Virginia Tech

CPES
Center for Power Electronics Systems

Use of SiC Devices in Medium-Voltage Converters

Dushan Boroyevich

April 15th, 2016

Outline

- Introduction

- Issues / Approaches / Challenges:
  - Modularity / scalability
  - High *dv/dt*, *di/dt*, EMI
  - Sensing / control / protection
  - High voltage

Center for Power Electronics Systems
The Bradley Department of Electrical and Computer Engineering
College of Engineering
Virginia Tech, Blacksburg, Virginia, USA

Advanced High-Megawatt Converters for New Grid Architectures

Dushan Boroyevich

Presentation at
High Megawatt Power Conditioning System Workshop

Technology Roadmap
for Increased Power Electronic Grid Applications and Devices

NIST
Gaithersburg, Maryland

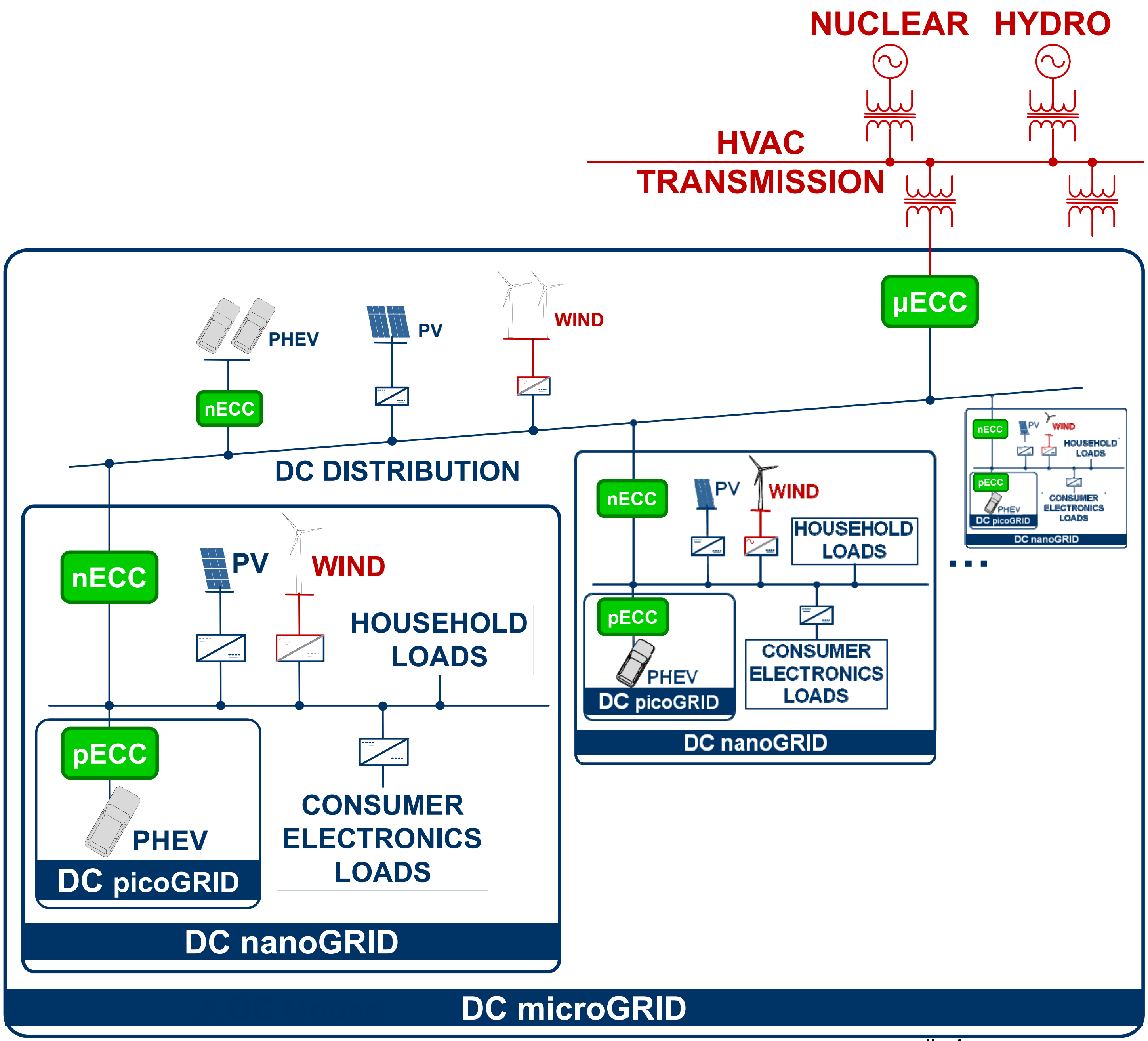
2012.05.24

¿ Intergrid ?

ECC = Energy Control Center
= Bidirectional power converter / substation

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 ?

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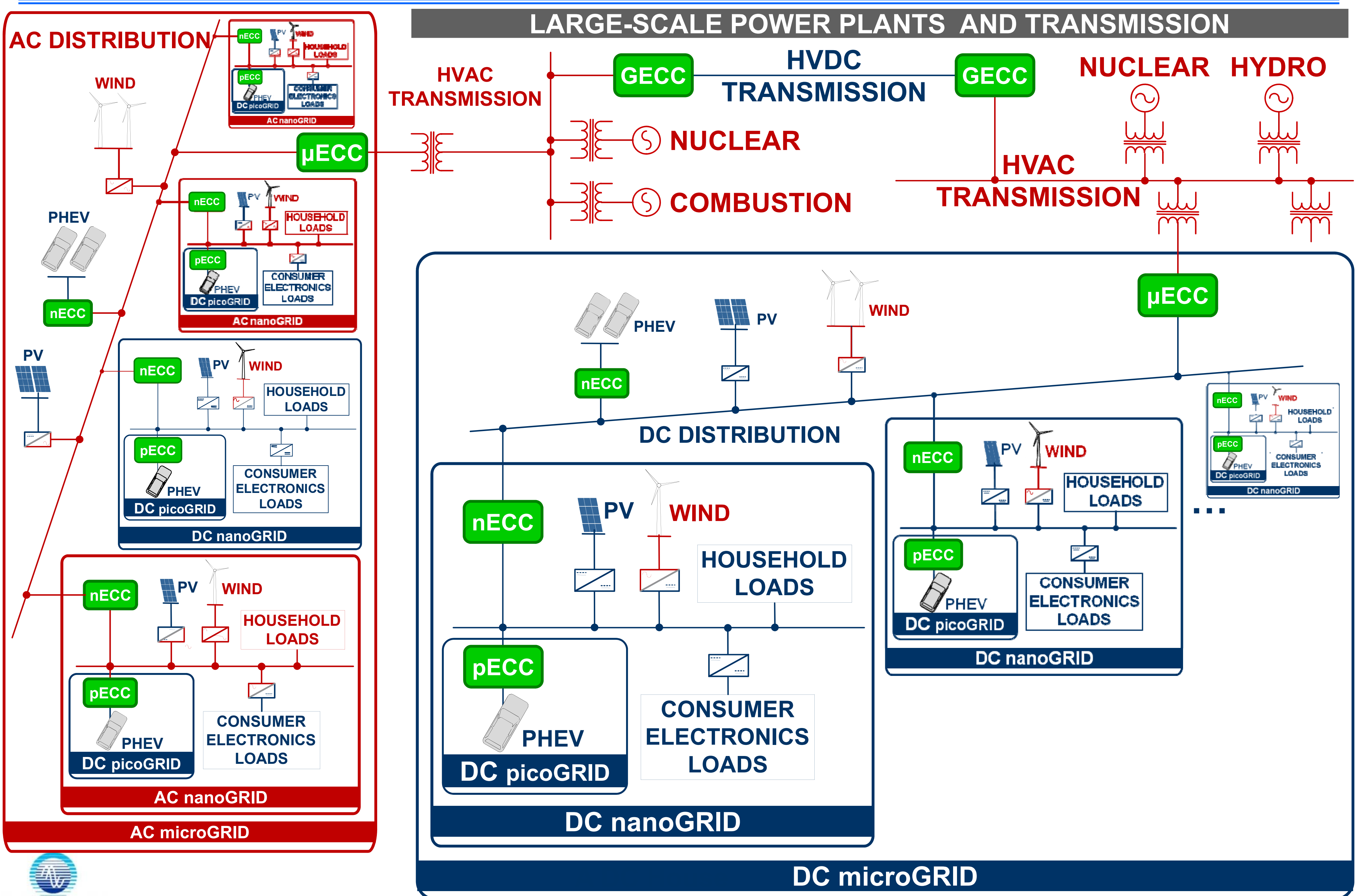

¿ Intergrid ?

ECC = Energy Control Center
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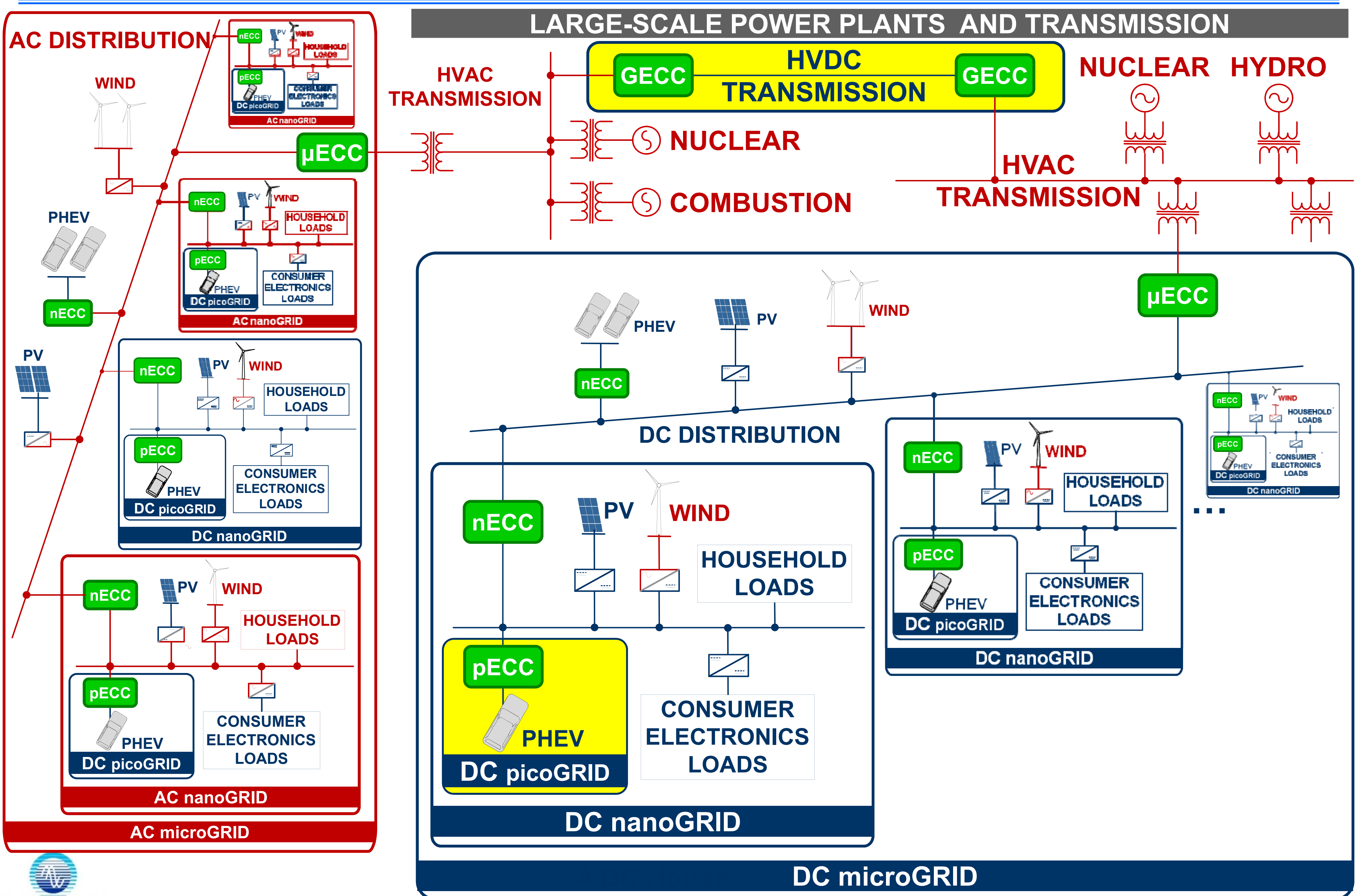
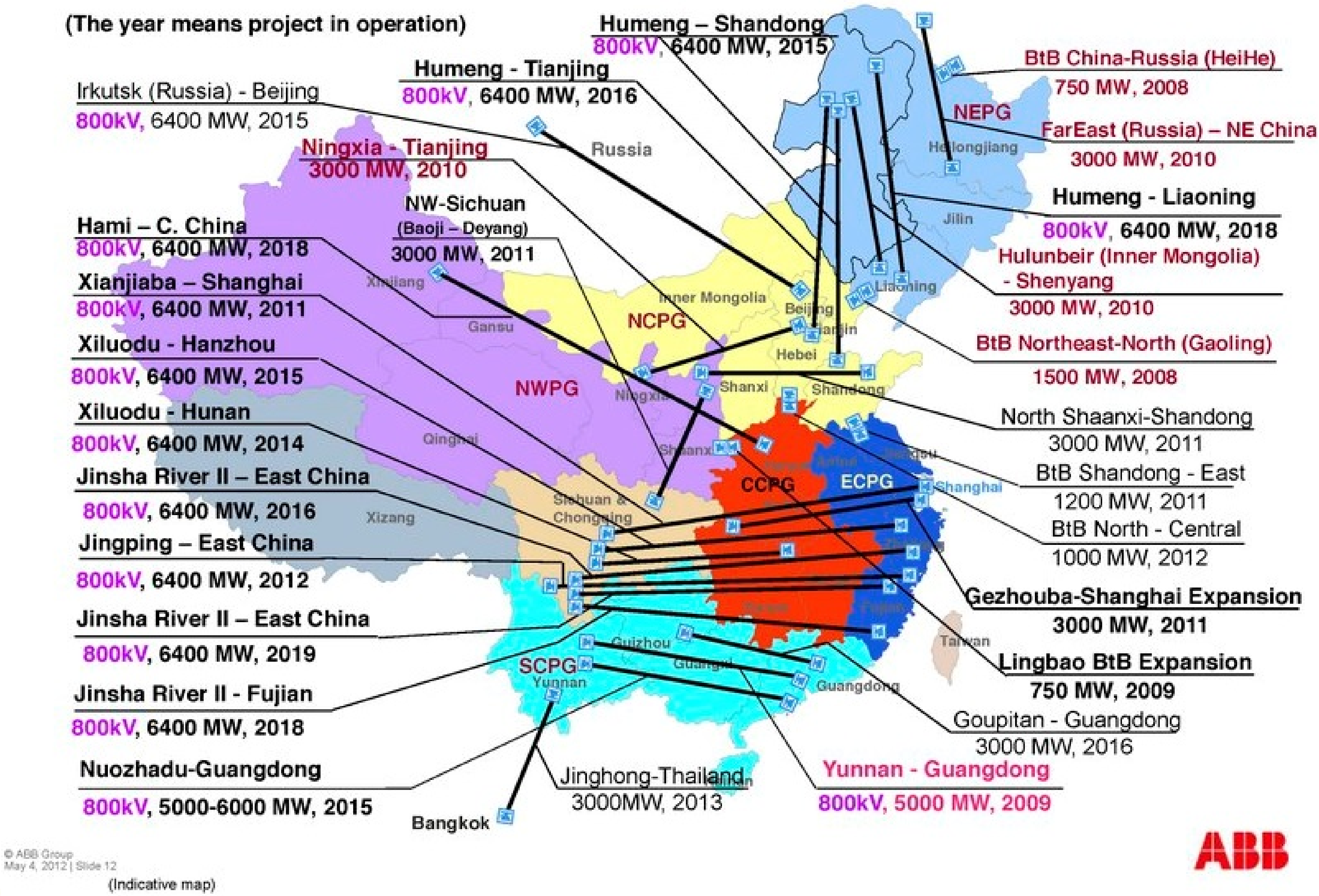


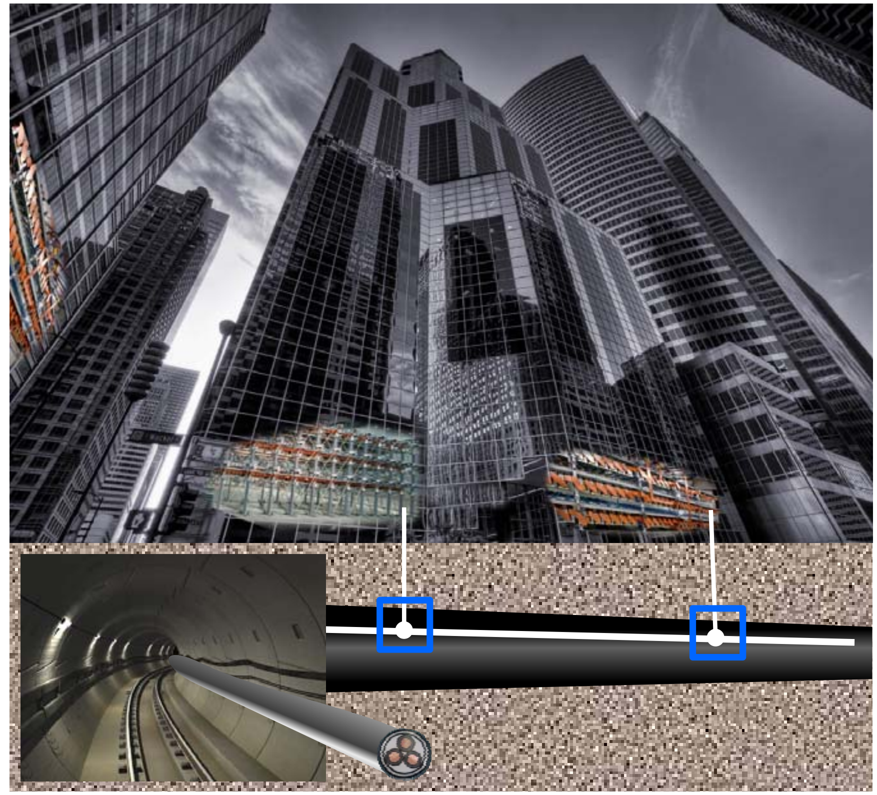
Planned Future HVDC Projects by 2020 in China



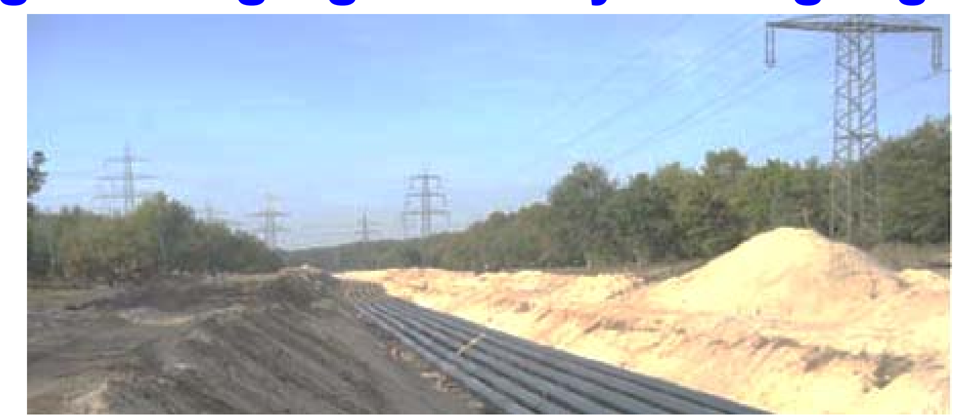
Can we Increase Power Density in Applications that Can Afford It?

Off-shore

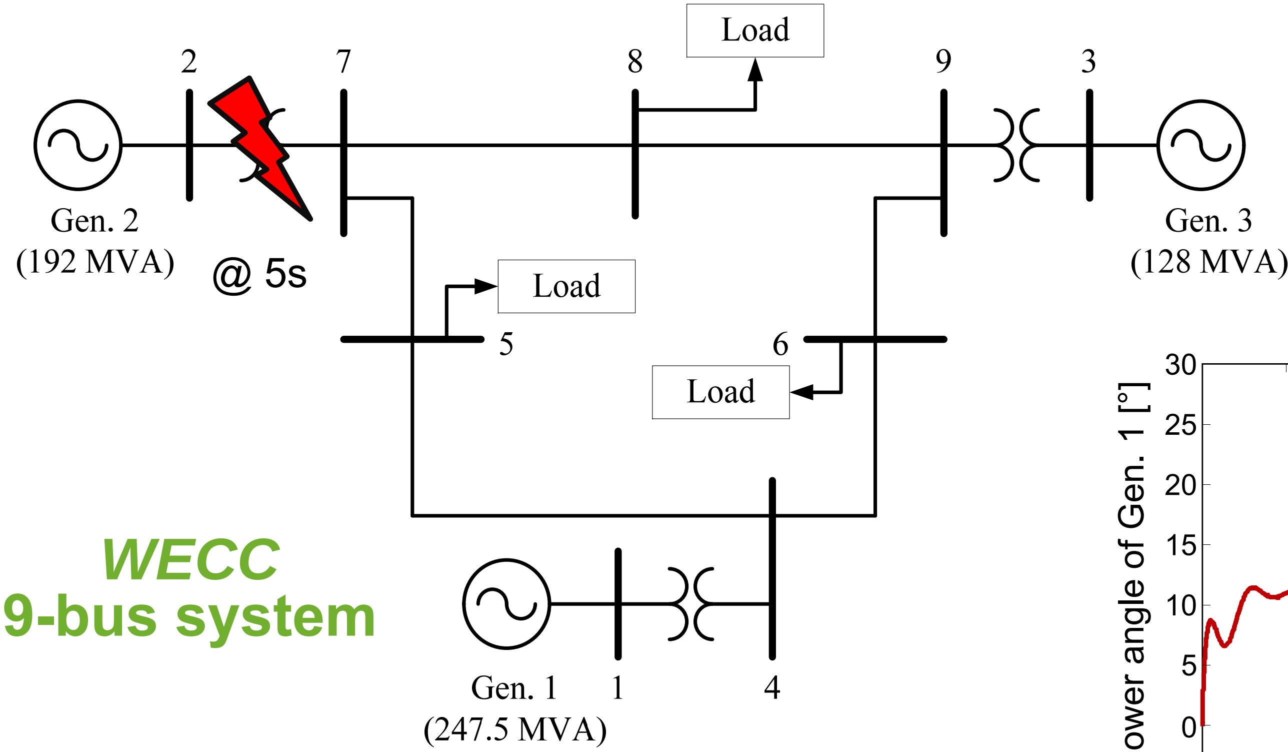
In densely populated urban areas



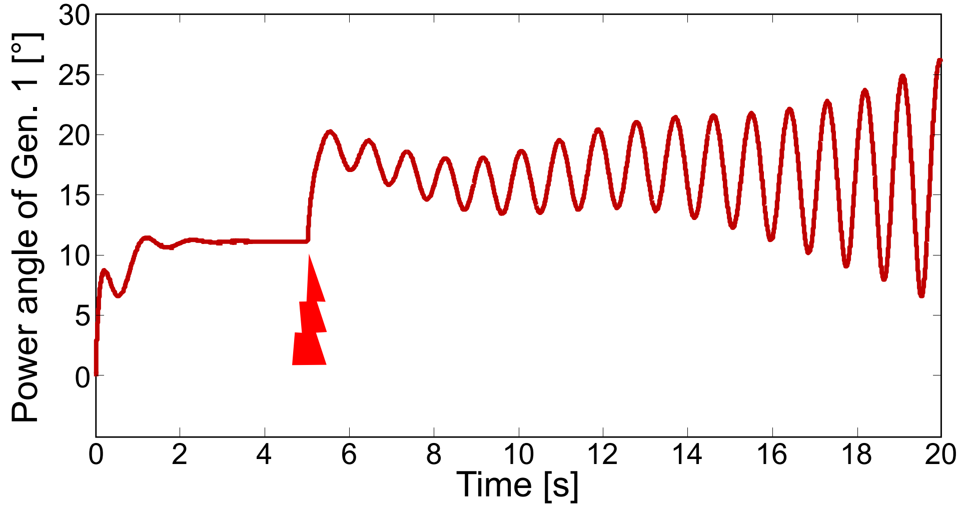
Using existing right-of-ways along highways



Instability in Traditional System Caused by Partial Loss of Generation



$$P_{\text{Total Load}} \approx 180 \text{ MVA} < P_{\text{Gen. 1}} + P_{\text{Gen. 3}}$$

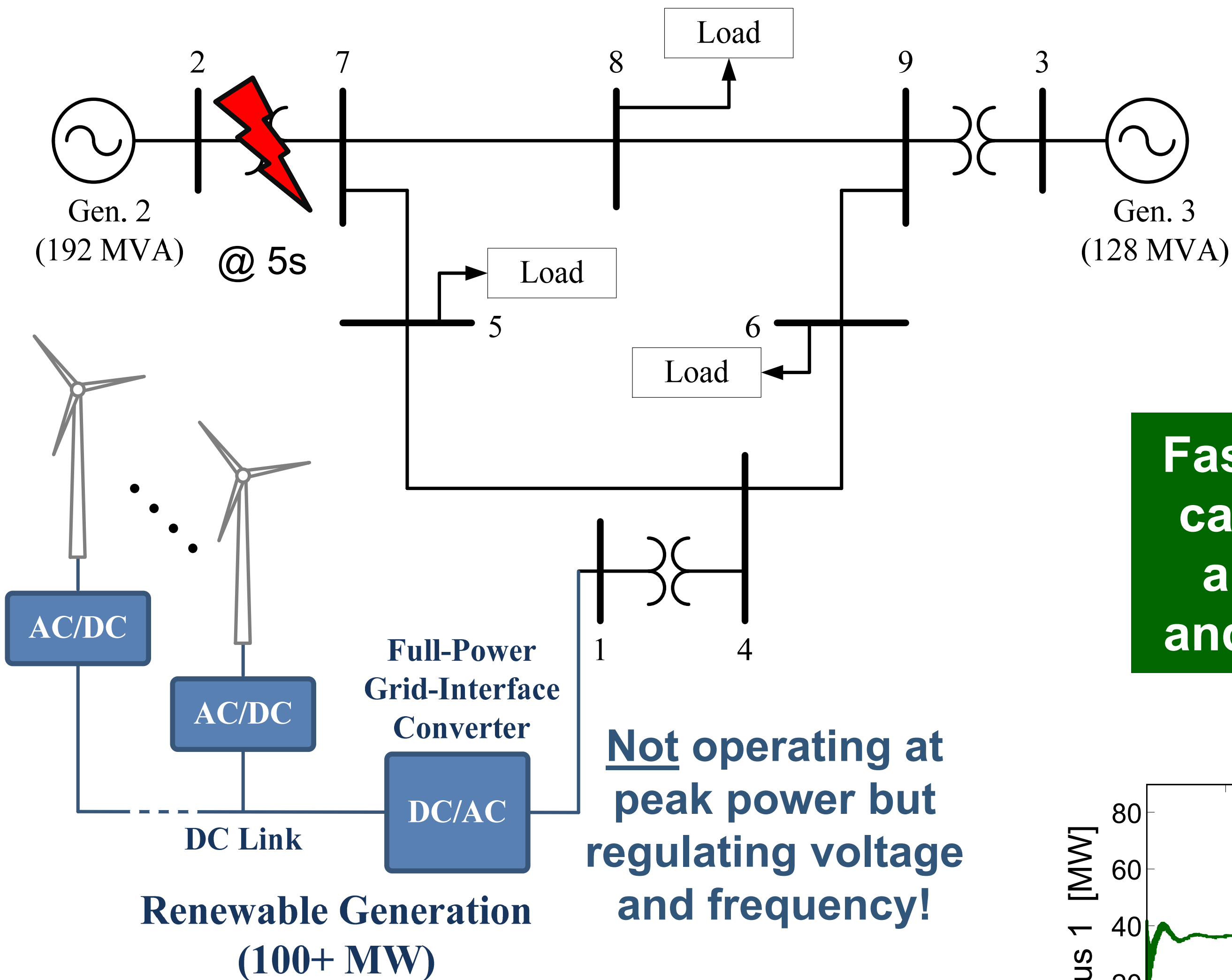


WECC
9-bus system

Total generating capacity > 550 MVA

Large transient causes overall system instability due to undamped power oscillations between Generators 1 and 3.

Mitigating Instability with Power Electronics-Interfaced Renewable Generation

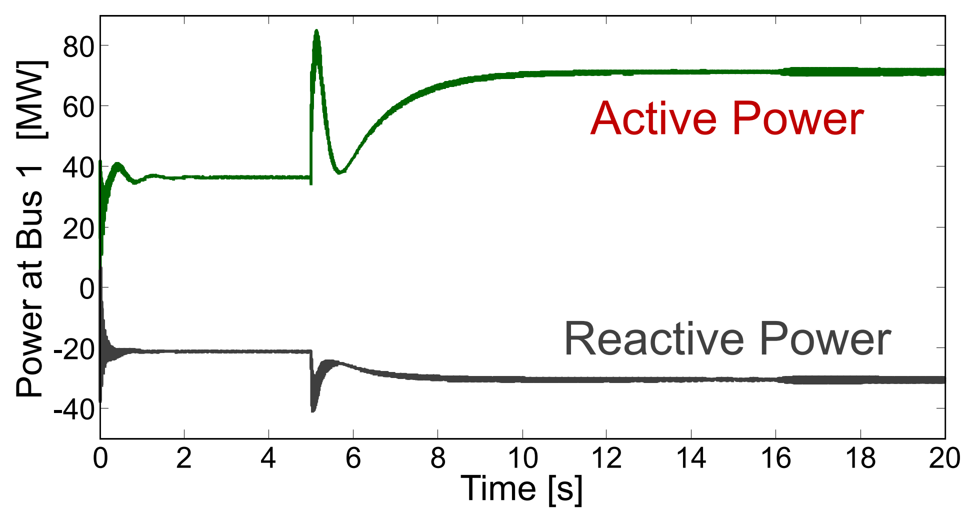


$$P_{\text{Total Load}} \approx 180\ \text{MVA} < P_{\text{Ren.}} + P_{\text{Gen. 3}}$$

Fast-reacting power electronics can dispatch necessary active and reactive power very fast and hence stabilize the system!

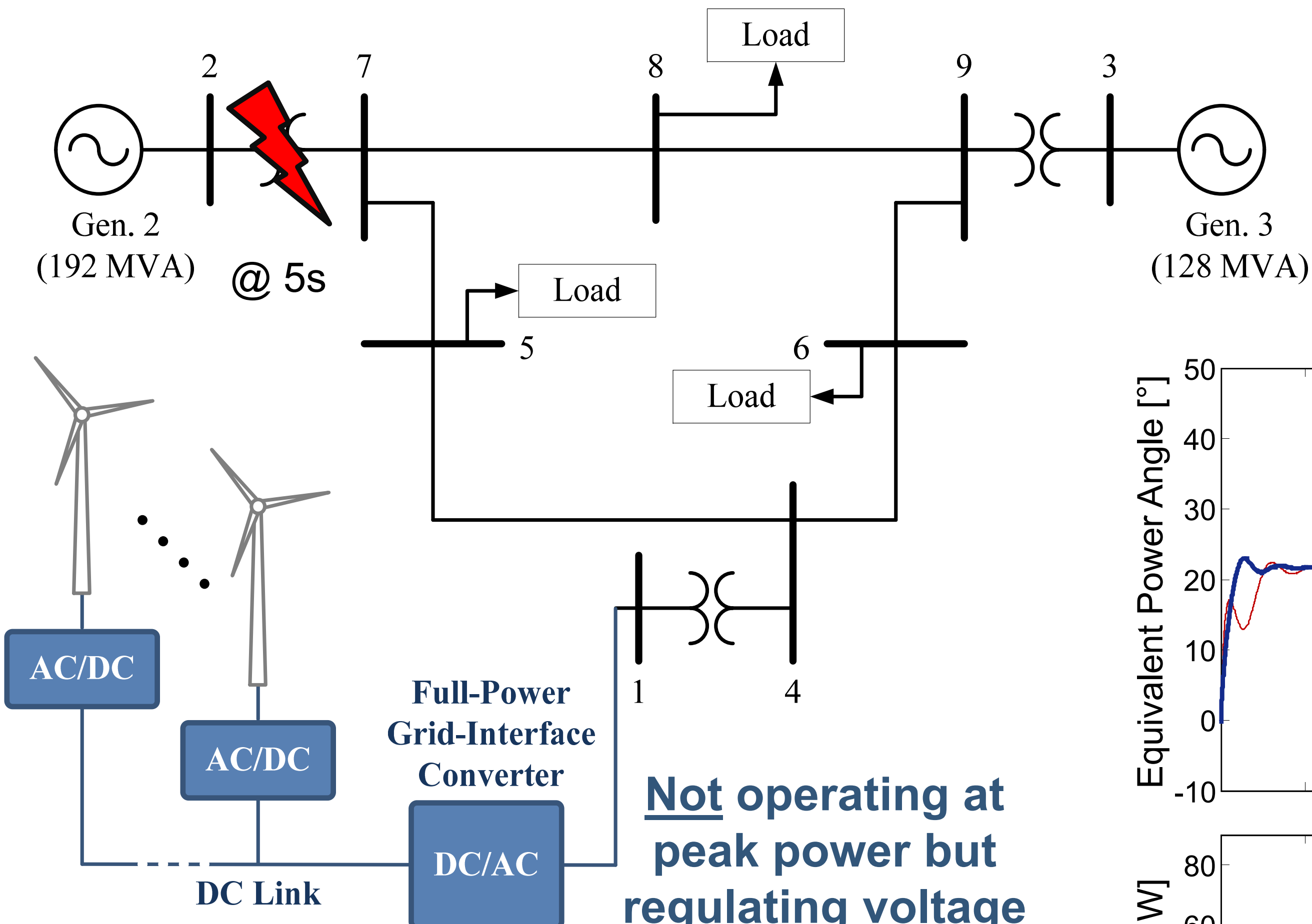
Not operating at peak power but regulating voltage and frequency!

Total generating capacity < 450 MVA



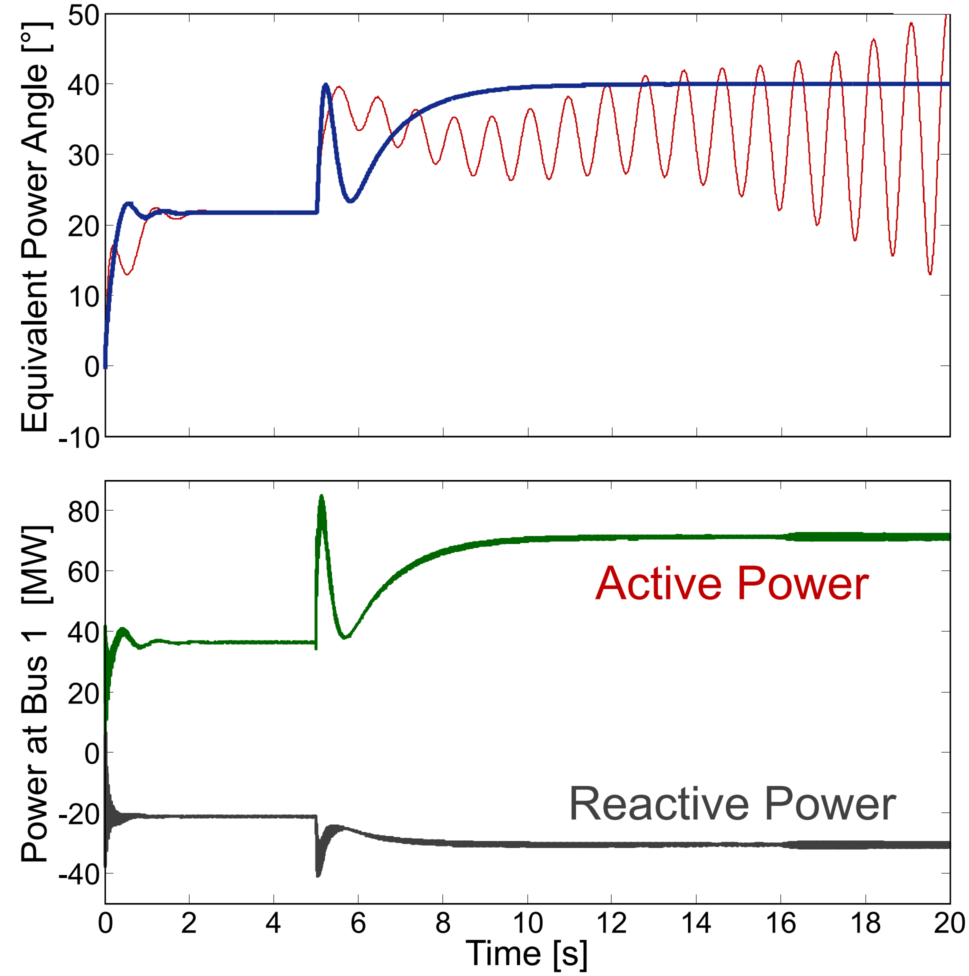
Mitigating Instability with Power Electronics-Interfaced Renewable Generation

$P_{\text{Total Load}} \approx 180 \text{ MVA} < P_{\text{Ren.}} + P_{\text{Gen. 3}}$



Renewable Generation (100+ MW)

Not operating at peak power but regulating voltage and frequency!



Total generating capacity < 450 MVA

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Tutorial:

Is SiC a Game Changer?

Dushan Boroyevich

2015 CPES Annual Conferen
Virginia Tech
Blacksburg, VA
April 12, 2015

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Tutorial:

Is SiC a Game Changer?

Dushan Boroyevich, Christina DiMarino

Congresso Brasileito de Electrônica de Potência
Southern Power Electronics Conference
Fortaleza, Brazil
November 29, 2015

COBEP 2015

Conclusions

For Vdc < 500 V:

- **SiC SBD + Si Super-junction MOSFET will compete with GaN-on-Si**

For 0.5 kV < Vdc < 1 kV:

- **SiC Schottky (SBD) will be increasingly used instead of Si PiN**
- **SiC transistors will start competing with Si MOSFETs and IGBTs based on converter cost, efficiency, size and performance**
  - **(A tough proposition!)**
- **For high switching frequencies (> 10 kHz) better module and converter packaging must be developed**

For 1 kV < Vdc < 6 kV:

- **SiC could be overtaking Si within 3-8 years**
- **Improved packaging for higher switching frequencies, higher voltage, higher temperatures, and longer lifetime will provide competitive advantage**
- **Much improved systems based on new designs for electric machines, passives, and converters will be a game changer**

Conclusions

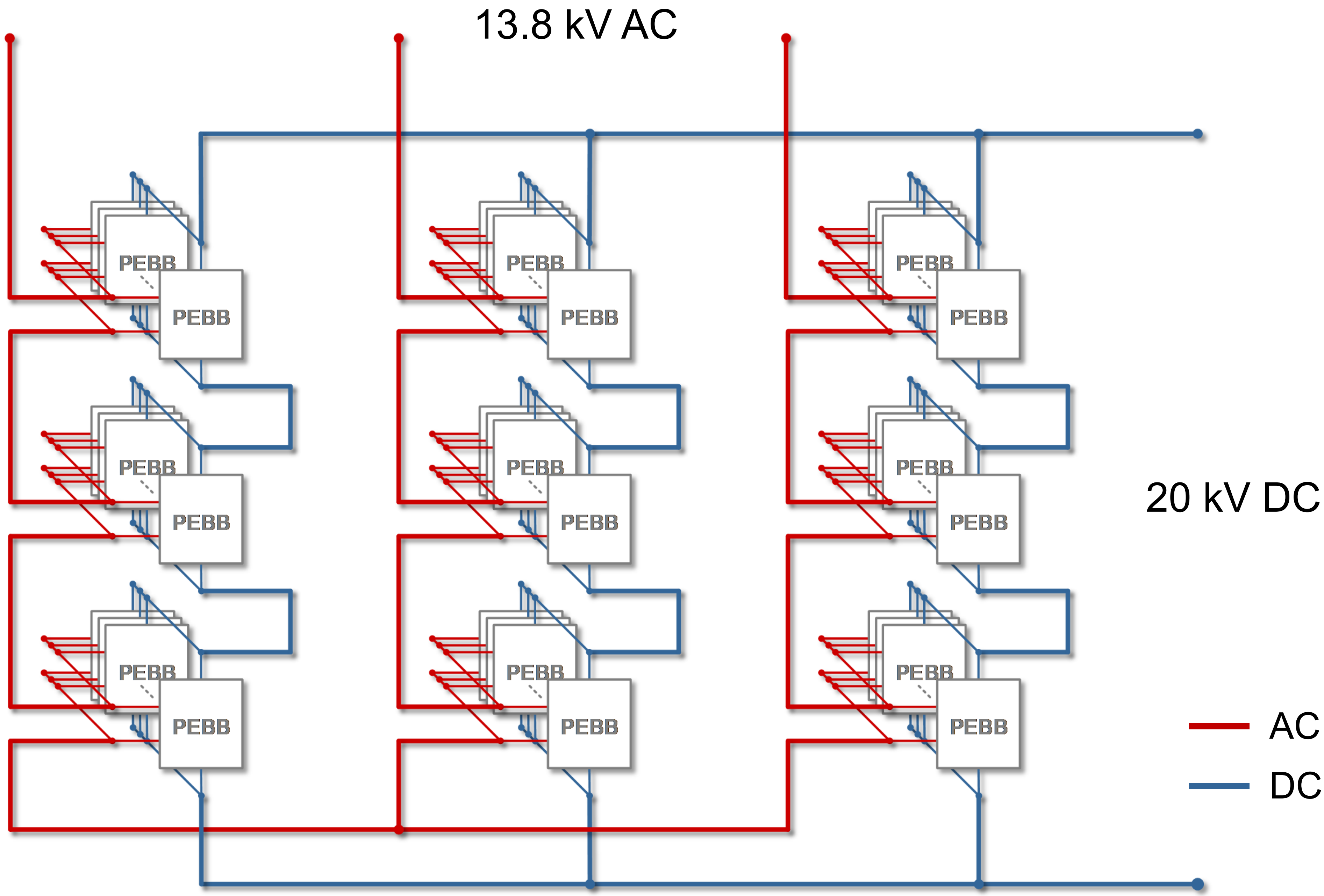
For Medium and High Voltage (Vdc > 6 kV):

- **SiC is the future! (*Not a game changer, but a New Game.*)**
- **Very innovative packaging and system design for high voltage, higher switching frequencies and long lifetime is required**
- **Completely new systems and new applications will be developed**
- **This will become huge when the new electronic grid will start to be built**

For High Ambient Temperature (> 200 ºC):

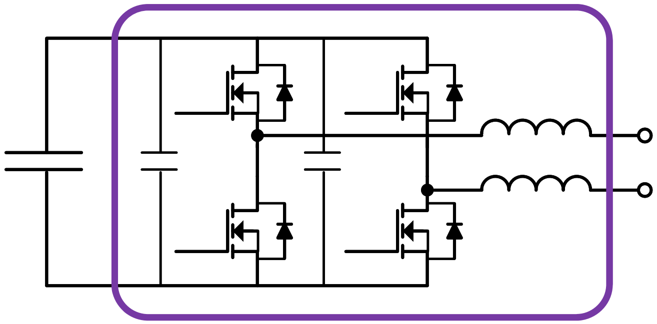
- **SiC is the future! (*Not a game changer, but a New Game.*)**
- **Very innovative packaging for high temperature, higher switching frequencies and long lifetime is required**
- **Novel components for the "balance of system" (sensing, control, passives, interconnects, …) will have to be invented and developed**
- **Completely new systems and new applications will be developed**
  - **("Physics" will remain the problem!)**

Ex: 35 MW 3-phase AC to DC Power Converter for Bidirectional MV Motor Drive or Grid-Interface



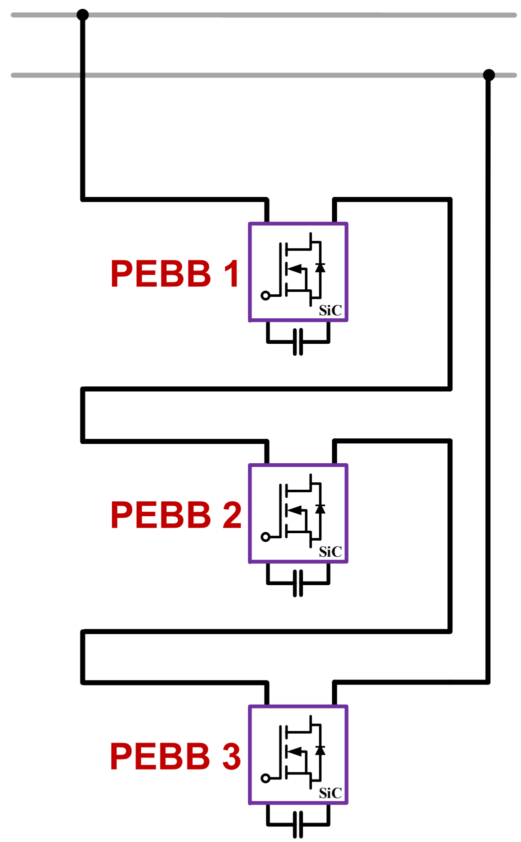
SiC H-Bridge Modules
Power Electronics Building Block (PEBB)

- Concept: **Integration of fundamental components into blocks** with defined functionality that can be used in a variety of applications.
- Motivation: The **versatility** reduces the cost, size, weight, loss, design complexity, installation, and maintenance of power electronic systems.

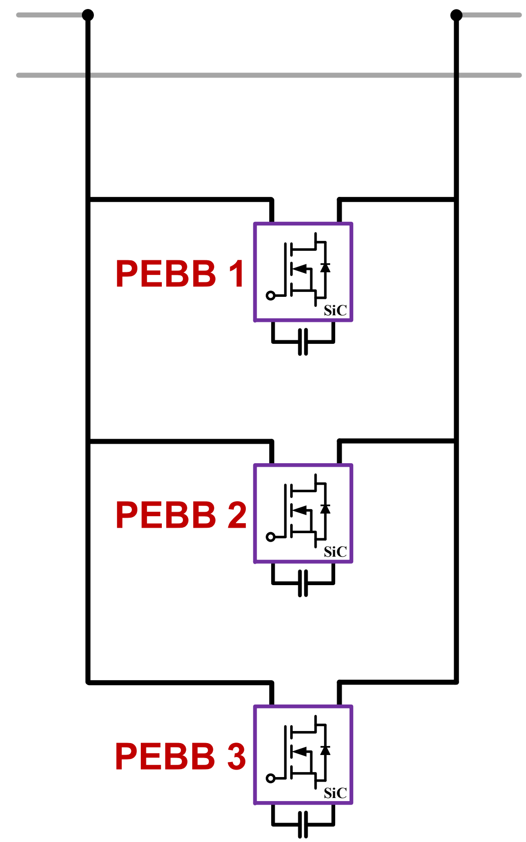


PEBB H-Bridge

Series PEBB Connection



Parallel PEBB Connection

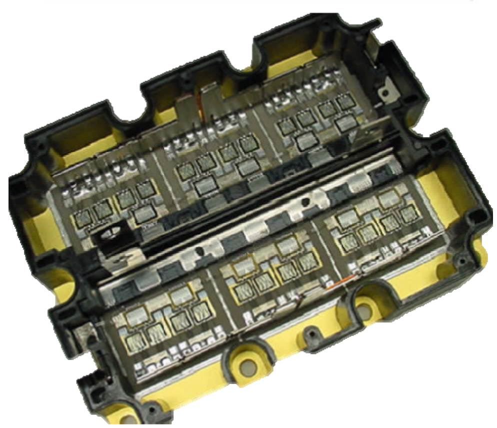


PEBB 1000

1.7 kV **SiC MOS**

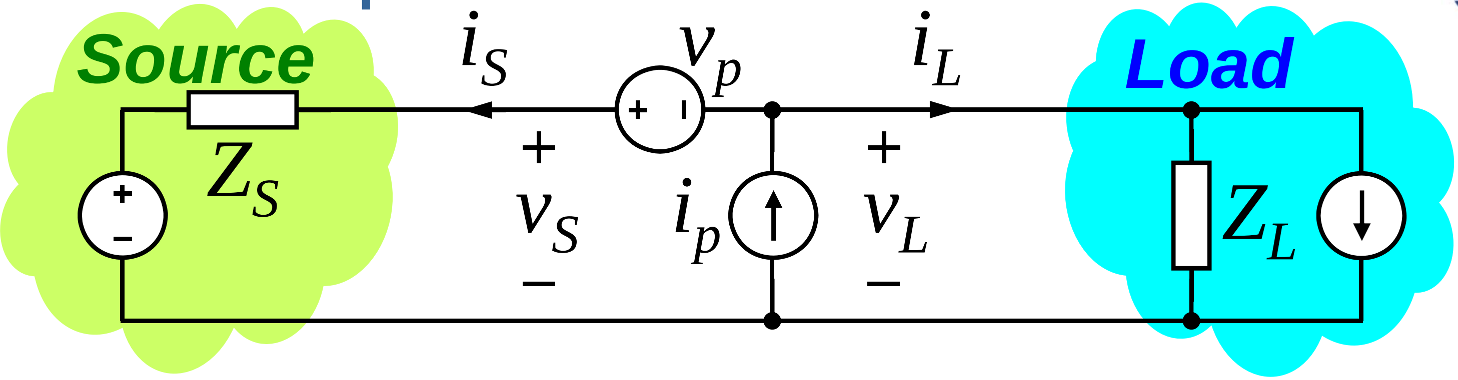
PEBB 6000

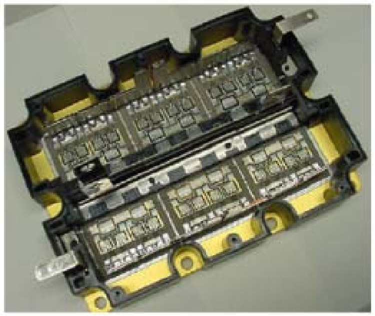
10 kV **SiC MOS**



Impedance Measurement Unit using 10 kV SiC MOSFETs for Medium Voltage (4.16 kV) Medium Power (2 MW) Systems

▶ In-situ impedance measurements



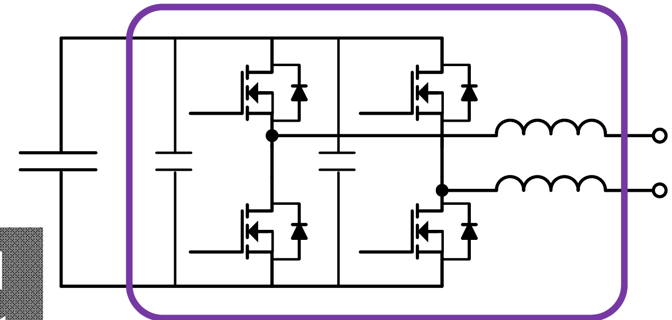


10 kV / 120 A
SiC half-bridge

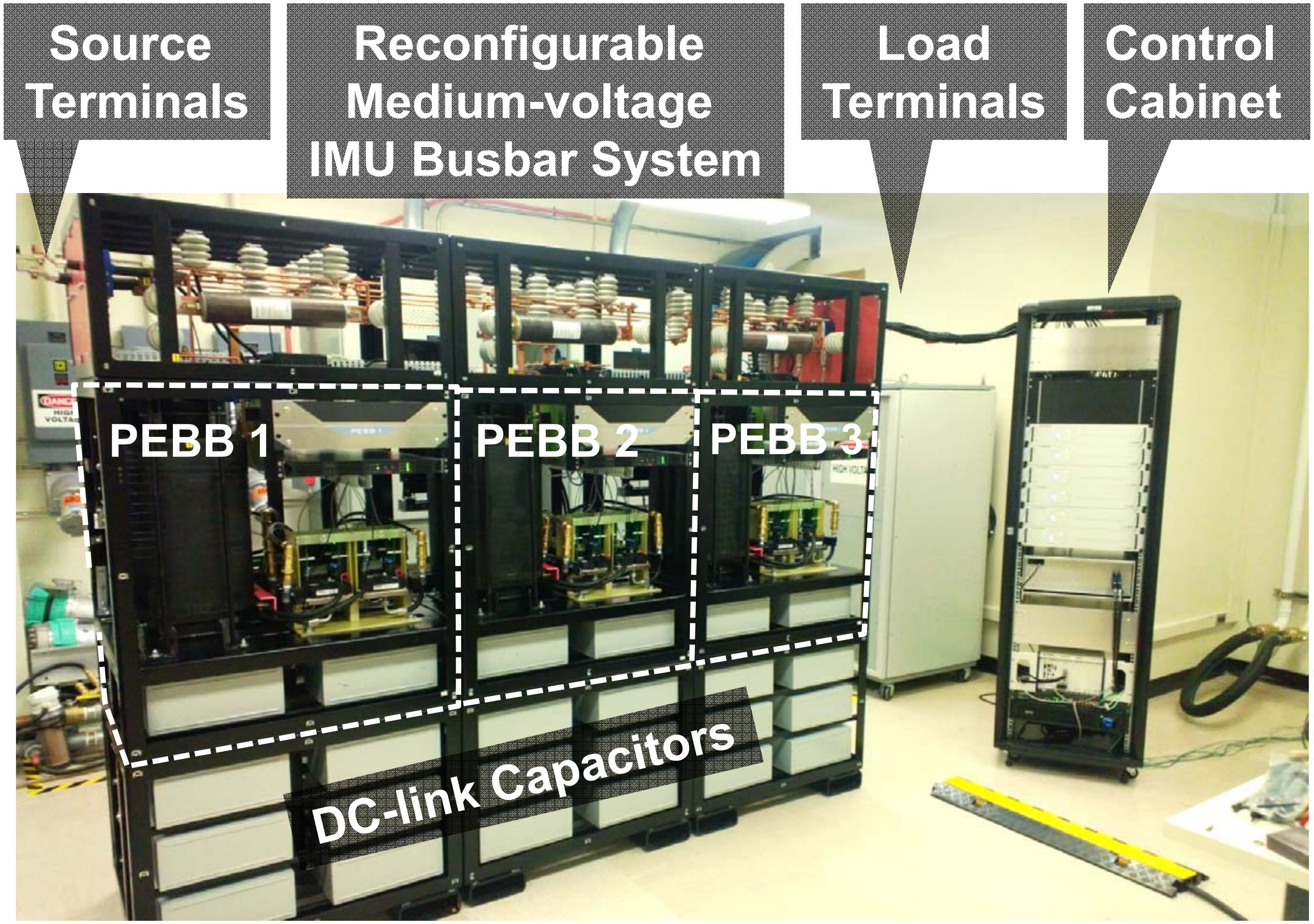
5 kV / 100 A H-bridge

Impedance Measurement Unit using 10 kV SiC MOSFETs for Medium Voltage (4.16 kV) Medium Power (2 MW) Systems

System Ratings: 10 kV dc or 4.16 kV rms ac
300 A dc or rms ac
DC, 50 Hz, 60 Hz or 400 Hz



PEBB H-Bridge

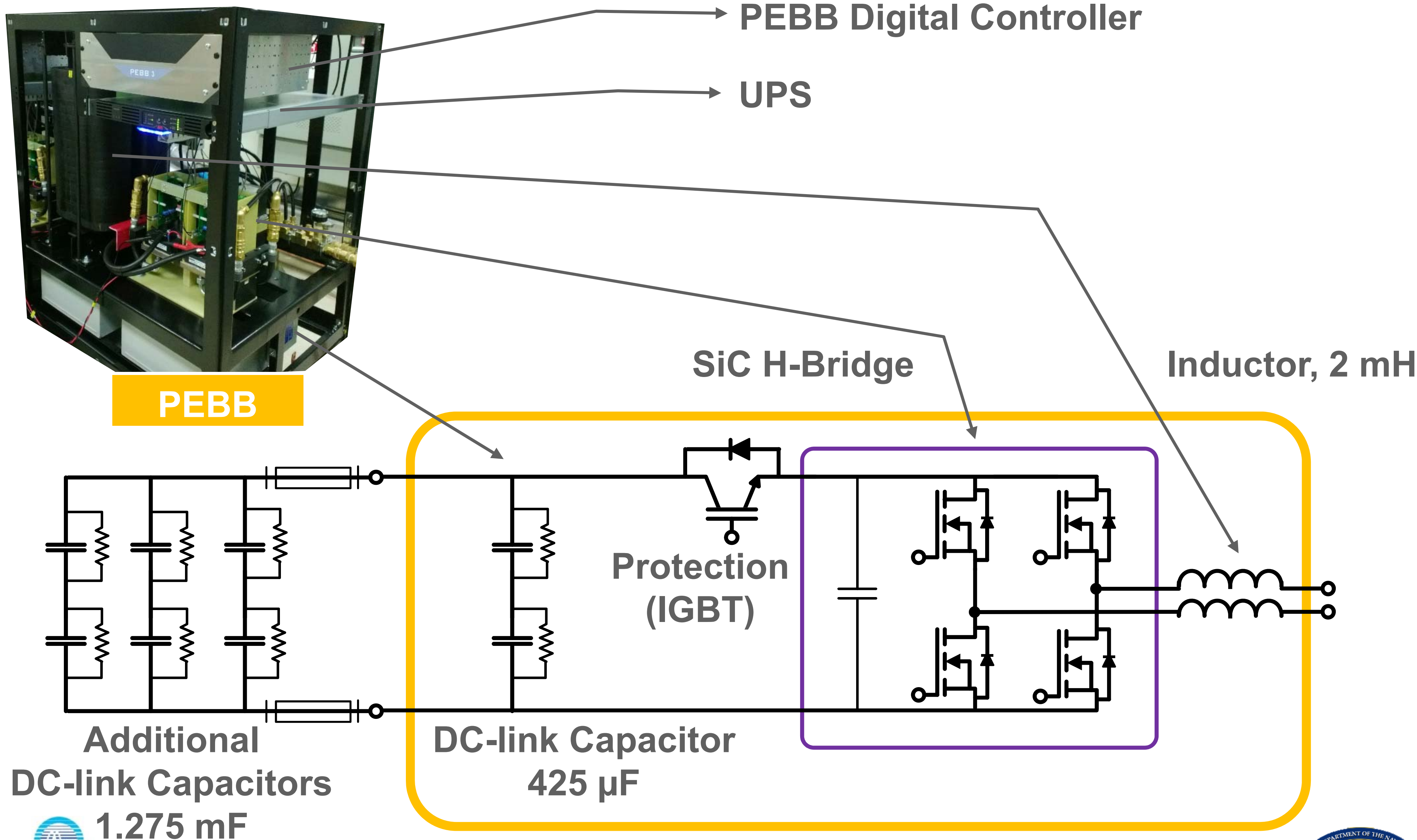


5 kV / 100 A H-bridge

Measurement frequency range: 0.1 Hz - 1 kHz

6 kV Power Electronic Building Block (PEBB) Design

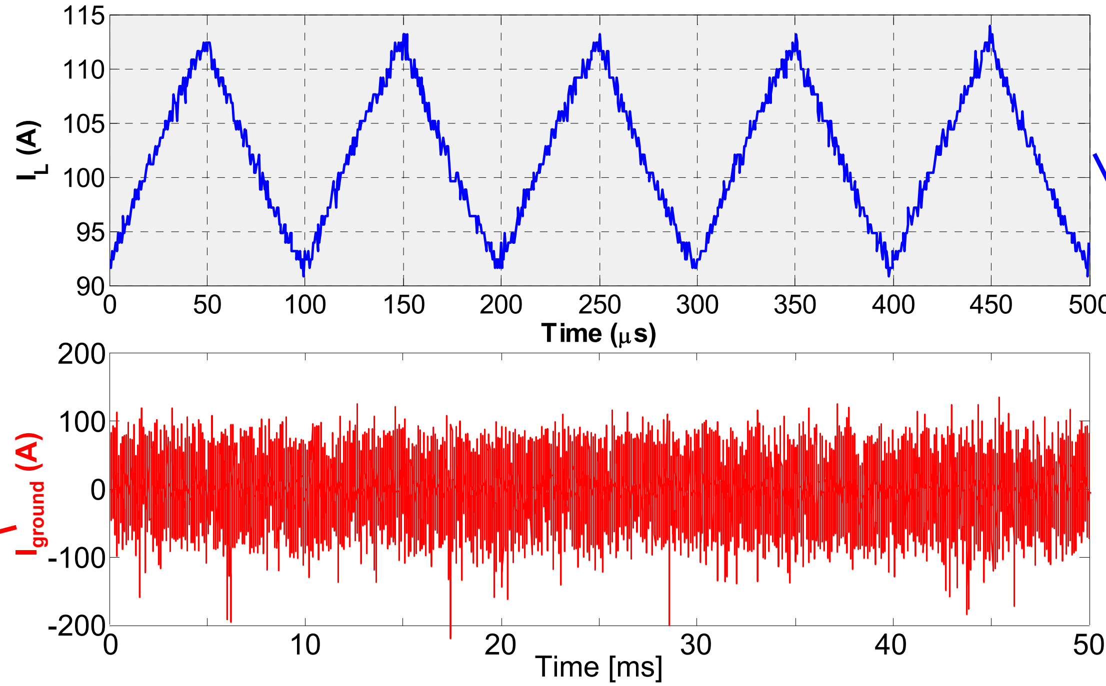
PEBB Design

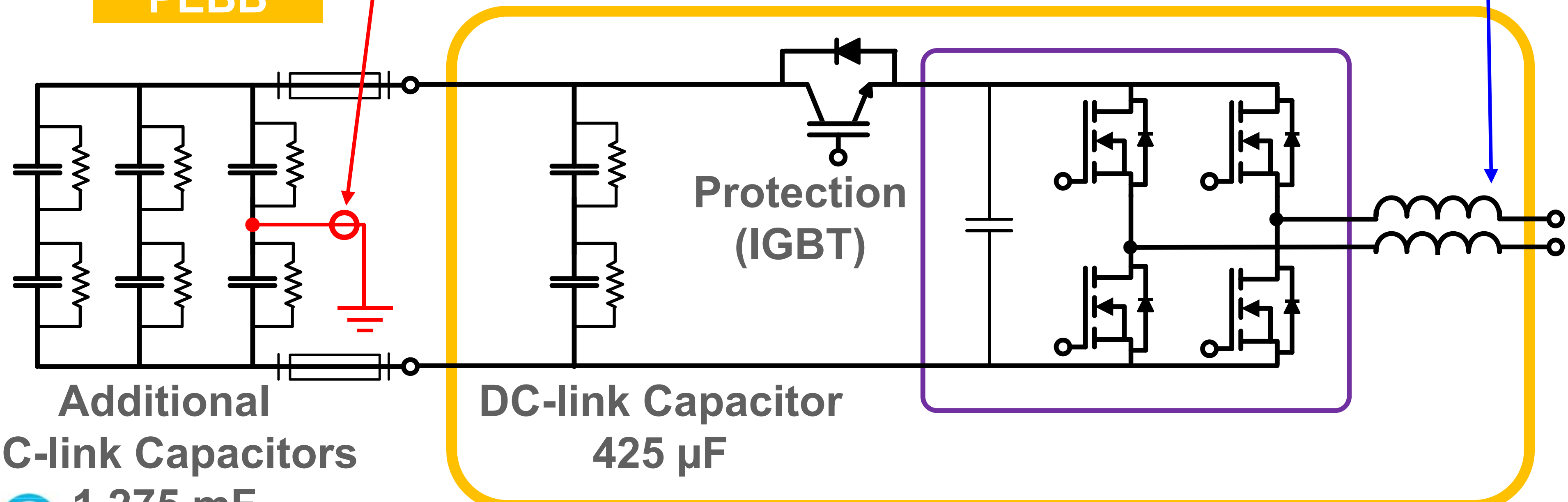


Significant common-mode currents limited the operation of the converter to 3 kV.

Continuous Operation

PEBB

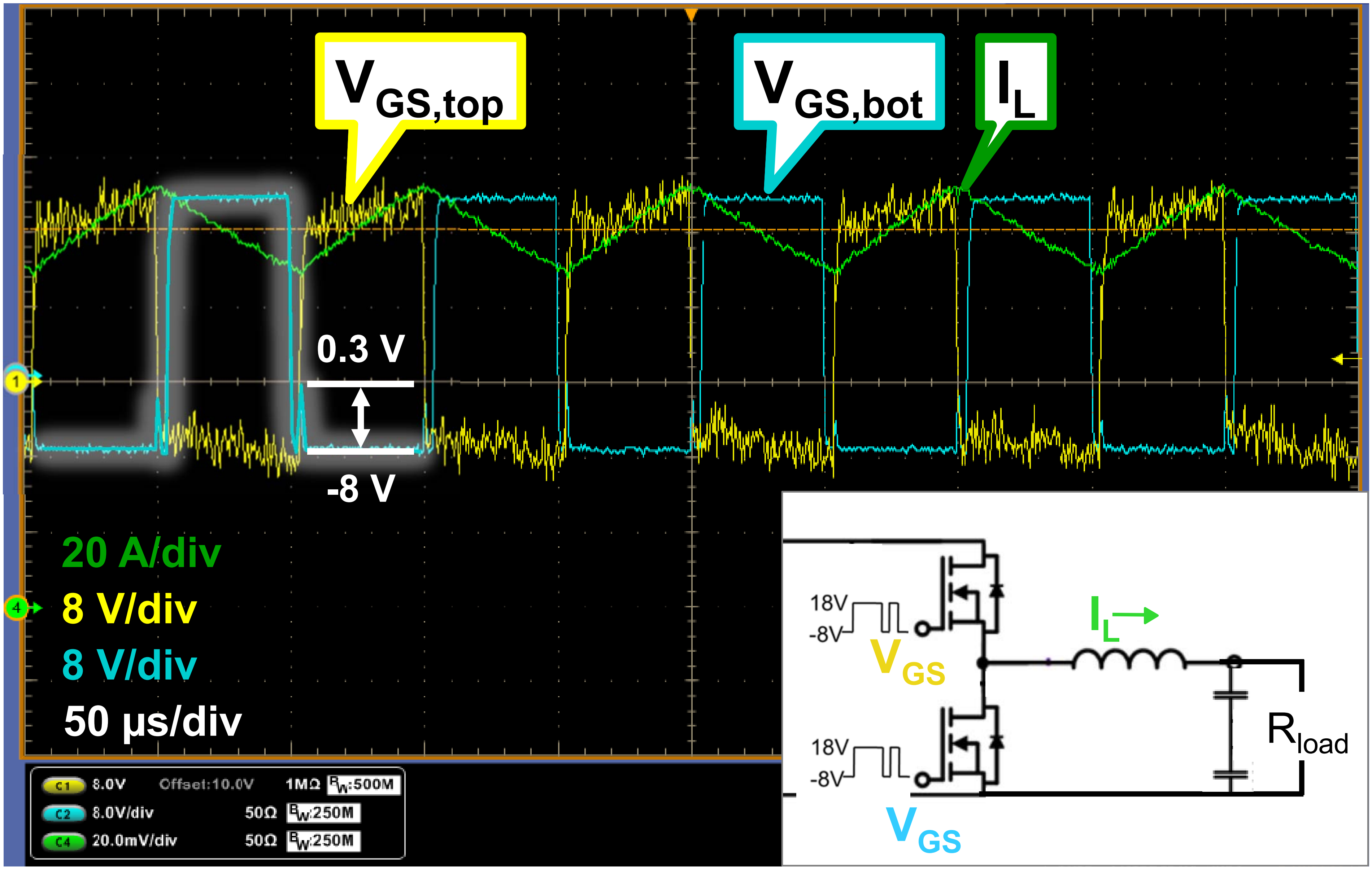




Additional
DC-link Capacitors
1.275 mF

DC-link Capacitor
425 μF

Significant Miller effect limited the operation of the converter to 3 kV.

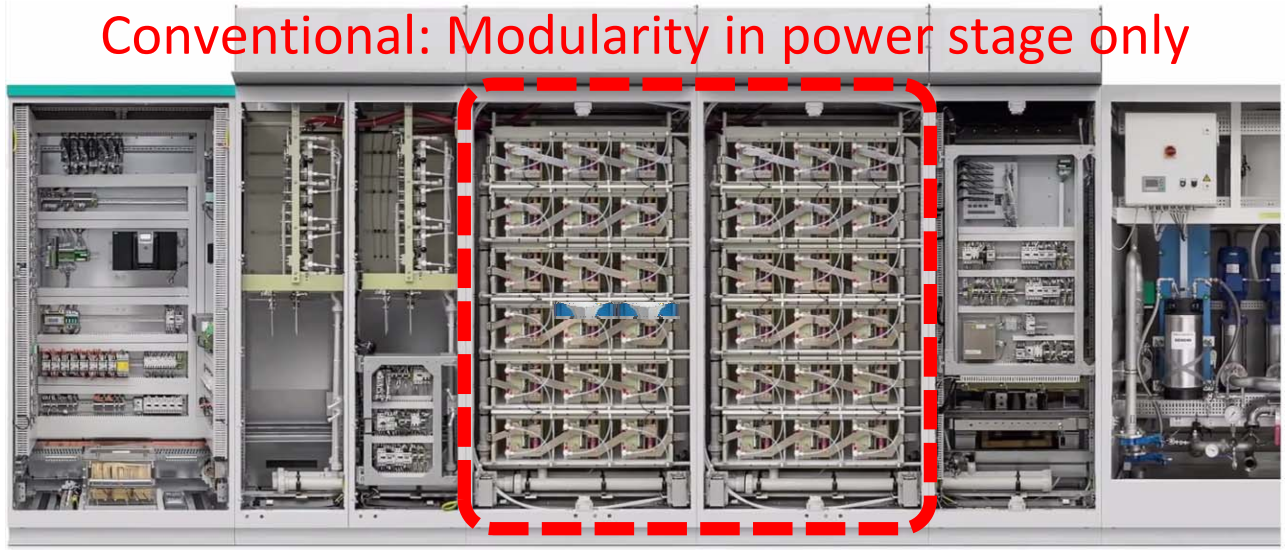


New-Generation PEBB Design

State-of-the-Art PEBB (1990's)

"A universal power processor":

- Si IGBT based technology
- Modular power stage
- Scalable in voltage & current
- Low cost for easy production



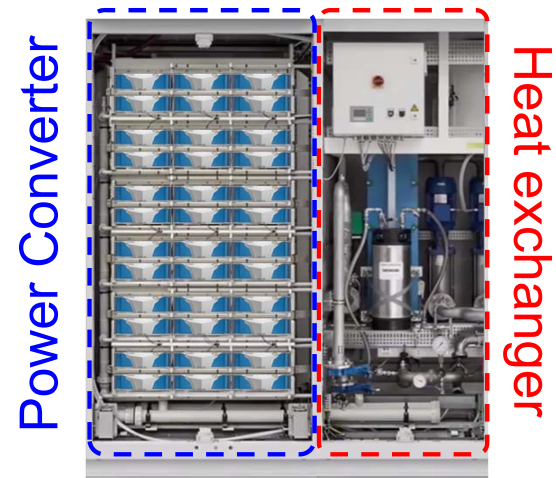
switching frequency ≈ 1 kHz

New-Generation PEBB (2010's)

"ONE" PEBB (LRU) for all converters on a ship:

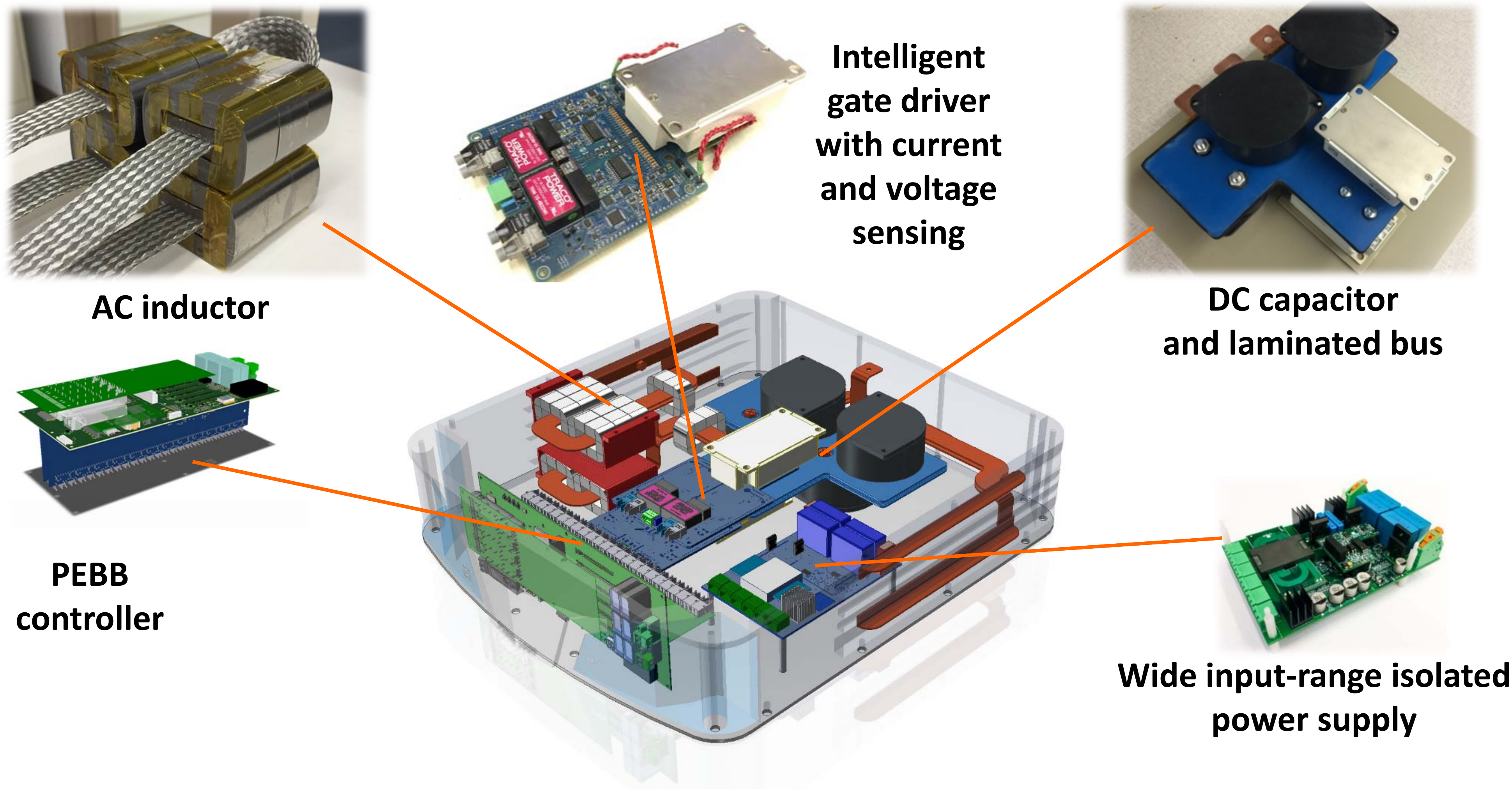
- Merits of the state-of-the-art PEBB
- with SiC MOSFET based technology
- + Modular & distributed controls
- + Modular integrated protection
- + Low sensitivity to parasitics & EMI
- + Integrated redundancy reconfiguration for high reliability

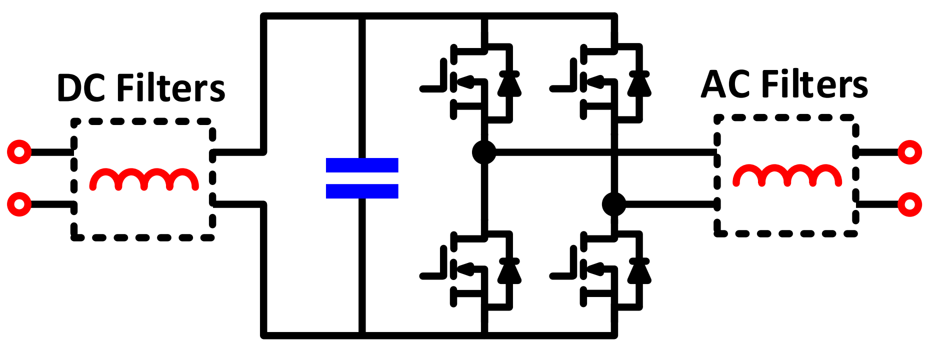
5x smaller, 50x faster



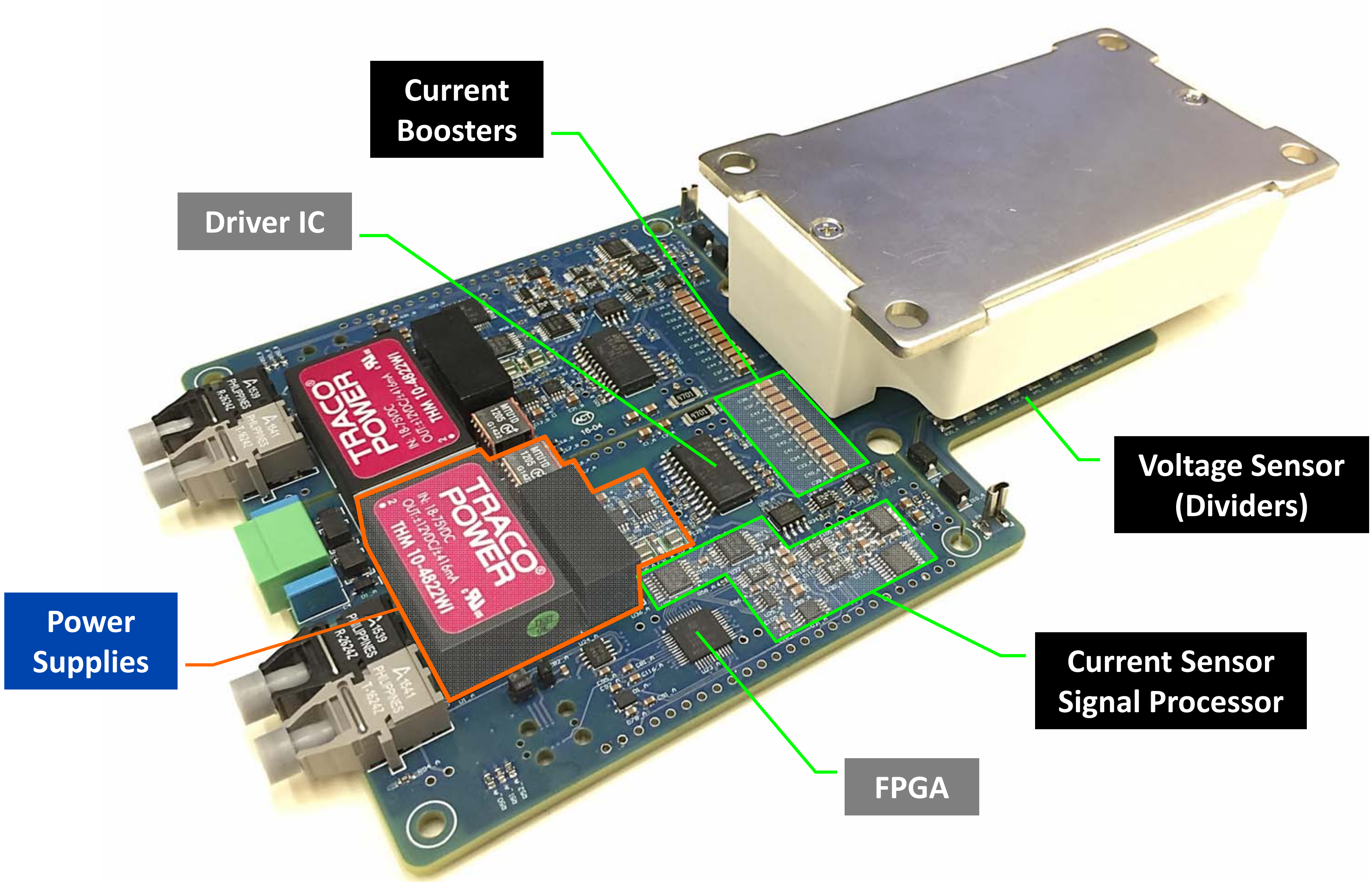
sw. freq. ≈ 100 kHz

SiC PEBB 1000: 100 kW, 100 kHz

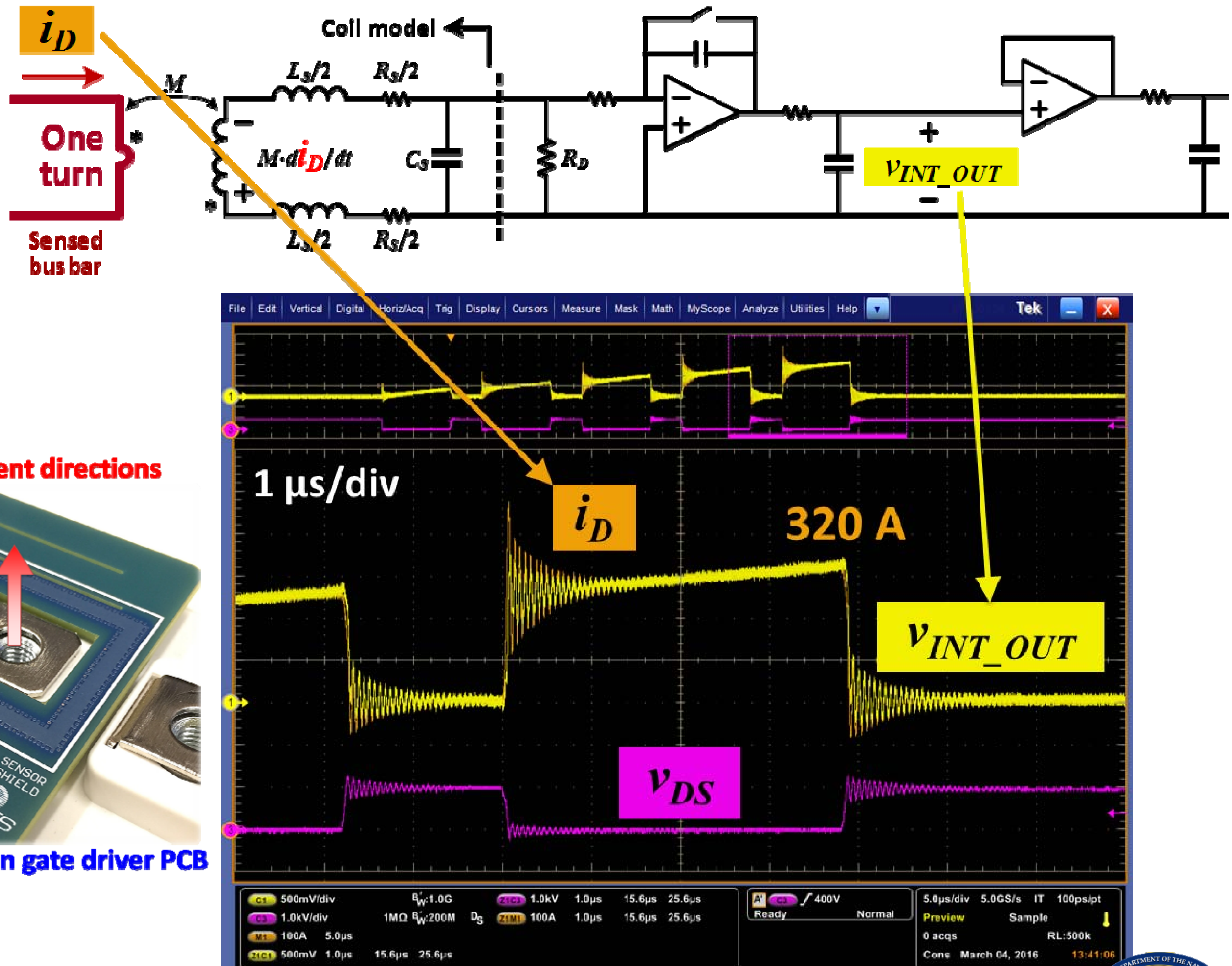




Intelligent Gate Driver for SiC Modules

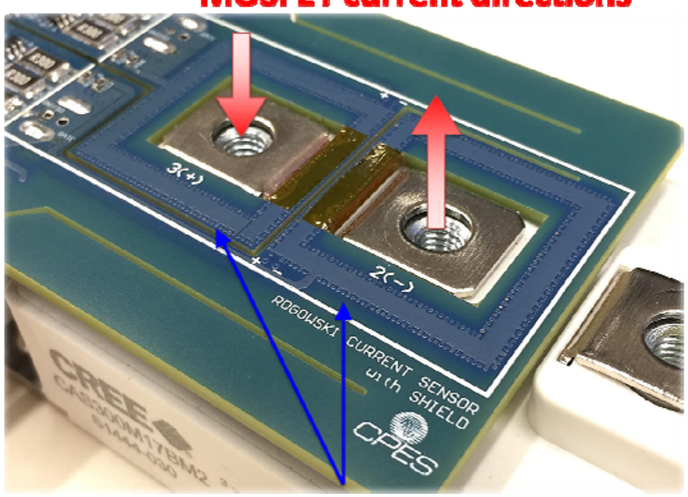


Sensing the device current will allow for faster overcurrent protection and control.



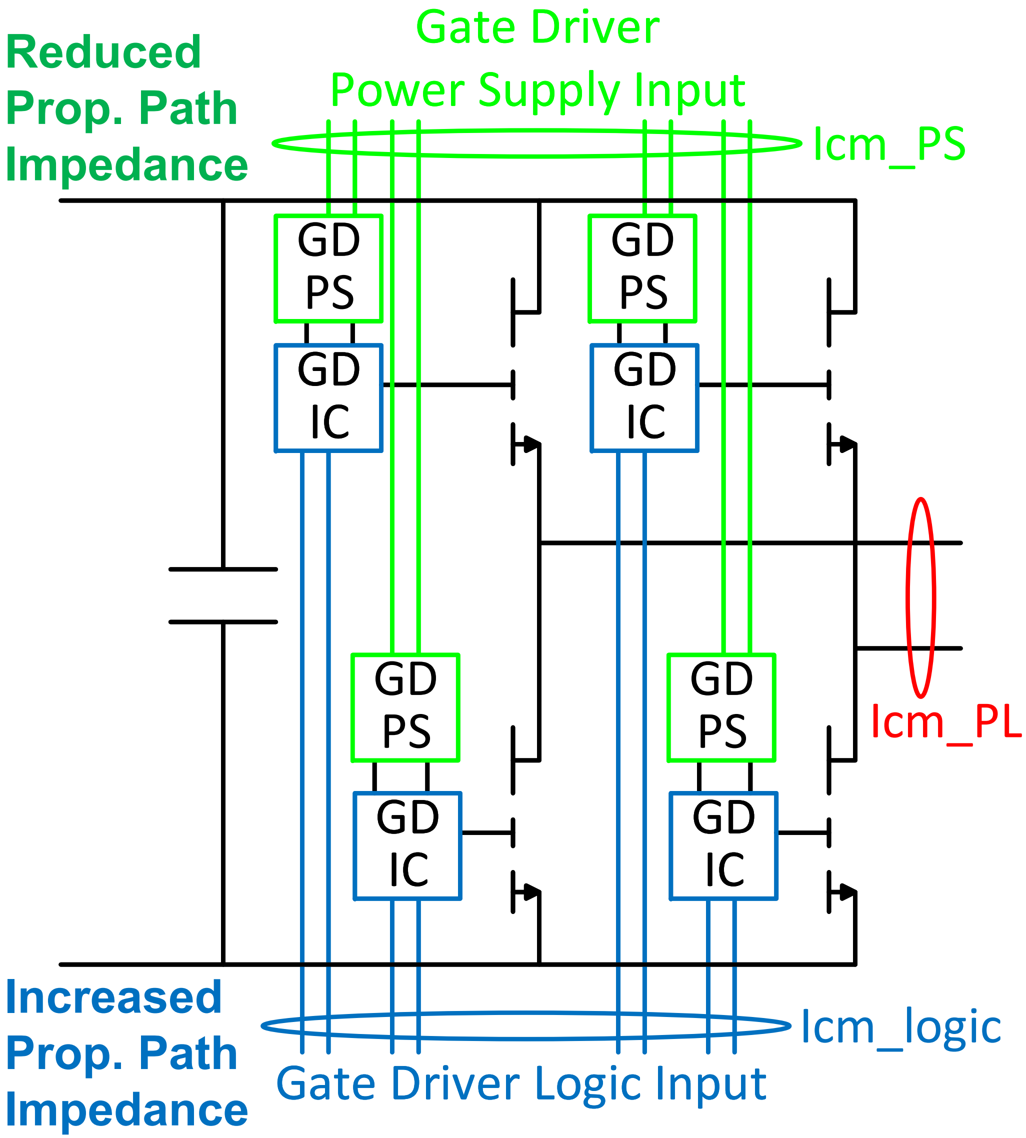
Cree **SiC MOSFET** CAS300M17BM2

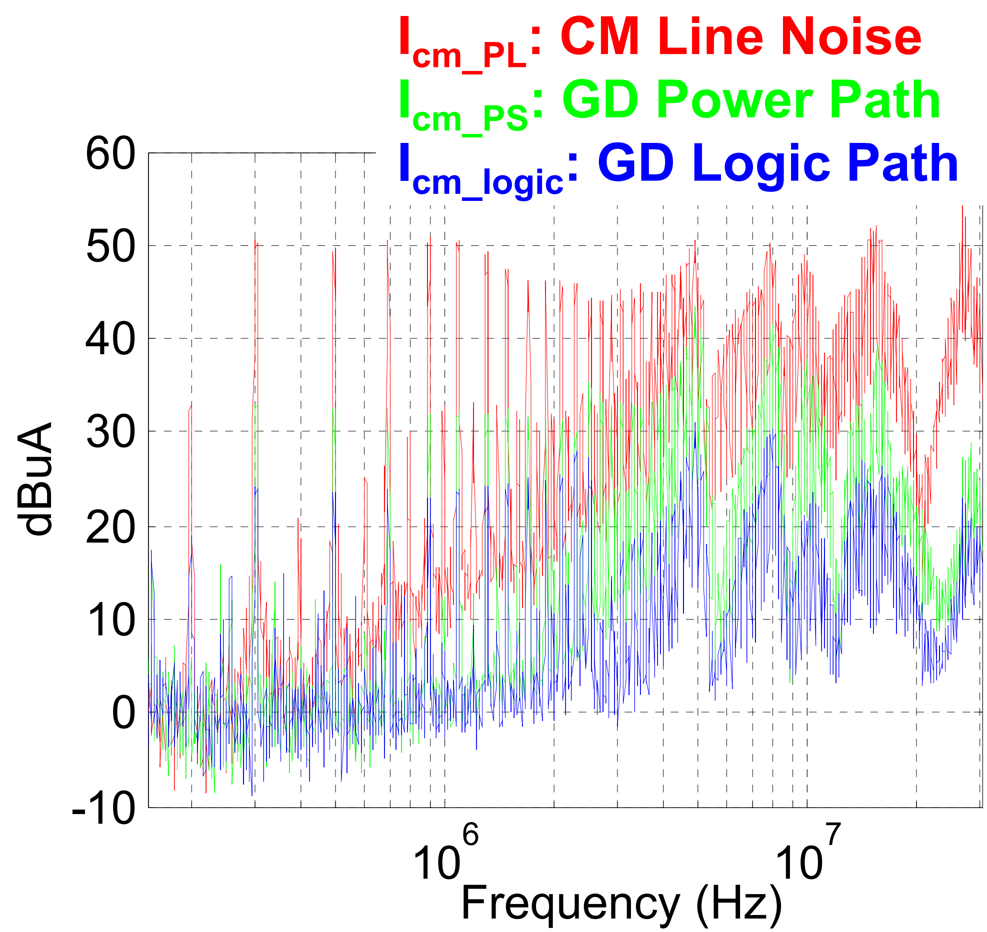
MOSFET current directions



Rogowski coils embedded in gate driver PCB

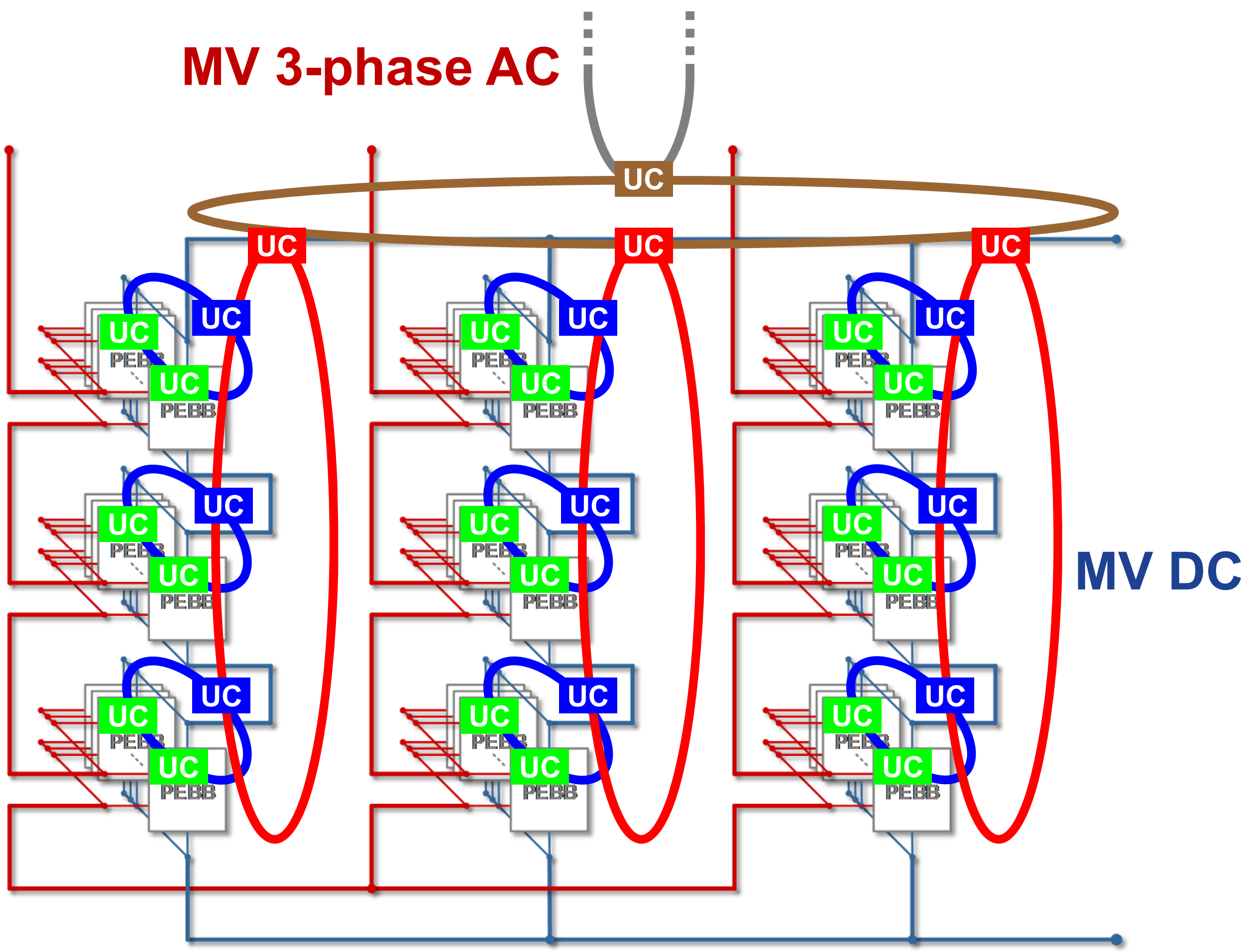
Reducing Control Logic Sensitivity to CM EMI





- **CM noise in all three paths have the same profile.**
- **GD PS path has higher CM noise than GD logic path due to CM noise propagation control design.**

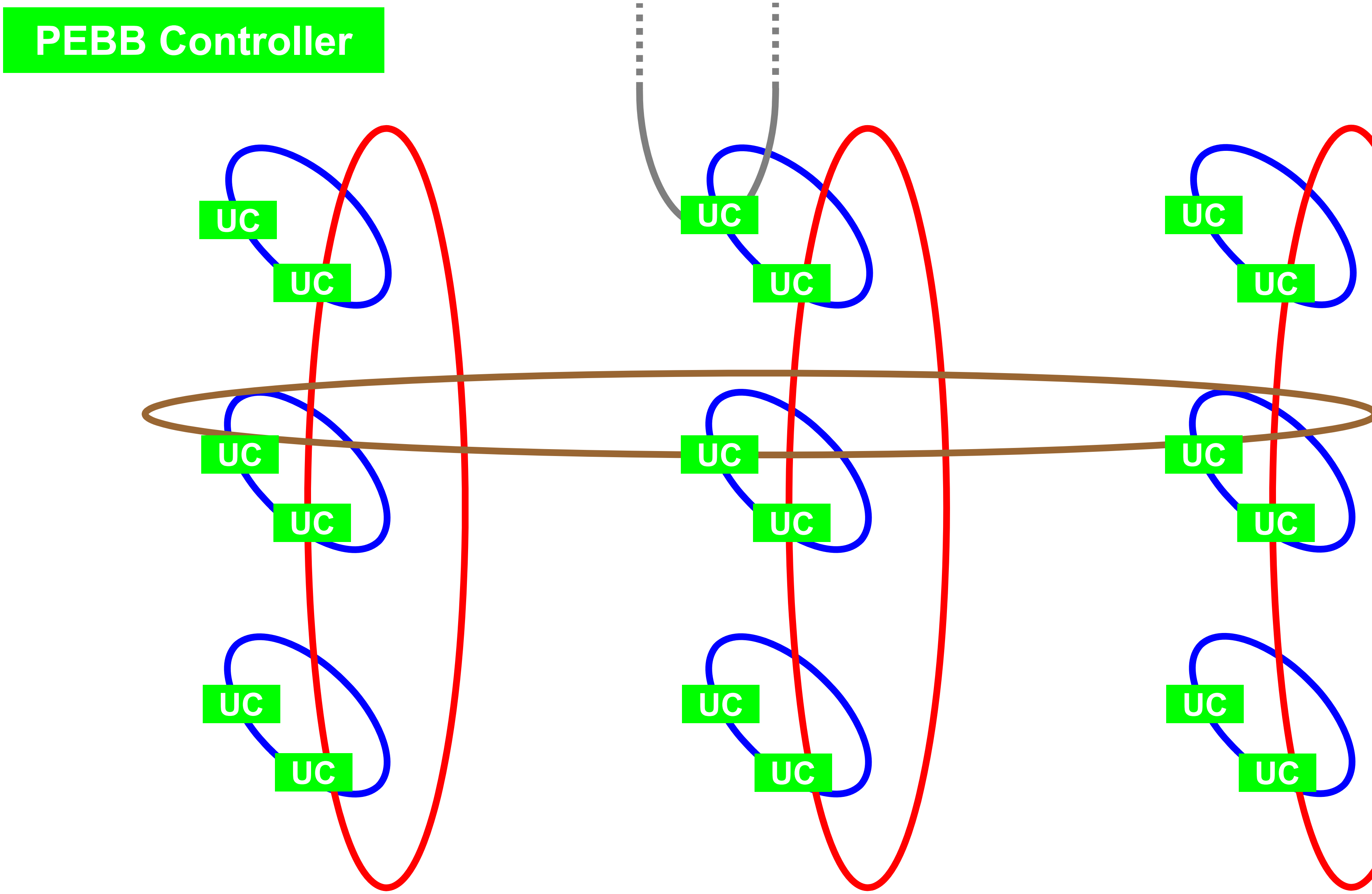
Scalable PEBB-based Converter with Distributed Hierarchical Control



Scalable PEBB-based converter

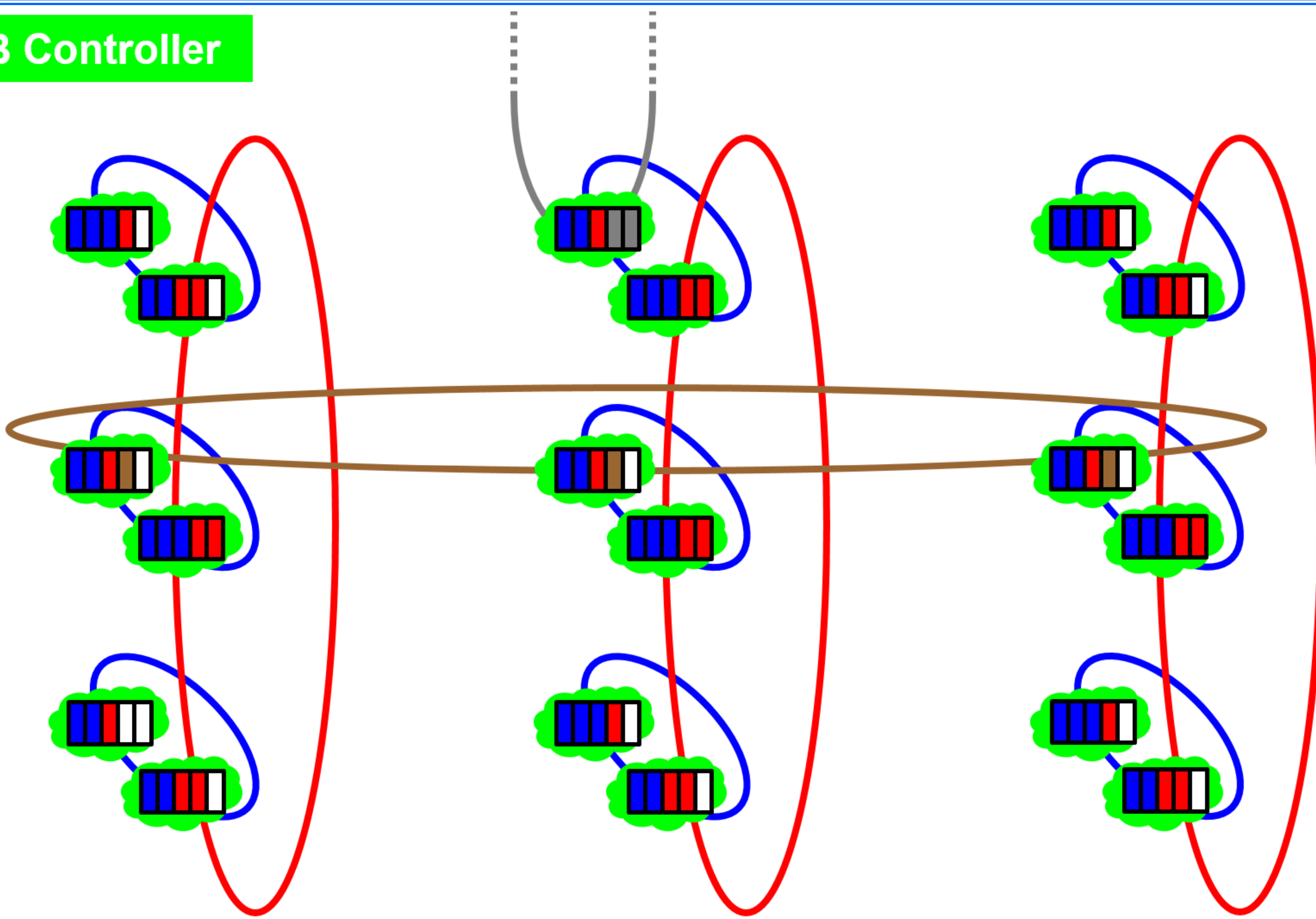
- Mission Control
- Converter Control
  - Multi-phase coordination
  - Application specific control (E.g. Motor control)
- Stacking Control
  - Voltage balancing
  - Output voltage / current control
- Paralleling Control
  - Current balancing
- PEBB Control
  - Gate signal generation
  - Local high frequency control (> f_{sw})
  - Fast local protection

Software Defined Controller



Software Defined Controller

PEBB Controller

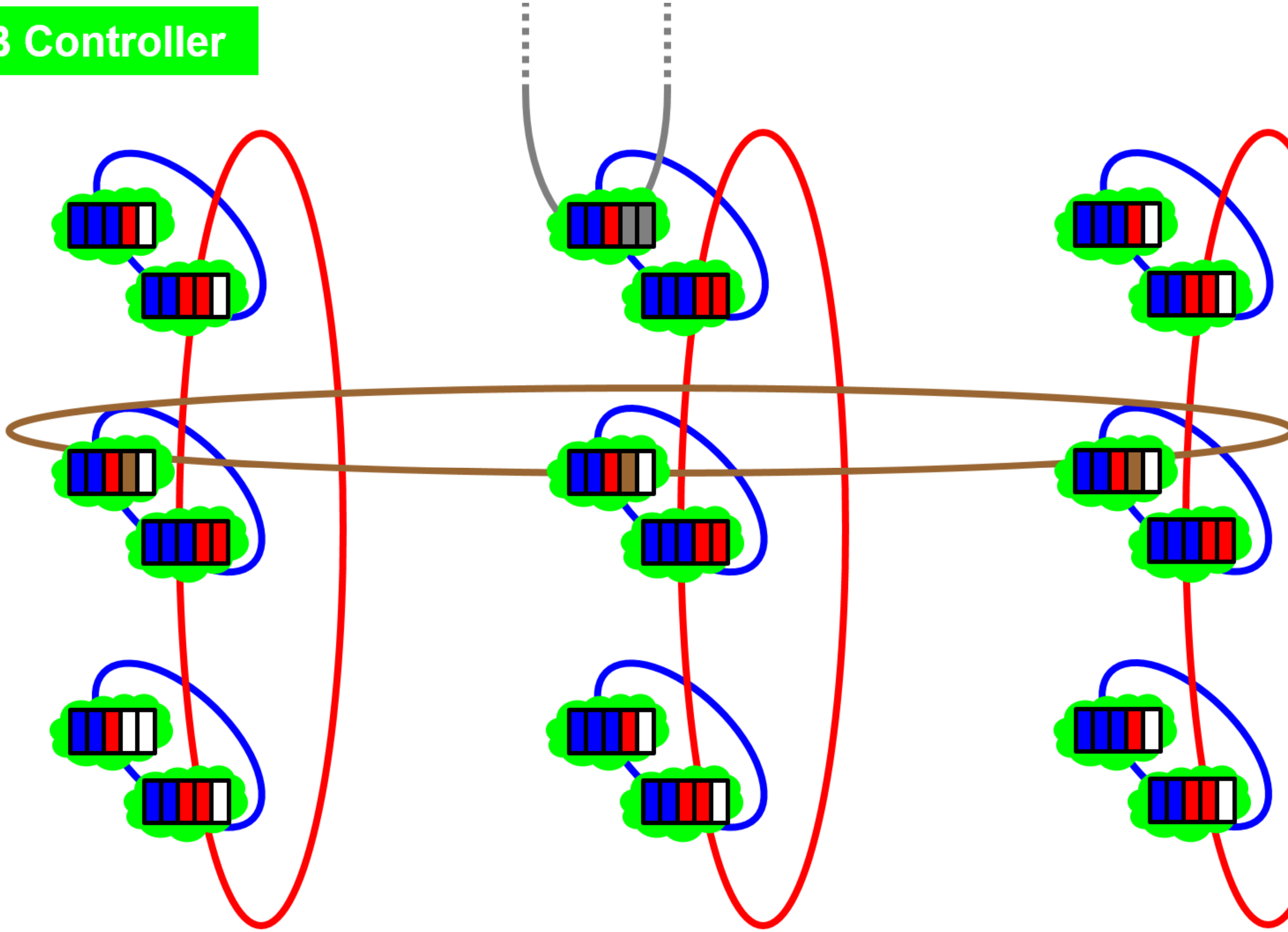


Secured Code

Paralleling Controller | Stacking Controller | Converter Controller | Mission Controller

Software Defined Controller

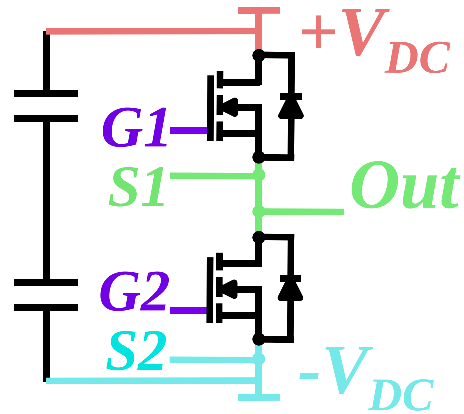
PEBB Controller

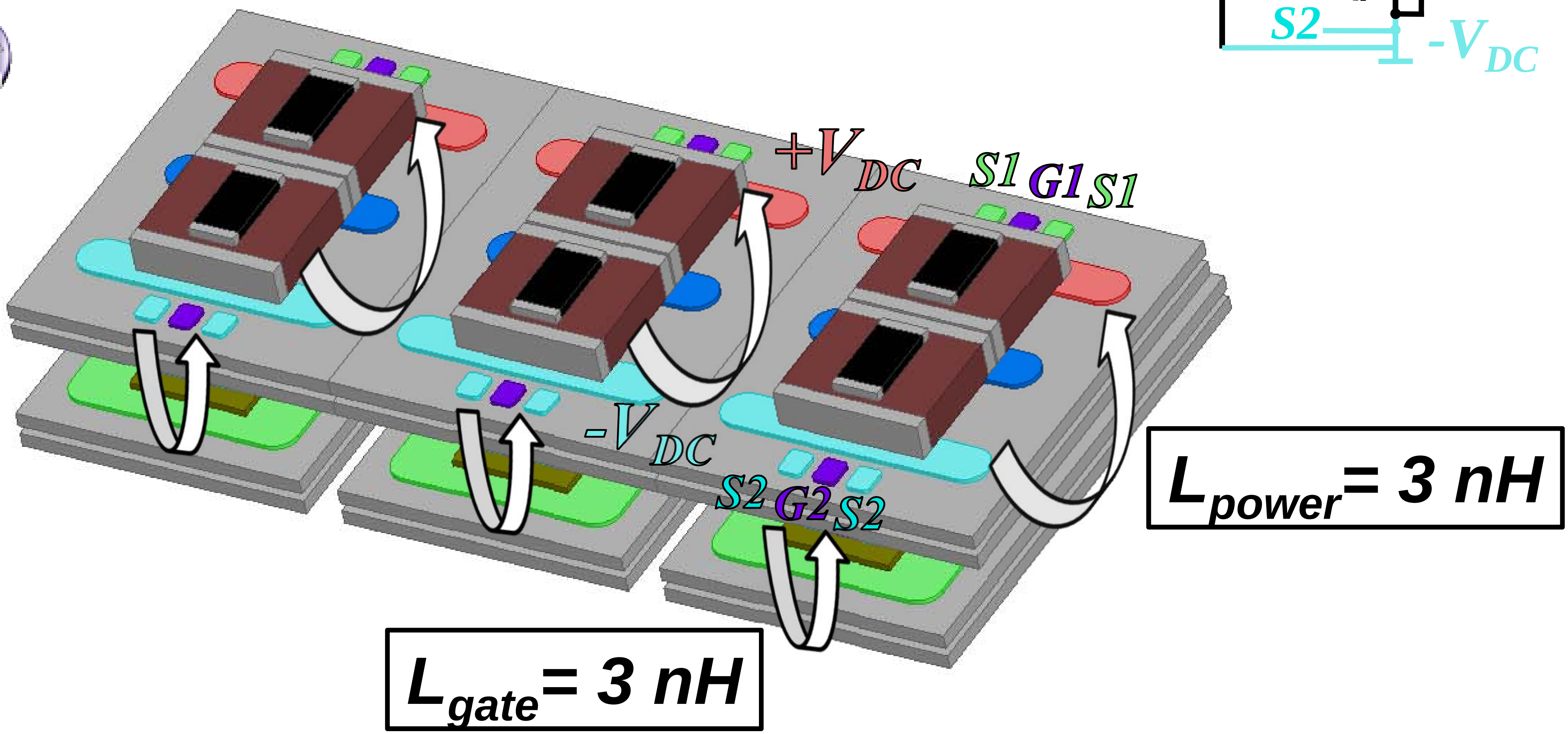


Cloud based Code Execution

SiC power module design for HF, HV, and scalability.

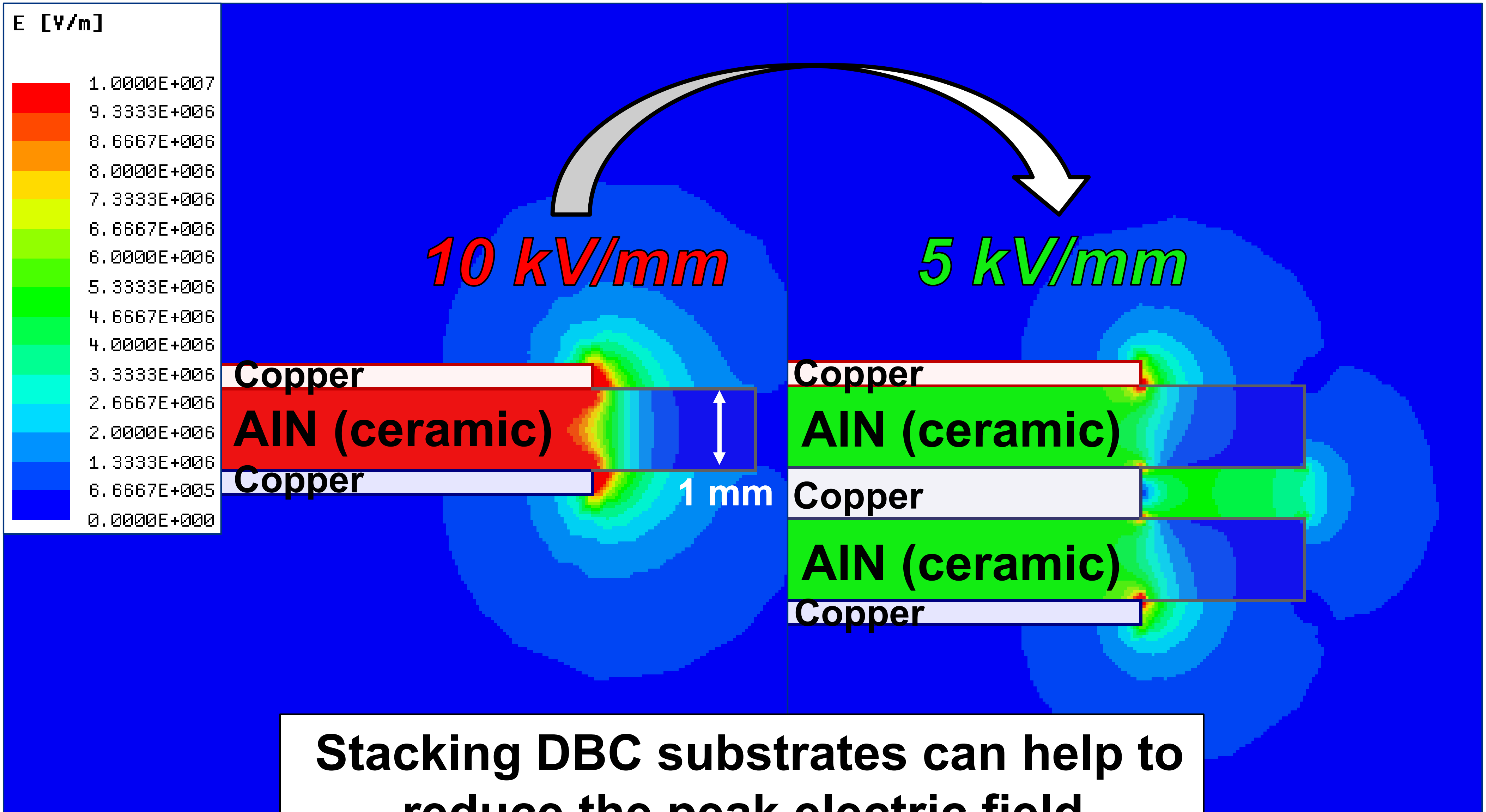
- **Each MOSFET pair** has its own **gate** and **power loop.**
- **Decoupling capacitors** are integrated in the module to **shorten the commutation loop**.





20 mm x 35 mm each.

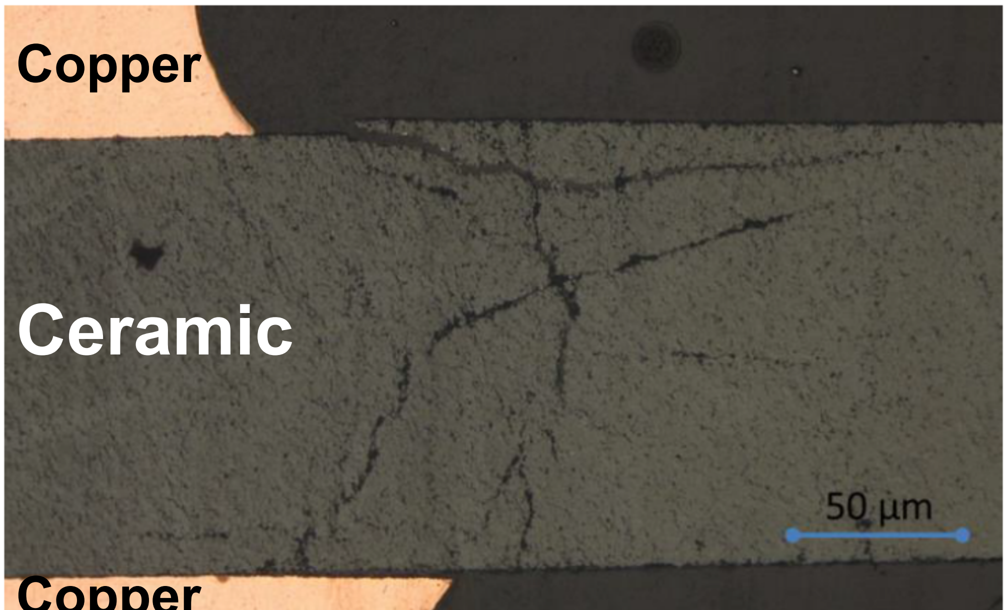
Finite element analysis (FEA) tools can be used to simulate the electric fields.



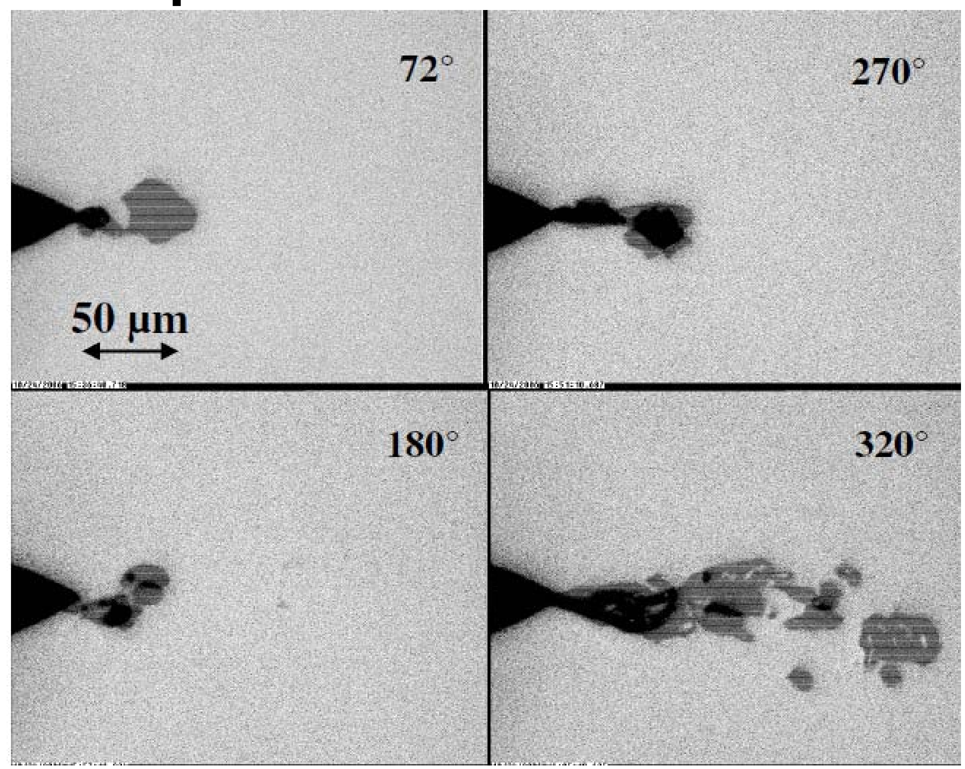
Stacking DBC substrates can help to reduce the peak electric field.

High electric field concentration can result in partial discharge and ultimately breakdown.

Repeated partial discharge stress can create **cracks** in the ceramic of direct bonded copper (DBC) substrates.



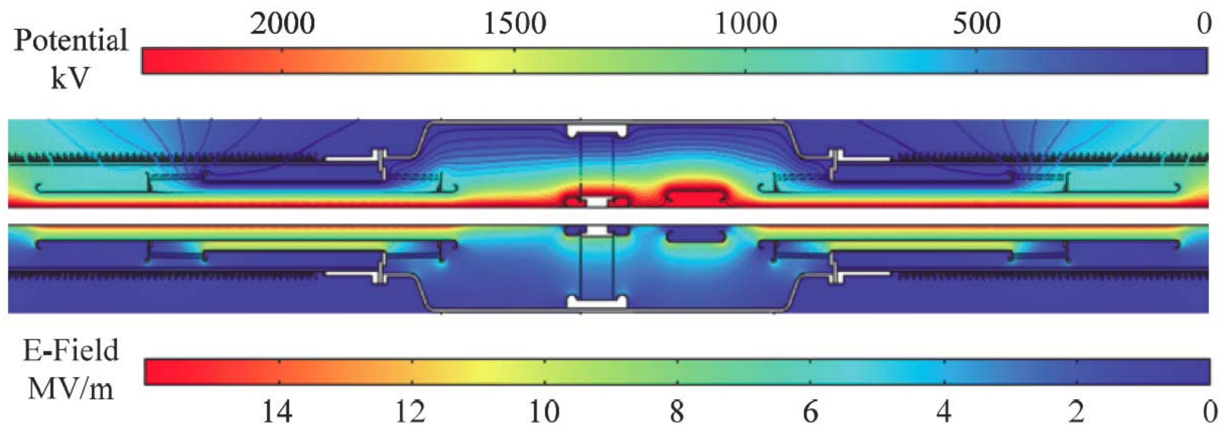
AC voltages can cause **bubbles to form continuously** in encapsulants, ultimately causing **permanent destruction.**



C. Bayer, et al., "Enhancing partial discharge inception voltage of DBCs by geometrical variations based on simulations of the electric field strength," IEEE CIPS, 2016.
M. Do, et al., "Partial discharges and streamers in silicone gel used to encapsulate power electronic components," IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2007.

How to Interconnect High-density Apparatus?

Electric Field Distribution in SF6 gas insulated HVDC wall bushing



- **Avoid air as insulator?**
  - **New architectures (without bushings)?**
    - **New materials?**