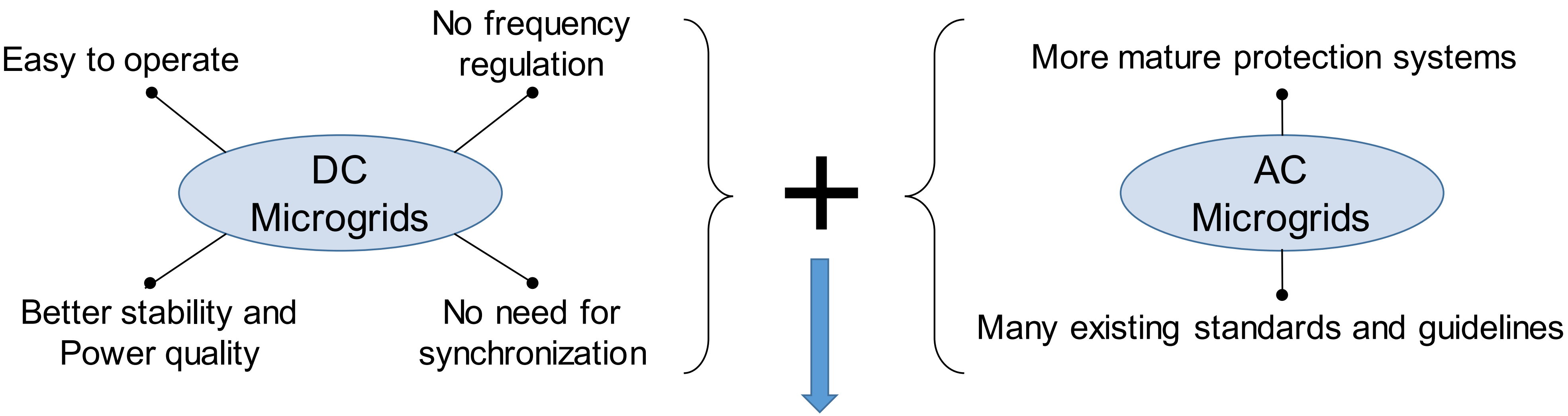
Asynchronous Microgrid Power Conditioning System

Nithin Kolli, Sanket Parashar, Raj Kumar Kokkonda,
Dr. Subhashish Bhattacharya, and Dr. Victor Veliadis
North Carolina State University

Background – 1

- Microgrids
  - Flexible, efficient, and adaptable
  - Reduces energy losses in transmission and distribution
- Type of energy resource dictates whether an ac or dc microgrid is deployed



- Hybrid Microgrids comprise both dc and ac bus, and offer the best of both microgrids

Background – 2

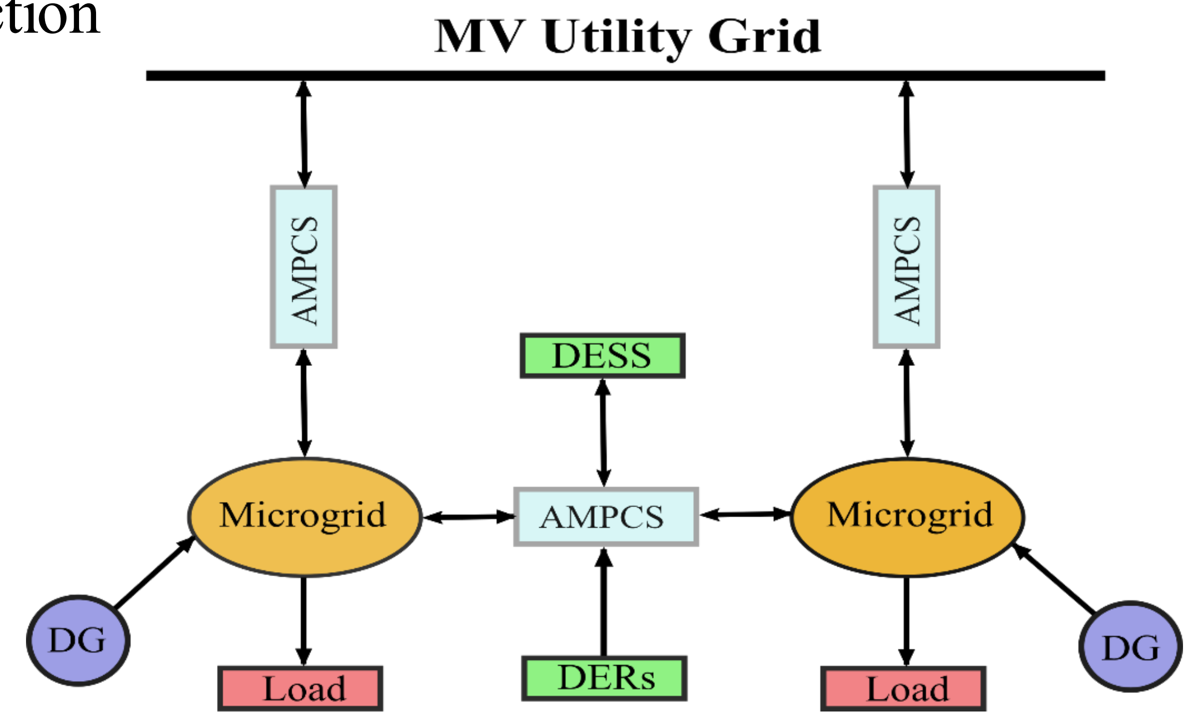
- Integration of Distributed Generators (DGs) to utility has challenges associated with:
  - Smart power flow control and conversion
  - Concerns over the voltage quality, protection issues, and grid stability
- DGs contribute to short-circuit currents that requires interruption by the circuit breakers

↓

- With the presence of non-synchronous or asynchronous microgrids, fault propagation can be prevented
- Microgrids will be consistently islanded and no additional costs needed for synchronization

Introduction – 1

- Asynchronous Microgrid Power Conditioning System (AMPCS) is an SST
- It has AC-DC-AC links to enable interconnection
- AMPCS can be used to connect:
    - A grid and a microgrid
    - Two microgrids
    - Interconnection of DERs and DESS



- AMPCS has grid-connected converters that interface with grid and microgrids and the dc-links enable asynchronous connections

Introduction – 2

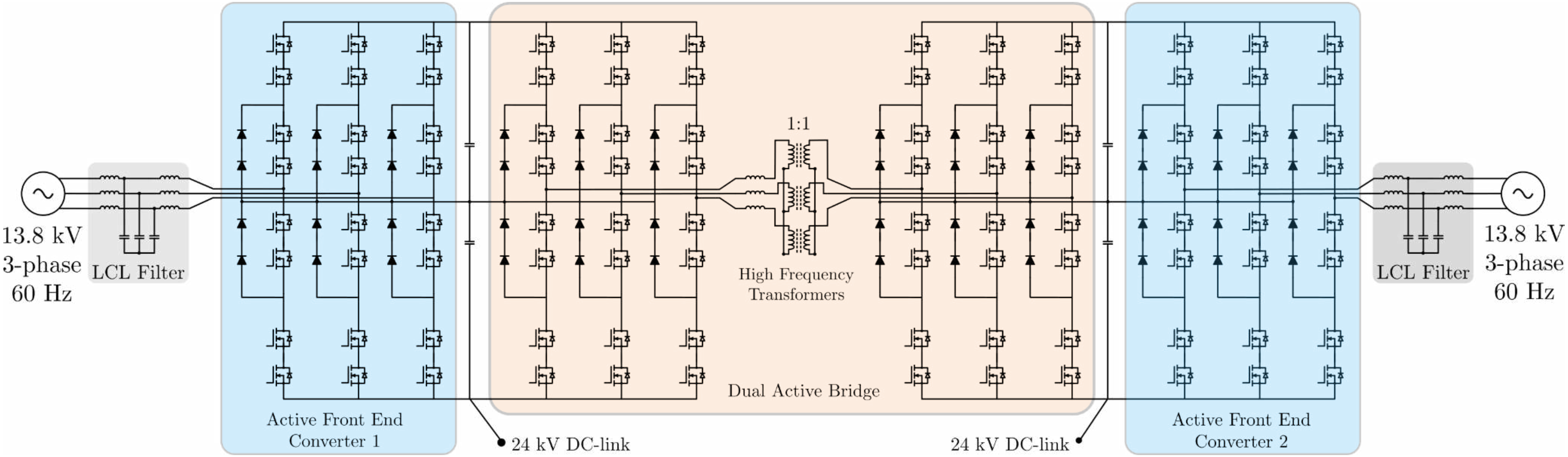
- Multiple approaches can be taken to interface a converter with MV ac or dc
  - Modular
  - Semi-modular
  - Single cell

Modular and Semi-modular configurations	Single cell configurations
▪ Advantage of using low-blocking voltage switches ▪ Economically beneficial ▪ Can offer potential benefits in manufacturing costs ▪ Benefits system redundancy in case of faults	▪ Lower system and control complexity ▪ Higher power density

Sources:
- J. E. Huber and J. W. Kolar, "Solid-state transformers: On the origins and evolution of key concepts," IEEE Industrial Electronics Magazine, vol. 10, no. 3, pp. 19–28, 2016.
- M. Vasiladiotis and A. Rufer, "A modular multiport power electronic transformer with integrated split battery energy storage for versatile ultrafast ev charging stations," IEEE Transactions on Industrial Electronics, vol. 62, no. 5, pp. 3213–3222, 20

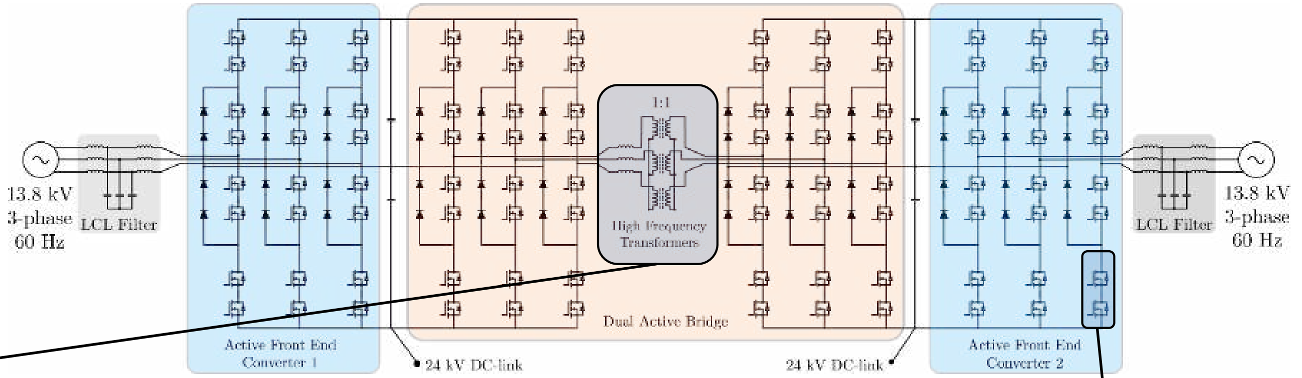
Introduction – 3

- AMPCS is a three-stage, single-cell topology that interfaces medium voltage 13.8 kV grid
- Implemented using 10 kV SiC MOSFETs and 10 kV SiC JBS Diodes in series-connected configuration

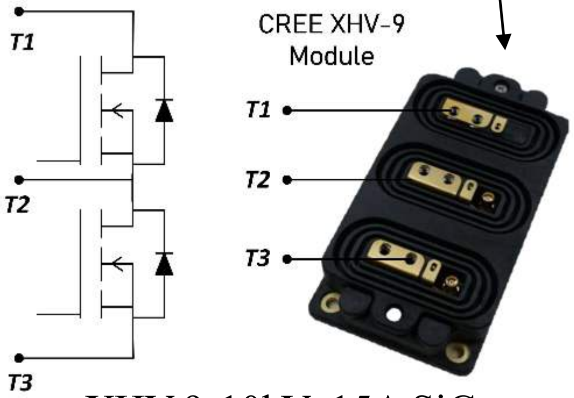


System Specifications

High Frequency Transformers
35 kVA, 20 kHz, 1:1



Parameter	*Value*	Parameter	*Value*
Rated Power	100 kVA	Net DC-link capacitance	90 µF
Rated AC voltage	13.8 kV	Grid side inductor	7.7 mH
Grid frequency	50/60 Hz	Filter capacitor	2 μF
DC-link voltage	24 kV	Converter side inductor	15.5 mH
f_{sw} of Inverter	10 kHz	Damping resistor	120 Ω
f_{sw} of DAB	20 kHz	Transformer ratio	1:1



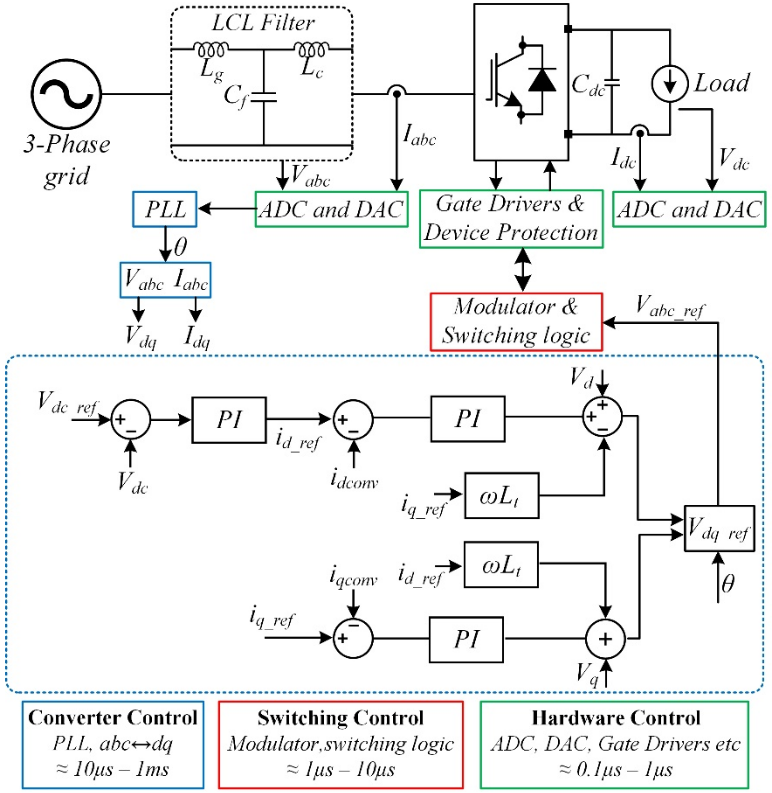
XHV-9 10kV, 15A SiC
MOSFET Module

- Two MV grid-connected converters interfaced by a Dual-Active Bridge (DAB)

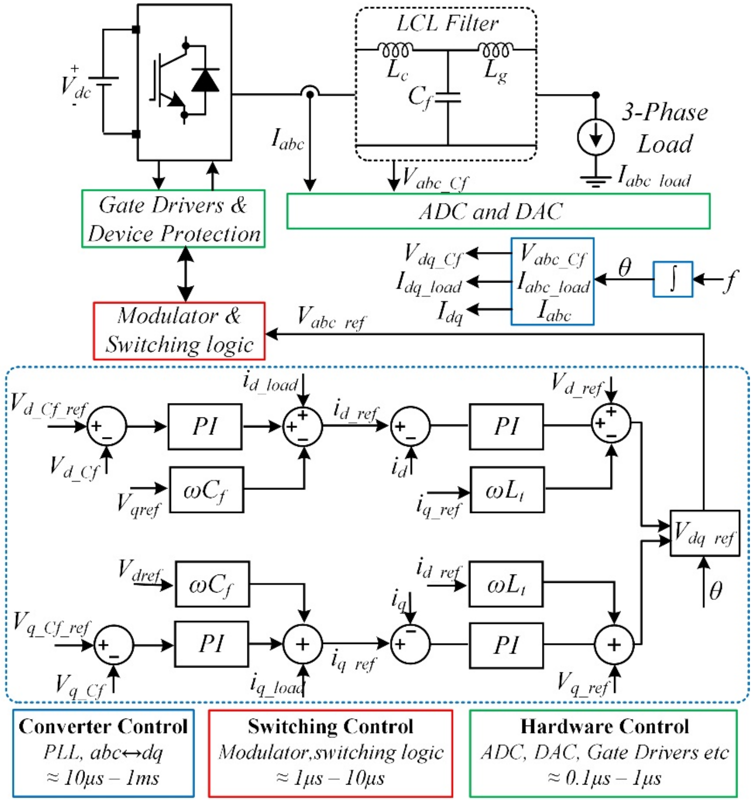
Controller Overview

Grid-connected converters

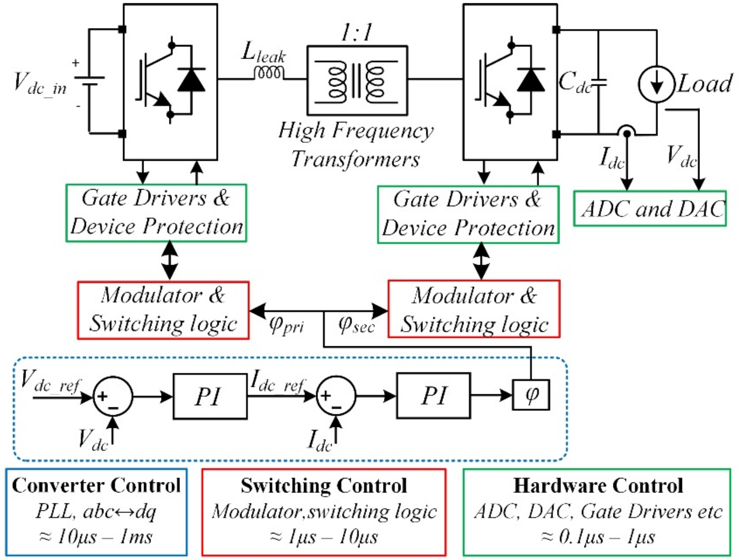
Active Front End Converter (Grid-Following)



Grid Forming Control



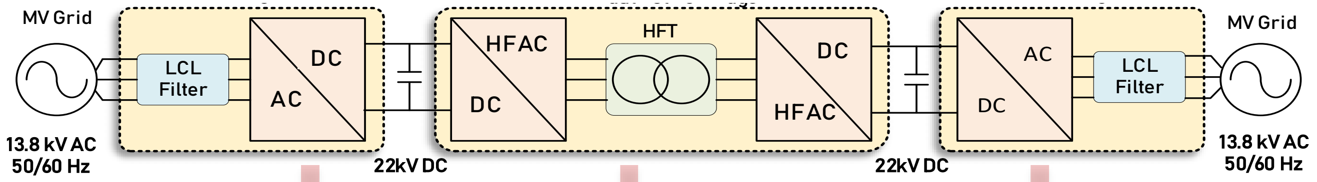
Dual Active Bridge



Sources:

- N. Kolli, H. Nath, S. Parashar, R. K. Kokkonda, S. Bhattacharya and V. Veliadis, "Operating Mode Analysis and Controller Design for Medium Voltage Asynchronous Microgrid Power Conditioning System," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 1205-1211a, doi: 10.1109/ECCE53617.2023.10362555.

Operating Modes

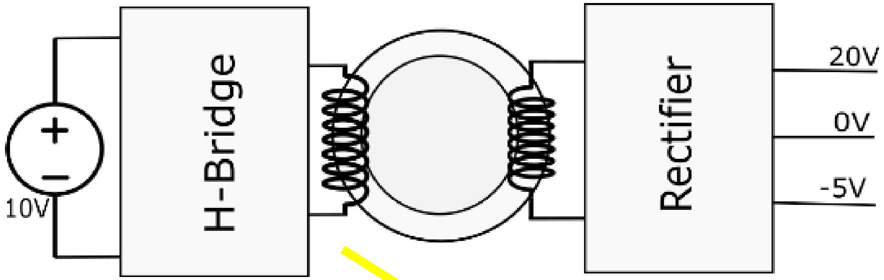


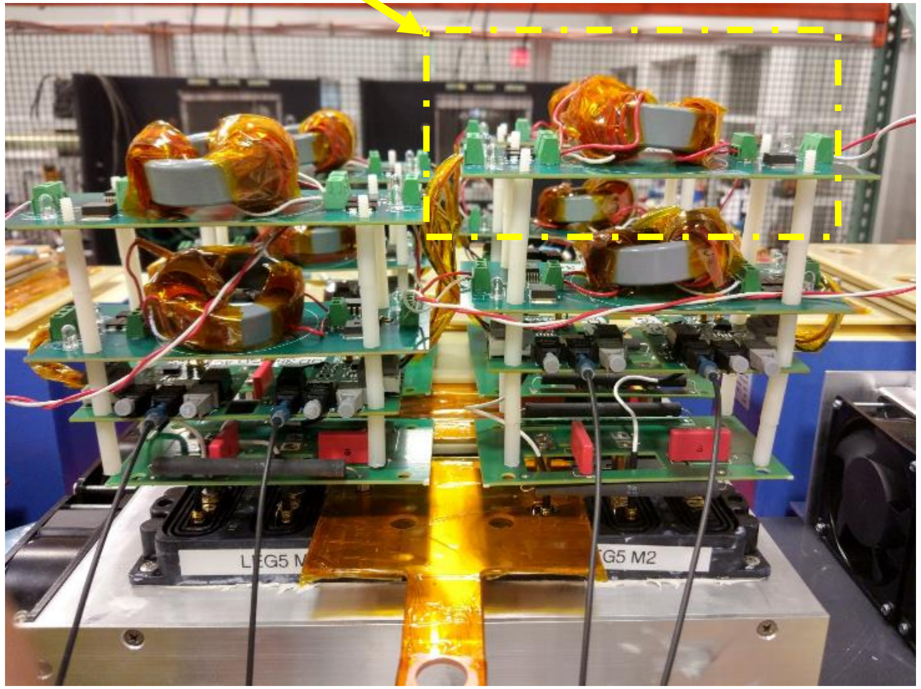
Operating Mode	State of Operation and Control					
	Grid 1	Converter 1	DAB	Converter 2	Grid 2	Comments
Start	Normal	Uncontrolled rectifier	Idle	Uncontrolled rectifier	Normal	The dc-links are energized
Shut	Normal or Faulty	Disconnected	Idle	Disconnected	Normal or Faulty	The dc-links are de-energized
1	Normal	AFEC	Current Control	AFEC	Normal	Stiff grids on both sides
2	Normal	AFEC	Voltage Control	GFC	Weak grid	Grid-2 needs support
3	Weak grid	GFC	Voltage Control	AFEC	Normal	Grid-1 needs supprt
4	Faulty	LVRT/HVRT - AFEC	Voltage Control	AFEC	Normal	Low/High Voltage Ride-Through mode
5	Normal	AFEC	Voltage Control	LVRT/HVRT - AFEC	Faulty	Low/High Voltage Ride-Through mode
6	Faulty	LVRT/HVRT - AFEC	Idle	LVRT/HVRT - AFEC	Faulty	Low/High Voltage Ride-Through mode

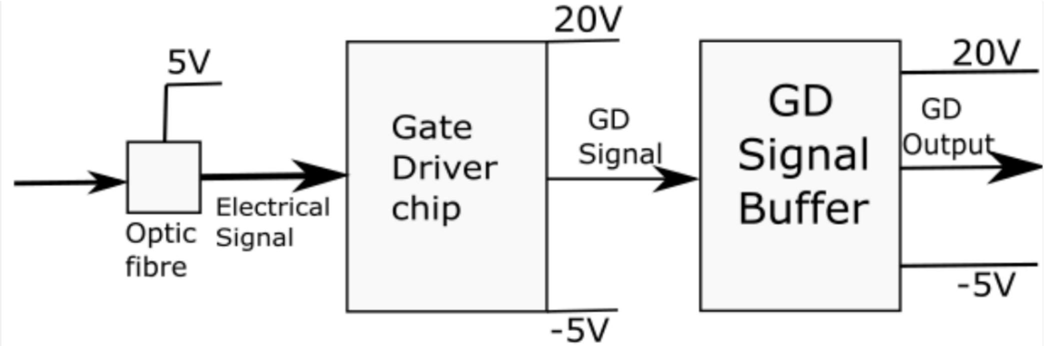
Sources:

- N. Kolli, H. Nath, S. Parashar, R. K. Kokkonda, S. Bhattacharya and V. Veliadis, "Operating Mode Analysis and Controller Design for Medium Voltage Asynchronous Microgrid Power Conditioning System," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 1205-1211a, doi: 10.1109/ECCE53617.2023.10362555.

Enabling Technologies – Gate Driver + Power Supply







Isolated power supply provides +20V and -5V for each gate driver

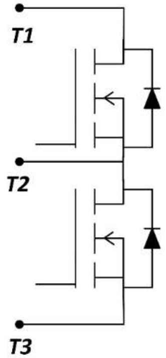
Sources:

- N. Kolli et al., "Design Considerations of Three Phase Active Front End Converter for 13.8 kV Asynchronous Microgrid Power Conditioning System enabled by Series Connection of Gen-3 10 kV SiC MOSFETs," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1211-1218, doi: 10.1109/ECCE47101.2021.9594975.

Enabling Technologies – Short Circuit Protection

- **Desat based short circuit protection is employed**
  - A galvanic isolated fault communication link is established on the board for two series-connected MOSFETs and fault detected in either of them is communicated across this link and turns off both the series-connected MOSFETs.

Each board has two gate drivers for series-connected MOSFETs



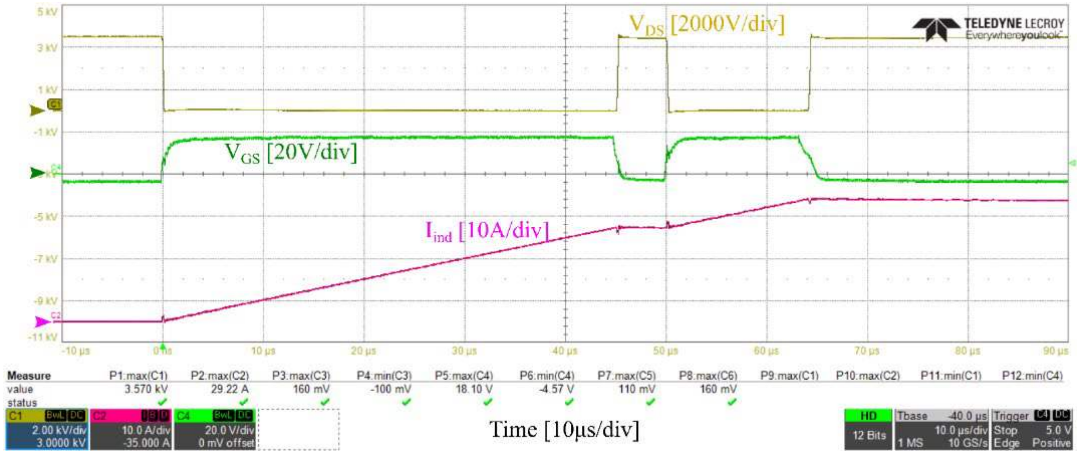
CREE XHV-9 Module

Sources:
- N. Kolli et al., "Design Considerations of Three Phase Active Front End Converter for 13.8 kV Asynchronous Microgrid Power Conditioning System enabled by Series Connection of Gen-3 10 kV SiC MOSFETs," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1211-1218, doi: 10.1109/ECCE47101.2021.9594975.

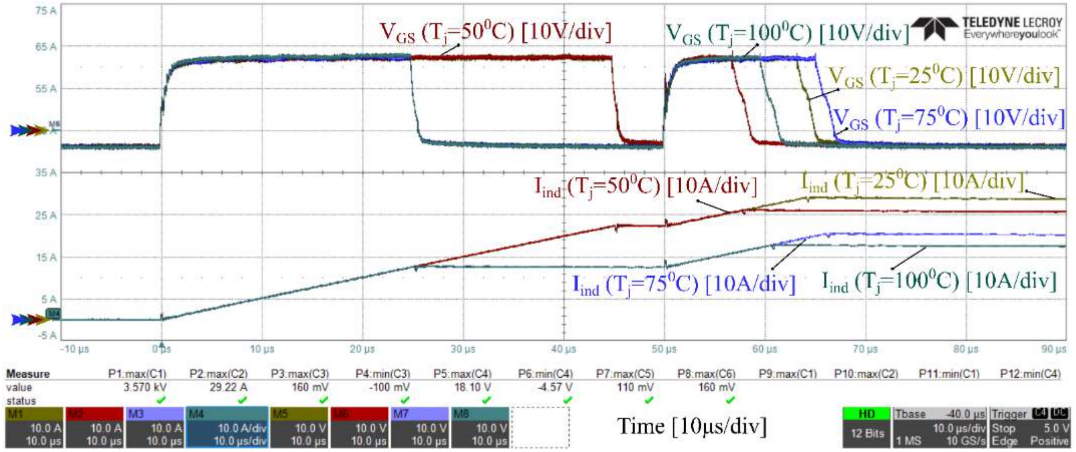
Enabling Technologies – Short Circuit Protection

- **Over current trip levels**
  - Trip current levels at different temperatures are evaluated experimentally on a Double Pulse Test circuit

Over-current trip levels	
Temperature	**Current trip level**
25ºC	28 A
50ºC	23 A
75ºC	19 A
100ºC	17 A



Experimental results of DPT conducted at 25ºC with 3500 dc-link

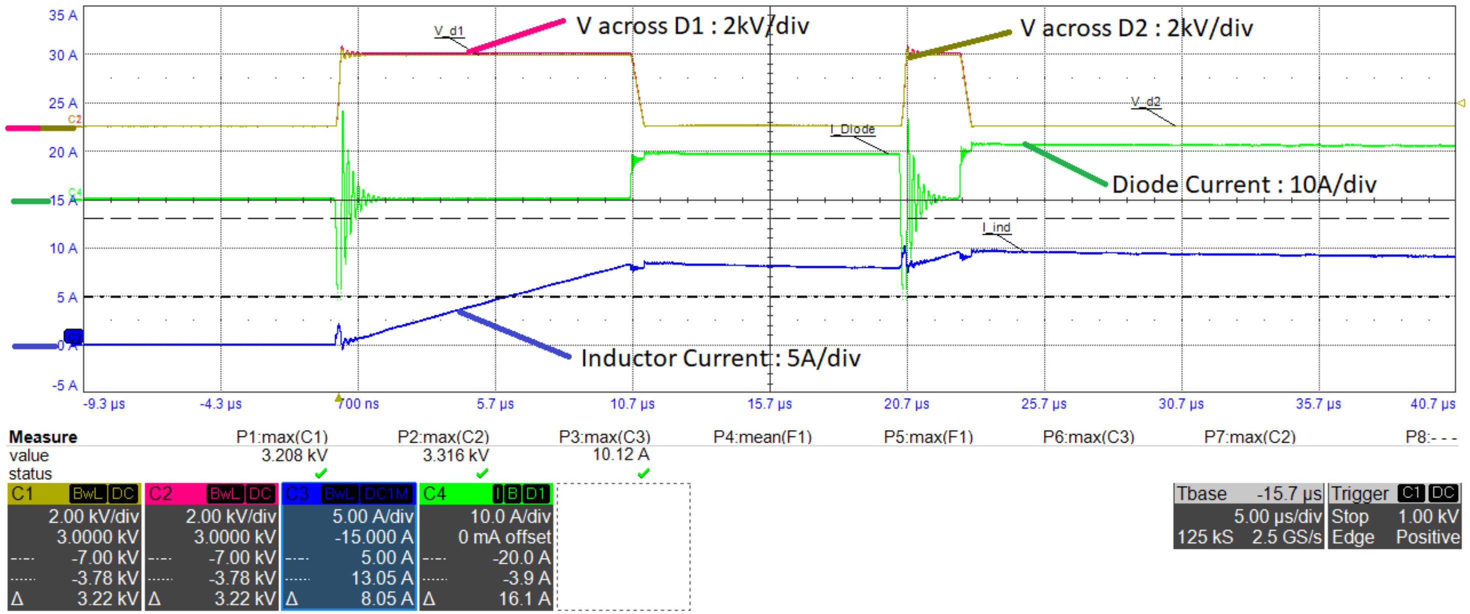


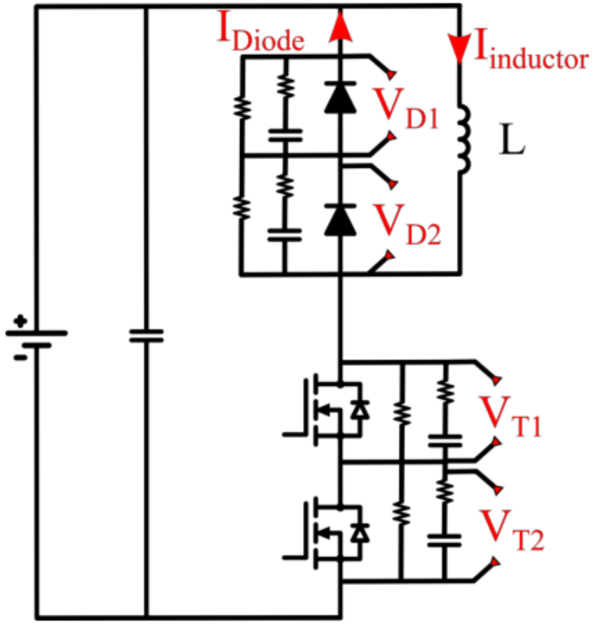
Experimental results of DPT conducted at 25ºC, 50ºC, 75ºC, and 100ºC

Sources:
- N. Kolli et al., "Design Considerations of Three Phase Active Front End Converter for 13.8 kV Asynchronous Microgrid Power Conditioning System enabled by Series Connection of Gen-3 10 kV SiC MOSFETs," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1211-1218, doi: 10.1109/ECCE47101.2021.9594975.

Enabling Technologies – Series-connection of Diodes

- **Series connection of SiC JBS Diodes**
  - RC snubbers are used for voltage balancing
  - Double Pulse Test is conducted at 6 kV dc-link
  - Voltage imbalance of 50 V (0.8%) is observed



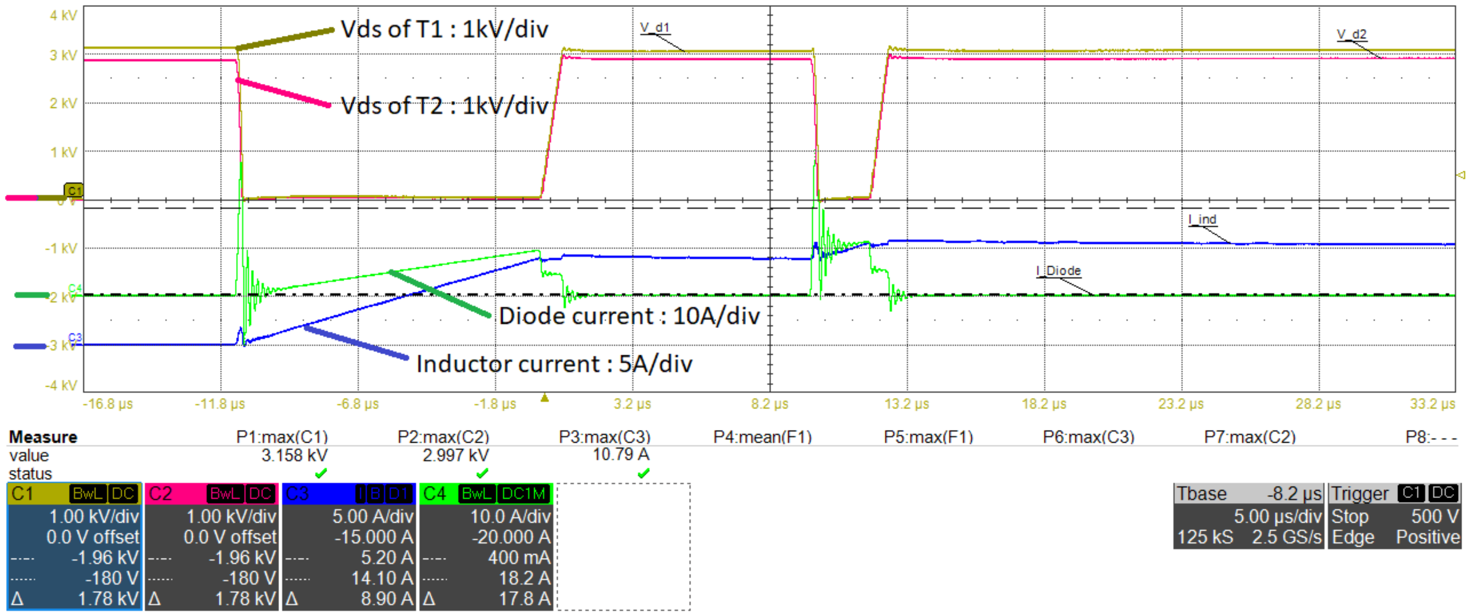


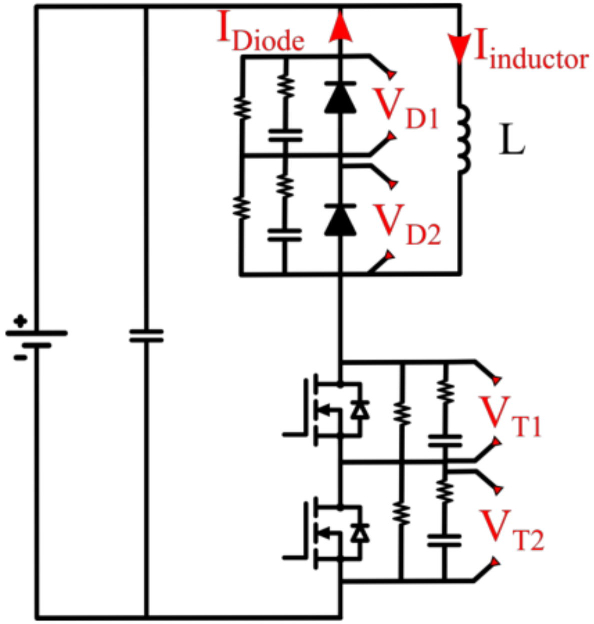
Voltage sharing across series-connected 10 kV SiC JBS diodes at 6 kV dc-link

Sources:
- A. Kumar, S. Parashar, N. Kolli and S. Bhattacharya, "Asynchronous Microgrid Power Conditioning System Enabled by Series Connection of Gen-3 SiC 10 kV MOSFETs," 2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Atlanta, GA, USA, 2018, pp. 60-67, doi: 10.1109/WiPDA.2018.8569088.

Enabling Technologies – Series-connection of MOSFETs

- **Series connection of SiC MOSFETs**
  - RC snubbers are used for voltage balancing
  - Double Pulse Test is conducted at 6 kV dc-link
  - Voltage imbalance of 230 V (3.8%) is observed





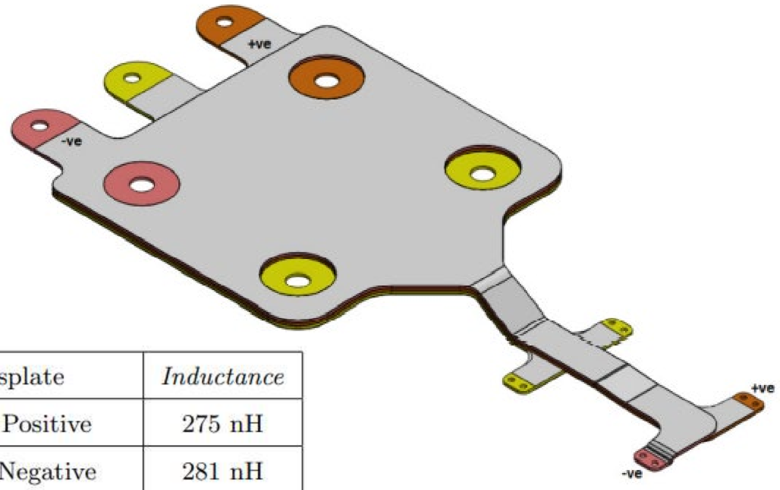
Voltage sharing across series-connected 10 kV SiC MOSFETs at 6 kV dc-link

Sources:

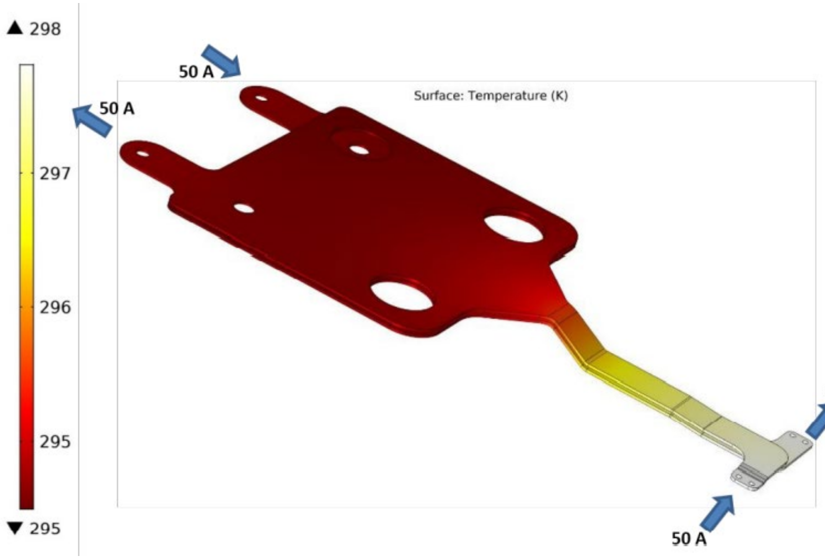
- A. Kumar, S. Parashar, N. Kolli and S. Bhattacharya, "Asynchronous Microgrid Power Conditioning System Enabled by Series Connection of Gen-3 SiC 10 kV MOSFETs," 2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Atlanta, GA, USA, 2018, pp. 60-67, doi: 10.1109/WiPDA.2018.8569088.

Enabling Technologies – Busbar

- **DC busbar design**
  - Sandwiched busbar structure to minimize the dc-loop inductance
  - Inductance analysis is done in Q3D
    - Effective dc-loop inductance is found as 8.6 nH/inch
  - Joule heating analysis is done in COMSOL
    - Temperature rise of 5°C is observed for 50 A continuous current

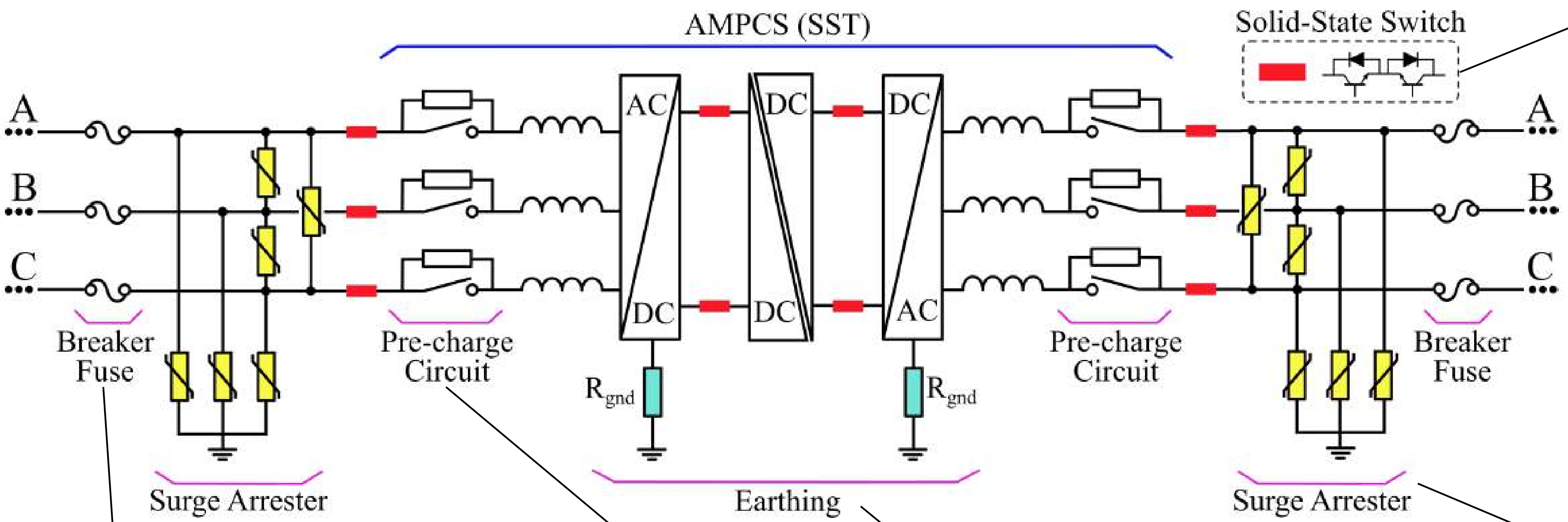


Busplate	*Inductance*
Only Positive	275 nH
Only Negative	281 nH
Sandwiched Busbar	60 nH



Sources:
- N. Kolli et al., "Design Considerations of Three Phase Active Front End Converter for 13.8 kV Asynchronous Microgrid Power Conditioning System enabled by Series Connection of Gen-3 10 kV SiC MOSFETs," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1211-1218, doi: 10.1109/ECCE47101.2021.9594975.

Enabling Technologies – Protection



- Fast-acting bidirectional soli-state switches are used as circuit breakers for fault isolation
- Two 15 kV, 40 A SiC IGBTs are connected in back-to-back configuration to create a solid-state switch

- Used for backup protection
- ABB CEF-type fuse links are used
- Rated breaking current off 35 A

- MV grid-connected converters act as diode rectifiers during start-up process
- To limit inrush currents while charging the dc-link pre-charging resistors are used, which will be bypassed after charging

- MV side grid typically does not have protective earth neutral (PEN)
- Earthing through an impedance is necessary
- Value of impedance is typically decided by short-circuit currents

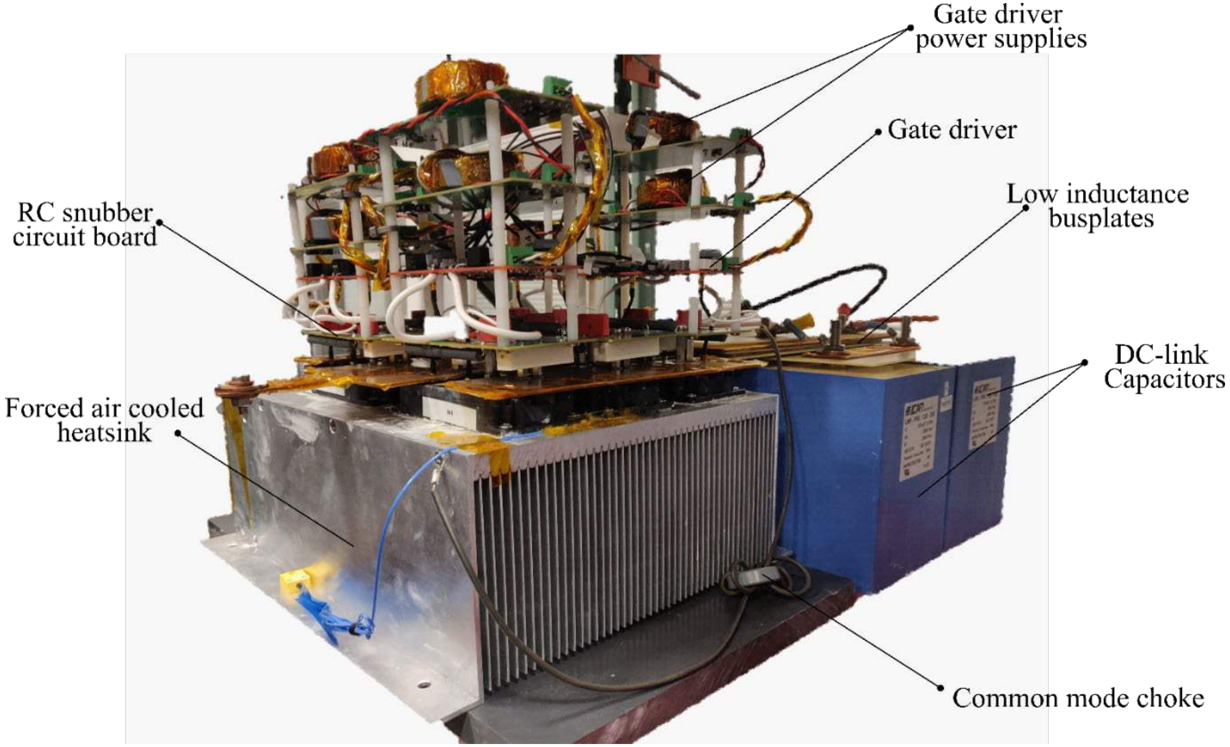
- Metal-Oxide Varistors (MOVs) are used
- They clamp the surge voltages
- Hitachi's Polim-K series are used

Sources:

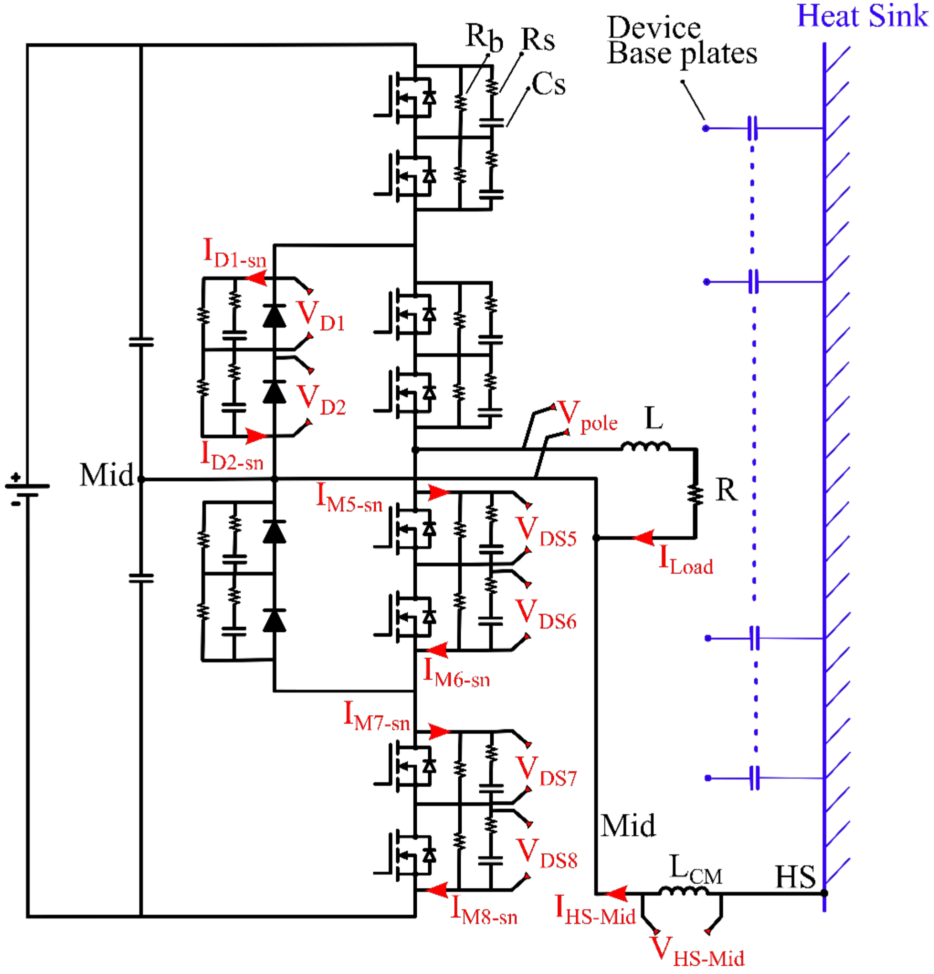
- N. Kolli et al., "Design of Asynchronous Microgrid Power Conditioning System with Gen-3 10 kV SiC MOSFETs for MV Grid Interconnection," 2024 IEEE Applied Power Electronics Conference (APEC), Long Beach, CA, USA, 2024.

Hardware Demonstration – NPC Pole

- **Three-level NPC pole**
  - All poles are tested individually and subjected to continuous operation tests



Hardware setup of a modular 3L-NPC pole

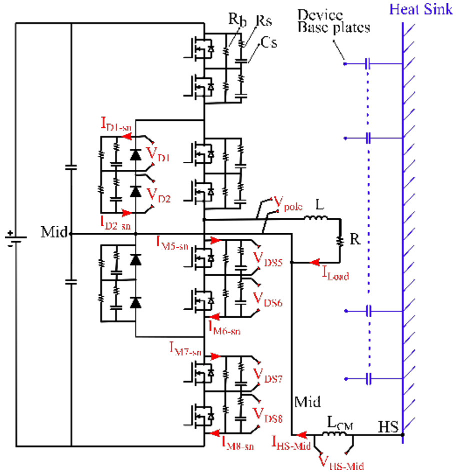


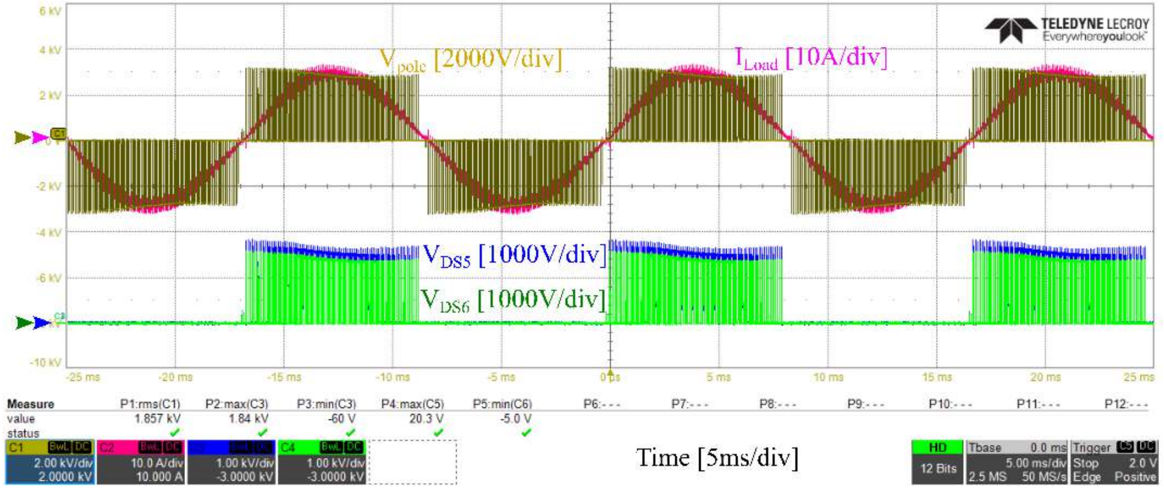
Schematic of NPC pole highlighting the test measurements

Sources:
- N. Kolli et al., "Design Considerations of Three Phase Active Front End Converter for 13.8 kV Asynchronous Microgrid Power Conditioning System enabled by Series Connection of Gen-3 10 kV SiC MOSFETs," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1211-1218, doi: 10.1109/ECCE47101.2021.9594975.

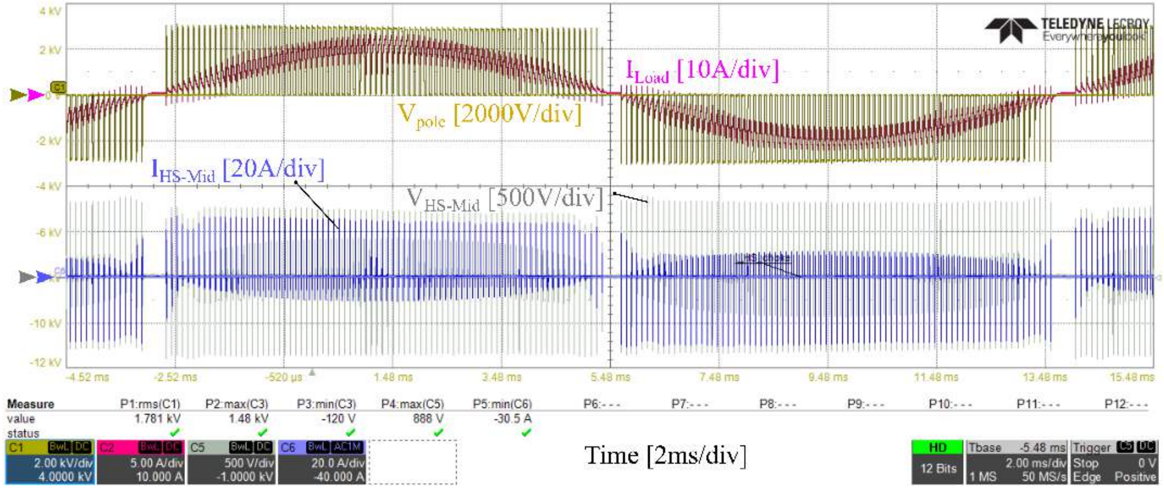
Experimental Results – NPC Pole

Experimental results summary	
Parameter	**Value**
Power	14 kW
DC-link	5.8 kV
Modulation index	0.7
Losses	560 W
Heat sink temperature	40°C
Heatsink-Midpoint voltage peak	800 V
Common mode current peak	20 A





Pole-midpoint voltage, load current, voltage across series connected switches



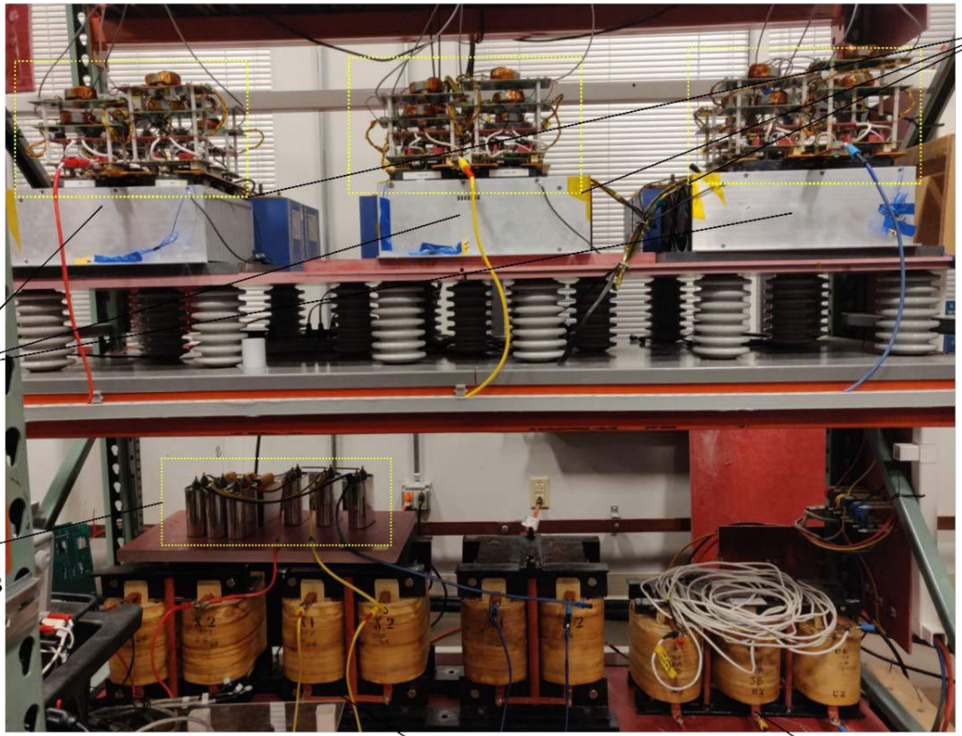
Pole-midpoint voltage, load current, heatsink-midpoint voltage and common mode current in choke

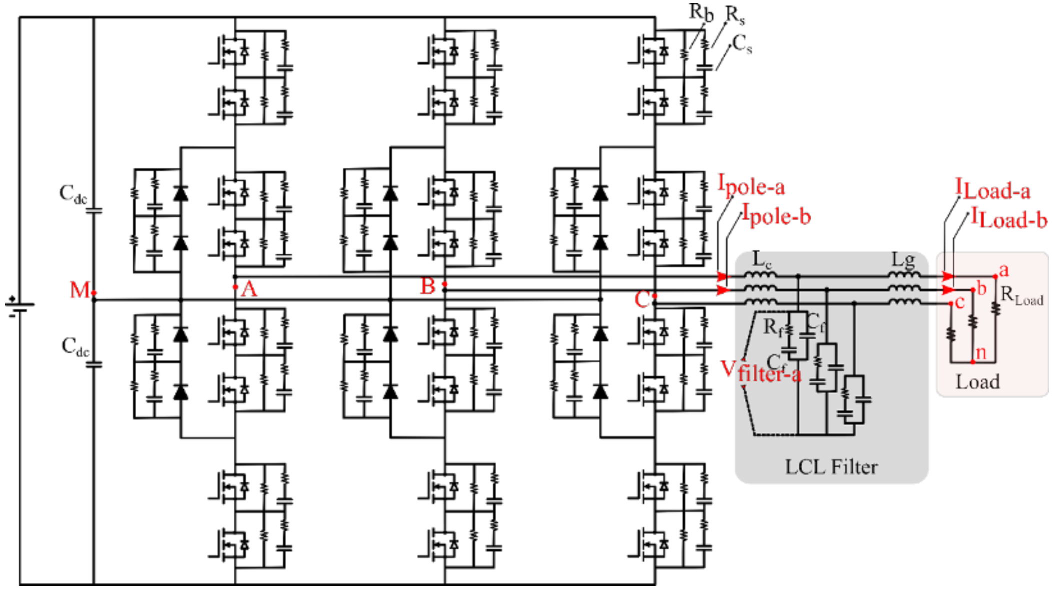
Sources:

- N. Kolli et al., "Design Considerations of Three Phase Active Front End Converter for 13.8 kV Asynchronous Microgrid Power Conditioning System enabled by Series Connection of Gen-3 10 kV SiC MOSFETs," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1211-1218, doi: 10.1109/ECCE47101.2021.9594975.

Hardware Demonstration – Three-phase NPC

- **Three-phase three-level NPC Converter**
  - Three modular poles are put together for testing in 3P3L-NPC



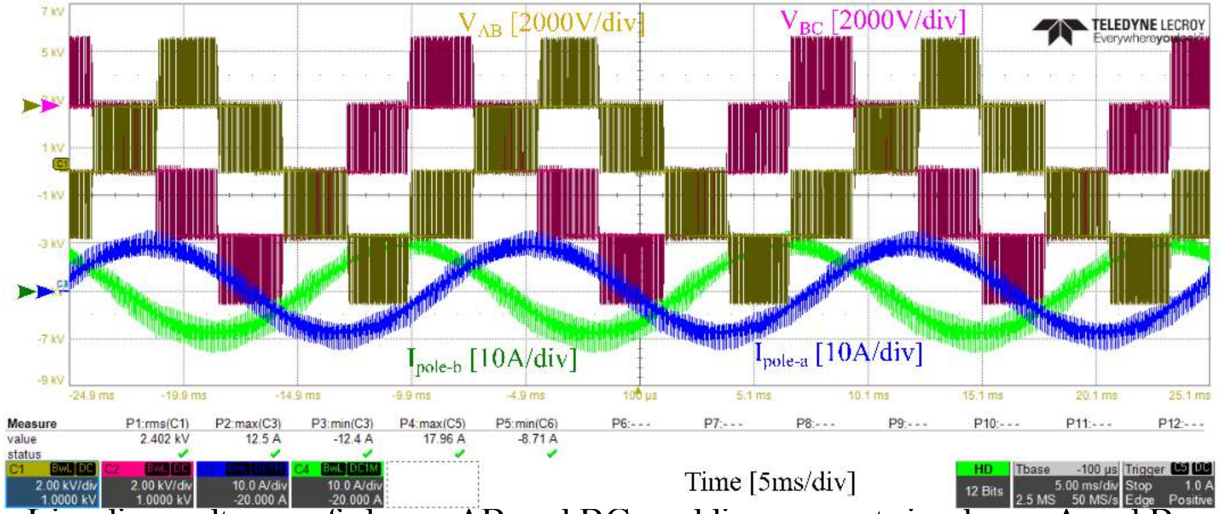


Sources:

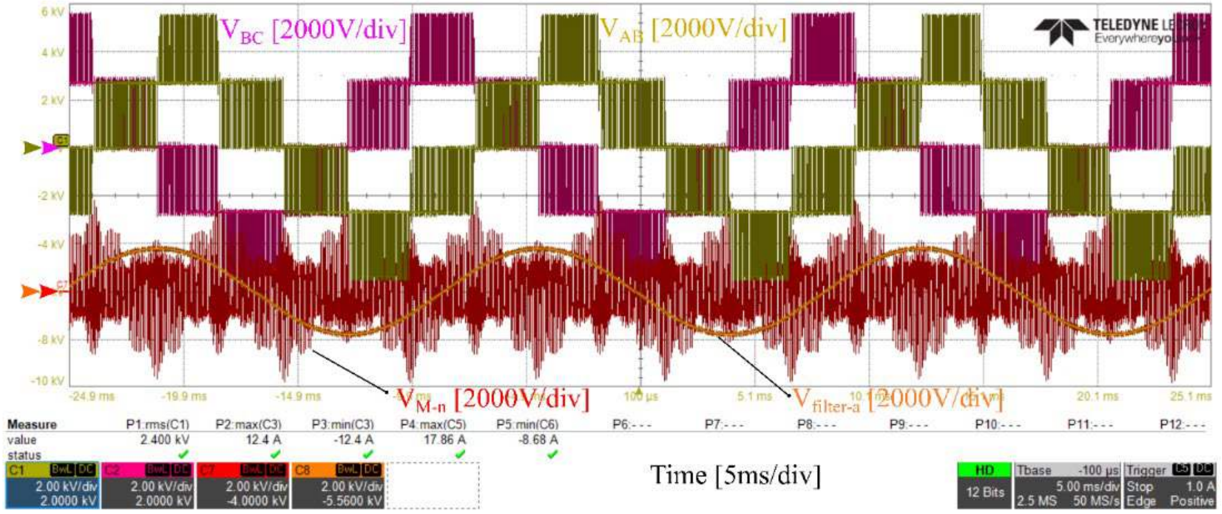
- N. Kolli et al., "Design Considerations of Three Phase Active Front End Converter for 13.8 kV Asynchronous Microgrid Power Conditioning System enabled by Series Connection of Gen-3 10 kV SiC MOSFETs," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1211-1218, doi: 10.1109/ECCE47101.2021.9594975.

Experimental Results – Three-phase NPC

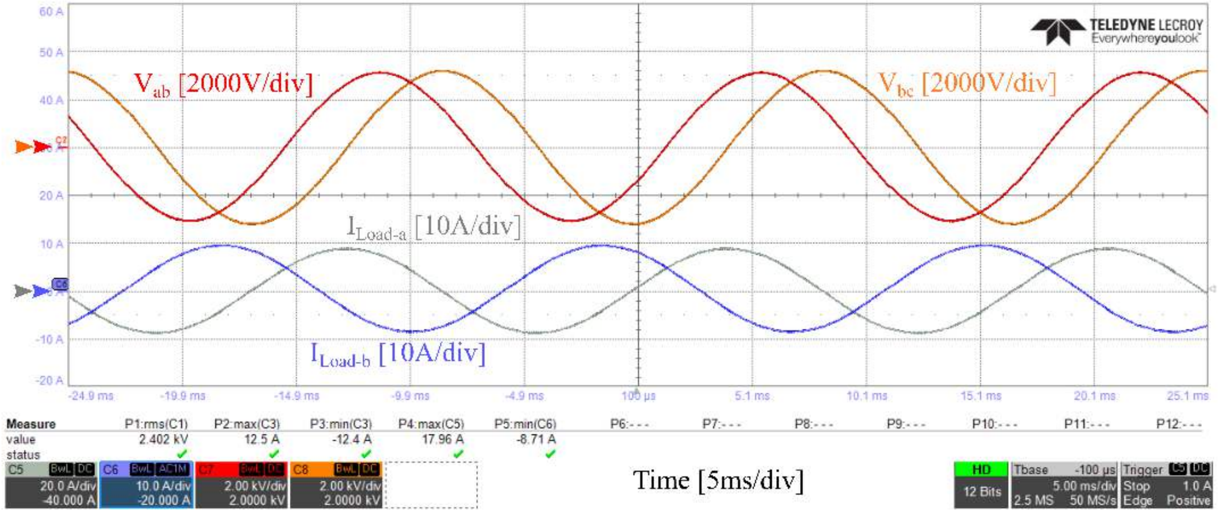
Experimental results summary	
Parameter	**Value**
Power	25 kW
DC-link	5.5 kV
Modulation index	0.7
Peak filter capacitor voltage	1800 V



Line-line voltages of phases AB and BC, and line currents in phases A and B



Line-line voltages of phases AB and BC, midpoint to neutral point voltage, and voltage across filter capacitor



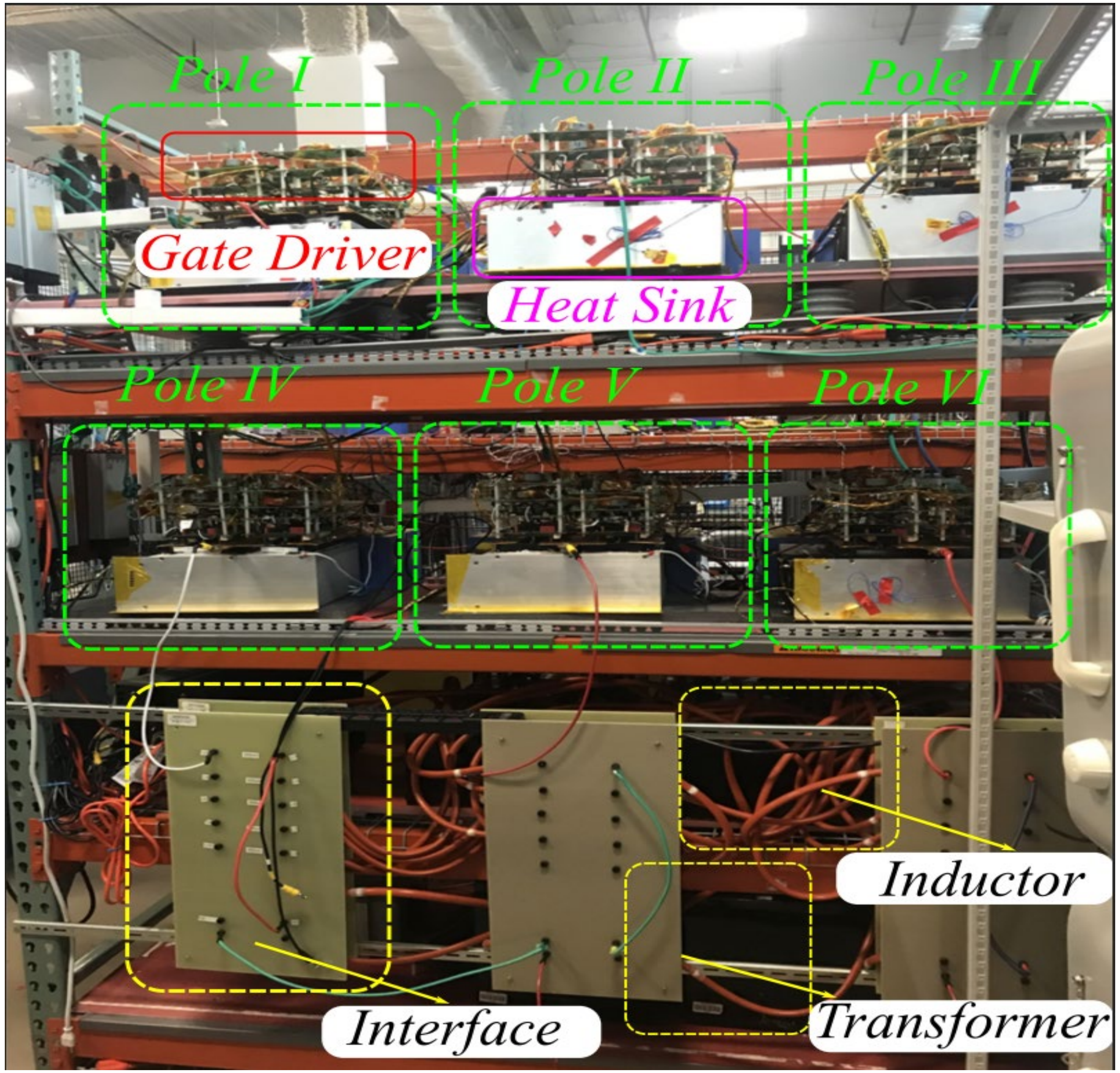
Line-line voltages measured at the load points ab and bc, and load currents in phases A and B

Hardware Demonstration – Three-phase DAB

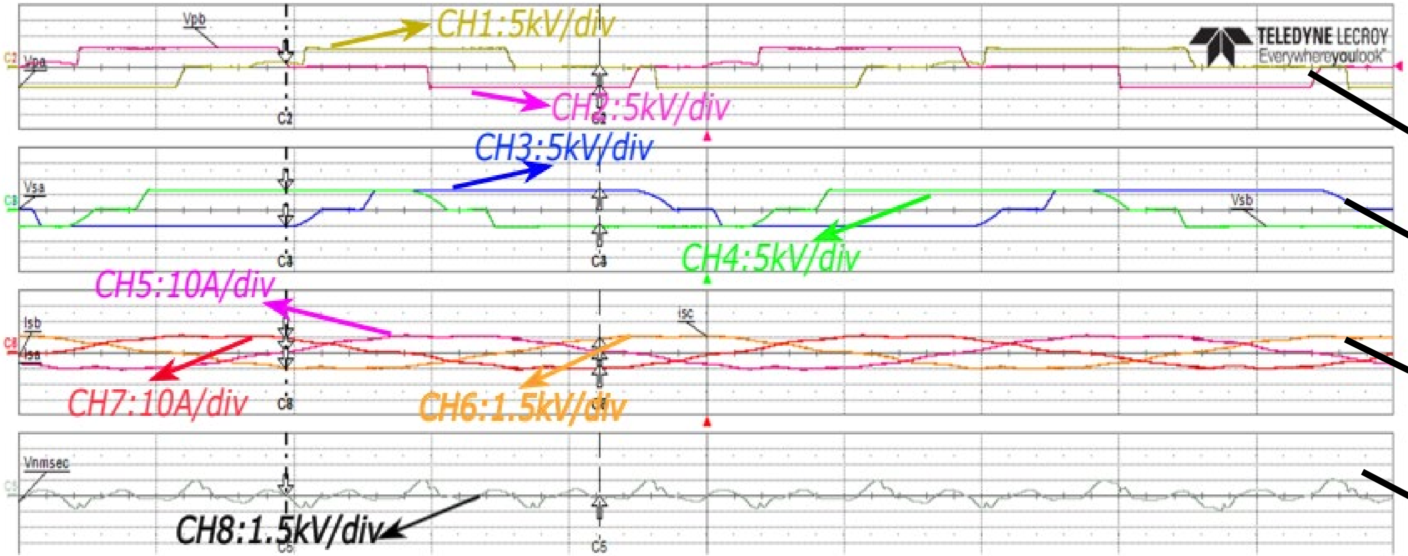
- **Three-phase three-level NPC DAB**
  - Six modular poles are put together for testing in 3P3L-NPC DAB

Transformer Specifications

Parameter	Value
Turns ration	1:1
kVA rating	35kVA
Acceptable temperature rise in transformer terminal	120C
Primary Voltage	3.395kV, 4.5kV peak
Secondary Voltage	3.395kV, 4.5kV peak
Primary current	20A
Secondary current	20A
Frequency	20kHz
Magnetization inductance (from primary)	300mH, 10
Parasitic capacitance (inter-turn Cp)	¡ 1200pF
Isolation primary to secondary	20kV rms
Efficiency	99



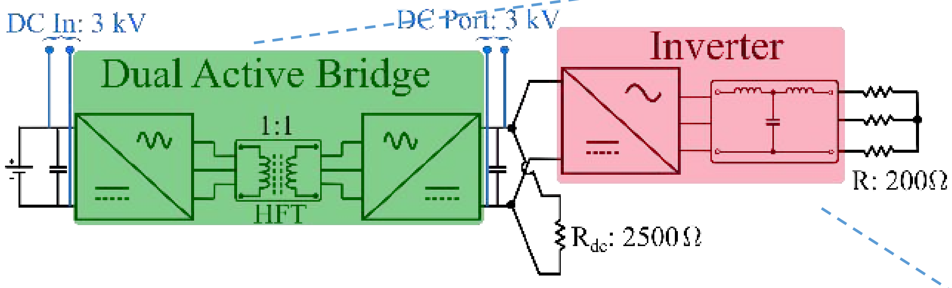
Experimental Results – Three-phase DAB

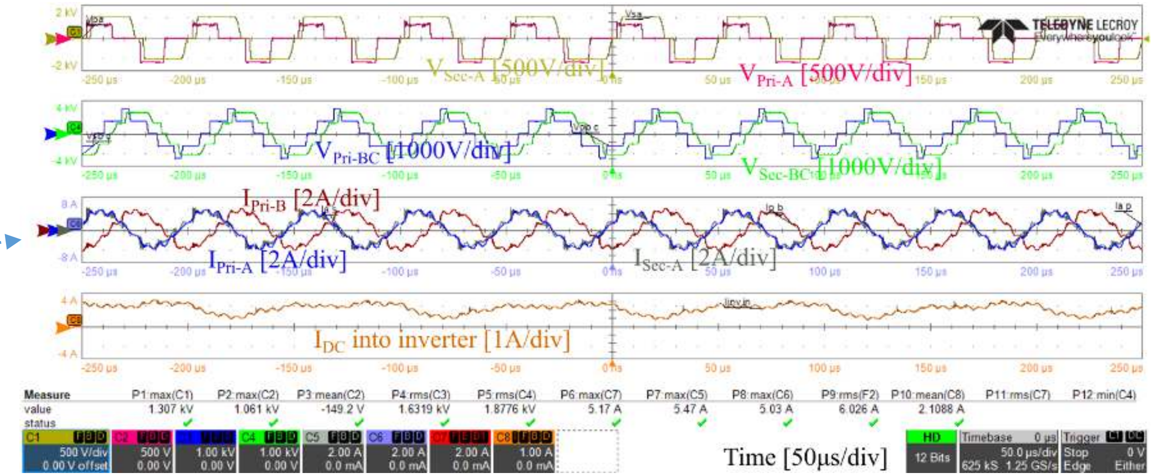


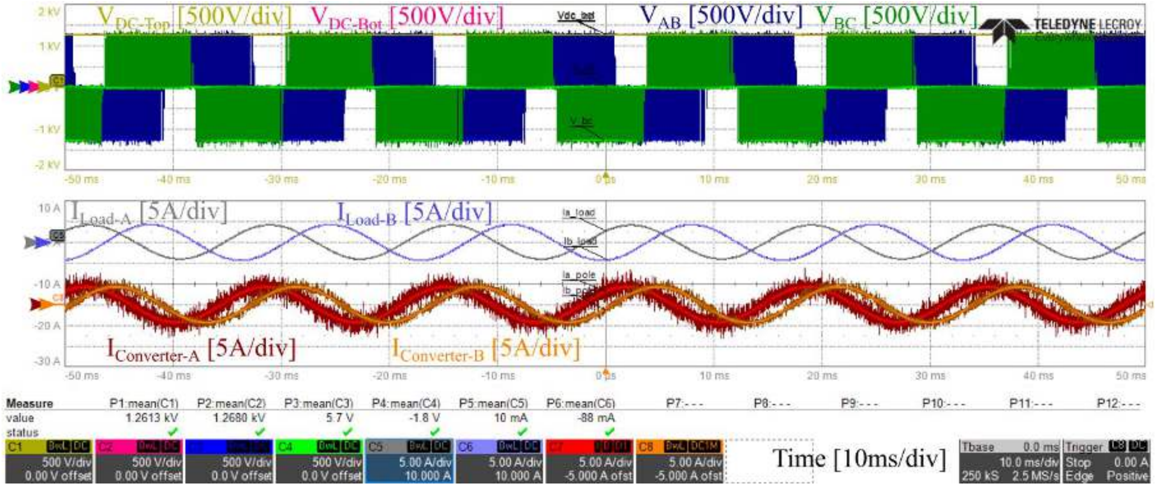
Experimental result:
Three-phase three-level DAB at **6.5 kV** DC bus and **28 kW** load

CH1, CH2: Phase A, Phase B primary voltages – 5 kV/div
CH3, CH4: Phase A, Phase B secondary voltage – 5 kV/div
CH5, CH6, CH7: Phase A, Phase B, Phase C transformer currents – 10 A/div
CH8: Neutral point voltage – 1.5 kV/div

Experimental Results – Cascaded AFE + DAB







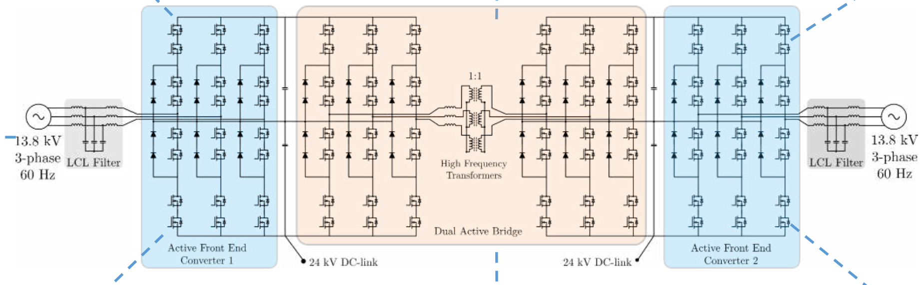
AMPCS Project – Research Outcomes

High voltage Gate Driver power supply design

Snubber optimization for series-connected JBS Diodes and SiC MOSFETs

Gate Driver for series-connected devices

A novel Grid Forming Control strategy for frequency support



Operational mode analysis of a SST interfacing Medium Voltage grid

Seamless mode transition between GFL and GFM controls for a grid-connected SST

Over voltage protection and fault isolation for Medium Voltage 3L-NPC

Switching loss distribution analysis (snubber + device) for 3L-NPC

and more….

FREEDM SYSTEMS CENTER

Thank You!

POWERAMERICA

NC STATE UNIVERSITY