Next Generation Power Electronics Infrastructure System

Johann W. Kolar
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch
The EEnergy Internet

Johann W. Kolar
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch
Outline

► Introduction
► Demands on Future EE Infrastructure
► Fractal Smart Grid
► Smart Grid Power Electronics - SST
► Conclusions / Challenges
Energy Consumption Growth

→ Consequences / Countermeasures
Global Energy Consumption Growth

Not a Sustainable Path!

Source: Energy Outlook 2030 / BP 2012
Global CO₂ Emissions from Energy Use

*Risk to Exceed Recommended Emission Limit → Global Warming*

*“Policy Case” → (1) Renewable Energy, (2) Increase Prices, (3) Increase Efficiency (“Negawatts”)*

Source: *Energy Outlook 2030 / BP 2012*
Renewable Energy

→ Characteristics / Grid Integration
Characteristics of Renewable Energy Sources I

- Fluctuating (Partly Unpredictable) ➔ Storage (all Scales) and/or Demand Management

Source: IEC White Paper 2012
Characteristics of Renewable Energy Sources II

- Doubly Fed Induction Generator
- Full-Power Conv. Wind Turbine Generator (allows to provide Ancillary Services to the Grid)

- Variable Frequency AC Output → Power Electronics Interface for Grid Integration
Characteristics of Renewable Energy Sources II

Source: IEC White Paper 2012

- Structure of a PV Power Station

DC Output → Power Electronics Interface for Grid Integration
Characteristics of Renewable Energy Sources III

- Decentralized / Remote (e.g. Off-Shore)  \(\rightarrow\)  (Multi-Terminal) HVDC Transm. / EU Super Grid
Local “Grid-Friendly” Integration of Renewable Sources

- Contribution to Power System Reliability / Stability
  - Short-Circuit Current Control
  - Voltage / VAR Control (VSC or FACTS Equipment)
  - Fault Ride Through (Fault: Low/High Voltage or Frequency)

Source: IEC White Paper 2012
Grid-Integration of Distributed Renewable Energy

- Multi-Layer Centralized Control of Renewable Energy Plant Cluster

→ NEW Approach Required to Allow Integration of (also Small Scale) Renewable Energy Sources / Storages & Load Control etc. All Over the Grid
Future Fractal Smart Grid

→ Fractal Grid Structure
→ Convergence of IT & Energy Systems
Advanced (High Power Quality) Grid Concept

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

Source: ABB / Heinemann 2001
Future Renewable Electric Energy Delivery & Management (FREEDM) Syst.

“Energy Internet”
- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Enables Distrib. Intellig. through COMM


Source: Ayyanar / Huang 2008
Smart Grid Concept

- **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
  - “Virtual Power Plants”
  - 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 Communication
  - Intentional / Unintentional Islanding for Up- or Downstream Protection
  - etc.

Source: Borojevic 2010
Smart Grid Control Challenge I

- Generation Control
  \[ P_i(t) = \Delta P_s(t) + P_g(t) \]

- Load Control
  \[ P(t) = \Delta P_s(t) + P_g(t) \]

- Constant Power Loads
- Ren. Energy = Variable / Distributed Sources
- Red. Kinetic Energy Storage in Future Grids → Provide other Storage & Control for Power Balance
Smart Grid Control Challenge II

Large Number & Low / High Dynamics → Clustering and Decentr. / Autonomous Contr. or Response

Source: J. Sun, EPRI-PSMA Workshop 2013
Smart Grid Control Challenge III

Source: J. Sun, EPRI-PSMA Workshop 2013

Dynamics \(\rightarrow\) from Transient Balance by Kin. Storage (No Cntrl) to ms-Active Power Flow Control
Example of Autonomous Response

- Grid Connection Based on “Virtual Impedance”

Power Converter Emulates Synchronous Generator Behavior (according to EM Model)
Smart Home / Microgrid

- Energy Trading
  (Scheduling of Power Supply / Consumpt., Operating Reserves, Power Quality Services, Energy Storage / Balancing etc.; Smart Meters)

- Smart Picogrid
  (Smart Homes, Smart Buildings etc.)

- Distributed Control of Power Electronic Interfaces in Smart Picrogrids
Smart Grid Power Electronics → Solid State Transformer
Classical Transformer - Basics

- Advantages

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

- 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

- Construction Volume

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

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

- No Controllability
- Low Mains Frequency Results in Large Weight / Volume
SST Functionalities

- **Protects Load from Power System Disturbance**
  - Voltage Harmonics / Voltage Sag Compensation
  - Outage Compensation (UPS Functionality)
  - 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 Circuit

- **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
  - High Efficiency
  - No Fire Hazard / Contamination
► Electronic Transformer - McMurray 1968

- Matrix-Type $f_1 = f_2$

- Electronic Transformer = HF Transf. Link & Input and Output Sold State Switching Circuits
- AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption
Electronic Transformer - McMurray 1968

- Matrix-Type $f_1=f_2$

- 50% Duty Cycle Operation @ Primary and Secondary
- Output Voltage Control via Phase Shift Angle
Electronic Transformer

- Matrix-Type $f_1 = f_2$

- Inverse-Paralleled Pairs of Turn-off Switches
Basic Solid-State Transformer (SST) Structures

- Power Conversion
  - Three-Stage Power Conversion with MV and LV DC Link
  - Two-Stage Concept with LV DC Link (Connection of Energy Storage)
  - Two-Stage Concept with MV DC Link (Connection to HVDC System)
  - Direct or Indirect Matrix-Type Topologies (No Energy Storage)

- Realization of 3ph. Conversion
  - Direct 3ph. Converter Systems
  - Three-Phase Conn. of 1ph. Systems
  - Hybrid Combinations

- Handling of Voltage & Power Levels
  - Multi-Level Converters / Single Transf.
  - Cascading / Parallel Conn. of Conv. Modules
  - Series / Parallel Connection of Semicond.
  - Hybrid Combinations

- Medium Freq. Required for Achieving Low Weight (Low Realiz. Effort) AND High Control Dynamics
DC-Link Based *Fully Phase-Modular SST* Topologies

- Akagi (2005/2007)

Application for MV Motor Drives Replacing the 50/60 Hz Transformer
Unidirectional DC-Link Based SST Structures

- Enjeti (2012)

- SST Appl. for MV Adjustable Speed Drive (Unidir. AC/AC Front End / Cascaded 2L 1ph.-Inverters)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)
UNIFLEX Project

- 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
MEGALink @ ETH Zürich

- 2-Level VSI on LV Side / HC-DCM-SRC DC-DC Conversion / Multilevel MV Structure

\[ S_H = 630\text{kVA} \]
\[ U_{LV} = 400\text{ V} \]
\[ U_{MV} = 10\text{kV} \]
Examples of SST Applications

→ Future Traction Vehicles
→ Subsea Power Systems
Electric Railway Systems – Today’s Drive Scheme

- 16.7 Hz 1ph.-Transformer Required to Step-Down the Catenary Voltage to the Drive’s Operating Voltage

- Low Frequency Transformer
  - 15% Weight of Locomotive
  - e.g. for 2MW ca. 3000kg
  - 90-92% Efficiency
**SST Application I - Next Generation Locomotives**

- **Trends**
  - Distributed Propulsion System → Weight Reduction (pot. Decreases Eff.)
  - Energy Efficient Rail Vehicles → Loss Reduction (would Req. Higher Volume)
  - Red. of Mech. Stress on Track → Mass Reduction (pot. Decreases Eff.)

---

- Replace Low Frequency Transformer by *Medium Freq.* (MF) Power Electronics Transformer (PET)
- Medium Freq. Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction
- El. Syst. of Next Gen. Locom. (1ph. AC/3ph. AC) represents Part of a 3ph. AC/3ph. AC SST for Grid Appl.
ABB 1ph. AC/DC Power Electronic Transformer I

- Dujic / Zhao (ABB, 2011)

- Cascaded H-Bridges & Resonant LLC DC/DC Converter Stages
> **ABB 1ph. AC/DC Power Electronic Transformer II**

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

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
► ABB 1.2 MVA 1ph. AC/DC Power Electronic Transformer III

\[ P = 1.2 \text{MVA}, 1.8 \text{MVA pk} \]
9 Cells (Modular)
SST Application II - Subsea Oil and Gas

Source: ABB
Devold 2012

- ABB Future Subsea Power Grid → “Develop all Elements for a Subsea Factory”
SST Application II - Subsea Oil and Gas

Source: ABB Devold 2012

- ABB Future Subsea Power Grid → “Develop all Elements for a Subsea Factory”
SST Application II - Subsea Oil and Gas

- Future Subsea Distr. Network for Oil & Gas Processing

- DC Transmission, No Platforms/Floaters
- Longer Distances Possible

- Weight Opt. / Pressure Tol. Power Electronics
SST Reliability / Protection

→ Multi-Level vs. WBG Semiconductors
→ Overcurrent Requirements
- **Trade-Off - Reliability / Power Density / Efficiency**

- **Reliability / Power Density Pareto Front**

(5 Casc. H-Bridges, 1700V IGBTs, No Red., FIT-Rate calculated acc. to $T_j$, 100FIT Base)

- **Equivalent 2-Level SiC Converter** → 15.5kA/us & 1.1MV/us (!) for Equal Switching Losses
• MV Transformers must Provide Short-Circuit Currents of up to 40 Times Nominal Current for 1.5 Seconds (EWZ, 2009)

• Traction Transformers: 150% Nominal Power for 30 Seconds (Engel 2003)

• Power Electronics: Very Short Time Constants!
SST Protection Challenge – Overcurrent Requirements II

- Lower Grid Voltage Levels → Higher Relative Short Circuit Currents
Hybrid SST Concepts

→ LF Transformer (!)
→ Power Quality Enhancement
Hybrid Distribution Transformer

- Reactive Power Compensation (Power Factor Correction, Active Filter, Flicker Control)
- $5^{th}$ and $7^{th}$ Harmonics Compensation by proper Selection of Vector Group
- Available DC Port (Isolated in Option 1a)
- Option 2: Controlled Output Voltage

Source: ABB/Bala 2012
Hybrid Distribution Transformer

- Commercial Product (ABB)
- Direct Connection of Input to Output (Bypass) or
- Compensation of Inp. Voltage Sag (Contr. Output Voltage)

Source: ABB/Bala 2012
Critical Remark I - Technology Hype Cycle

Different States of Development of SSTs for Smart Grid and Traction Applications

- Peak of Inflated Expectations
- Plateau of Productivity
- Through of Disillusionment
Critical Remark II - Limitations / Applications

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

- **Potential Application Areas**
  - Replacement of Multi-Stage Conversion System (Efficiency Margin) or DC Grids
  - Applications for Volume/Weight Limited Systems where 3-4% of Losses Could be Accepted

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

- Traction - LF Transf. vs. SST
- Distribution - LF Transf. vs. SST
Main SST Optimization Potential

- Cost & Complexity Reduction by Functionality Limitation (e.g. Unidirectional Power Flow)

Future Research Topics

- Insulation Materials under MF Voltage Stress
- Low Loss High Current MF Interconnections
- MF Transformer Construction featuring High Insulation Voltage
- Thermal Management (Air and H₂O Cooling, avoiding Oil)
- “Low” Voltage SiC Devices for Efficiency Improvement
- Multi-Level vs. Two-Level Topologies with SiC Switches → “Optimum” Number of Levels
- Multi-Objective Cost / Volume / Efficiency / Reliability Optimization (Pareto Surface)
- SST Protection (e.g. Overvoltage)
- SST Reliability
- Hybrid (LF // SST) Solutions
- SST vs. FACTS (Integration vs. Combination of Transformer and Power Electronics)
- System-Oriented Analysis → Clarify Benefits on System Level (Balancing the Low Eff. Drawback)
Challenges of Smart Grid Realization

→ Technologies
→ Reliability
→ Costs
Challenges of Smart Grid Realization I

- **Engineering Challenge**: Competence in - Power Systems - Power Electronics - ICT - etc.

- **Technological Challenge**: Power Converters (WBG, Modular, Scalable) Control Concepts (Autonom. Cntrl etc.) New Protection / Monitoring Concepts etc.

- **Economic Challenges**: Standardization (Power Electr., ICT) Forecasting / Planning Establish Business Models etc.

- **Operation Challenge**: Grid Stability Reliability Data Security (!) etc.
Challenges of Smart Grid Realization II

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