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

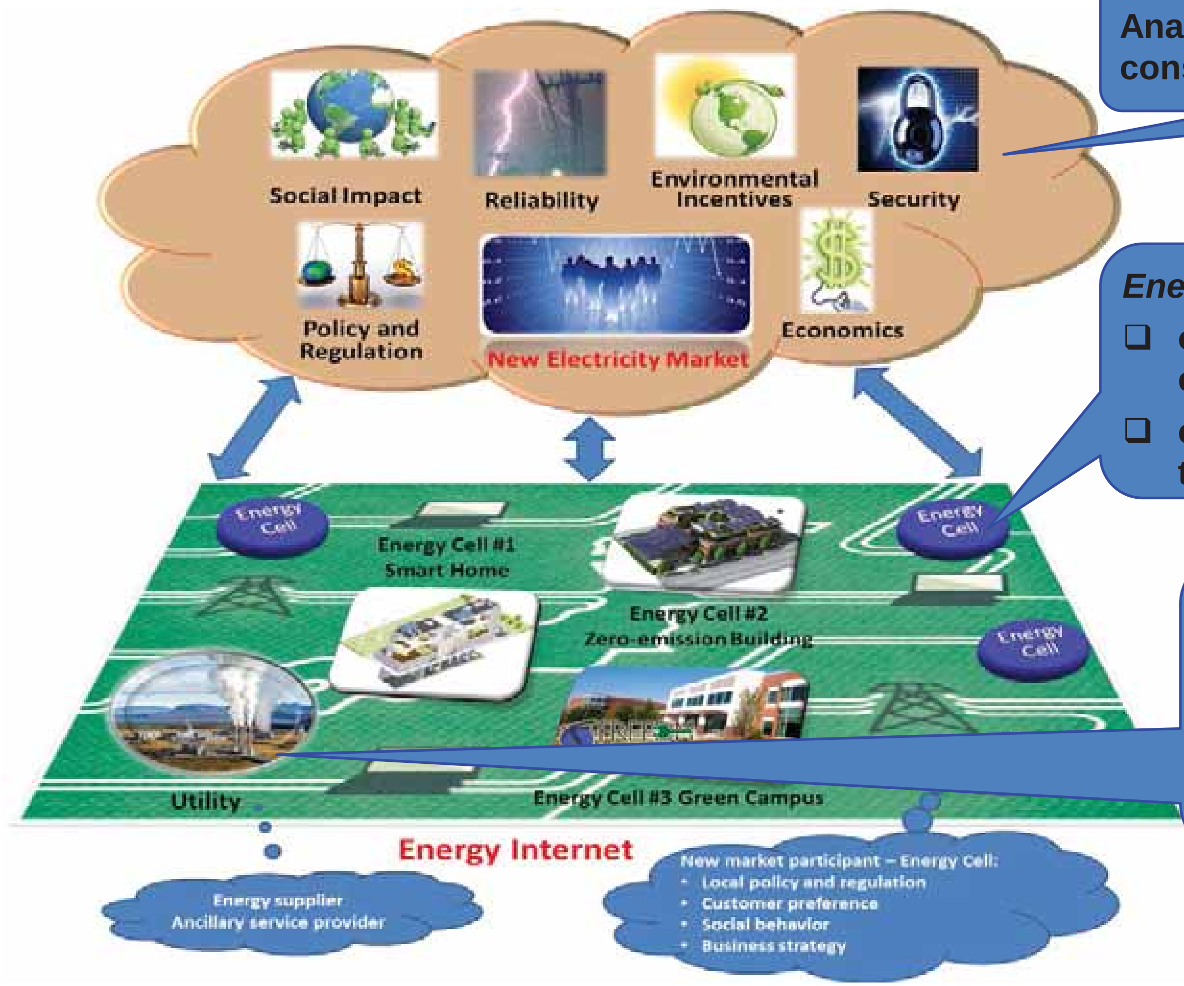
1) 100% penetration: Voltage Issue?
2) Market transformation:
   Energy Internet (proposed in 2007 by Dr. Huang)

Frequencies

Losses

*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

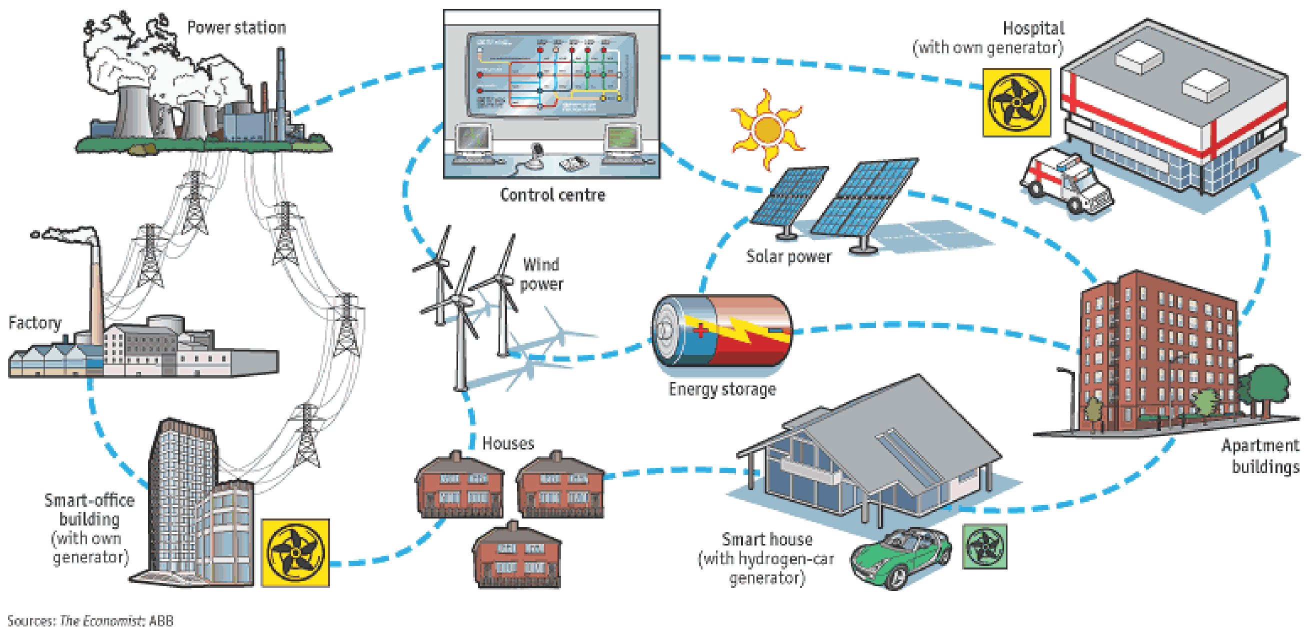
[1] Huang, A.Q.; Crow, M.L.; Heydt, G.T.; Zheng, J.P.; Dale, S.J.; , "The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet," *Proceedings of the IEEE* , vol.99, no.1, pp.133-148, Jan. 2011

[2] W. Su, and A.Q. Huang, “A Game Theoretic Framework for a Next-generation Retail Electricity Market with High Penetration of Distributed Residential Electricity Suppliers” *Applied Energy,* vol.119, pp.341-350, April 2014.

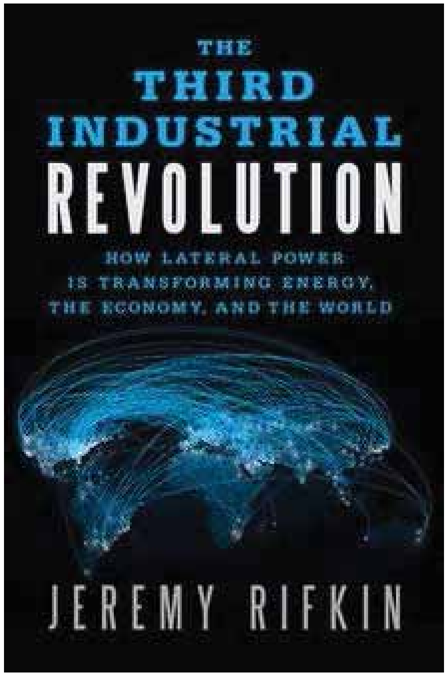
[3] W. Su, “The Role of Customers in the U.S. Electricity Market: Past, Present, and Future”, *The Electricity Journal,* 2014. (invited)

The Third Industrial Revolution

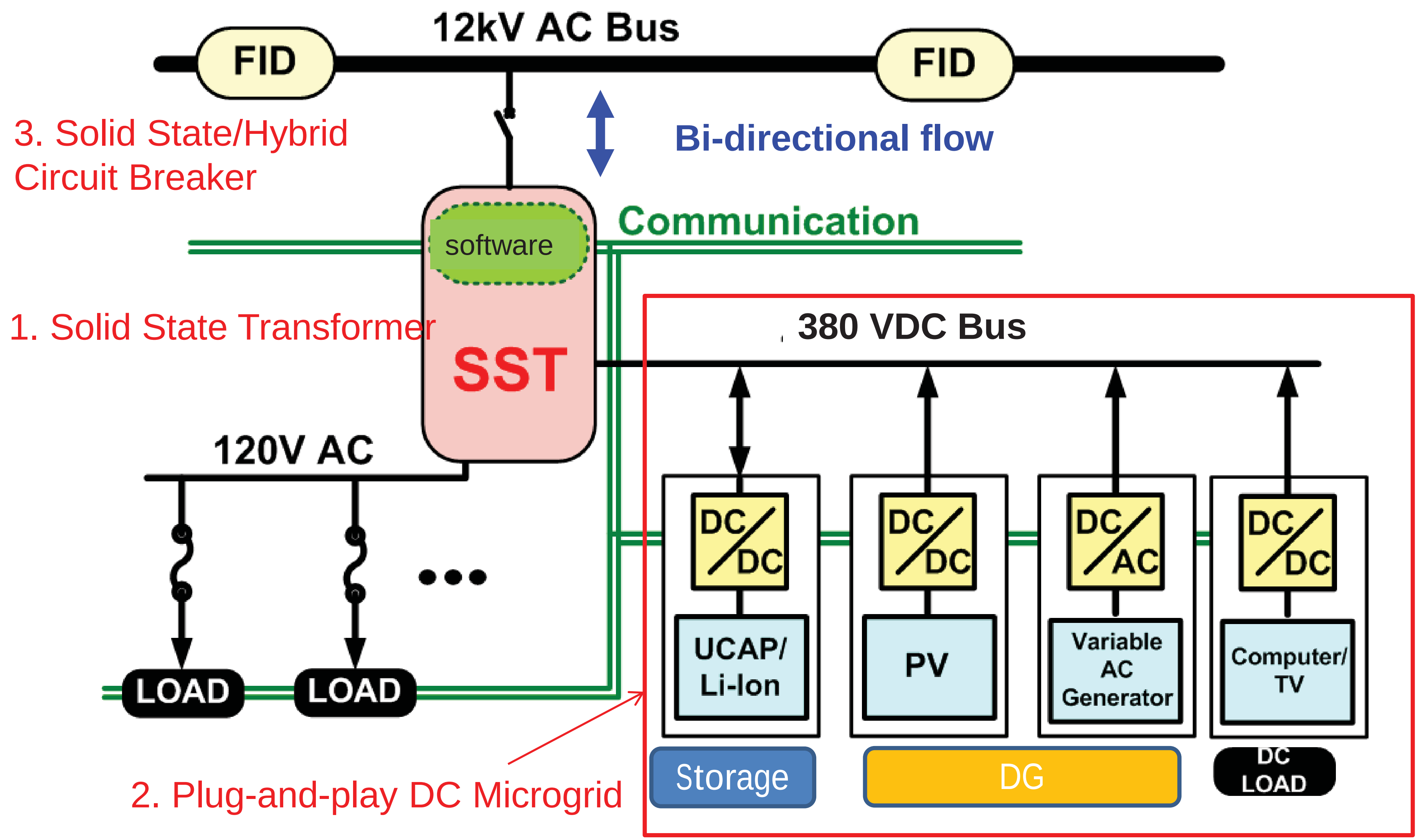
"using Internet technology to transform the power grid of every continent into an **energy internet** that acts just like the Internet (when millions of buildings are generating a small amount of renewable energy locally, on-site, they can sell surplus green electricity back to the grid and share it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



Picture from "Economist"

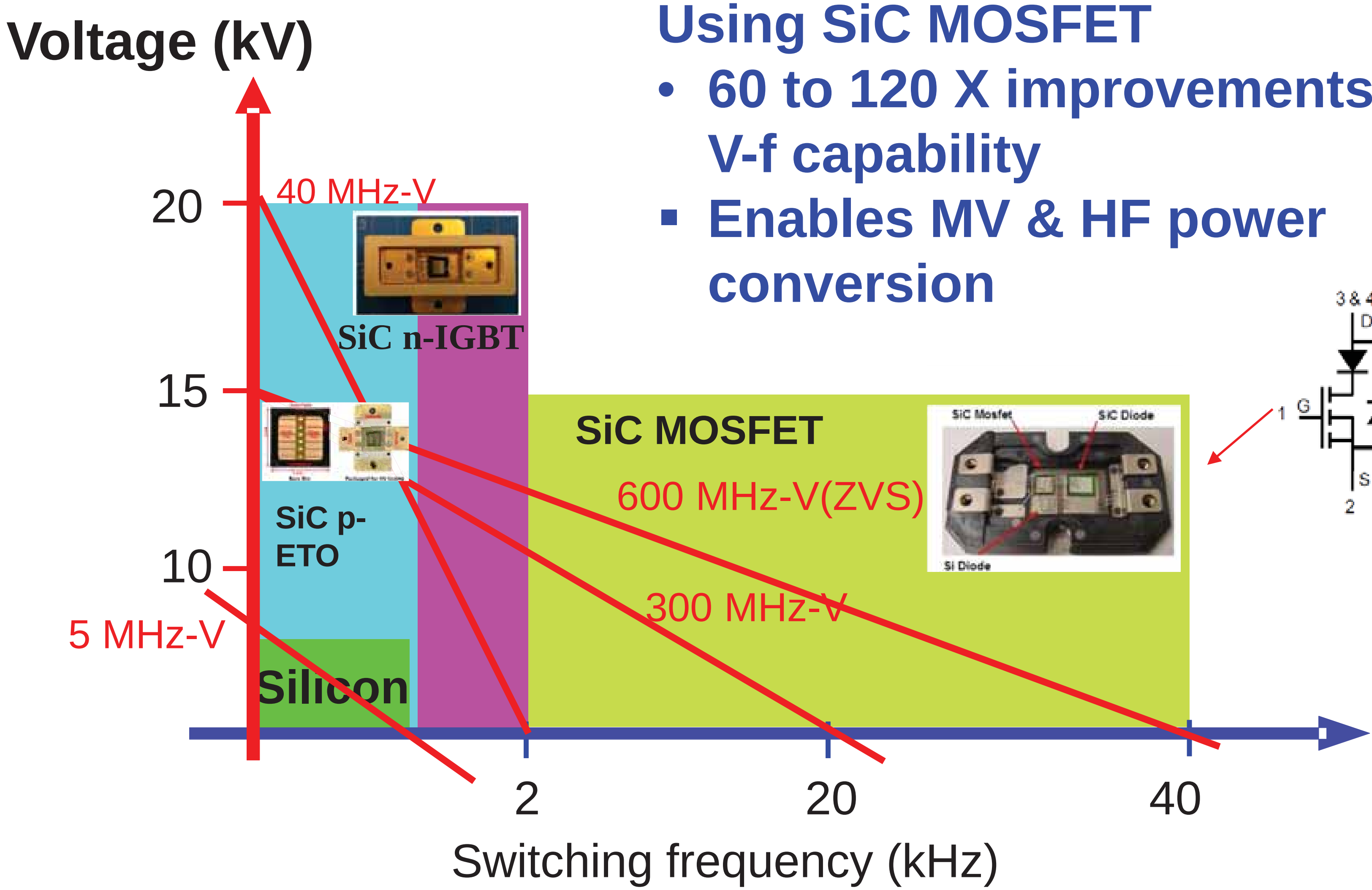


FREEDM System: Resilient Grid



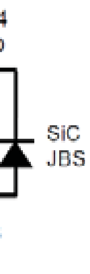
*Proposed by Dr. Huang in 2007

Medium Voltage SiC Technology



Using SiC MOSFET

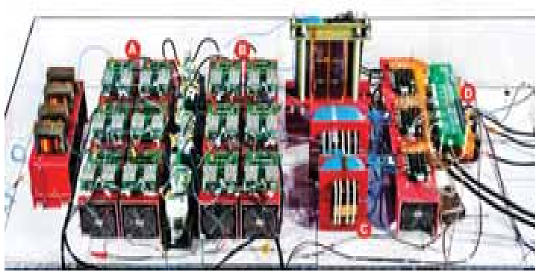
- **60 to 120 X improvements in V-f capability**
- **Enables MV & HF power conversion**



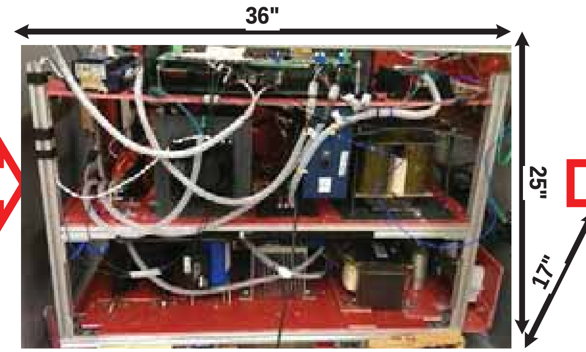
FREEDM systems center

Solid State Transformer

60Hz Transformer

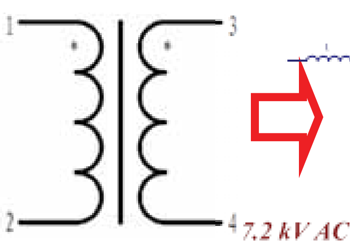


Gen- 1 SST: Si-based (3 kH 6.5 kV IGBT)

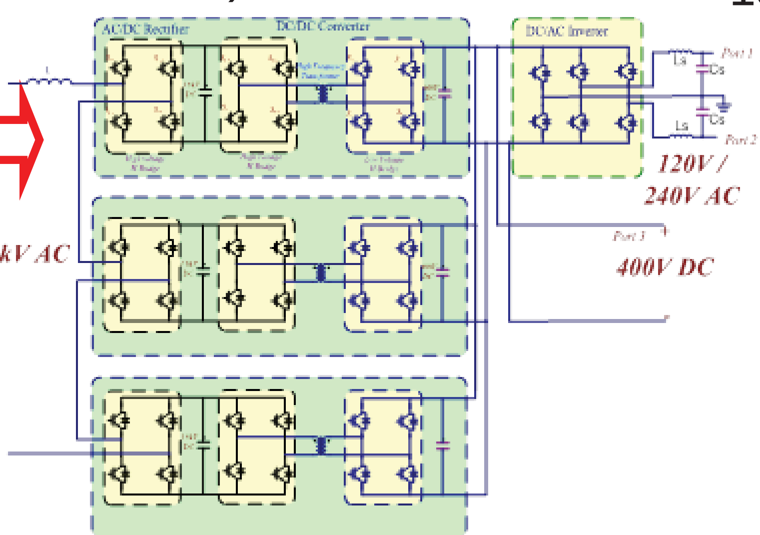


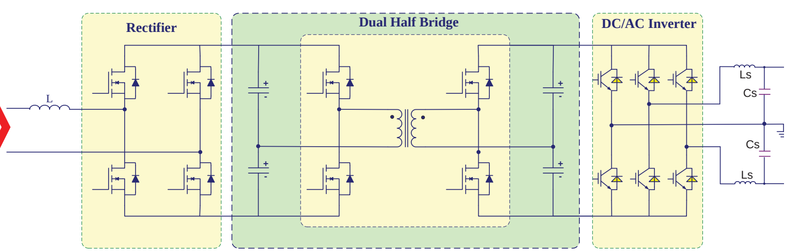
Gen- 2 SST: SiC-based (10 kHz
15 kV SiC MOSFET)

Gen- 3 SST:
40 kHz
15 kV SiC

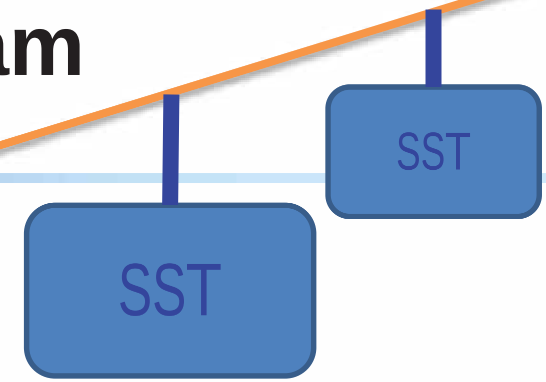


Pole mounted transformer

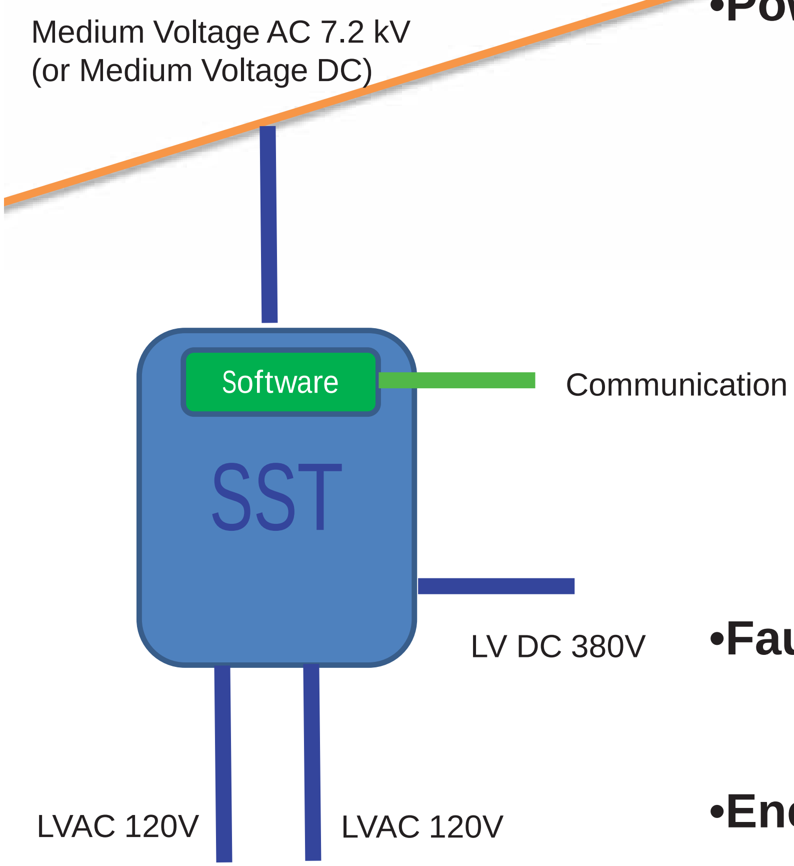




SST Functional Diagram

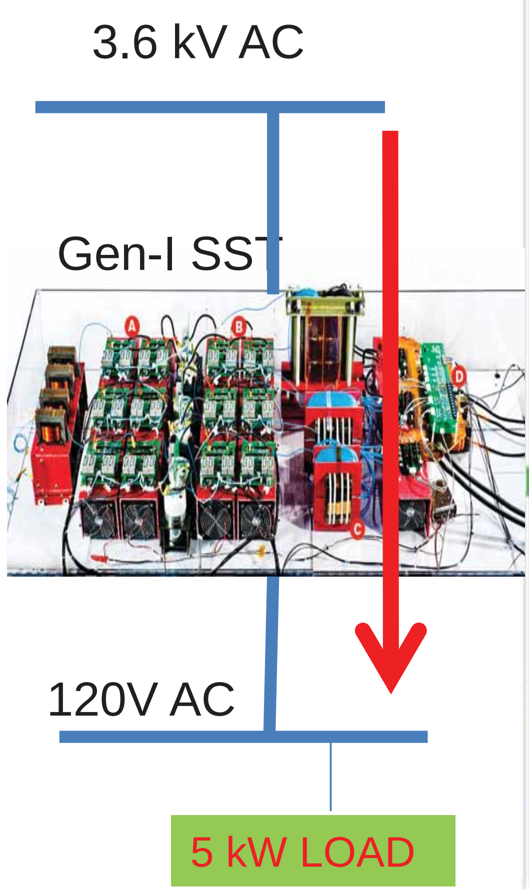


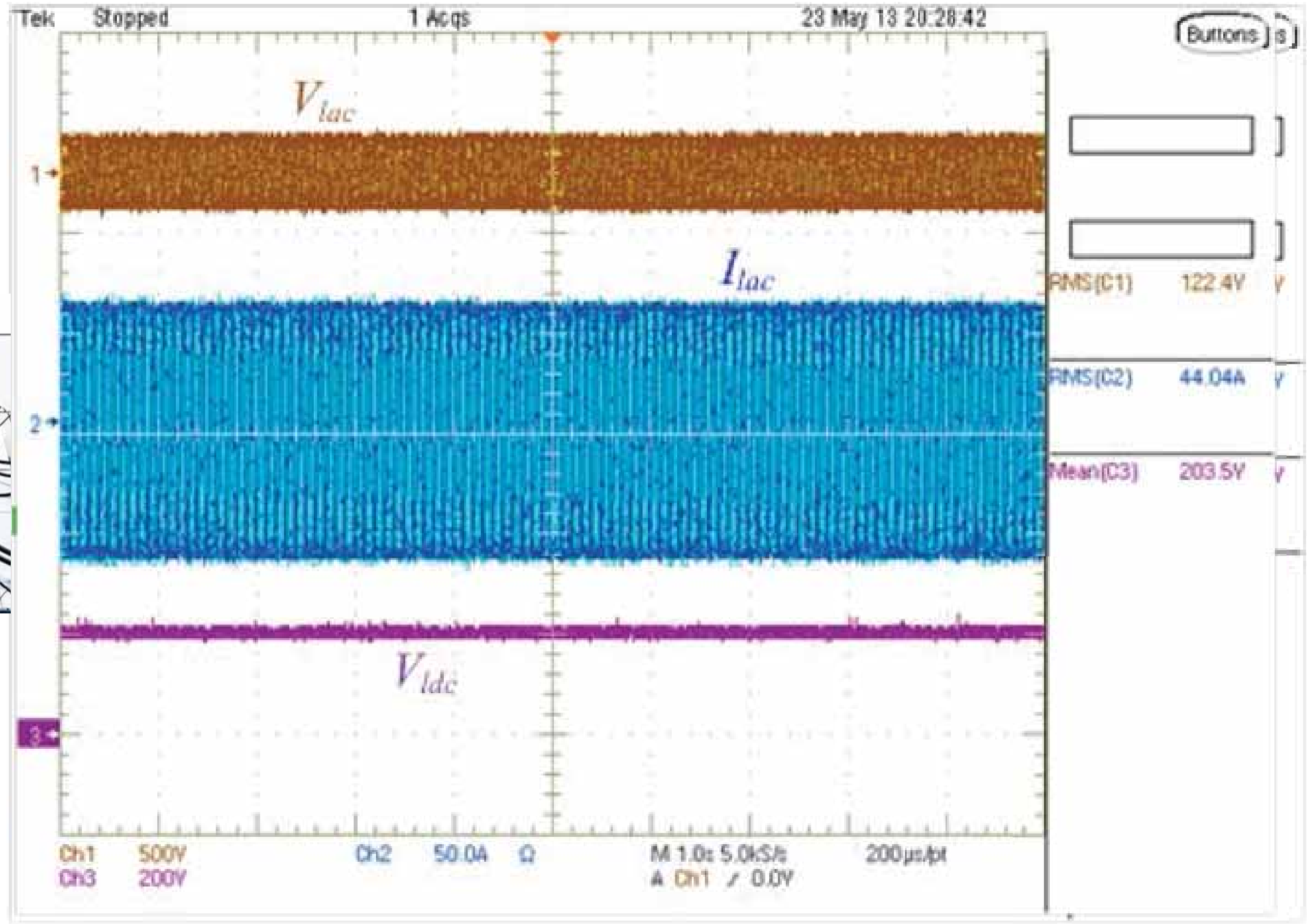
From 60Hz to SST to Smart Transformer to Energy Router



- **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: MV AC voltage sag operation: 25% voltage sag, 5KW



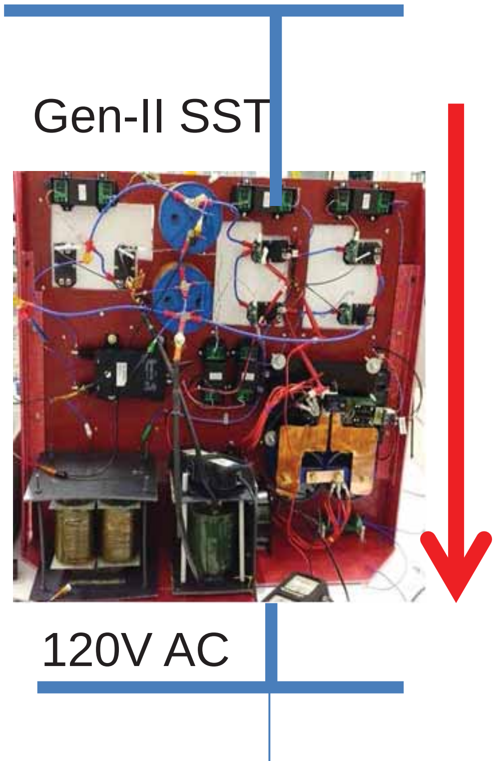


Input voltage, current, PWM voltage, high voltage DC link 3
Output DC voltage, AC voltage and current

SST Integration with a Non-linear Load: Harmonic Mitigation

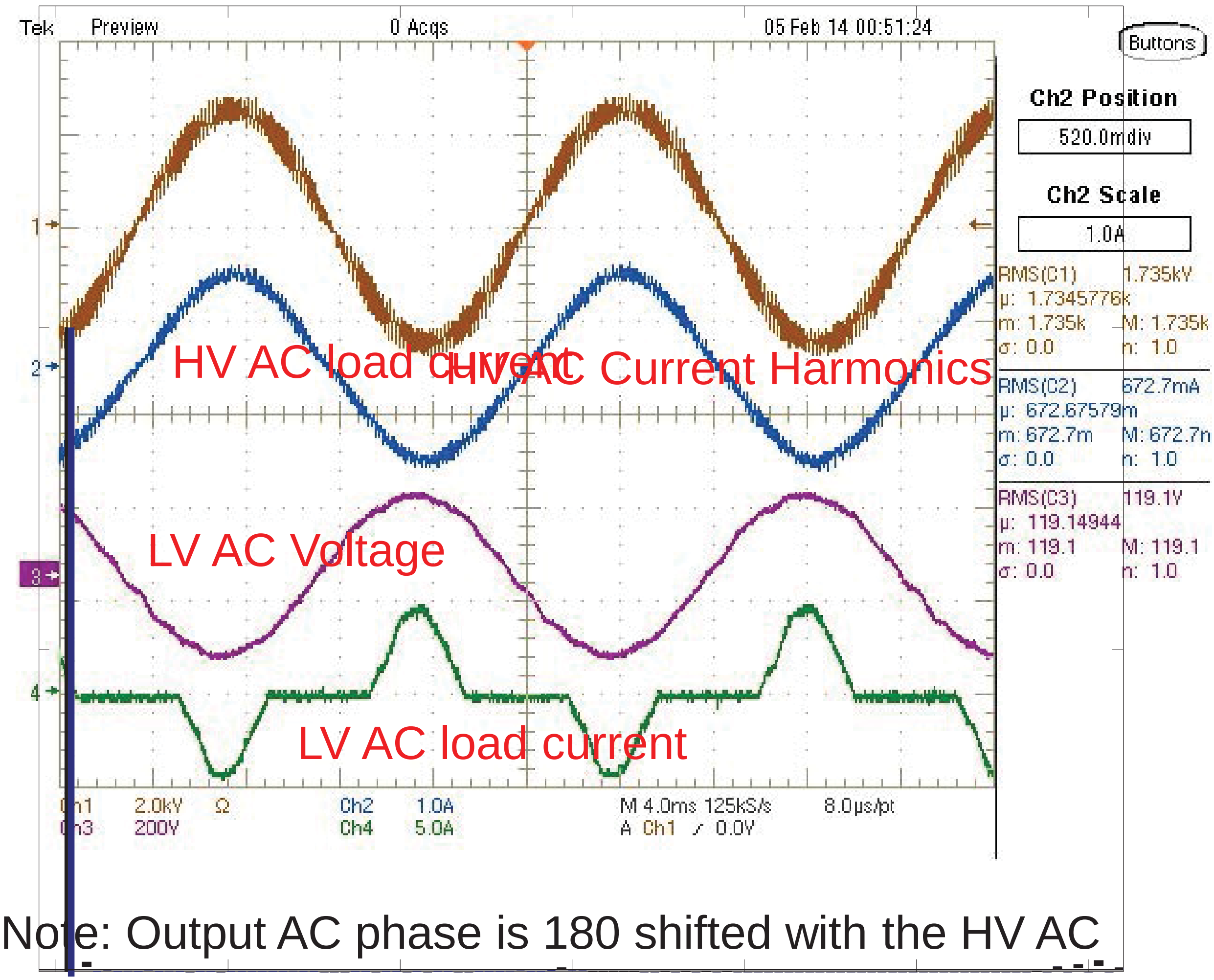
1.8 kV AC

Gen-II SST



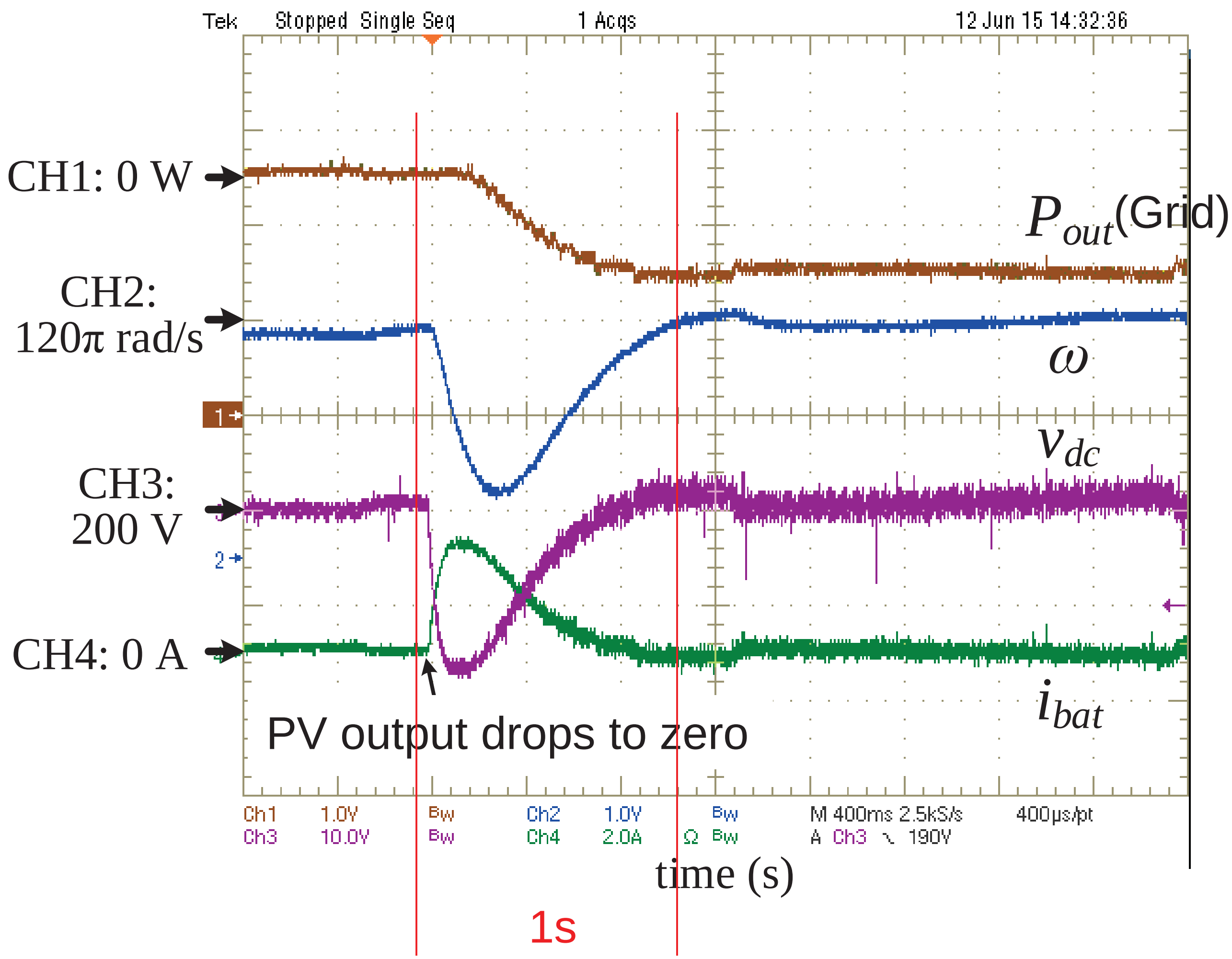
120V AC

Non linear LOAD



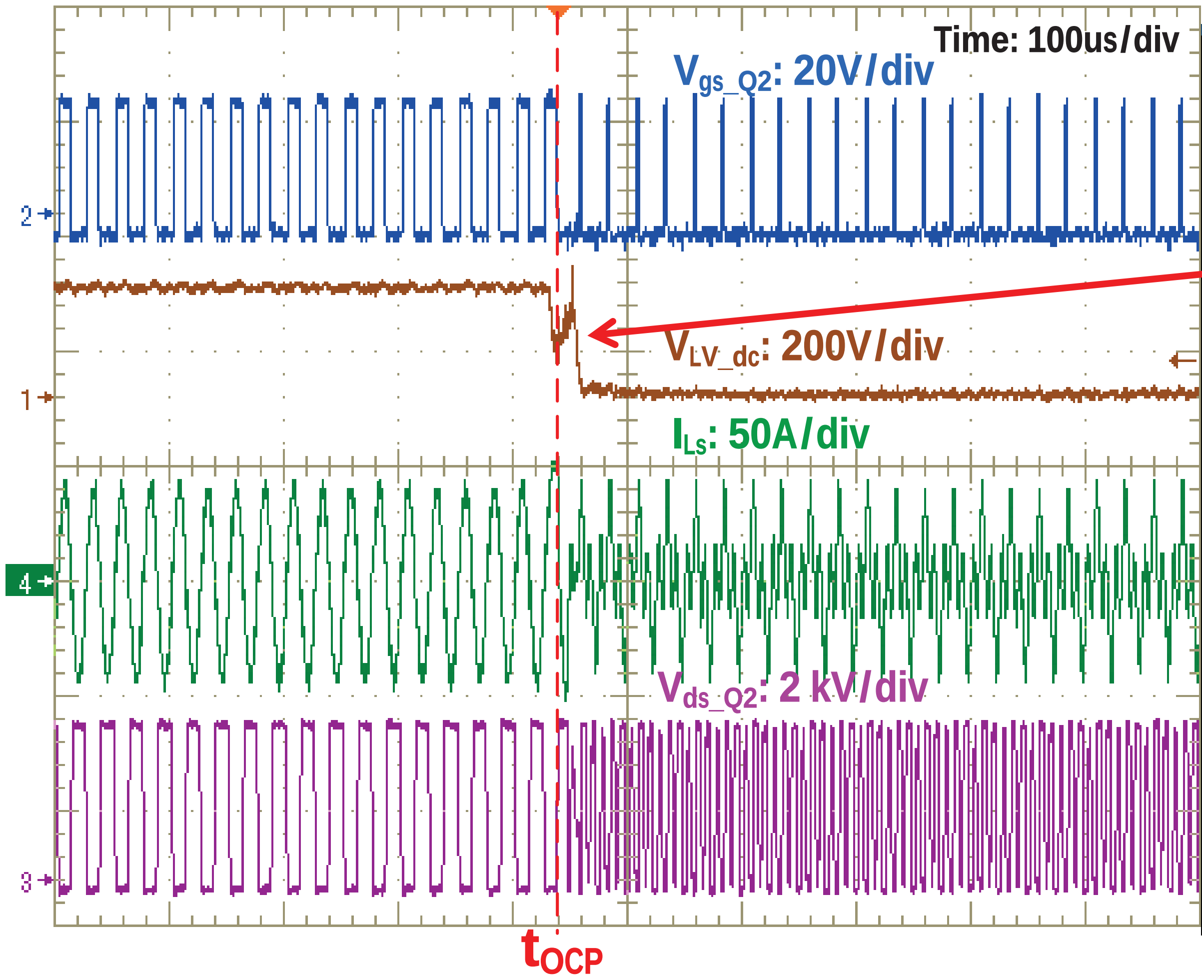
Note: Output AC phase is 180 shifted with the HV AC

Frequency Response: SSSM Demo



Short-Circuit Protection

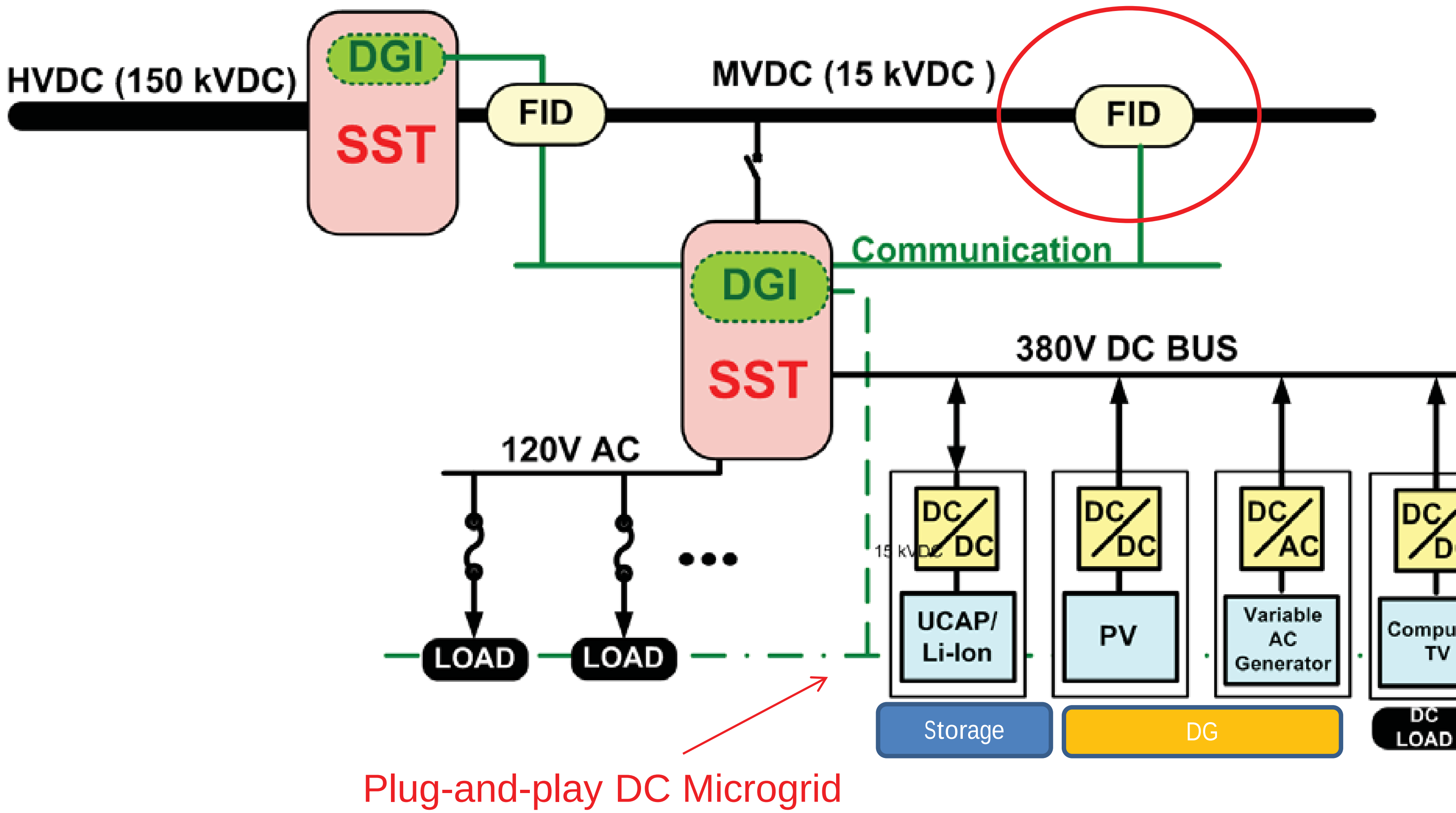
Experimental results of worst-case short circuit protection
(V_{HV_dc}=3kV, V_{LV_dc}=200-0V)



Worst-case short circuit happens within 0.01 ms

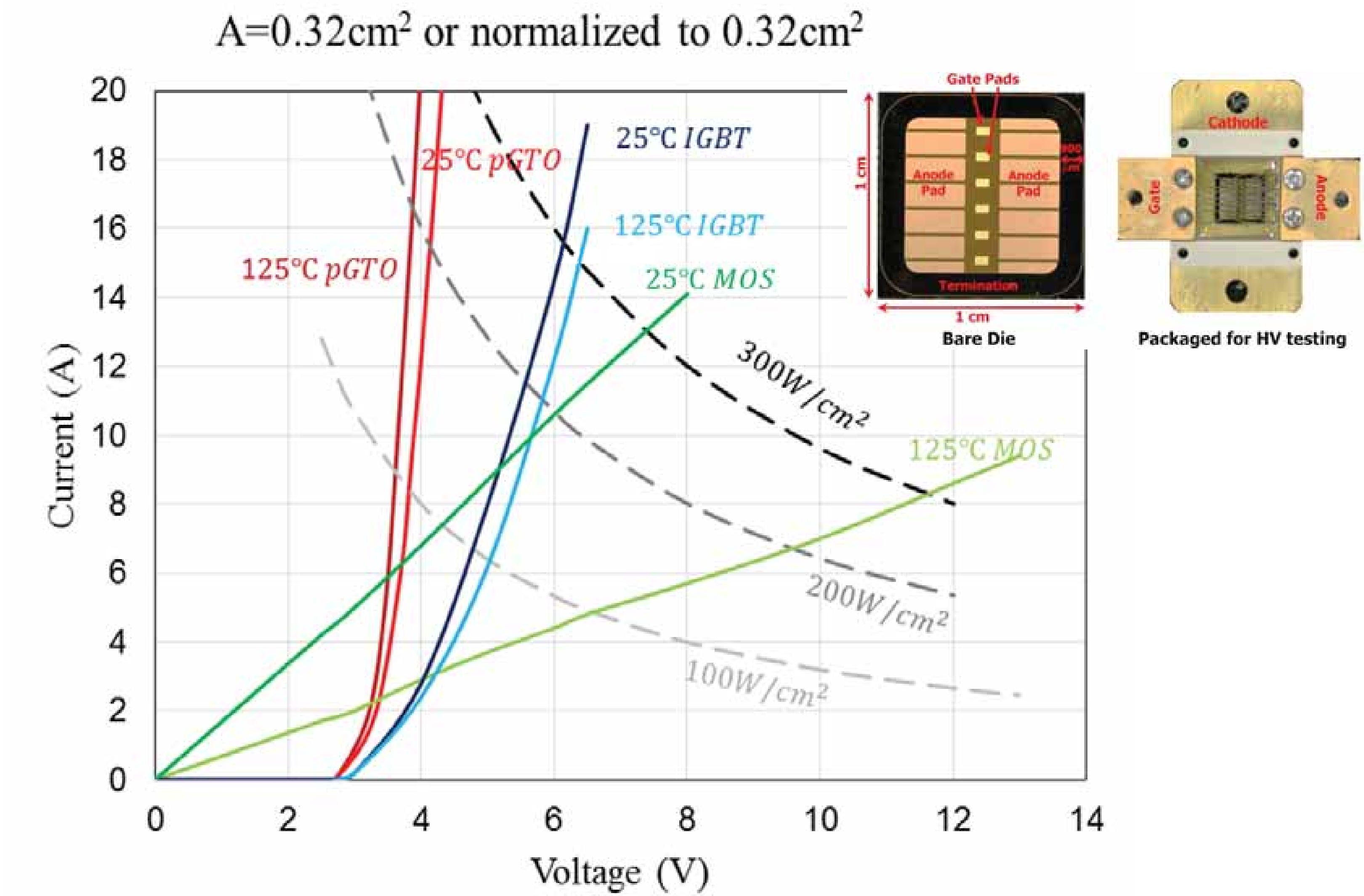
Naturally switch to DAB mixed LLC mode,
Current is well controlled

All DC Electric Grid



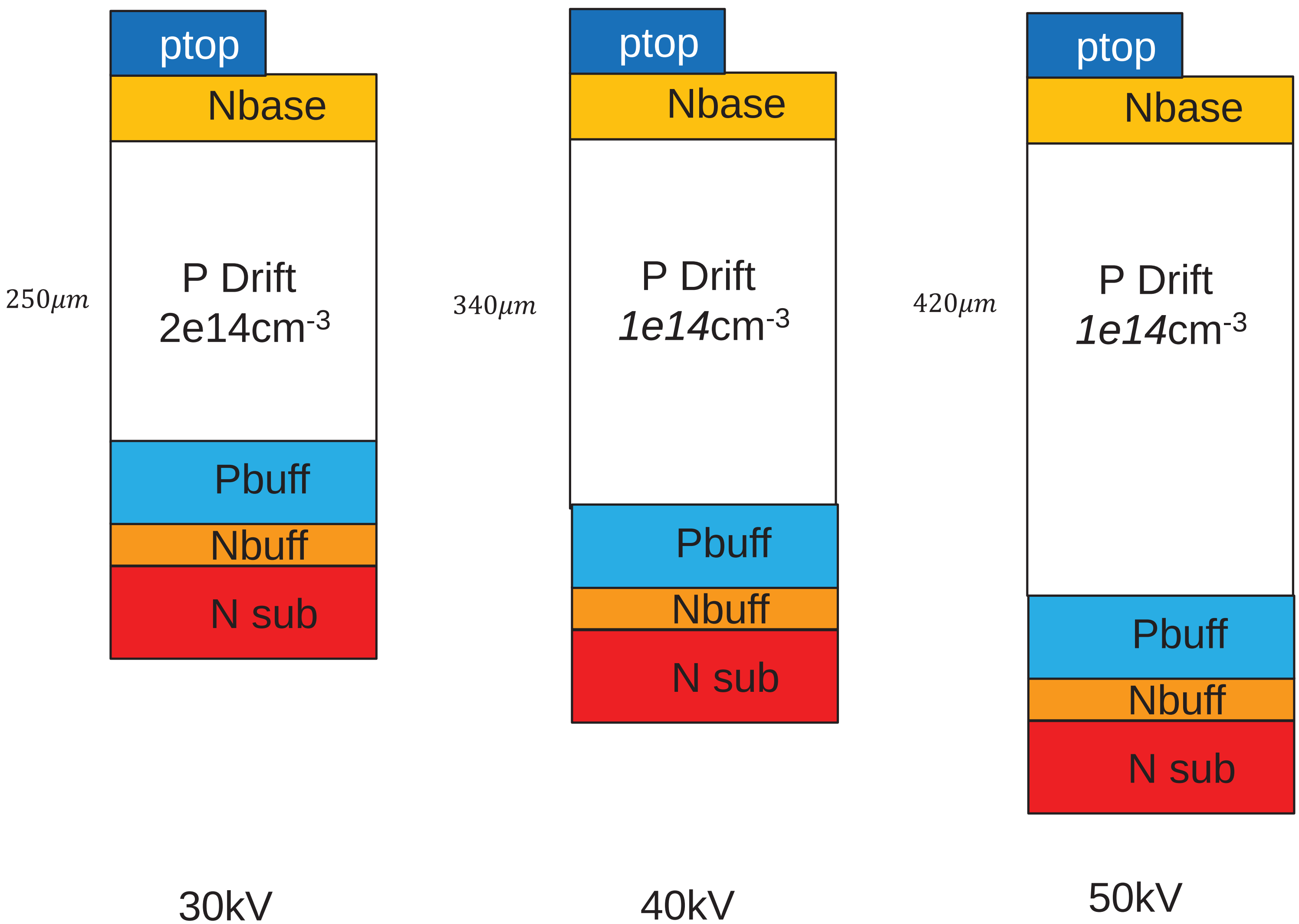
MAJOR ADVANATGE Over AC: 1) Loss reduction, 2) Better utilization of cables, and 3)Easy for DER integration

15kV p-GTO, n-IGBT and n-MOSFET



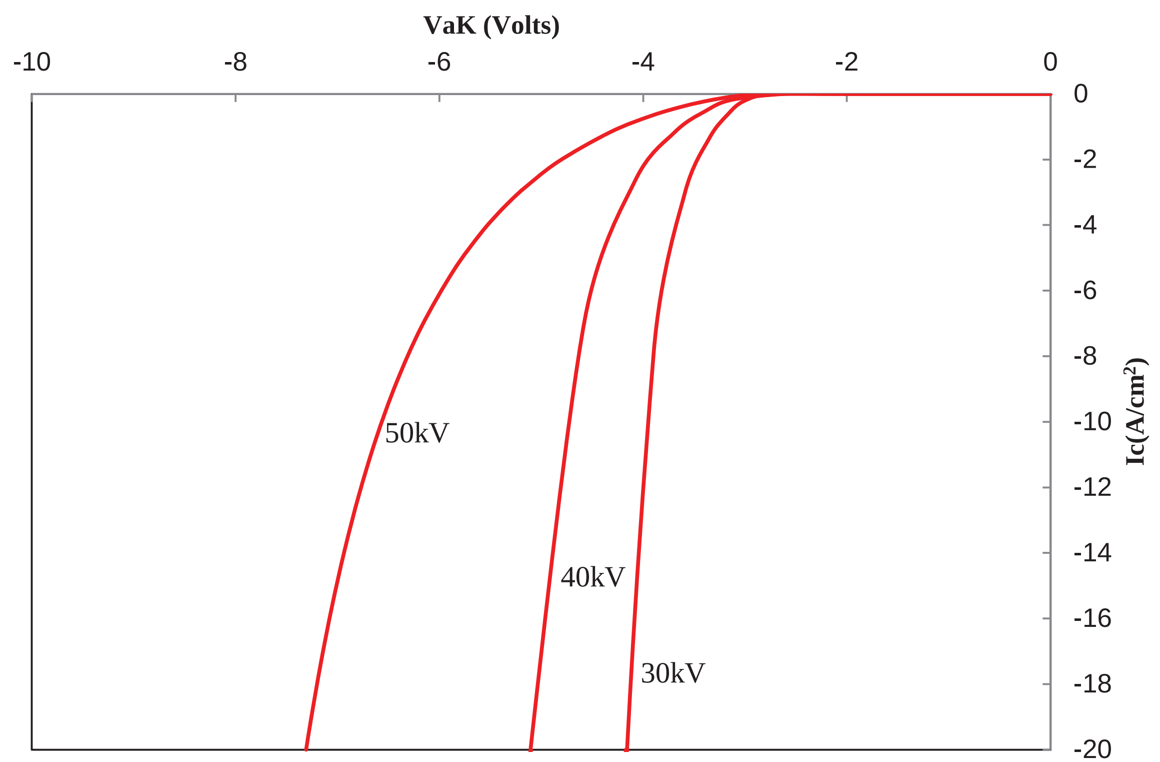
GTO thyristor demonstrate the best current carry capability and small T dependence

How about 50 kV thyristor?



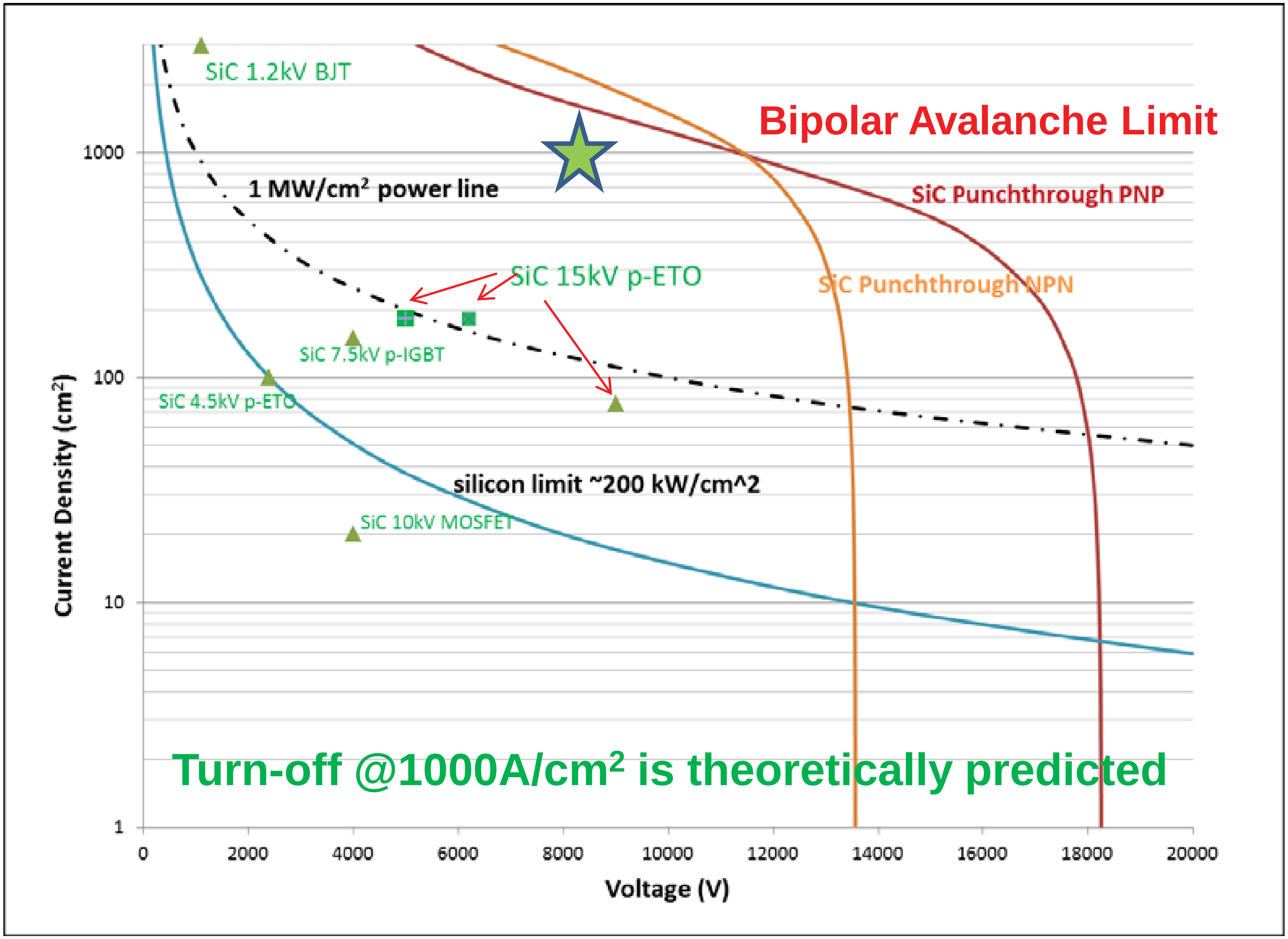
Current capability at 50 kV

p-GTO IV with $\tau\_HL=10\mu s$, good anode injection



Better lifetime enhancement will lower forward drop at 50 kV to < 5V

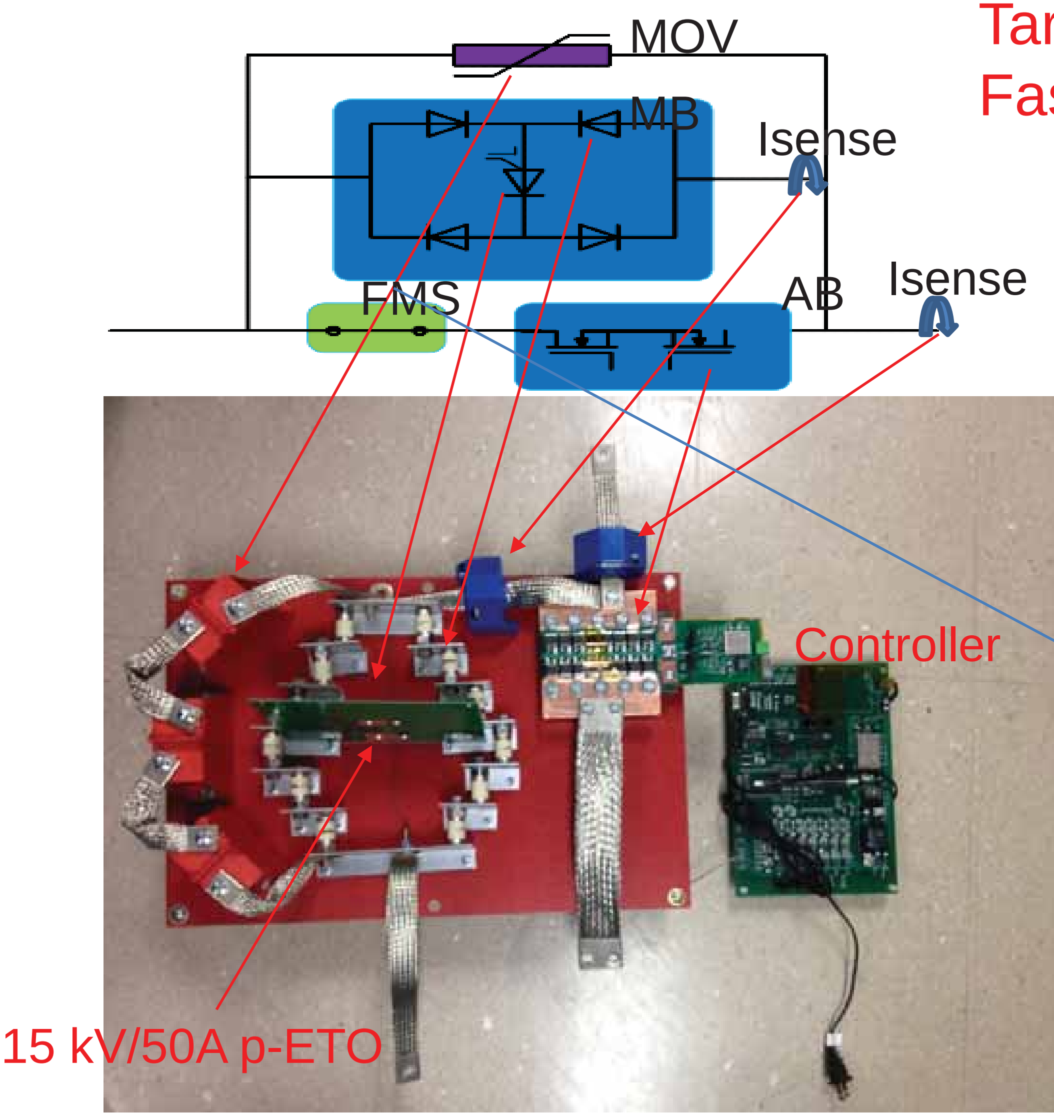
15 kV GTO/ETO Safe Operation Area



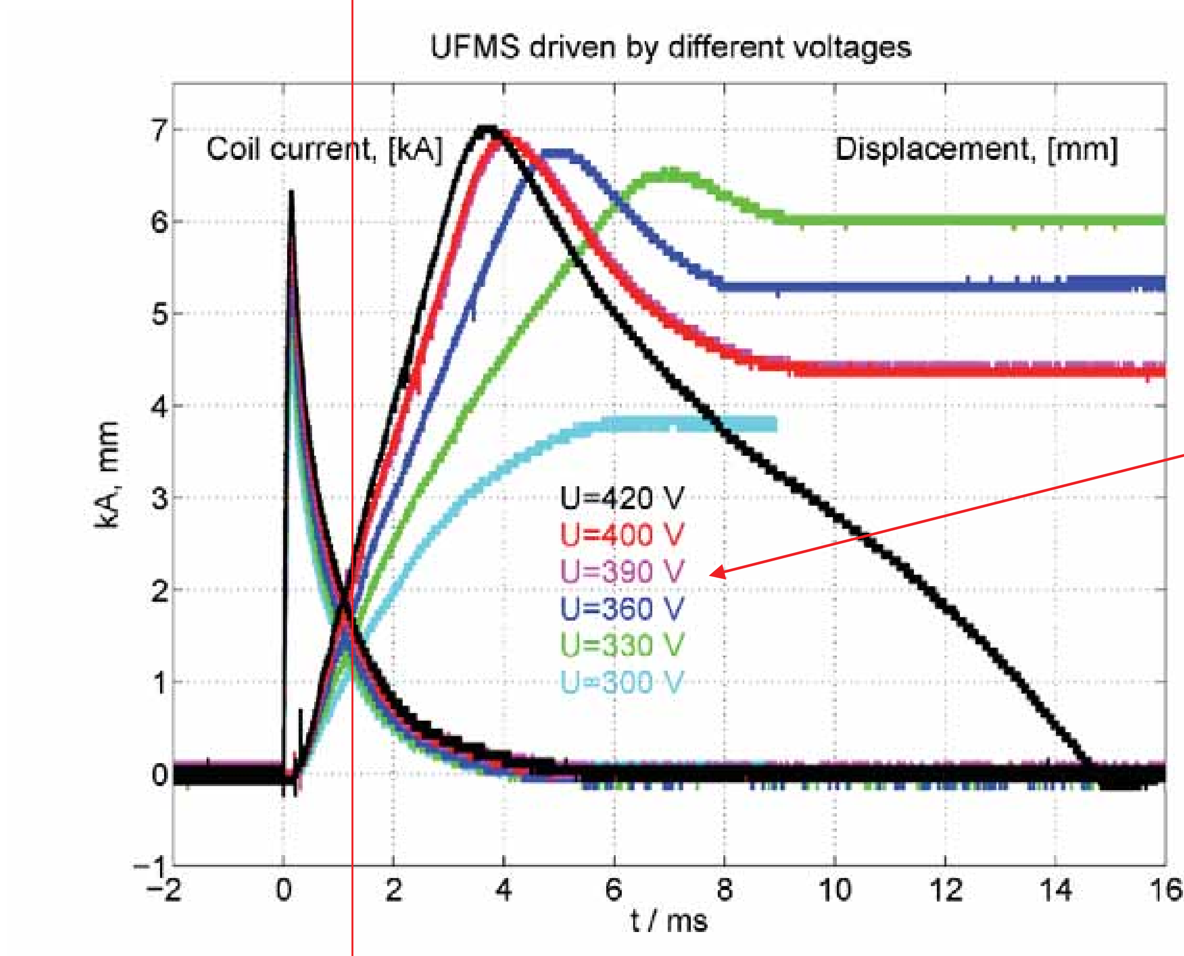
15 kV SiC p-ETO in Action: Hybrid Solid State Circuit Breaker

Target: 2 ms opening AC breaker

Fast enough as a DC breaker!



FMS: 1.5 ms opening speed



Cap bank voltage

15 kV withstand voltage separation achieved at around 1.5 ms

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) easer 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 a in a DC circuit breaker