Ultra High Voltage SiC Power Devices and
All DC Electric Power Grid

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Big Picture: Moving from Centralized Grid to Distributed (& Renewable) Energy Resources

Challenges of large scale use of renewables for electrical grids:

- On the one hand many small decentralized units connected to distribution and low voltage grid (micro- and mini-CHP, Wind, PV, solar, “prosumers”)
- On the other hand many large-scale wind farms, PV farms and solar power stations, that have to transmit the energy over long distances
- Power generation of wind and solar (PV) is volatile, which requires medium and long-term energy storage

1) 100% penetration: Voltage Issue?
2) Market transformation: Energy Internet (proposed in 2007 by Dr. Huang)

*Courtesy slide from: Dr. DeDoncker, PEDG2015*
Energy Internet Market/Business

- Analogous to internet consumer-to-consumer commerce (eBay) or stock market

- **Energy Cells** are to:
  - operate and manage local generators, energy storage, and dispatchable load
  - compete with each other to maximize their own profits

- **Utilities** are expected to make more profit on providing ancillary services to ensure the residential distribution system security and reliability, in addition to electricity transaction.

- Who owns data rules

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The Third Industrial Revolution

“using Internet technology to transform the power grid of every continent into an **energy internet** that acts just like the Internet (when millions of buildings are generating a small amount of renewable energy locally, on-site, they can sell surplus green electricity back to the grid and share it with their continental neighbors); and”

Picture from “Economist”
FREEDM System: Resilient Grid

1. Solid State Transformer
2. Plug-and-play DC Microgrid
3. Solid State/Hybrid Circuit Breaker

*Proposed by Dr. Huang in 2007*
Medium Voltage SiC Technology

Using SiC MOSFET
- 60 to 120 X improvements in V-f capability
  - Enables MV & HF power conversion

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>SiC MOSFET</th>
<th>SiC n-IGBT</th>
<th>SiC p-ETO</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>40 MHz-V</td>
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<tr>
<td>15</td>
<td></td>
<td>600 MHz-V(ZVS)</td>
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<tr>
<td>10</td>
<td></td>
<td>300 MHz-V</td>
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<tr>
<td>5 MHz-V</td>
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</table>

Switching frequency (kHz)
Solid State Transformer

Gen-1 SST: Si-based (3 kH 6.5 kV IGBT)

Gen-2 SST: SiC-based (10 kHz 15 kV SiC MOSFET)

Gen-3 SST: 40 kHz 15 kV SiC
8

From 60Hz to SST to Smart Transformer to Energy Router

Medium Voltage AC 7.2 kV (or Medium Voltage DC)

- Power Management:
  - Control Voltage: Control power factor/VAR injection
  - Frequency Response: SSSM
  - Demand Response/CVR: Change/Control customer voltage
- Energy Efficiency: Provide DC power
- Improve Power Quality:
  - Eliminate customer side harmonics
  - Low voltage ride through
- Resilience: Supports multiple islanding modes

- Fault management
  - Current limiting
  - Disconnect/reconnect

- Energy Management
  - AMI: Monitor energy usage
  - Can control/dispatch power via (Energy Cell)
- Energy Router

SST Functional Diagram
SST: MV AC voltage sag operation: 25% voltage sag, 5KW

3.6 kV AC

Gen-I SST

120V AC

5 kW LOAD

Input voltage, current, PWM voltage, high voltage DC link

Output DC voltage, AC voltage and current
SST Integration with a Non-linear Load: Harmonic Mitigation

1.8 kV AC

Gen-II SST

120V AC

Non linear LOAD

Note: Output AC phase is 180 shifted with the HV AC load current and LV AC current harmonics.
Frequency Response: SSSM Demo

- CH1: 0 W
- CH2: 120\pi \text{ rad/s}
- CH3: 200 V
- CH4: 0 A

PV output drops to zero

$P_{out}^{(\text{Grid})}$

$\omega$

$V_{dc}$

$i_{bat}$

1s
Short-Circuit Protection

Experimental results of worst-case short circuit protection
($V_{HV_{dc}}=3kV$, $V_{LV_{dc}}=200-0V$)

Naturally switch to DAB mixed LLC mode, Current is well controlled.

Worst-case short circuit happens within 0.01 ms.
All DC Electric Grid

MAJOR ADVANTAGE Over AC: 1) Loss reduction, 2) Better utilization of cables, and 3) Easy for DER integration

Plug-and-play DC Microgrid
GTO thyristor demonstrate the best current carry capability and small T dependence.
How about 50 kV thyristor?

30kV

40kV

50kV

P Drift
2e14cm$^{-3}$

ptop

Nbase

Pbuff

Nbuff

N sub

250μm

340μm

420μm

30kV 40kV 50kV
Current capability at 50 kV

p-GTO IV with $\tau_{HL}=10\mu s$, good anode injection

Better lifetime enhancement will lower forward drop at 50 kV to < 5V
15 kV GTO/ETO Safe Operation Area

Bipolar Avalanche Limit

1 MW/cm² power line

SiC 1.2kV BJT

SiC 7.5kV p-IGBT

SiC 4.5kV p-ETO

SiC 15kV p-ETO

SiC Punchthrough PNP

SiC Punchthrough NPN

silicon limit ~200 kW/cm²

Turn-off @1000A/cm² is theoretically predicted
15 kV SiC p-ETO in Action: Hybrid Solid State Circuit Breaker

Target: 2 ms opening AC breaker
Fast enough as a DC breaker!
FMS: 1.5 ms opening speed

15 kV withstand voltage separation achieved at around 1.5 ms

Cap bank voltage
Conclusions

• **All DC Electric Grid has numerous advantages and should be considered as a long term modernization goal**
  - 1) Lower losses & better cable utilization, 2) easier for DER integration

• **High Voltage and High Frequency Capability Switch**
  - Ultra High Voltage SiC MOSFET can enable HVDC-MVDC-LVDC Power Grid Architecture

• **High Voltage and High Temperature Switch**
  - Ultra High Voltage SiC bipolar devices such as GTO and thyristor are very attractive for very high voltage and high temperature operation such as in a DC circuit breaker