Distribution Grids with DC Technology

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Background: Energy market mechanisms that enabled more decentralized power production

Market changes that were introduced stepwise (EU):

1. **Market liberalization** allowed decentralized power generation, creating prosumers, typically small scale power generation (CHP) and REN sources (mostly volatile sources, such as PV and wind)

2. **CO₂ certificates**

3. **Unbundling** of power generation and grid operation

4. **Unbundling** of TSO and DSO

Challenge:

Need to find technical solutions that are socially and economically viable within these new markets and regulations
487 GW\textsubscript{peak} installed capacity by the end of 2016 – assuming 50\% DFG, this translates in approximately **750 GVA** of power electronic converters

Multi-megawatt power electronic converters are becoming a mass product. During the past 25 years a major cost reduction of voltage source inverters took place; from 500 €/kVA down to 25 €/kVA
Global installed capacity of PV is accelerating

- 285 GW_{\text{peak}} of PV installed by 2016
- About 315 GVA of PV (string and central) inverters are installed by 2016
- LCE of PV in some countries is lower than that of wind or coal power plants

Source: PowerWeb

487 GW instead of 497 GW
Silicon is made of SiO₂ (i.e. sand, an abundant material) and energy. Energy is produced by PV. PV energy is controlled and converted by power electronics made of silicon.
Electrical Grids for a CO₂ Neutral Electrical Energy Supply System
Sector coupling to provide massive energy storage
Electrical Grids for a CO₂ Neutral Electrical Energy Supply System
About 1/3 in HV, 1/3 in MV, 1/3 in Low-Voltage Distribution Grid

Interesting observation: The transmission grid requires just minimal extension with HVDC. ETG Task Force expects less cost for DC integration in infrastructure. The MV distribution grid will become bottleneck.
The “1/3 rule” already applies to the German installed capacities.

Conventional power sources

- Central power stations: 54.2 GW
- Industrial power plants: 22.2 GW
- Municipal power plants: 4.5 GW
- Local distribution grids: ~

Bi-directional, interconnected grid structure

- High voltage from 100 kV: 40.7 GW
- Medium voltage: 25.6 GW
- Low voltage: 23.2 GW

Renewable power sources

- Offshore-wind parks: 3.4 GW
- Large solar and wind parks: ~
- Solar and wind parks: 4.5 GW
- PV-systems in local Distribution grids: 40.7 GW

(5 GW not associated)

Future grids cannot ignore the energy feed-in in medium- and low-voltage distribution grids and must become interconnected.

Daten: Bundesnetzagentur - Daten und Informationen zum EEG (31.12.2015), Kraftwerksliste und Zahlen (10.06.2016, Status 2015)
Intelligent MVDC Interconnected Substations

Dual-Active Bridge as modular PEBB
Further development with ARCP
ZVS extension with tap changer
Multiport converter as power router
Urban Regional, Flexible MVDC Distribution Grid linked to HVDC Cellular „Underlay“ structure
Intelligent MVDC Interconnected Substations

- Physiology
- Landscape architecture
- AixControl XRS7070
- DC-DC converter
- Medium-frequency transformer
- Research grid
Dual Active Bridge DC-DC Converter
Medium-Voltage High-Power DC-DC Converter

- $P = 7 \text{ MW, } V_{DC} = 5 \text{ kV } \pm 10\%$
- Si-Steel 180 $\mu$m lamination
- Efficiency up to 99.2% @1 kHz
- Ultimately air-cooled devices are an option
- DC substation at 1/3 weight of 50 Hz transformer

R. Lenke, „A Contribution to the Design of Isolated DC-DC Converters for Utility Applications“, Diss. RWTH Aachen University, E.ON ERC, 2012
N. Soltau, „High-power medium-voltage DC-DC converters : design, control and demonstration“, Diss., RWTH Aachen University, E.ON ERC, 2017

DAB uses ABB IGCT Stacks
Dual Active Bridge DC-DC Converter
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5 MW DAB DC-DC Converter

![Diagram of Dual Active Bridge DC-DC Converter](attachment:image.png)

\[ P \approx \frac{V_{in} V_{out}}{X} \sin \phi \]
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5 MW DAB DC-DC Converter
Medium-Voltage High-Power DC-DC Converter
Dual-Active Bridge as a universal PEBB

- Three-Phase Dual-Active Bridge (DAB)
  - High efficiency (99%)
  - Medium-frequency ac-link
  - Modular approach- PEBB
  - Scalable in power and voltage
  - Buck-Boost operation
  - Short circuit proof
  - Primary and secondary side can be connected in series or parallel
  - Can be built with redundancy
Dual Active Bridge DC-DC Converter
Further Development with ARCP

- Operation Principle of the Dual-Active Bridge with Auxiliary-Resonant Commutated Pole
- Main goal is to guarantee a zero-voltage condition at the main converter legs


Dual Active Bridge DC-DC Converter
Further Development with ARCP

- Characterization of Four-Quadrant Switches for ARCP

<table>
<thead>
<tr>
<th>Switch Type</th>
<th>Losses (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thyristor with SiC</td>
<td>3.41 kW</td>
</tr>
<tr>
<td>IGBT</td>
<td>10.19 kW</td>
</tr>
<tr>
<td>IGBT with SiC</td>
<td>3.37 kW</td>
</tr>
<tr>
<td>IGCT with SiC</td>
<td>3.76 kW</td>
</tr>
</tbody>
</table>

Tested up to 2kV - Extrapolated Losses @ 5 kV
Dual Active Bridge DC-DC Converter with Tap Changer
Zero Voltage Switching Extension

- Tap changer extends the zero-voltage switching
  - The DAB with tap changer can be modulated completely in ZVS if at low load the triangular modulation strategy is used
- Trade-off between reduction of losses and number of taps

\[ V_1 = 50 \text{ V} \]

\[ T_r = 5 \]

\[ T_r = 3, 5, 7 \]

\[ T_r = 2 \text{ to } 8 \]
Dual Active Bridge DC-DC Converter with Tap Changer
Prototype DAB with Tap Changer

LV H-bridges  Transformer  Tap changer  HV H-bridge

Modulation Schemes to Extend Soft-Switching Range

Asymmetrical Duty-Cycle Control

- Injection of common-mode voltage into the transformer neutral point
- Zero-current switching is achieved in extended operation range by three modulation modes

New modulation waveforms
Original soft-switching range
Extended soft-switching range


Modulation Schemes to Extend Soft-Switching Range
Asymmetrical Duty-Cycle Control

- Efficiency for various voltage ratios and power levels

![Graphs showing efficiency for various voltage ratios and power levels](image)

Multiport DC-DC Converters as Power Router

- Fully bidirectional power flow between different loads/grids, i.e., no intermediate (high voltage) stage is required to exchange power between loads/grids of different or equal voltage levels
- Low component count (each load/grid requires only one power electronic port)
- High utilization of components
- Arbitrary number of loads/grids can be operated in island mode

→ Highly efficient and flexible way for interconnecting dc grids/loads
Three-Phase Triple-Active Bridge DC-DC Converter

- 150 kW, 20 kHz
- 5 kV, 760 V and 380 V
- 10 kV SiC MOSFETs

Protection Strategies and Control

Underlay grids
Protection in meshed DC grids
Converter control methods
Hardware-in-the-Loop enabling real-time control evaluation
Classical Distribution Grids are radial. Integration of decentralized supplies, renewables, storage, and e-Mobility is difficult.
Classical Distribution Grids are radial and massively oversized. Integration of decentralized supplies, renewables, storage and e-Mobility is difficult.
Hybrid Approach to Maximize Capacity of Distribution Grids
Integration of e-Mobility, PV, Wind, Storage ... by MVDC-Backbone
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Integration of e-Mobility, PV, Wind, Storage ... by MVDC-Backbone
Possible MVDC Grid Structure
Dual-Active Bridge and Multiport Converter

- Galvanically isolated sub-grid structures
  - Multi-/ Three-Port DC-DC converter
  - Galvanic isolation
  - Connection of three different voltage levels possible
Fault in Meshed DC Grids
Fault Isolation With DC Circuit Breaker

- Normal operation
Fault in Meshed DC Grids
Fault Isolation With DC Circuit Breaker

- Normal operation - fault occurs
Fault in Meshed DC Grids
Fault Isolation With DC Circuit Breaker

- Normal operation - fault occurs
- Clearing and isolation of the fault with DC Circuit Breakers
- Non affected part of three-port converter continued operation
Fault in Meshed DC Grid
Fault Isolation with DC Disconnects

- Normal Operation

Picture: Siemens, Sicat 8WL6134 DC disconnector, 3 kV
Fault in Meshed DC Grid
Fault Isolation with DC Disconnects

- Fault occurs
Fault in Meshed DC Grid
Fault Isolation with DC Disconnects

- Fault occurs
- Fault extinction via DC-DC converters (short interruption in power supply)

Picture: Siemens, Sicat 8WL6134 DC disconnector, 3 kV
Fault in Meshed DC Grid
Fault Isolation with DC Disconnects

- Fault occurs
- Fault extinction via DC-DC converters (short interruption in power supply)
- Isolation of fault with disconnectors
- Non affected part of three-port converter can continue operation

Picture: Siemens, Sicat 8WL6134 DC disconnector, 3 kV
DC-Switching
State of the Art

- Products are available for low voltage applications, ex. Traction applications (high speed mechanical circuit breakers)
- Wide variety of designs proposed in research, hybrid, snubbered mechanical, active current injection, and solid-state circuit breakers topologies
- Prototypes developed by different manufacturer (ex. Mitsubishi, ABB), ultra fast mechanical circuit breaker is a key component
- Project Goal
  - Design of a circuit breaker in MVDC systems

DC – Switching
Circuit Breaker Concepts of Interest

- **Hybrid Circuit Breaker**
  - Circuit breaker opens upon fault current detection
  - Current commutate through a PE-device commutation path, low voltage drop develops over the mech. circuit breaker
  - Active turn-off PE devices interrupt the current when arc extinguishes

- **Snubbered Mechanical Circuit Breaker (SMCB)**
  - Circuit breaker opens upon fault current detection
  - Capacitors limits the voltage over circuit breaker during opening
  - Thyristors turn off at zero current detection to eliminate oscillations with the network
Hybrid DC Breaker
Development of a new Power Electronic Device

- **Device**
  - Consists of a GTO-wafer, a diode stack, and a gate MOSFET
  - For a successful commutation and turn-off, the condition to be satisfied is
    \[ V_{pn} + V_{Diode} > V_{MOSFET} \]
  - Work in progress: Proof of concept and package design and construction (presspack)

- **Driver**
  - Develop a driver based on similar thyristor based power electronic devices
  - Building prototype II after defining and solving issues of prototype I
Dynamic Control of Dual Active Bridge DC-DC Converter
Medium-Voltage High-Power DC-DC Converter

- DAB is a third order system (C - L - C)
- Oscillates when disturbances occur
- Active damping or predictive control is needed to prevent instabilities
Dynamic Behavior at Abrupt Change of Load Angle $\phi$

- Step change of $\phi$ leads to asymmetric phase currents
  - Oscillations of the dc current can be observed

- Oscillations decay exponentially with time constant:
  $$\tau = \frac{L_s}{R}$$
  with $R$ being the winding resistance of the transformer.
  - Strong oscillations with highly efficient converters (low $R$) featuring an increased dynamic voltage range (high $L_s$)
  - Limited bandwidth of current control
Abrupt Change of Load Angle $\phi$

- Phase currents and dc current
- Phase currents in the $\alpha\beta$ plane
Predictive Instantaneous Current Control

- Edges of the hexagon are proportional to load angle
- Introduction of pre-calculated intermediate steps in the load angle force the current to settle on the intended trajectory, within half the switching period
Load Angle Change with the Instantaneous Current Control

- Phase currents and dc current
- Phase currents in the $\alpha\beta$ plane
Real-Time Control Evaluation

- Replacement of bulky expensive hardware with real-time model

- Extensive testing of control
  - Interfaces
  - Control Algorithm
  - Platform / Processor Hardware

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Real-Time Simulation Setup

- Control Signals
- Control Algorithm Real-Time Controller
- Virtual Plant Real-Time Simulator
- Measurement Signals
Roadmap development of DC Converters

Cost development
Impact of New Materials – Increased power density
Price development for transformer can change the AC-paradigm

- Metal prices (Cu, Al, Si-Fe) for transformers at LMEx are increasing on long term
- Prices of power electronic systems are continuously dropping
  - Increasing production quantities, new semiconductor generations and materials
  - Higher operating frequency and voltage levels
- During last 25 years a reduction of specific cost for frequency inverters from 500 €/kVA to 25 €/kVA, 5 €/kVA expected in 2020

Milestone: In 2013 a frequency inverter was no longer more expensive (20 k€/MVA) than a 50 Hz transformer
Technology Drivers
Price Development of Power Electronics

• Specific cost for EV inverters
  – 1995: $50/kVA\textsuperscript{1}
  – 2015: $5/kVA\textsuperscript{2}
  – 2020 R&D target: $3.3/kVA

\begin{itemize}
  \item Source: Data provided by R. De Doncker
  \item Source: U.S. Department of Energy, Vehicle Technologies Office
\end{itemize}
Technology Drivers
Price Development of Power Electronics

• Specific cost for EV inverters
  - 1995: $50/kVA\(^1\)
  - 2015: $5/kVA\(^2\)
  - 2020 R&D target: $3.3/kVA

• DC-DC converter cost
  - Comprises two inverters and HF transformer
  - 2020 R&D target: $7.7/kW
  - Cost reduction using soft-switching and Wide Bandgap Devices

\(^1\) Source: Data provided by R. De Doncker
\(^2\) Source: U.S. Department of Energy, Vehicle Technologies Office
HI-LEVEL
Demonstrator next generation, low-cost EV inverters

• Project goal
  – Novel compact concept for reliable electronics for drives of electric vehicles

• Technology
  – Drive converter based on high-current PCBs
  – Embedding of power electronic devices into the PSB

• Demonstrator
  – 3-phase inverter
  – 50 kW, battery voltage 170-320 V, phase current up to 320 A (short time)

![Diagram of inverter components]

![Graph showing turn-off transient]

Turn-off transient
Wide Bandgap and Si-Superjunction Converters

- **SiC HV Battery DC-DC converter**
  - $f_{sw} = 150$ kHz
  - $P_{max} = 126$ kW ($3 \times 42$ kW)
  - $V_{batt} = 300\ldots500$ V
  - $V_{dc-link} = V_{batt}\ldots800$ V

- **SiC Traction Inverter**
  - $f_{sw,\text{max}} = 100$ kHz
  - $P_{max} = 160$ kW
  - $V_{in} = 800$ V

- **Superjunction LV Battery DC-DC Converter**
  - $f_{sw} = 100$ kHz
  - $P_{max} = 3$ kW
  - $V_{batt} = 10\ldots16$ V
  - $V_{dc-link} = 170\ldots380$ V

- **GaN MHz DC-DC Converter**
  - $f_{sw} = 30,3$ MHz
  - $P_{max} = 150$ W
  - $V_{in} = 200$ V
  - $V_{out} = 40$ V

- **GaN Bidirectional Charger**
  - $f_{sw} = 300 - 500$ kHz
  - $P_{max} = 3.7$ kW
  - $V_{grid} = 230$ V
  - $V_{battery} = 250\ldots400$ V

- **SiC Traction Inverter**
  - $f_{sw,\text{max}} = 100$ kHz
  - $P_{max} = 160$ kW
  - $V_{in} = 800$ V
Power Density Development of DC-DC Converters

- 2012
  - $f_{sw} = 16$ kHz
  - Si-Module
  - classic cooler and inductances

- 2016
  - $f_{sw} = 150$ kHz
  - SiC-Module
  - classic cooler and inductances

- 2018
  - $f_{sw} = 400$ kHz
  - discrete SiC devices
  - 3D-printed cooler and inductor bobbin
Distribution Grids with DC Technology

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Future Vision: City of Geilenkirchen

- **Load balancing substations**
- **Fast-charging**
- **Elimination 110 kV**
- **280 ha (160 ha GI)**
- **60-100 MWp**
- **≅ 4-7 Mio. €/a *)**
- **± 900 h/a, 7,5 ct/kWh**

*) 900 h/a, 7,5 ct/kWh