Smart (Solid-State) Transformers
Concepts/Challenges/Applications

J. W. Kolar et al.
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch
Smart (Solid-State) Transformers
Concepts/Challenges/Applications

J. W. Kolar, J. Huber, Th. Guillod, D. Rothmund, D. Bortis, F. Krismer
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch
Outline

► Transformer Basics
► Solid-State Transformer (SST) Concept
► Key SST Realization Challenges
  #1 Power Semiconductors
  #2 Topologies
  #3 Medium Frequency Transformer
  #4 Protection
  #5 Reliability
► Industry Demonstrator Systems
► Potential Future Applications
► Conclusions
Transformer Basics

History
Scaling Laws
Efficiency / Power Density Trade-off
Classical Transformer (XFMR) – History (1)

* 1830 - Henry/Faraday  → Property of Induction
* 1878 - Ganz Company (Hungary)  → Toroidal Transformer (AC Incandescent Syst.)
* 1880 - Ferranti  → Early Transformer
* 1882 - Gaulard & Gibbs  → Linear Shape XFMR (1884, 2kV, 40km)
* 1884 - Blathy/Zipernowski/Deri  → Toroidal XFMR (inverse type)

Europe

USA

* 1885 - Stanley & (Westinghouse)  → Easy Manufact. XFMR (1st Full AC Distr. Syst.)
Classical Transformer – History (2)

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

- Magnetic Core Material
  - Silicon Steel / Nanocrystalline / Amorphous / Ferrite
- Winding Material
  - Copper or Aluminium
- Insulation/Cooling
  - Mineral Oil or Dry-Type
- Operating Frequency
  - 50/60Hz (El. Grid, Traction) or $16^2/3$ Hz (Traction)
- Operating Voltage
  - 10kV or 20 kV (6…35kV)
  - 15kV or 25kV (Traction)
  - 400V
- Voltage Transf. Ratio
  - Fixed
- Current Transf. Ratio
  - Fixed
- Active Power Transf.
  - Fixed ($P_1 \approx P_2$)
- React. Power Transf.
  - Fixed ($Q_1 \approx Q_2$)
- Frequency Ratio
  - Fixed ($f_1 \approx f_2$)

Magnetic Core
- Cross Section

Winding Window

$$A_{Core} = \frac{1}{\sqrt{2\pi}} \frac{U_1}{B_{max}} \frac{1}{f N_1}$$

$$A_{Wdg} = \frac{2I_1}{k W_j_{rms}} N_1$$
Classical Transformer – Basics (2)

Advantages

- Relatively Inexpensive
- Highly Robust / Reliable
- Highly Efficient
- Short Circuit Current Limitation

Source: www.faceofmalawi.com
Classical Transformer – Basics (3)

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
- Not Directly Controllable
- Dependency of Weight / Volume on Frequency
- Sensitivity to DC Offset Load Imbalances
- Sensitivity to Harmonics
- Construction Volume

Construction Volume
\[ A_{\text{Core}} A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi} \frac{P_i}{k_W J_{\text{rms}} B_{\text{max}} f} \]

- \( P_i \) ..... Rated Power
- \( k_W \) ..... Window Utilization Factor
- \( B_{\text{max}} \) ..... Flux Density Amplitude
- \( J_{\text{rms}} \) ..... Winding Current Density
- \( f \) ..... Frequency

- Low Frequency \( \rightarrow \) Large Weight / Volume

Vacuum Cast Coil Dry-Type Distribution Transformer

1 MVA – 12kV/400V @ 2600kg
0.2%/1% Losses @ No/Rated Load
Classical Transformer – Basics (4)

- **Construction Volume**

\[
A_{Core} \cdot A_{Wdg} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_w \cdot J_{rms} \cdot B_{max} \cdot f}
\]

180kVA
Weight-Optimized
Air-Cooled / Insulation
Forced Convection
\( \times \ldots 50Hz / Oil \)
...... Therm. Limit

- **Higher Frequency** → Lower Weight / Volume

- **Higher Volume** → Higher Efficiency

\( P_t \) .... Rated Power
\( k_w \) .... Window Utilization Factor
\( B_{max} \) .... Flux Density Amplitude
\( J_{rms} \) .... Winding Current Density
\( f \) .... Frequency
SST Motivation

Next Generation Traction Vehicles
Classical Locomotives

- Catenary Voltage: 15kV or 25kV
- Frequency: 16\(^2/3\) 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

Replace LF Transformer by Medium Frequency Power Electronics Transformer → SST

Medium Frequency Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction

Source: ABB
Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives

- Medium Freque. Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction
Future Smart EE Distribution

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

- Heinemann / ABB (2001)

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

- Huang et al. (2008)

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

- Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonomous Cntrl
**Terminology (1)**

- 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.
Terminology (1)

United States Patent [19]
Brooks et al.

[54] Solid State Regulated Power Transformer with Waveform Conditioning Capability

[75] Inventors: James L. Brooks, Oxnard; Roger I. Staab, Camarillo, both of Calif.; James C. Bowers; Harry A. Niemhaus, both of Tampa, Fla.

[73] Assignee: The United States of America as represented by the Secretary of the Navy, Washington, D.C.

[21] Appl. No.: 188,419
[22] Filed: Sep. 18, 1980

Fig. 1.

- No Isolation (!)
- "Transformer" with Dyn. Adjustable Turns Ratio
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)
Challenge #1/5

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 $\rightarrow$ $\approx 1000V$ max. DC Voltage

- **Interfacing to Medium Voltage** $\rightarrow$ Multi-Level Converter Topologies
SiC Power Semiconductors

- Samples
  * 10kV & 15kV / 10A MOSFETs
  * 10kV & 15kV / 8A JBS Diodes
  * 15kV / 20A IGBTs

- Soft-Switching (ZVS) Performance
  10kV MOSFET @ 15A (250μJ)

- Interfacing to Medium Voltage
  → Two-Level OR Multi-Level Converter Topologies
SiC Power Semiconductors

- Samples
  * 10kV & 15kV / 10A MOSFETs
  * 10kV & 15kV / 8A JBS Diodes
  * 15kV / 20A IGBTs

- Derating Requirement due to Cosmic Radiation for 100 FIT @ 25°C & 0 m AMSL $A_{act}=7.2\text{cm}^2$

- Interfacing to Medium Voltage → Two-Level OR Multi-Level Converter Topologies
Commercially Available SiC Power Semiconductors

- High Current 3.3kV / 1.7kV / 1.2 kV Power Modules
- Mitsubishi (CREE, ROHM, GE, etc.)
**Vertical (!) FETs on Bulk GaN Substrates**

- GaN-on-GaN Means Less Chip Area

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

- **Vertical FET Structure**

  - GaN-on-GaN lowers die cost while improving \( R_{\text{on}} \times C_{\text{eff}} \) switching characteristic

<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>4.8x10^16</td>
<td>3.7</td>
</tr>
<tr>
<td>1200</td>
<td>2.4x10^16</td>
<td>7.3</td>
</tr>
<tr>
<td>1800</td>
<td>1.6x10^16</td>
<td>10.9</td>
</tr>
<tr>
<td>2400</td>
<td>1.2x10^16</td>
<td>14.6</td>
</tr>
<tr>
<td>3200</td>
<td>0.9x10^16</td>
<td>19.4</td>
</tr>
<tr>
<td>4800</td>
<td>0.6x10^16</td>
<td>29.1</td>
</tr>
<tr>
<td>5600</td>
<td>0.5x10^16</td>
<td>34.0</td>
</tr>
</tbody>
</table>
Challenge #2/5

Creation of MV → LV SST Topologies
Interfacing to Medium Voltage

- Partitioning of Blocking Voltage
- Series Connection or Multi-Cell and Multi-Level Approaches
- High Number $N$ Cells $\Rightarrow$ Quadratically Reduces Curr. Harmonics

* Two-Level Topology

Akagi (1981)

McMurray (1969)

Marquardt

Alesina/Venturini (1981)

* Multi-Level/Multi-Cell Topologies
Scaling of Series Interleaving of Converter Cells

- Interleaved Series Connection Dramatically Reduces Switching Losses (or Harmonics)
- Converter Cells Could Operate at VERY Low Switching Frequency
- Minimization of Passives (Filter Components)

\[ P_{S,N} \approx P_{S,N=1} \left( \frac{1}{2N^2} \right) \left( \frac{1}{N^3} \right) \]
United States Patent

{54} FAST RESPONSE STEPPED-WAVE SWITCHING POWER CONVERTER CIRCUIT
18 Claims, 13 Drawing Figs.

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

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

1969!

Fig. 1.

- Cascaded H-Bridge Multi-Cell Converter
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

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

POWER CONVERSION APPARATUS FOR DC/DC CONVERSION USING DUAL ACTIVE BRIDGES

Inventors: Rik W. DeDoncker, Niskayuna, N.Y.; Mustansir H. Kheraluwala; Deepakraj M. Divan, both of Madison, Wis.

Filed: Sep. 29, 1989

FIG. 1

- Soft Switching in a Certain Load Range
- Power Flow Control by Phase Shift between Primary & Secondary Voltage
A Method of Resonant Current Pulse Modulation for Power Converters

FRANCISC C. SCHWARZ, SENIOR MEMBER, IEEE

- Load-Insensitive DCM Series Resonant Converter

- Resonant Tank

- Transformer Voltage

- Transformer Current

Fig. 4. Alternative simplified schematic of a controllable and load-insensitive series capacitor dc converter with transfer of inductive energy to the load.
Half-Cycle DCM Series Resonant Converter (HC-DCM-SRC)

- $f_s \approx$ Resonant Frequency → “Unity Gain”
- Fixed Voltage Transfer Ratio Independent of Transferred Power (!)
- Power Flow / Power Direction Self-Adjusting
- No Controllability / No Need for Control
- ZCS of All Devices

![Diagram of Half-Cycle DCM Series Resonant Converter](image1)

![Graph showing Relative Voltage vs. Relative Frequency](image2)

![Waveforms of HV & LV side currents](image3)
Remark: Concept also Used for Low-Power (!)

- BCM Bus Converter Family
- Sine Amplitude Converter (SAC)
- Fixed Voltage Conversion Ratio DC/DC Converter

- Very High Power Density
- Very High Efficiency
Combining the Basic Concepts I

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

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

Source: Zhao / Dujic (ABB / 2011)
Reversal of the Sequence of Current Shaping & Isolation

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

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

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

- Single Transformer Isolation
- Highly Modular / Scalable
- Allows for Redundancy
- Challenging Balancing on Cell DC Voltages

Source: Zhao / Dujic (ABB / 2011)

SIEMENS
- Marquardt/Glinka (2003)

Source: Zhao / Dujic (ABB / 2011)
Combining the Basic Concepts II

Three-Phase AC-AC Conversion / Smart Grid Applications

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

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

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

- Trade-Off
  - High Number of Levels →
  - High Conduction Losses/ Low Cell Sw. Frequ./Losses
    (also because of Device Char.)

- Opt. Device Voltage Rating for Given MV Level
- ηρ-Pareto Opt. (Compliance to IEEE 519 @ Eff. Sw. Frequ., only Cascaded H-Bridges, i.e. DC/DC Converter Stages Not Considered)

1 MVA
10kV → 400V
50Hz

- Optimum Number of Converter Cells
  - 1700V Power Semiconductors Best Suited for 10kV Mains → 10kV or Higher SiC Not Required (!)
**Single-Cell Structure**

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

![Single-Cell Structure Diagram](image)

- Redundancy Only for Series-Connection of Power Semiconductors (!)
Challenge #3/5

Medium-Frequency Transformer Design

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

- Nano-Crystalline 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
Further MF Transformer Examples

- Coaxial Windings – Shell Type
- Tunable Leakage Inductance
- Simple Terminations

- 450kW @ 8 kHz / 50kg
- 99.7% Efficiency
- Dry Type / Liquid Isolation for 34.5kV

- 350kW @ 8 kHz
- Water Cooling / Hollow Conductors
- Isolation for 33kV

Steiner (2007)

STS (2014)
www.sts-trafo.com
Challenge #4/5

Mains $\leftrightarrow$ SST $\rightarrow$ 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 $t_r = 3-100$ ns, $t_b = 1-3$ ms
- Fast front: Lightning surge $t_r = 0.1-20$ µs, $t_b = 100-300$ µs
- Slow front: Switching transient $t_r = 20-1000$ µs, $t_b = 1-20$ ms

Voltage [p.u.]

- $>10.0$
- $3.0$
- $2.0$
- $1.7$
- $1.2$
- $1.0$

Time [µs]

- $10$ µs
- $100$ µs
- $1$ ms
- $10$ ms
- $100$ ms
- $1$ s

Diagram showing different fault types:
1. Internal Fault
2. Lightning Surge
3. Switching Transient
4. MV Short Circuit
5. LV Short Circuit
6. Non-Ideal Load
Protection of LF-XFRM vs. SST Protection

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

- Proposed SST Protection Scheme with Minimum # of Protection Devices

- Overvoltage Protection (Lightning Strike)
  * High Arrester Clamping Voltage
  * Filter Inductor > 8% for Current Limiting
  * Min. DC Link Capacitance
  * Sufficient Blocking Capability
  * Grounding – Lower Stress if Unearthed

- Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed /Safety /Reliability
Distribution Transformer Overcurrent Requirements

- Low-Frequ. 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)

- Lower Grid Voltage Levels → Higher Relative Short Circuit Currents
- SST is NOT (!) a 1:1 Replacement for a Conventional Low-Frequency XFRM
Challenge #5/5

Ensuring Reliability of Highly Complex Multi-Cell Converter Topologies
Reliability Model (1) – Failure Rate

- Failure Rate $\lambda(t)$ is a Function of Time – „Bathtub Curve“
- Useful Life Dominated by Random Failures $\Rightarrow \lambda(t) = \text{const.}$
- $[\lambda] = 1 \text{ FIT} \ (1 \text{ Failure in } 10^9 \text{ h})$
- Typ. Value for IGBTs: 100 FIT

Sources for Empirical Component Failure Rate Data: MIL-HDBK-217F, IEC Standard 62380, etc.
Reliability Model (2) – Reliability Function

- Reliability Function: Probability of System being Operational after $t$:

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

- Mean Time Between Failures

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

- Series Structure

$$\lambda_s = \sum_{i=1}^n \lambda_i$$

Independent Cells with Equal Failure Rate
Redundancy in Multi-Cell Converter Systems

- **k-out-of-n Redundancy**
  Redundancy of Cells in Phase Stack

  System is Operational as Long as at Least k-out-of-n Subsystems are Working

- Effect of q Redundant Cells on $R_S(t)$ and/or MTBF (Area below $R_S(t)$)

  Redundancy Significantly Improves System Level Reliability (!)
Redundancy in Single-Cell Converter Systems

- Example: Three-Level MV Motor Drive
- Redundant Series Device
- Fail-to-Short Behavior Required (!)
- Only Feasible with Press-Pack Modules

Press-Pack NPC Phase Module
SST Demonstrator Systems

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

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

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

9 Cells (Modular)

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

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

- 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
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-L, 4 Modules in Series)
- LV Y-Connection (265V, Modules in Parallel)

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

- Das et al. (2011)

- Fully Phase Modular System
- Indirect Matrix Converter Modules \( (f_1 = f_2) \)
- MV \( \Delta \)-Connection \( (13.8kV_{\text{L-L}}, 4 \text{ Modules in Series}) \)
- LV \( \text{Y} \)-Connection \( (265V, \text{ Modules in Parallel}) \)

- SiC Enabled 20kHz/1MVA “Solid State Power Substation”
- 97% Efficiency @ Full Load / 1/3rd Weight / 50% Volume Reduction (Comp. to 60Hz)
SST vs. LF Transformer + AC/AC or 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**
Potential Future
SST Application Areas

Datacenters
Off-Shore Wind
Oil and Gas Industry
Power-to-Gas
Distributed Propulsion Aircraft
More Electric Ships
AC vs. Facility-Level DC Systems for Datacenters

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

- Conventional US 480V_{AC} Distribution

- Facility-Level 400 V_{DC} Distribution

Future Concept: Unidirectional SST / Direct 6.6kV AC → 400V DC Conversion
DC Collection Grids for Offshore Wind Parks

- ± 320kV HVDC Transmission to Shore
- ± 2kV
- ± 50kV

- 50kV / ± 320kV Offshore Substation

- ± 50kV Offshore Collection Grid
- ± 50kV / ± 320kV Offshore Substation
- MMLC-Based MF Isolation

Unidirectional Series Resonant MF DC→MVDC Conversion in each Wind Turbine

Source: Kjaer/2016
Subsea Applications – Oil & Gas Processing

ABB’s Future Subsea Power Grid → “Develop All Elements for a Subsea Factory”
Future Subsea Distribution Network

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

Source: Devold (ABB 2012)
Power-to-Gas

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

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

Source: www.r-e-a.net
Future Hybrid Distributed Propulsion 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 Distributed Propulsion 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)
Future Naval 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
Future Naval Applications

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

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

SST Limitations / Concepts

Research Areas
SST Ends the “War of Currents”

No “Revenge” of T.A. Edison but Future “Synergy” of AC and DC Systems!
SST Applications - The Road Ahead

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

- **AC/AC**
  - Efficiency Challenge
  - Controllability also by More Efficient Alternatives
    * Tap Changers
    * Series Regulators (Partial Power Processing)
  - Not Compatible w. Existing Infrastr.
  - Cost / Robustness / Reliability

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

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

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

- DC/DC
- AC/DC
- AC/AC
  - Sw. Frequ. as DOF of Design
  - Low Weight/Volume @ High Eff.
  - Local Applic. (Load/Source Integr.)
SST Development Cycles - Outlook

1. Wave
MF Isolation Concepts for Traction (Thyristors)

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

3. Wave
Advanced SST Concepts (HV-SiC)

4. Wave
SST Applications & Products

1. Wave (Grid)
SST Concepts for Smart Grid

2. Wave (Grid)
Appl. in Datacenters and Microgrids

Development Reaching Over Decades – Matched to “Product” Life Cycle
Thank You!
Questions