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CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Opportunities and Challenges of Next Generation Power Electronics for Grid Applications

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THE UNIVERSITY OF TENNESSEE KNOXVILLE | Northeastern | Rensselaer | TUSKEGEE UNIVERSITY

Outline

- Grid power Electronics Overview and Emerging Needs
- WBG Semiconductors and Opportunities
- New Challenges and Research Needs

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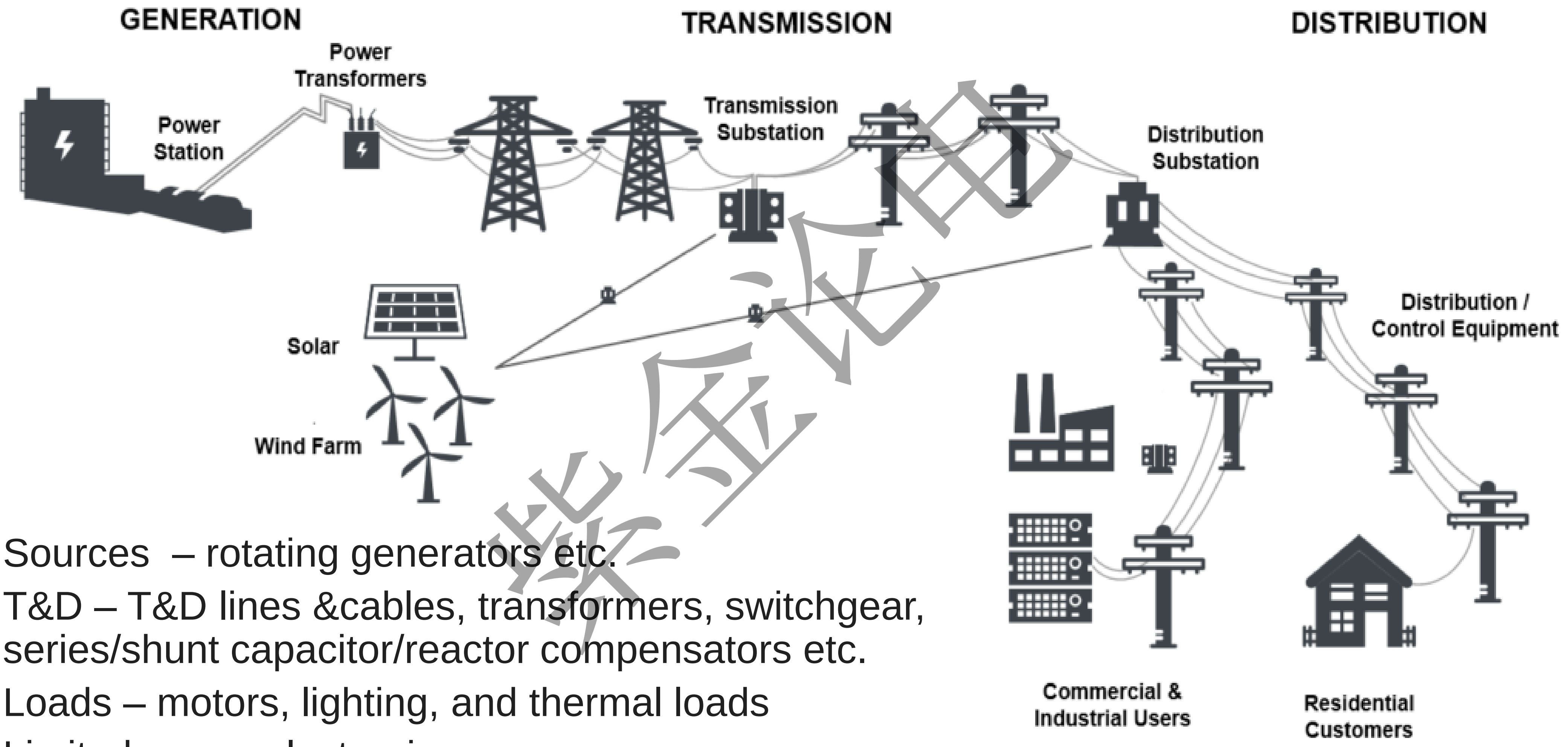
Conventional Power Grid Equipment



- Sources – rotating generators etc.
- T&D – T&D lines &cables, transformers, switchgear, series/shunt capacitor/reactor compensators etc.
- Loads – motors, lighting, and thermal loads
- Limited power electronics

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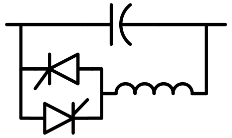
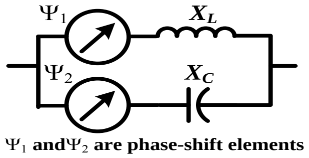
Power Electronics for AC Transmission – FACTS

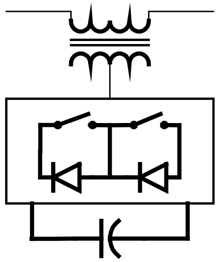
- **Series connected compensators)**



TCSC

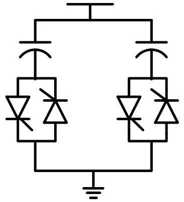


IPC

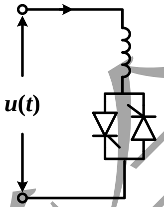


SSSC

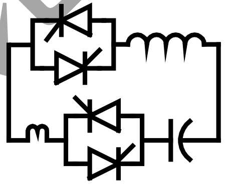
- **Shunt connected compensators)**



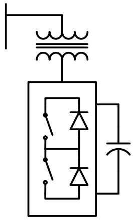
TSC



TSR

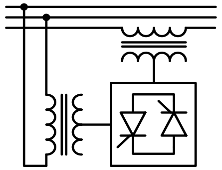


SVC

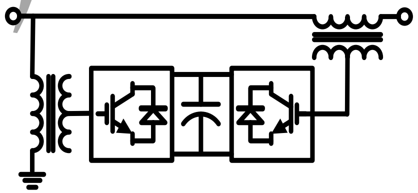


STATCOM

- **Series and shunt connected compensators**



TCPST



UPFC

Conventional FACTS based on thyristor technology, with limited performance and capabilities

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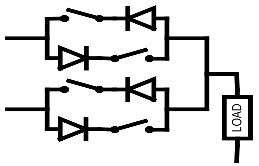
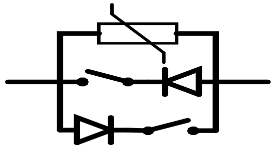
Power Electronics for AC Distribution – Custom Power

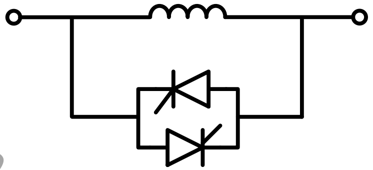
- Power flow control and interruption



SSTS

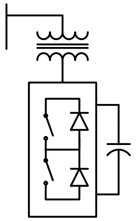


SSCB

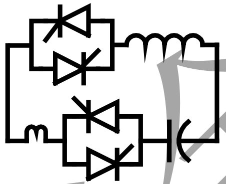


SSFCL

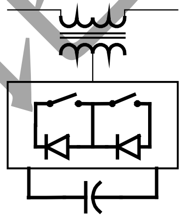
- Power system conditioning and compensation



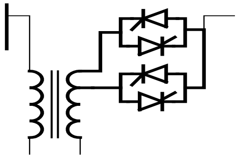
DSTATCOM



SVC

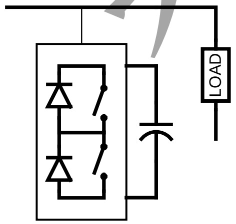


DVR

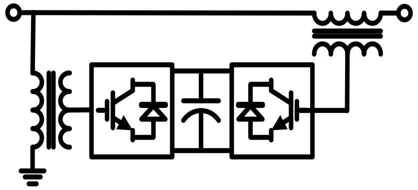


TCVR

- Power quality enhancement



Shunt AF



UPQC

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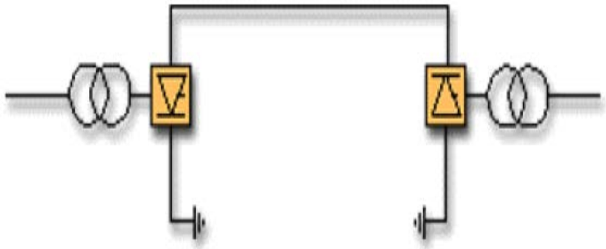
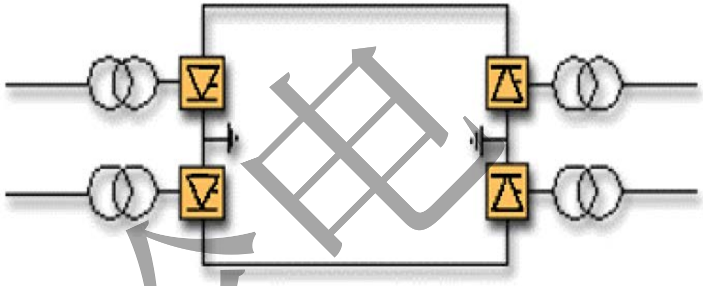
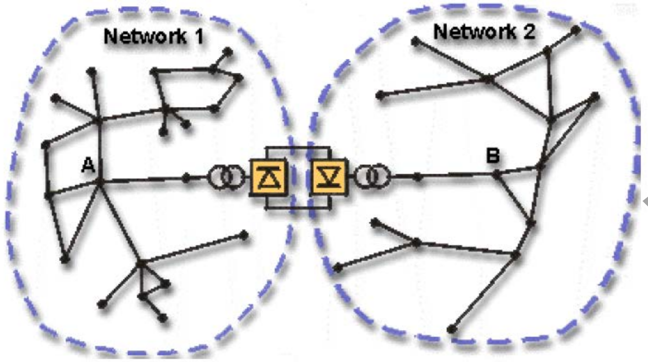
High Voltage DC (HVDC) Transmission

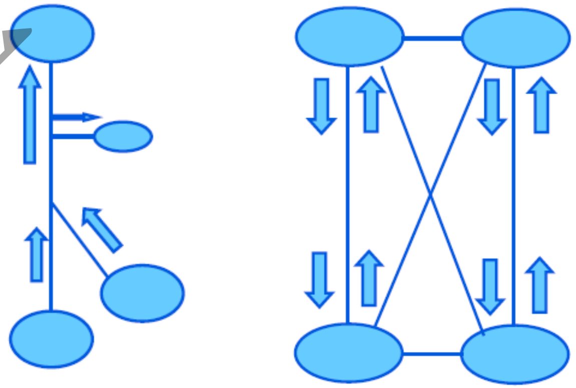
- Point to point transmission





- Back-to-back system
- Multi-terminal system





HVDC more economical for long-distance transmission; HVDC can decouple dynamics of AC systems, benefiting system stability and protection

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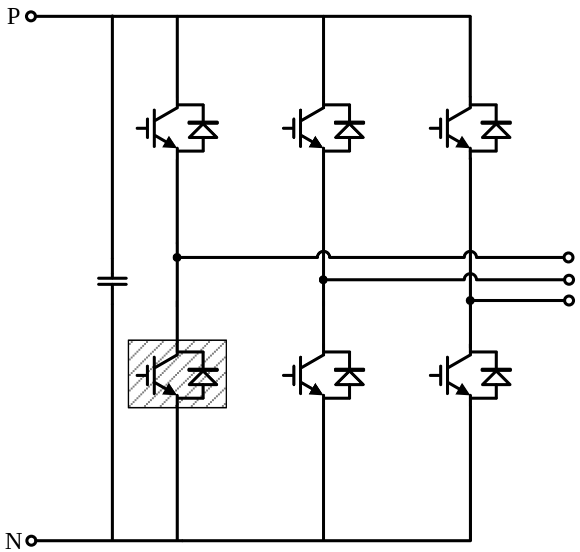
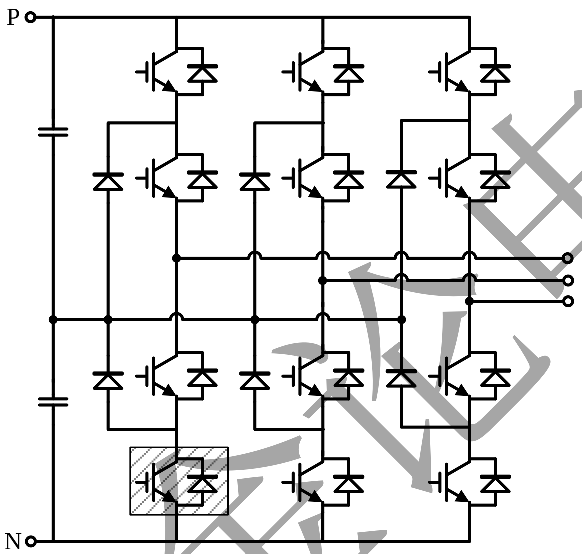
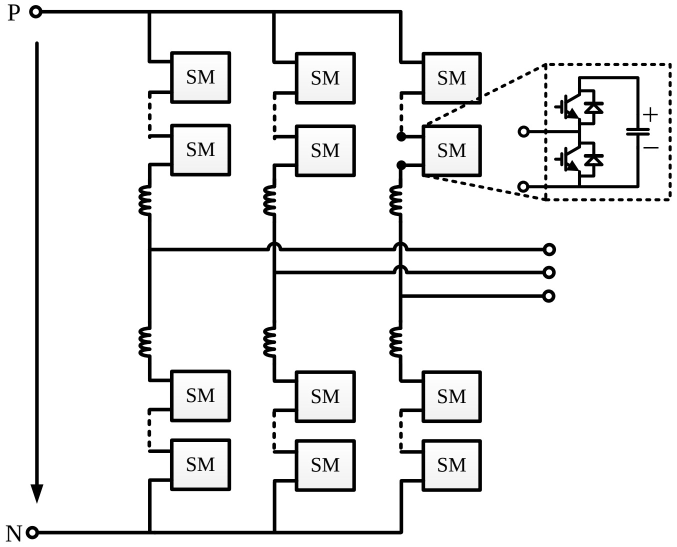
HVDC Technology Evolution: VSC Topologies



Two-level



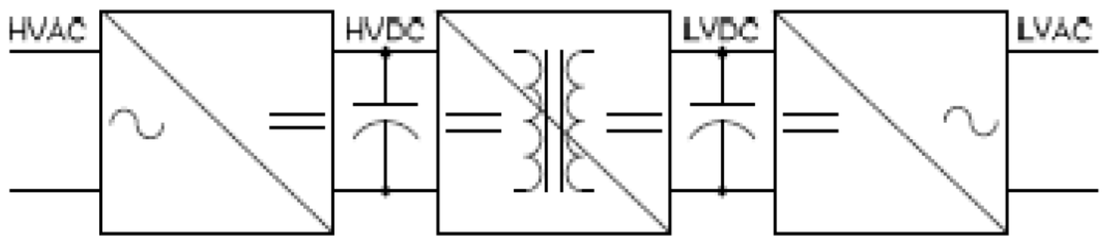
Three-level (NPC)



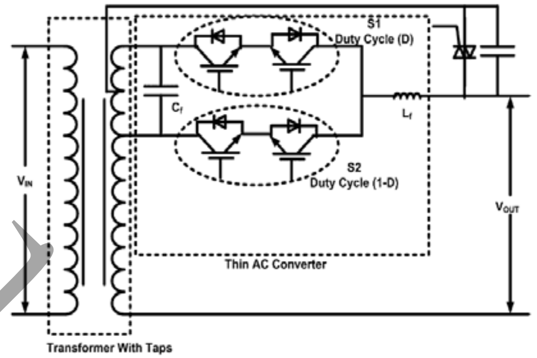
Modular multi-level converter (MMC)

- **VSC based on switching devices (IGBT/IGCT), with better performance than thyristor based LCC, and significantly converter station footprint and less right-of-way**
- **MMC latest generation of VSC topology: low loss, and avoid series devices.**

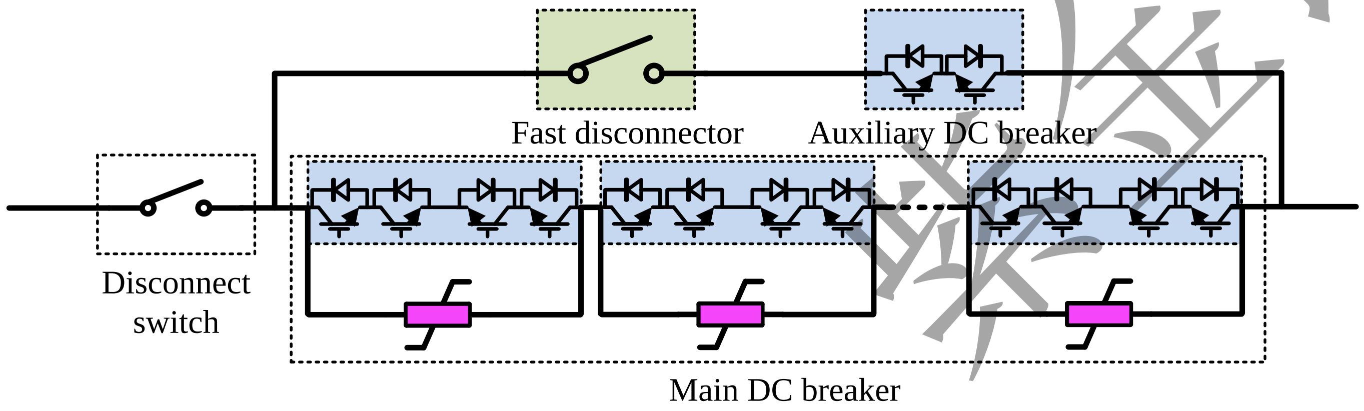
Grid Power Electronics – More Recent Development



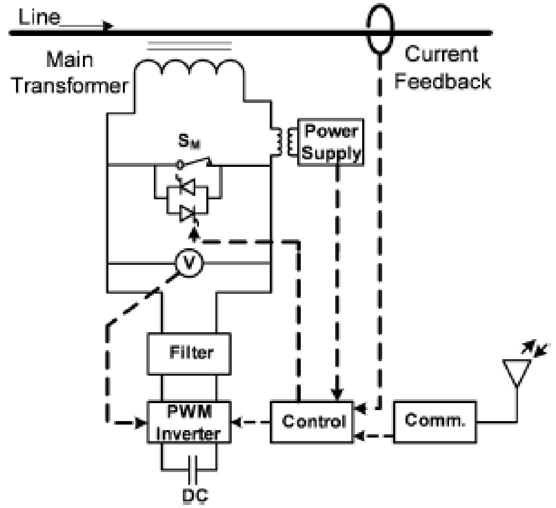
固态变压器
Solid-state Transformer



可控网络变压器
Controllable Network Transformer



混合型直流断路器
Hybrid DC Circuit Breaker



分布式静态串联补偿器
Distributed Static Series Compensator

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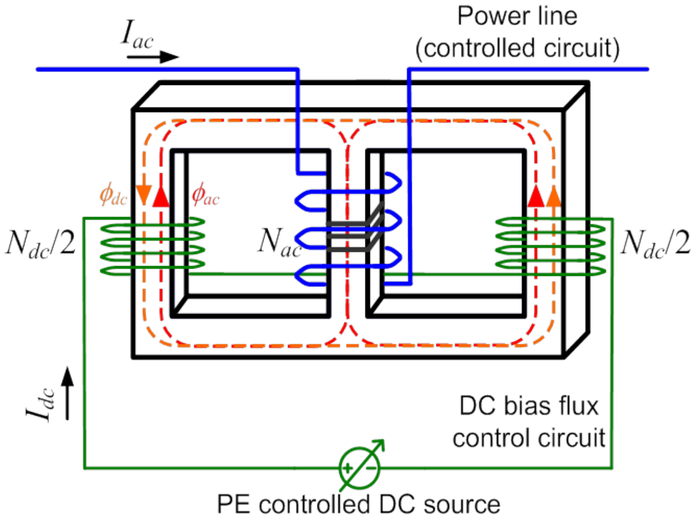
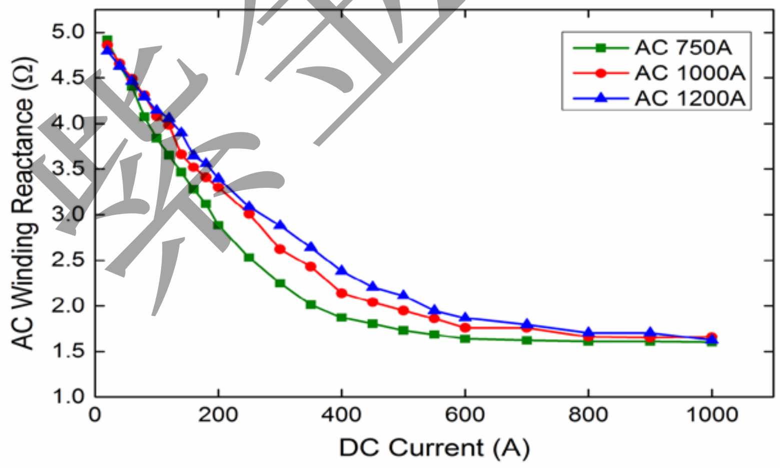
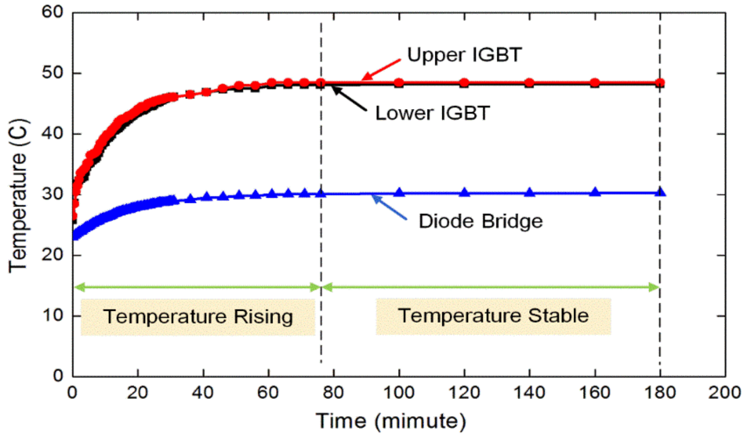
Grid Power Electronics – More Recent Development







Continuously Variable Series Reactor (CVSR)

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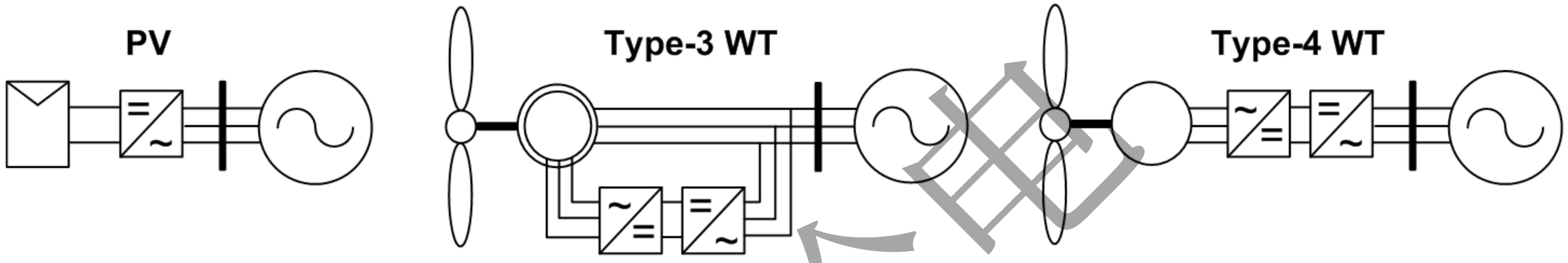
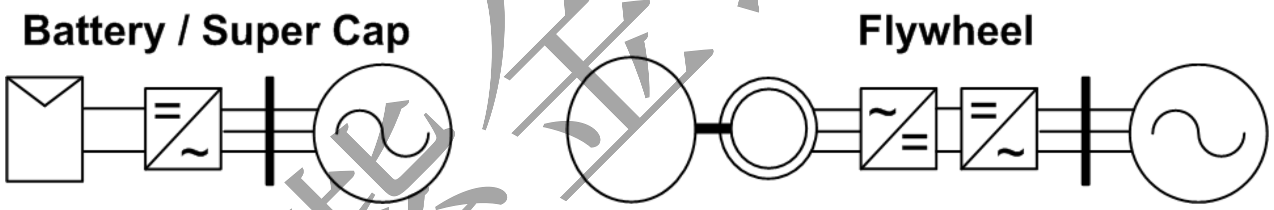
Grid Power Electronics – Emerging Needs

- Renewable energy source interface



- Energy storage systems



- Power electronic loads: data center, EV charging station, large motor drive
- Multi-terminal HVDC, microgrid (AC or DC)

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Needs, Challenges, and Opportunities

Needs	需求	新能源 (renewable energy sources)	电力电子负载 (power electronics loads)	直流电网 (DC grid)
Challenges	挑战	成本，体积，及可靠性 (cost, size, and reliability)	功能局限性 （limited functionality)	缺乏对系统影响的理解 (lack of knowledge on system impact)
Opportunities	机遇	新器件 (new semiconductor devices	控制及通讯技术 （Control and communication)	信息及数据技术 （IT & data science)

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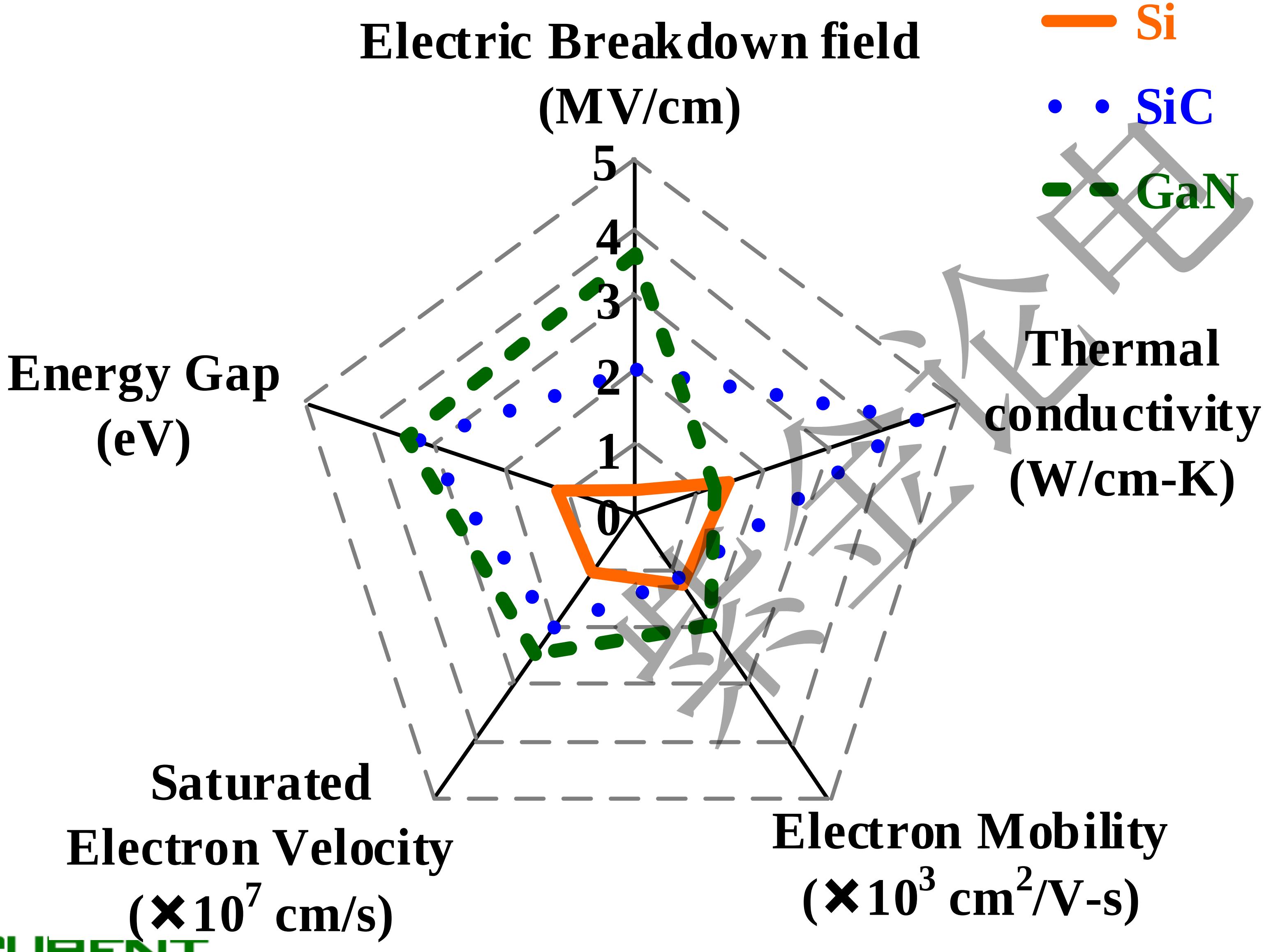
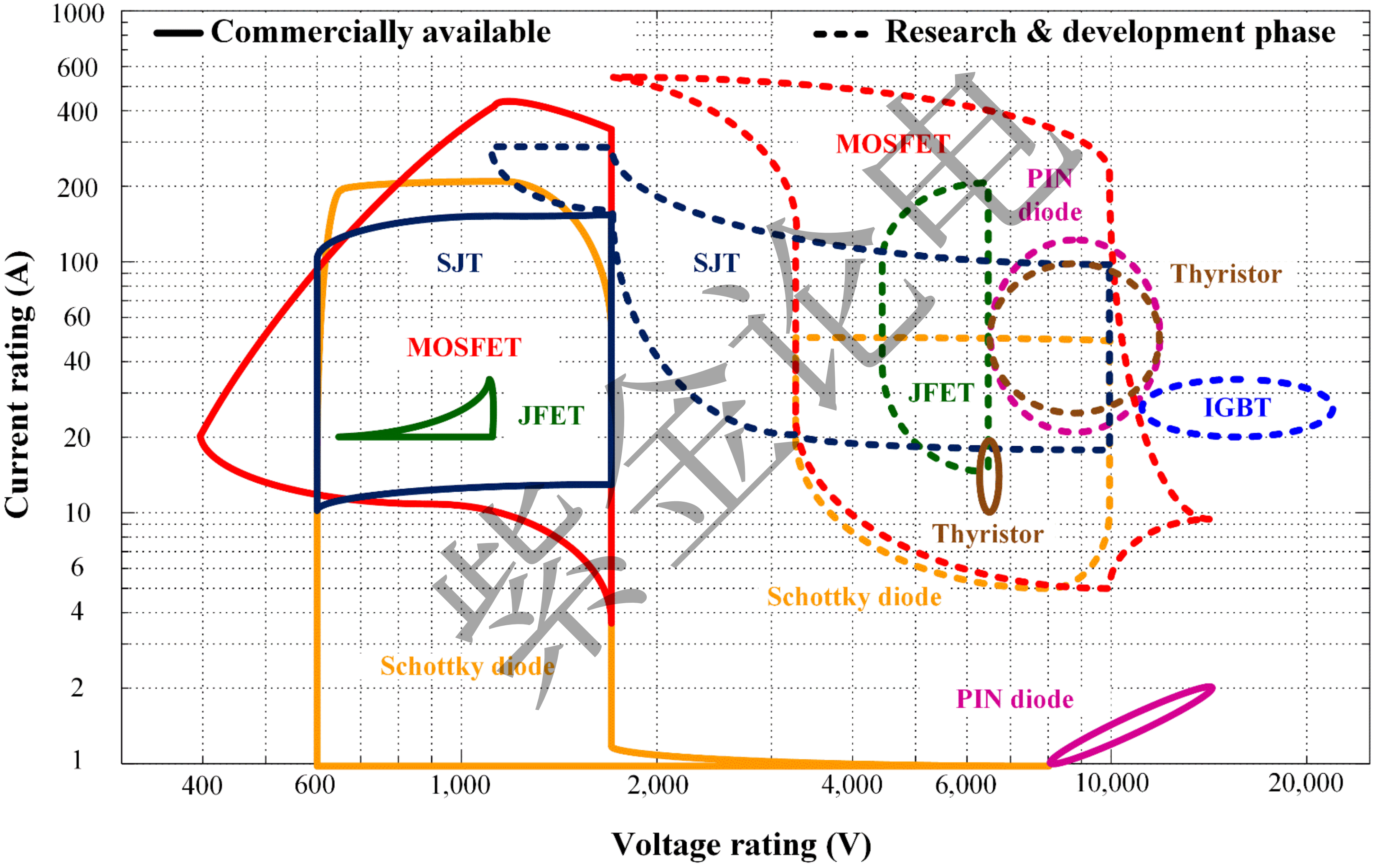
Properties of Wide Bandgap Semiconductors



- Low conduction loss
- High switching speed
- High voltage capability
- High temperature

[1] T. P. Chow, 2014.

State-of-the-art SiC Devices



(High Voltage) WBG Device Applications

❑ Wide band-gap (WBG) vs. Silicon

- High breakdown electric field, high voltage rating, low conduction loss
- Fast switching speed, high switching frequency
- Superior thermal characteristics

❑ Applications should take advantages of

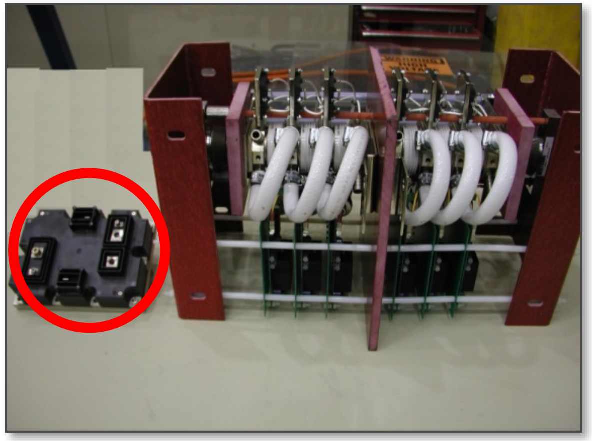
- Low loss
- Fast switching speed
- High frequency application

❑ Benefits of HV SiC can be realized in several ways

- Direct substitution – improved efficiency and power density
- Simplified topology – further loss reduction and increased power density
- Enable new capability and functionality for system-level
- Enable new applications or replace the non-PE equipment

<u>SiC vs. Silicon</u>

1MW Comparison of Switches



Wolfspeed 10 kV/240A SiC MOSFET

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WBG Potential Applications in Grid

- Improve the performance of the existing PE equipment
  - Efficiency improvement for all;
  - density improvement for some;
  - performance improvement (e.g. circuit breakers)
- Replace non-PE equipment
  - Solid-state Transformer,
  - solid-state circuit breaker/current limiter
- Enhance functionality/capability
  - Smart inverter
- Enable new applications
  - DC grid
  - high bandwidth conditioner
  - direct-tied PV inverter

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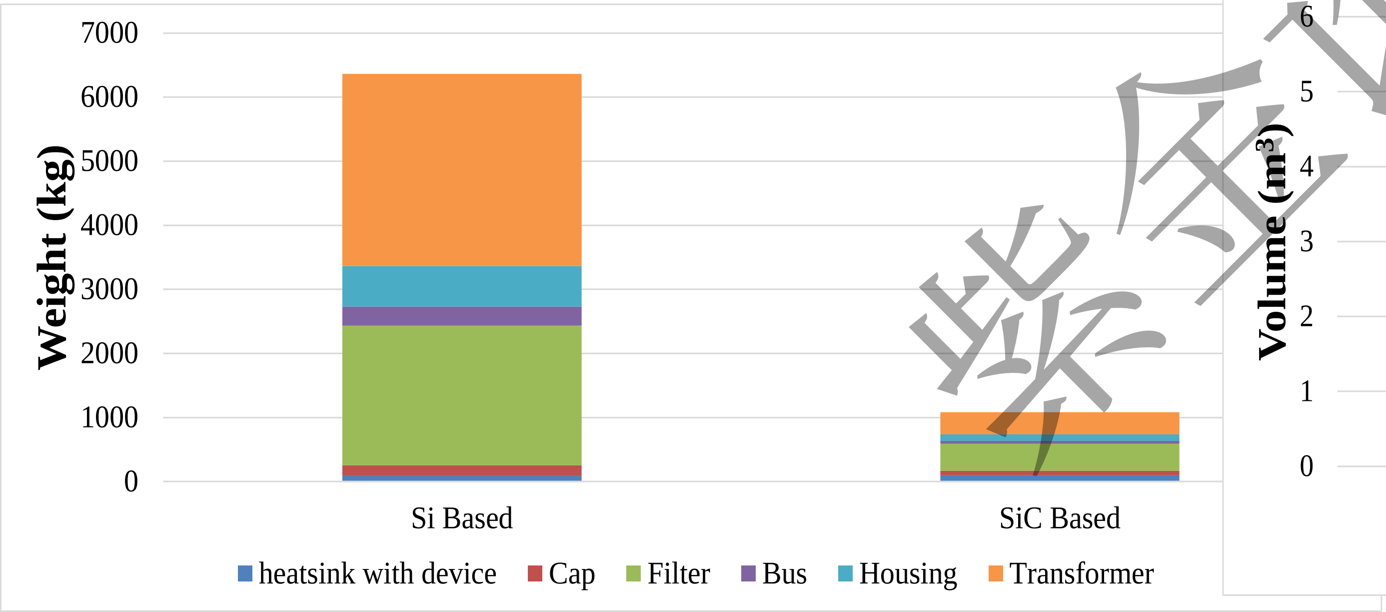
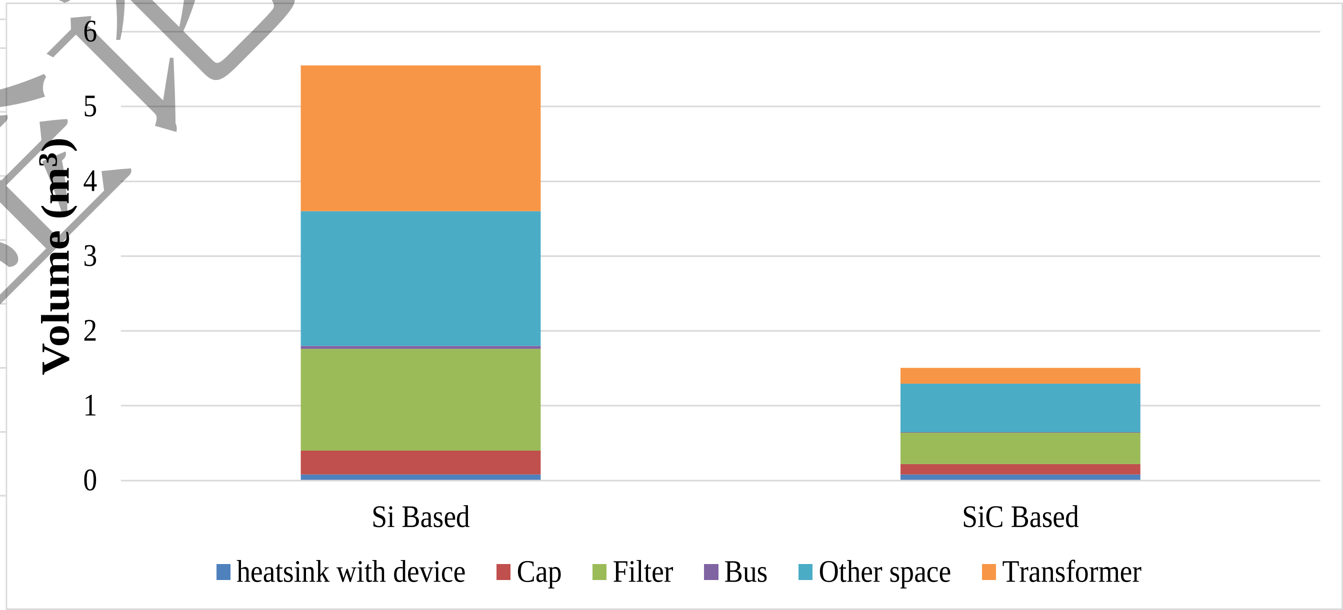
SiC Impact on PV Inverter

- Benchmark study on MV MW-class Si- and SiC-based PV converter design
  - Si solution: 2-level with LF transformer (commercial product)
  - SiC solution: 3-level NPC & DC/DC with HF transformer (ARPA-e)
- Converter comparison
  - Weight is reduced by 82.9% (1,088 kg for SiC vs. 6,362 kg for Si)
  - Size is reduced by 73.2% (1.49 m^3 for SiC vs. 5.55 m^3 for Si)





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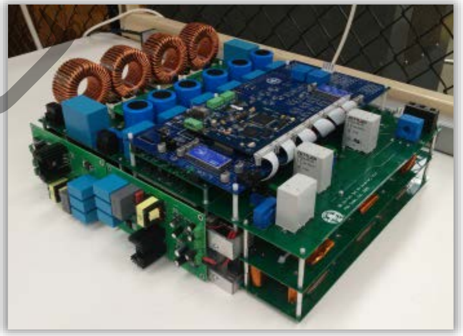
WBG Device Application

Hitachi 160 kW SiC PV inverter

- High voltage rating for higher power
- Low loss for higher efficiency/smaller heatsink
- Fast switching for passive reduction
- High temperature for cooling reduction

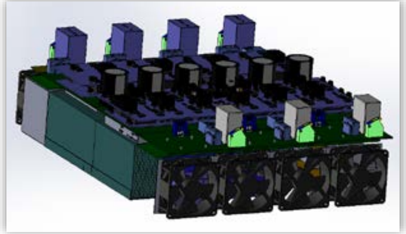
	Conventional Si inverter		Prototype SiC inverter
Semiconductor Device	Si-IGBT		SiC-MOSFET
Topology	2-level	3-level	2-level
Rating Capacity	100 – 750 kW		160 kW
Peak efficiency of the inverter	98.2% (measured)	97.7 - 98.8% [4,5]	Over 99.1% (measured)

3x Specific Power



FSU Gen-I SiC PV converter prototype (~2.5 kw/kg
99% peak efficiency

6x Specific Power



FSU Gen-II SiC PV converter conceptual design (~5 kW/kg)
99% peak efficiency

[1] S. Kouro, J. I. Leon, D. Vinnikov and L. G. Franquelo, in *IEEE Industrial Electronics Magazine*, March 2015
[2] S. Wall, R. h. Ruan, C. g. Wang and J. r. Xie, *EPE'16 ECCE Europe)*, Karlsruhe, 2016
[3]A. Hatanaka, H. Kageyama and T. Masuda, *INTELEC*, Osaka, 2015

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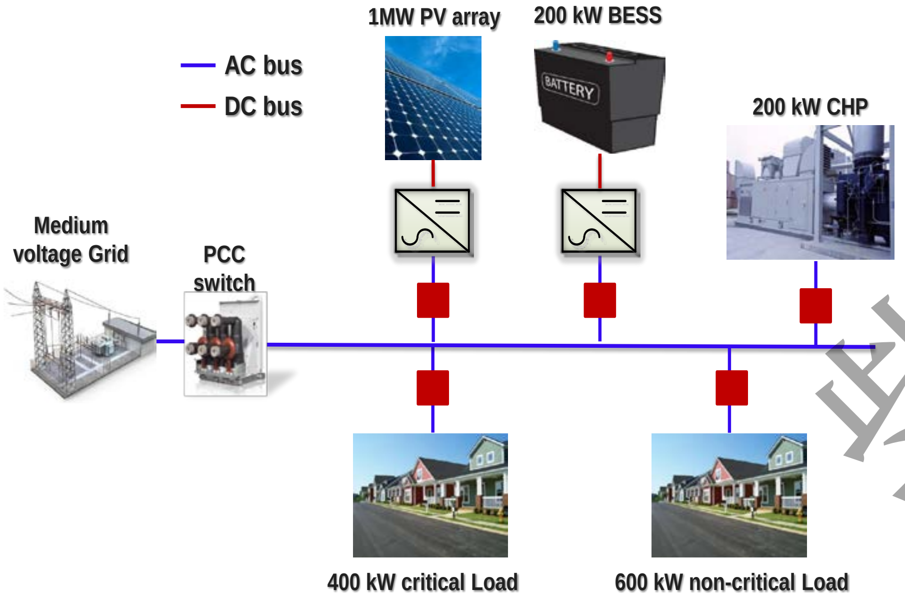
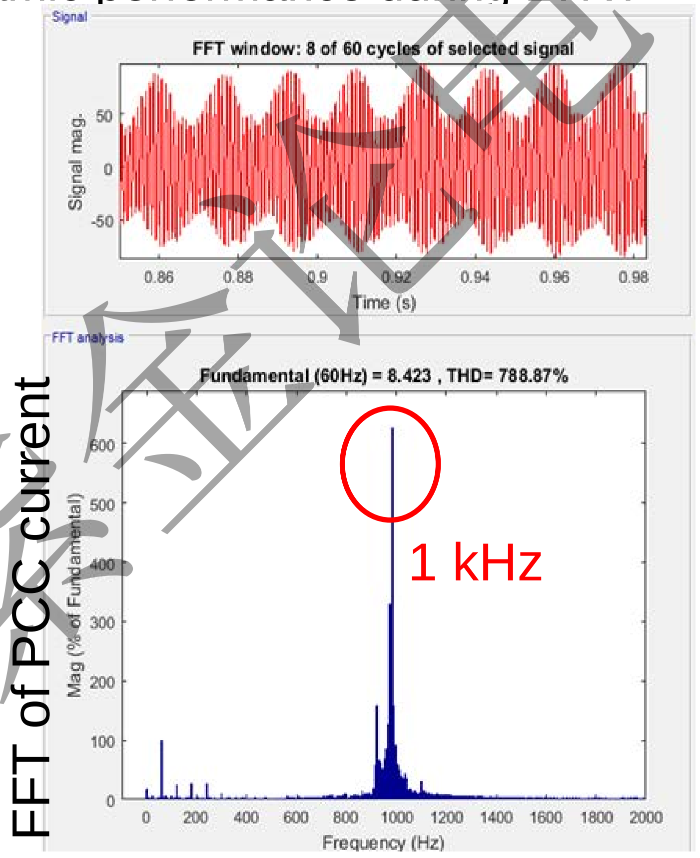
System Level Benefits of SiC-Based PV Converter

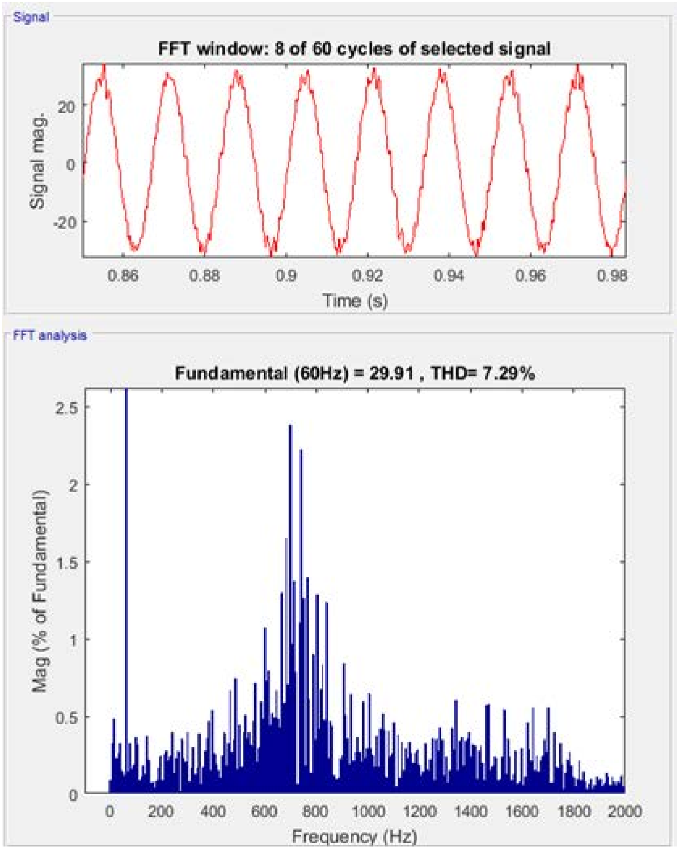
- Benchmark study on system level benefits of SiC-based PV converter
  - Active filter function with SiC-based PV inverter
  - System stability is improved with the higher control bandwidth enabled by MV SiC converter
  - SiC-based converter has better dynamic performance during LVRT



Configuration of MV microgrid



Si-based solution



SiC-based solution

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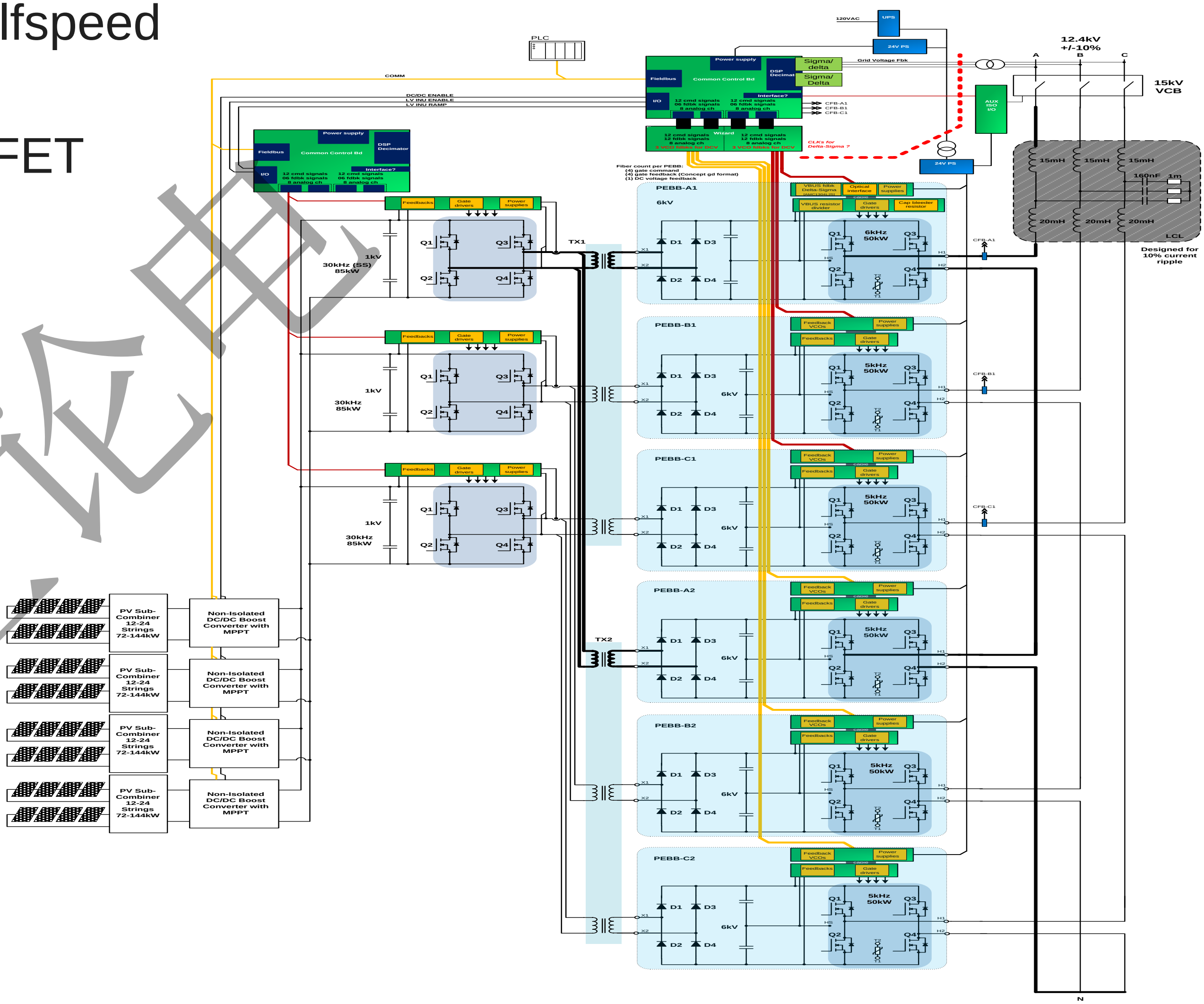
Utility-scale MV Transformer-less PV Inverter

- Supported by ARPA-e and collaborated with Wolfspeed and Danfoss
- 12.4 kV, 1 MW PV inverter with 10 kV SiC MOSFET



MW-scale MV PV inverter topology

HV SiC-enabled Solid-state Transformer

250 kVA, 20 kHz transformers (35-45 kg)

220 kVA/ 330 kVA, 60 Hz transformers

Prototype 1 MW, 4160-V AC/1000-V DC converter

Research Needs

WBG-based converter Issues due to fast switching, high dv/dt & di/dt, high voltage, high temperature, high power; unique grid application requirements

Converter	Scaling	Grid Condition Tolerance	Grid Support
• Device module & packaging • Gate drive & protection • Parasitics impact • Control • Passives & filters (dv/dt, di/dt, EMI etc.) • Thermal management • Insulation (dv/dt, lightning and switching overvoltage) • Reliability and management	• Device module series and paralleling • Converter stacking and paralleling • Modular topology	• Faults • Unbalance • Grounding • Fault detection and protection coordination	• Frequency and voltage support • Inertia emulation • Low voltage ride through • Stability enhancement • Active filtering • Black start

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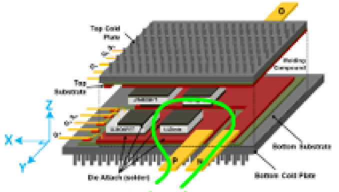
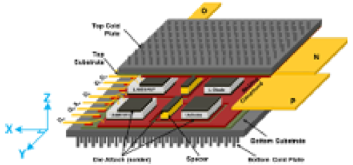
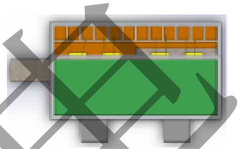
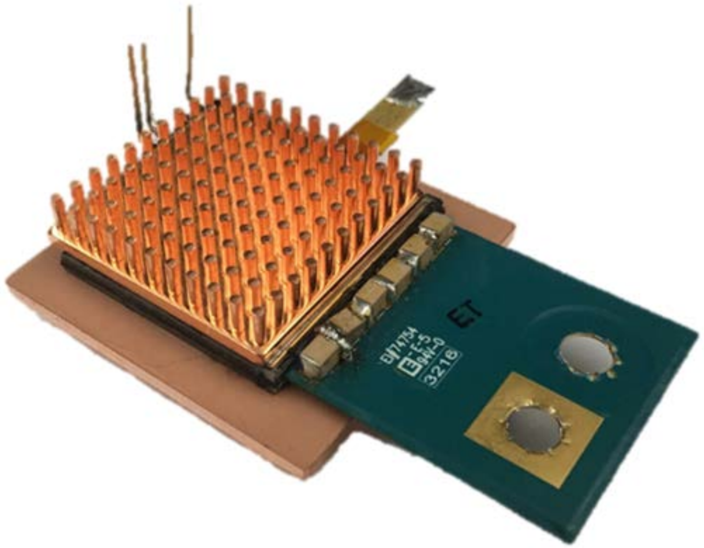
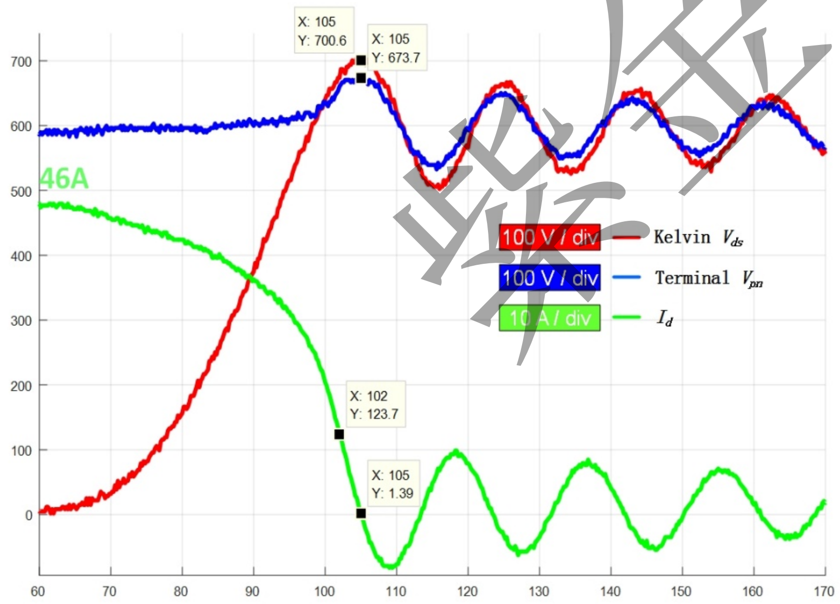
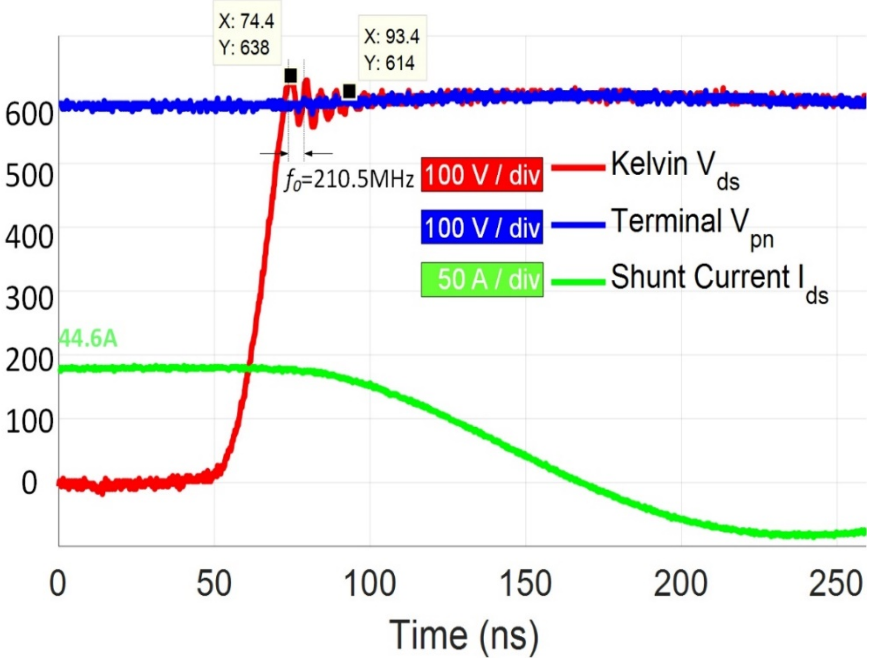
SiC Module with Low Inductance

	Gen 1 Baseline Module	Gen 2 Module Design	Modified Stack Module
Condition (@100MHz)			
Lower MOSFET Turn off Loop Inductance during di/dt	6.03 nH	1.63 nH	1.03 nH







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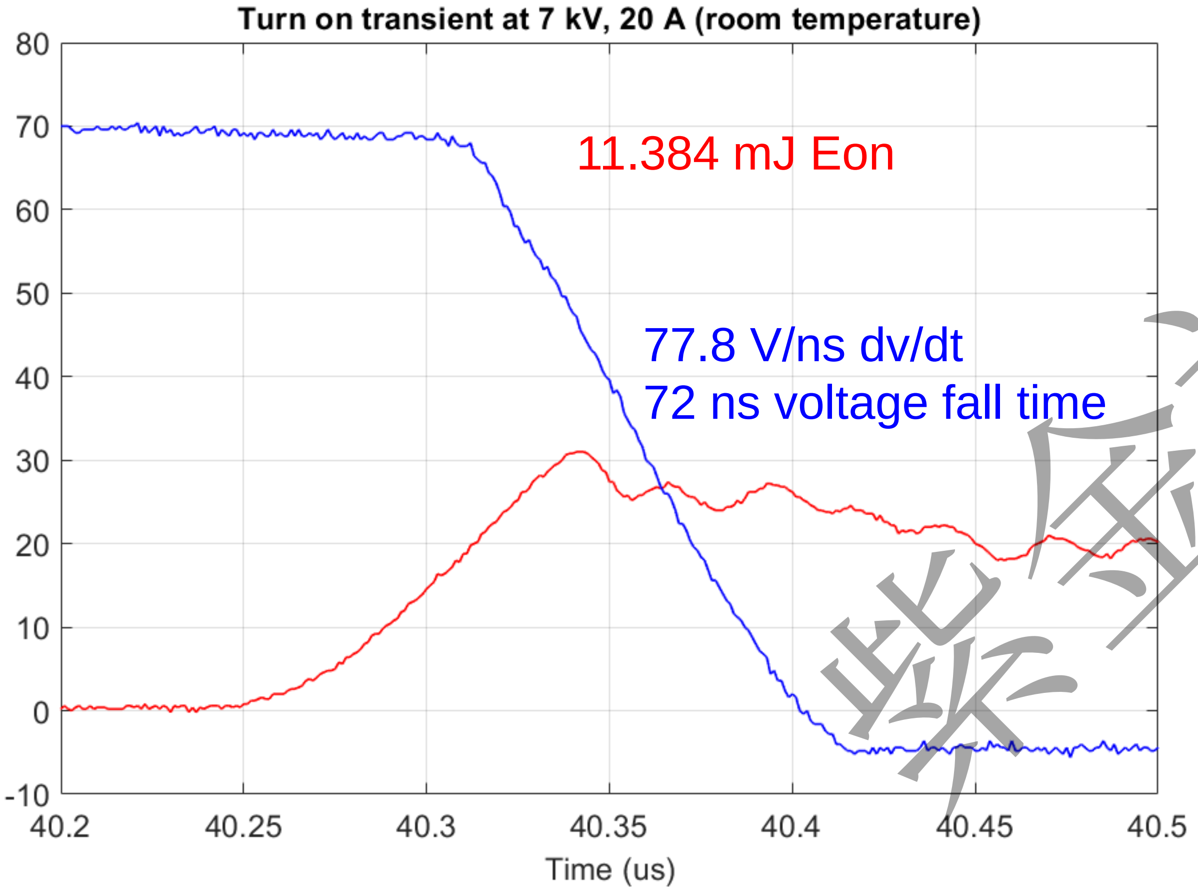
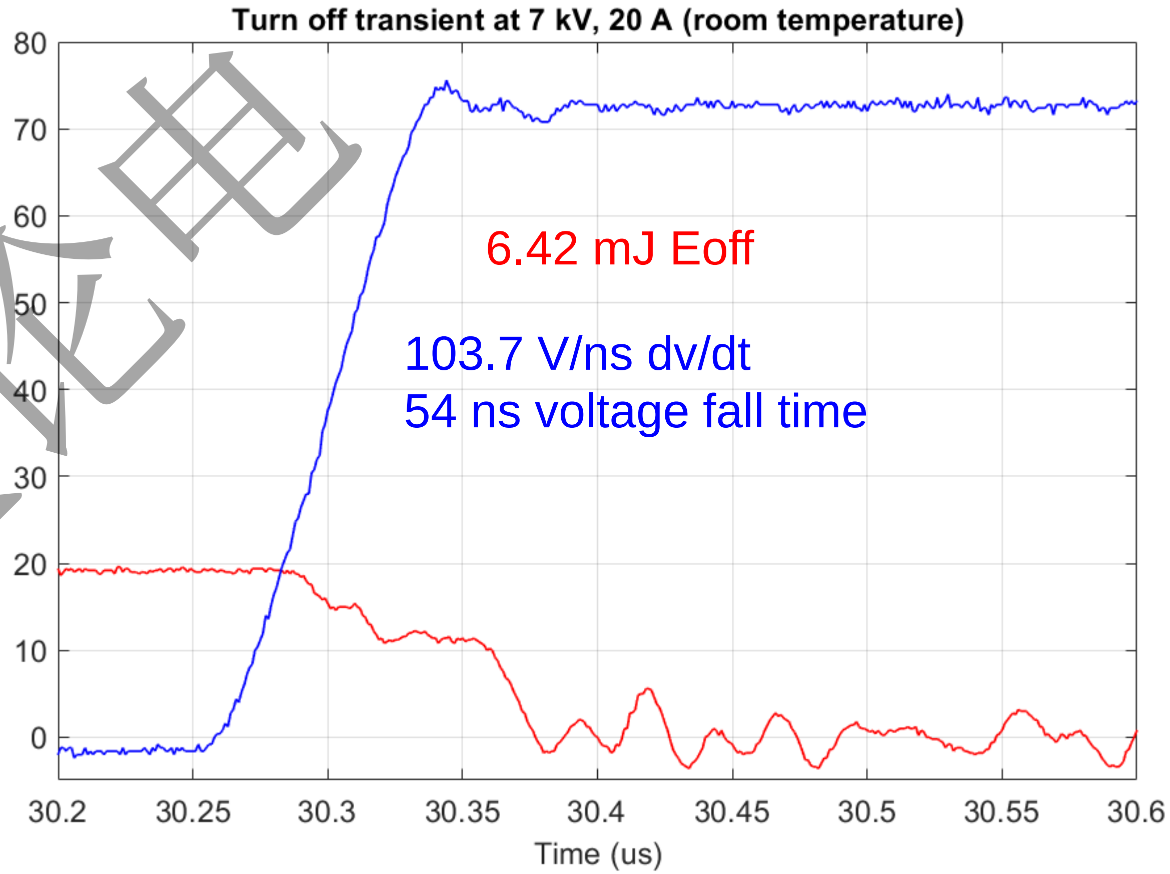
Switching Results of 10 kV SiC MOSFET





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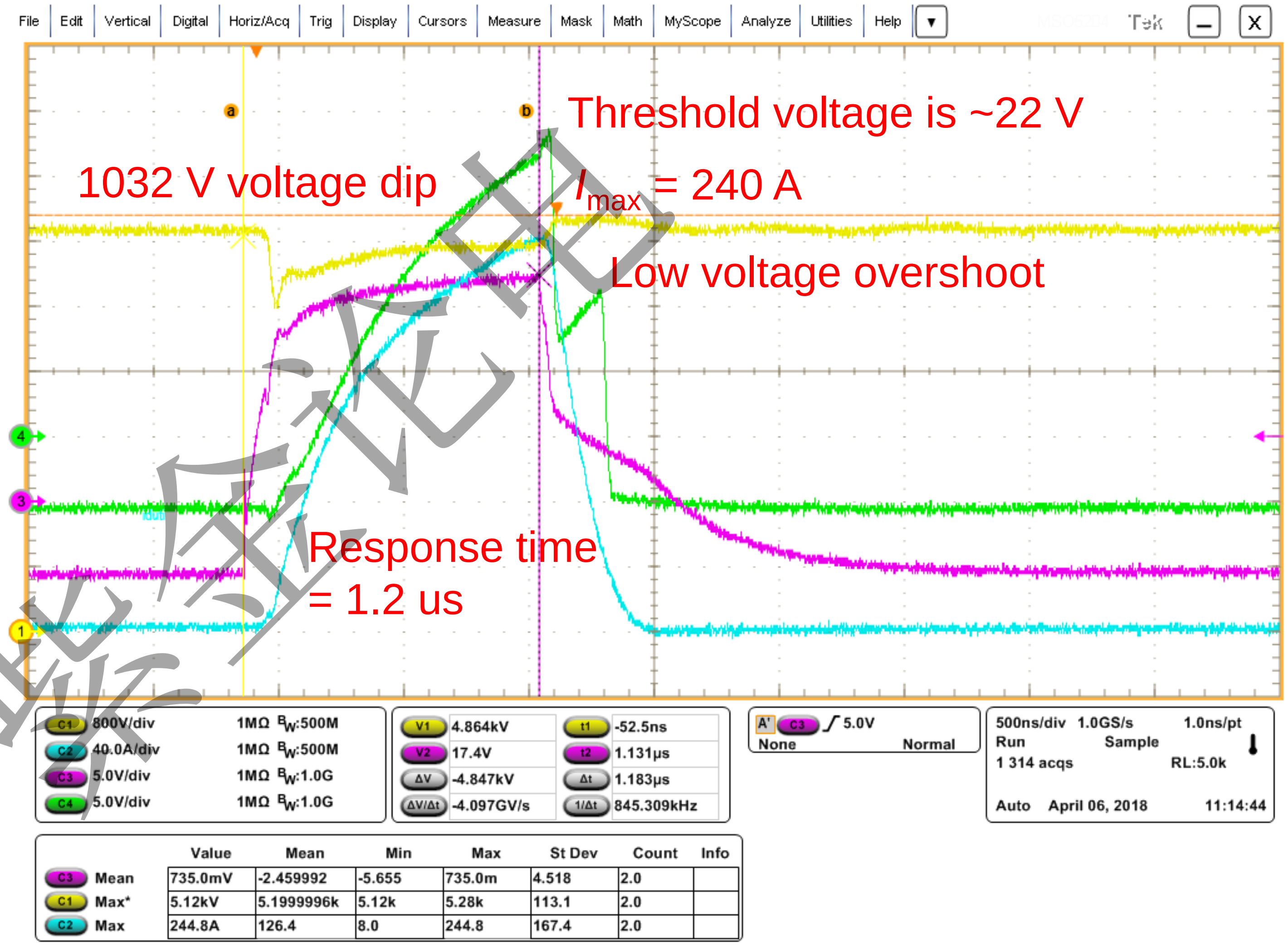
Short Circuit Protection Test of 10 kV SiC MOSFET

Ch1: drain-source voltage

Ch2: drain current

Ch3: gate-source voltage

Ch4: monitored Vds in desat circuit



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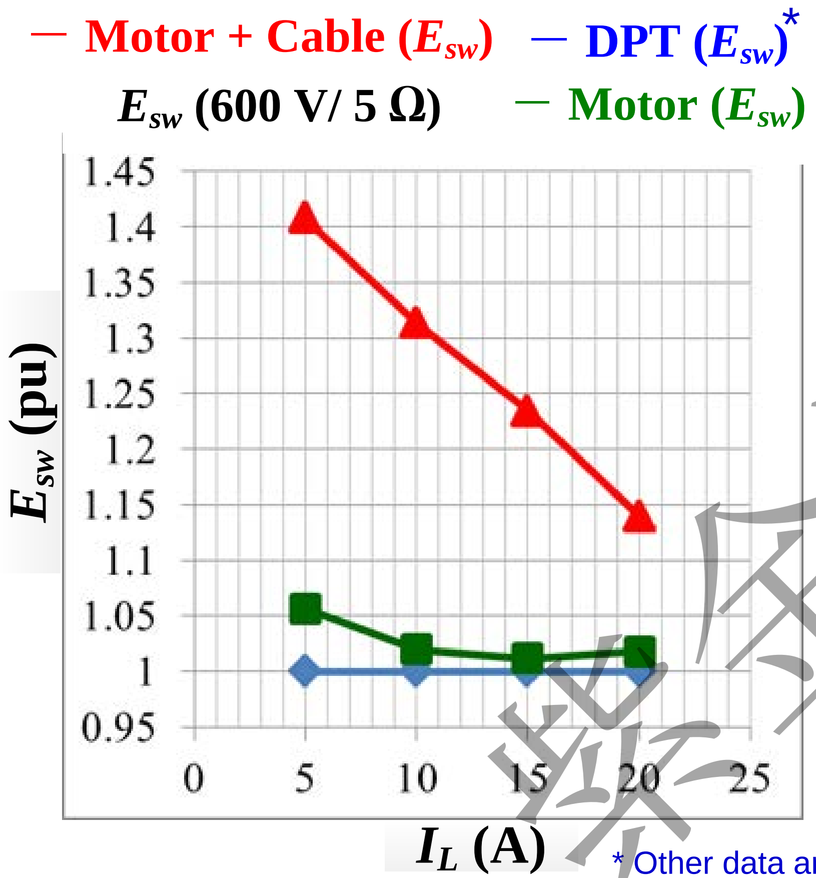
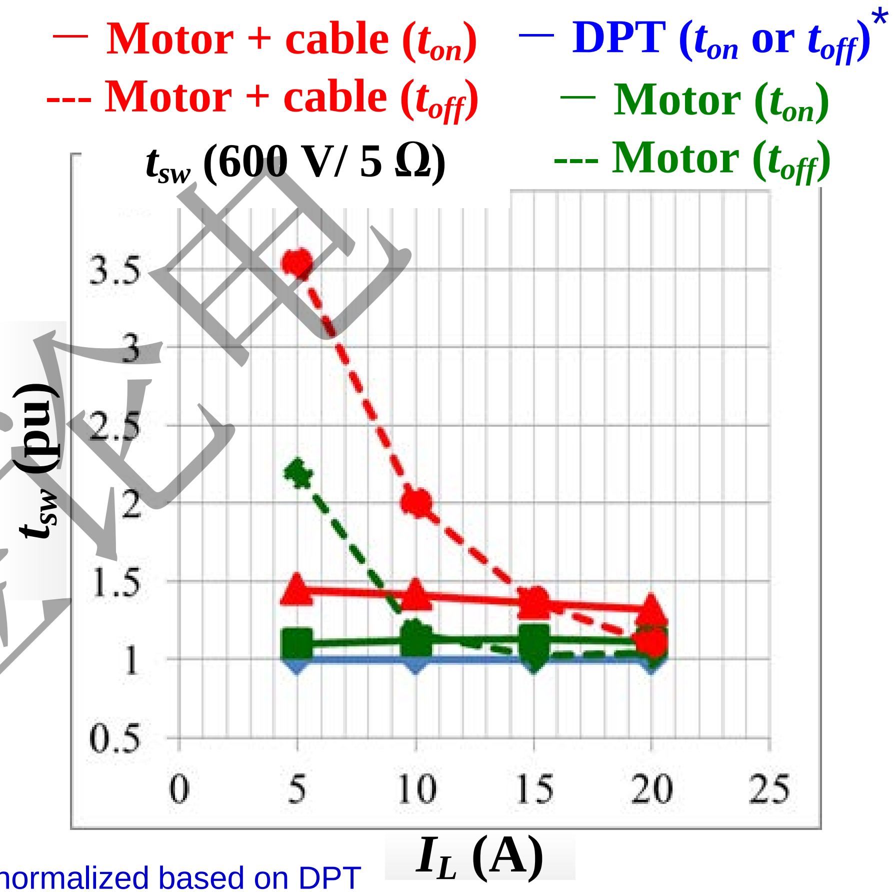
Impact of Motor & Cable on Drive Design





* Other data are normalized based on DPT

- Cooling system cannot be designed based on switching loss from typical DPT
- Switching frequency and dead time cannot be set based on switching time from DPT

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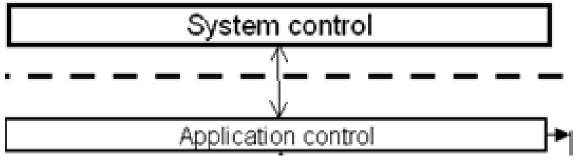
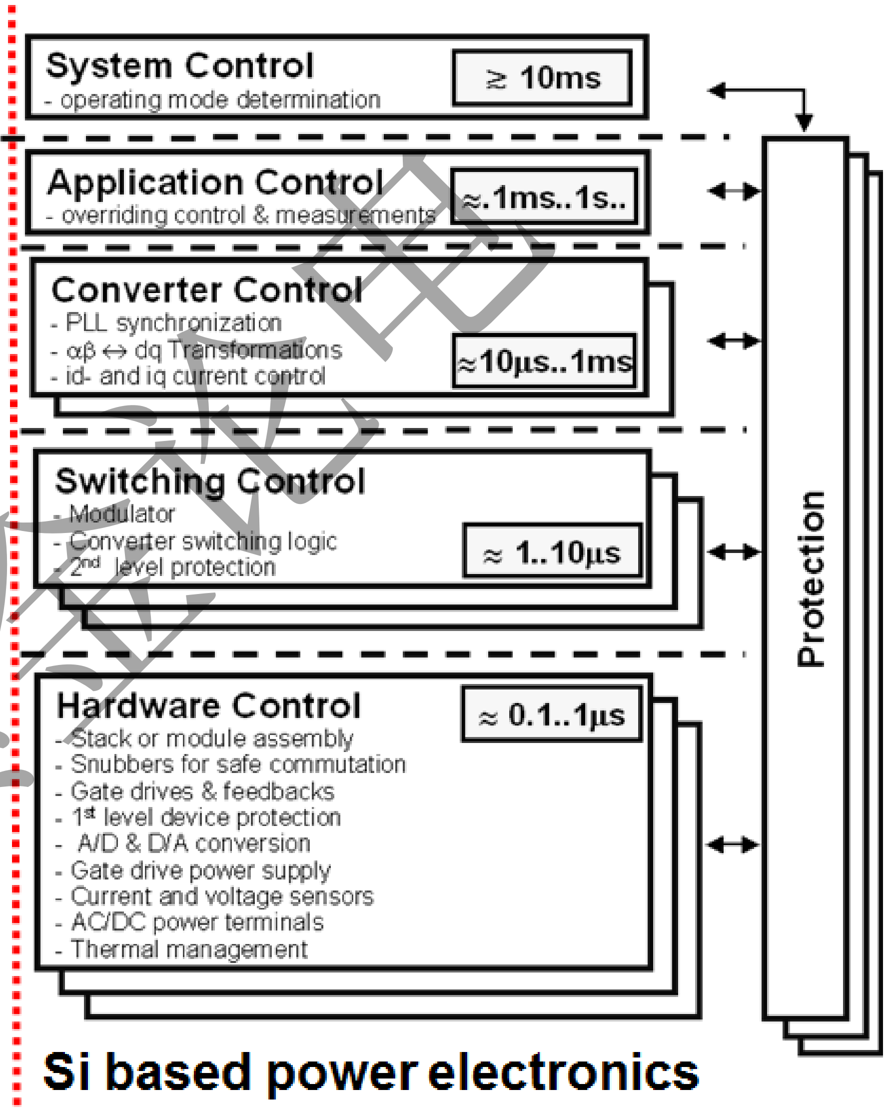
Control Challenges of WBG Converters



- **Converter Control**
  - High frequency, current/voltage sensing
- **Switching Control**
  - Modulation, dead-time setting & compensation
- **Hardware Control**
  - Gate drive, isolation, device level protection

Challenges due to SiC



Si based power electronics

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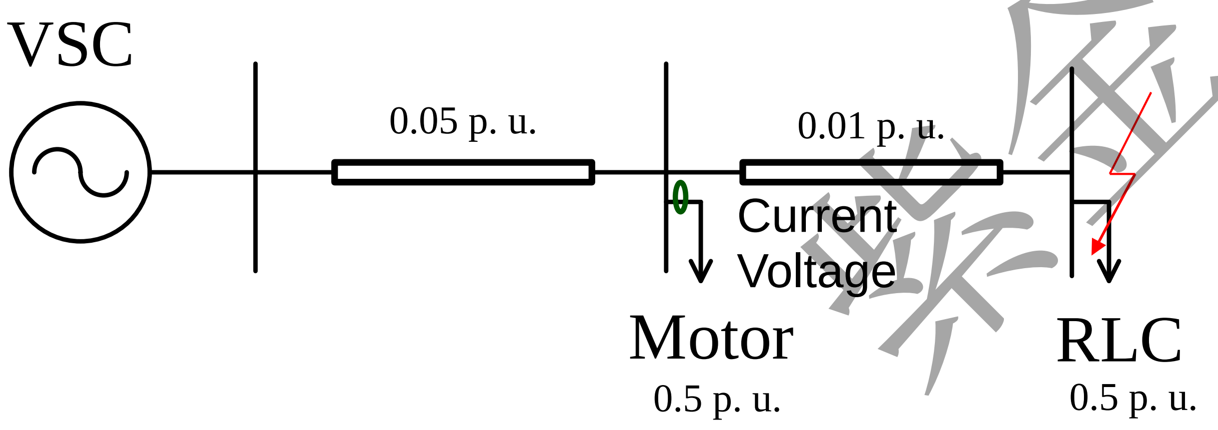
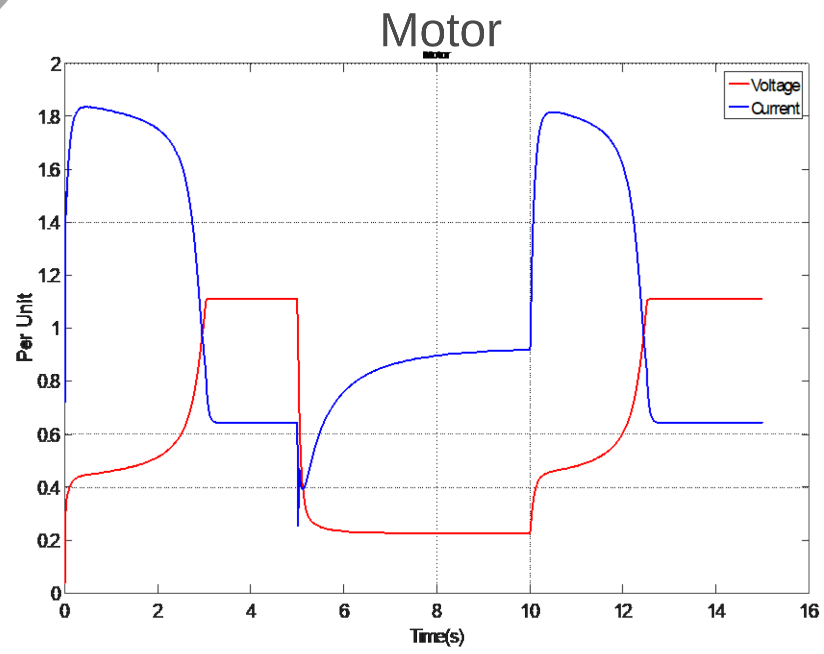
Converter Fault Current and Protection

- Case study of the VSC with 2X rated current capability
  - A short-circuit fault can be distinguished from the induction motor start with a time delay shorter than 5s
  - Utilizing the bus voltage can distinguish the short-circuit fault from induction motor start within 0.1s
  - VSC has similar performances for different fault locations, so a larger time delay is needed to avoid relay protection misoperation
  - RLC load branch can distinguish the short-circuit fault quickly based only on the current
  - Short-circuit faults within the induction motor branch can be detected quickly by the current





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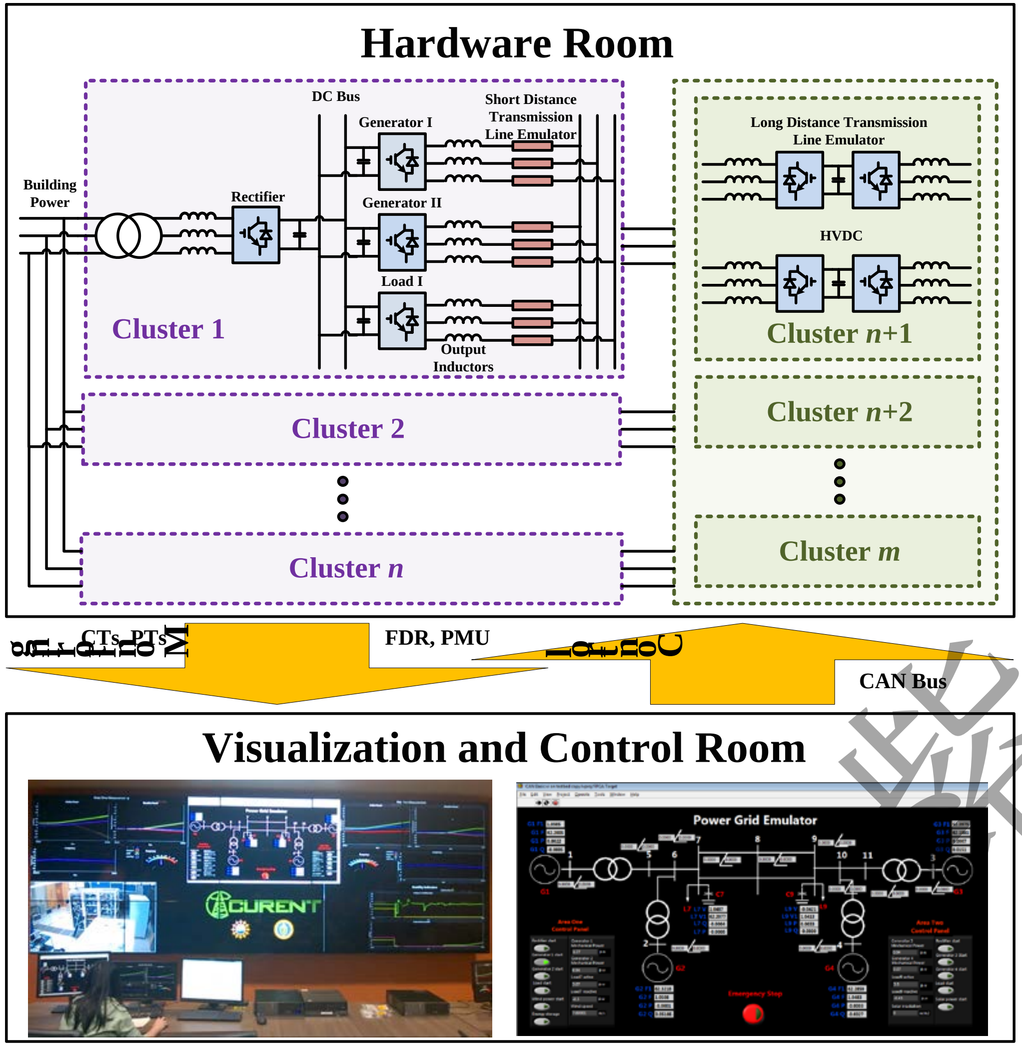
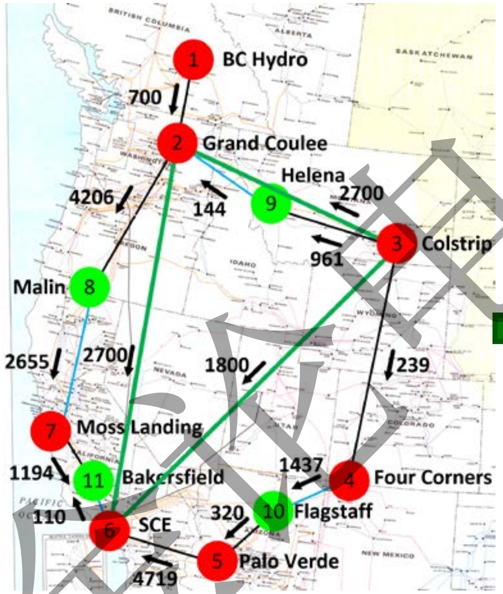
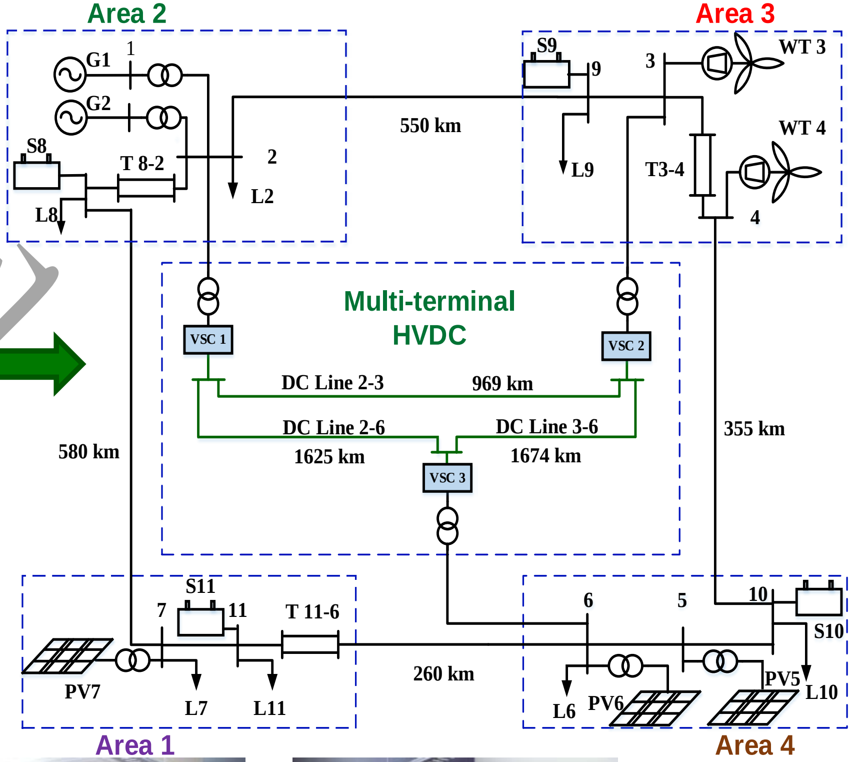
Power Electronics Grid Emulation Hardware Testbed (HTB)








Front row


Middle row


Back row

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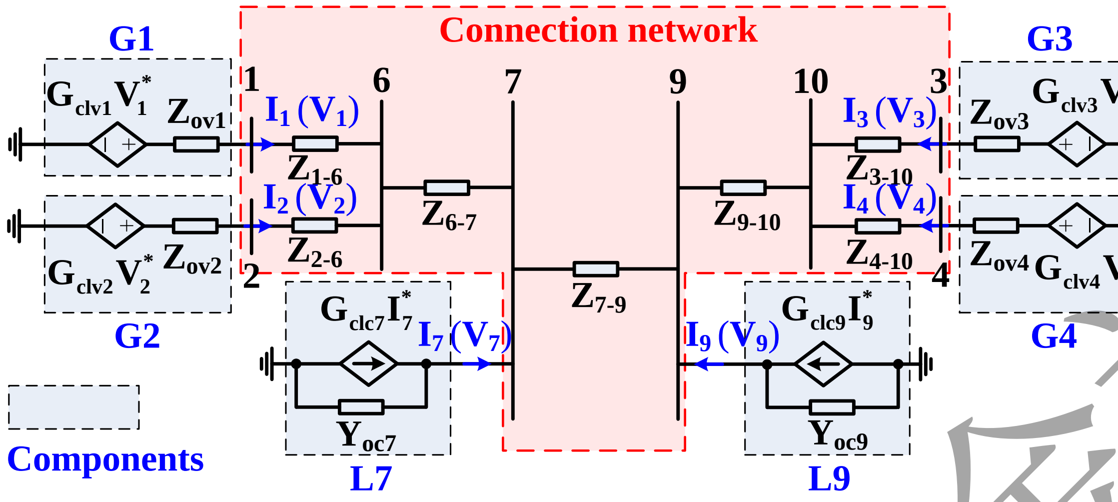
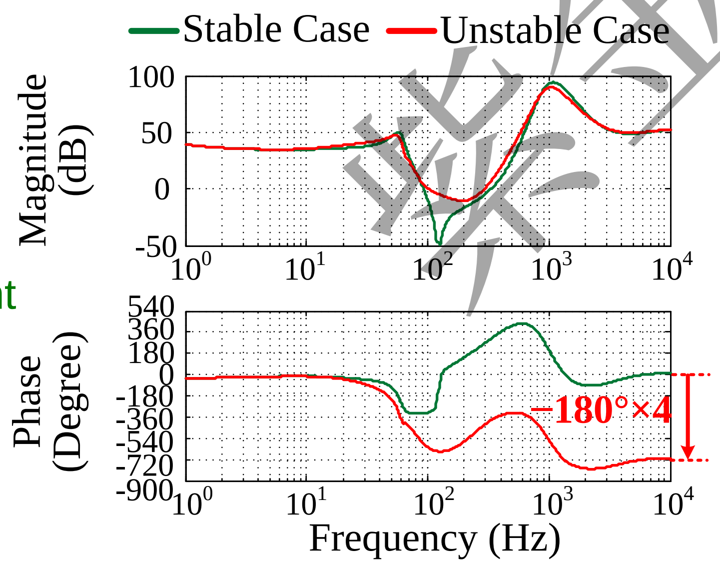
Renewable Converter Stability Analysis and Controller Design

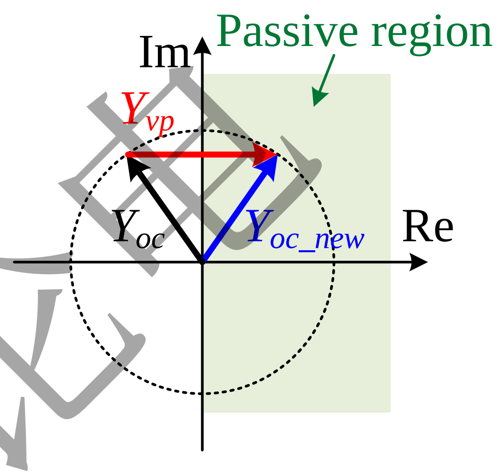
Impedance-based stability analysis in *d-q* frame



- Component Connection Method
- Generalized Nyquist stability criterion
- Stable if zero encirclement of point (0, *j*0)
- Avoid pole calculation



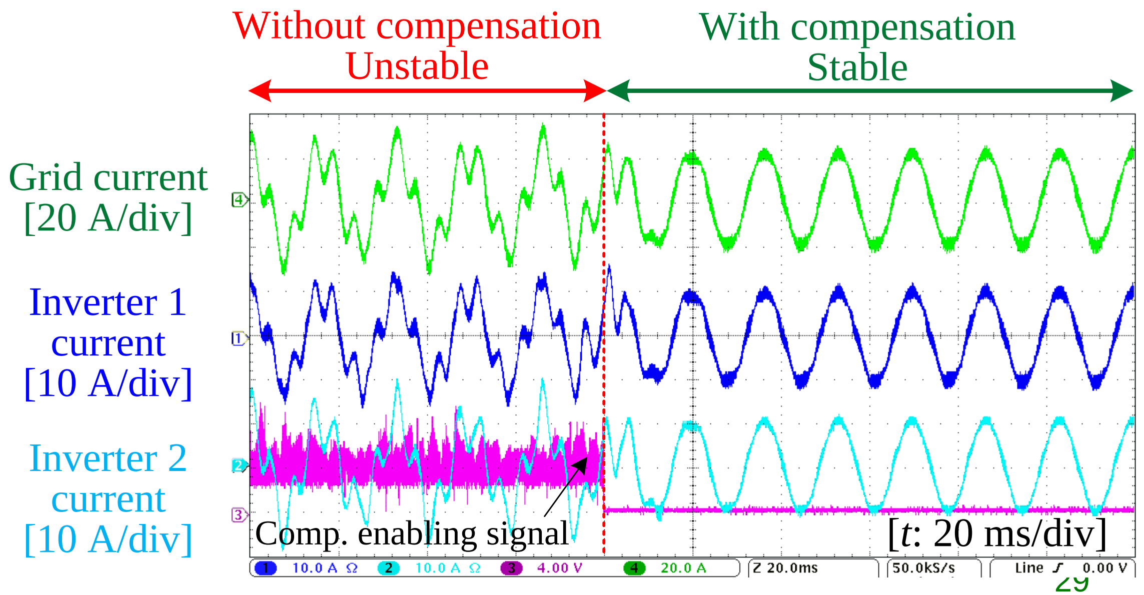
Adaptive passivity compensation



Y_{oc}: inverter admittance without compensation

Y_{vp}: virtual resistance for passivity compensation

Y_{oc_new}: inverter admittance with compensation



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Conclusion

- The power grid becomes increasingly based on power electronics, due to the changing sources, loads, and T&D technologies.
- WBG devices and other new technologies provide new opportunities for power electronics in grid applications.
- The emerging needs and technologies also pose many new challenges, requiring new paradigm for power electronics and grid.

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Thank You!