The Bradley Department of Electrical and Computer Engineering
College of Engineering

CPES Research:
SSPS - Building Blocks for the Future Electronic Power Grid

Presented by: ***Dushan Boroyevich***

at

U.S. DEPARTMENT OF ENERGY | Office of Electricity Delivery and Energy Reliability

SOLID STATE POWER SUBSTATION ROADMAPPING WORKSHOP

Clemson University Restoration Institute, Zucker Family Graduate Education Center
North Charleston, South Carolina
June 27-28, 2017

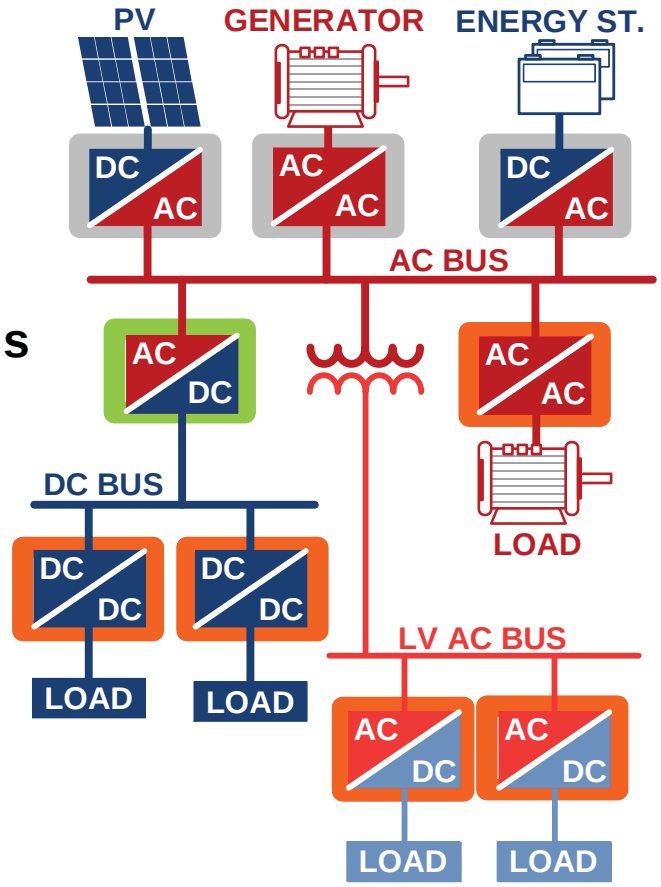
Hybrid AC/DC Electronic Power Distribution Systems



More Power Electronics Improves System Performance!

- **Load Converters:**
  Meet dynamic energy requirements of the loads
- **Source Converters:**
  - **Meet distribution bus standards**
  - **Improve source utilization**
- **Power Distribution Converters:**
  - **Increase power density**
  - **Improve energy efficiency**

REDUCE COST !



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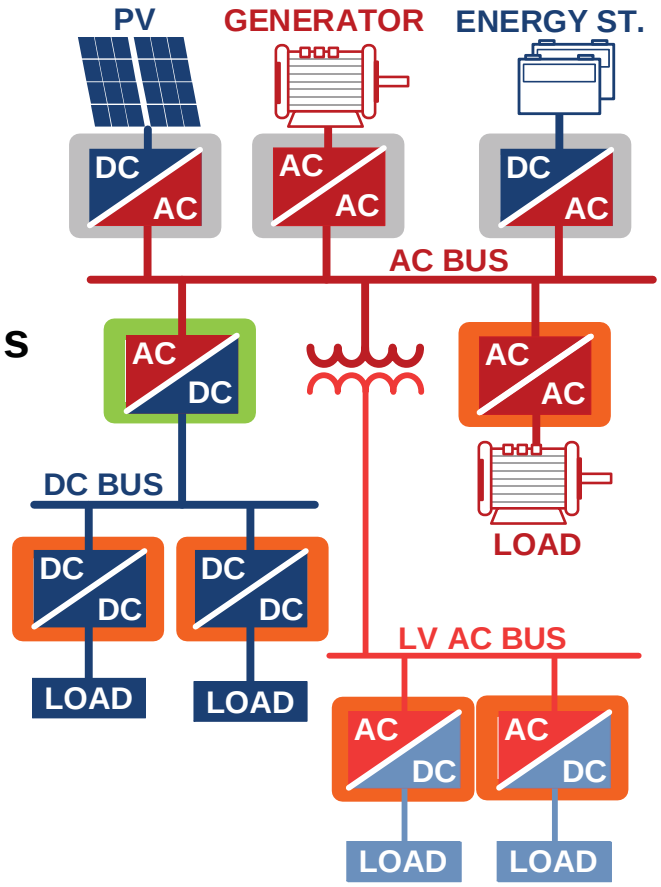


But …

- **Weight & Size**
- **Reliability & Lifetime**
- **Thermal Management**
- **Power Management**
- **Subsystem Interactions**
- **Power Quality**
- **EMI**
- **Cost**

Current Research Areas in CPES

Emerging Applications

SSPS 0.0

SSPS 1.0

SSPS 2.0

Application Areas

- Vehicular Power Converter Systems
- Point-of-Load Conversion
- Power Management for Computers & Telecommunications
- Sustainable Energy Systems

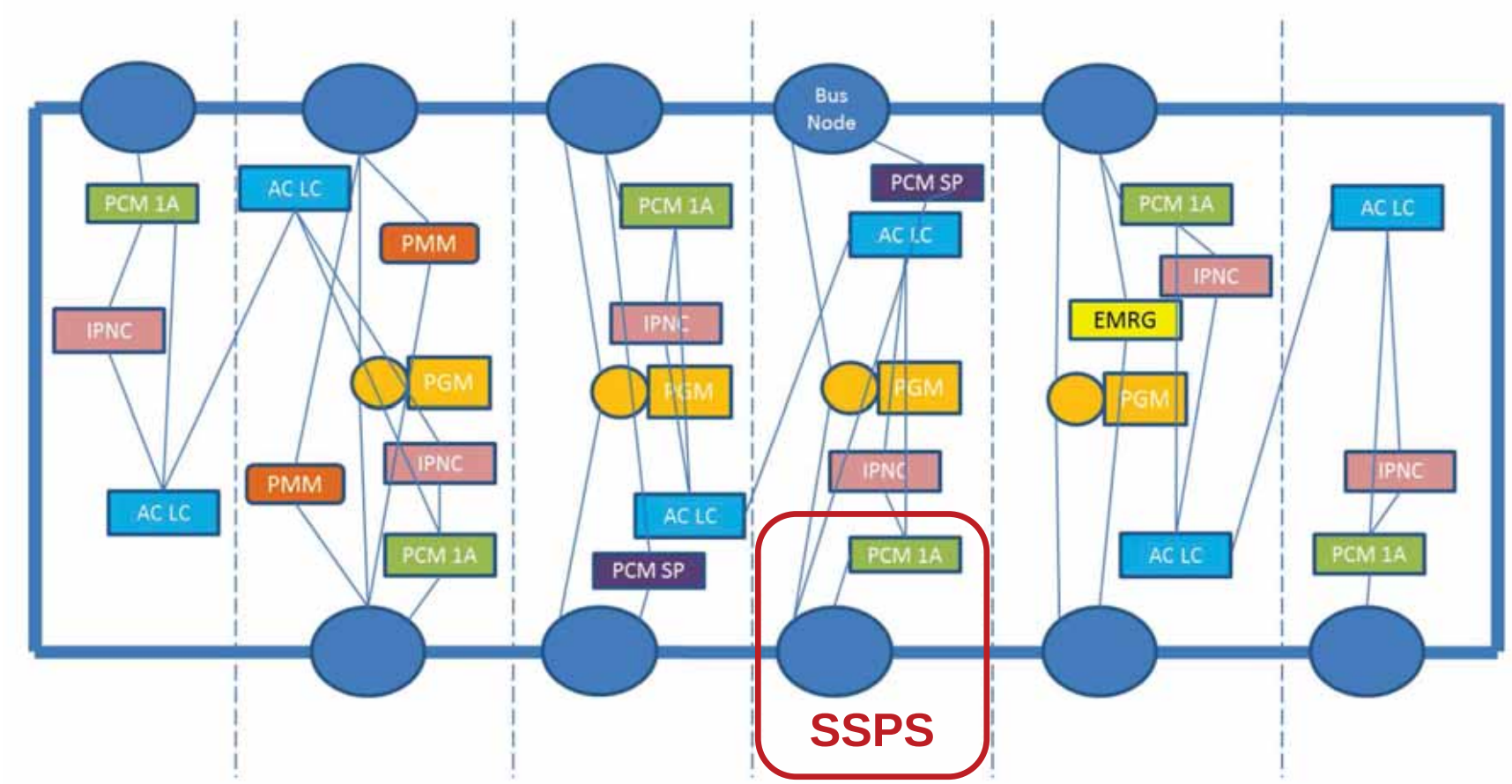
Technology Areas

- Power Electronics Components
- High Density Integration
- EMI and Power Quality
- Modeling and Control
- Power Conversion Topologies and Architectures

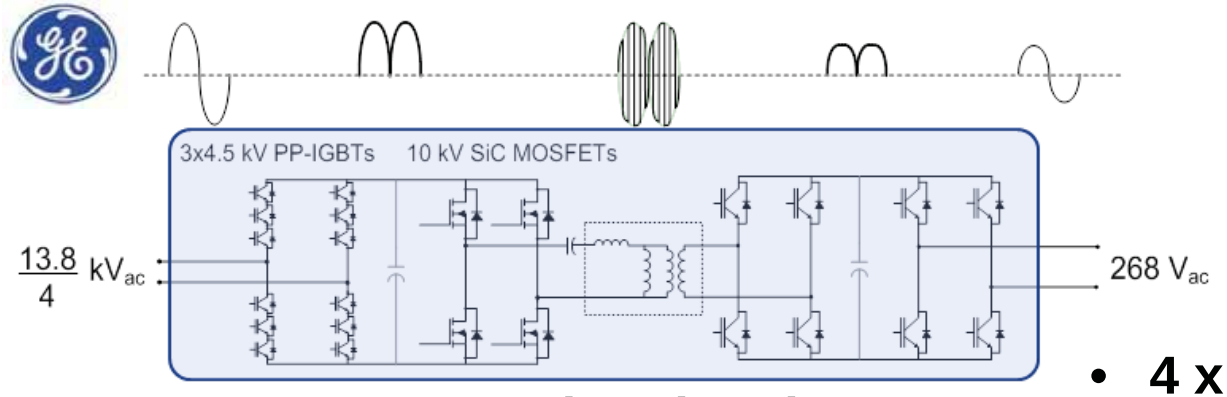
watts to megawatts

Zonal Power Distribution System
Bus- & SSPS-based

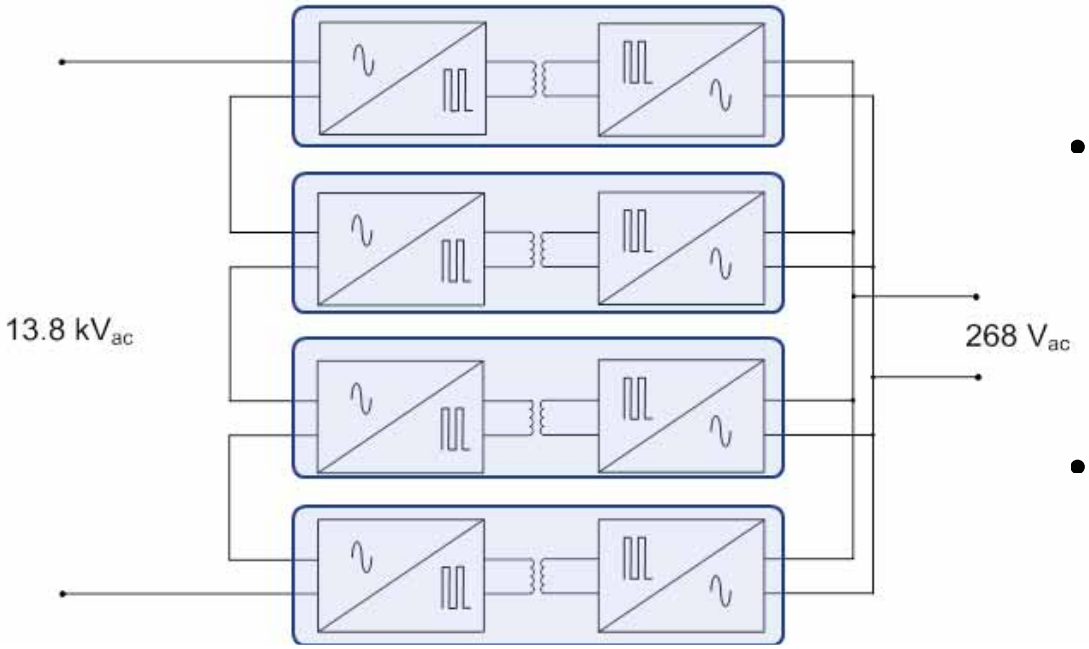
Notional ±6 kV DC Zonal System for the Future Navy Ships



1 MVA SSPS Prototype



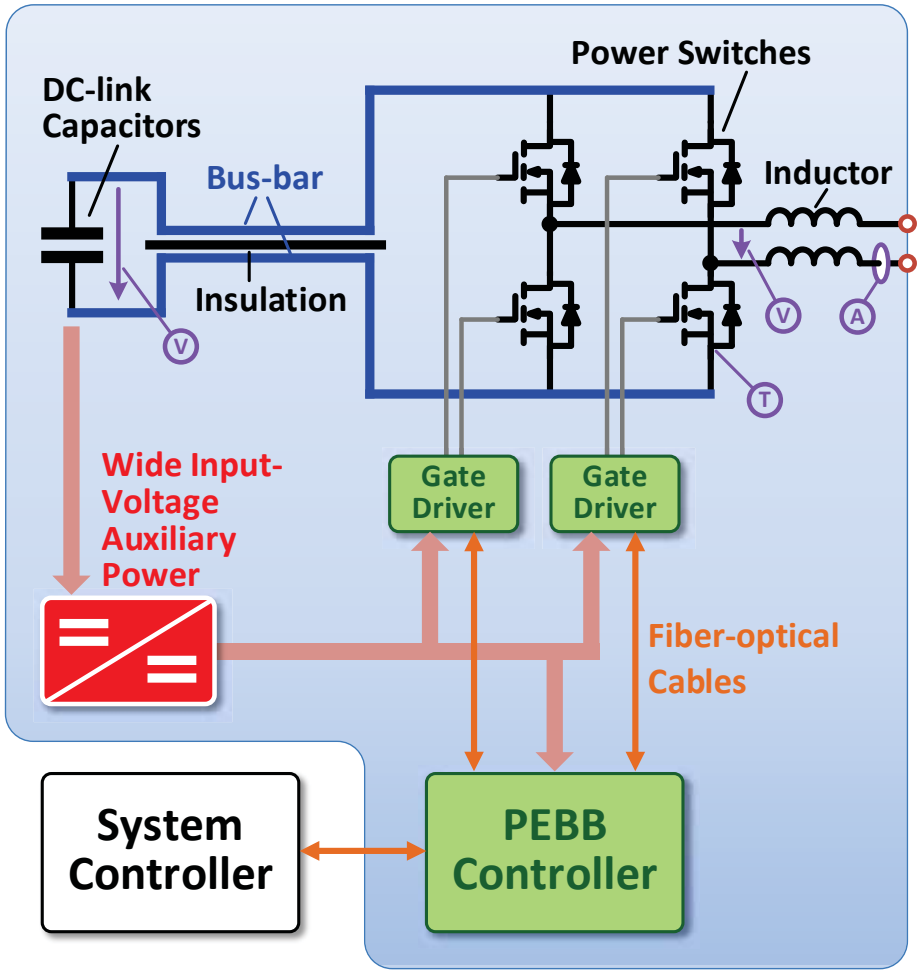
250 kVA block

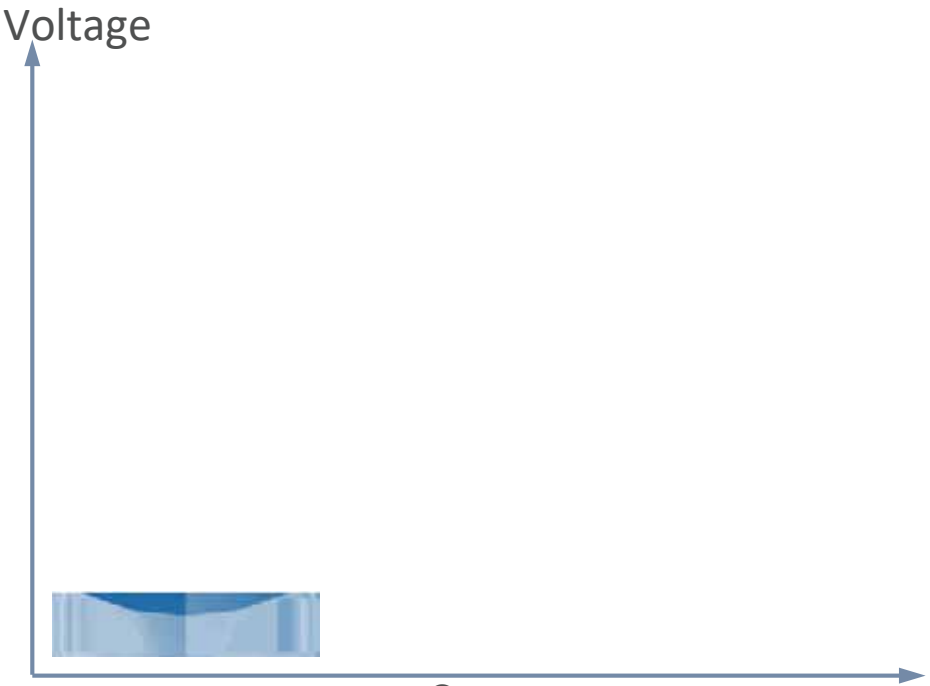


Features

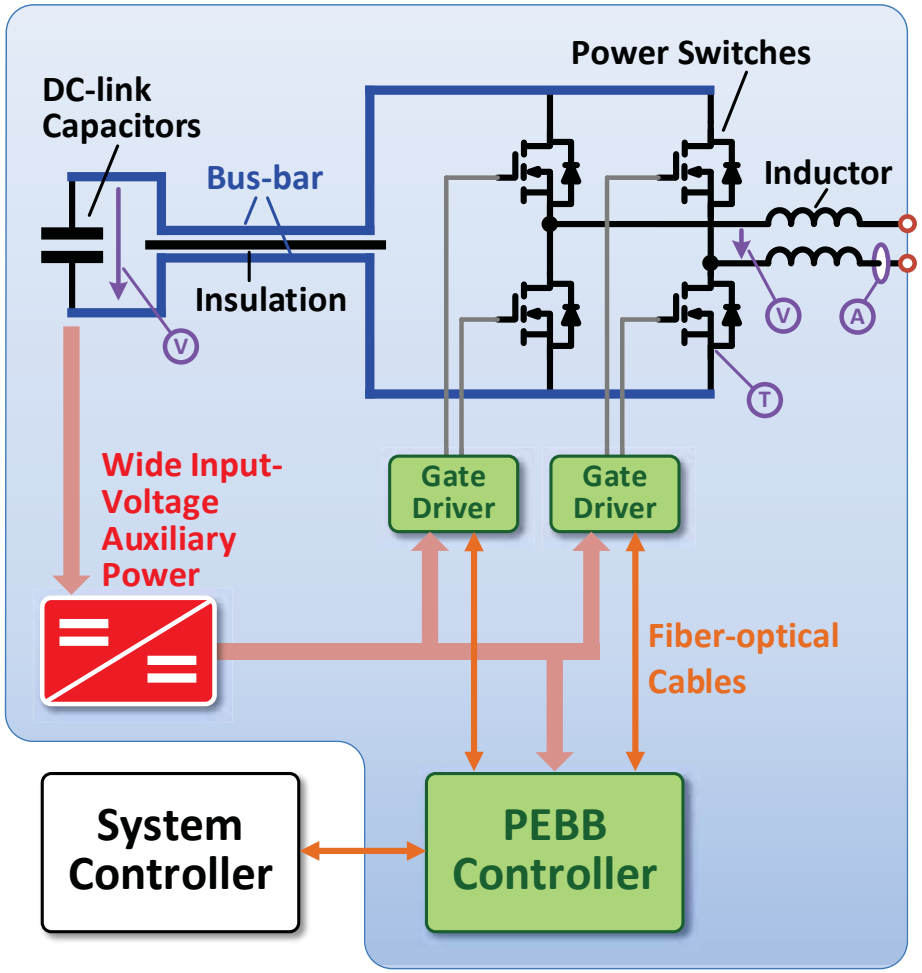
- **4 x 250 kVA AC-AC converters with 20 kHz transformers**
- **Input and output bridges switched at line frequency**
- **High frequency section uses series-resonance**
  - ➢ **Leakage inductance and resonant capacitor**
- **Inputs in series and outputs in parallel to enforce voltage and current sharing.**

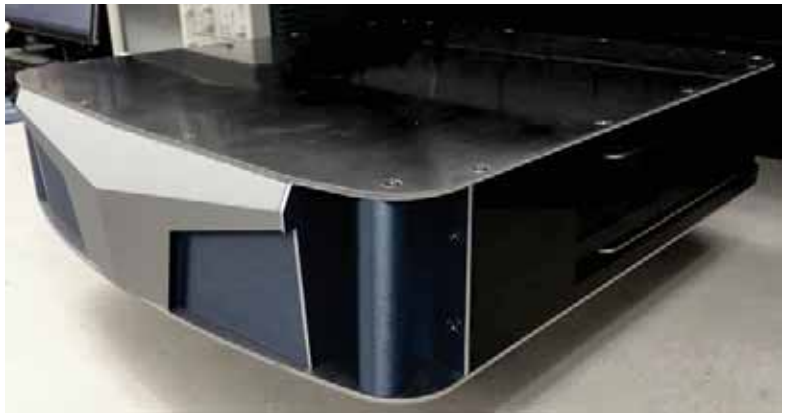
Power Electronics Building Block

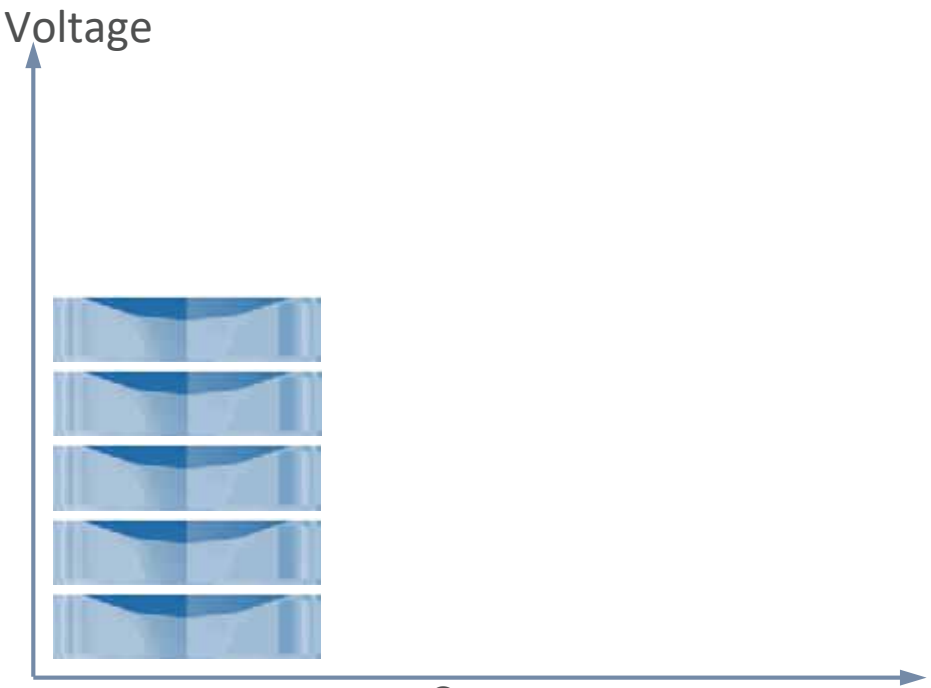




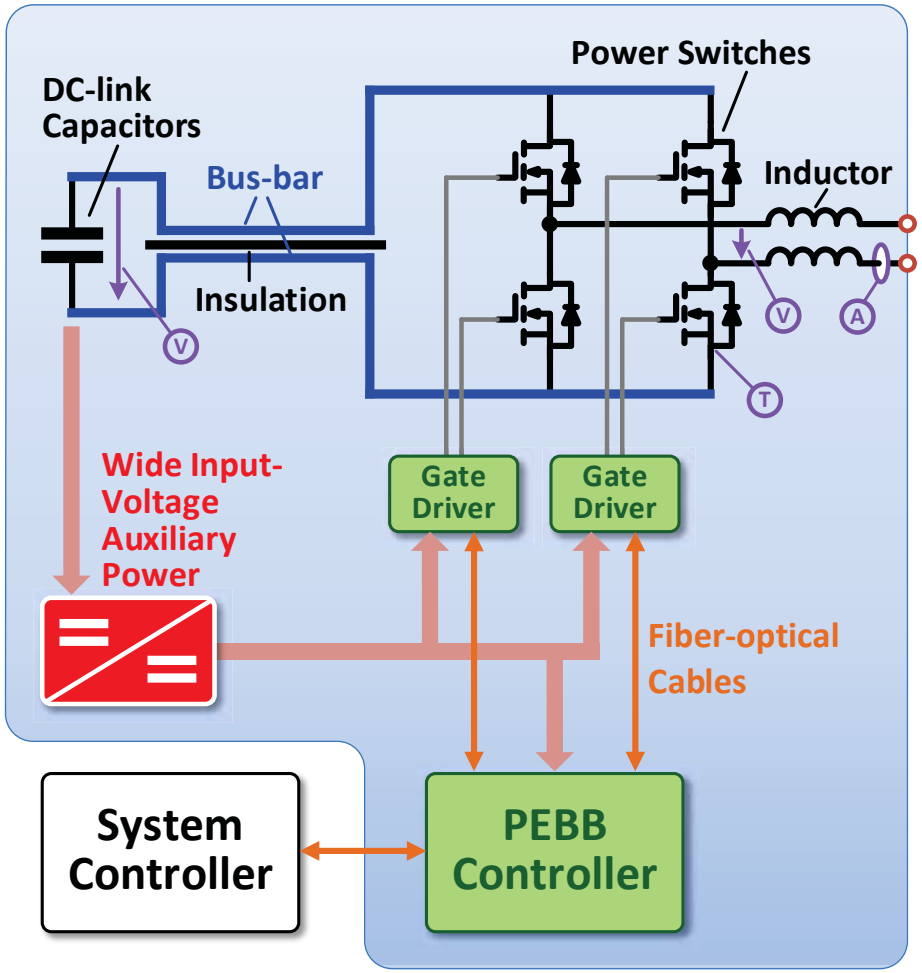
Power Electronics Building Block

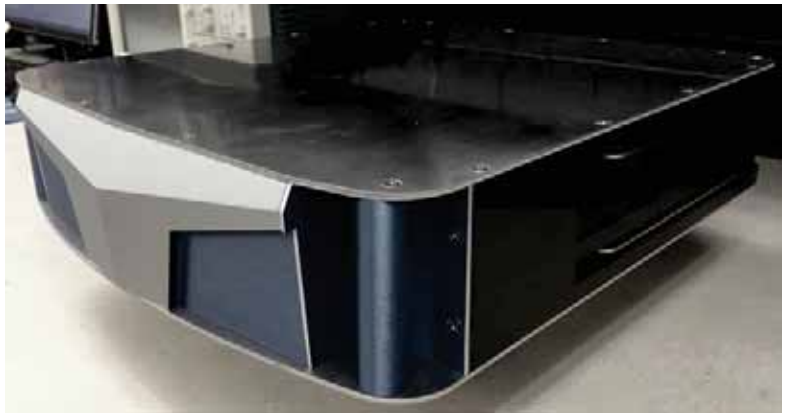


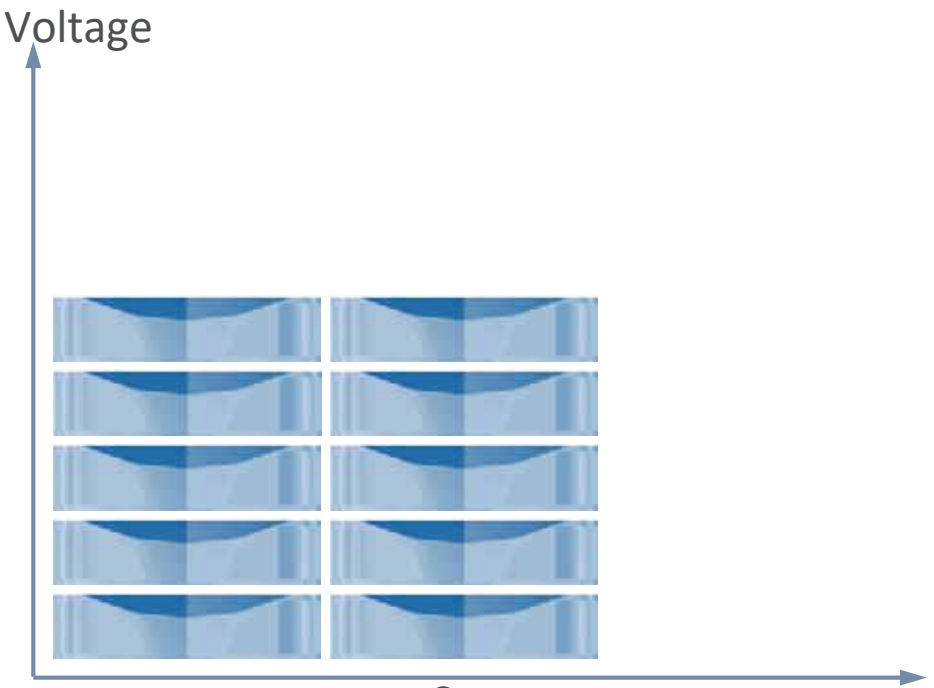




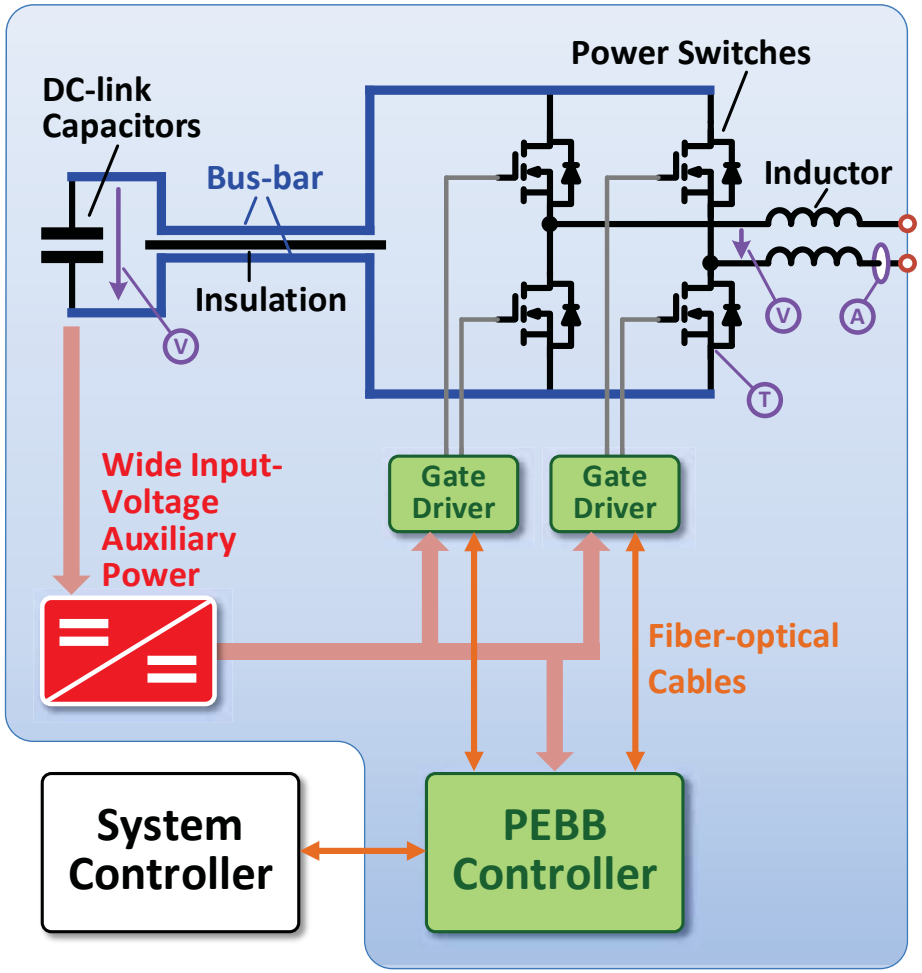
Power Electronics Building Block

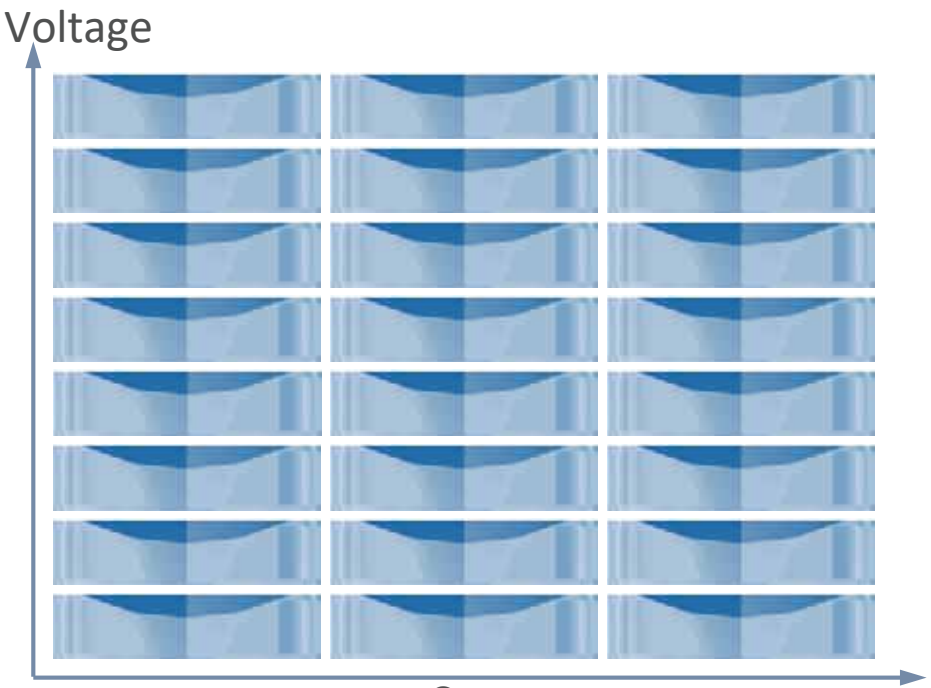




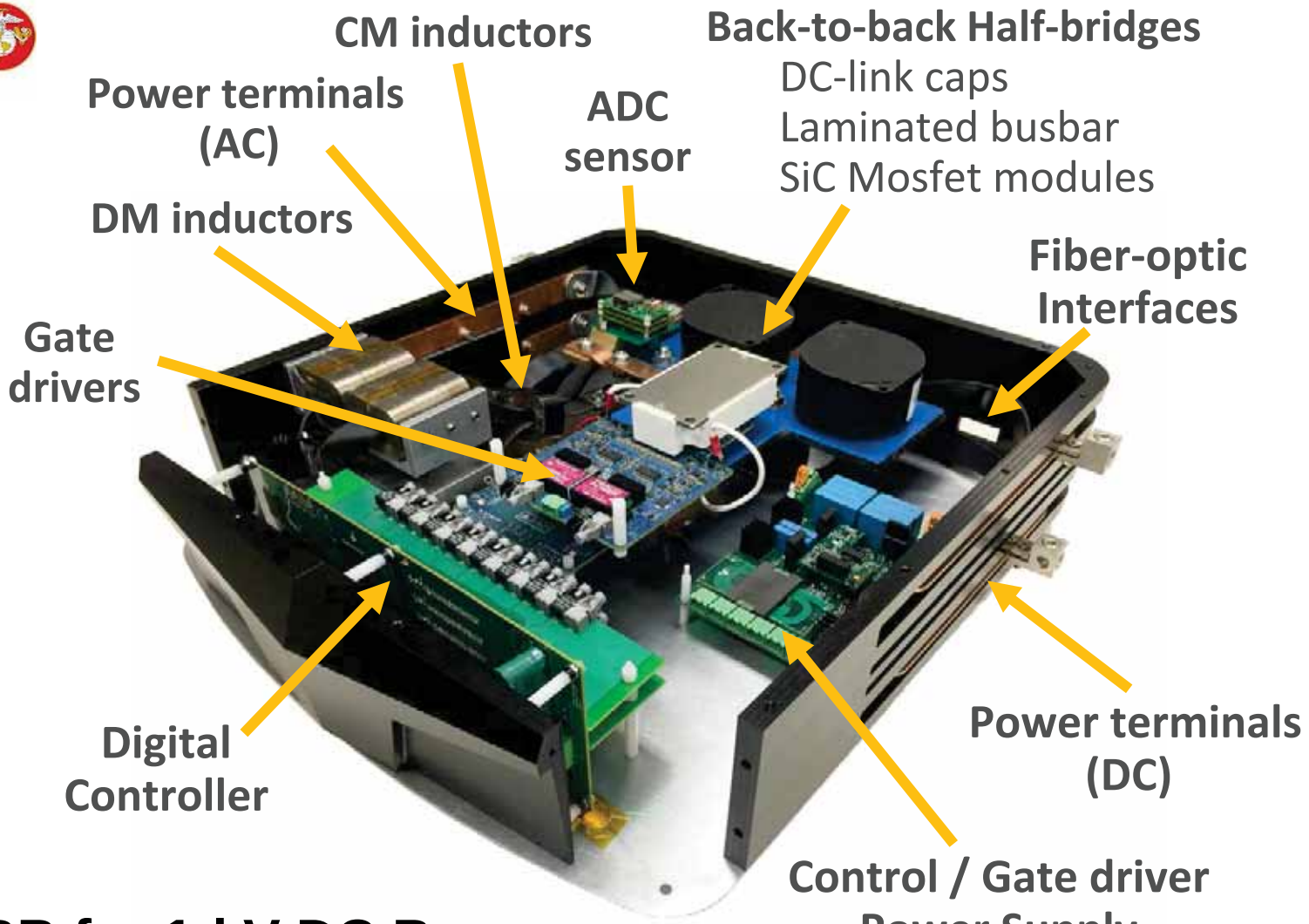


Power Electronics Building Block





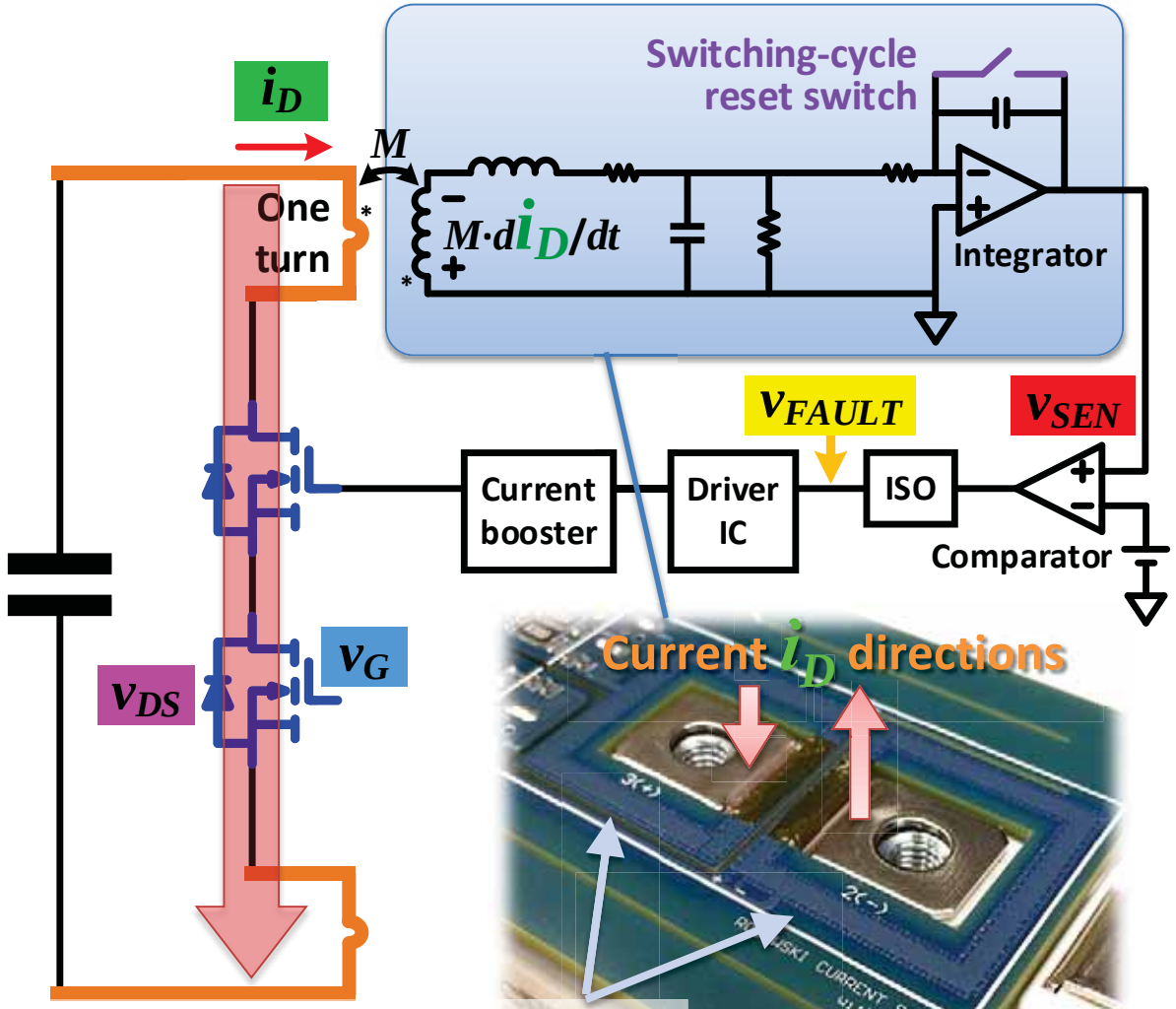
PEBB 1000 (SSPS 2.0)

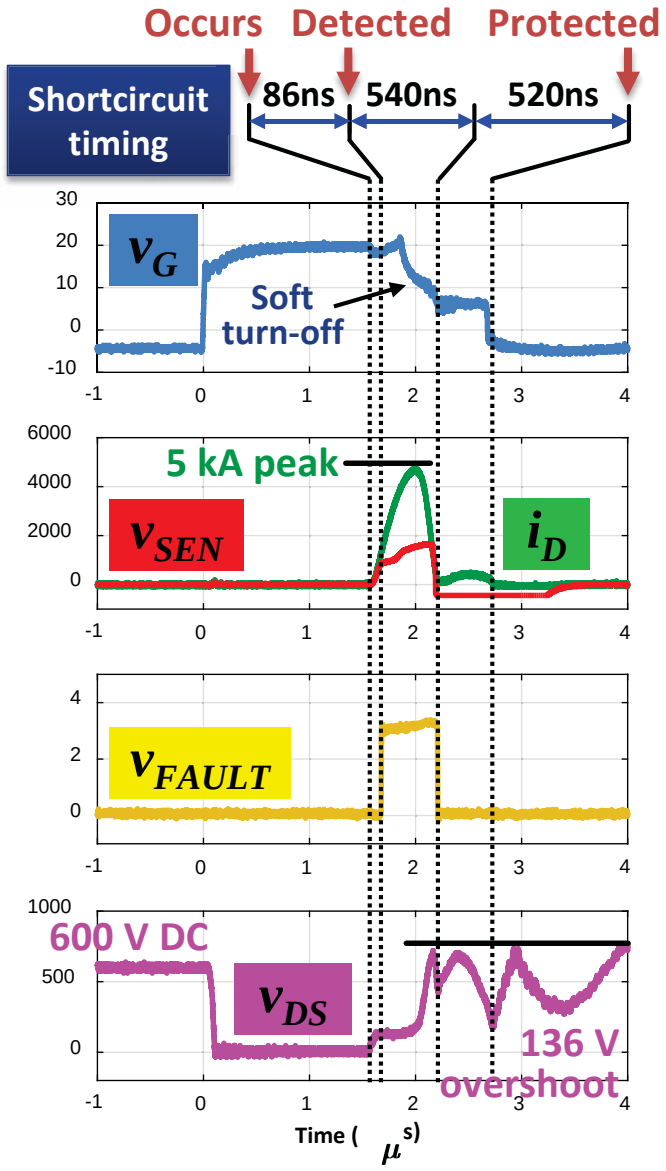


SiC PEBB for 1-kV DC Bus

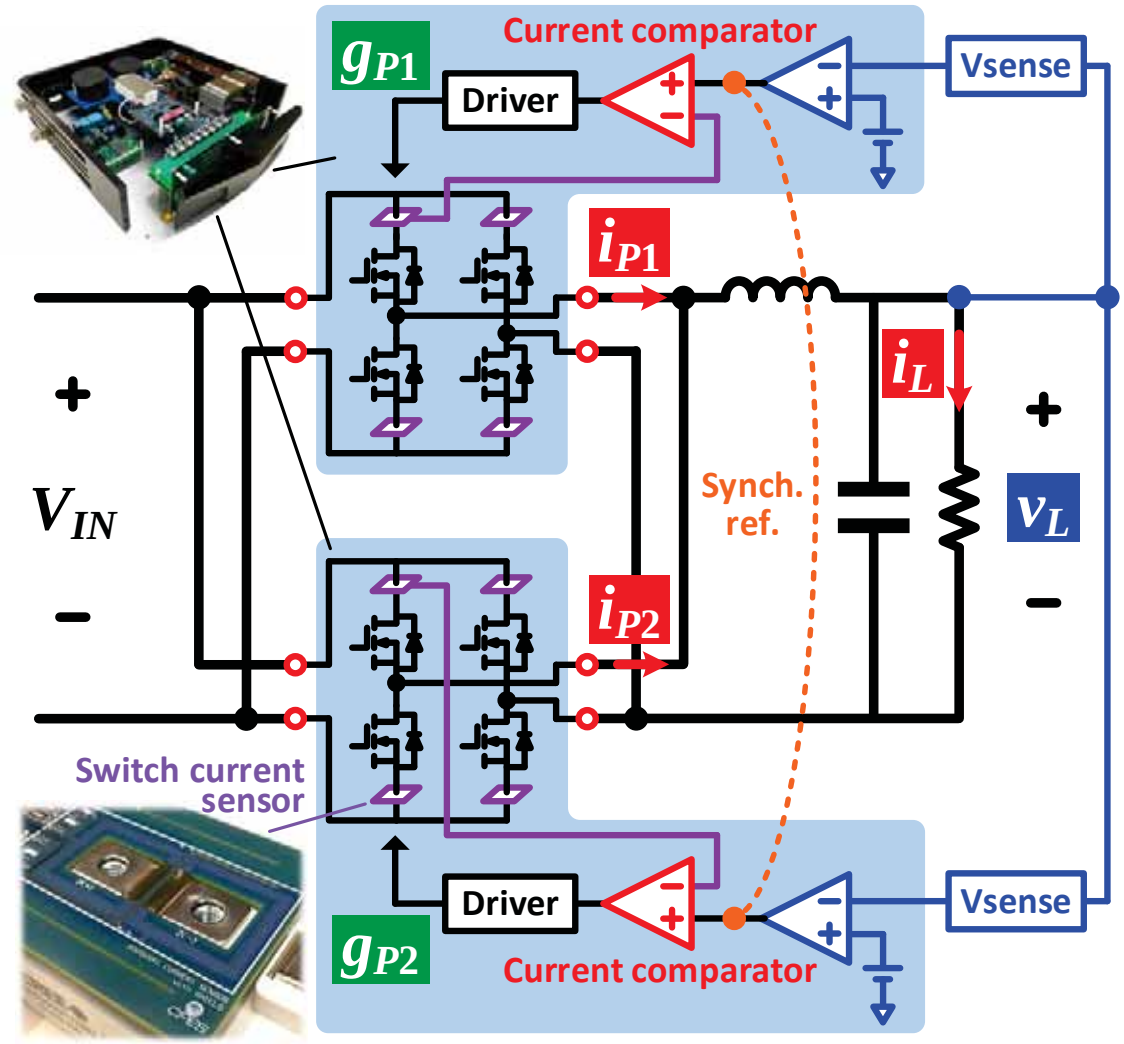
100 kW, 100 kHz, 98%, 108 W/inch^3

PEBB 1000 Fault Handling: Short Circuit Protection



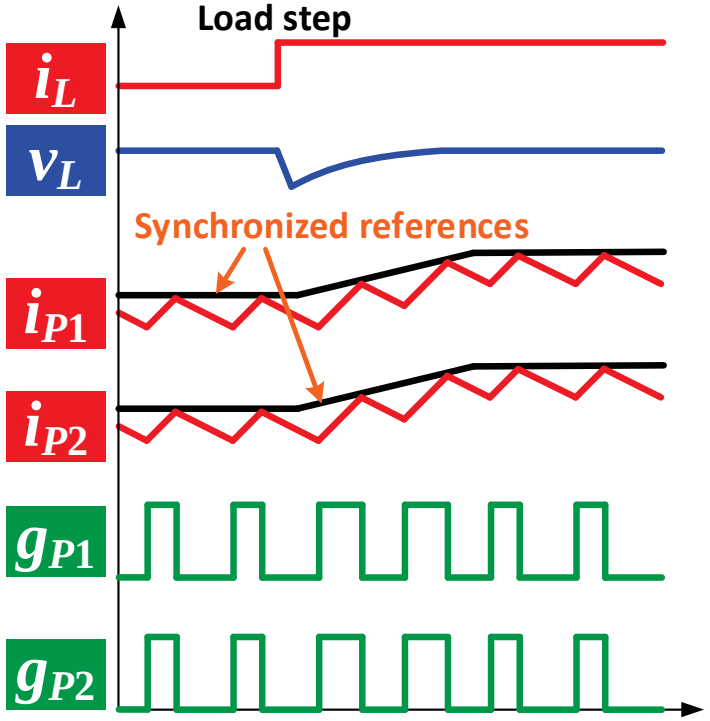


PEBB 1000 in Parallel: Peak Current Mode

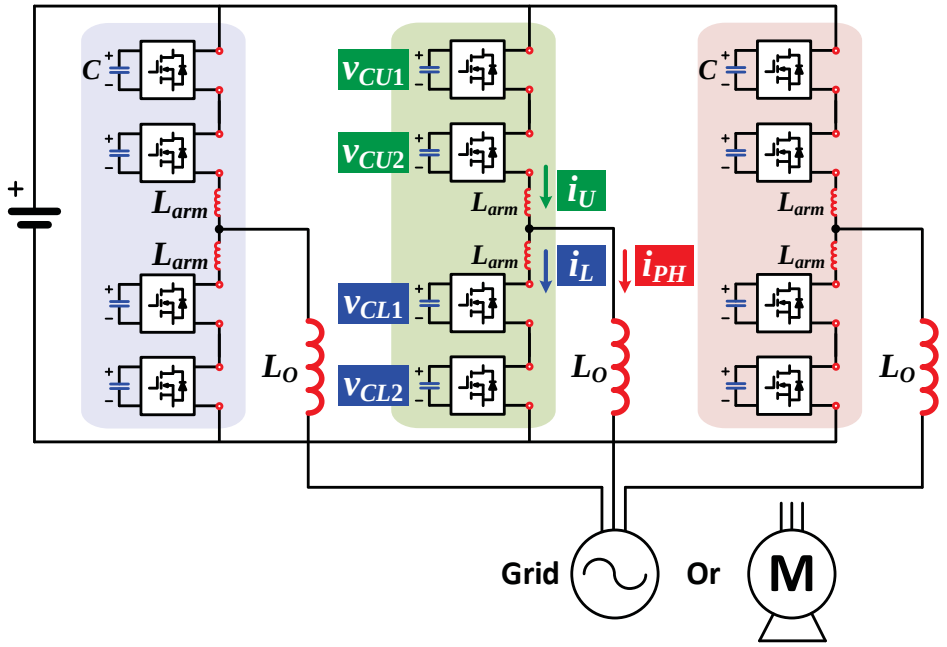


Paralleled PEBB with PCM control:

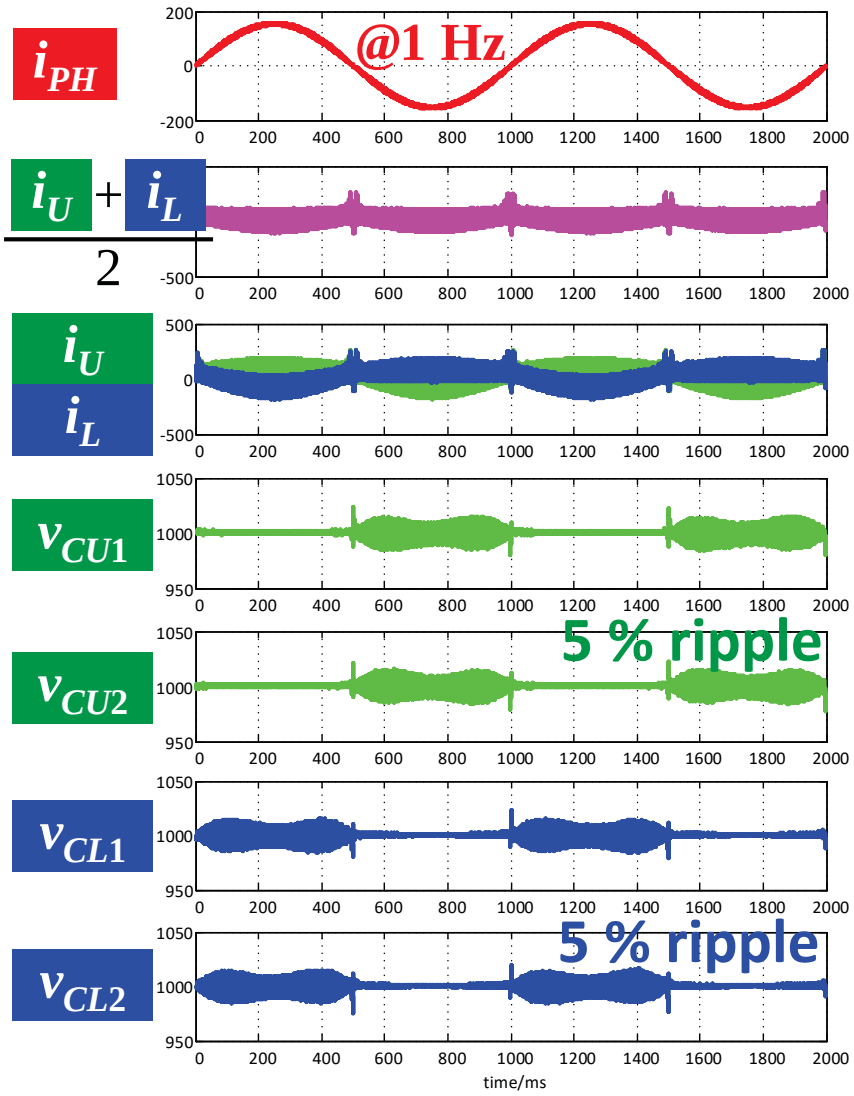
Improved dynamics with current limiters



PEBB 1000 in Series: Switching-Cycle Control of MMC Capacitor Volatges

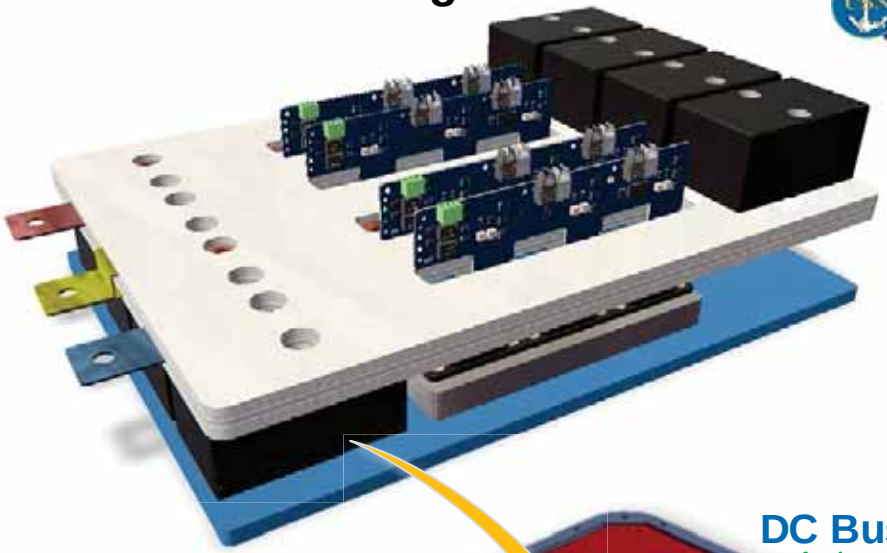


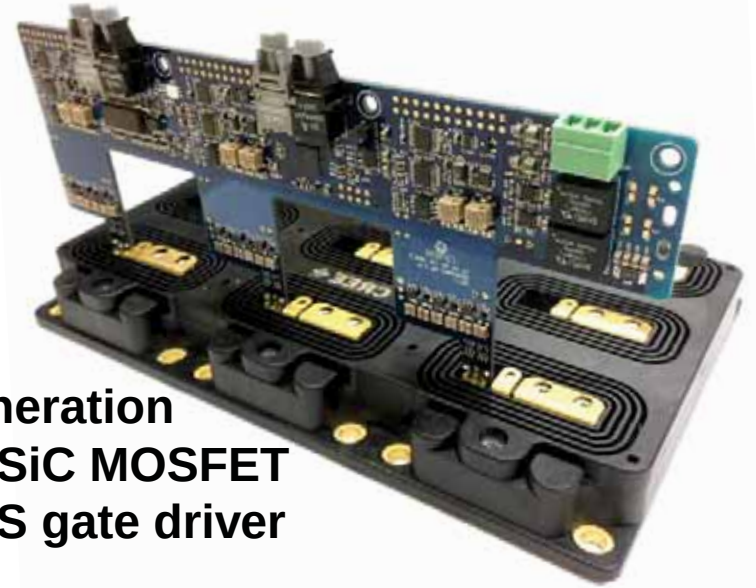
Improved power density



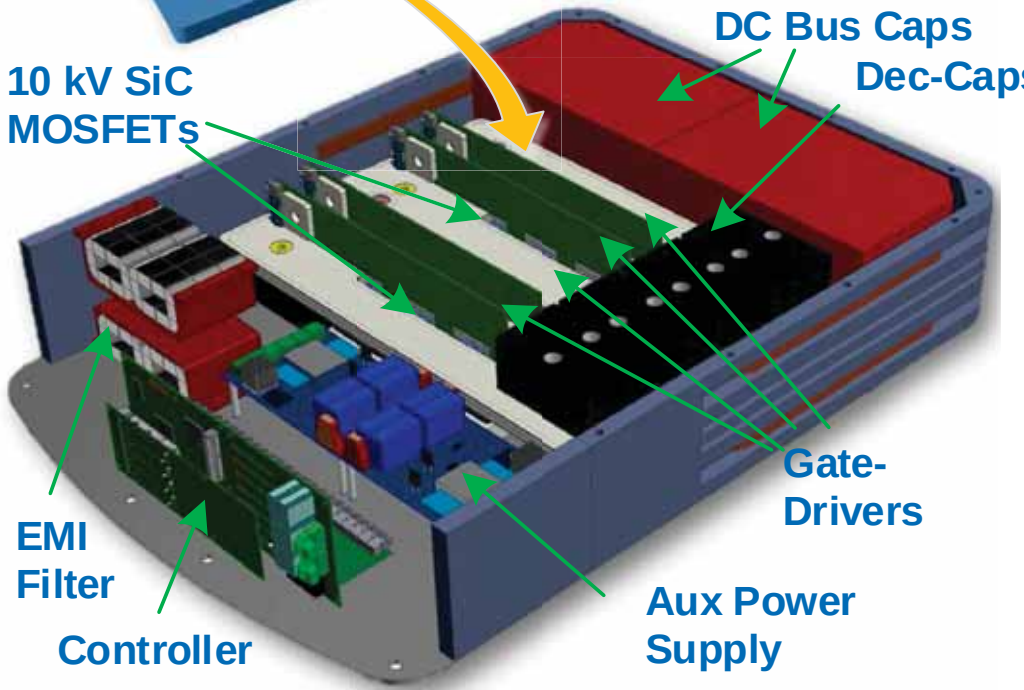
PEBB 6000 (SSPS 3.0)

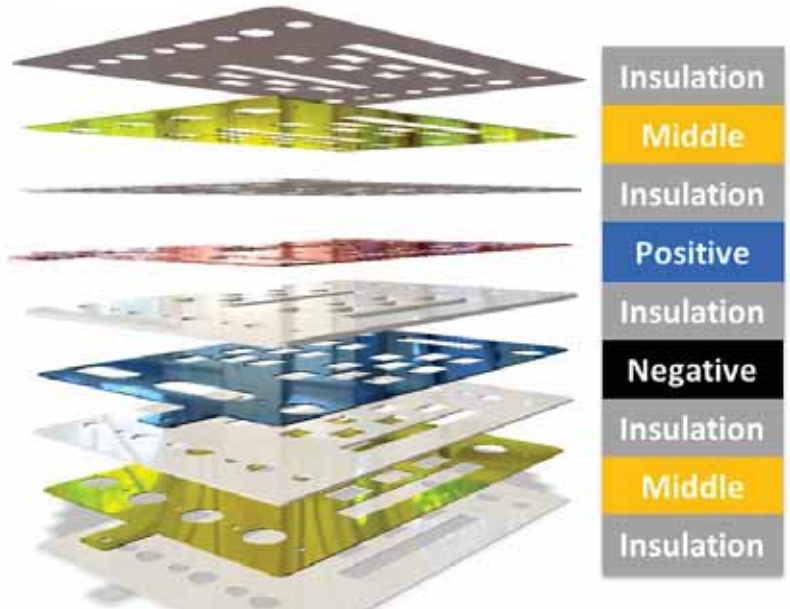
PEBB 6000 H-bridge





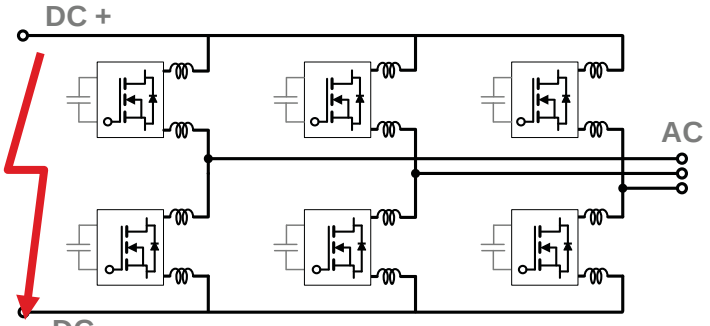
3rd Generation CREE SiC MOSFET & CPES gate driver



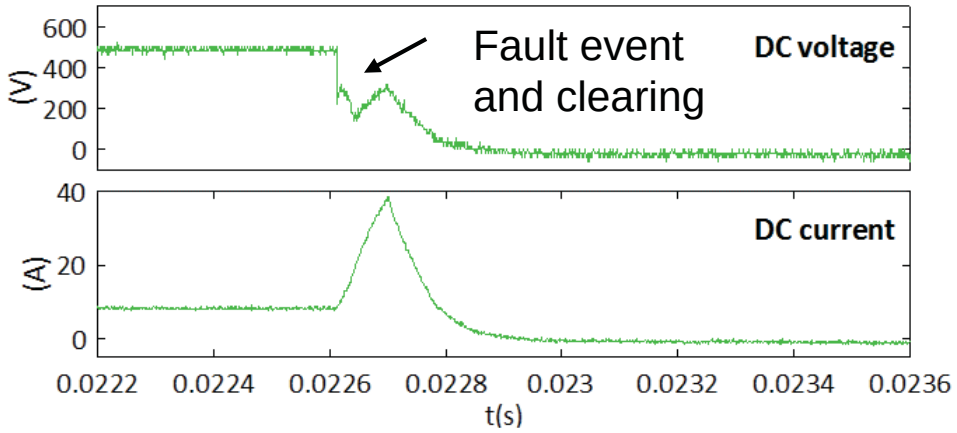


10 kV laminated bus

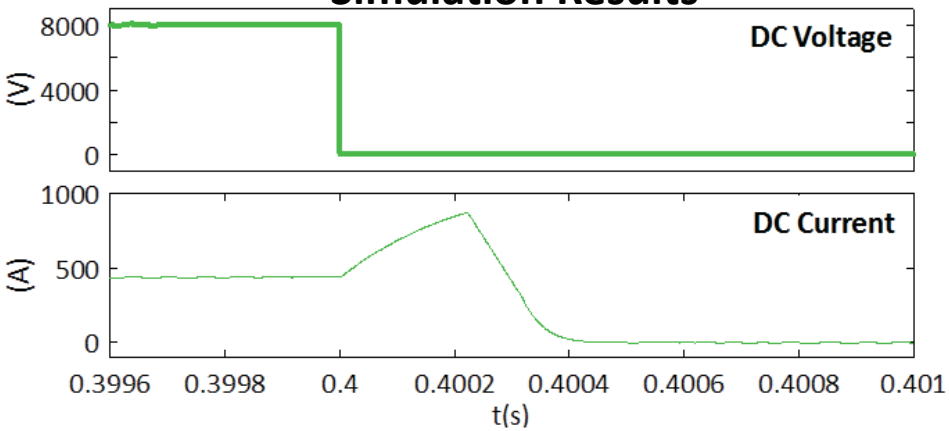
Current Limiting Function of Modular Multilevel Converter



Experimental Results



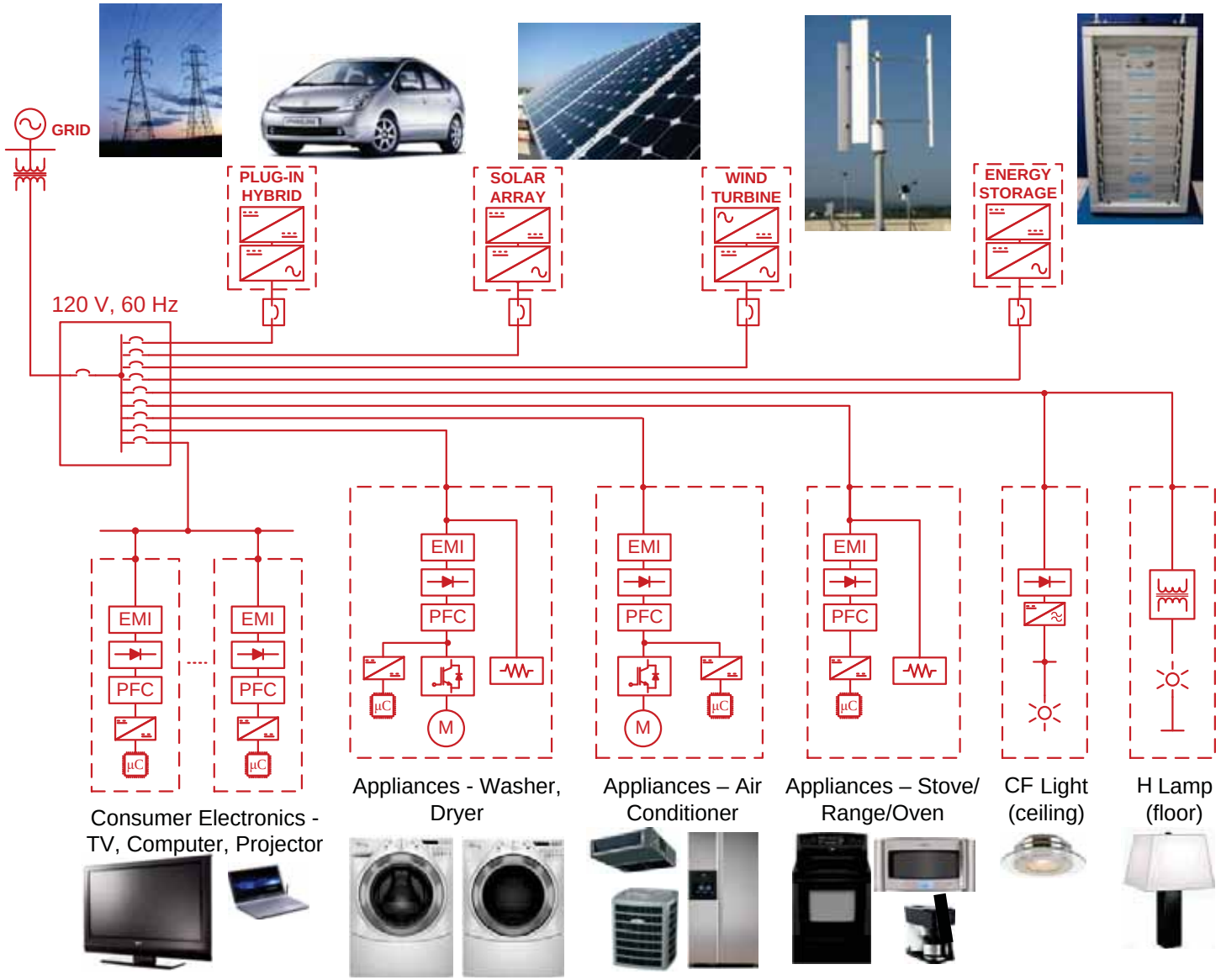
Simulation Results



- **1 kV PEBBs operating at 100 kHz using 1.7 kV SiC MOSFETs**
- **A three-phase PEBB-based MMC prototype for MVDC applications**

Patching-up the 20th Century Technology

Integration of grid, renewables, and storage saves money!



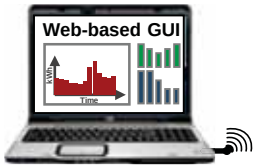
"Smart" appliances save energy!

21st Century Electronic Power Distribution

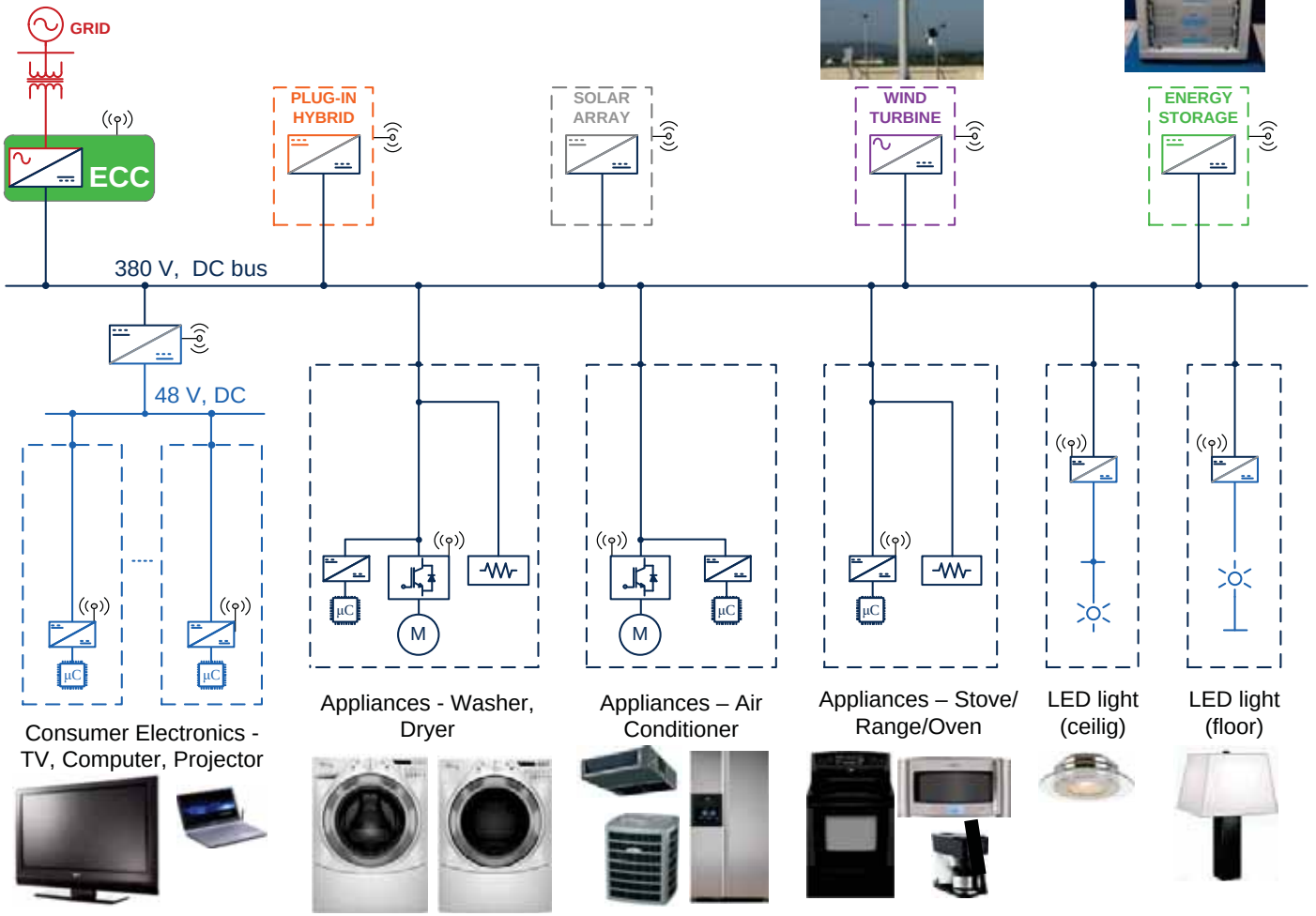
efficient, programmable, safe, … affordable

Nanogrid * with the bus architecture

- Two voltages
- Wireless communication



- Bidirectional power conversion
- Separation of dynamics
- Integrated protection
- Load management
- DG management
- Data acquisition
- Communication
- Islanded operation



* J. Bryan, R. Duke, S. Round, 2003

21st Century Electronic Power Distribution

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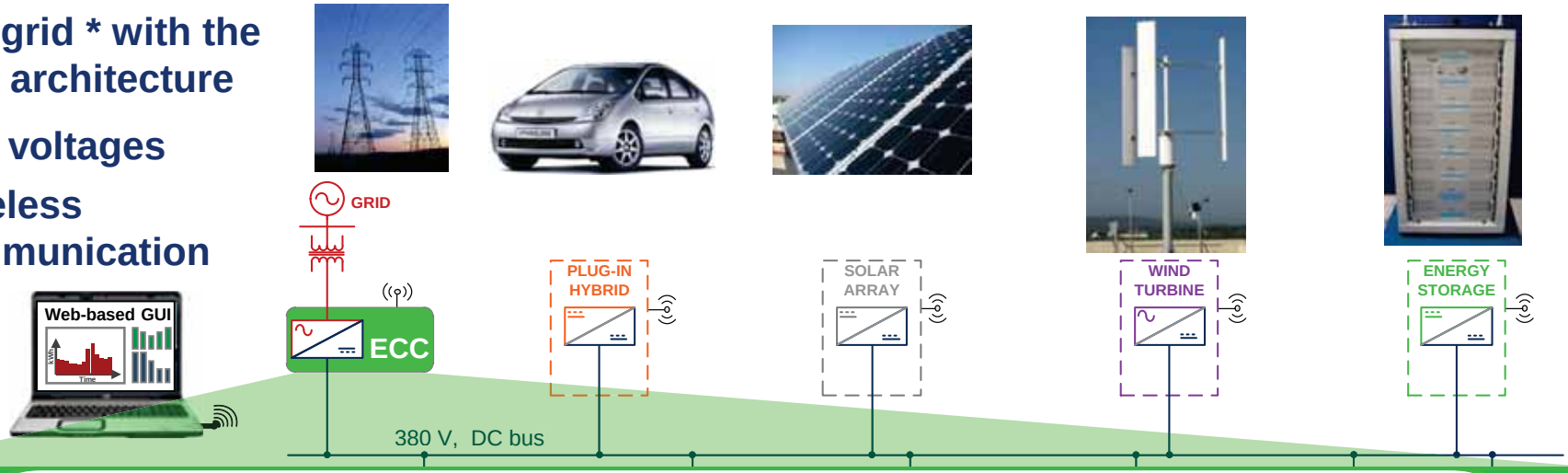
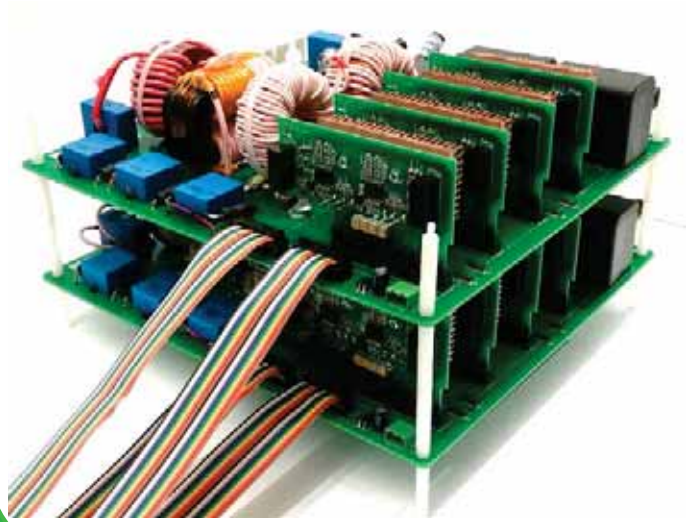


Solid State Power Station (Energy Control Center)

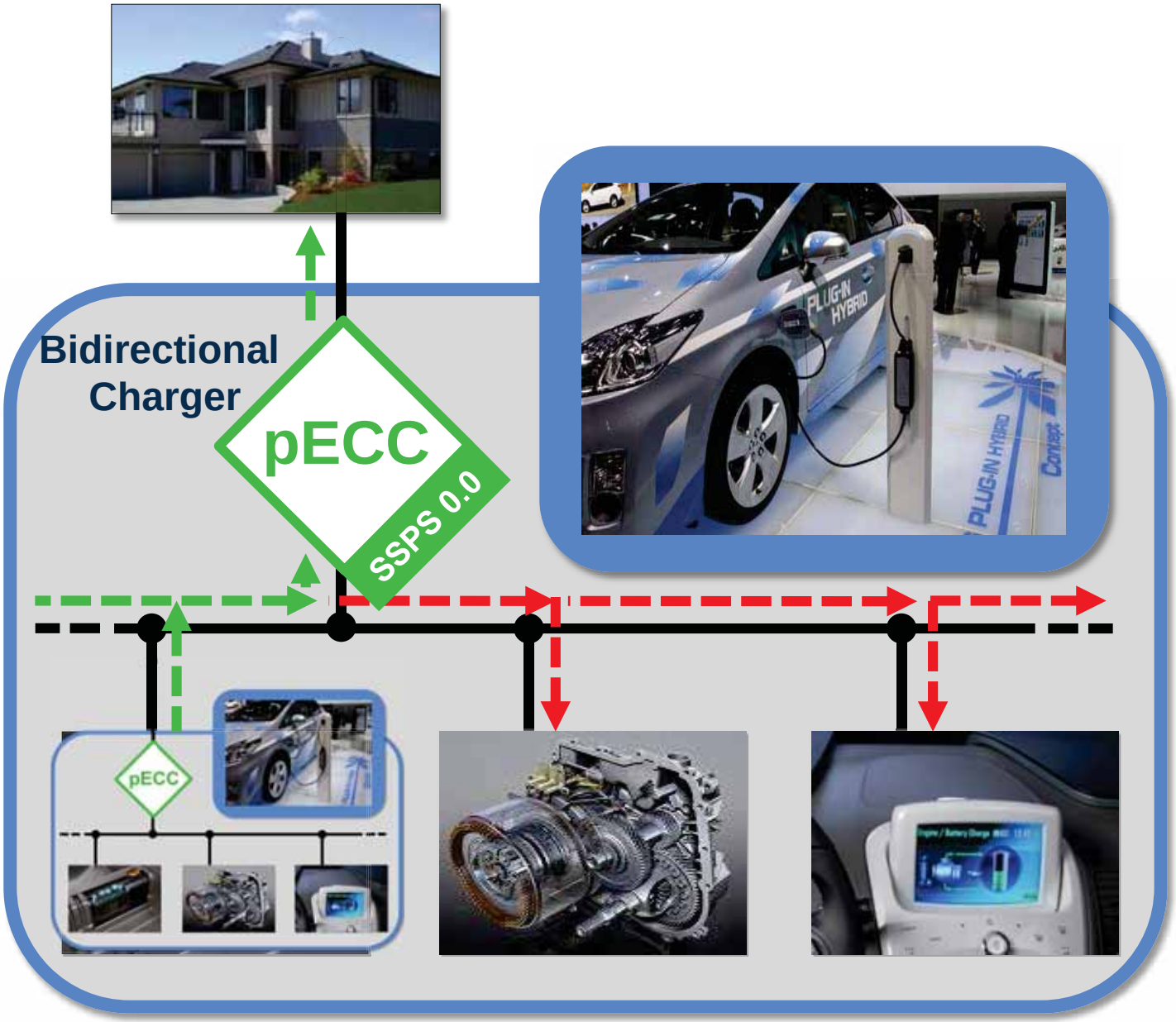


Features:

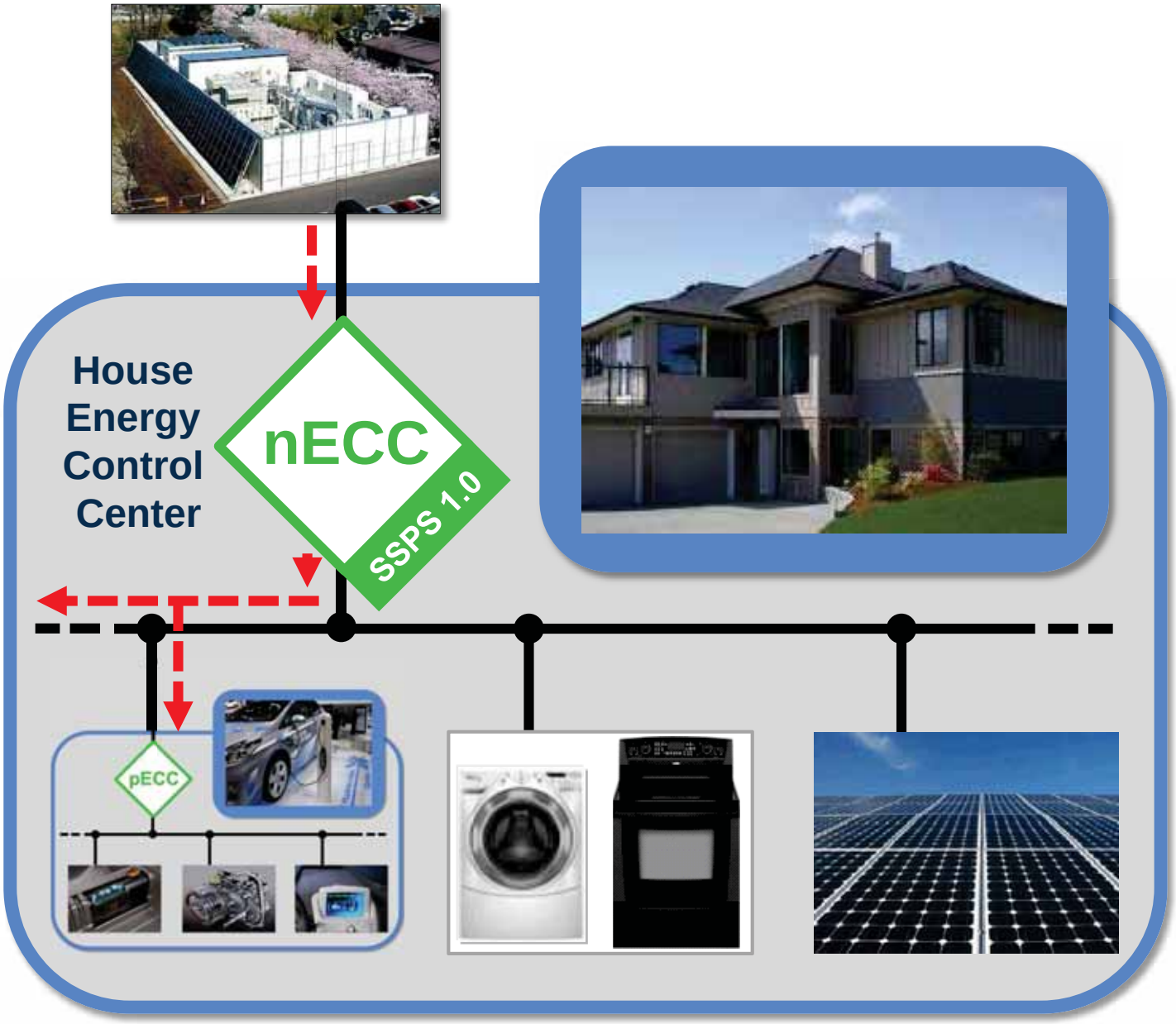
Bi-directional topology
Bi-directional control system
Bi-directional current limit
Bi-directional decoupling due to dc-link
Bi-directional EMI compatibility
Low dc leakage current
High power density; high efficiency

Plug-in Hybrid Electric Vehicle (Picogrid)

Plug-in Hybrid Electric Vehicle (Picogrid)



A house (Nanogrid)



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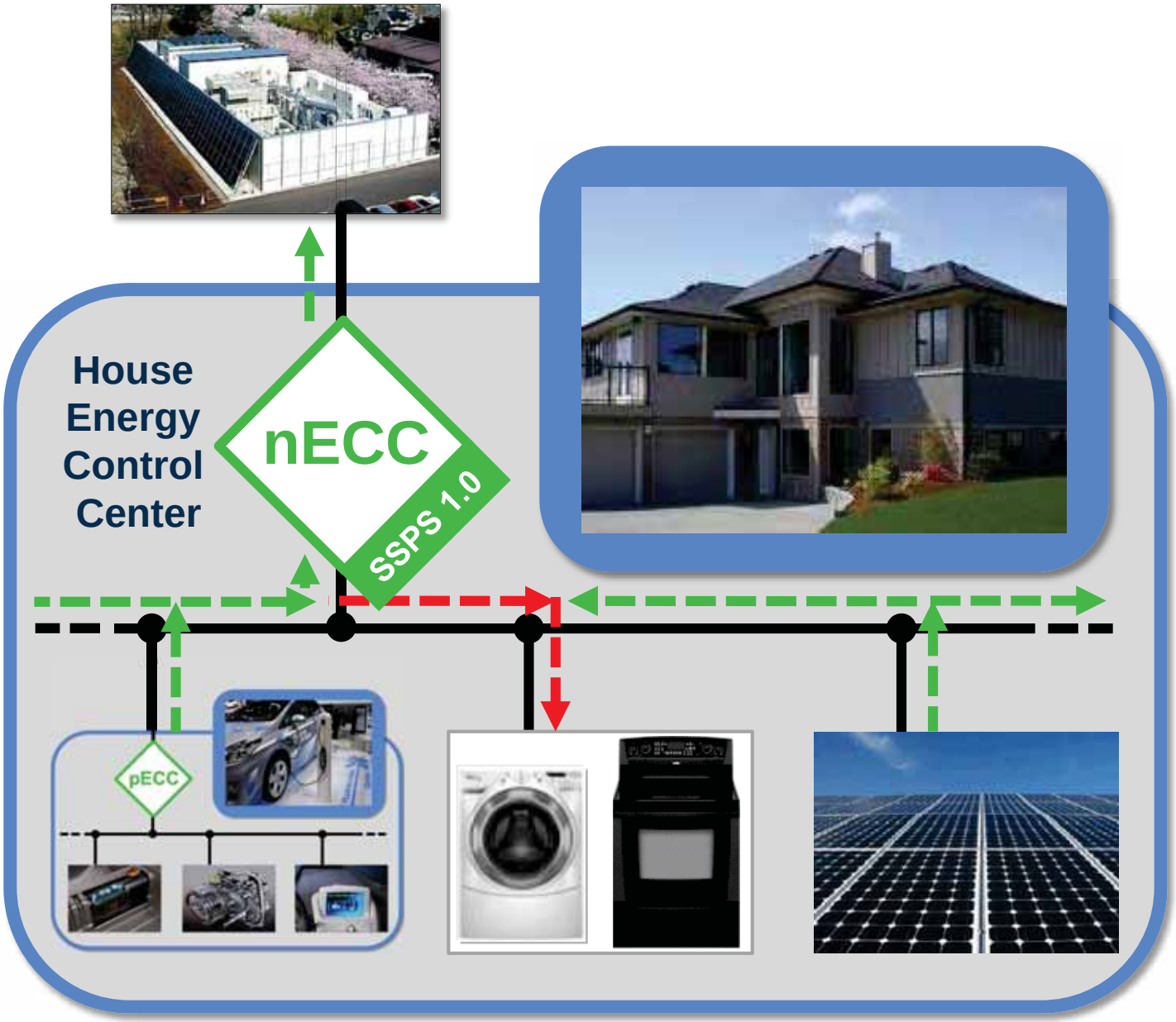
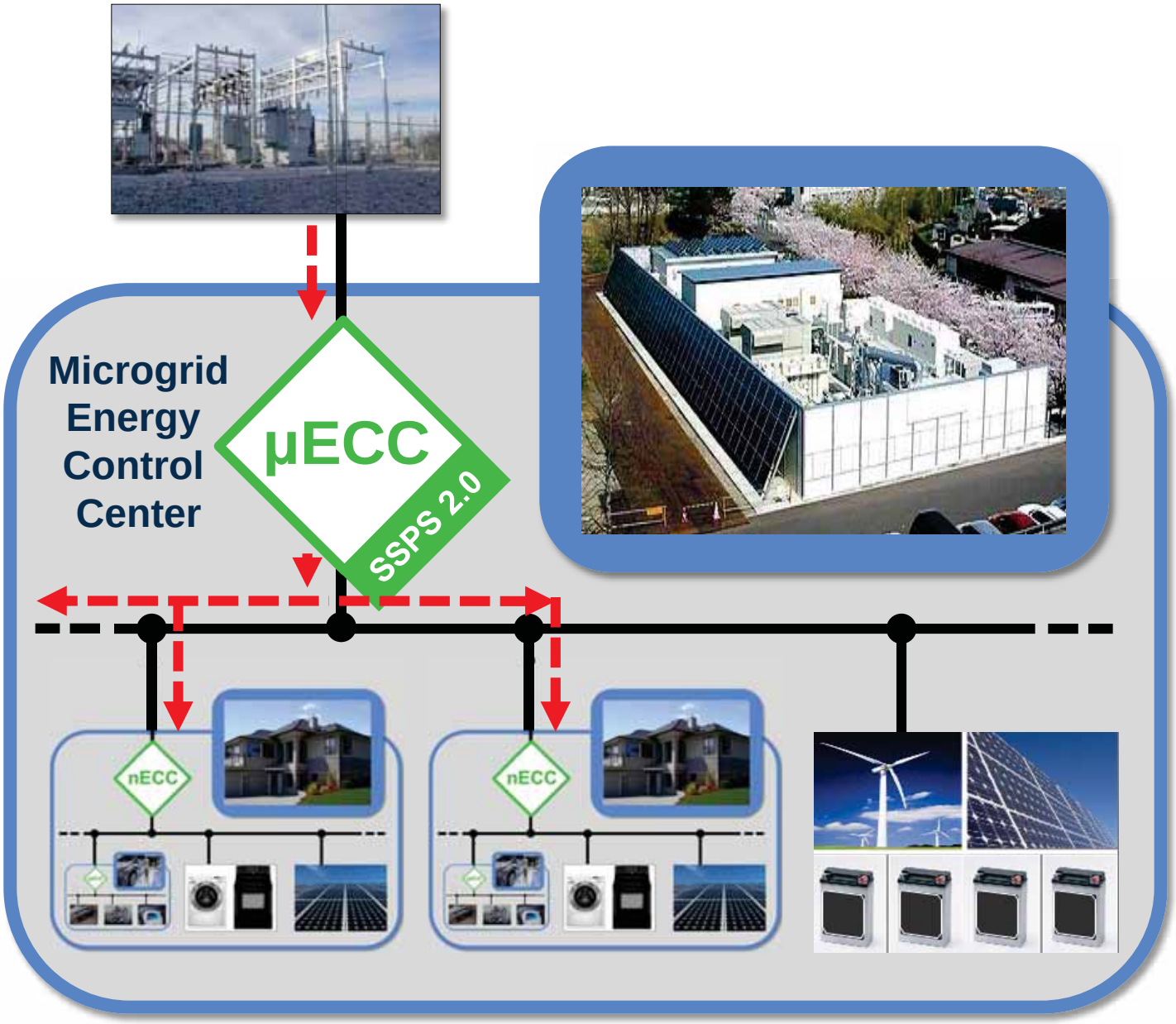
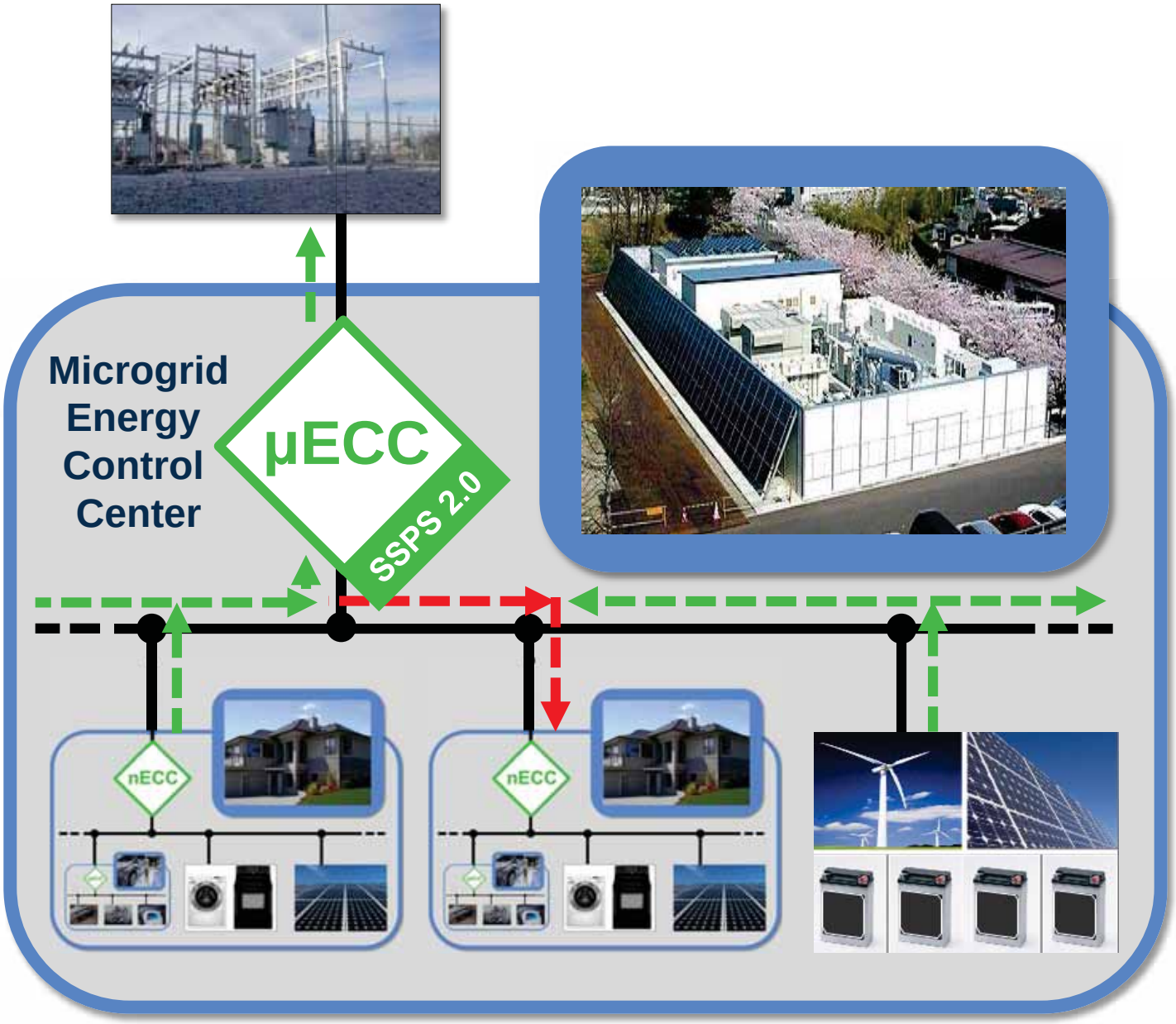


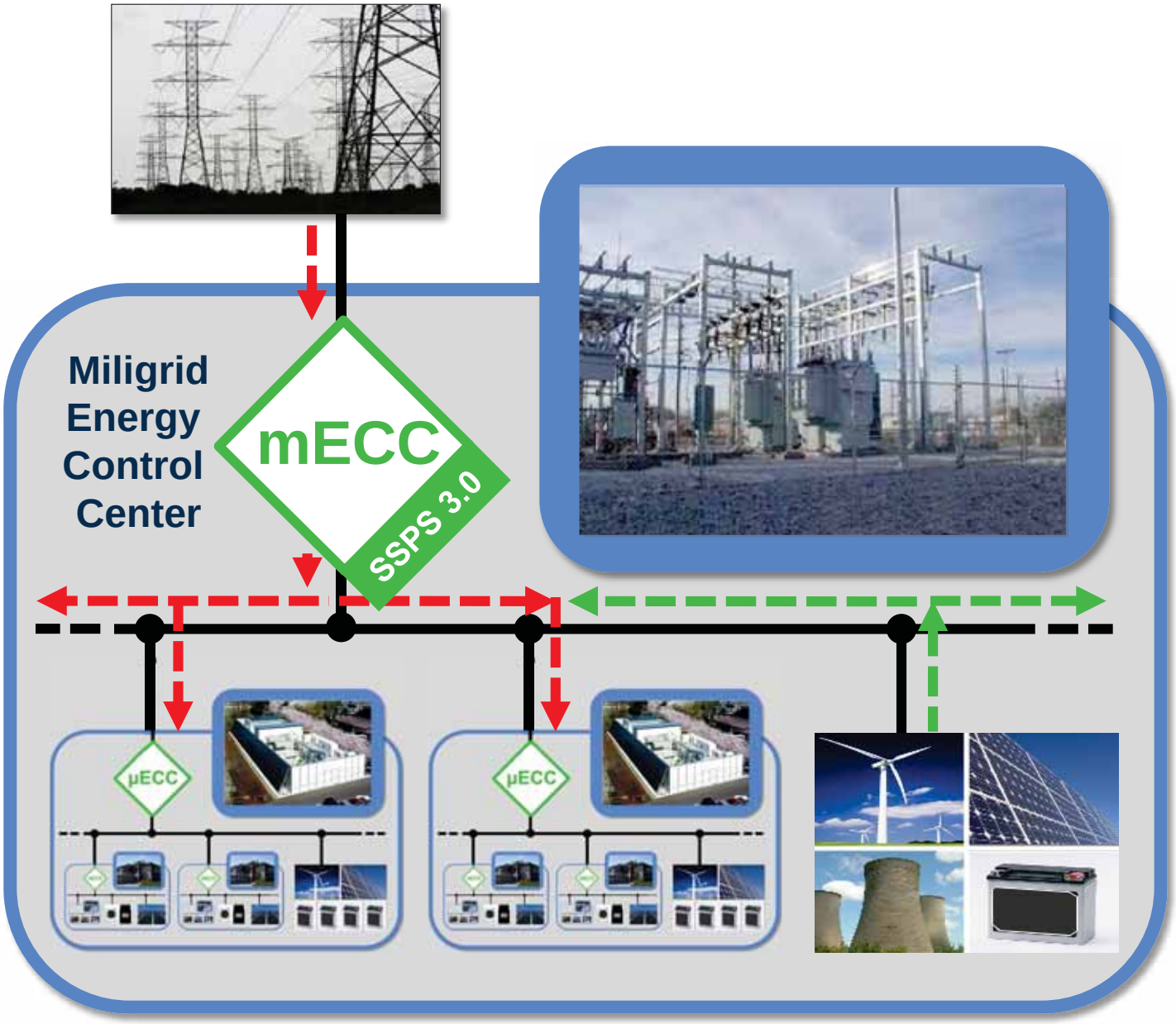
Microgrid



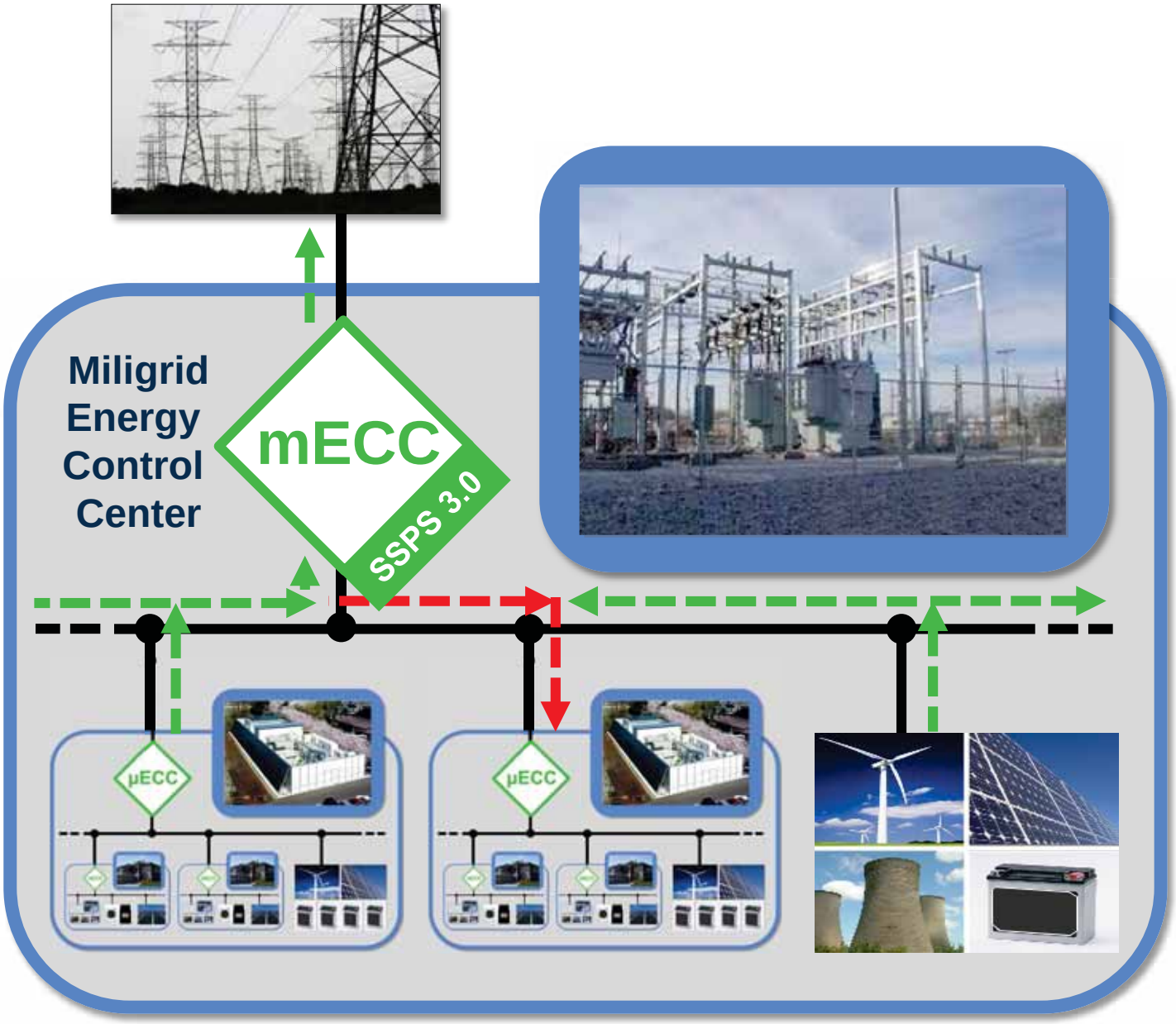
Microgrid



Miligrid



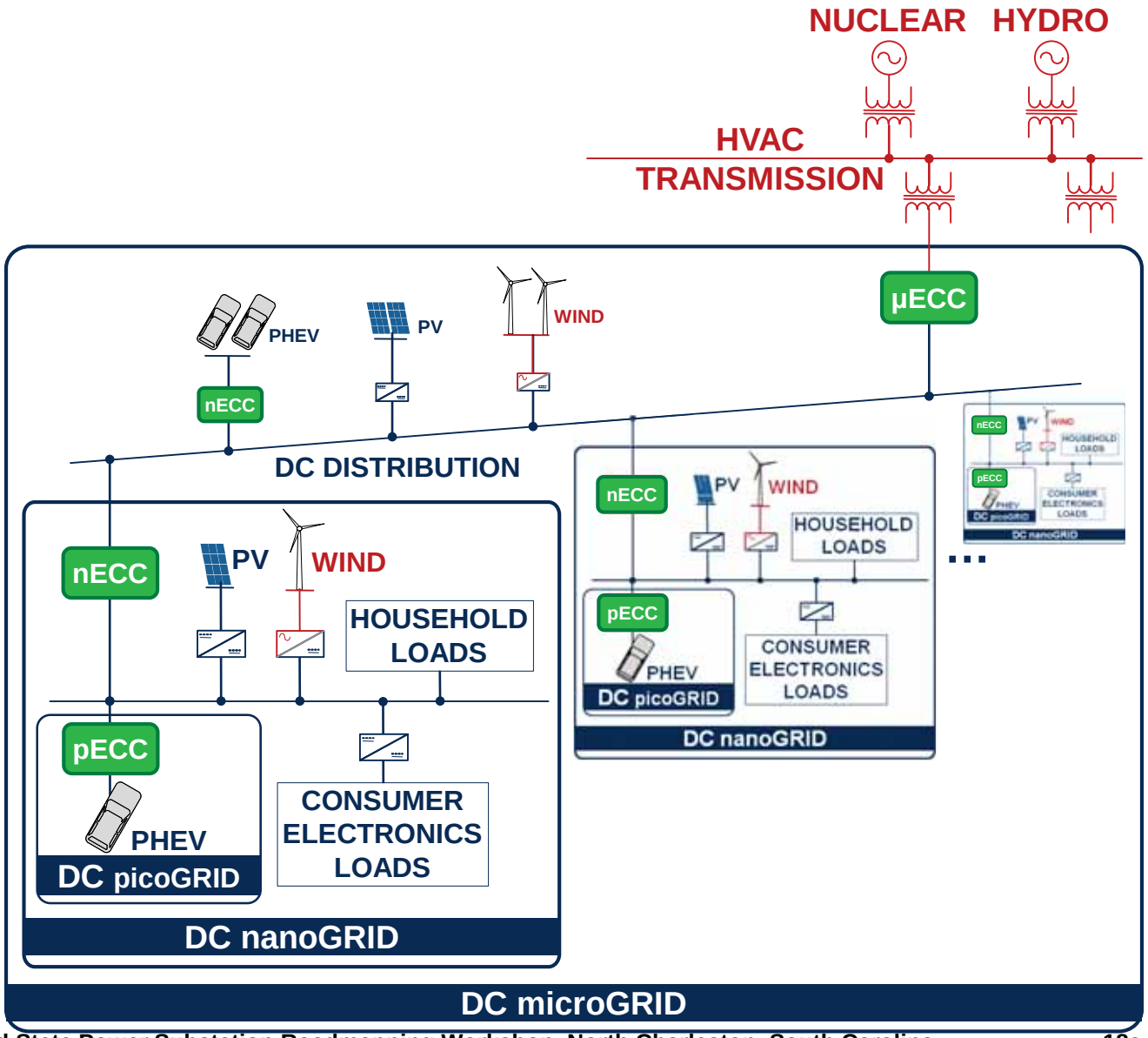
Miligrid



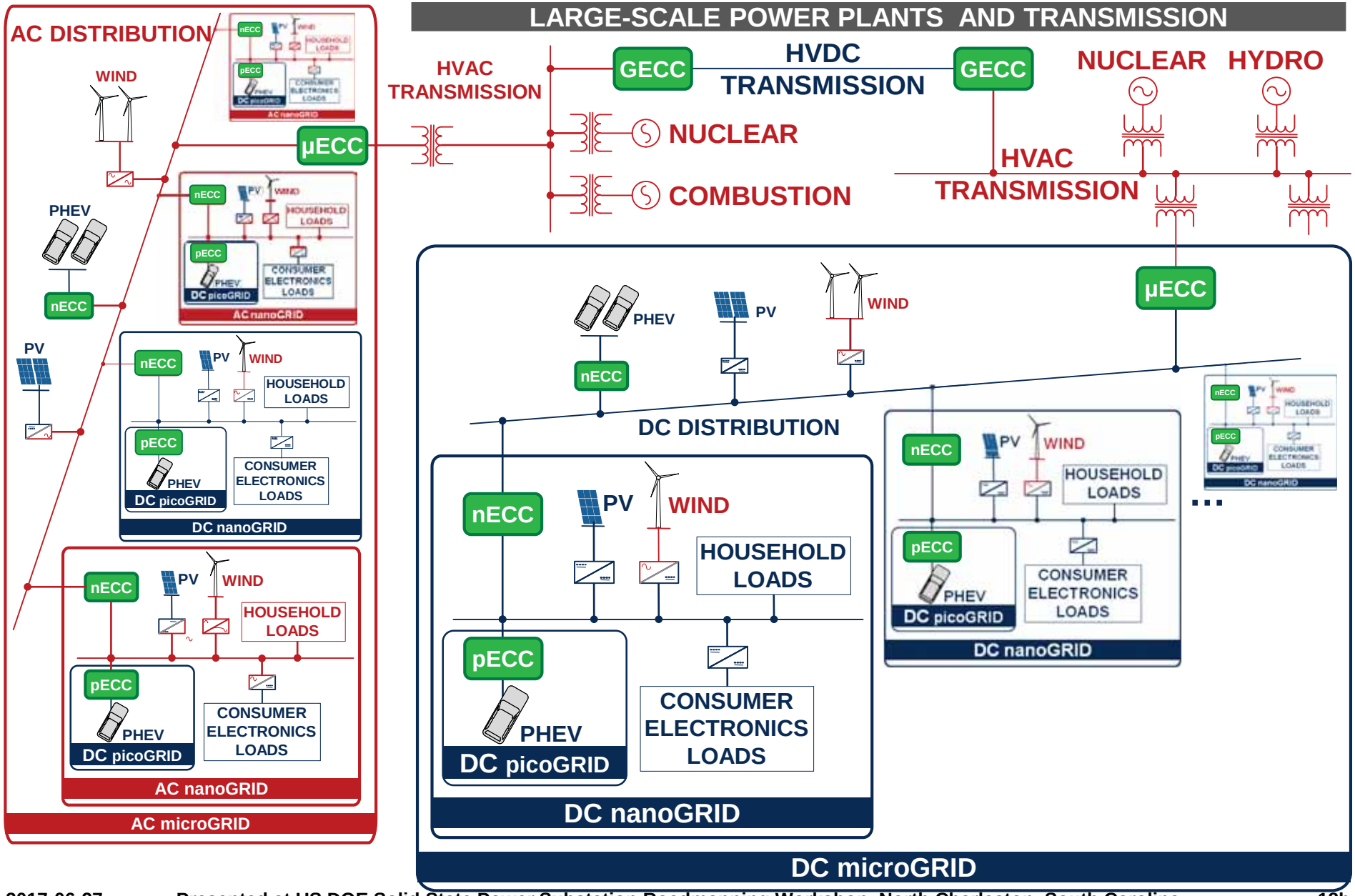
¿ Intergrid ?

Main features:

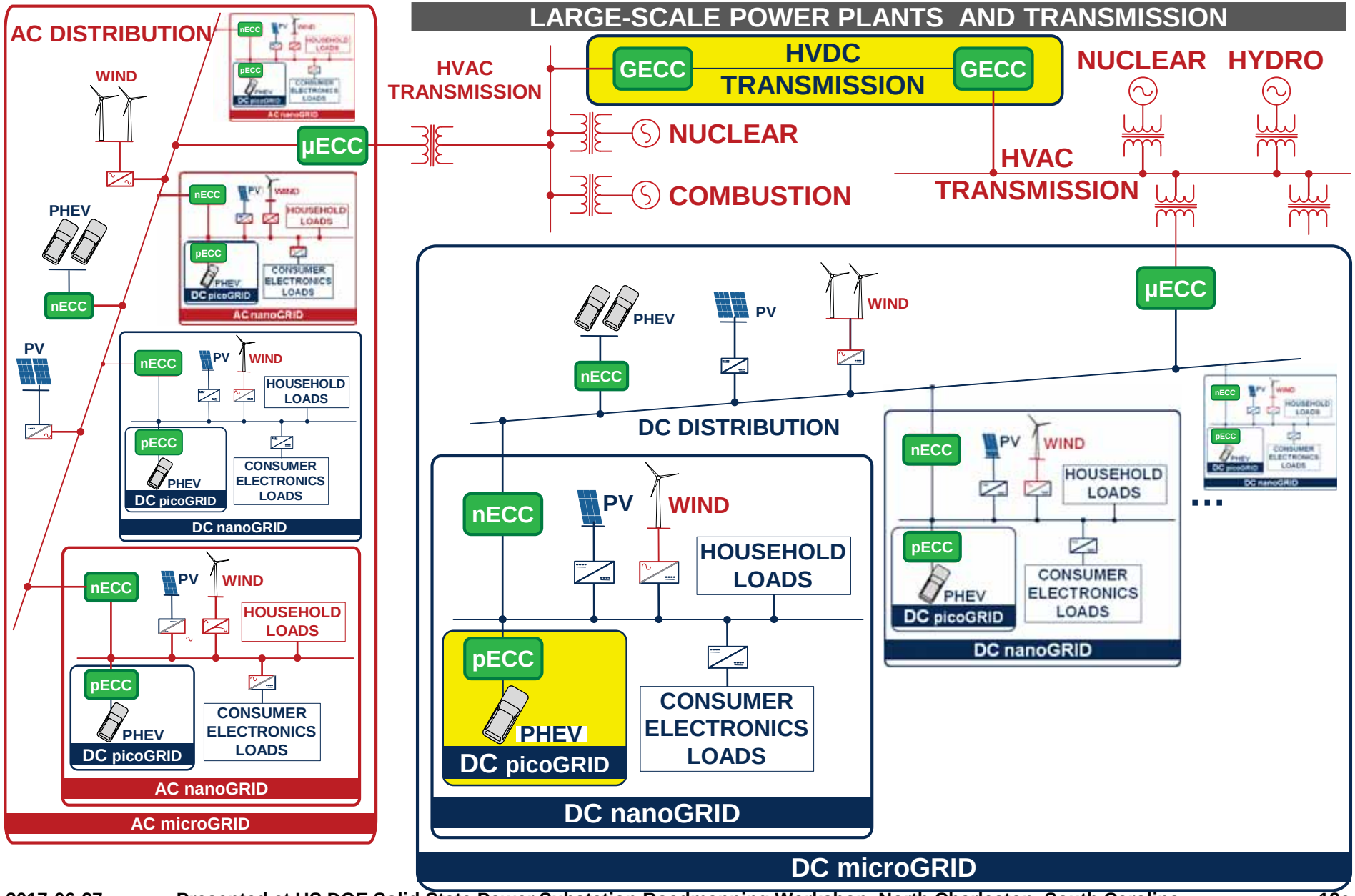
- At least minimal level of local energy generation and storage;
- Interfaces to the higher-level system through bidirectional power converters;
- Ability to operate in islanded mode;
- Extensive communication and control capabilities;
- No thermo-mechanical switchgear;
- Step-up/down and isolation functions provided by the power converters (no low-frequency transformers);



¿ Intergrid ?


AC DISTRIBUTION
WIND
µECC
PHEV
nECC
PV
HOUSEHOLD LOADS
pECC
PHEV
DC picoGRID
CONSUMER ELECTRONICS LOADS
DC nanoGRID
AC nanoGRID
AC microGRID
LARGE-SCALE POWER PLANTS AND TRANSMISSION
HVAC TRANSMISSION
GECC
HVDC TRANSMISSION
NUCLEAR
COMBUSTION
HYDRO
DC DISTRIBUTION
DC microGRID

¿ Intergrid ?


AC DISTRIBUTION
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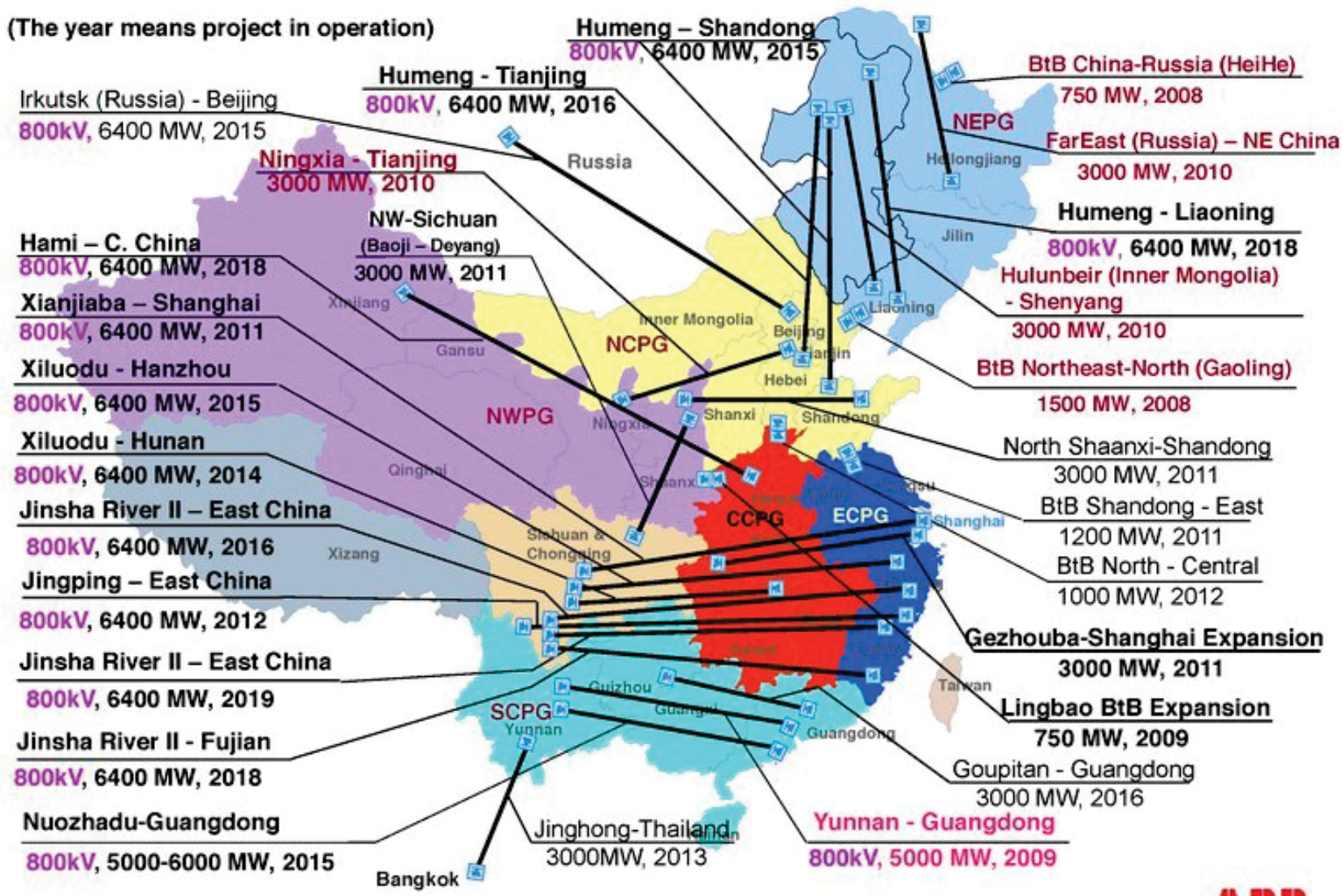
DC nanoGRID
AC nanoGRID
AC microGRID
LARGE-SCALE POWER PLANTS AND TRANSMISSION
HVAC TRANSMISSION
HVDC TRANSMISSION
GECC
NUCLEAR
COMBUSTION
HYDRO
DC DISTRIBUTION
DC microGRID

Smart System Integrator with a New System to Build: China

- Coal and hydro resources are located in Northern and Southwestern China
- Load centers are in Central and Eastern China
- UHVDC is required due to large power transmission over long distance

J. Cao & G. Tang, "Leading HVDC transmission technology and its application in China," *HVDC 2015*, Seoul, Oct. 2015.

Planned Future HVDC Projects by 2020 in China



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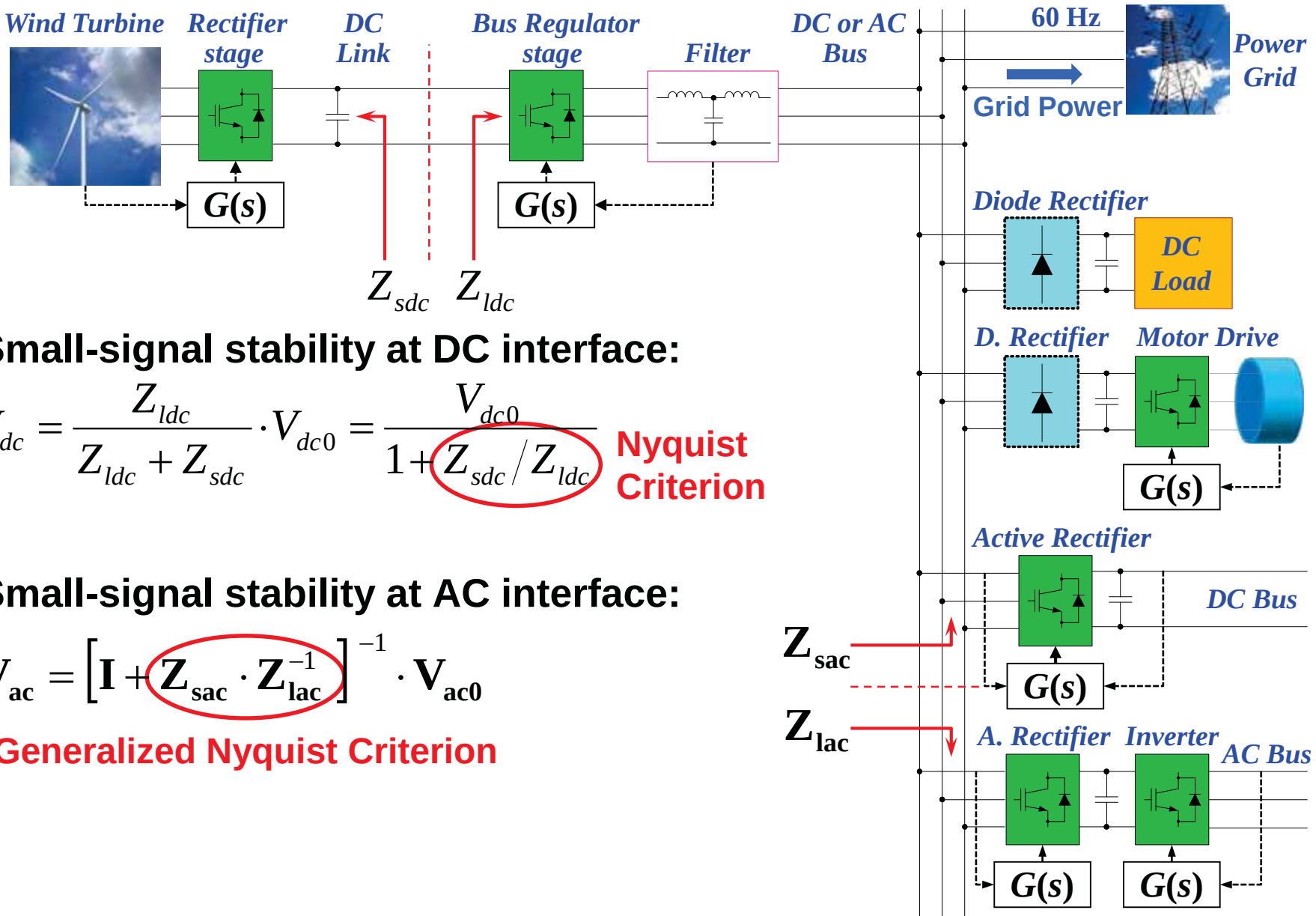
May 4, 2012 | Slide 12

(Indicative map)

Electronic Power Distribution System Stability



- **Small-signal stability at DC interface:**

$$V_{dc} = \frac{Z_{ldc}}{Z_{ldc} + Z_{sdc}} \cdot V_{dc0} = \frac{V_{dc0}}{1 + Z_{sdc} / Z_{ldc}}$$

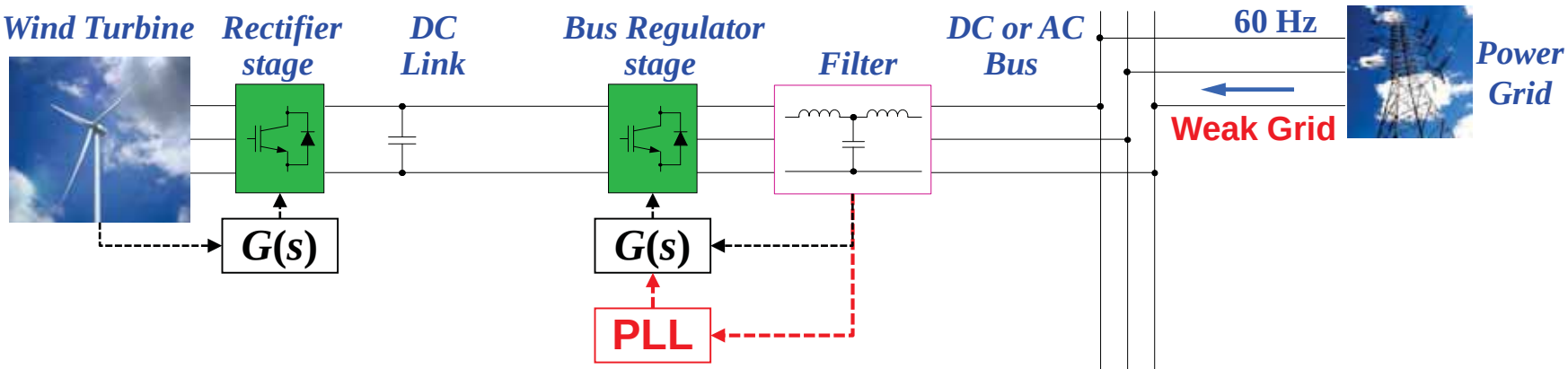
Nyquist Criterion

- **Small-signal stability at AC interface:**

$$\mathbf{V_{ac}} = \left[\mathbf{I} + \mathbf{Z_{sac}} \cdot \mathbf{Z_{lac}^{-1}}\right]^{-1} \cdot \mathbf{V_{ac0}}$$

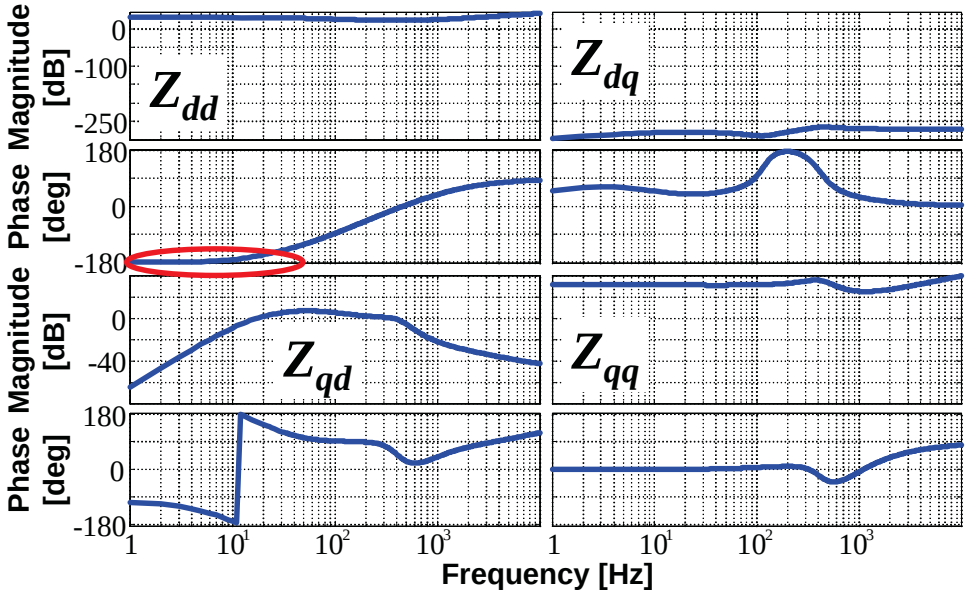
Generalized Nyquist Criterion

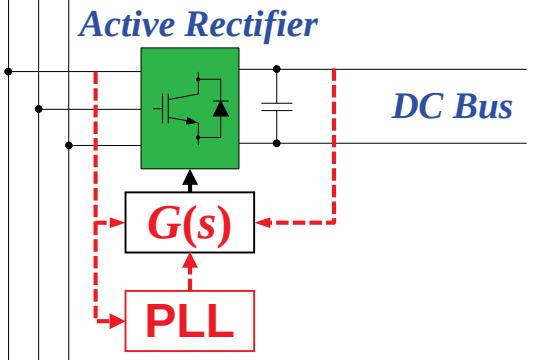
Three-Phase Impedance and System Stability



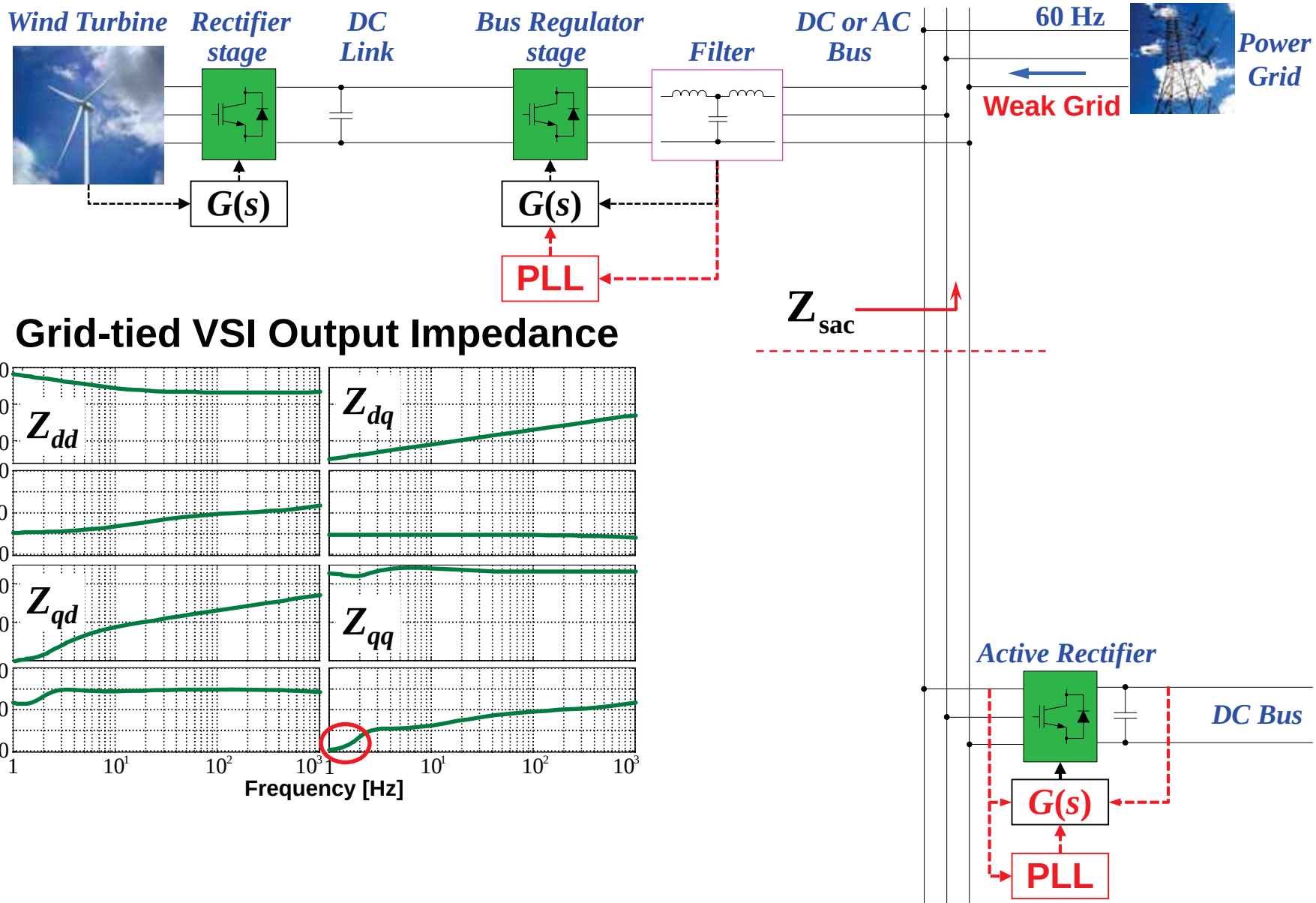
Z_{lac}

AFE Input Impedance

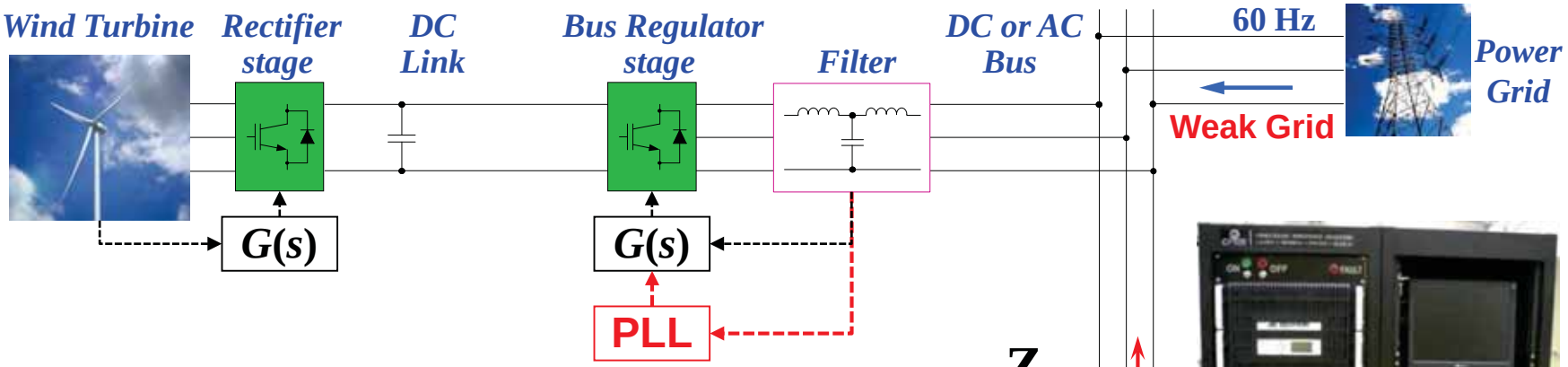




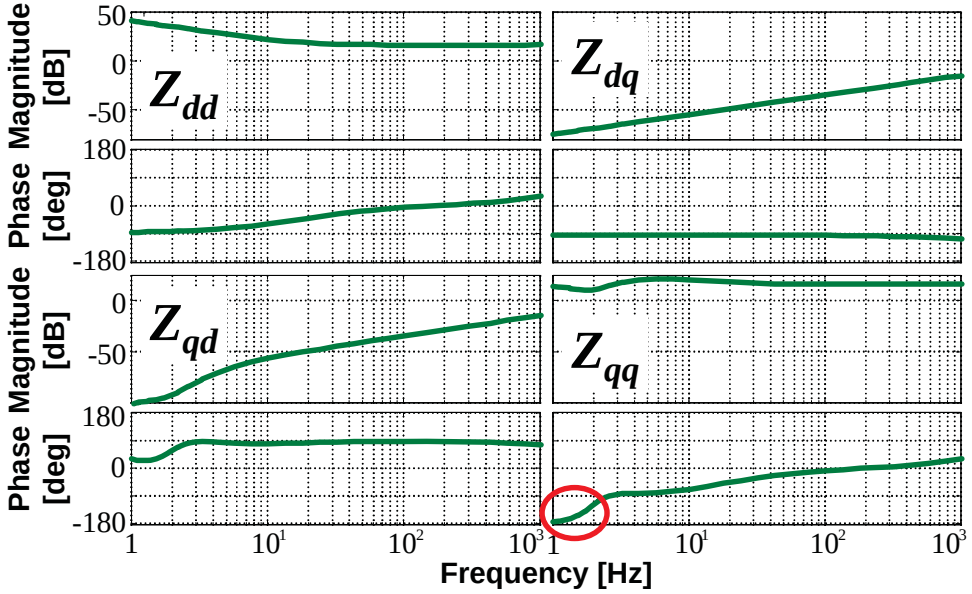
Three-Phase Impedance and System Stability

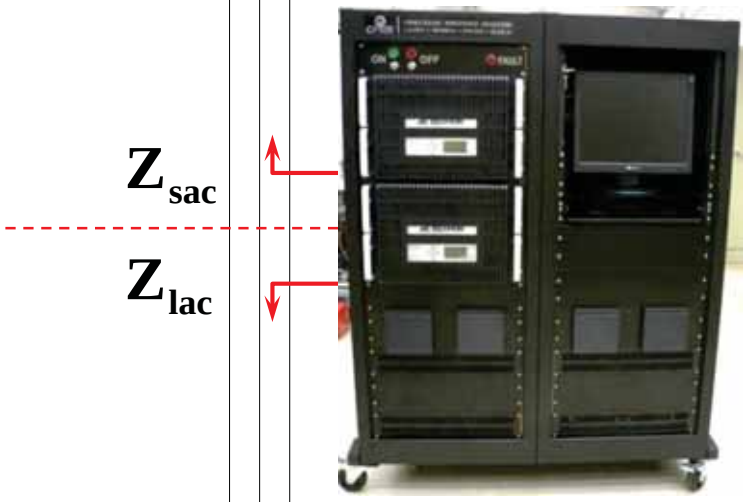


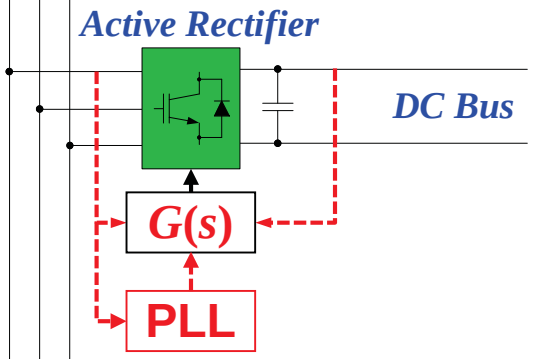
Three-Phase Impedance and System Stability



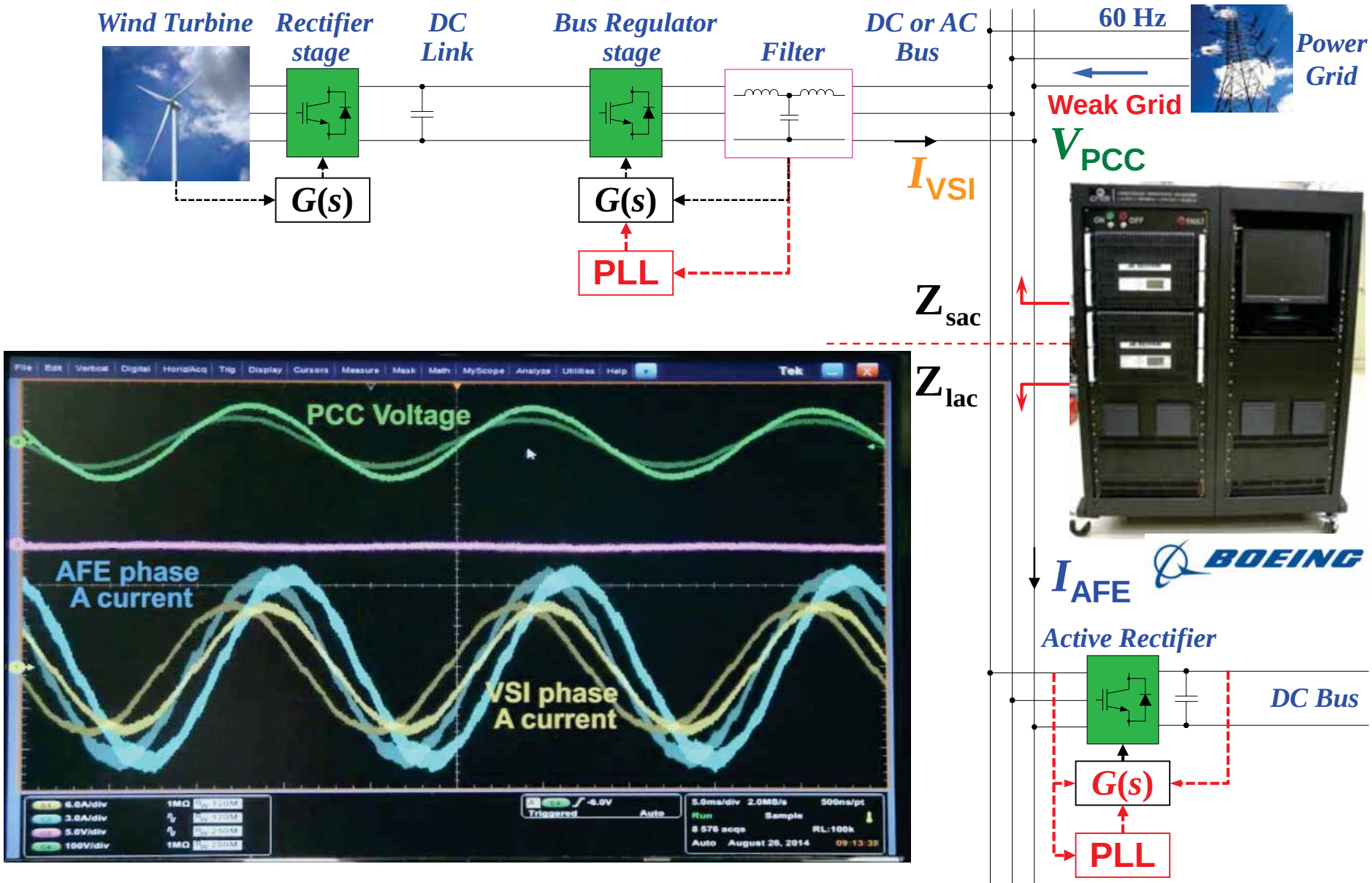
Grid-tied VSI Output Impedance







Three-Phase Impedance and System Stability

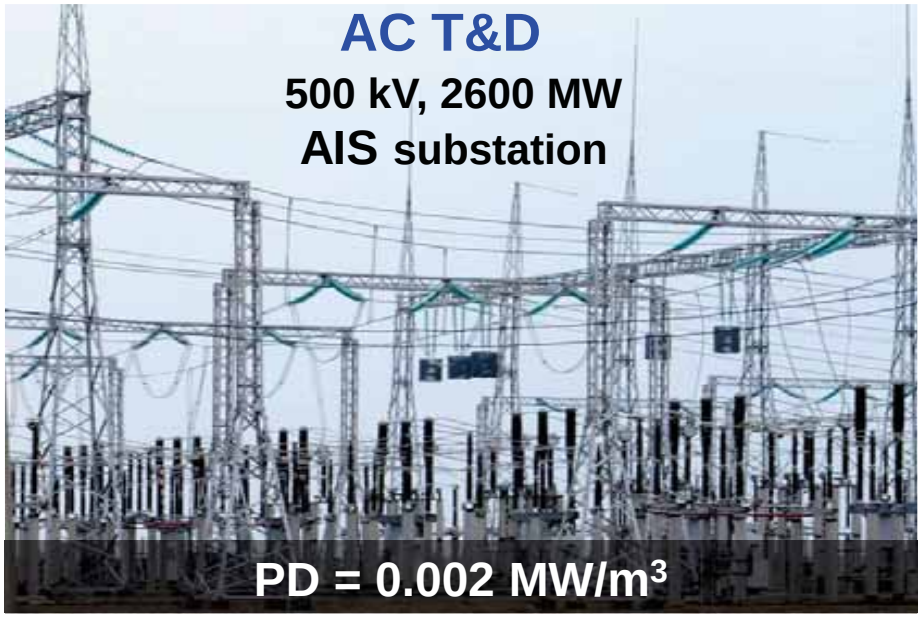


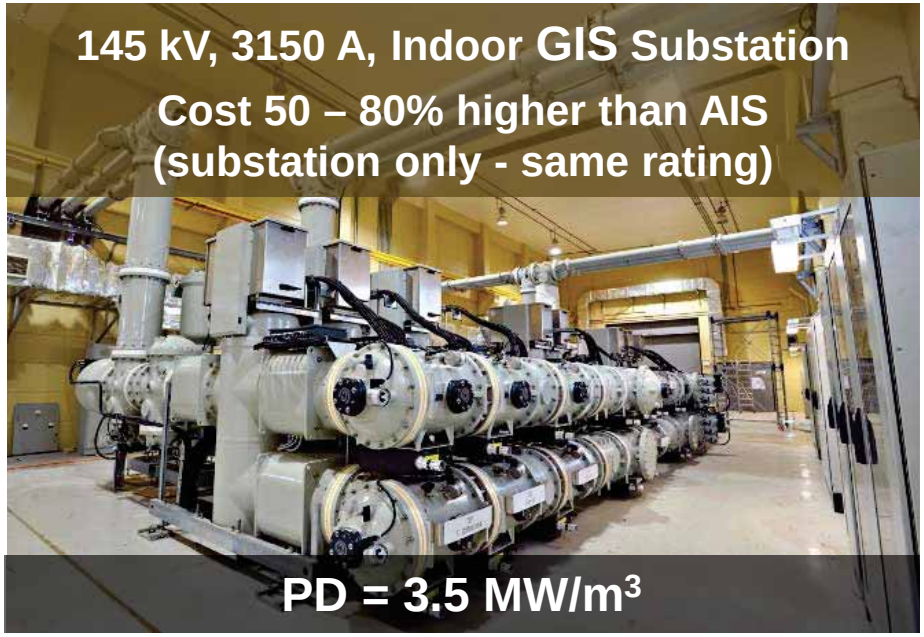
Distribution Voltage Impedance Measurement Unit

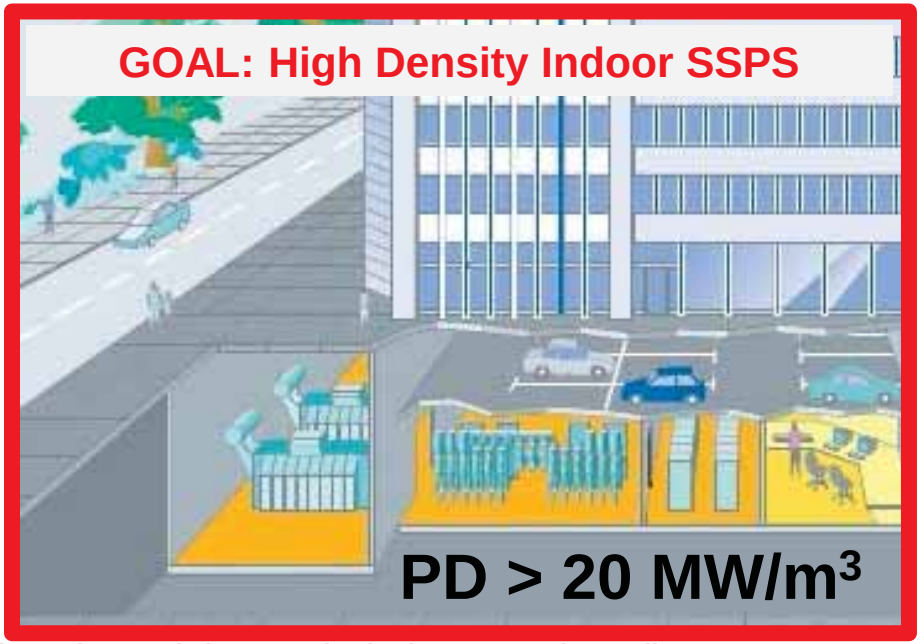
Using three H-bridges with 10 kV, 100 A SiC modules

- In-situ impedance measurements (Series and Shunt Injection)
  - System frequency: DC, 50 Hz, 60 Hz, 400 Hz
  - System voltage: 10 kV dc, 4.16 kV rms ac
  - System current: 300 A dc or rms ac
  - Measurement frequency range: 0.1 Hz – 1 kHz

Substation Power Density (SSPS 3.0)







SSPS at the Vienna Metro Station on I-66

PEBB-based SSPS at every relevant interchange

- New academic program
- 10 faculty positions at Virginia Tech