High-Voltage Power Semiconductors - Key Enabler for Grid Transformation

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Project Leader for Power Semiconductor Devices and Thermal Measurements
Grid Transformation via Power Conditioning System (PCS) Functionality

• **Today’s Grid:**
  - Electricity is generated by rotating machines with large inertia
  - Not much storage: generation instantaneously matches load using
    - load shedding at large facilities
    - low efficiency fossil generators for frequency regulation

• **Future Smart Grid:**
  - High penetration of renewables with power electronic grid interface:
    - dispatchable voltage, frequency, and reactive power
    - response to abnormal conditions without cascading events
    - dispatchable “synthetic” inertia and spinning reserve (w/ storage)
  - Storage for frequency regulation and renewable variability / intermittency
    - High-speed and high-energy storage options
    - Load-based “virtual storage” through scheduling and deferral
  - Plug-in Vehicles increase efficiency, provide additional grid storage
  - HVDC, DC circuits, SST, SSCB provide stability, functionality at low cost

• **Microgrids & automation provide secure, resilient operation**
High-Voltage, High-Frequency (HV-HF) Switch Mode Power Conversion

• Switch-mode power conversion (Today):
  • advantages: efficiency, control, functionality, size, weight, cost
  • semiconductors from: 100 V, ~MHz to 6 kV, ~100 Hz

• New semiconductor devices extend application range:
  • 1990’s: Silicon IGBTs
    • higher power levels for motor control, traction, grid PCS
  • Emerging: SiC Schottky diodes and MOSFETs, & GaN
    • higher speed for power supplies and motor control
  • Future: HV-HF SiC: MOSFET, PiN diode, Schottky, and IGBT
    • enable 15-kV, 20-kHz switch-mode power conversion
Power Semiconductor Applications

- Switching speed decreases with voltage
- SiC enables higher speed and voltage

HVDC and FACTS

- Power distribution, transmission and generation
- MV and High-Power Motors

DARPA/EPRI Megawatt Program

Device Blocking Voltage (V)

DARPA/ONR/NAVSEA HPE Program

10 kV HV-HF MOSFET/JBS

High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns

Silicon IGBT: 4.5 kV, >2us

ARPA-e ADEPT
12 kV SiC IGBT
Future option

NRL/ONR
4.5 kV SiC-JBS/Si-IGBT
Low cost now

SiC IGBT: HV, high Temp, ~1 us

SiC JBS: improves Si IGBT turn-on


Army HVPT, Navy HEPS
SiC ManTech Program

SiC MOSFET: 15 kV, ~100ns
SiC n-IGBT: 20 kV, ~1us
NIST High-Megawatt PCS Workshops

- High-Megawatt Converter Workshop: January 24, 2007
- HMW PCS Industry Roadmap Workshop: April 8, 2008
- Future Large CO2 Compressors: March 30-31, 2009
- High Penetration of Electronic Generators: Dec. 11, 2009
- Plugin Vehicle Fleets as Grid Storage: June 13, 2011
- Grid Applications of Power Electronics: May 24, 2012
- High-Power Variable-Speed Motor Drives: April, 2014
- High-Power Direct-Drive Motor Systems: September, 2014
10 kV SiC MOSFET/JBS Half-Bridge Module Model and Circuit Simulation

- **Half-bridge module model:**
  - 10 kV SiC power MOSFETs
  - 10 kV SiC JBS for anti-parallel diodes
  - low-voltage Si Schottky diodes
  - voltage isolation and cooling stack

- **Validated models scaled to 100 A, 10 kV half bridge module**

- **Model used to perform simulations necessary to:**
  - optimize module parameters
  - determine gate drive requirements
  - SSPS system integration
  - high-megawatt converter cost analysis
SECA: 300 MW PCS

http://www.nist.gov/pml/high_megawatt/

Semiconductors
Packaging and Interconnects
HF transformers
Filter Inductors and Capacitors
Cooling System
60 Hz Transformer up to 18 kV
Breakers and Switchgear

~700 V DC

Approx. 500 Fuel Cells

18 kV AC → 345 kV AC

$40-$100 / kW

Ripple < 2%
Stack Voltage Range
~700 to 1000 V

IEEE – 519
IEEE – 1547
Harmonic Distortion
Future: HVDC transmission

~700 V DC
## Estimated $/kW: MV & HV Inverter

<table>
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<tr>
<th>Inverter Voltage</th>
<th>Medium</th>
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<th>High</th>
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<tbody>
<tr>
<td>HV-SiC Diode</td>
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<td>PiN</td>
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<td>HV-SiC Switch</td>
<td>MOSFET</td>
<td>MOSFET</td>
<td>IGBT</td>
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<td>HF Transformer</td>
<td>Nano</td>
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<tr>
<td>60 Hz Transformer</td>
<td>yes</td>
<td>yes</td>
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</table>

### Risk Level:
- Low
- Moderate
- Considerable
- High

### Cost Breakdown:
- Transformer & Switchgear
- Other PE
- Semiconductor
- Cooling
- Magnetics

### Considerations:
- Loss
- Potential for increased efficiency and reduced operational costs
- Importance of selecting high-quality components to ensure longevity and reliability
Goal: $1/W by 2017 for 5 MW PV Plant

$0.5/W – PV module

$0.4/W – BOS

$0.1/W – Power electronics

Smart Grid Functionality

High Penetration

Enhanced Grid Value

$1/W achieves cost parity in most states!
MV Direct Connect Solar Inverter (ARPA-E)

- Utilize 10kV, 120 A SiC MOSFET Module:
  - Design Developed for DARPA/ONR/NAVSEA WBG HPE Program
  - Already tested at 1 MW-scale system for HPE SSPS requirements
- MV Solar Inverter Goals:
  - Improve cost, efficiency, size, and weight
  - High speed, series connected to grid: rapidly respond/clear faults, tune power quality

Contributed by: Leo Casey (Google)
High Penetration of Distributed Energy Resources

- Power Conditioning Systems (PCS) convert to/from 60 Hz AC for interconnection of renewable energy, electric storage, and PEVs

- “Smart Grid Interconnection Standards” required for devices to be utility-controlled operational asset and enable high penetration:
  - Dispatchable real and reactive power
  - Acceptable ramp-rates to mitigate renewable intermittency
  - Accommodate faults without cascading/common-mode events
  - Voltage regulation and utility-controlled islanding

http://www.nist.gov/pml/high_megawatt/2008_workshop.cfm
PCS Architectures for PEV Fleet as Grid Storage

http://www.whitehouse.gov/blog/2011/09/09/air-force-jumpstarts-electric-vehicle-program
Single Large Inverter with DC Circuits to PEV Fleet

Renewable/Clean Energy

Charging Station (Multiple Vehicles)

Energy Storage

DC Circuits or DC Bus

Storage Asset Management

On-board, Off-board

Plugin Vehicle Fleet

DC Microgrid: DC-AC with DC Circuits

24 V DC Loads

380 V DC Loads

Renewable/Clean Energy

Smart Grid

24 V DC Loads

380 V DC Loads

Renewable/Clean Energy

DC-AC

Microgrid Controller

DC Circuits / DC Bus

Energy Storage

Device Asset Management

On-board, Off-board

Plugin Vehicle Fleet

DC-DC

DC-DC

DC-DC

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Renewable/Clean Energy
Flow Control Microgrid: AC-AC with AC Circuits

- DC Options
- AC Loads & Generators
- Renewable/Clean Energy
- AC-AC or Multiport
- Microgrid Controller
- AC circuits
- Energy Storage
- Device Asset Management
- On-board, Off-board
- Plugin Vehicle Fleet
- NIST Smart Grid Program
Synchronous AC Microgrid: Disconnect and Local EMS

- AC Loads & Generators
- Disconnect Switch
- Microgrid Controller
- Smart Grid
- AC circuits
- Renewable/Clean Energy
- Energy Storage
- Device Asset Management
- On-board, Off-board
- PCS
- Plugin Vehicle Fleet

NIST Smart Grid Program
NIST Role in Smart Grid


In cooperation with the DoE, NEMA, IEEE, GWAC, and other stakeholders, NIST has “primary responsibility to coordinate development of a framework that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems…”
NIST Plan to Meet EISA’07 Responsibility

PHASE 1
Initial Framework and Standards based on Summer 2009 workshops, finalized Jan 2010

PHASE 2
Public-Private Smart Grid Interoperability Panel (SGIP)

PHASE 3
Testing & Certification

NEXT CHAPTER
Private-Public “New” Smart Grid Interoperability Panel (2.0)

NIST Smart Grid Research & Standards Program

2008
2009
2010 & 2011
2012
2013 and on
NIST Framework and Roadmap

Release 3
Summer 2014
- Public Comment closed May
- www.nist.gov/smartgrid
- New topic “Resiliency”

Release 1
January 2010

Release 2
February 2012
Distributed Renewables, Generators and Storage DEWG

- **DRGS Domain Expert Working Group** initiated September 2011
- Identify Smart Grid standards and interoperability issues/gaps for
  - Integration of renewable/clean and distributed generators and storage
  - Operation in high penetration scenarios, weak grids, **microgrids, DC grids**
  - Including interaction of high-bandwidth and high-inertia type devices

**Focus on Smart Grid functions that**
- mitigate impact of **variability and intermittency** of renewable generators
- enable generators and storage to provide valuable **grid supportive services**
- prevent unintentional islanding and cascading events for clustered devices

**Activities of DRGS DEWG**
- Consistent approaches for generators/storage types and domains
- Use cases and information exchange requirements
- Define new PAPs to address standards gaps and issues

**Subgroups:** A-Roadmap, B-Information, C-Microgrid, D-Test, E-Regulatory, F-Interconnection
Cyber-Physical Architecture for Resilient/Transactive Electricity Delivery Systems

- Markets
- Providers
- Bulk Generation and Storage
- Distributed Generation and Storage “DER”
- Premises, Loads “Prosumer”
- Transmission
- Distribution
- Microgrids
- uG-Operator

Electrical connections (Physical)
Secure Communications (Cyber)

Mobile: EV, rail, ship, air, microgrids
PAP 7: Smart Grid ES-DER Standards

Task 0: Scoping Document
Prioritized timeline for ES-DER standards

Task 1: Use Cases, *EPRI Smart Inverter
Define requirements for different scenarios

Task 2: IEEE 1547.4 for island applications and IEEE 1547.6 for secondary networks

Task 3: Unified interconnection method with multifunctional operational interface for range of storage and generation/storage.

IEEE 1547.8
(a) Operational interface
(b) Storage without gen
(c) PV with storage
(d) Wind with storage
(e) PEV as storage

Task 4: DER Object Models and Mappings
IEC 61850-7-420, -90-7: Expanded to include
- Multifunctional ES-DER operational interface
- Harmonized with CIM & MultiSpeak
- Map to MMS, DNP3, web services, & SEP 2

Task 5: Test, Safe and Reliable Implementation
UL 1741, NEC-NFPA70, SAE, CSA and IEC
PAP 24: Microgrid Operational Interfaces

Task 0: Scoping Document
Define microgrid standards needs

Task 1: Use Cases: Functional + Interactive EPRI DERMS
Define requirements for different scenarios

Task 2: Microgrid Interconnection standard for grid-interaction
IEEE 1547 Series

Task 3: Unified microgrid-EMS controller standard
IEEE P2030.7

Task 4: Regulatory Framework
a) State
b) Federal
c) NARUC

Task 5: Smart Microgrid Controller Information Models
IEC 61850 Series: CIM, MultiSpeak

Task 6: Microgrid Controller and Interconnection Equipment Test
Interconnection; Info exchange; Safety; System Impact

Other SGIP Info exchanges
Requirements