Converter Integration of High-Voltage High-Frequency SiC Power Devices

Session:

Medium-Voltage WBG Devices and Converters Development for Advanced Distribution Grids

Subhashish Bhattacharya
Dept. of ECE
FREEDM Systems Center
North Carolina State University

Outline of presentation

- HV SiC devices – 10kV MOSFET, 15kV MOSFET, 15kV IGBT, 6.5kV JFET, 3.3kV - 5kV MOSFET

- What MV Power Conversion applications are enabled

- Grid integration of renewables

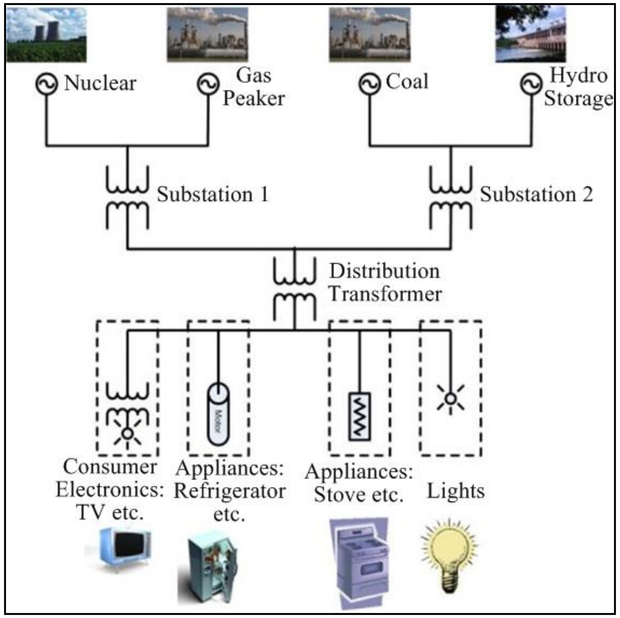
- High MW and MV Motor Drives

- FACTS and D-STATCOM applications

- Are these HV SiC devices easy to use – like 1.2kV/1.7kV SiC MOSFET devices ?

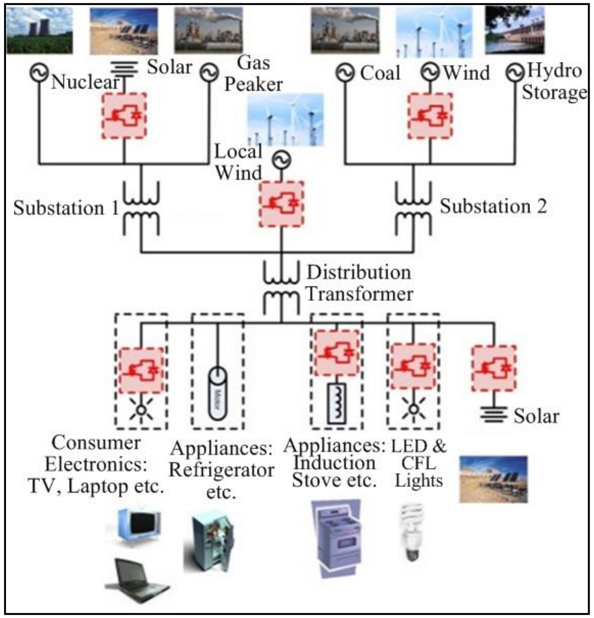
Introduction

Traditional Power System



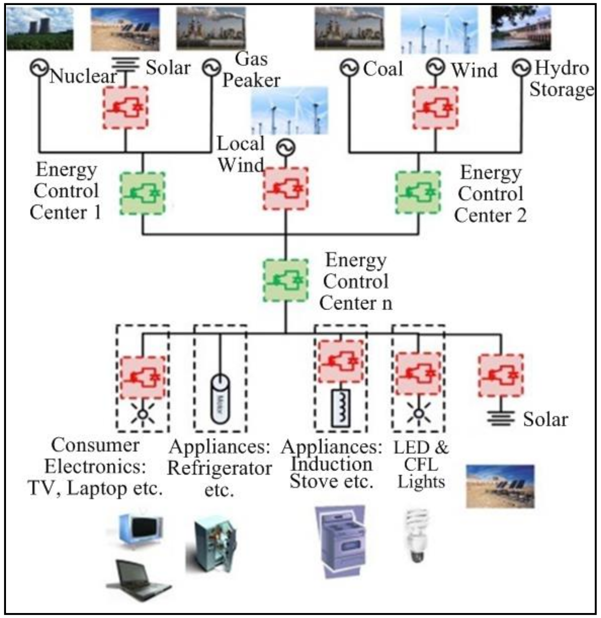
- Complex - large no. of variables
- Limited scope for control
- Non-linear loads
  - Harmonics
  - Lagging reactive power

Modern Power System



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

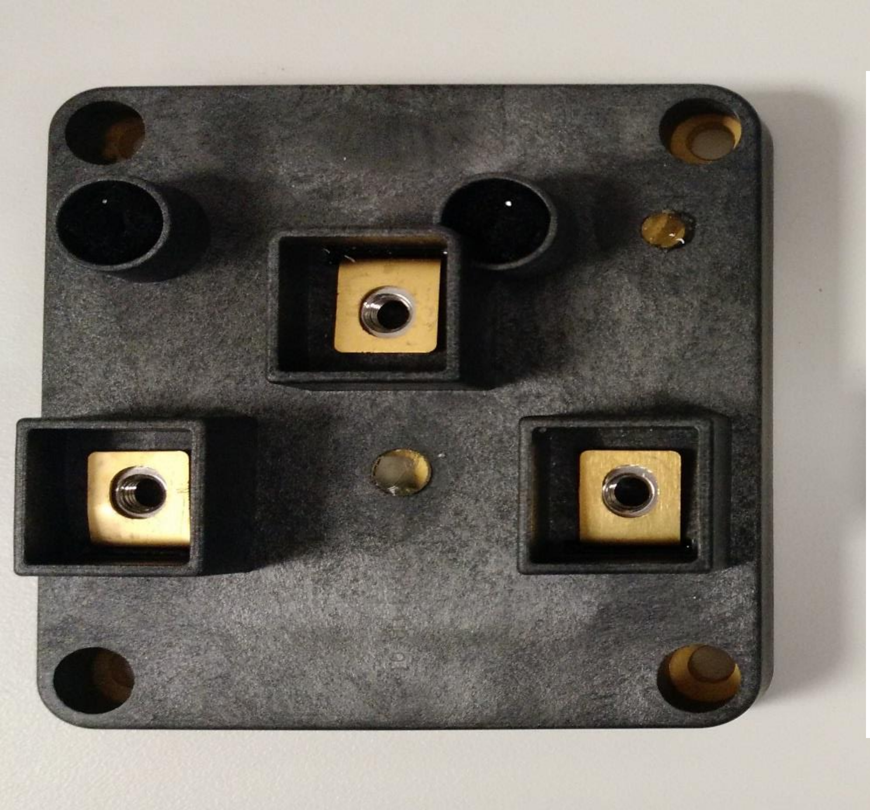
Replacing 60 Hz Transformer



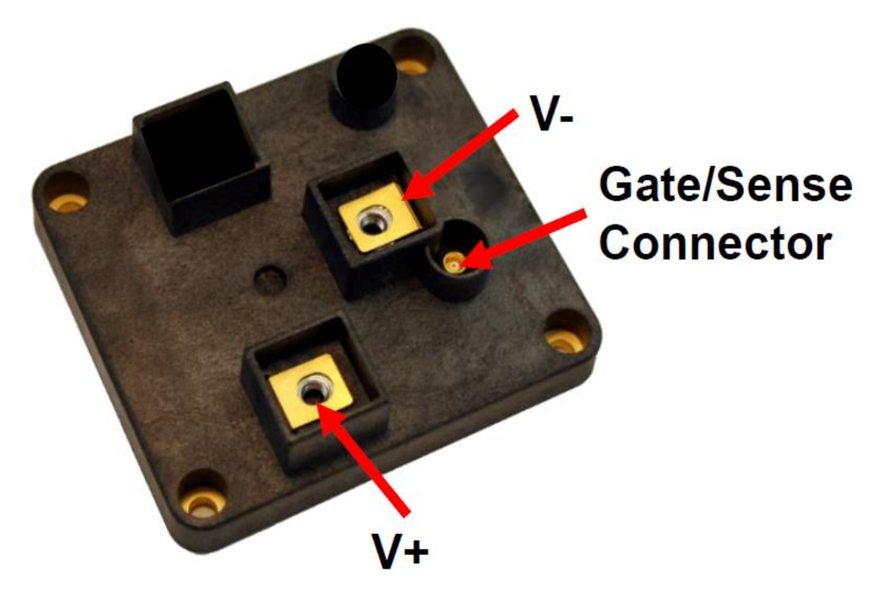
- Increased controllability
  - Energy Control Center
  - Solid State Transformer
  - Power Electronic Transformer
  - Intelligent Transformer

APEI SiC Modules

APEI Power Module - 10kV, 10A SiC MOSFET

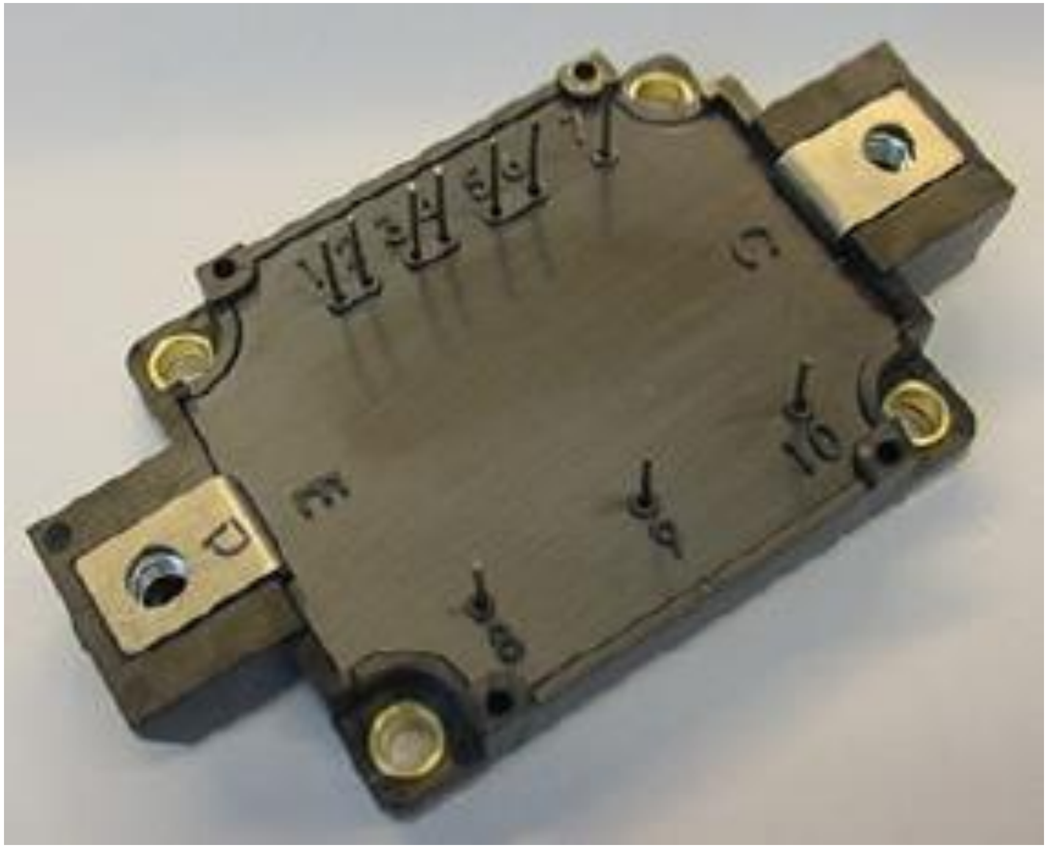


APEI Half-bridge Module



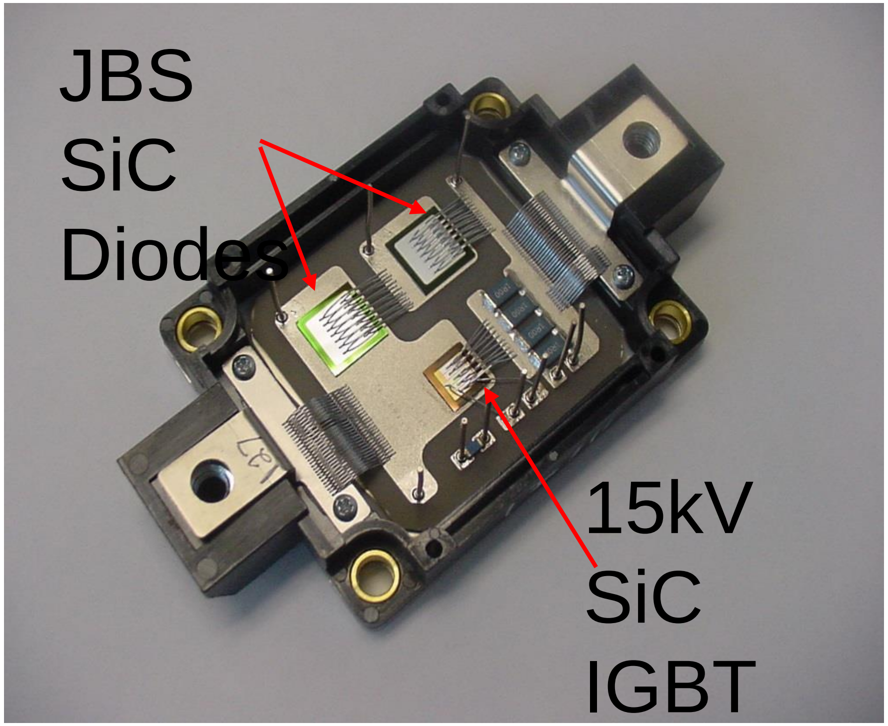
APEI Co-pack Module

10kV SiC MOSFET Co-pack Modules

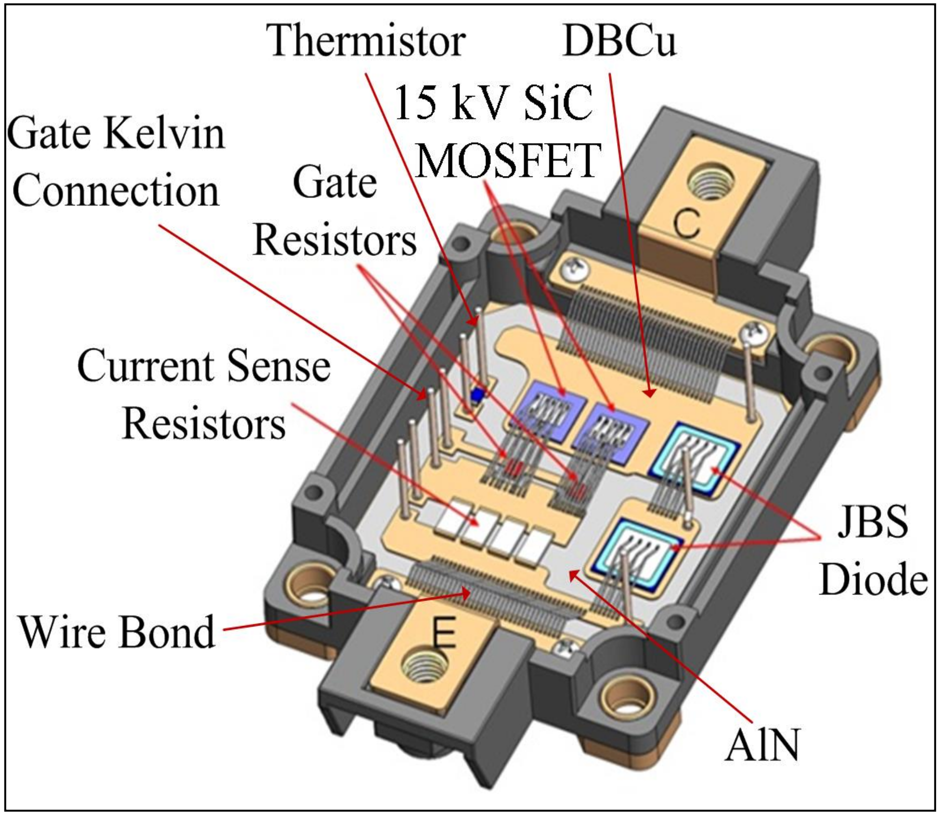


Single 10kV SiC MOSFET Module

15 kV SiC IGBT & 15 kV SiC MOSFET Modules

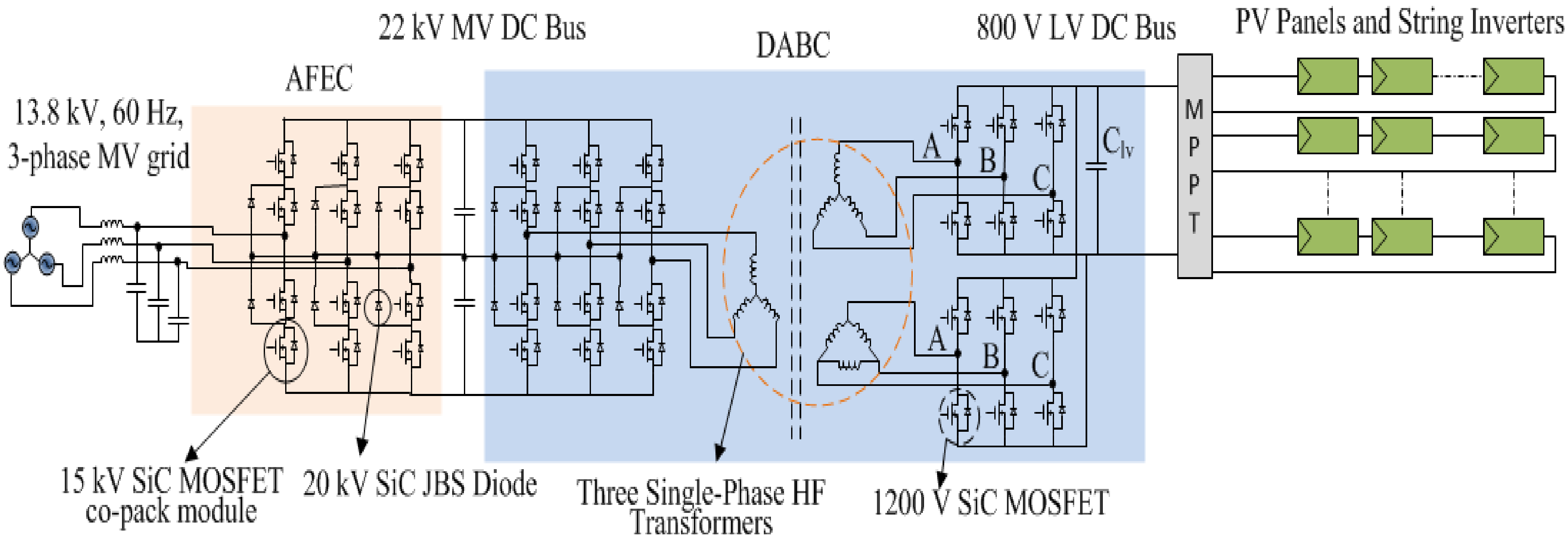


15 kV SiC IGBT (single chip) co-pack module



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

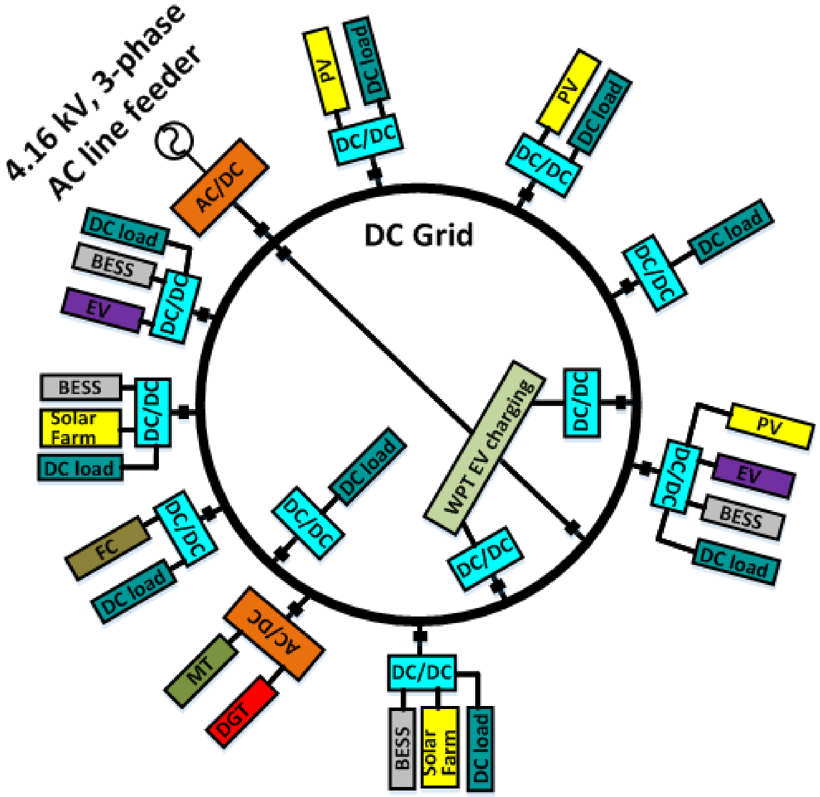
PV Integration with 13.8 kV Grid using SiC Devices – Enabler for Renewables on the Grid



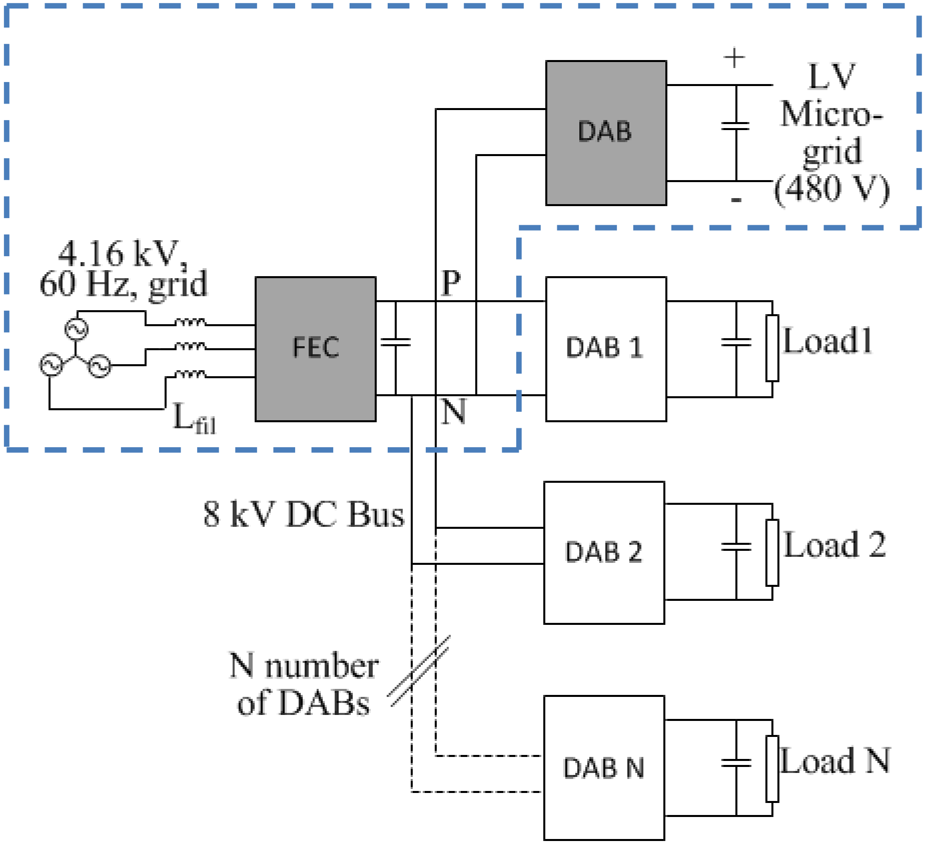
- Provide power and voltage support functions in sub-cycle time scales to keep the grid and embedded Microgrids stable

Enabling DC Micro-grid

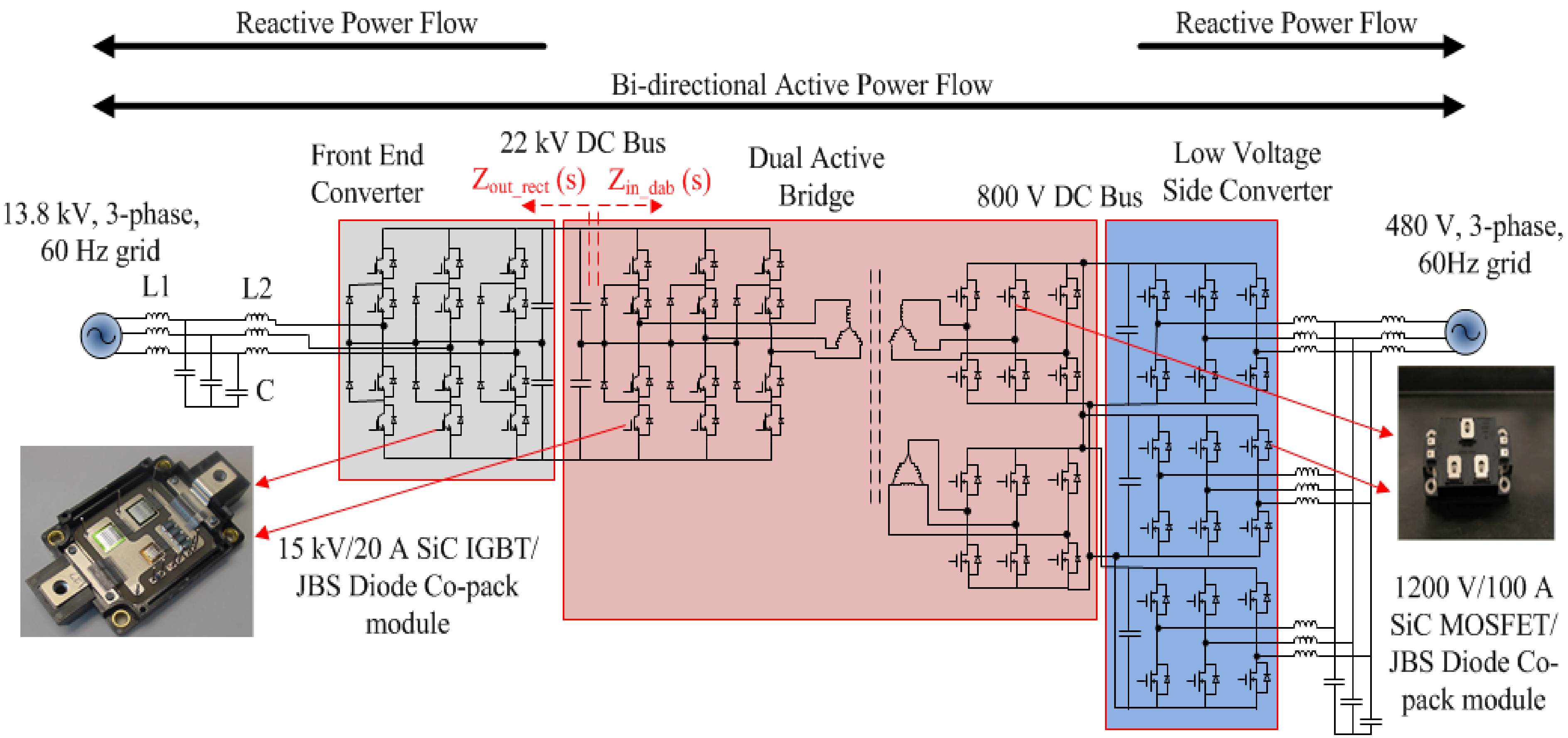
Schematic layout of a dc micro-grid



Example: DC micro-grid interface configuration



Transformerless Intelligent Power Substation (TIPS)

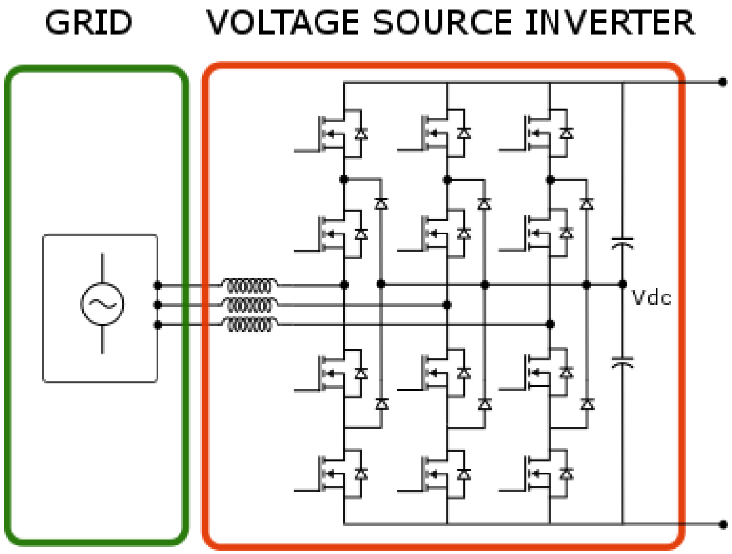


- Three-Phase SiC Devices based Solid State alternative to conventional line frequency transformer for interconnecting 13.8 kV distribution grid with 480 V utility grid.
- Smaller and Light Weight High Frequency Transformer operating at 10 kHz used for Isolation.
- Advantages – Better Power Quality, Controllability, VAR Compensation, Small Size/Light Weight, lower Cooling Requirement, Integration of Renewable Energy Sources/Storage System

POWER ELECTRONIC CONVERTERS FOR MEDIUM VOLTAGE APPLICATIONS

Smart SiC Converters for Grid Support

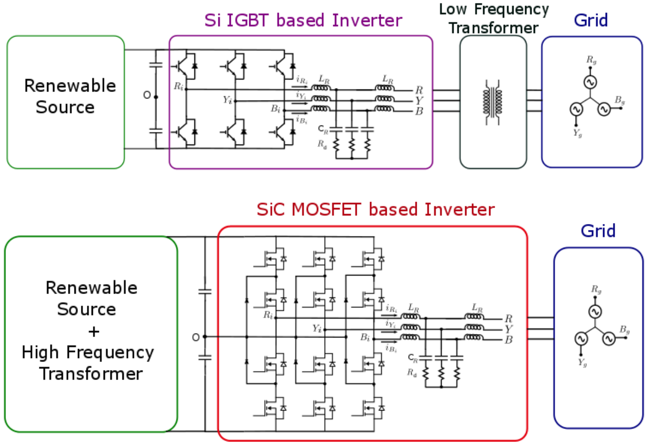
- High voltage SiC devices will enable transformerless MV converters.
- This simple single stage topology can eliminate the need for modular multilevel approach being used currently.
- Higher thermal ratings of SiC can help improve overload capability and power density.
- SiC converters are superior to Si based converters as they can offer improved grid support features such as frequency and VAR support for microgrid applications.



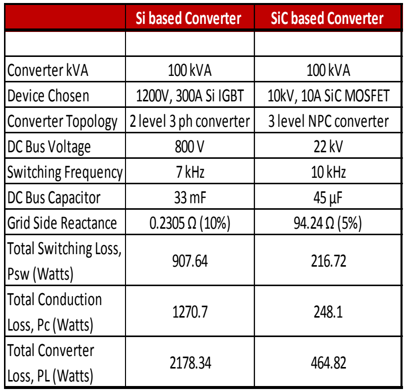
SiC enabled 3 level NPC inverter

Smart SiC Converters for Grid Support Case Study

- Aim is to investigate the thermal performance of SiC MOSFETs and its impact on medium voltage grid tie applications during grid disturbances.
- A simple 3-leg inverter with SiC MOSFET is compared with a Si IGBT based converter for renewable integration to MV grid.
- For this analysis, three modules (each module comprising of two switches with body diodes) were mounted on a single heat-sink.
- The heat-sinks were chosen so as to have similar cooling performance.

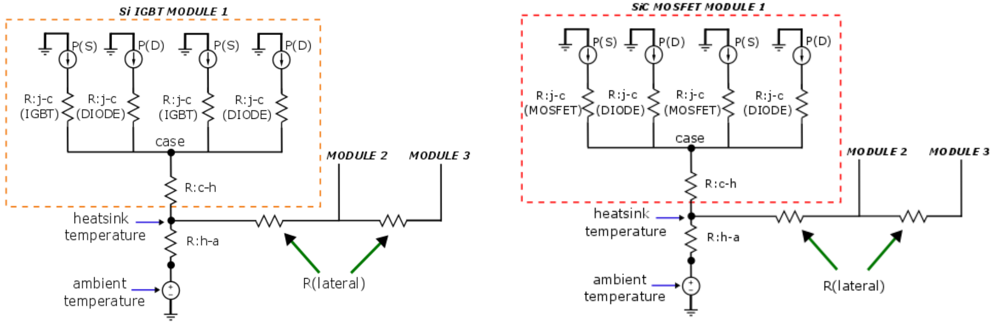


Si and SiC grid-connected inverters.



	Si based Converter	SiC based Converter
Converter kVA	100 kVA	100 kVA
Device Chosen	1200V, 300A Si IGBT	10kV, 10A SiC MOSFET
Converter Topology	2 level 3 ph converter	3 level NPC converter
DC Bus Voltage	800 V	22 kV
Switching Frequency	7 kHz	10 kHz
DC Bus Capacitor	33 mF	45 µF
Grid Side Reactance	0.2305 Ω (10%)	94.24 Ω (5%)
Total Switching Loss, Psw (Watts)	907.64	216.72
Total Conduction Loss, Pc (Watts)	1270.7	248.1
Total Converter Loss, PL (Watts)	2178.34	464.82

Si vs SiC for MV grid tie application.



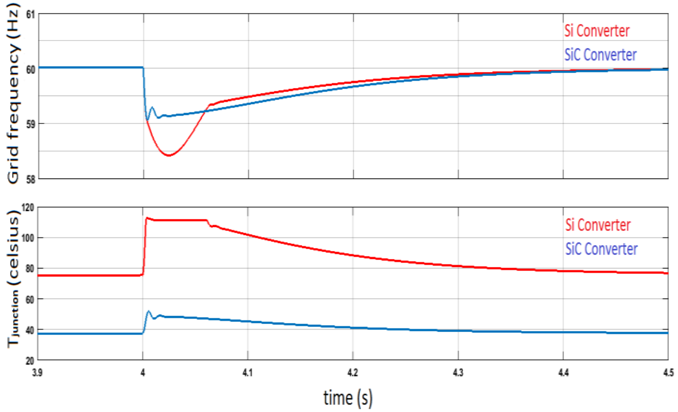
Thermal equivalent models for Si IGBT and SiC MOSFET.

Smart SiC Converters for Grid Support : Case Study

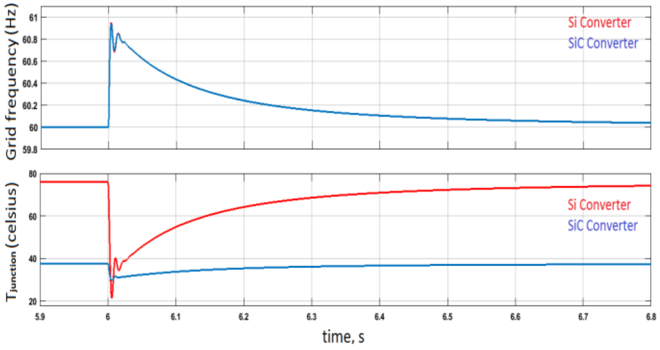
- During a sudden load demand, the SMART inverter will instantaneously increase its power output to stabilize the microgrid frequency.

- It was seen that the temperature estimate of the Si based converter switch reached its allowable junction temperature limit. Hence the converter had to be operated in a current limit mode.

- For the SiC MOSFET based converter the estimated junction temperature always remained within safe limits and hence it could offer better grid support.



Load Demand Scenario

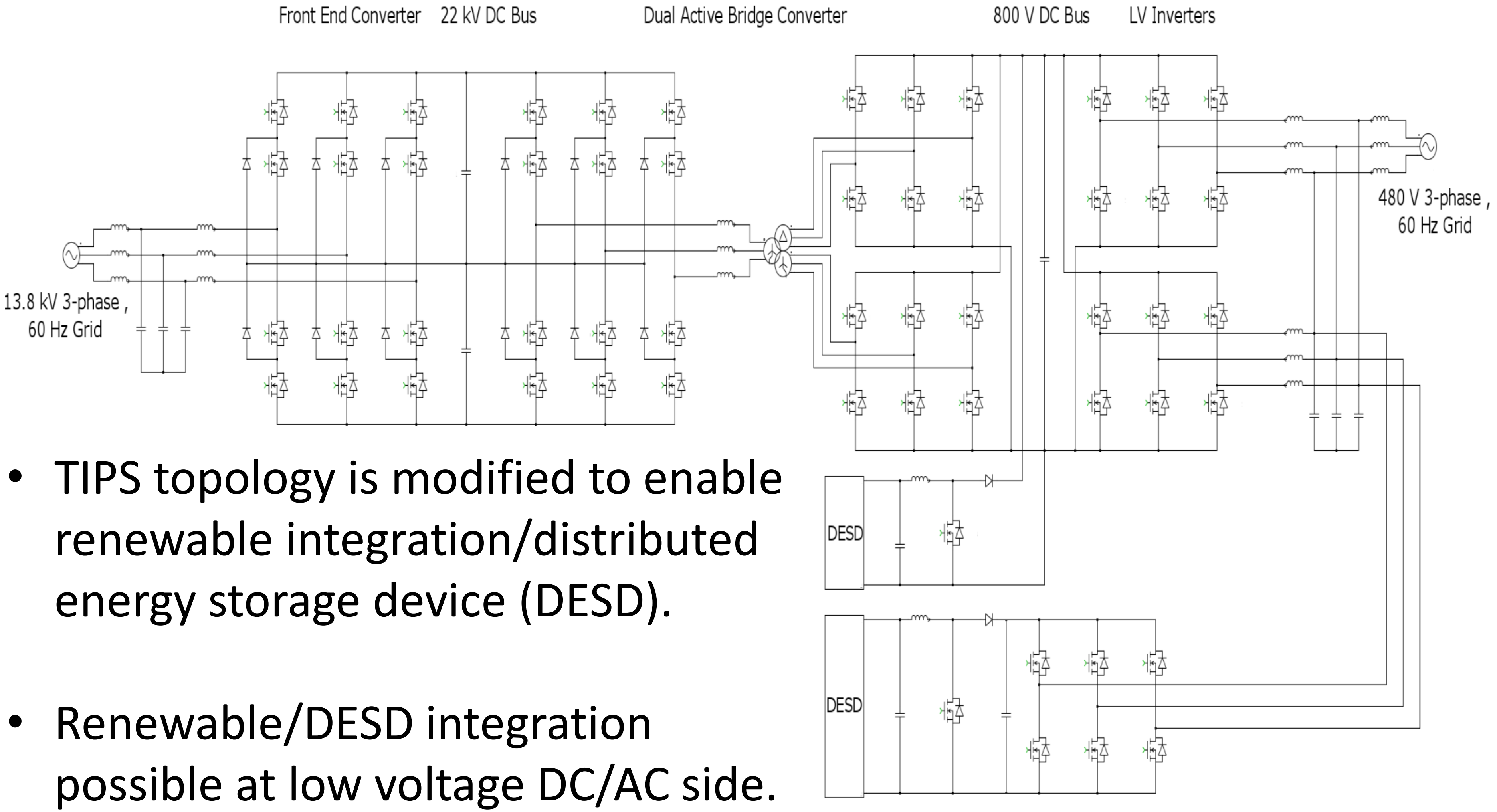


Load Shedding Scenario

- During a load shedding, even though there is no junction temperature constraint in this case, the thermal cycling effect is more pronounced for Si system than the SiC system.

- This same concept can be extended to reactive power compensation by STATCOMs where a voltage sag/swell occurs.

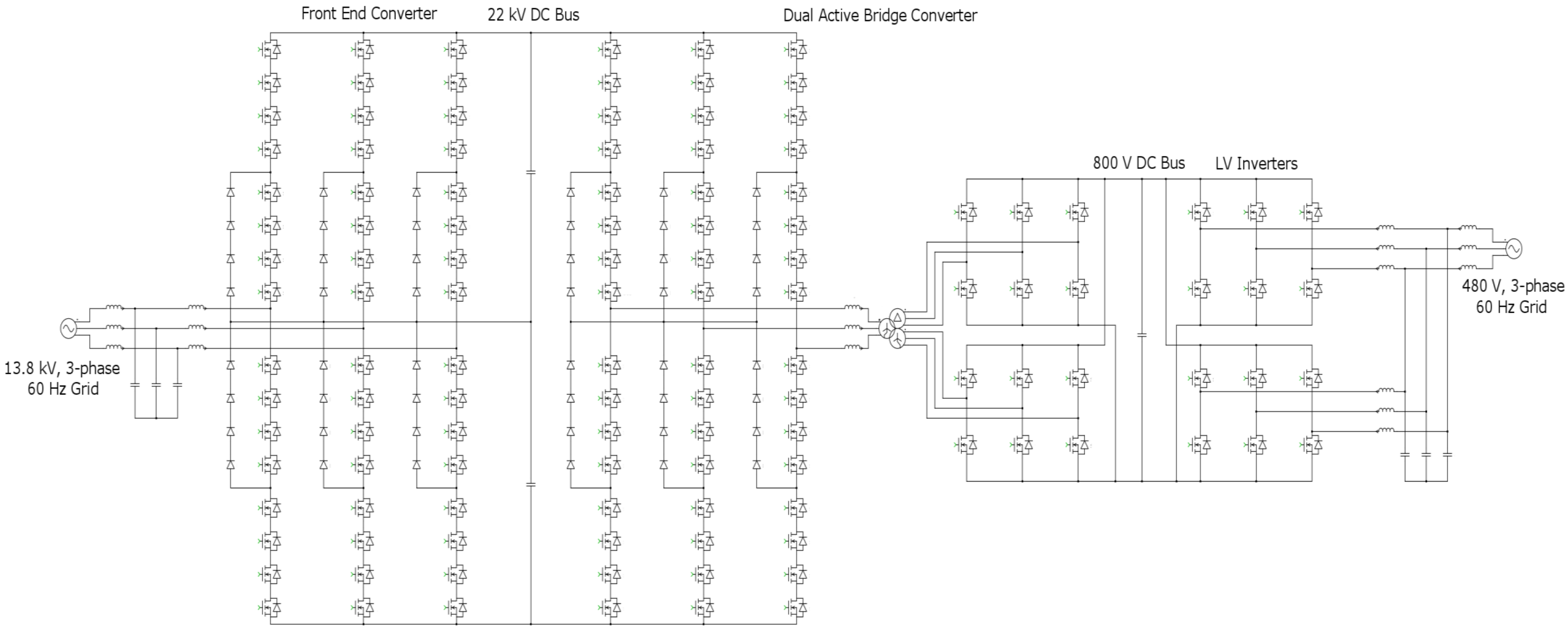
Renewable Energy + Battery Energy Storage System Integration



- TIPS topology is modified to enable renewable integration/distributed energy storage device (DESD).

- Renewable/DESD integration possible at low voltage DC/AC side.

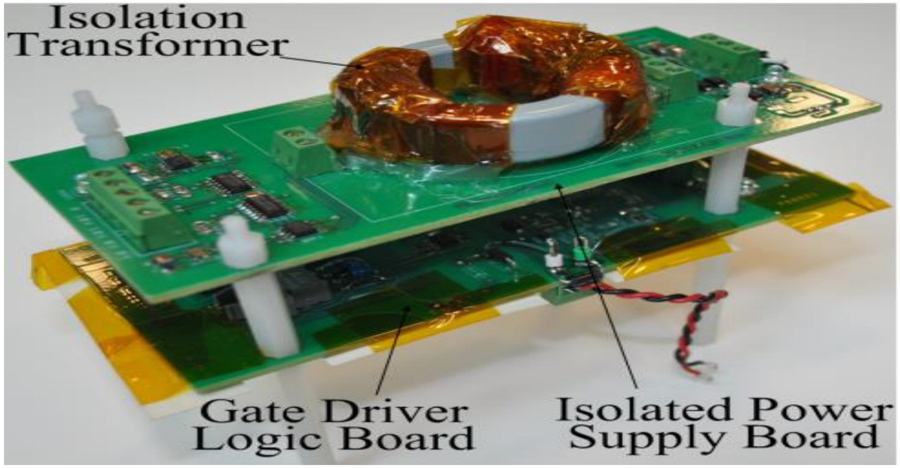
Interconnection of AC,DC and AC-DC Micro-Grids, VAR Compensation



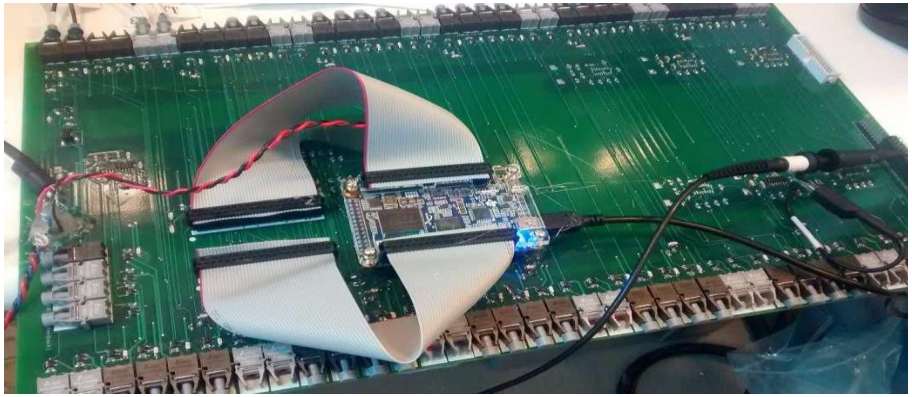
- TIPS variant using series connected 3.3 kV SiC devices.
- Potential topology for interconnection of AC/DC/Hybrid asynchronous microgrids.
- VAR compensation possible by both HV and LV converters.

Intelligent MV (15kV) Isolated Gate Driver

One Gate Driver Photo – Six Used for 3-Phase Converter

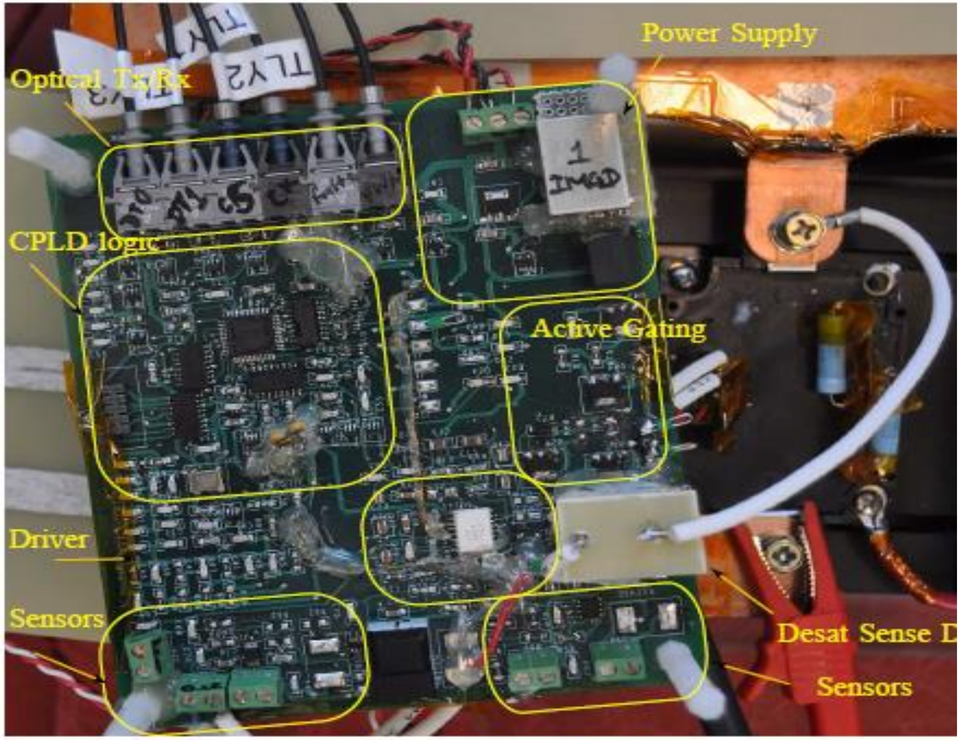


Intelligent MV Gate Driver Interface Board



- Reduction of coupling capacitance needed for high dv/dt motor drive applications*
- High voltage insulation requirement for high side device operation – Kapton Tape used
- Active gate drive can reduce dv/dt**

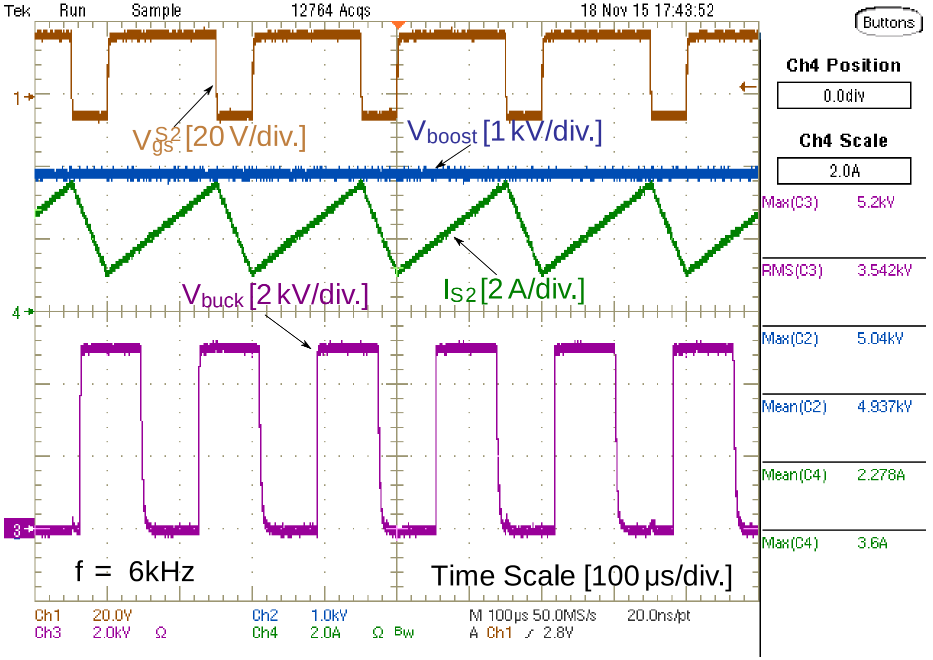
Intelligent MV Gate Driver



Specification	Value
Turn-on Voltage	20V
Turn-off Voltage	-5 V
Supply Input Voltage	9 V
Switching Frequency	Up to 20 kHz
Turn-on Gate Resistance	14.7 Ω
Turn-off Gate Resistance	14.7 Ω
Isolation Voltage	Up to 15 kV
dv/dt capability	> 50 kV/µs

Monitoring test with IMGD Boost-buck

- Boost-buck at 3.75 kW for 30 min - Switching test of 10 kV SiC MOSFET at 5 kV
- Boost input is 1.25 kV and output is 5 kV. The boost duty is 25%



Ch4 Position 0.0div
Ch4 Scale 2.0A
Max(C3) 5.2kV
RMS(C3) 3.542kV
Max(C2) 5.04kV
Mean(C2) 4.937kV
Mean(C4) 2.278A
Max(C4) 3.6A

Figure: 5 kV boost-buck GD qualification results

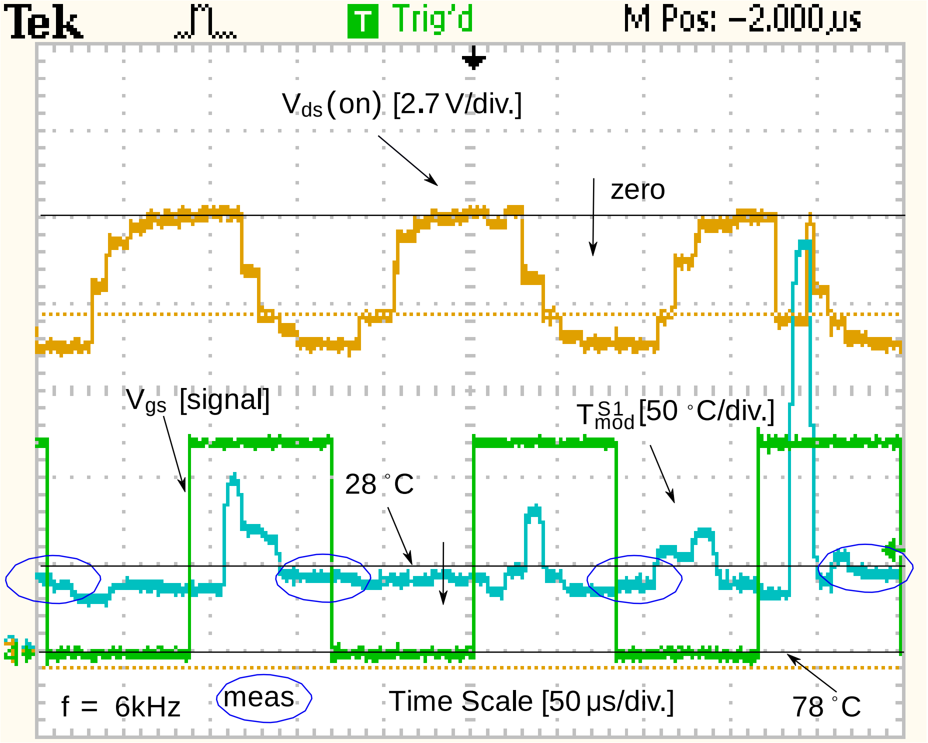
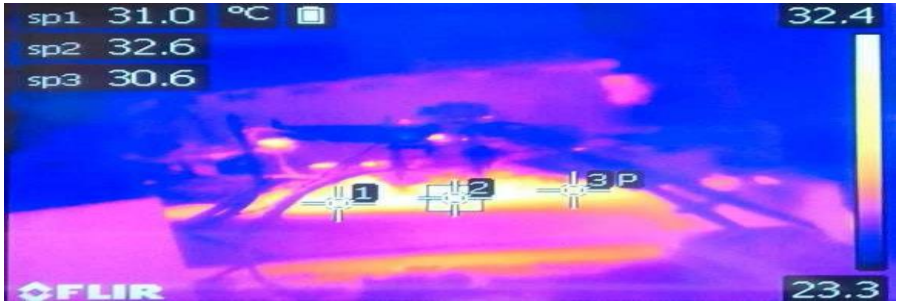
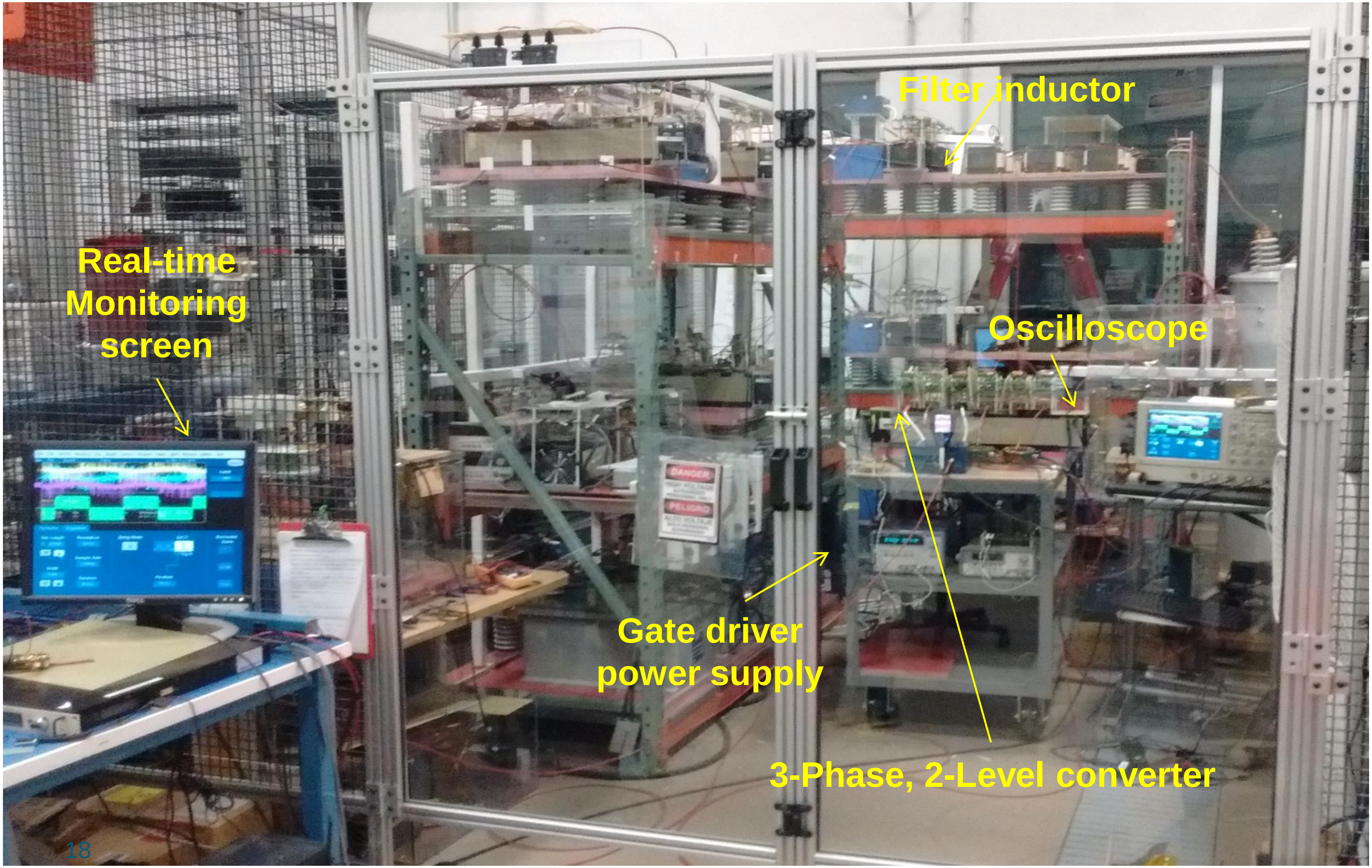


Figure: **5 kV boost-buck GD qualification interface side results**



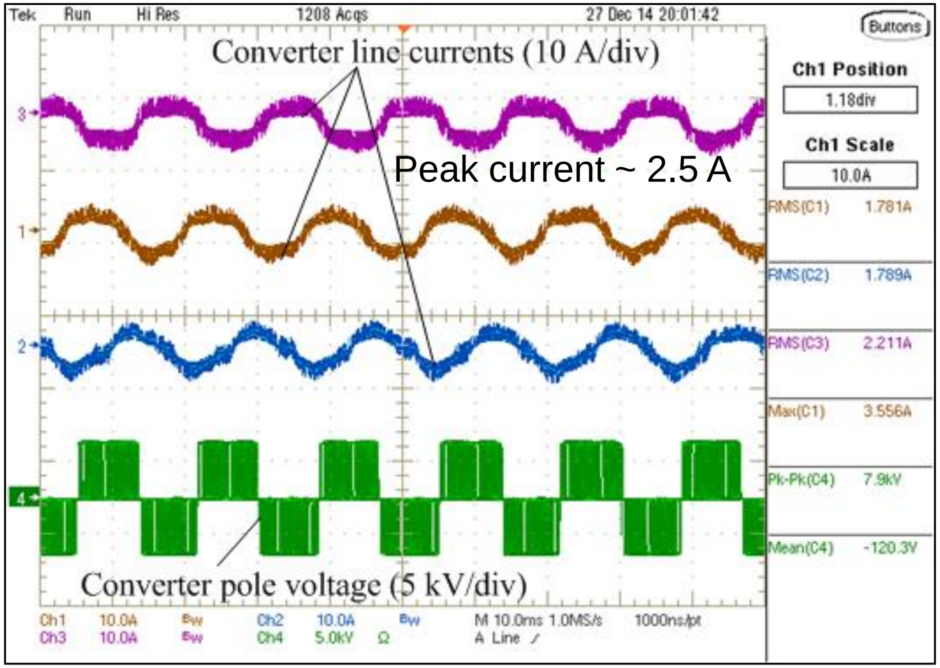
- 30 min thermal run at 5 kV and 3.75 kW power
- sp1 pointer near high side IGBT
- Desat-sensing, V_{ds}(on), T_{mod} and I_d are verified

MV Converter “SAFE” Operation

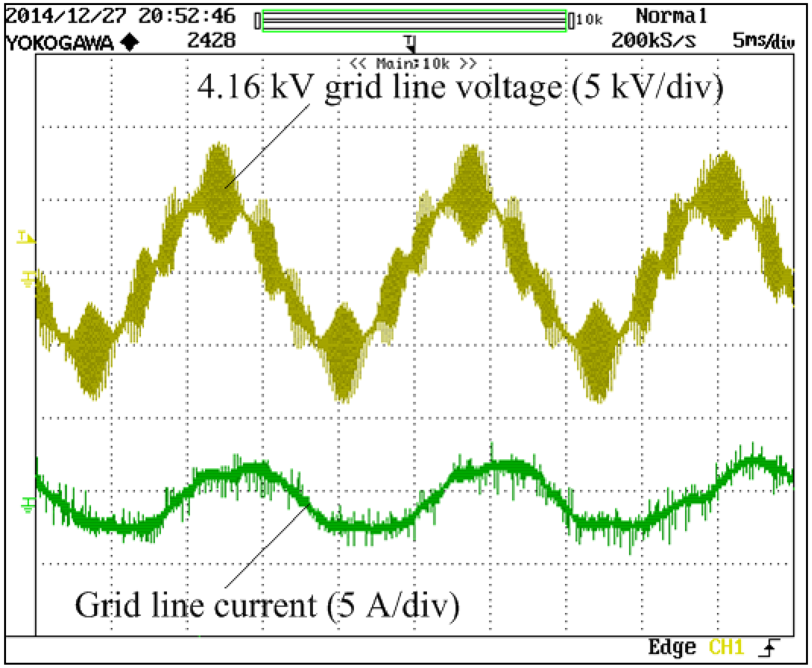


TIPS Grid Connected Converter Experimental Demonstration

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

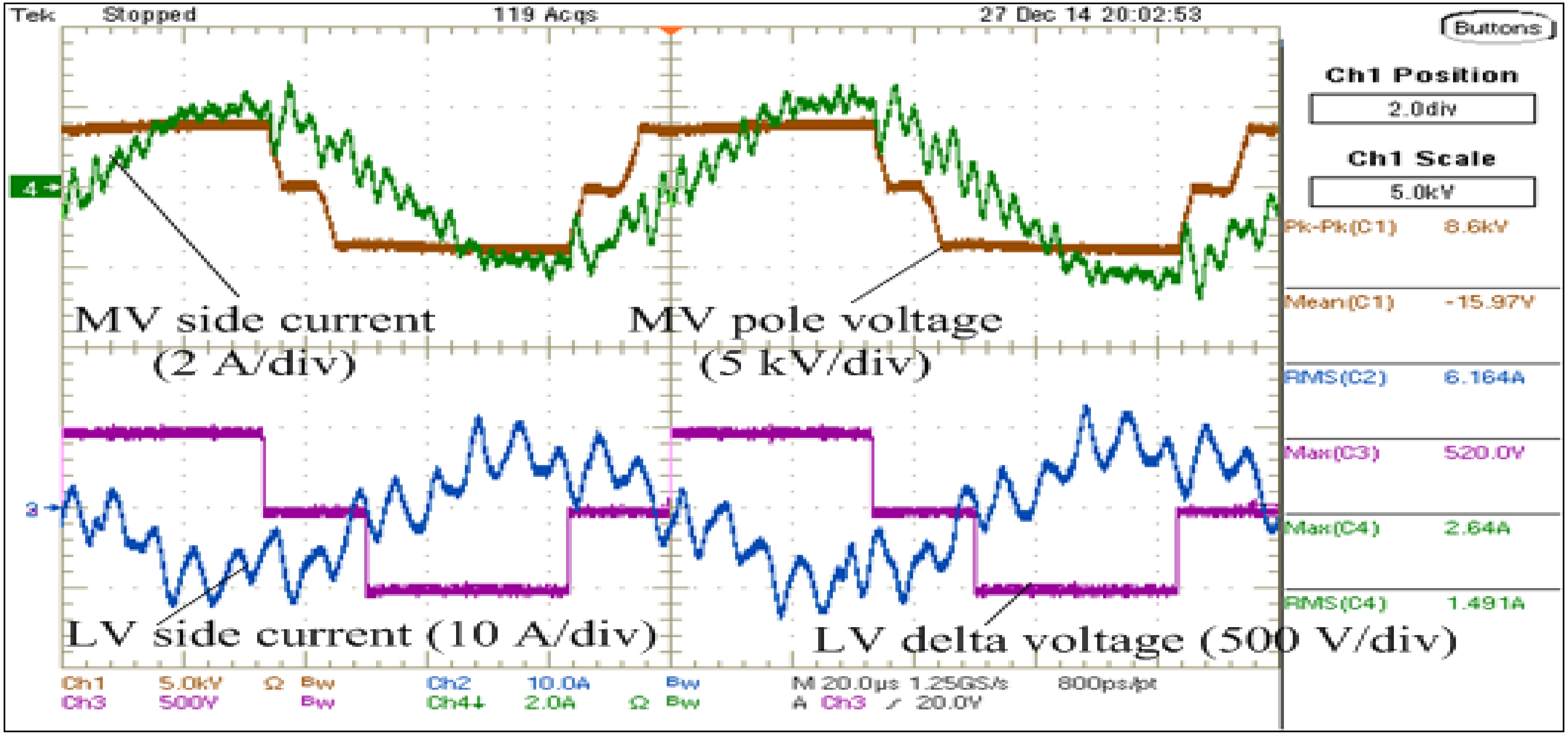


RY-grid voltage and R-phase grid current

- 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

TIPS 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



```
Tek    Stopped            119 Acqs                 27 Dec 14 20:02:53

Ch1 Position
2.0div
Ch1 Scale
5.0kV
Pk-Pk(C1)    8.6kV
Mean(C1)     -15.97V
RMS(C2)      6.164A
Max(C3)      520.0V
Max(C4)      2.64A
RMS(C4)      1.491A

Ch1   5.0kV   Ω Bw    Ch2    10.0A     Bw    M 20.0µs 1.25GS/s    800ps/pt
Ch3   500V      Bw    Ch4↓   2.0A    Ω Bw    A  Ch3  ∕  20.0V
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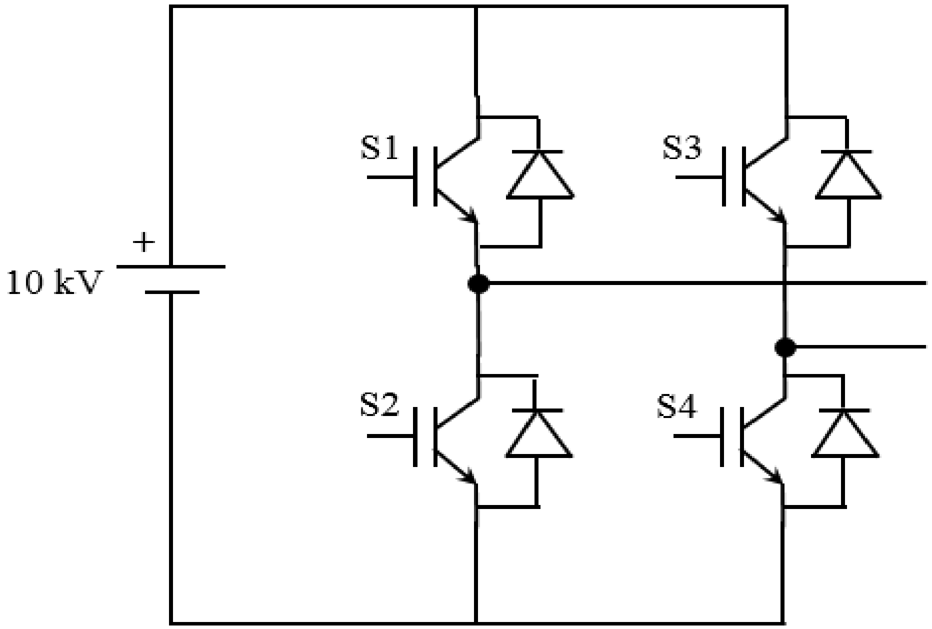
- All waveforms captured at the HF transformer terminals
- Ripple in the DAB currents is due to the HF transformer parasitics

10kV H-Bridge for 7.2 kV AC grid interface



15kV/20A SiC IGBTs

No need for complex multilevel converter topologies

Simple 2-level VSC control

Robust 2-level VSC converter

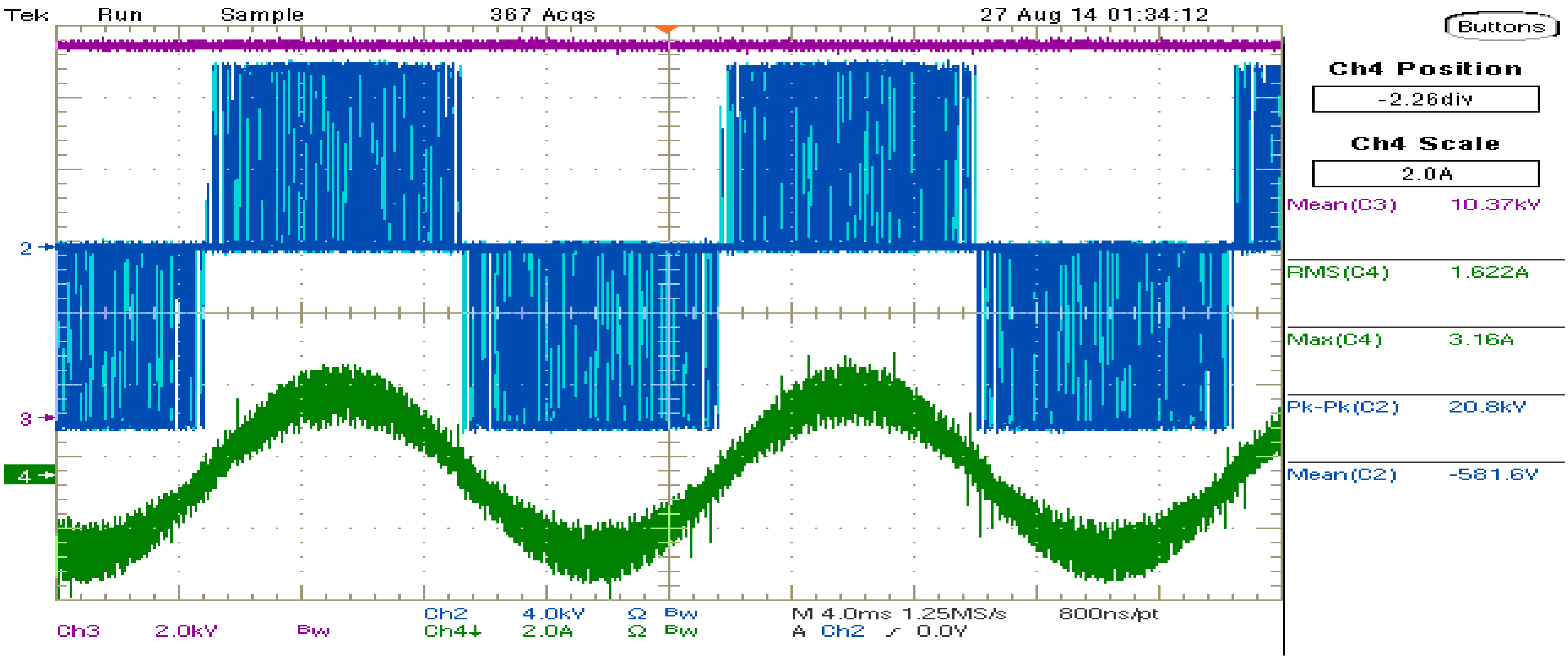
Compact – size, weight, volume

Efficient MV power conversion

- **Only four 15 kV SiC IGBTs are sufficient for 7.2kV AC single-phase (7.2kV is single-phase of 3-phase 12.47kV) grid integration, whereas, at least twelve 6.5 kV Si IGBTs are needed for the same voltage.**

- **This H-Bridge test showcases the MV power conversion possibilities of the Cree developed 15kV SiC IGBT device [funded byARPA-E/DOE]**

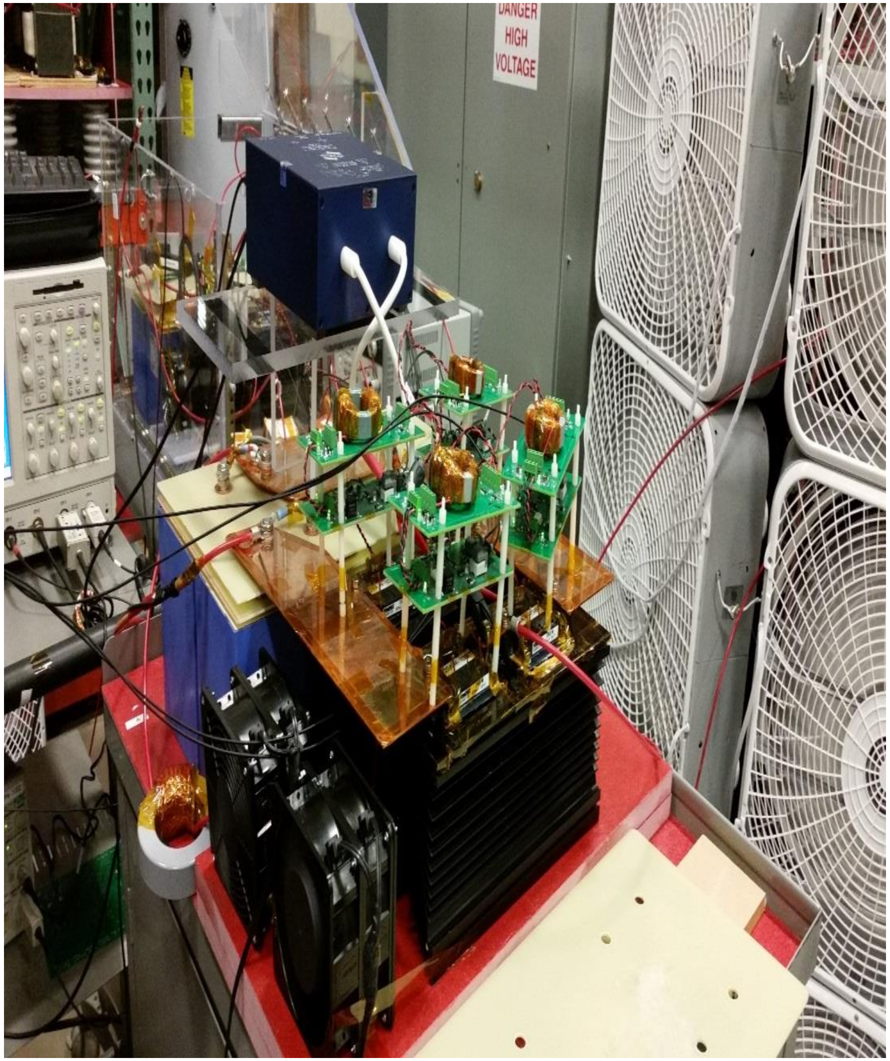
10 kV DC bus Voltage Demonstration

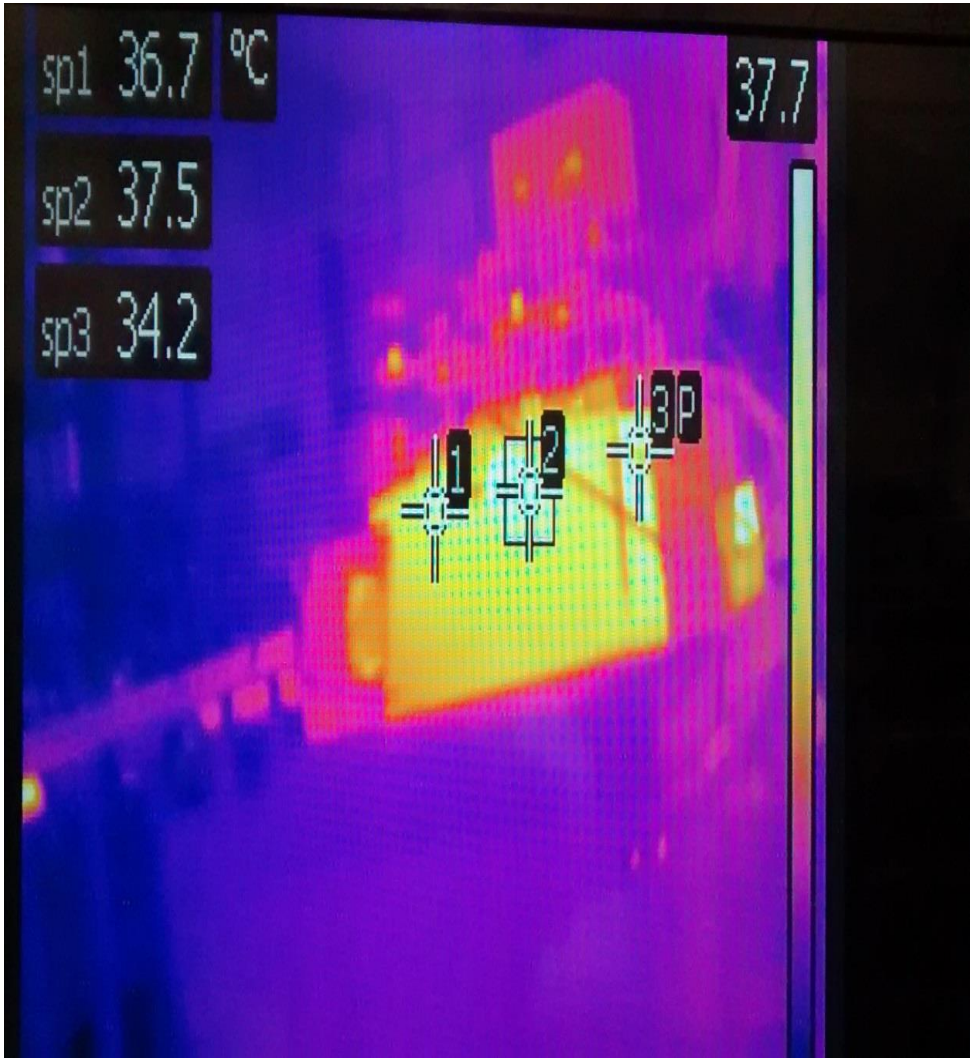


Ch2: AC voltage output (4 kV/div); Ch3: DC Voltage (2 kV/div); Ch4: AC current in R-L load (2 A/div)

- **The 10kV H-Bridge operated at 10 kV, 5 kHz, 6 kW for 15 mins.**
- **Peak to Peak output ac voltage of 20 kV at 5 kHz PWM switching**

10 kV DC bus Voltage Demonstration - Experimental setup



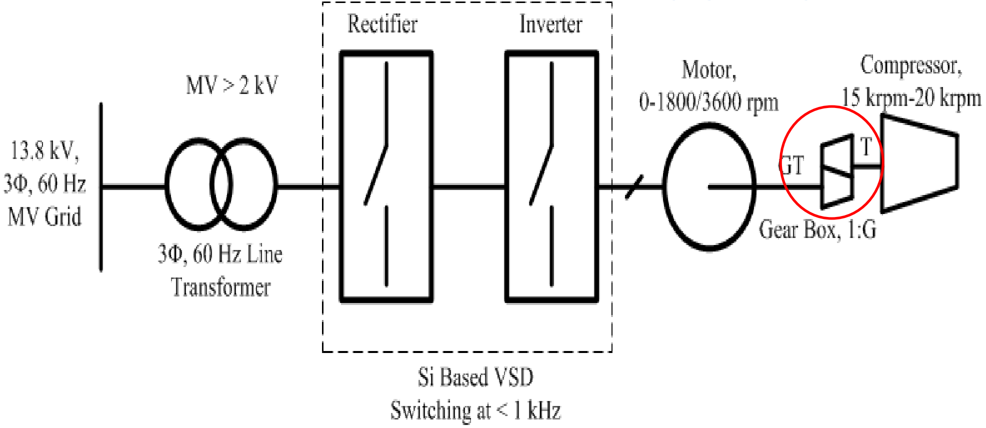


The 10 kV dc input is provided by 1:4 Boost Converter with the same 15kV / 20A SiC IGBT

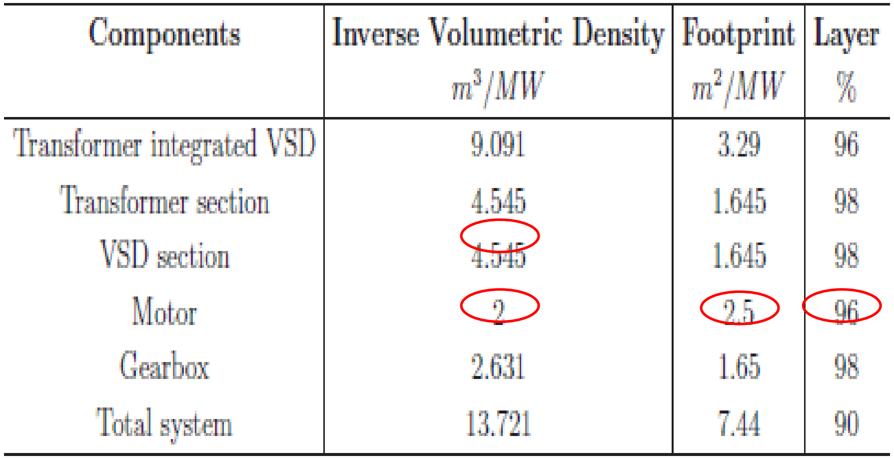
Motivation – DOE NGEM HSM Program

- High Speed Motor Drives Application

Si based VSD showing the bulky gear system



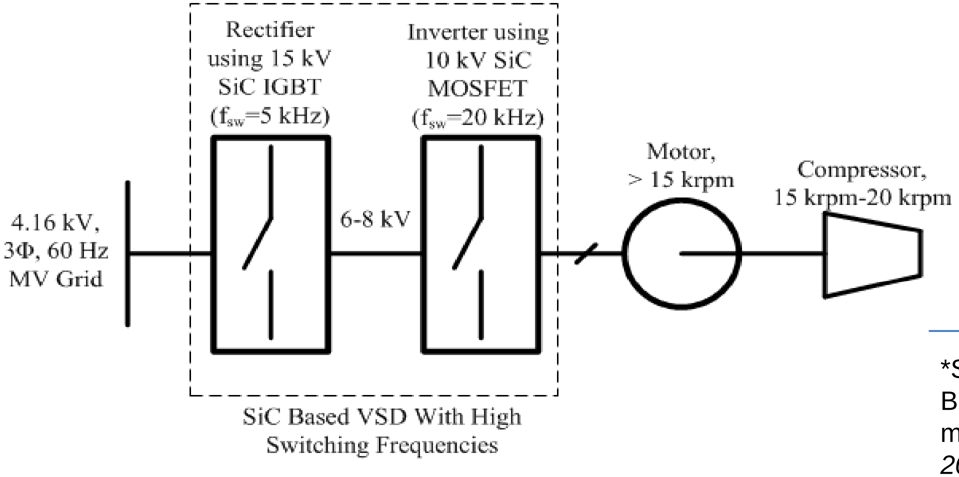
Density, Footprint and Efficiency of Si Based High Speed Motor Drive



Components	Inverse Volumetric Density m^3/MW	Footprint m^2/MW	Layer %
Transformer integrated VSD	9.091	3.29	96
Transformer section	4.545	1.645	98
VSD section	4.545	1.645	98
Motor	2	2.5	96
Gearbox	2.631	1.65	98
Total system	13.721	7.44	90

- 15 kV SiC IGBT used for AFEC* and TIPS
- 10 kV SiC MOSFET used for HF Inverter
- Remove the bulky and inefficient gear system
- Direct drive at medium voltage and high frequency
- **Achieved - 4 m^3/MW**

Proposed SiC based Back-Back MV VSD



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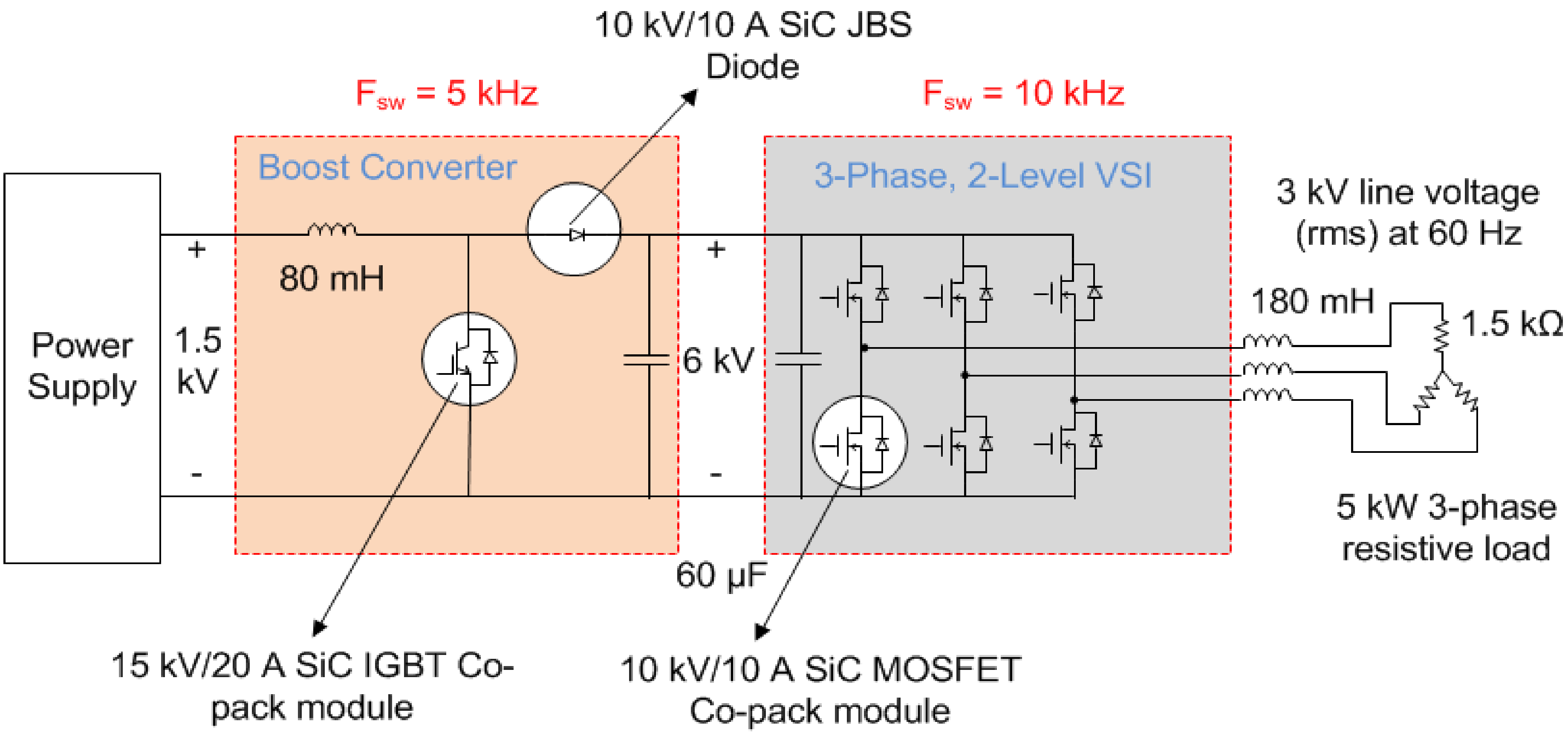
*S. Madhusoodhanan, K. Mainali, A. Tripathi, D. Patel, A. Kadavelugu, S. Bhattacharya, and K. Hatua, "Performance evaluation of 15 kV SiC IGBT based medium voltage grid connected three-phase three-level NPC converter," in *proc. 2015 IEEE Energy Conversion Congress and Exposition*, Montreal, Canada, pp. 3710-3717, Sept. 2015.

3-Phase, 2-Level Converter Development and Testing using 10 kV/10 A SiC MOSFETs

High Fundamental Frequency Three-Phase Converter Test Setup and Results

MV Converter Test Setup



10 kV/10 A SiC JBS Diode

F_{sw} = 5 kHz

F_{sw} = 10 kHz

Boost Converter

3-Phase, 2-Level VSI

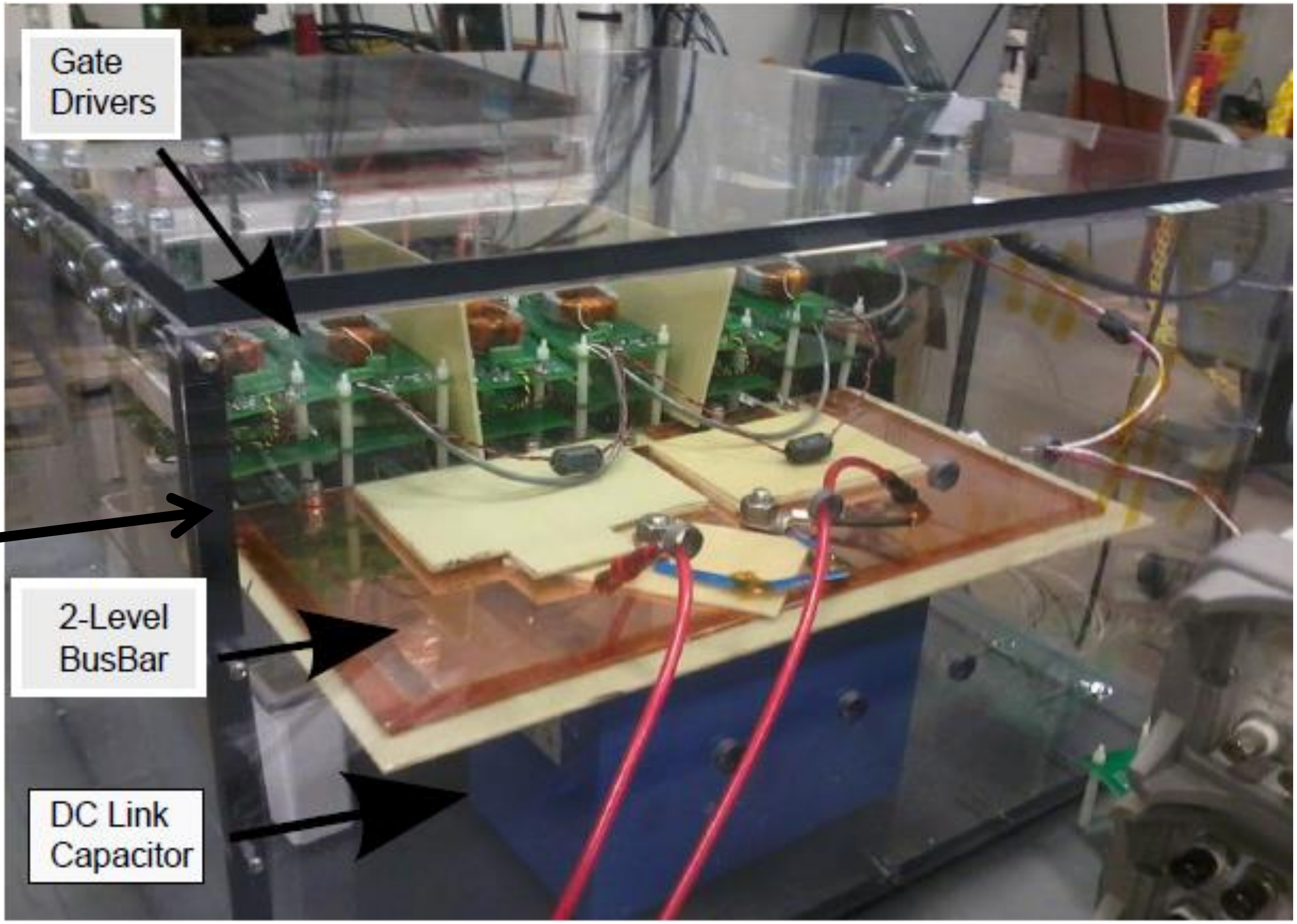
3 kV line voltage (rms) at 60 Hz

5 kW 3-phase resistive load

15 kV/20 A SiC IGBT Co-pack module

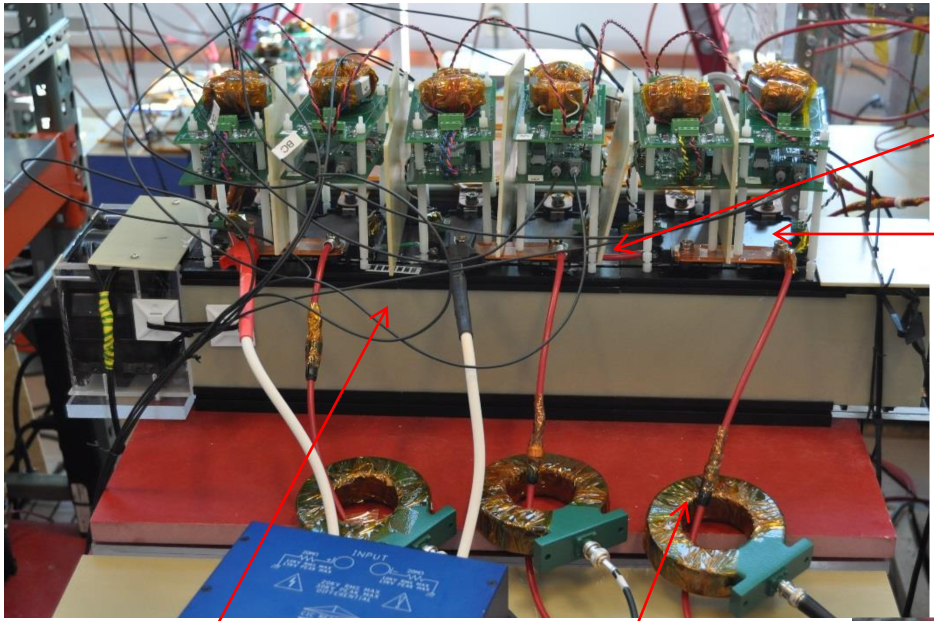
10 kV/10 A SiC MOSFET Co-pack module

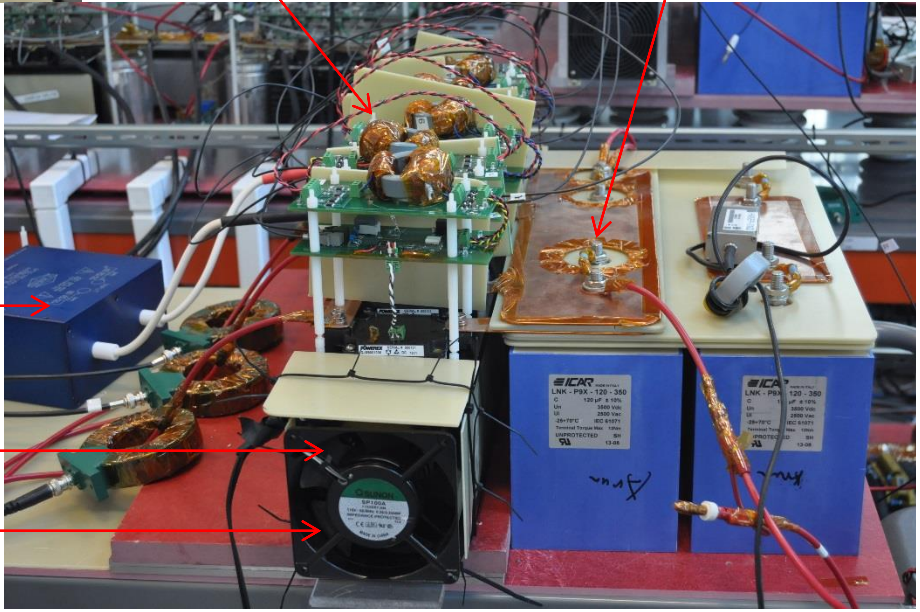
10kV SiC MOSFET 3-phase 2-level MV Inverter



2-level 3-phase Inverter built using 10kV SiC MOSFET

MV Converter Test Setup





All three phase-leg heat sinks connected together electrically

Six 10 kV/10 A SiC MOSFETS

Six gate drivers

Sandwich bus bar with FR4 Insulation

Heat Sinks with Air Guide

Pearson current sensor

CIC Research HV differential probe

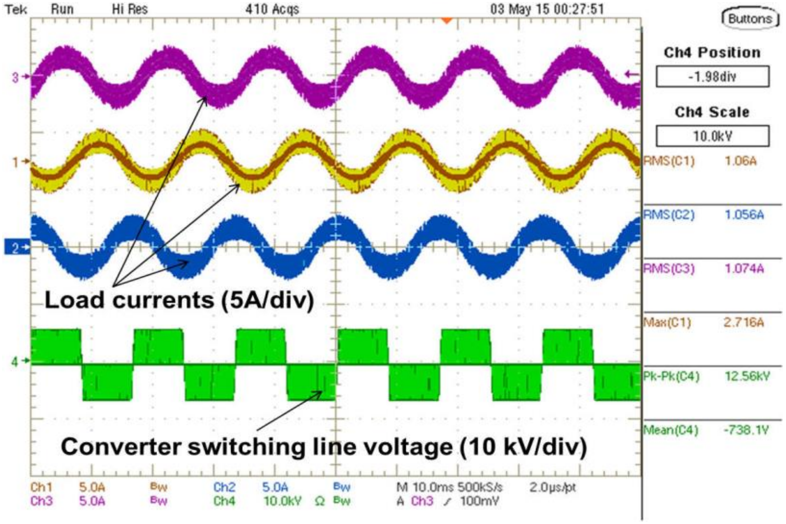
Cooling Fan

DC bus capacitors

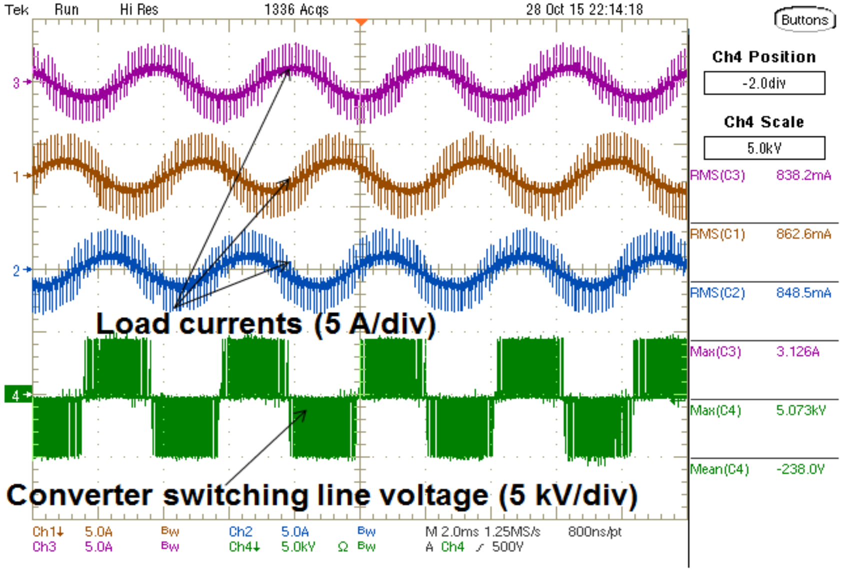
Three-Phase Converter Hardware Development and Demonstration

Three-Phase Converter Experimental Waveforms

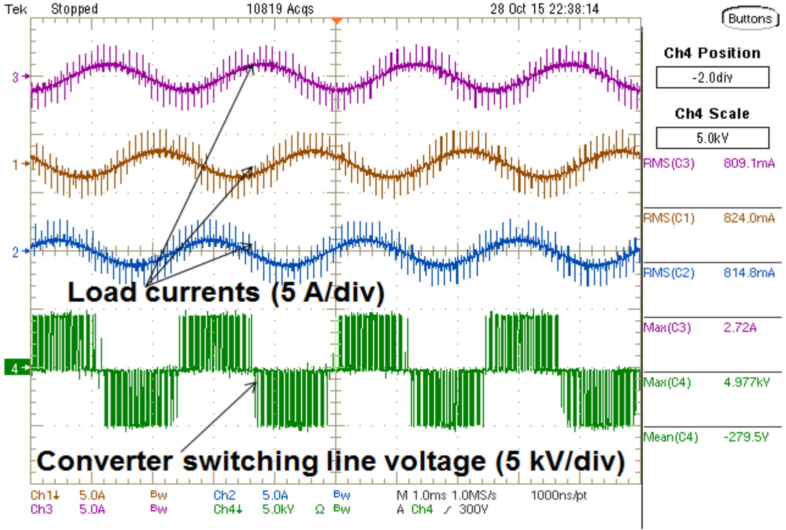
6 kV DC, 3 kV AC, 5 kW, f_{sw}=10 kHz, f_m=60 Hz



5 kV DC, 2.6 kV AC, 3.8 kW, f_{sw}=10 kHz, f_m=240 Hz



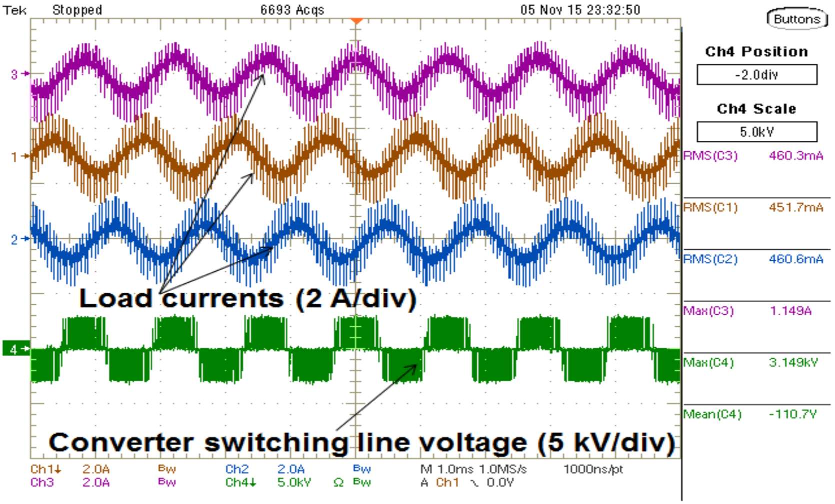
5 kV DC, 2.6 kV AC, 3.8 kW, f_{sw}=10 kHz, f_m=400 Hz



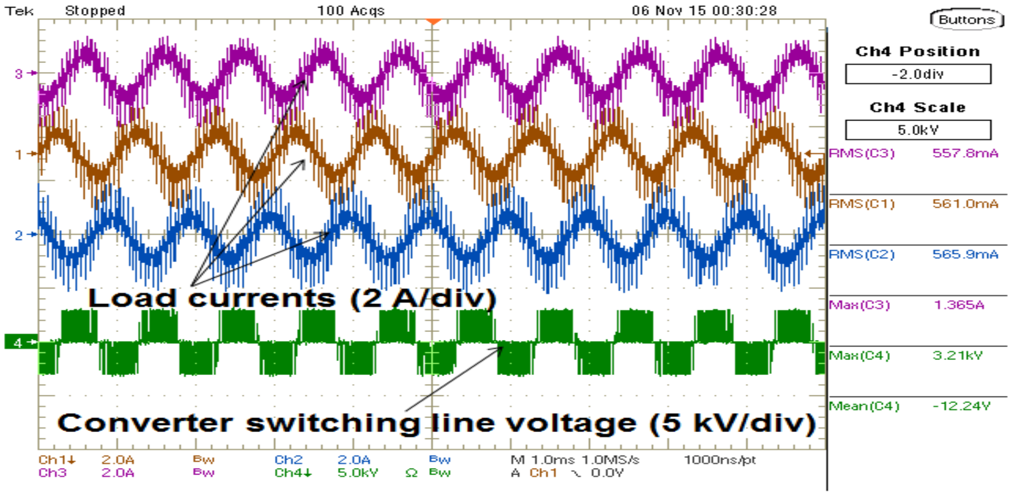
- Up to 400 Hz Fundamental Frequency with 10 kHz Switching Frequency
- For Fundamental Frequency Higher than 400 Hz, Switching Frequency increased to 20 kHz

Three-Phase Converter Hardware Development and Demonstration

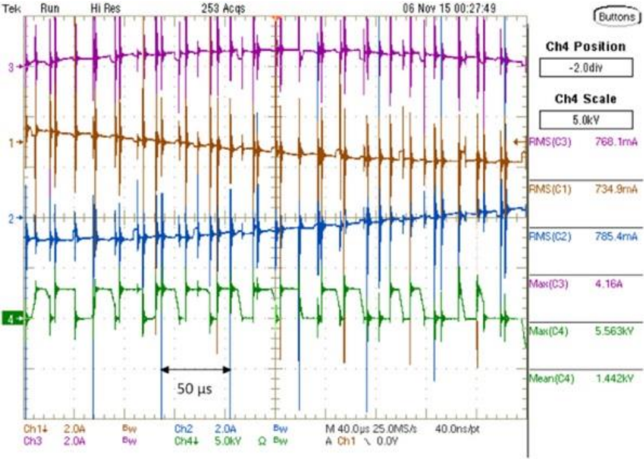
3 kV DC, 900 V AC, 1.45 kW, f_{sw}=20 kHz, f_m=720 Hz



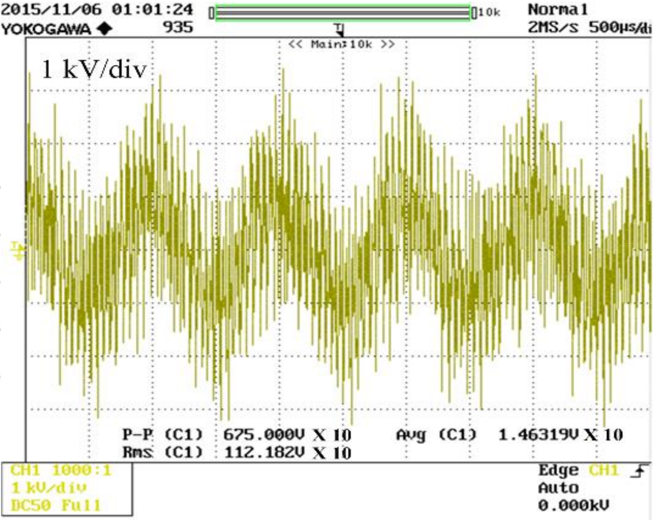
3 kV DC, 900 V AC, 1.45 kW, f_{sw}=20 kHz, f_m=1 kHz



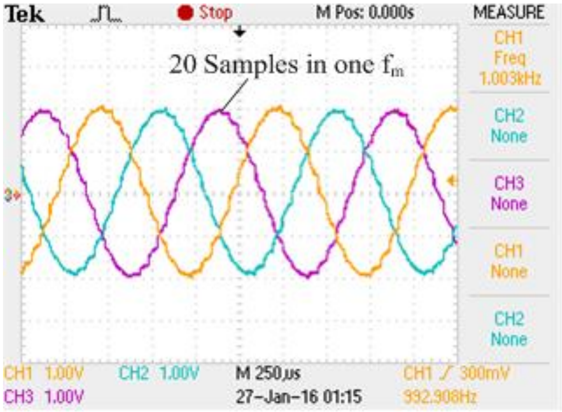
3 kV DC, f_{sw}=20 kHz, f_m=1 kHz (Zoomed)



Filter Voltage at f_m=1 kHz



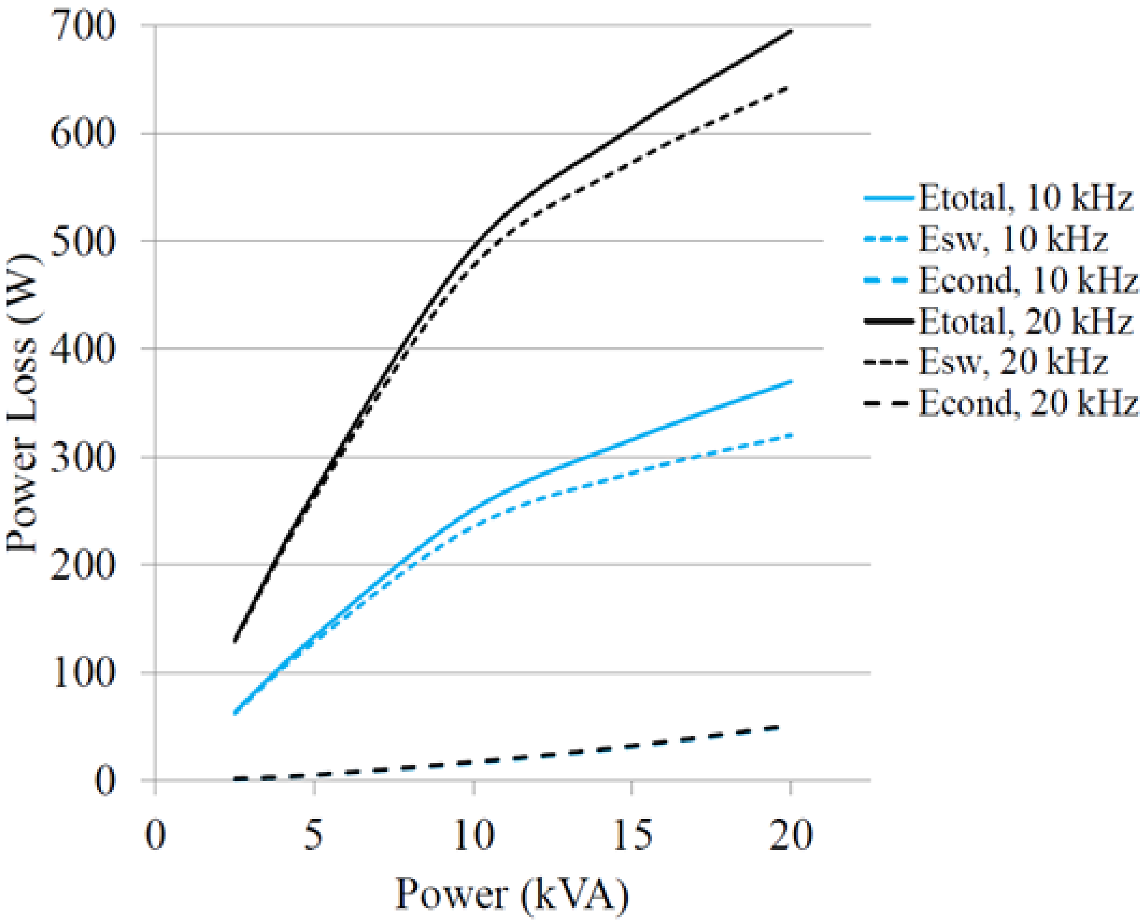
Modulating Signals at f_m=1 kHz



Three-Phase Converter Loss Analysis

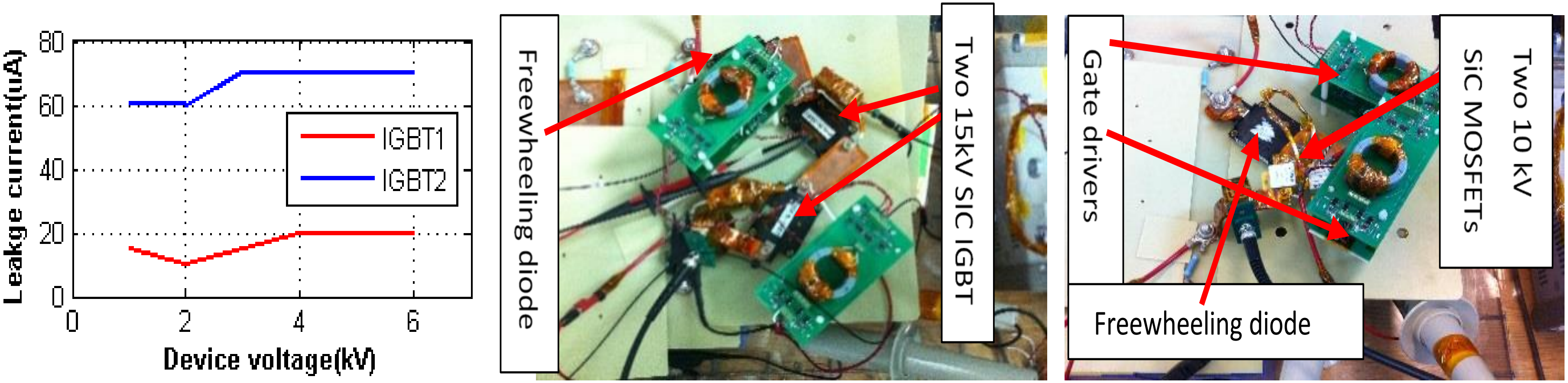
- PLECS simulation based on real experimental data

Loss Variation with Load at f_m = 1 kHz, 6 kV DC, 3 kV AC



- Semiconductor loss does not vary much with fundamental frequency – only 1 kHz considered
- At f_{sw} = 20 kHz and 20 kVA load, total loss - 695 W
- Efficiency - 96.64% at a power density of 4.11 W/inch^3

Experimental setup of series connection HV SiC devices



(a) (b) (c)

Figure1 : (a): Leakage current with blocking voltage; (b): Experimental setup of two series connected 15kV SiC IGBT devices; (c) Experimental setup of two series connected 10kV SiC MOSFET devices;

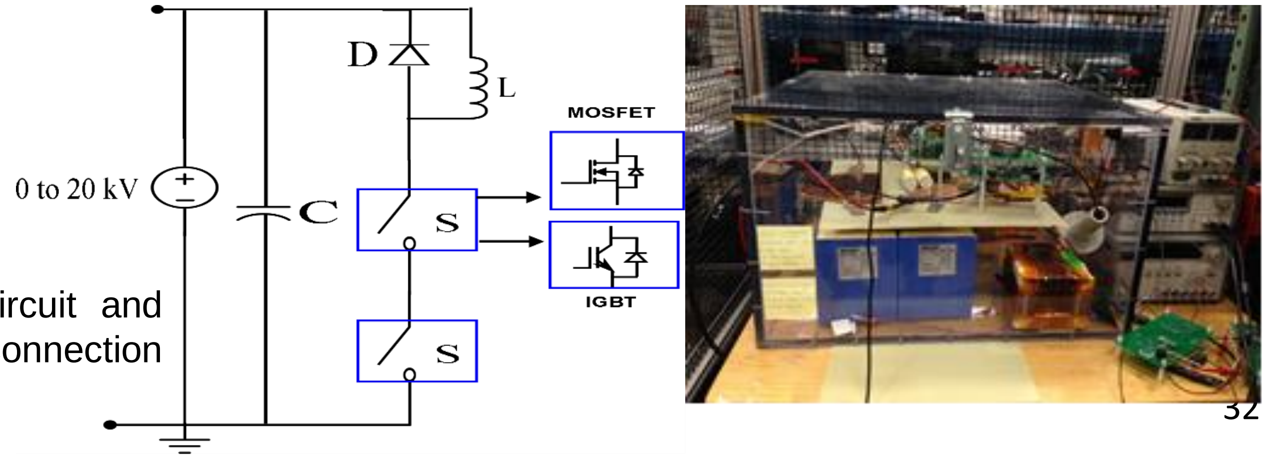


Figure 2: Inductive clamped circuit and experimental setup to test series connection of devices.

Experimental results series connection of two 15kV SiC IGBT devices with RC snubber

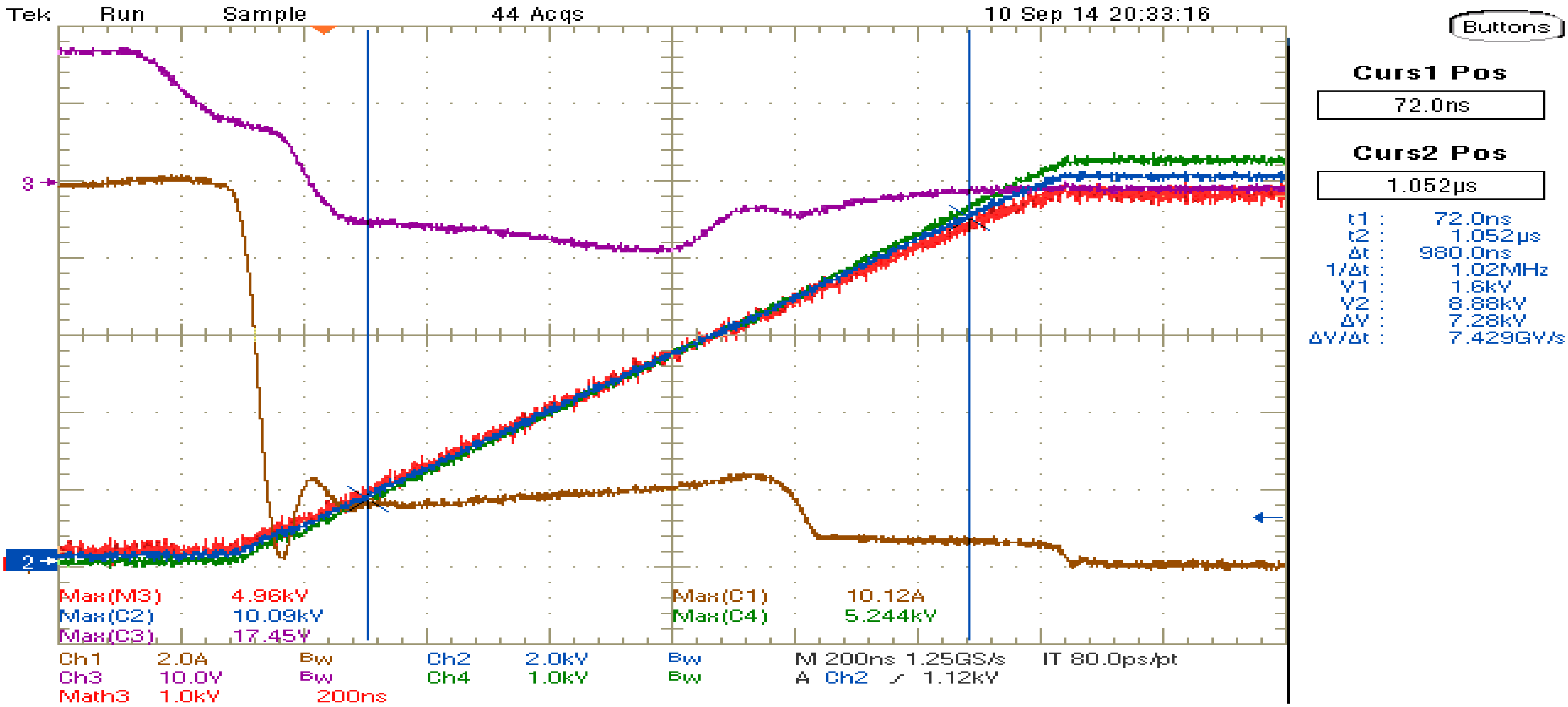


Figure: Balanced Turn-off characteristics At 10kV DC bus voltage with RC snubber.

[Ch3: Top device V_{GE} (20 V/div); Ch2: Total voltage (1 kV/div); Ch4: Bottom device V_{CE} (1 kV/div); Math1: Ch2-Ch4: Top device V_{CE} (1 kV/div) Ch1: Bottom device current: I_C(5 A/div);]

Experimental results series connection of two 10kV SiC MOSFET devices with RC snubber

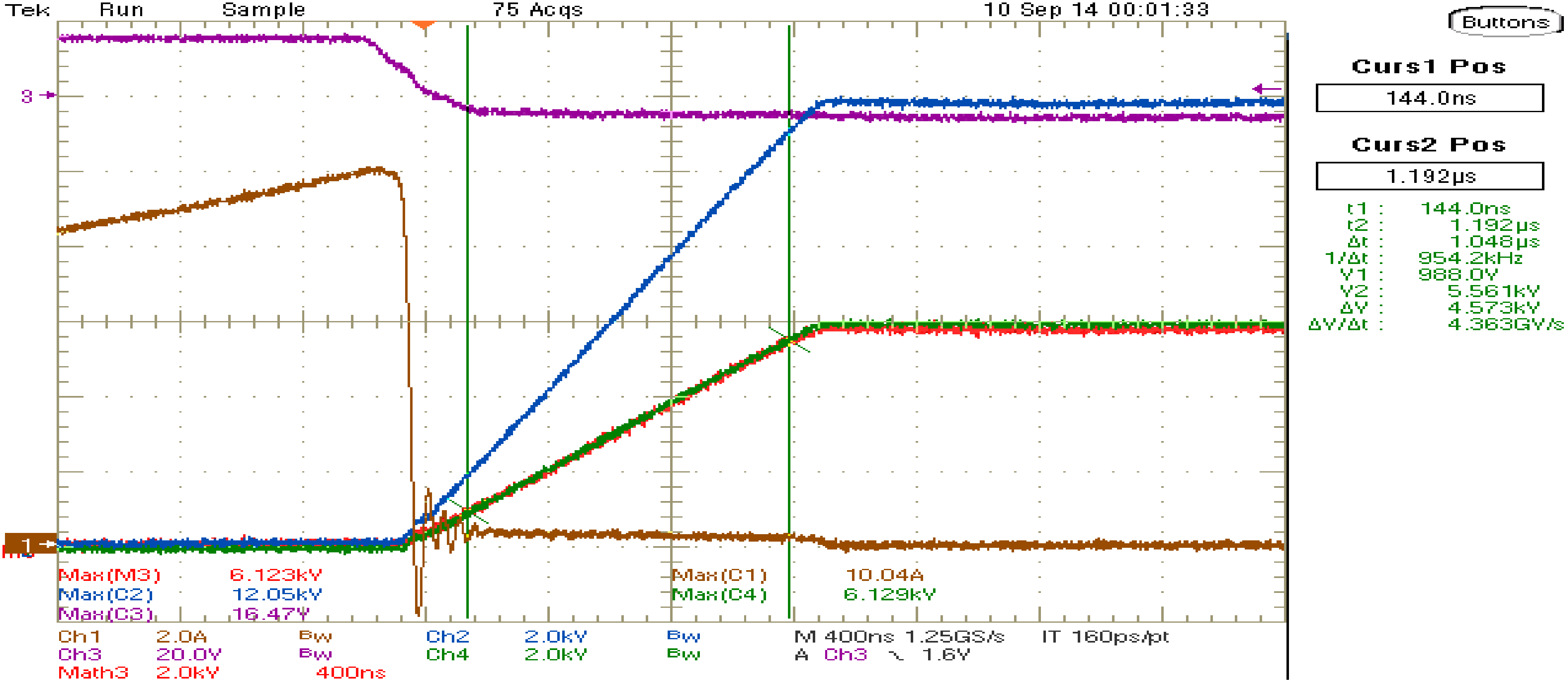


Figure: Balanced static & dynamic voltage sharing between two 10kV SiC MOSFETs 12kV DC bus voltage with RC snubber.

[Ch3: Top device V_{GS} (20 V/div); Ch2: Total voltage (1 kV/div); Ch4: Bottom device V_{DS} (1 kV/div); Math1: Ch2-Ch4: Top device V_{DS} (1 kV/div) Ch1: Bottom device current: I_D(5 A/div);]

- Comparison of HV switch with series connected 1.7kV SiC MOSFETs at 100A and 10kV-15kV SiC MOSFET modules (10 parallel connected 10A modules for 100A)

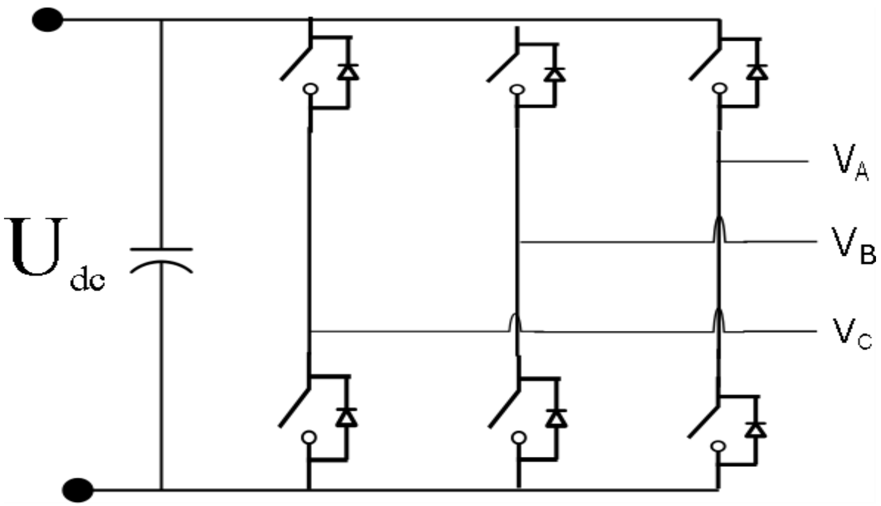
Outline of LV SiC MOSFET (1.7kV) Series Connection

1. Switching loss comparison of 10kV/100A module (10 parallel connected 10A modules) with series connected LV MOSFET (1.7kV/225A modules) at nearly 5kV/100A switching.

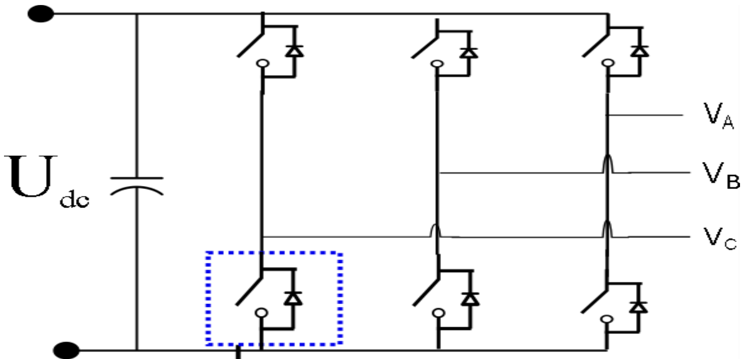
2. Switching loss comparison of 15kV/100A module (10 parallel connected 10A modules) with series connected LV MOSFET (1.7kV/225A modules) at nearly 10 kV/100A switching.

Motivation: For Series Connection of LV SiC Devices

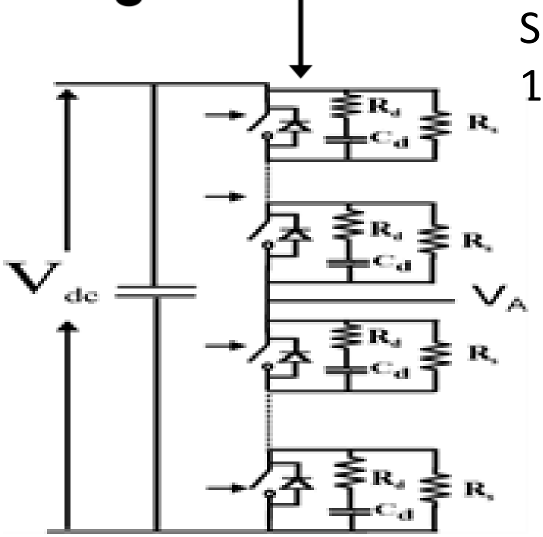
- Impact of series connected low voltage SiC devices vs single HV SiC device in **non- isolated** medium voltage converters.
- DEVICES FOR THE STUDY: 1.7kV SiC MOSFET 10kV SiC MOSFET, 15kV SiC MOSFET



Single High voltage SiC device (>10kV)



Series connected 1.7kV SiC devices



1.7kV/300A Half bridge module 2 (CAS300M17BM)

Conduction losses of 1.7kV SiC MOSFET module and HV switch (10kV-15 kV) made using series connection of 1.7kV SIC MOSFET at 100A

- The on-state resistance of 1.7kV SiC MOSFET per device in a half bridge module is 0.015 Ω at 100A, T_j=150^0C as mentioned in the datasheet.

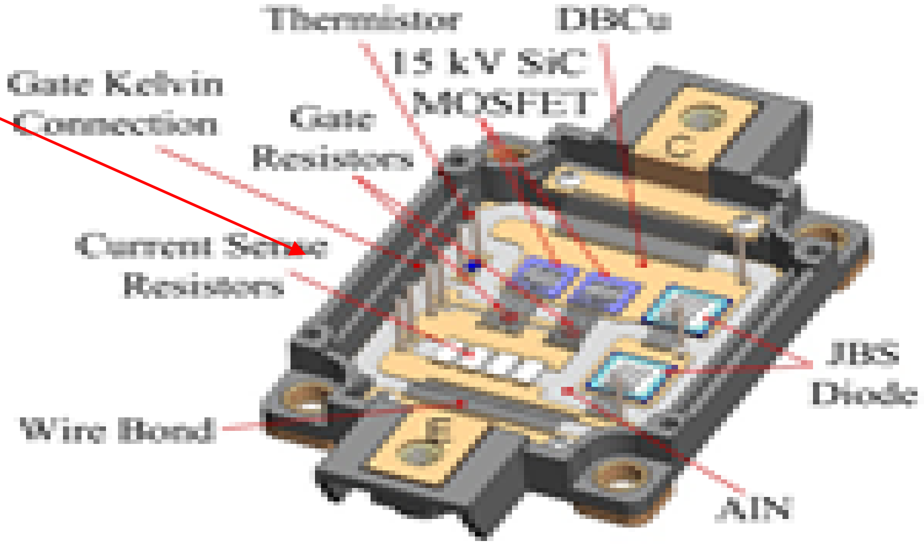
Table : Conduction loss of high voltage switch using series connected 1.7 kV SiC MOSFET at T_j=150 ^{0}C

	No of 1.7 kV SiC MOSFETs for series	R_{dson} per device	Total R_{dson}	Conduction loss
10kVswitch with 5 series connected 1.7kV SiC MOSFET	5	0.015Ω at 100A	0.75	750W at 100A
15kVswitch with 10 series connected 1.7kV SiC MOSFET	10	0.015Ω at 100A	1.5	1500 W at 100A

Comparison of Switching loss and conduction losses and dv/dt per HV module

Table: Comparison of Switching loss and dv/dt per HV module

Module type, maximum rating	Switching voltage, current	Turn-off dv/dt (kV/µs)	Turn-on dv/dt (kV/µs)	Eoff per module (mJ)	Eon per module (mJ)	E_T = (En+Eoff) per module (mJ)	R_{dson} at Tj=150 ^{0}C	Conduction loss
10kV/10A SiC MOSFET	4.7 kV, 10A	42	20	2.24	11.82	**14.06**	0.8Ω at 10A	**80 W at 10A**
15kV/10A SiC MOSFET	10 kV, 10A	32	20	5	47.5	**52.5**	1.8Ω at 10A	**180 W at 10A**



Comparison of total losses of HV SiC module and HV switch with series connected LV SiC MOSFETs

- For 100A operation, it has been assumed that the ten number of HV modules connected in parallel of 10kV/10A and 15kV/10A devices respectively.

- The thermal resistances of module ($R^{th}_{j\text{-}c}$) of 15kV, 20A SiC IGBT (with single IGBT chip) **0.65^{0}C/W**[1]. 10kV/15kV SiC MOSFET has same packaging of that 15kV SiC IGBT, so it has been assumed same thermal resistance .Therefore, the effective thermal resistance with ten parallel devices of 10kV module will be 0.065^{0}C/W and of 15 kV module will be 0.0358^{0}C/W (because each module has two parallel chips).
- The thermal resistance of 1.7kV SiC MOSFET device is 0.071^{0}C/W. Therefore, the effective thermal resistance with **five**, **ten series** connected devices will be 0.0014^{0}C/W and 0.007^{0}C/W respectively for making 5kV, 10kV HV series switch.

1. Kasunaidu Vechalapu, et al.,” Comparative Evaluation of 15 kV SiC MOSFET and 15 kV SiC IGBT for Medium Voltage Converter under Same dv/dt Conditions”, Energy Conversion Congress and Exposition (ECCE), 2015 IEEE

Comparison of total losses of HV SiC module (10kV/10A ten parallel modules) and HV switch with series connected LV SiC MOSFETs

Table: Total losses comparison of single 10 kV/120 A module, five series 1.7 kV devices, and ten parallel devices of 10 kV/20 A at 4.7 kV 100 A switching.

Device	No of devices for series or parallel for **4.7 kV,100A** operation	Total Switching loss	Total switching losses at **5 kHz**	Total conduction losses	Total semi-conductor losses	Effective Thermal resistance	Junction temperature for case T_c=40 ^{0}C	Total Snubber Resistor loss	Total losses
10kV/10A SiC MOSFET	**10 devices parallel**	140.6 mJ	703 W	800 W	1503 W	0.065 ^{0}C/W	**137.6 ^{0}C**	0	**1503 W**
1.7kV SiC MOSFET with snubber:33nF, 4.7Ω	**5 devices in series**	104.5 mJ	**522.5W**	750 W	1272.5W	0.014 ^{0}C/W	**57.8^{0}C**	716W	**1988W**

- Total loss using HV module is **24%** less than HV switch using series connected device for 4.7kV/100A operating condition
- But the junction temperature of HV switching using series connected 1.7kV SiC MOSFETs is significantly less than HV module. Hence more saving in heat sink size.
- Need to perform more detailed analysis for power density comparison.

Comparison of total losses of HV SiC module(single or parallel) and HV switch with series connected LV SiC MOSFETs

Table :Total losses comparison of **ten series 1.7 kV devices**, and **ten parallel devices of 15 kV/20 A** at 10 kV 100 A switching.

Device	No of devices for series or parallel for **10kV,100A** operation	Total Switching loss	Total switching power losses at 5 kHz	Total conduction losses	Total semi-conductor losses	Effective Thermal resistance of module (R^{th}_{j-c})	Junction temperature	Total Snubber Resistor loss	Total losses
15kV/20A SiC MOSFET	**10 devices in parallel**	525 mJ	2625 W	1800 W	4425 W	0.0358 ^{0}C/W	**158 ^{0}C**	0	**4425 W**
1.7kV SiC MOSFET with 33nF, 4.7Ω	**10 device in Series**	209 mJ	1045 W	1500 W	2545 W	0.007 ^{0}C/W	**57.8^{0}C**	1432 W	**3977 W**

- For 10 kV, 100A operation, HV switch with series connected 1.7kV SiC MOSFETs has lower total loss (10 % less) compared to 15kV HV SiC MOSFET for one of the snubber value.
- Also the junction temperature of HV switching using series connected 1.7kV SIC MOSFETs is significantly less than HV module. Hence more saving in heat sink size.

- Therefore the breakeven point for HV SiC MOSFET module more efficient could be around 10kV to 12kV beyond that series connection LV SiC MOSFET is more favorable for high voltage bus.

Acknowledgement

- This work is supported by US Govt. through the DOE NNMII Power America Institute
- This work made use of FREEDM ERC shared facilities supported by National Science Foundation under award no. EEC-0812121.

Thank You!!!

Questions

Acknowledgements:

FREEDM Systems Center, PowerAmerica

ARPA-E and DOE

Dept. of ECE, NC State University