Electric Grid Modernization Enabled by SiC Device based Solid State Transformers and Innovations in Medium Frequency Magnetics

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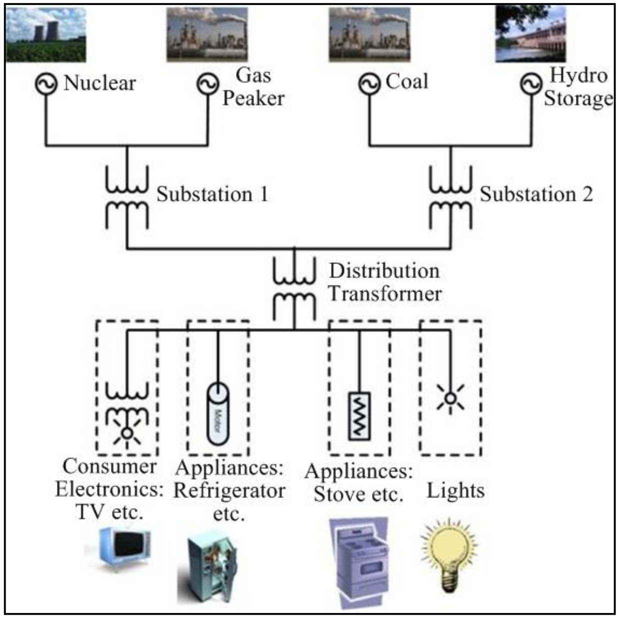
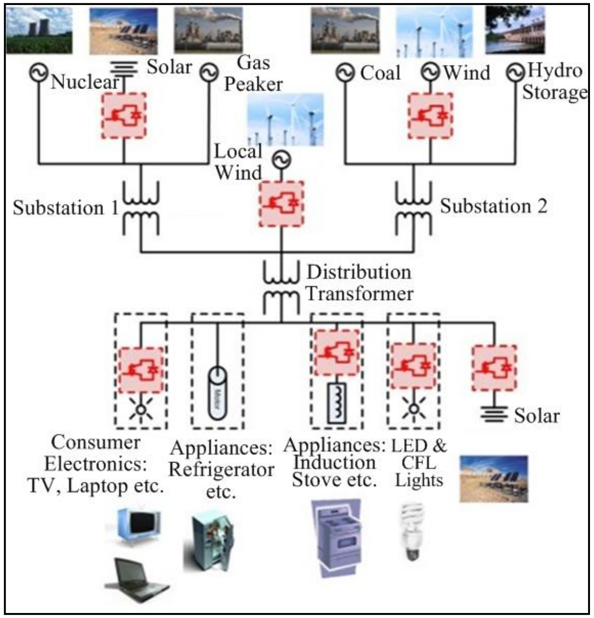
Introduction

Traditional Power System



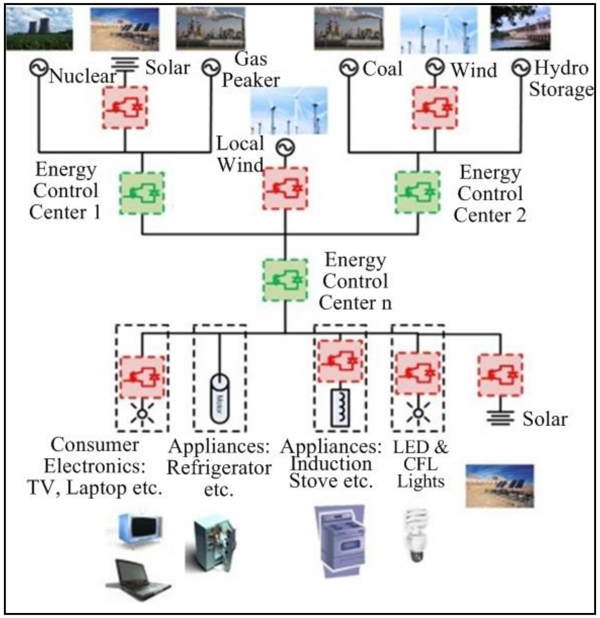
- Complex - large no. of variables
- Limited scope for control
- Non-linear loads
  - Harmonics
  - Lagging reactive power

Modern Power System



- Penetration of renewables
- Power electronic converters
  - dc-ac
  - ac-ac

Replacing 60 Hz Transformer

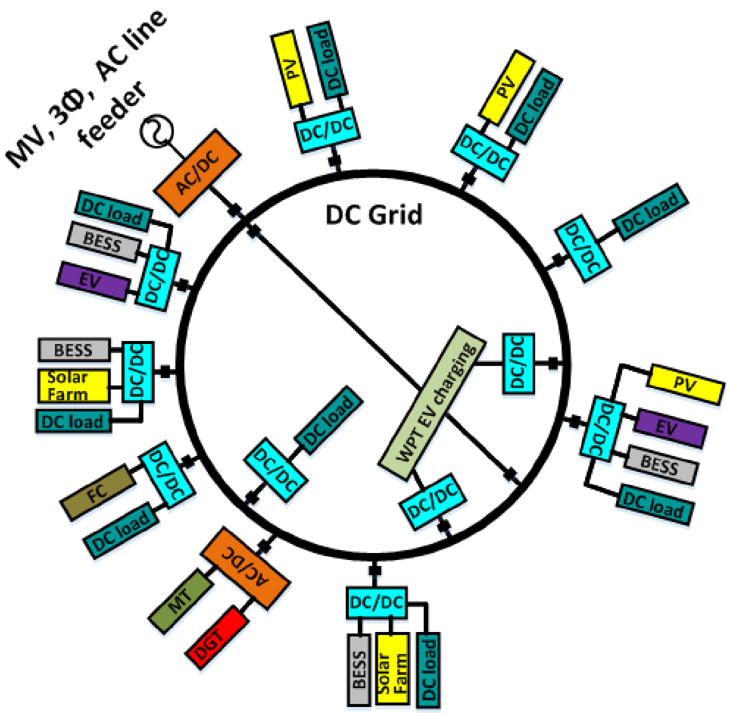


- Increased controllability
  - Energy Control Center
  - Solid State Transformer
  - Power Electronic Transformer
  - Intelligent Transformer

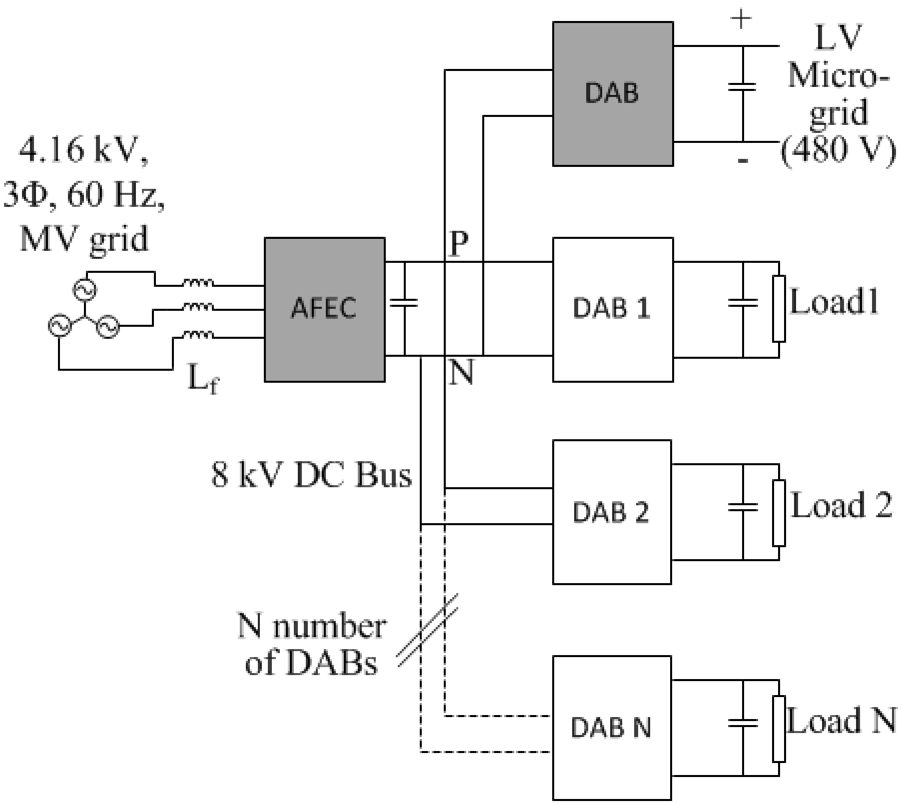
Medium Voltage DC Microgrids

- DC Micro-grid Application

Ring type DC micro-grid



DC micro-grid interface with DABs



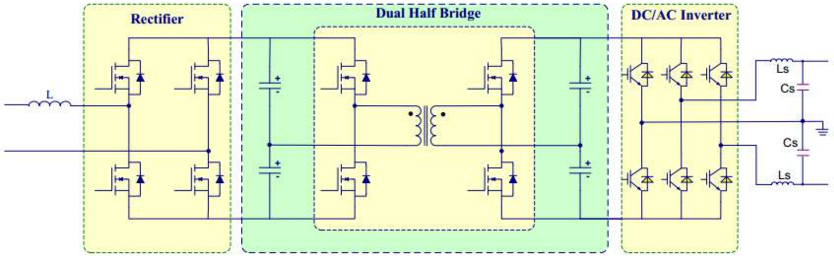
Solid State Transformer Technology

- **Conventional Distribution Transformers**
  - Bulky in size and weight
  - Unidirectional power flow
  - No solution for improving power quality
  - Improper voltage regulation
  - Lesser flexibility in control
  - Cannot connect asynchronous networks
  - Complex integration of renewables and DESD

60 Hz Distribution Transformer

- **Solid State Transformers (SST)**
  - Smaller in size and light in weight
  - Bidirectional power flow
  - Improves power quality
    - UPF operation
    - Harmonic elimination
  - Better voltage regulation
    - Reactive power compensation
  - Flexibility in control
  - Renewable integration
    - ac and dc links
  - SiC devices
    - Improving efficiency
    - Lesser cooling requirements

FREEDM SST



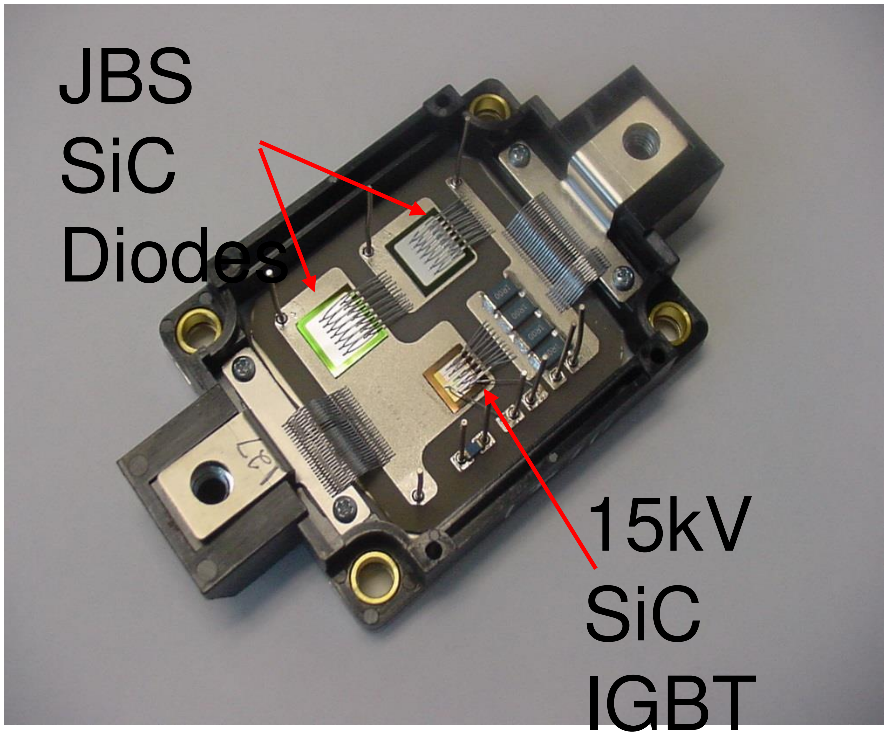
Work done at FREEDM Systems Center on Single Phase SSTs using HV SiC MOSFETs

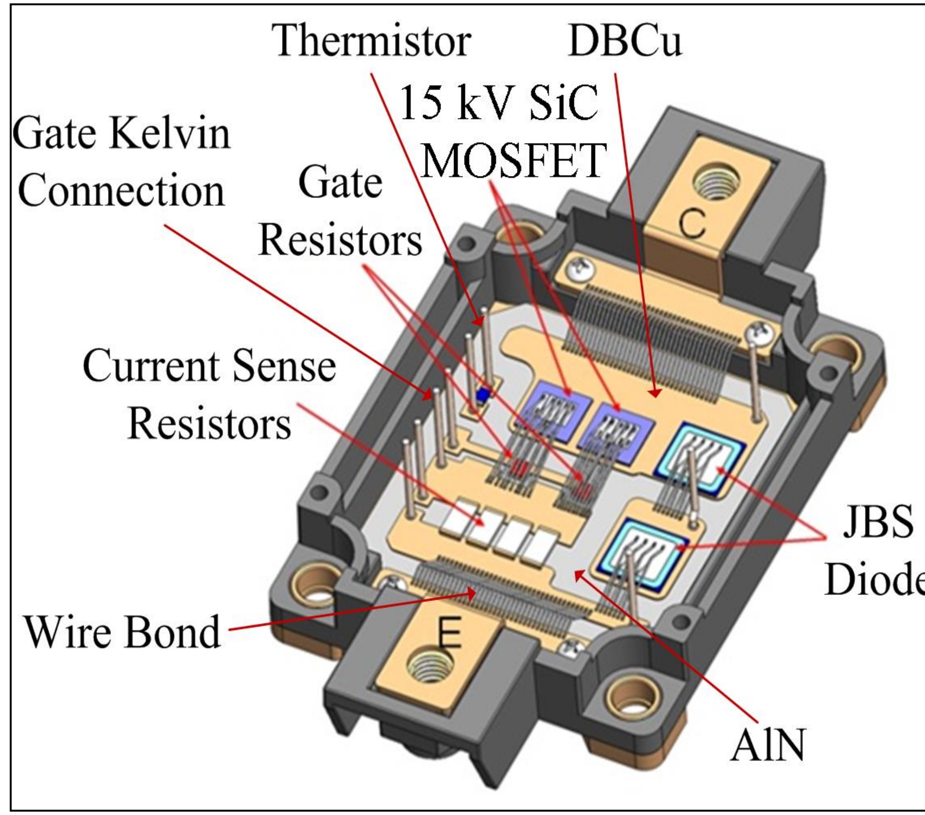
Conventional Distribution Transformers

Transformer Core Physical Dimensions 1MVA, 15kV:480Y/277V		
Frequency	Mass lb (kg)	Volume f^3 (m^3)
60 Hz	8,160 (3,700)	169 (4.8)
400 Hz	992 (450)	125 (3.54)
1 kHz	790 (358)	101 (2.86)
20 kHz	120 (54.4)	0.5 (0.14)
50 kHz	100 (45.4)	0.5 (0.14)

SST Topologies Enabled by SiC HV Devices: 15kV IGBTs and MOSFETs, 10kV MOSFETs

15 kV SiC IGBT & 15 kV SiC MOSFET Modules

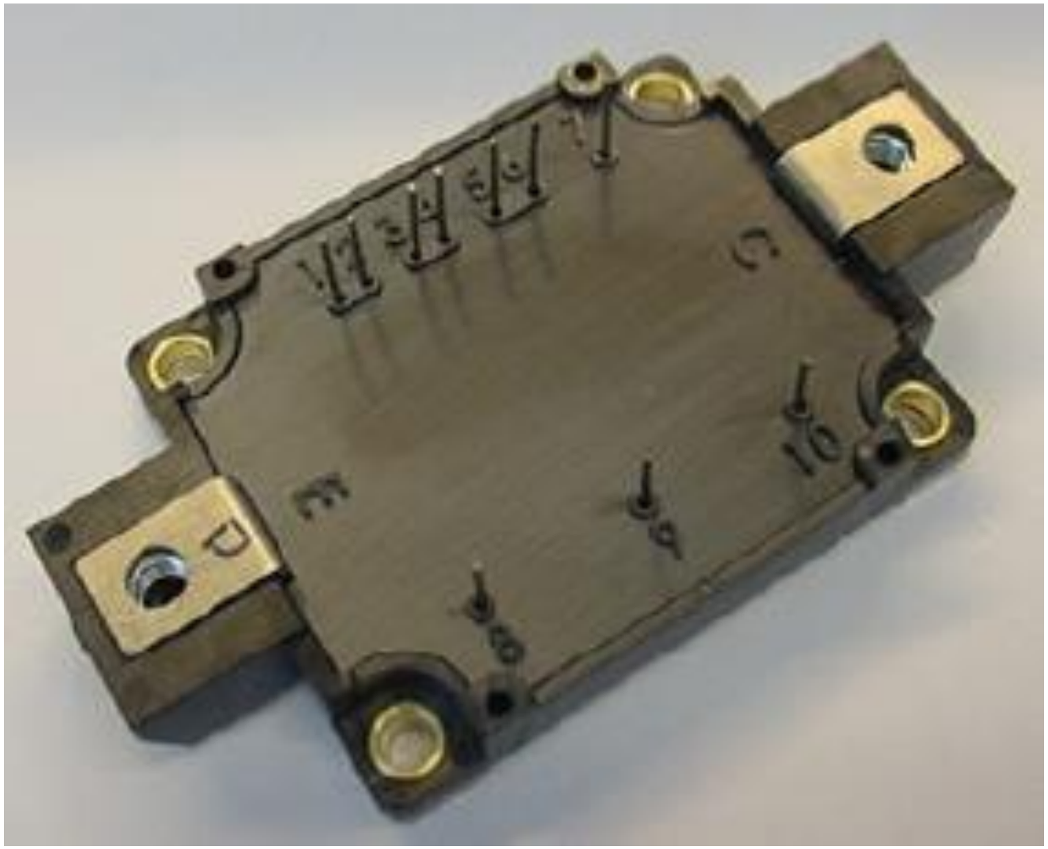




15 kV SiC IGBT (single chip) co-pack module

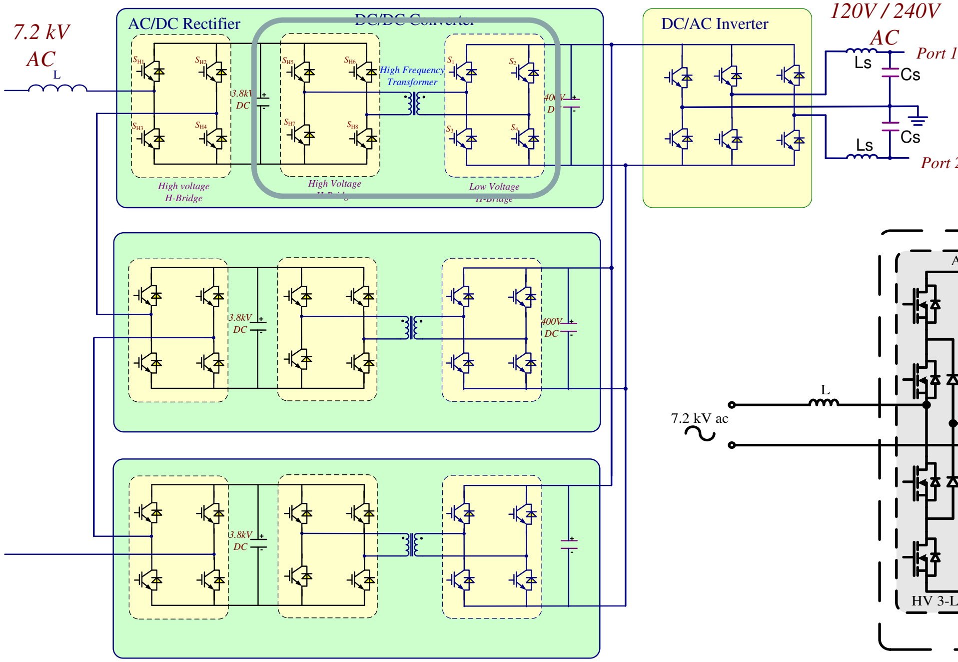
15 kV SiC MOSFET(Two chip) co-pack module

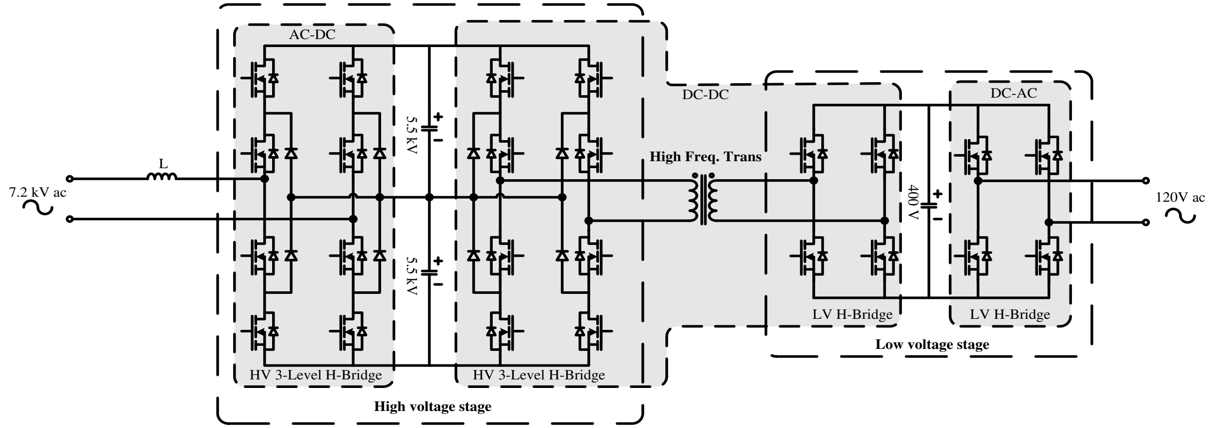
10kV SiC MOSFET Co-pack Modules



Single 10kV SiC MOSFET Module

Solid State Transformer: Gen-I and Gen-II





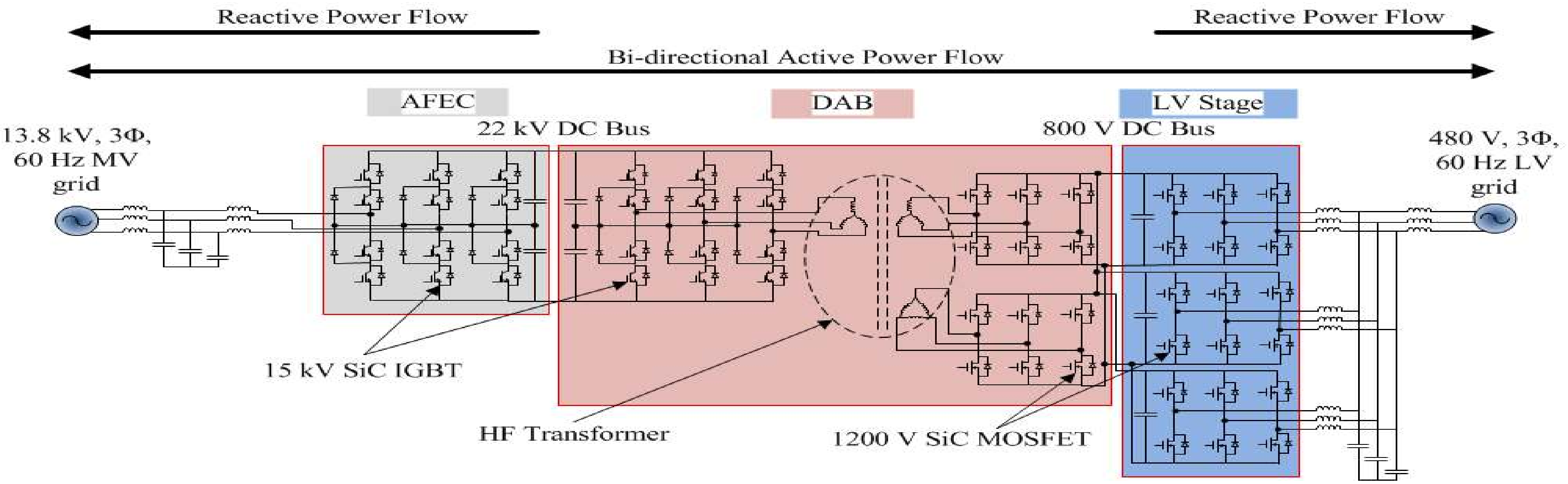
Gen-1 SST

	High Voltage Side	Low Voltage Side
DC-bus	3800 V	400 V
Current at maximal load	2.66 A	25.27A
Power	7 kW	
Turns ratio	9.5:1	
Switching frequency	3kHz, 20kHz	
Phase Shift	pi/ 6 ~ pi/ 4	

Gen-2 SST

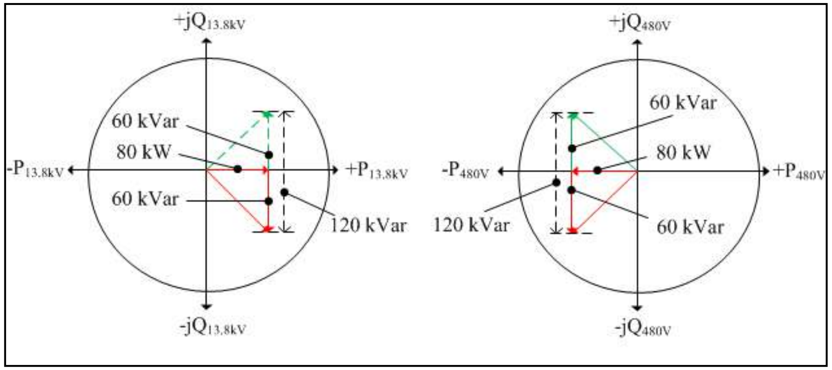
	High Voltage Side	Low Voltage Side
DC-bus	3*3800 V	400 V
Current at maximal load	3*2.66 A	25.27A
Power	3*7 kW	
Turns ratio	9.5:1	
Switching frequency	3kHz, 20kHz	
Phase Shift	pi/ 6 ~ pi/ 4	

Transformerless Intelligent Power Substation (TIPS)

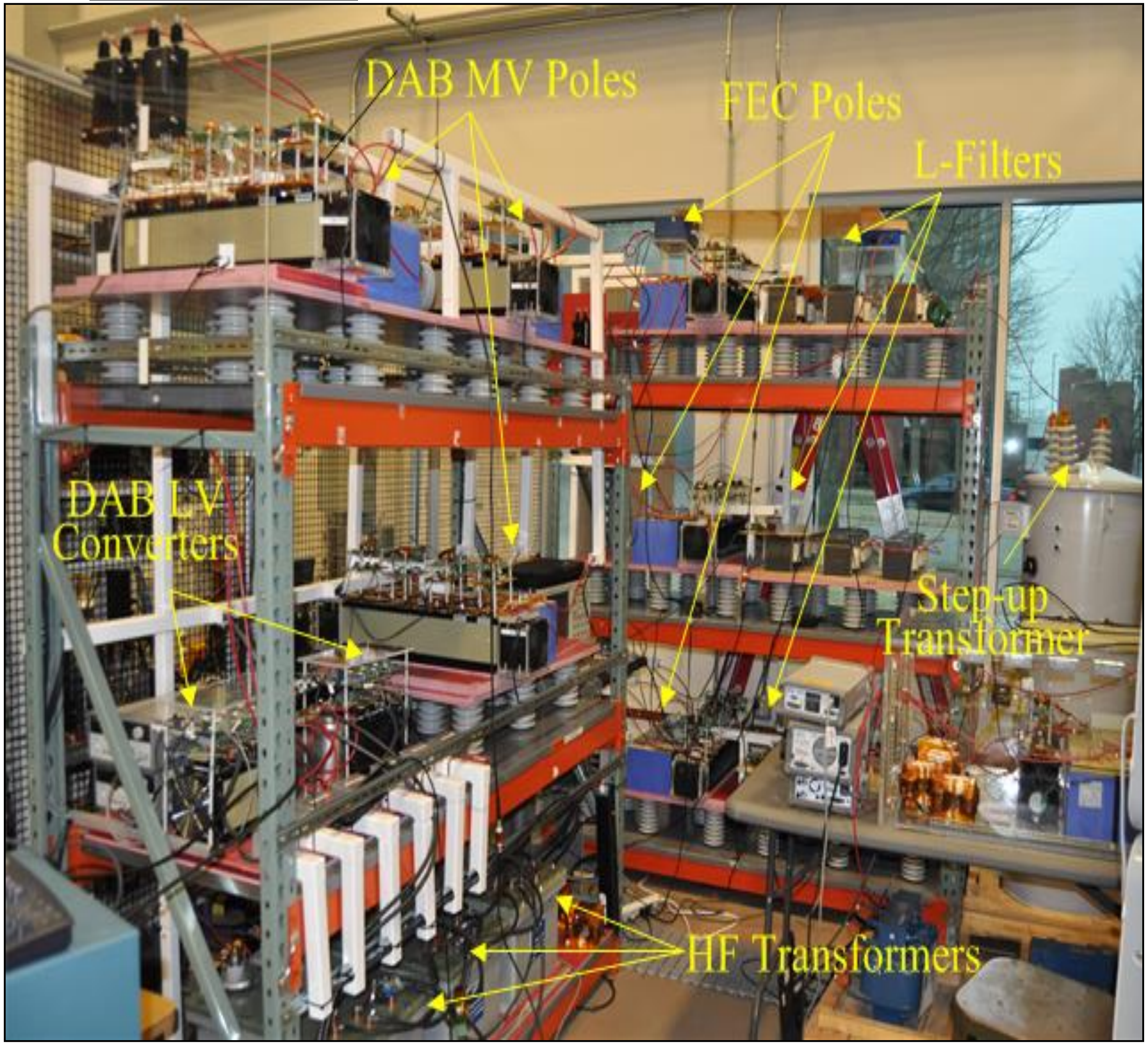


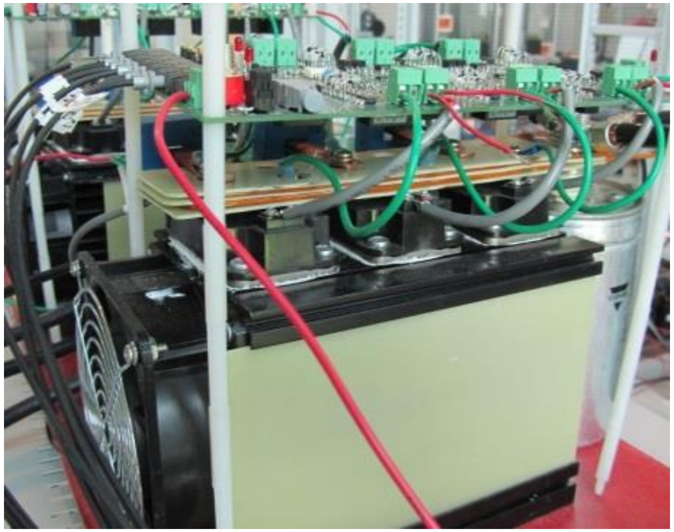
- 3-Phase SST - 13.8 kV to 480 V
- SiC based solid-state alternative to 60 Hz transformer
- Advantages – Controllability, Bi-directional Power Flow, VAR Compensation, Small Size and Light Weight, Lower Cooling Requirement, and Integration of Renewable Energy Sources/Storage Elements

TIPS Power Flow Diagram



TIPS Converter Laboratory Set-up



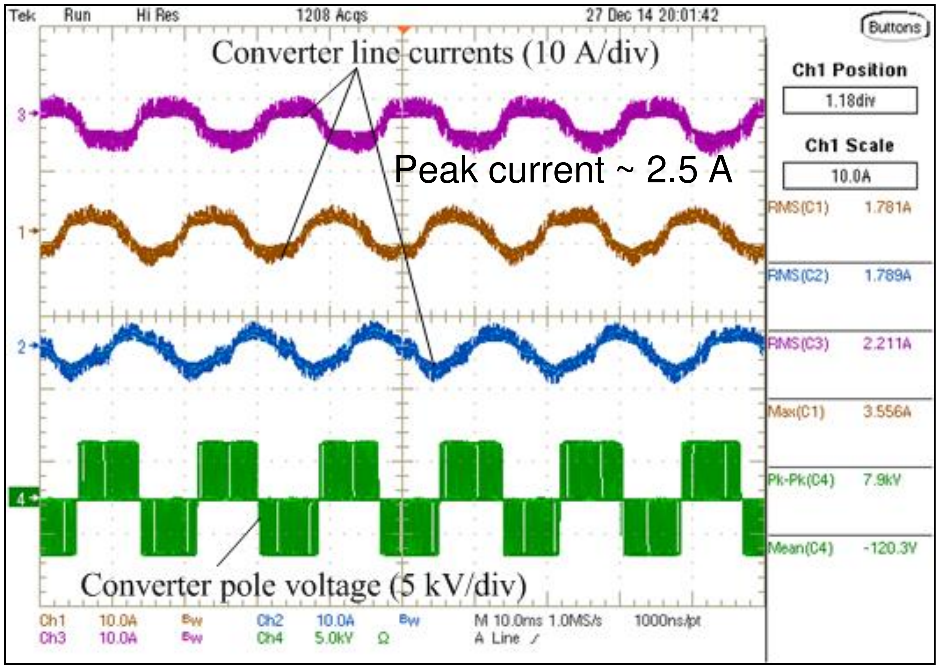


1200 V SiC MOSFET Based Low Voltage Side Converter

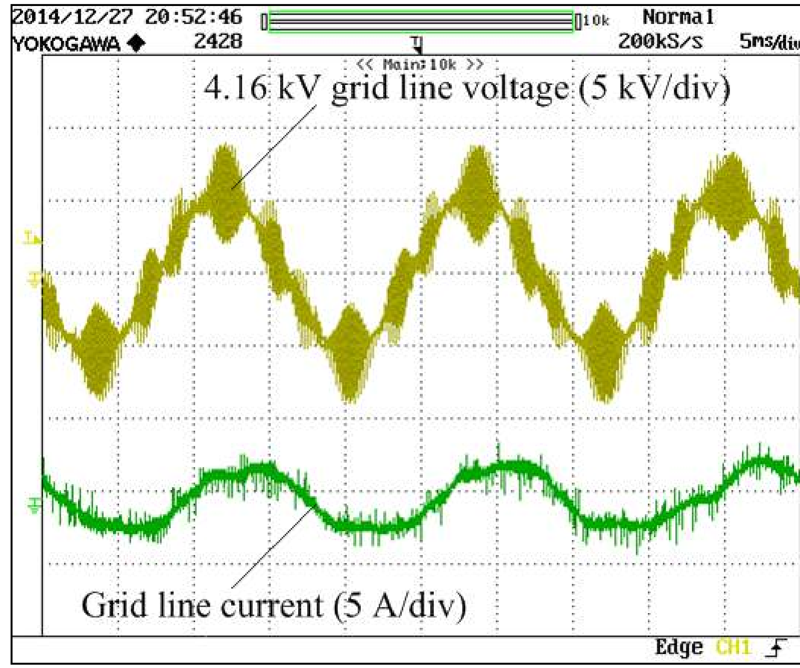
Single Phase High Frequency Transformer

Grid Connected Converter - Experimental Demonstration

FEC side waveforms for 4.16 kV MV ac grid tie operation with 8 kV MV dc bus and 9.6 kW load



FEC grid currents and R-phase pole-voltage

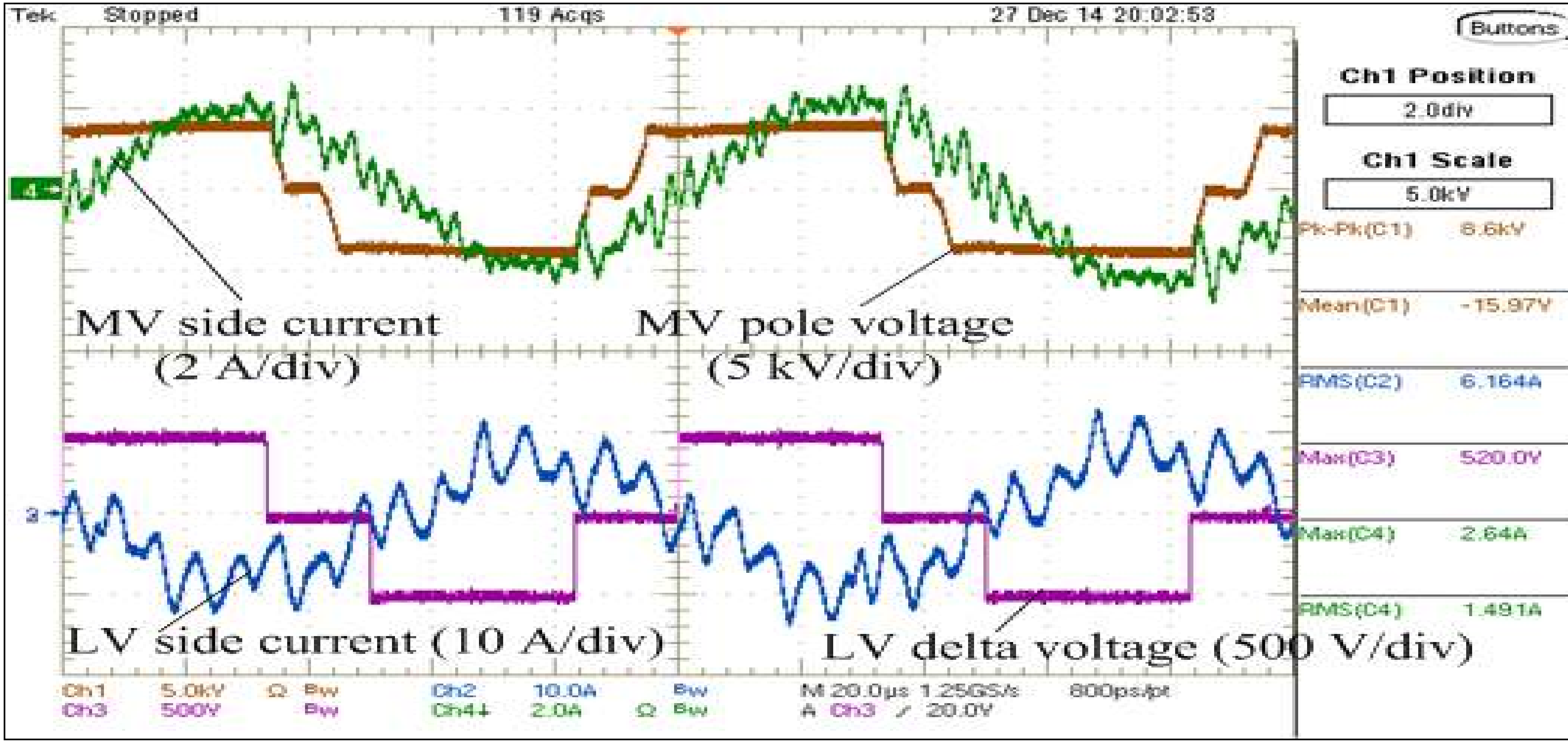


RY-grid voltage and R-phase grid current

- Ripple in the MV grid voltage is due to converter PWM voltage across the 60 Hz transformer leakage inductance (30 mH)
- Peak current shown is including the switching ripple

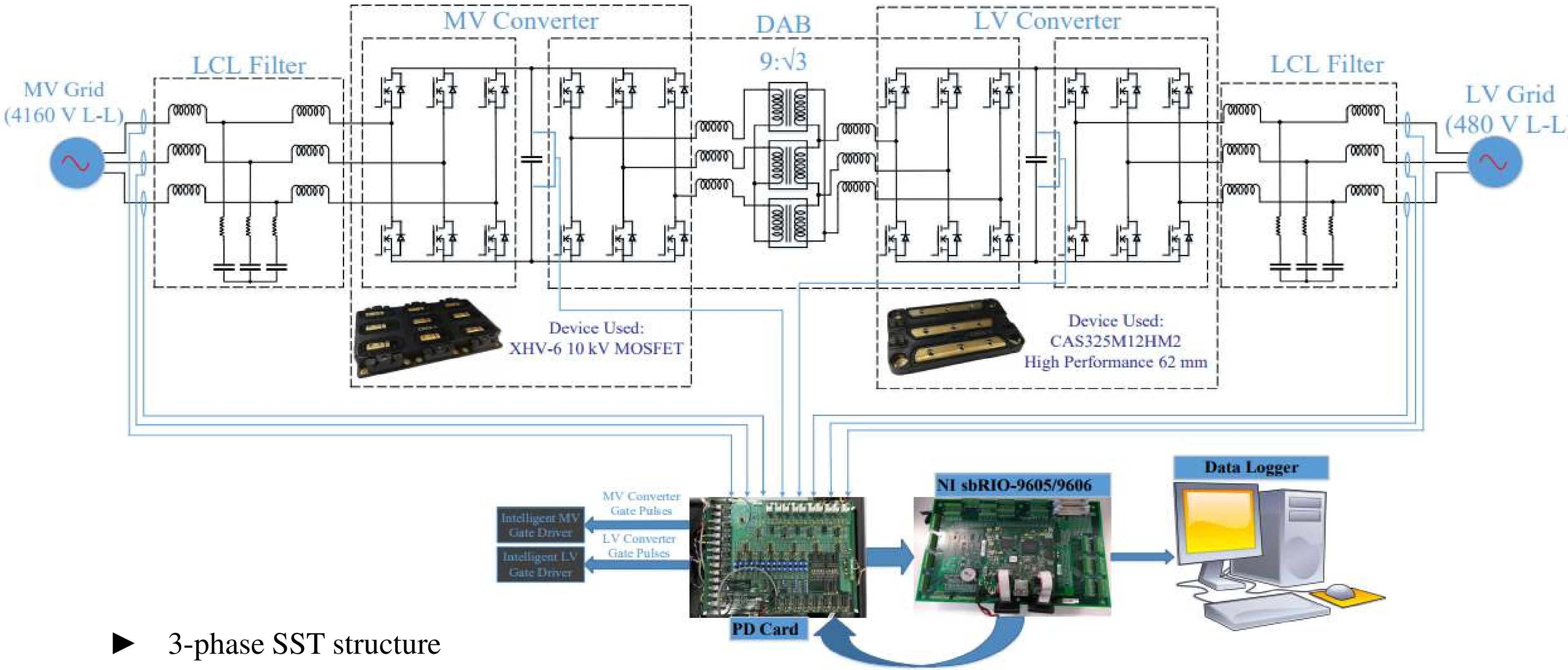
Grid Connected Converter - Experimental Demonstration

DAB side waveforms at 8 kV MV dc bus voltage, 480 V LV dc bus voltage and 9.6 kW



- All waveforms captured at the HF transformer terminals
- Ripple in the DAB currents is due to the HF transformer parasitics

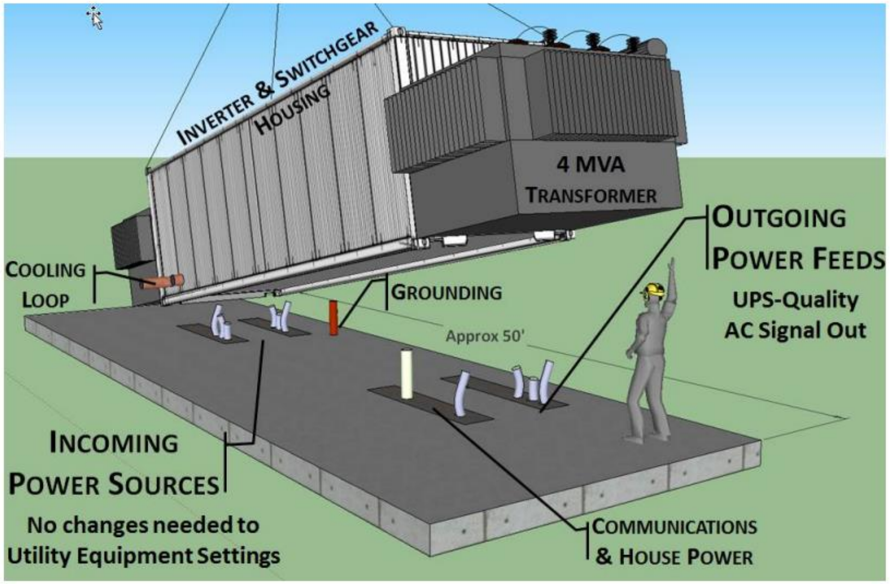
Solid State Transformers (SST) for Mobile Utility Support Equipment (MUSE)

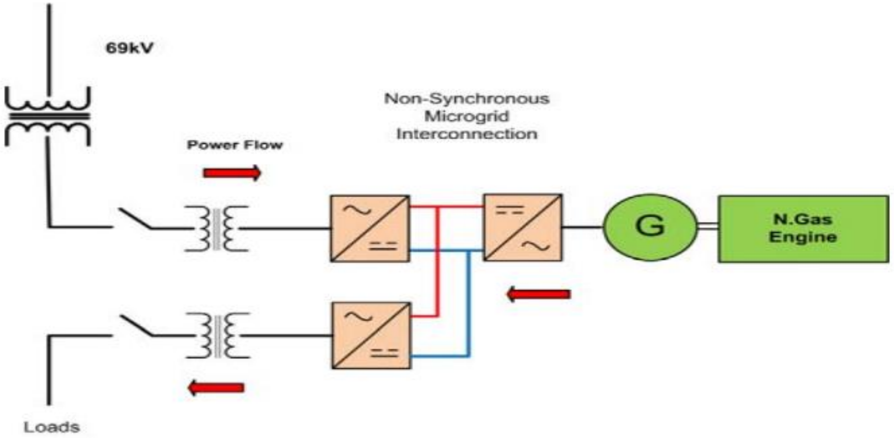


- 3-phase SST structure
- Connects 4.16 kV, 60 Hz grid to 480 V, 60 Hz grid with currently at 8 kV high voltage DC link and 800 V low voltage DC link
- High Voltage side converters are 3-Φ 2-level converters, Low voltage side converter is 2-level converter
- High frequency transformer forms Y-Δ connections for near sinusoidal current.

Non-Synchronous MV Microgrid Interconnection

Each GridLink eHouse can be customized for a particular load. The standard 6 MVA e-Houses use a redundant series of 2MVA blocks for converting the power from AC to DC and back to AC. Each package is the size of a shipping container, including two transformers. They are prepackaged and burned in at the factory for easy installation on-site.





Standard 6MVA AC-DC-AC module
Package size of a shipping container
Energy flow from multiple sources without requiring utility permits
Modular approach allows new energy to be added in future

- Nonsynchronous interconnection approach reduces the cost and time
- Always in islanding mode due to the DC link, mitigates the AC fault propagation
- Galvanic isolation by step-down transformer rated at 5MVA 27/3.3kV, 60Hz [2]
- High voltage silicon IGBTs in power stages

[1] Pareto Energy, **Microgrids for data centers**, Available online 2018
http://www.paretoenergy.com/whitepaperfiles/PresentationParetoEnergyMicrogridsForDataCentersWebPageVersion.pdf

Medium Voltage Asynchronous Microgrid Connector

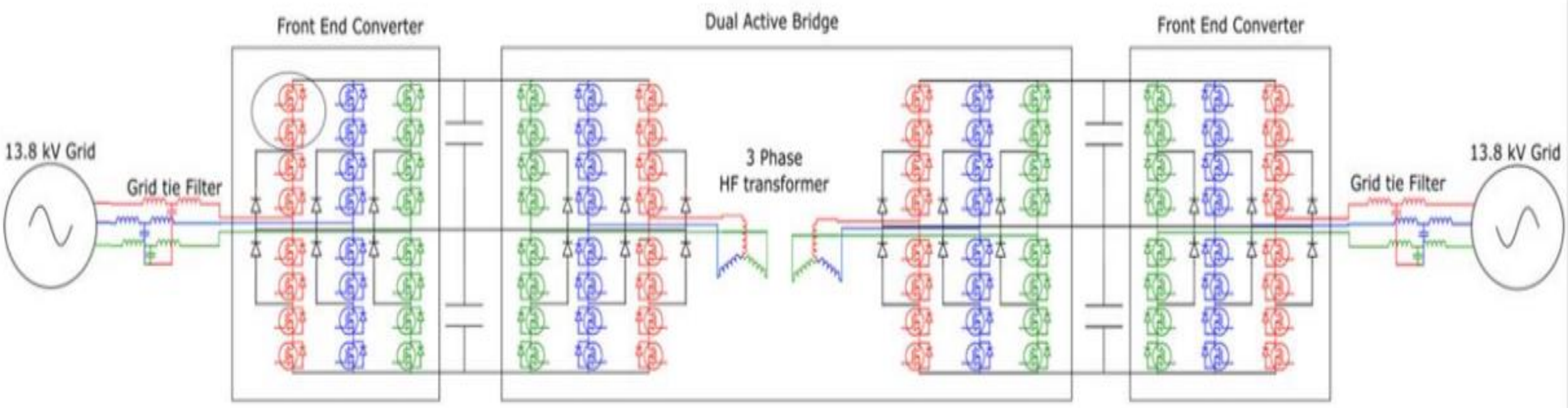


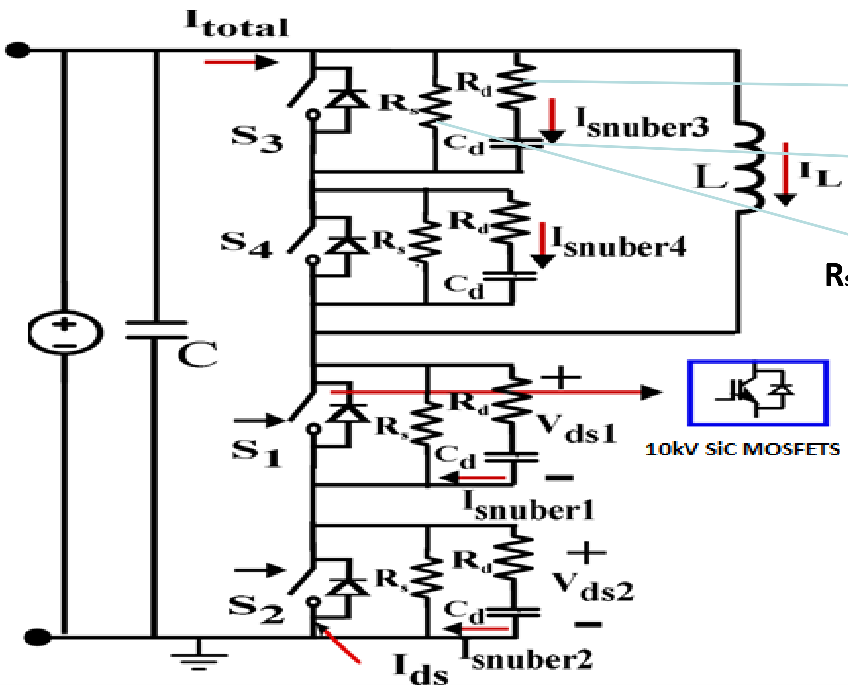
Fig. 2: Asynchronous microgrid power conditioning system enabled by series connection of Gen-3 10 kV, 15 A SiC MOSFETs. Intrinsic body diodes of the MOSFETs are used as the anti-parallel diodes.

- **13.8 kV asynchronous grid**, 50Hz or 60Hz; 100kVA bidirectional power flow
- 3L NPC pole realized by series connected Gen3 10kV, 15A SiC MOSFETs
- Intrinsic body diode as freewheeling diode, and 10kV, 15A SiC JBS diode as the clamping diodes
- 24kV DC link, 10kHz switching frequency in FEC and DAB

[3] 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, 2018, pp. 60-67.

AGC Testing Results

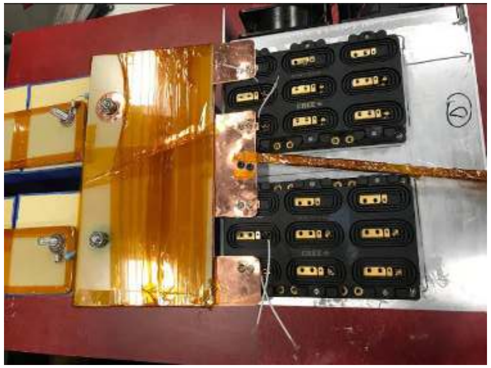
Step 1: Selection of the snubber resistor and capacitor values.

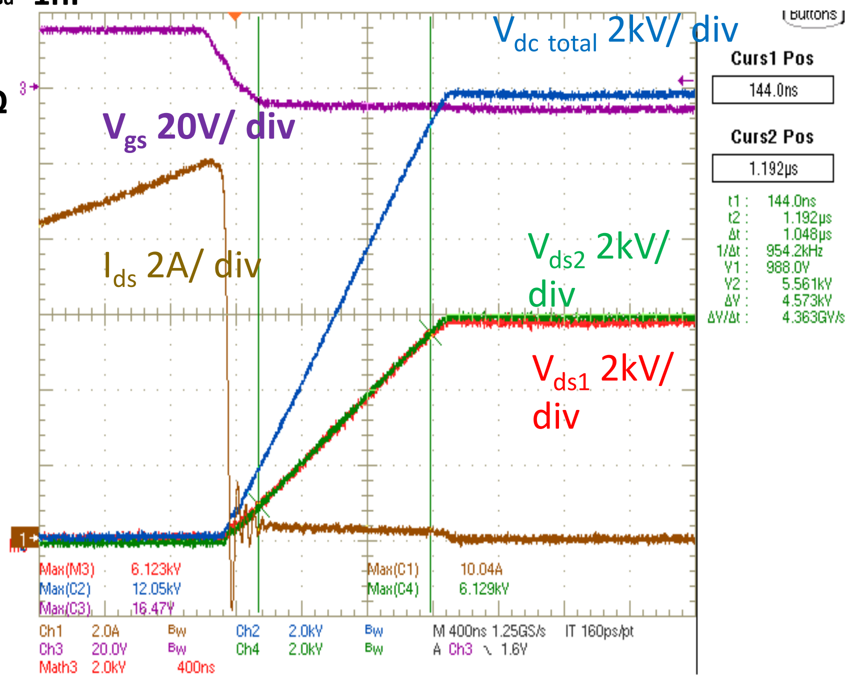


Rd=4.7Ω

Cd=1nF

Rs= 1M Ω

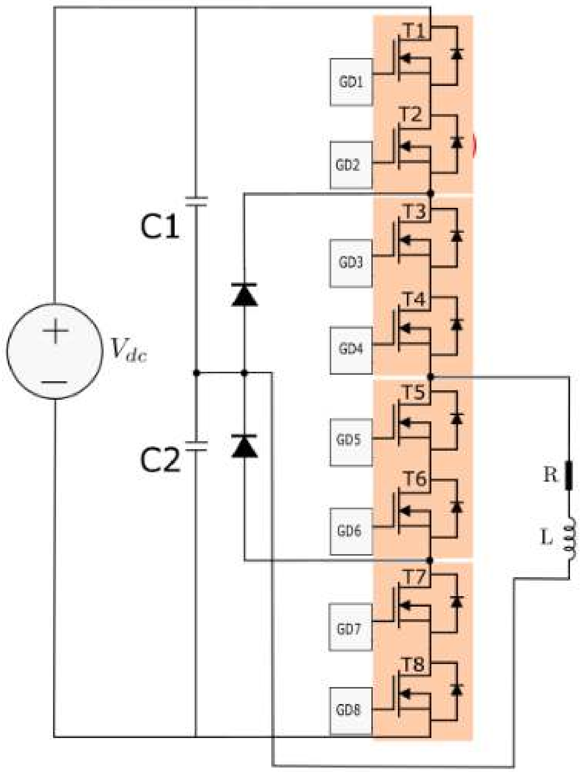




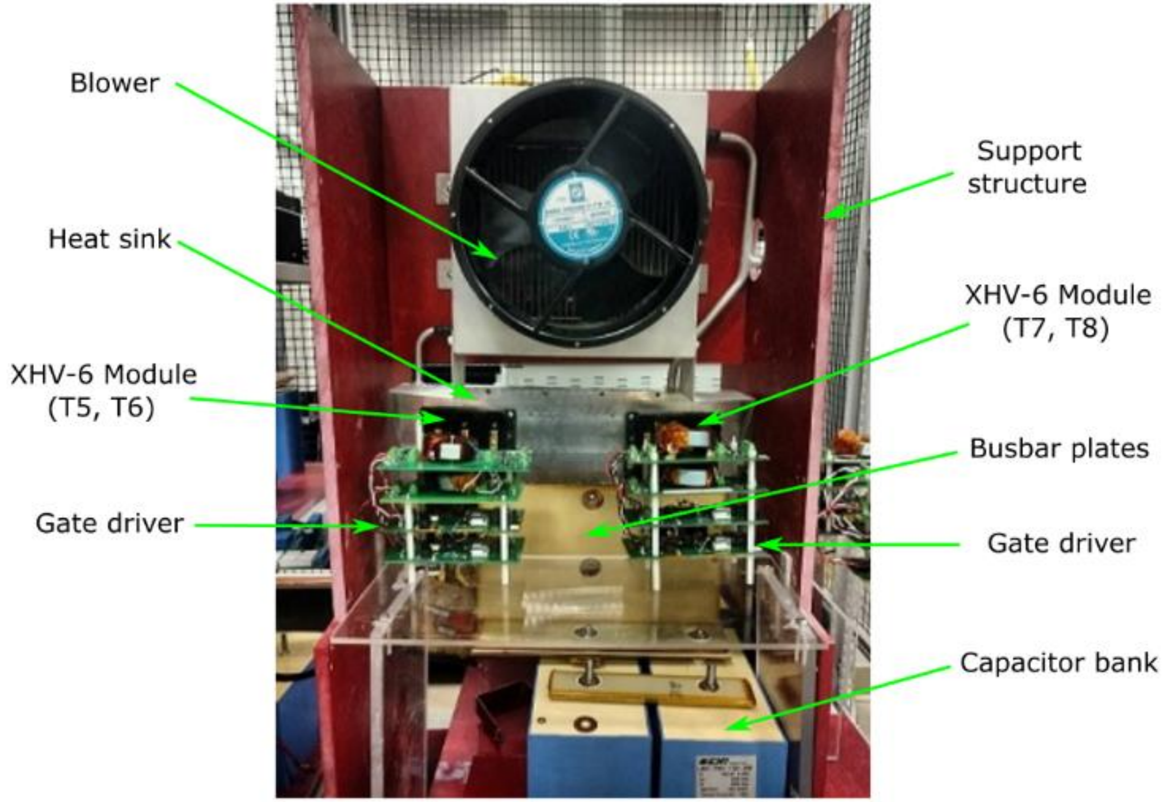
Double pulse test with the series connected MOSFETs.
Vdc: 12kV, Vgs=20V/-5V.

AGC Testing Results

Step 4:Three level converter test setup (Single phase with series connection)



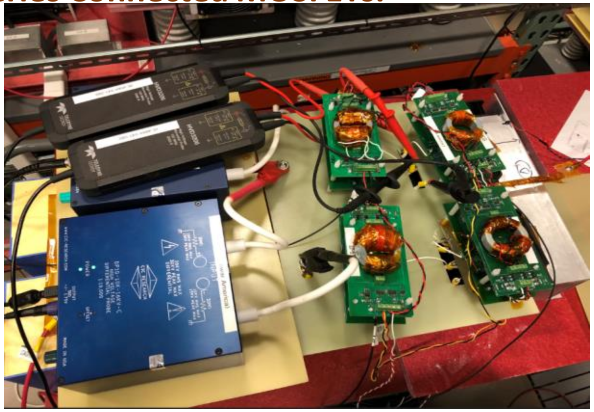
Schematic of the Single phase series connection



Experimental setup for series connected single phase leg

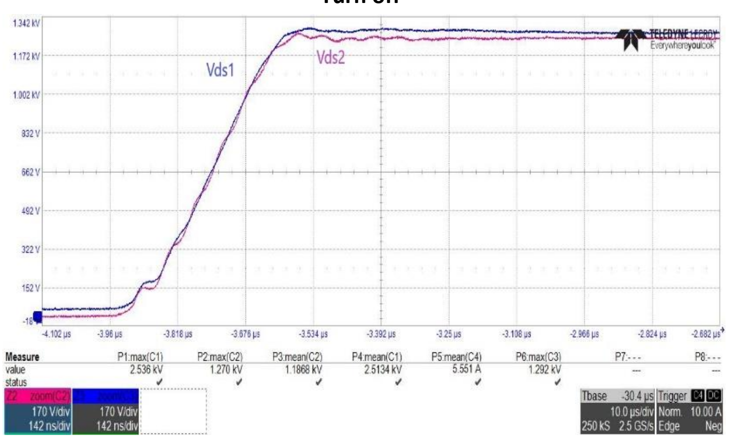
AGC Testing Results

Step 2: Half Bridge testing of the Series Connected MOSFETs.

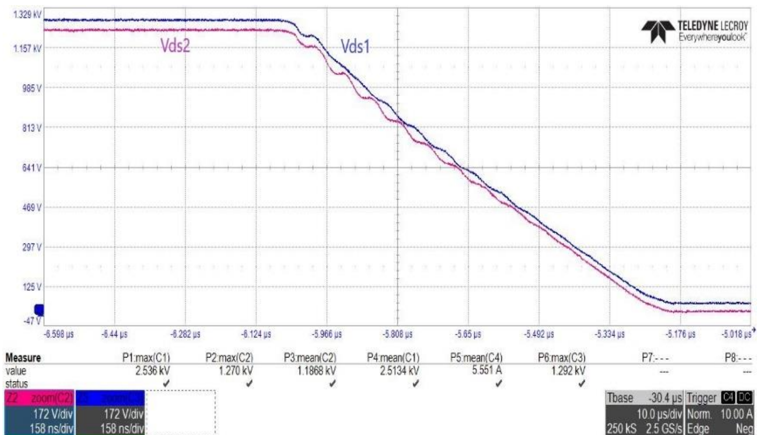


Test Set up

Turn off



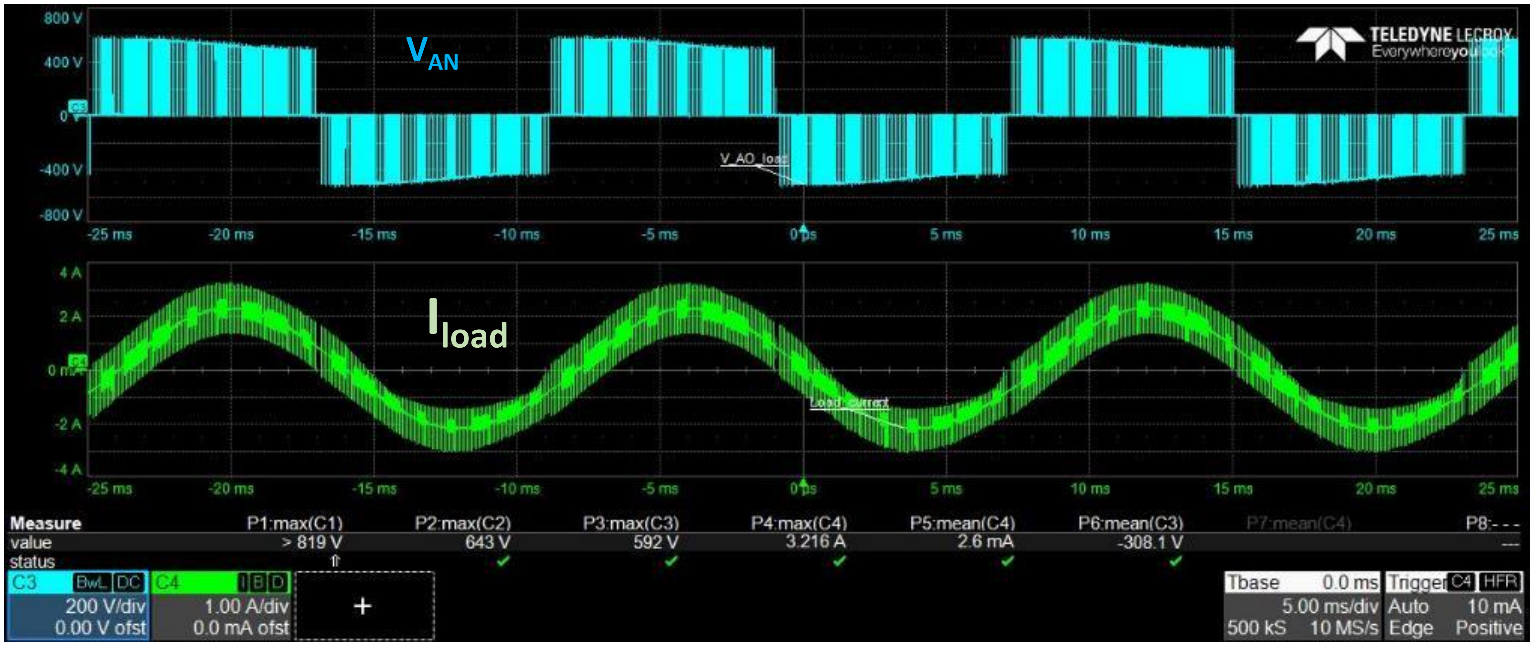
Turn on



V_{ds1}= 1.27kV, V_{ds2}= 1.292kV, t_{on} = 800ns, t_{off} = 300ns

Experimental Results

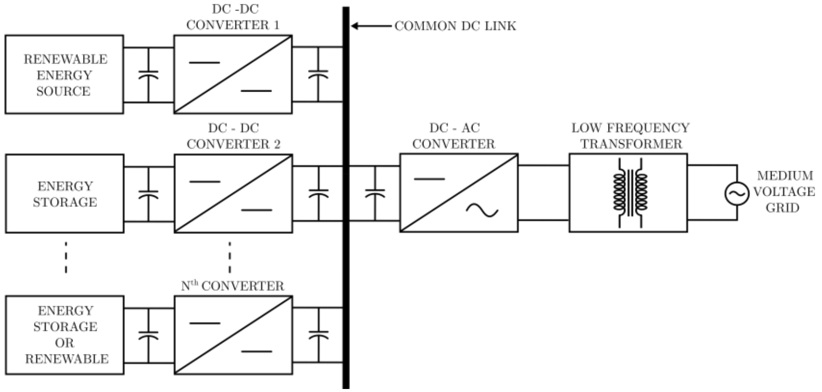
1000V DC bus voltage, 2.5A peak current, 60Hz fundamental, 10kHz switching frequency



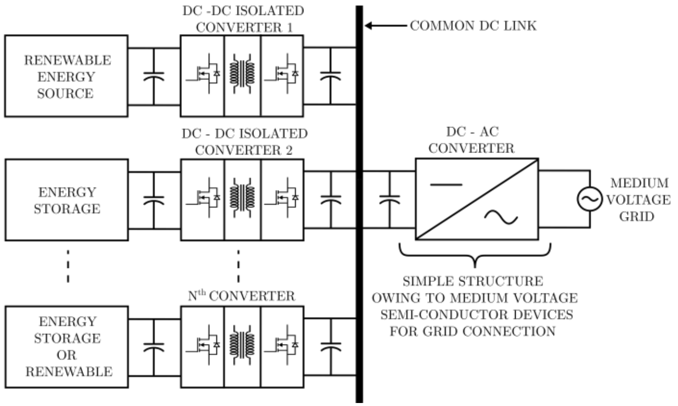
V_{AN} **(pole-to-DC midpoint voltage): 400V/div,** I_{load} **(load current): 2A/div; Time: 5ms/div**

High Power Medium Frequency Magnetics for Power Electronics Applications

Sunlamp Architecture



Conventional MV grid connection using low frequency transformer.



Proposed MV grid connection using isolated power electronic converters and simpler dc-ac converter structure.

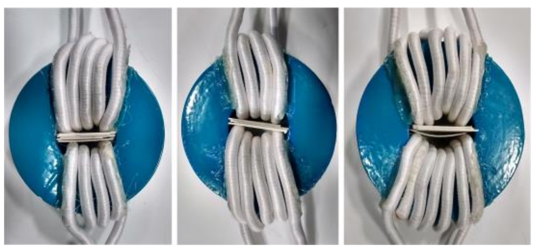
Contributions of the Sunlamp Project:

- Overall architecture selection and dc-dc and dc-ac converter designs.
- Combining PV and ES on the DC Side with a 3-winding transformer for new topologies and system benefits.
- System level Integration simulation and experimental demonstration
- Advanced magnetic core and high frequency transformer fabrication, design, and testing.

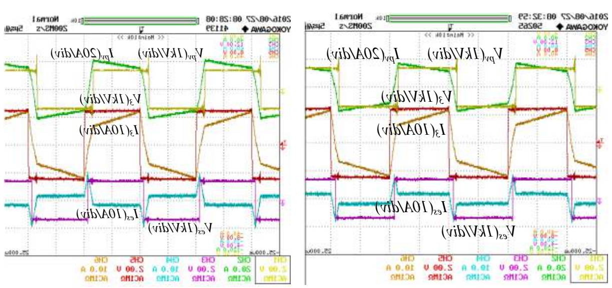
Triple Active Bridge (TAB) and Magnetic Designs

Highlights of the Sunlamp Project

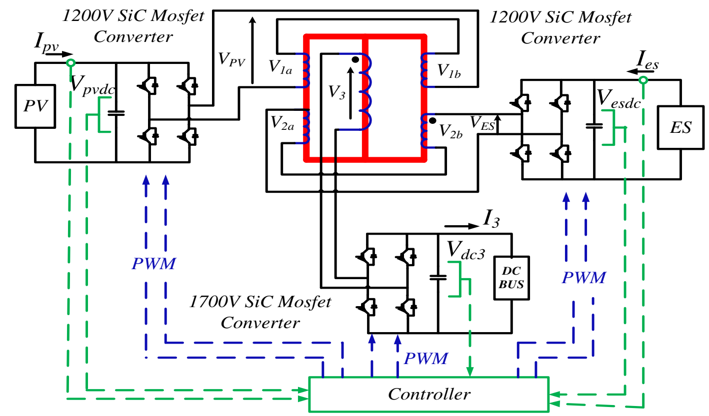
- 10kW, 20kW and 50kW TAB converter demonstrated at NC State University.
- Prototypes designed based Upon 3-Limb and Single Core, 3-Winding Transformers.
- HF Transformer Design, Build, and Test.



Various inductor designs realized for the TAB.



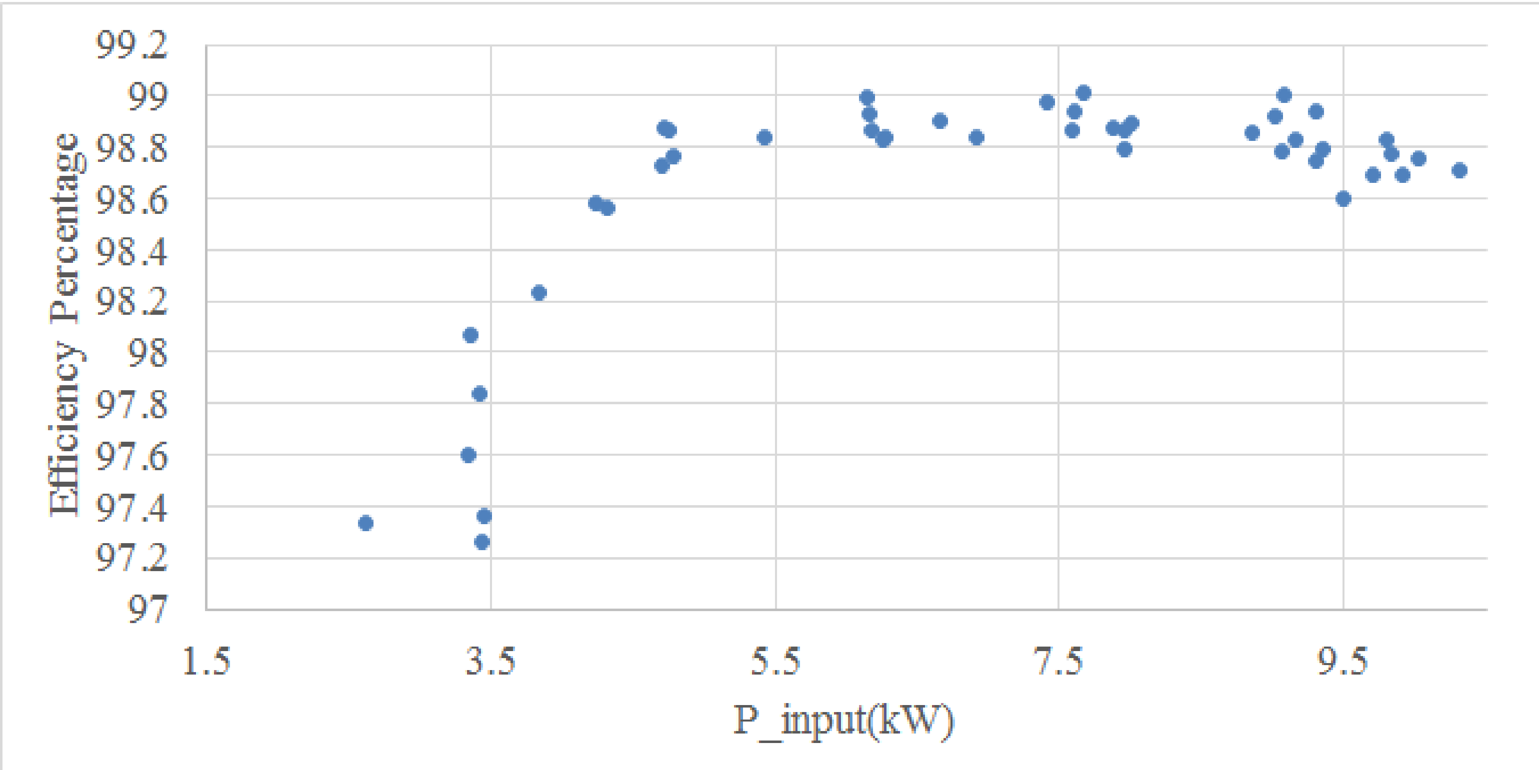
Experimental results from a TAB under test.



A triple active bridge (TAB) integrating PV and an energy storage.

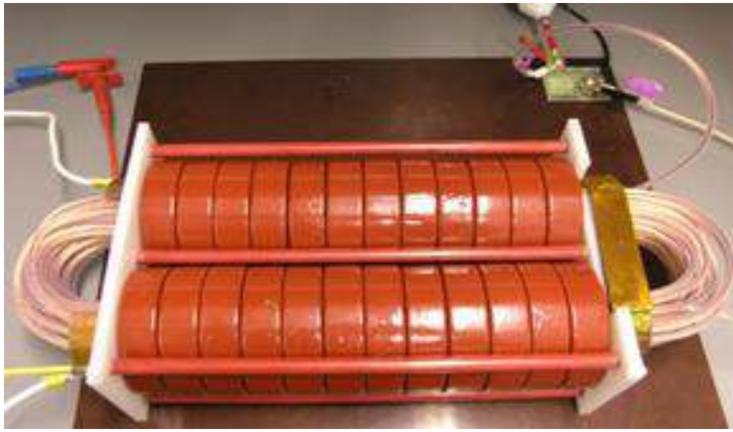
Various transformer designs realized for the TAB.

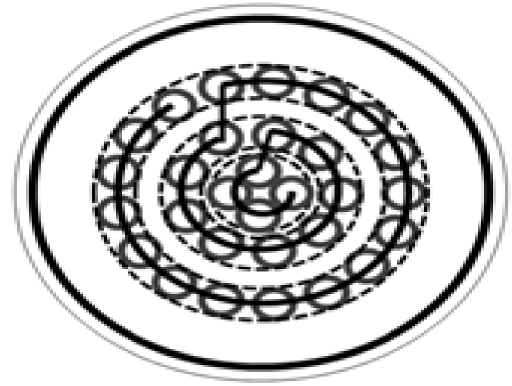
System Efficiency at 100kHz



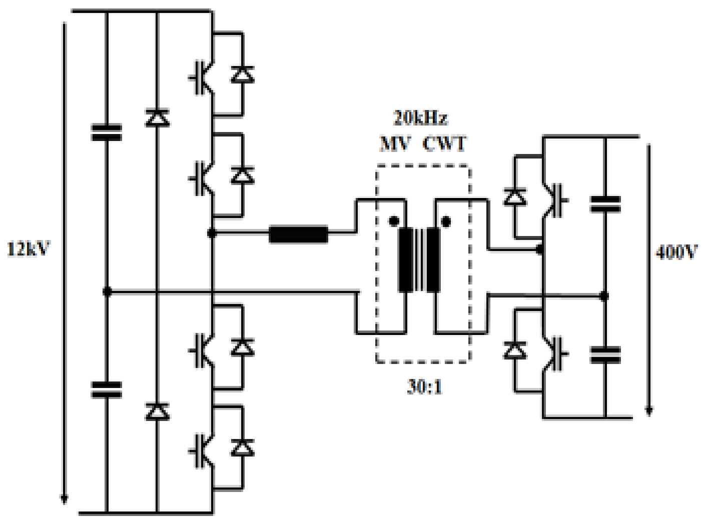
Efficiency variation with input power at 100kHz

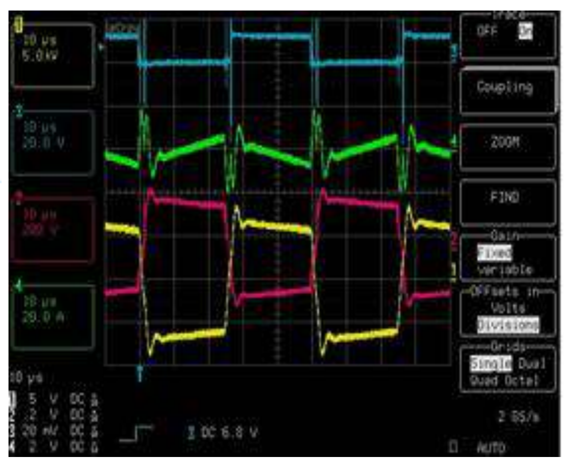
Gen-II SST High – Frequency Co-Axial Winding (CWT) Transformer - Design & Test at 20kHz, 30kW

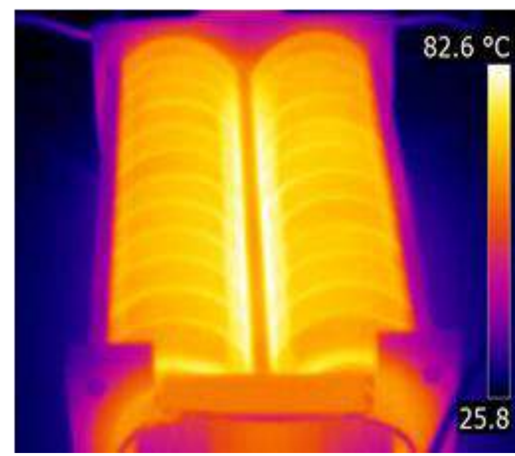




30cm*17cm*9cm







DC-DC converter of the SST; 30kVA, 20 kHz CWT test - Yellow (Vo) 5kV/div, pink (Vi) 200V/div, green (Imag) 20A/div; Heat distribution after 90 min operation

Fault-tolerancy Examples in Nature

- Bird flock or school of fish avoid predators by using multiple sensors (eyes)
- One animal can inform other animals by changing direction, forming a virtual single mass body
- Chance of survival for the species is much higher in the synchronization mode than living individually

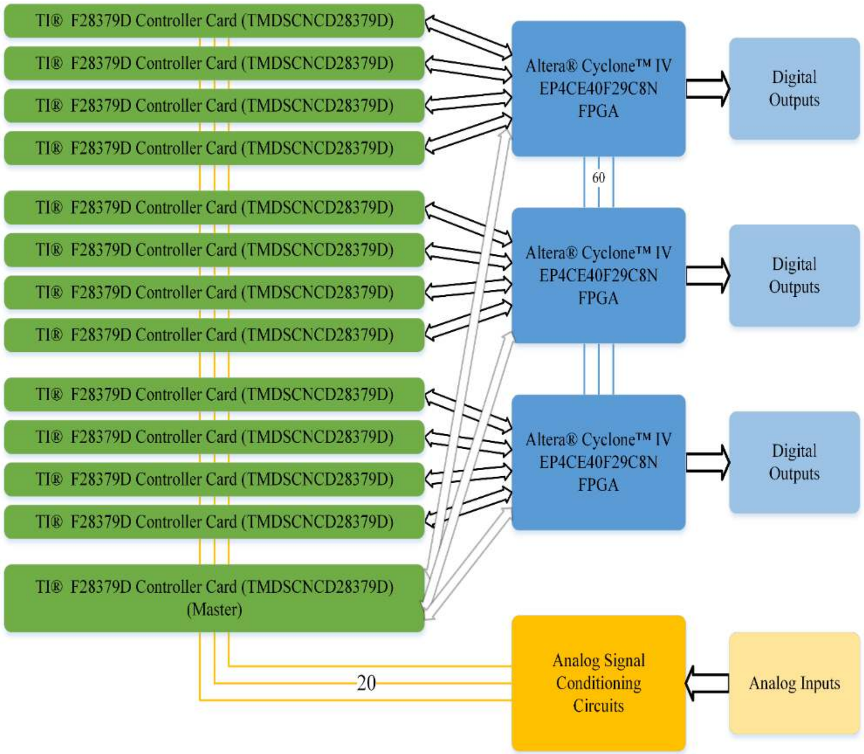
Implementation of the Proposed Controller

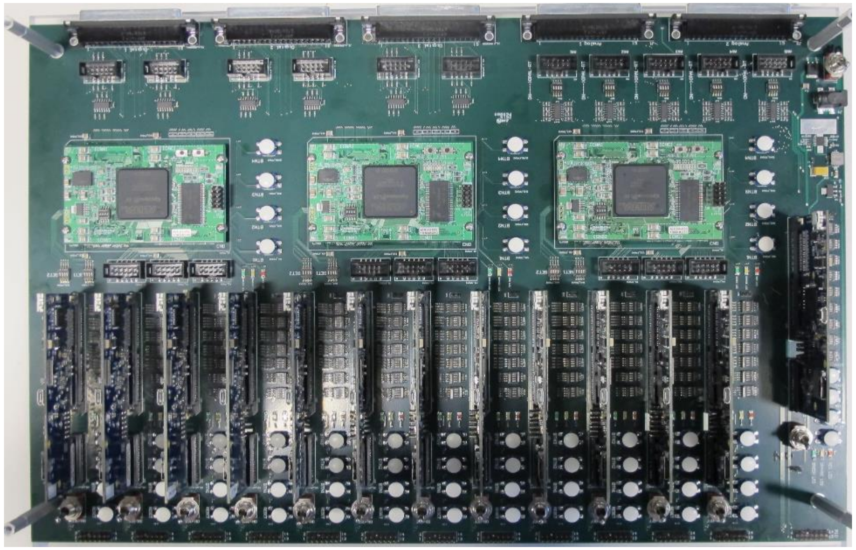
A hardware test-bed has been developed to test the functionality of the system in real scenario

It consists of 13 controllers (12 slave and one master) and 3 FPGAs which makes it capable to implement various architectures and gather data in the best format

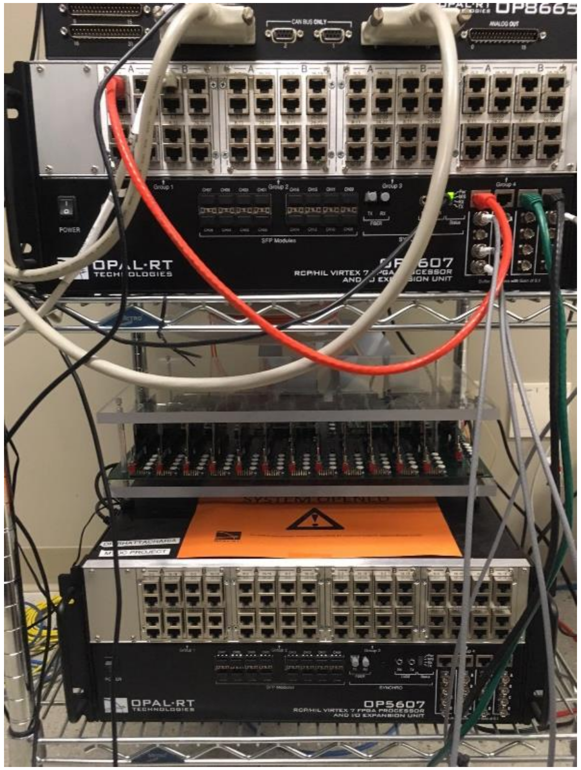
Analog inputs have been leveled to match the voltage rating of the controllers

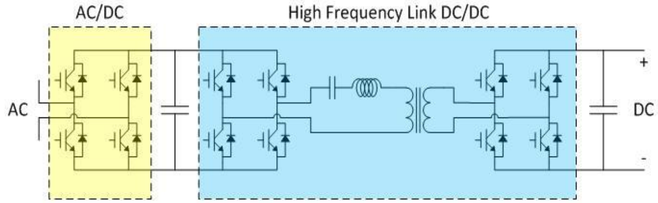
It is possible to use the controller with hardware in the loop (HIL) simulator and the experimental setup in the lab

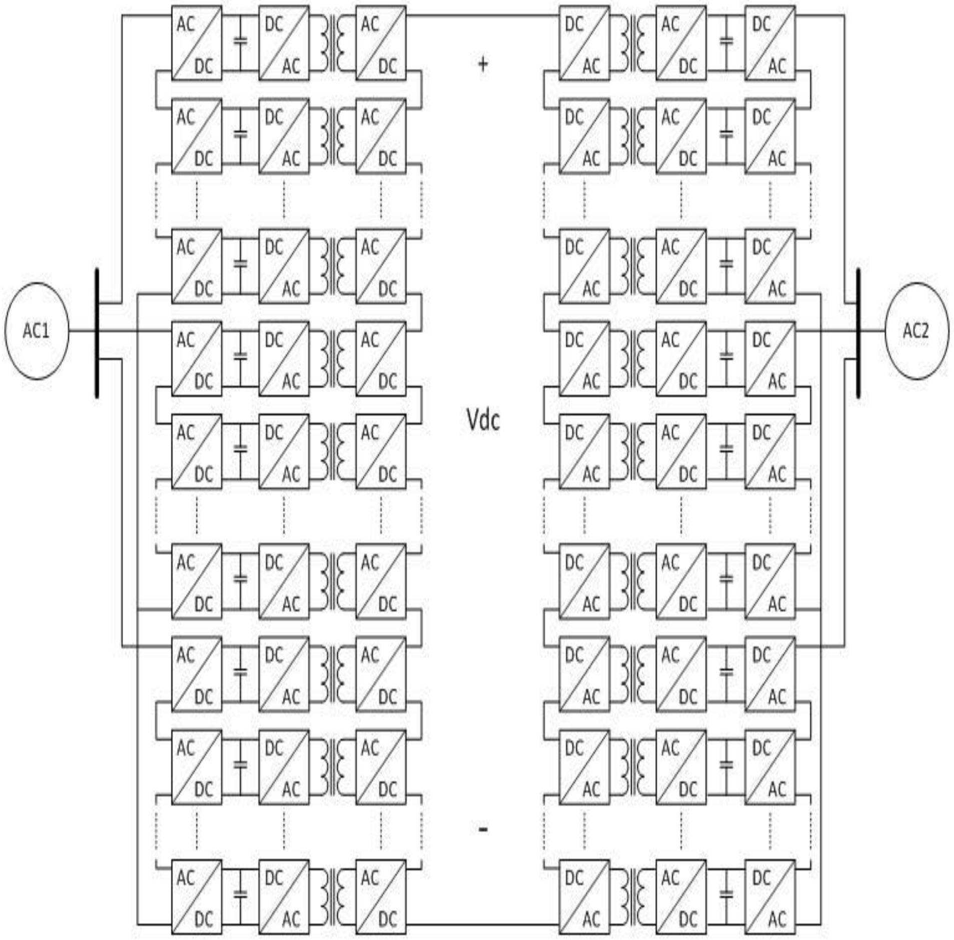




Cascaded H-bridge (CHB) Converter (OPAL-RT CHIL Results)







Conclusion

- Electric Grid Modernization requires plug-n-play feature provided by SST for integration of renewables, energy storage
- Magnetics is the most important component of SST !!!!!
- Rich sandbox for research – enabled by HV SiC devices
- Important to get students educated in SST and magnetics
- Efficient and reliable MV grid connected converters is key to enabled renewable energy power conversion systems
- Need to solve practical issues – hence industry + academic + DoE Lab participation / collaboration is key

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Thank You!!!

Questions

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