application
SST Applicability: The Road Ahead

**Grid AC-AC**
- Efficiency Challenge
- Controllability Can Be Provided By Alternative Approaches
  - More Efficient (e.g., Tap Changers)
  - Partial Power Processing
- Compatibility Issues With Existing Infrastructure (e.g., Protection)
- Cost, Robustness, Reliability Issues

**DC-DC Applications**
- Isolation Stage Frequency Is A Free Parameter
- Future Applications, e.g. MV DC Collection Grids for Wind/PV

**Grid AC-DC**
- Efficiency Challenge More Balanced
- Self-Contained Applications (e.g., Datacenter DC Distr.)
- Cost, Robustness, Reliability

**Weight/Space Limited Appl.**
- Medium Frequency Systems Offer
  - Weight/Volume Reduction AND
  - Efficiency Improvement
- Typically Self-Contained Environments On One Side Of The SST
- Several Industrial Prototypes, But So Far No Products
"Initial Use May be Found in Special Applications where Cost and Efficiency are Secondary to Size and Weight."

W. McMurray, 1971

**Conclusions**

thyristors. Thus practical application of the electronic transformer is dependent upon further circuit development and component improvements. Initial use may be found in special applications where cost and efficiency are secondary to size and weight.
Future SST Applications
Subsea Applications: Oil & Gas Processing (1)

- ABB’s Future Subsea Power Grid → “Develop all Elements for a Subsea Factory”
Subsea Applications: Oil & Gas Processing (2)

- Future Subsea Distribution Network (Devold, ABB, 2012)

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

- Weight Optimized Power Electronics
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 (1)

- Ultra-Light Weight Multi-Cell **All-SiC Solid-State Transformer** – $8kV_{dc} \rightarrow 700V_{dc}$

- Medium Voltage Port: 1750 ... 2000 VDC
- Switching Frequency: 100 kHz
- Low Voltage Port: 650 ... 750 VDC
- Cell Rated Power: 6.25 kW
- Power Density: 5.2 kW/dm³
- Specific Weight: 4.4 kW/kg

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ETH / [Gammeter2015]
100kW Airborne Wind Turbine (2)

- Ultra-Light Weight Multi-Cell **All-SiC Solid-State Transformer** – $8V_{DC} \rightarrow 700V_{DC}$

  - Medium Voltage Port: 1750 ... 2000 VDC
  - Switching Frequency: 100 kHz
  - Low Voltage Port: 650 ... 750 VDC
  - Cell Rated Power: 6.25 kW
  - Power Density: 5.2 kW/dm$^3$
  - Specific Weight: 4.4 kW/kg

ETH / [Gammeter2015]
Future Hybrid or All-Electric Aircraft

- 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 Aircraft

- 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)

- Potential SST Application: Supply of LV AC or DC Loads From MVDC Bus
Future Naval Applications (1)

- **HFAC** (High-Frequency AC)
  - Reduce Size/Weight of Equipment

- **MVDC** (Medium Voltage Direct Current)
  - Further Size/Weight Reduction
  - DC-DC SSTs

- **DDG 1000**

USS Zumwalt

Img.: US Navy, CC BY 2.0

[Doerry2009]
Future Naval Applications (2)

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

  ![Graph](image)

  **Source:** General Dynamics

  **Doerry2009**

- Bidirectional Power Flow for Advanced Weapon Load Demand
- Extreme Energy and Power Density Requirements
Conclusion & Outlook

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!

Source: Column Five, http://magazine.good.is
Key Messages #1/3

- Basic SST Limitations
  - **Efficiency** (Rel. High Losses of 2-4%)
  - **High Costs** (Cost-Performance Adv. still to be Clarified)
  - **Limited Weight/Volume Reduction vs. Conv. Transf.** (Factor 2-3)
    - Limited Overload Capability
    - Limited Overvoltage Tolerance
    - (Reliability)

- Potential Application Areas
  - **MV Grid/Load-Connected AC/DC and DC/DC Converter Systems**
  - **Volume/Weight Limited Systems where 2-4% of Losses Could be Tolerated**
    - Traction Vehicles
    - MV Distribution Grid Interface
      - DC Microgrids (e.g., Datacenters)
      - Renewable Energy (e.g., DC Collecting Grid for PV, Wind; Power-to-Gas)
      - High Power Battery Charging (E-Mobility)
      - More Electric Ships
      - etc.
    - Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)
    - Temporary Replacement of Conv. Distribution Transformer
    - Military Applications

*Img.: Marina Gallud / 123RF Stock Photo*
Key Messages #2/3

Advantageous Circuit Approaches

Fully Modular Concepts

- Resonant Isolated Back End Topology (ABB)
- Resonant Isolated Front End Topology (Swiss SST)

“It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change.”

Charles Darwin

Alternatives

- Single Transformer Solutions (MMLC-Based)
- HV-SiC Based Solutions (SiC NPC-MV-Interface)

Redundancy (!)
- Scalability (Voltage / Power)
- Natural Voltage / Current Balancing
- Economy of Scale
Key Messages  #3/3

- Main Research Challenges
  - Multi-Level vs. Two-Level Topologies with HV SiC Switches
  - Low-Inductance MV Power Semiconductor Package
  - Mixed-Freq./Voltage Stress on Insul. Materials
  - Low-Loss High-Current MF Interconnections / Terminals
  - Thermal Management (Air and H₂O Cooling, avoiding Oil)
  - SST Protection
  - SST Monitoring
  - SST Redundancy (Power & (!) Control Circuit)
  - SST vs. FACTS (Flexible AC Transmission Systems)
  - System-Oriented Analysis → Clarify System-Level Benefits (Balancing the Low Eff. Drawback)

- SST Design for Production → Multi-Disciplinary Challenge

- Required Competences
  - MV (High) Power Electronics incl. Testing
  - Digital Signal Processing (DSP & FPGA)
  - MF High Power Magnetics
  - Isolation Coordination / Materials
  - Power Systems
  - etc.

- 50/60Hz XFRM Design Knowledge is NOT (!) Sufficient
Waves of SST Innovations

1. Wave
- MF Isolation Concepts for Traction (Thyristors)

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

3. Wave
- Single-Cell SST Concepts (HV-SiC)
- 2. Wave (Grid)
  - Appl. in Datacenters and Microgrids

4. Wave
- SST Applications & Products
- 1. Wave (Grid)
  - SST Concepts for Smart Grid

Timeline:
- 1970
- 2000
- 2015
- 2025

Innovation
Different State of Development of SSTs for

- Traction Applications
- Hybrid / Smart Grid Applications
SST for Future Grid Applications

Huge Multi-Disciplinary Challenges / Opportunities (!)
Thank You!

Questions?

Source: Saddington Baynes / tmar.com
Acknowledgement

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• Dr. Gabriel Ortiz
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• Daniel Rothmund
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References

Download Full Slide Deck from www.pes.ee.ethz.ch
ETH Zurich: Recent Key Publications (1)


J. E. Huber, D. Rothmund and J. W. Kolar, “Comparative evaluation of isolated front end and isolated back end multi-cell SSTs,” in Proc. 8th Int. Power Electron. and Motion Contrl. Conf. (IPMEC/ECCE Asia), Hefei, China, May 2016. → Download


ETH Zurich: Recent Key Publications (2)


G. Ortiz, “High-power DC-DC converter technologies for smart-grid and traction applications,” PhD dissertation, ETH Zurich, Zurich, Switzerland, 2013. → Download
References: A – C


References: D – G


References: Gm – Ho


References: Hu – J


References: K – Q


# References: R – S


References: T – Z


Authors

Johann W. Kolar (F’10) received his M.Sc. and Ph.D. degree (summa cum laude / promotio sub auspiciis praesidentis rei publicae) from the University of Technology Vienna, Austria. Since 1982 he has been working as an independent international consultant in close collaboration with the University of Technology Vienna, in the fields of power electronics, industrial electronics and high performance drives. He has proposed numerous novel converter topologies and modulation/control concepts, e.g., the VIENNA Rectifier, the SWISS Rectifier, and the three-phase AC-AC Sparse Matrix Converter. Dr. Kolar has published over 400 scientific papers at main international conferences, over 150 papers in international journals, and 2 book chapters. Furthermore, he has filed more than 110 patents. He was appointed Assoc. Professor and Head of the Power Electronics Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich on Feb. 1, 2001, and was promoted to the rank of Full Prof. in 2004. Since 2001 he has supervised over 60 Ph.D. students and PostDocs.

The focus of his current research is on AC-AC and AC-DC converter topologies with low effects on the mains, e.g. for data centers, More-Electric-Aircraft and distributed renewable energy systems, and on Solid-State Transformers for Smart Microgrid Systems. Further main research areas are the realization of ultra-compact and ultra-efficient converter modules employing latest power semiconductor technology (SiC and GaN), micro power electronics and/or Power Supplies on Chip, multi-domain/scale modeling/simulation and multi-objective optimization, physical model-based lifetime prediction, pulsed power, and ultra-high speed and bearingless motors. He has been appointed an IEEE Distinguished Lecturer by the IEEE Power Electronics Society in 2011.

He received 7 IEEE Transactions Prize Paper Awards and 7 IEEE Conference Prize Paper Awards. Furthermore, he received the ETH Zurich Golden Owl Award 2011 for Excellence in Teaching and an Erskine Fellowship from the University of Canterbury, New Zealand, in 2003. He initiated and/or is the founder/co-founder of 4 spin-off companies targeting ultra-high speed drives, multi-domain/level simulation, ultra-compact/efficient converter systems and pulsed power/electronic energy processing. In 2006, the European Power Supplies Manufacturers Association (EPSMA) awarded the Power Electronics Systems Laboratory of ETH Zurich as the leading academic research institution in Power Electronics in Europe.

Dr. Kolar is a Fellow of the IEEE and a Member of the IEEJ and of International Steering Committees and Technical Program Committees of numerous international conferences in the field (e.g. Director of the Power Quality Branch of the International Conference on Power Conversion and Intelligent Motion). He is the founding Chairman of the IEEE PELS Austria and Switzerland Chapter and Chairman of the Education Chapter of the EPE Association. From 1997 through 2000 he has been serving as an Associate Editor of the IEEE Transactions on Industrial Electronics and since 2001 as an Associate Editor of the IEEE Transactions on Power Electronics. Since 2002 he also is an Associate Editor of the Journal of Power Electronics of the Korean Institute of Power Electronics and a member of the Editorial Advisory Board of the IEEJ Transactions on Electrical and Electronic Engineering.
Authors

Jonas E. Huber (S’10) received his M.Sc. (with distinction) degree from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, in 2012, after studying electrical engineering with focus on power electronics, drive systems, and high voltage technology. He worked on a new modulation concept for the modular multilevel converter during an industry internship with ABB Switzerland as part of his master studies, before he designed and constructed a 100 kW/20 kHz back-to-back test bench for a medium frequency transformer in the scope of his master thesis, which was carried out at the Power Electronic Systems Laboratory, ETH Zurich. In 2012, he then joined the Power Electronic Systems Laboratory, ETH Zurich, as a PhD student, where his main research interests are in the area of solid-state transformers for smart grid applications, focusing on the analysis, optimization, and design of high-power multi-cell converter systems, reliability considerations, control strategies, and grid integration aspects, among others. He has authored seven and co-authored three papers published at international IEEE conferences.