Thermal Issue of Power Magnetics:

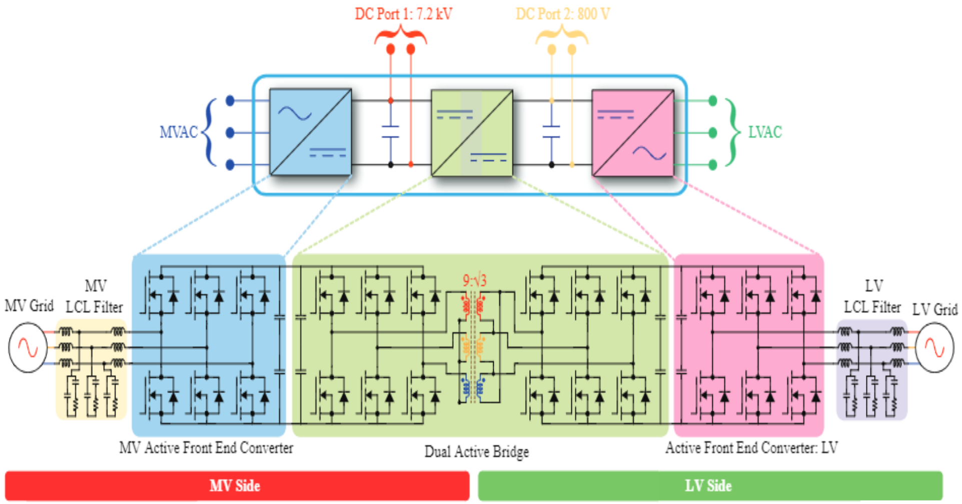
Solid State Transformer journey – from concept to pilot demonstration in a decade enabled by HV SiC 10-15kV IGBTs and MOSFETs

Subhashish Bhattacharya
FREEDM Systems Center, PowerAmerica Institute
Dept of ECE, NC State University

APEC March 2025

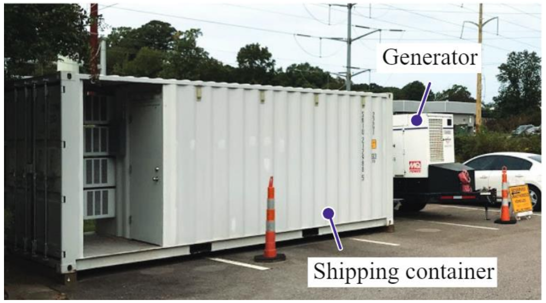
Solid State Transformer installed at Naval Base [Port Heuneme, CA]

SiC 10kV MOSFET based Mobile Utility Support Equipment [MUSE] SST 100kVA, 4.16kV/480V



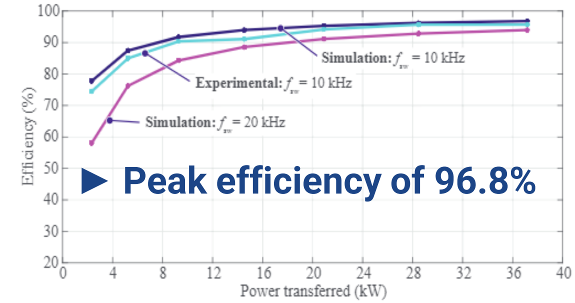
MV Side Device used:
10 kV SiC MOSFET module
XHV-6/XHV-9 half-bridge modules

LV Side Device used:
1200 V - 325 A SiC MOSFET
CAS325M12HM2 half-bridge module



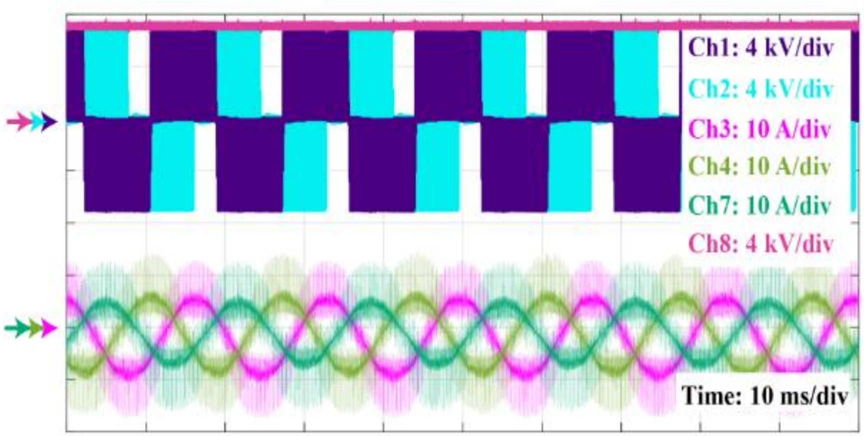
MUSE SST system container system

Internal dimensions: 4.4 m x 2.33 m x 2.33 m

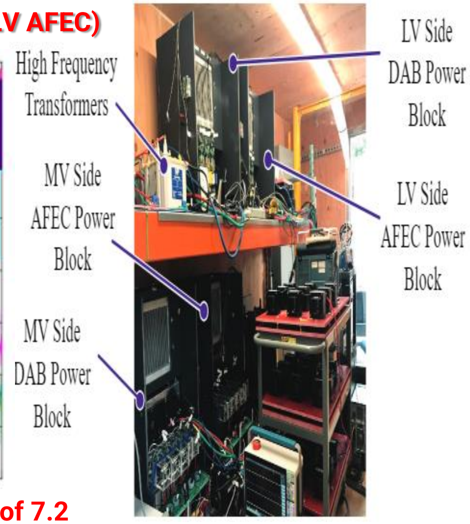


Efficiency of the MVac/MVdc system

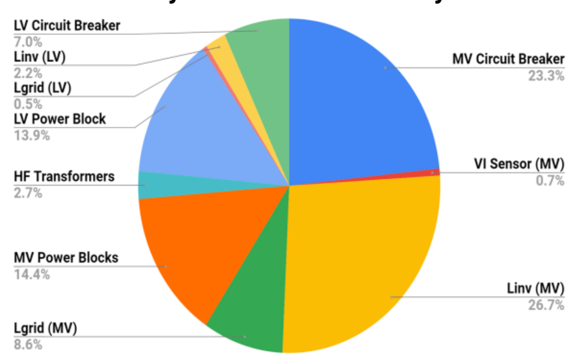
SST switching frequency: 10kHz (MV AFEC); 20kHz (DAB); 20kHz (LV AFEC)



Experimental results of MUSE SST HV converter at a DC-link voltage of 7.2 kV and 10kHz switching frequency (Ch1/Ch2: Line voltage (VYB/VRY); Ch3/Ch4/Ch7: R/Y/B inverter current; Ch8: DC bus voltage)



MUSE SST inside the container



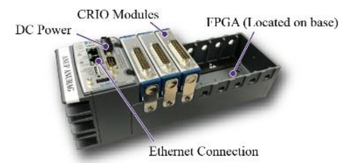
Power Density of MUSE SST

NC STATE UNIVERSITY

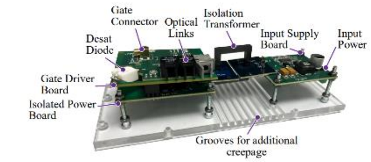
FREEDM SYSTEMS CENTER

MV Solid-State Transformer System

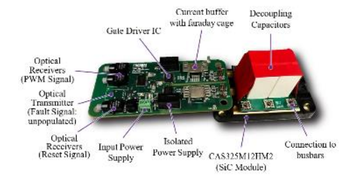
- **Architecture of MV-SST system**
  - Two-level front end converter at the MV grid (MV: AFEC)
  - Dual Active Bridge for HF isolation (DAB)
  - Two-level front end converter at the LV grid (LV: AFEC)
  - Grid connection between 4.16 kV grid to 480 V grid



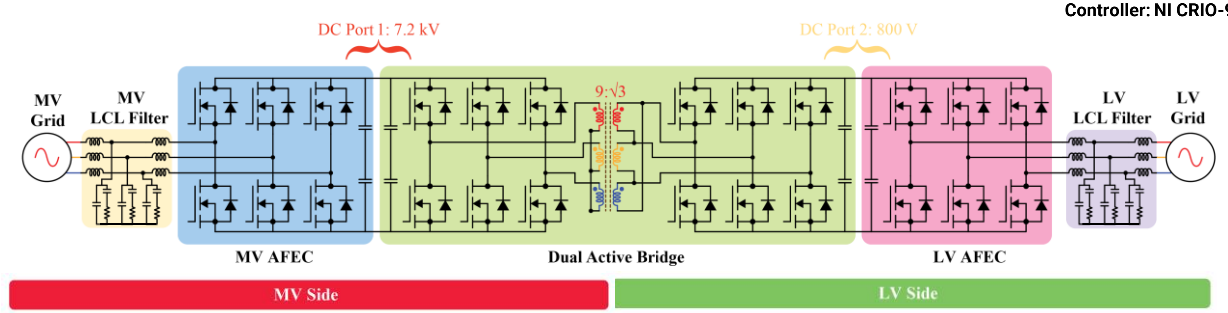
Controller: NI CRIO-9024



MV gate driver



LV gate driver



Device used:
10 kV SiC MOSFET module
XHV-6/XHV-9 modules

Device used:
1200 V - 325 A SiC MOSFET
CAS325M12HM2

Schematic of the MV-SST system

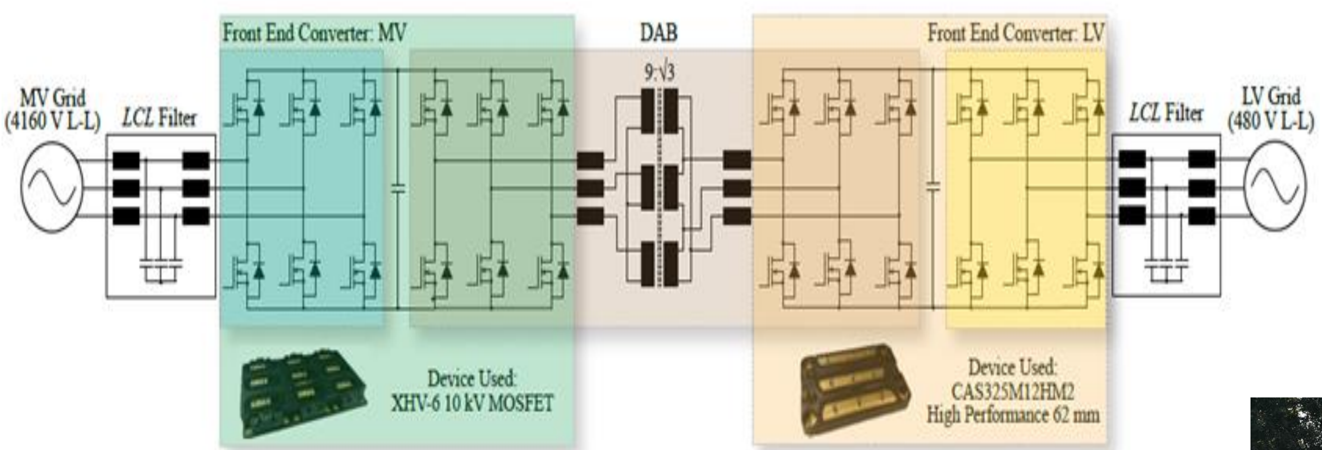
Table: Key design parameters of the MV-SST system

Parameter	*Value*
Power Rating	100 kW
MV side DC-link voltage	7200 V
LV DC-link voltage	800 V
MV:AFEC switching frequency	10 kHz
DAB switching frequency	10 kHz
LV:AFEC switching frequency	20 kHz
MV side inductors	L_{inv}/L_g=15.5 mH/7.7 mH
MV side filter capacitor	1.5 μF
LV side inductors	L_{inv}/L_g=0.2 mH/0.1 mH
LV side filter capacitor	21 μF
HFT Three-phase connection	Y-Δ
Effective HFT leakage inductance (MV)	1.8 mH

[1]A. Anurag, S. Acharya, Y. Prabowo, V. Jakka and S. Bhattacharya, "Mobile Utility Support Equipment based Solid State Transformer (MUSE-SST) for MV Grid Interconnection with Gen3 10 kV SiC MOSFETs," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 450-457

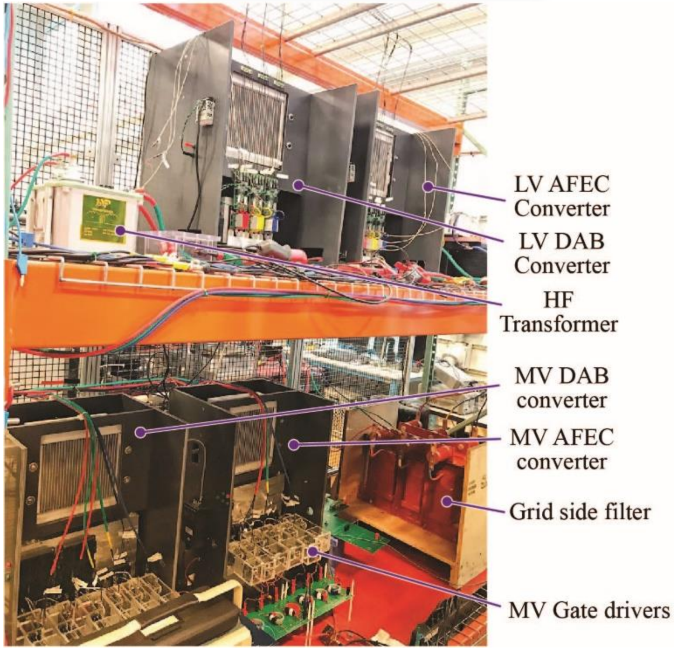
100kVA ESTEP-MUSE SST commissioned at NPS, Monterey, CA - Video Link
https://drive.google.com/drive/folders/1Q0vUYPvfCgiu-_85T0mmi-C7W65T-OBt

Mobile Utility Support Equipment (MUSE) SST [Navy ESTEP Program]: Ship to Shore SST; ac grid tie for large manufacturing facilities



Three High Frequency Transformers

Mobile container



Photograph of the entire MUSE-SST system in the laboratory

Photograph of the entire MUSE-SST system in the mobile container

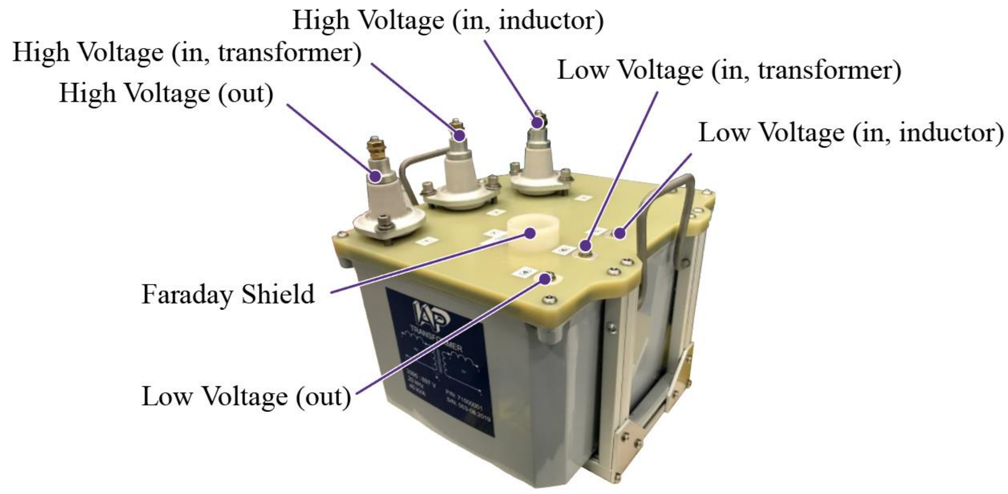
Demonstration of the entire MUSE-SST system in the mobile container

Testing the High Frequency Transformer

- ► **Characterizing and testing the HFTs**
  - ► HFT is manufactured by IAP Research
  - ► Characterization is carried out using an impedance analyzer
  - ► Dimensions: 11.5 inches x 9.5 inches x 7 inches. Filled weight: 42 lbs

Parameters	Value
Turns Ratio	9 : 1.732
RMS AC voltage rating	3395 V/656 V
Peak AC voltage rating	4800 V/805 V
RMS AC current rating	22 A/55.24 A
Peak AC current rating	30 A/83 A
Nominal Frequency	20 kHz
Leakage Inductance (referred to HV side)	1.8 mH
Magnetizing Inductance (referred to HV side)	> 300 mH
Isolation design	20 kV
Isolation capacitance (primary to secondary)	<1000 pF

Specifications of the HFT for the Dual Active Bridge converter system

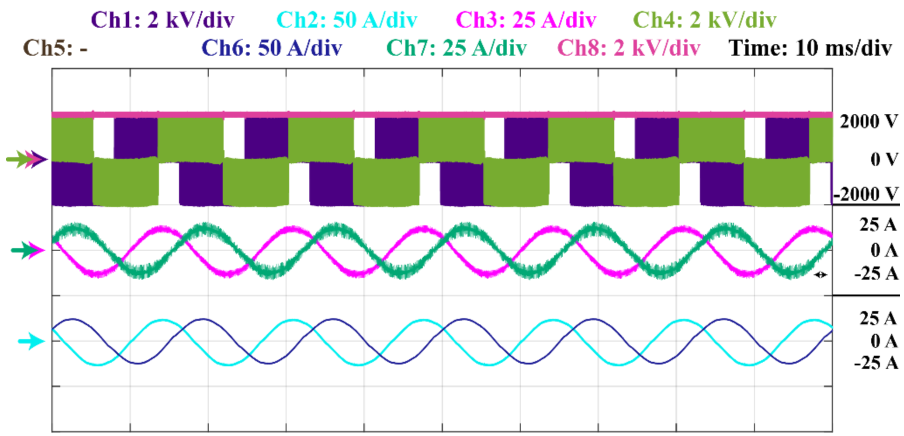


Photograph of the HFT used in the Dual Active Bridge converter system. Dimensions: 11.5 inches x 9.5 inches x 7 inches. Filled weight: 42 lbs

- ► Insulation tested up to 15kV
- ► Core material : nanocrystalline
- ► Filled with oil to achieve the required insulation level and thermal cooling
- ► Transformer design is very challenging to meet size, minimal parasitics and high magnetizing inductances

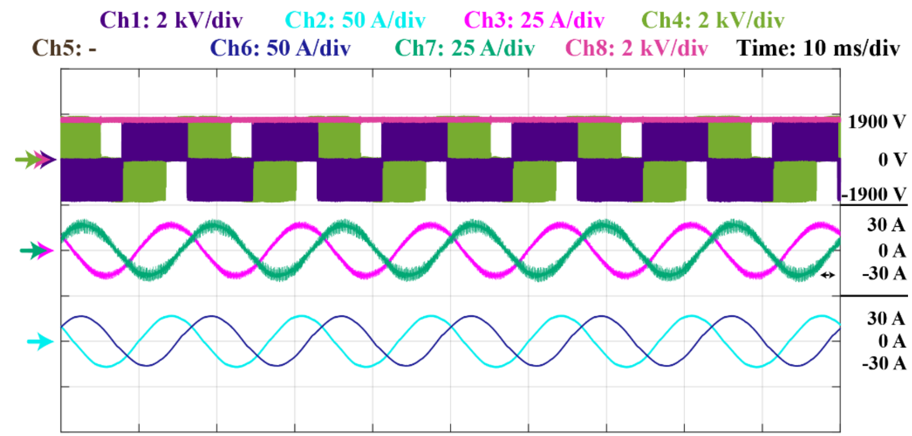
Final Operation of the Entire MUSE-SST System

► Operation at **7.2 kV MVDC; 600 V LVDC and an active power of 30 kW**



MV-AFEC system for a peak current of 25 A.

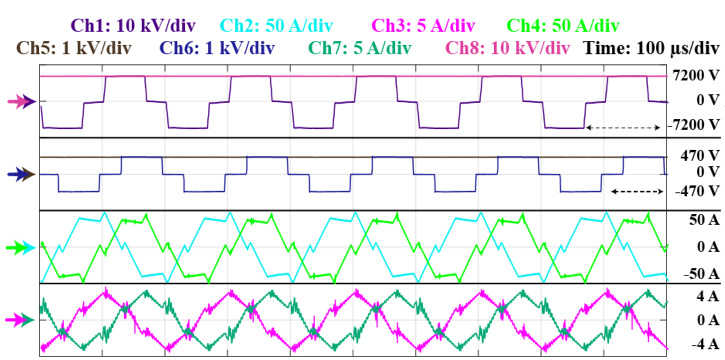
(Ch1/Ch4: MV pole voltage (V-RY/V-YB); Ch2: Grid current through R-phase; Ch3/Ch7: Inverter current through MV R/Y-phase; Ch8: MV DC-link voltage



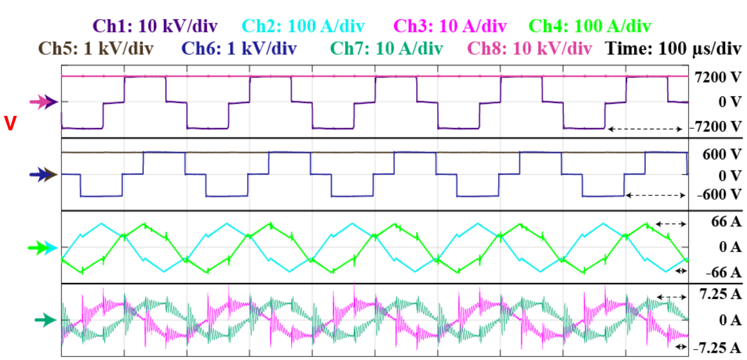
MV-AFEC system for a peak current of 30 A.

(Ch1/Ch4: MV pole voltage (V-RY/V-YB); Ch2: Grid current through R-phase; Ch3/Ch7: Inverter current through MV R/Y-phase; Ch8: MV DC-link voltage

► Operation of 3-phase DAB as MVdc/LVdc stage **at higher voltages and different operating conditions**



Phase shift: 20°
R load: 12.5 Ω
Input voltage: 7200 V
Power transfer: 17.5 kW



Phase shift: 30°
R load: 12.5 Ω
Input voltage: 7200 V
Power transfer: 30.5 kW

(Ch1/Ch6: Line-to-line voltage of MV/LV side (VRY); Ch2/Ch4: R/Y-phase LV side current; Ch3/Ch7: R/Y-phase MV side current; Ch5/Ch8: MV/LV side DC-link voltage)

Cascaded operation of the entire MUSE-SST System

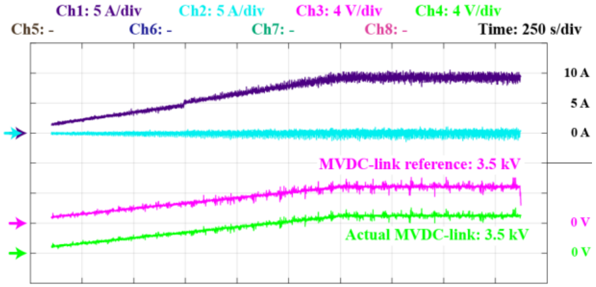
► **Steady state temperature results of the MV and LV converter system**

Thermal data of the Medium Voltage Front End Converter System

Thermal data of the Medium Voltage Bridge of DAB Converter System

Thermal data of the Low Voltage Front End Converter System

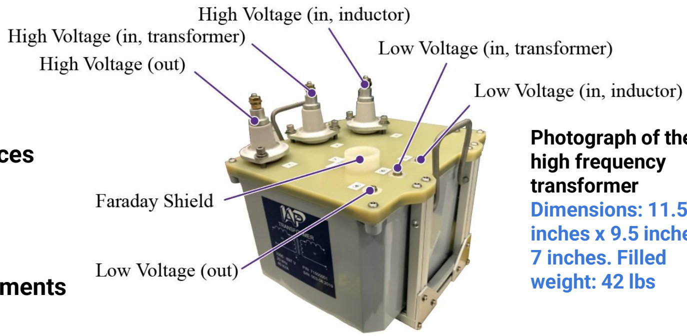
► **System Startup from the MV side to the LV side**



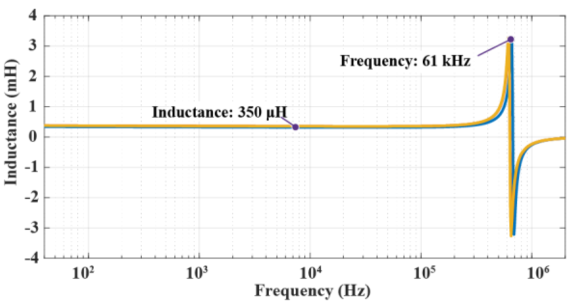
Experimental results showing the startup of the whole system. The DC-link voltage is increased slowly to reach a final voltage of 3500 V. (Ch1: Active current component (id); Ch2: Reactive current component (iq); Ch3: Reference DC-link voltage from controller; Ch4: Actual DC-link voltage from feedback).

High Frequency Transformer Characterization and Modeling

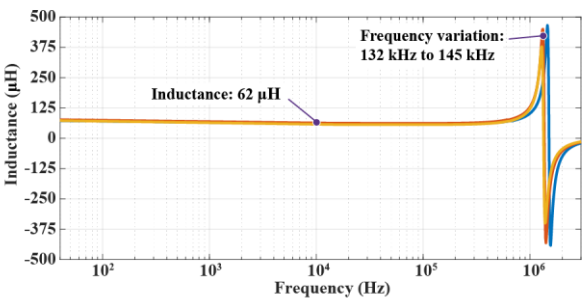
- **Three high-frequency transformers (Operating frequency 20 kHz)**
  - Manufactured using nanocrystalline core
  - Insulation and thermal management is provided by transformer oil
  - Small hole is provided on top to monitor and replace the transformer oil when necessary
  - Transformer houses the series-connected inductors in the same structure
  - Design is very challenging to meet size, minimal parasitics and high magnetizing inductances
- **Characterization and modeling of the high frequency transformer (HFT)**
  - Characterized using HP 4294A impedance analyzer
  - Impedance analysis for measuring various parameters including the parasitic elements
  - Short-circuit measurement, open-circuit measurement and coupling capacitance measurements



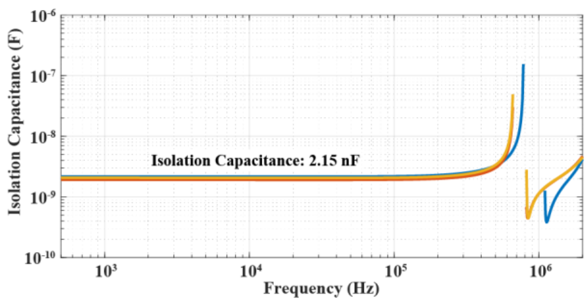
Photograph of the high frequency transformer
Dimensions: 11.5 inches x 9.5 inches x 7 inches. Filled weight: 42 lbs



Inductance measurement curves of MV side inductor



Inductance measurement curves of LV side inductor

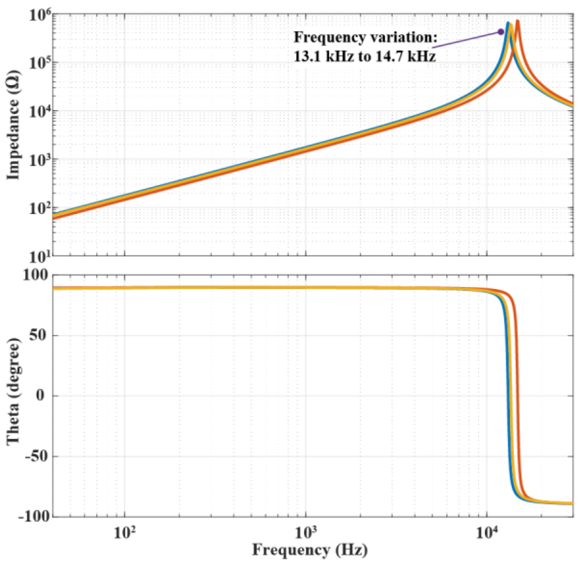


Isolation capacitance of the primary to secondary winding

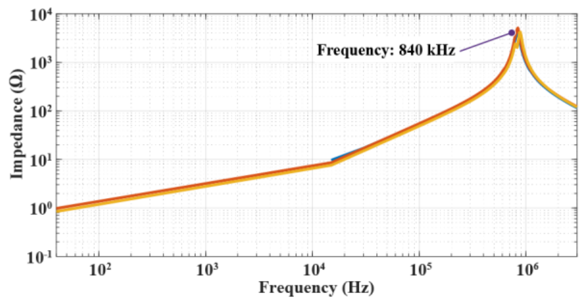
[1] A. Anurag, S. Acharya, S. Bhattacharya, T. R. Weatherford and A. Parker, "A Gen-3 10 kV SiC MOSFETs based Medium Voltage Three-Phase Dual Active Bridge Converter Enabling a Mobile Utility Support Equipment Solid State Transformer (MUSE-SST)," in IEEE Journal of Emerging and Selected Topics in Power Electronics, doi: 10.1109/JESTPE.2021.3069810.

High Frequency Transformer Characterization and Modeling

- **Characterization and modeling of the high frequency transformer**
  - Impedance analysis for measuring various parameters including the parasitic elements
  - Short-circuit measurement, open-circuit measurement and coupling capacitance measurements



Impedance curves of primary winding with secondary side open

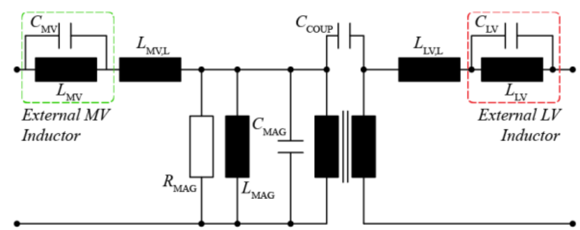


Impedance curves of primary winding with secondary side shorted

- **Calculate the respective capacitance and inductance using:**

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

Equivalent model of the high frequency transformer



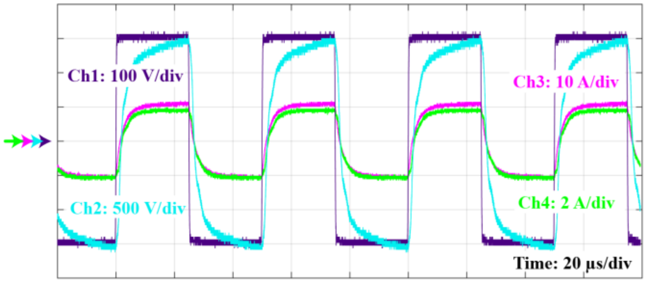
Key parameters of the high frequency transformer

Parameter	*Value*
L_{MV}, C_{MV}	350 μH, 19.5 nF
L_{LV}, C_{LV}	62 μH, 19.5 nF - 22.4 nF
L_{MAG}, C_{MAG}	261 mH, 0.45 nF - 0.56 nF
C_{COUP}	2.15 nF
$L_{MV,L}$	40 μH
$L_{LV,L}$	1.5 μH

[1] A. Anurag, S. Acharya, S. Bhattacharya, T. R. Weatherford and A. Parker, "A Gen-3 10 kV SiC MOSFETs based Medium Voltage Three-Phase Dual Active Bridge Converter Enabling a Mobile Utility Support Equipment Solid State Transformer (MUSE-SST)," in IEEE Journal of Emerging and Selected Topics in Power Electronics, doi: 10.1109/JESTPE.2021.3069810.

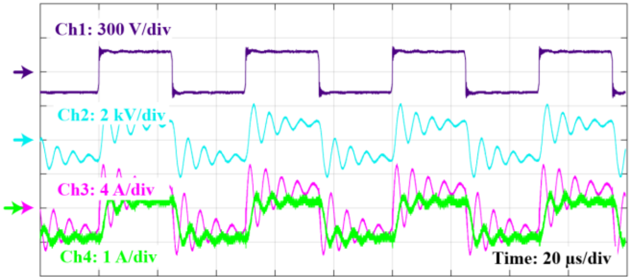
High Frequency Transformer Operation and Testing

- Characterizing the high frequency transformer
  - Voltage ratio tests: Ensures the designed turns ratio of 9:√3



MV side connected to a 800 Ω resistive load.
Input square wave voltage:300 V
Output peak voltage: ≈1500 V

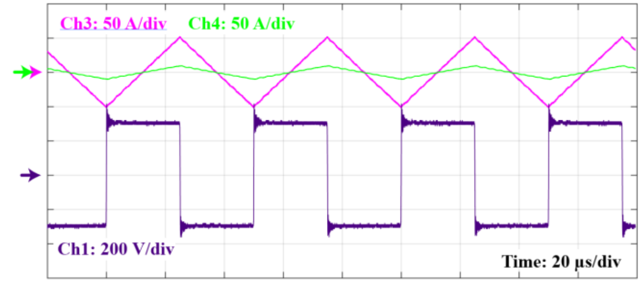
(Ch1: Voltage applied across the LV side of the HFT; Ch3: Current through the LV side of the HFT; Ch4: Current through the HV side of the HFT)



MV side connected to a 3000 Ω resistive load.
Input voltage:300 V; Output peak voltage: ≈1500 V

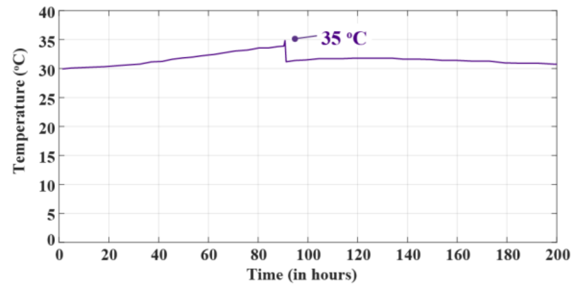
(Ch1/Ch3: Voltage applied/current across the LV side of the HFT; Ch4: Current through the HV side of the HFT)

- Secondary shorted tests/ Heat run tests:

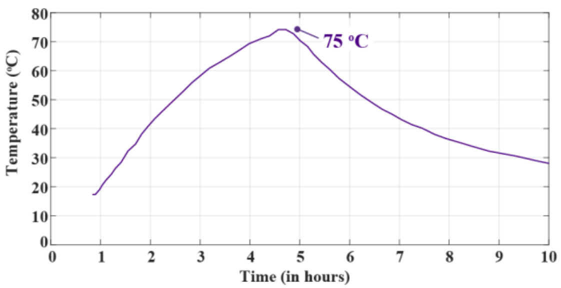


Input voltage: 300. Peak current: 52 A

(Ch1: Voltage applied across the LV side of the HFT; Ch3: Current through the LV side of the HFT; Ch4: Current through the HV side of the HFT)



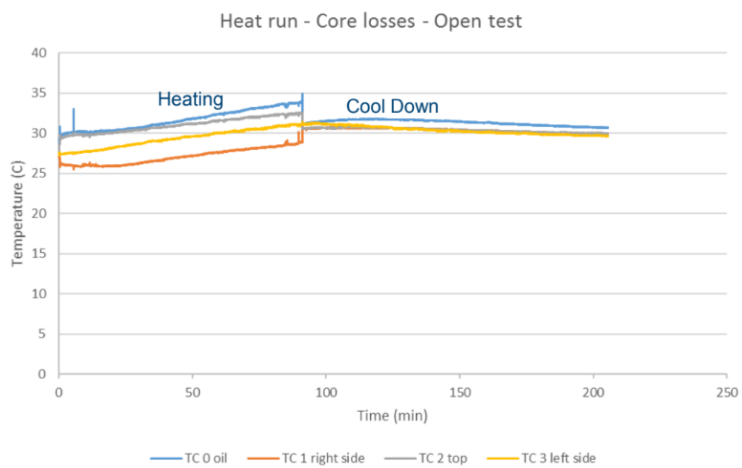
Temperature of the oil during core-loss test



Temperature of the oil during secondary shorted test

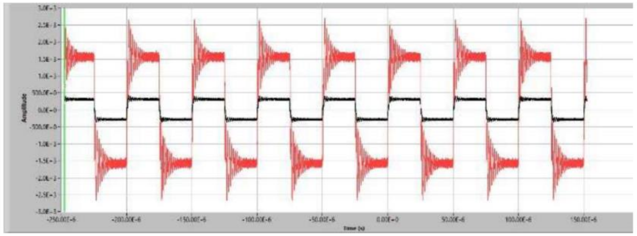
Testing the High Frequency Transformer

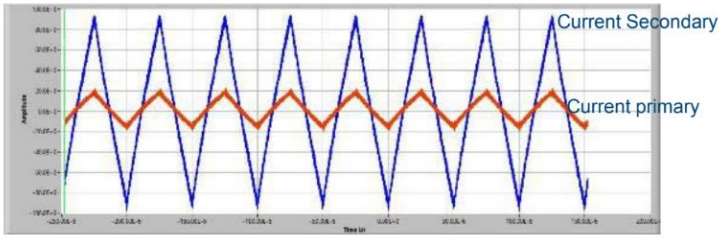
► Heat Run Tests



Experimental tests for testing temperature rise due to core losses in the transformer. A square wave of 20 kHz is used. The power source is connected to the secondary. A 300 V AC RMS is applied on the secondary side.

Experimental tests for testing temperature rise due to copper losses in the transformer. A square wave of 20 kHz is used. The power source is connected to the secondary. A 55 A AC RMS is applied on the secondary side.

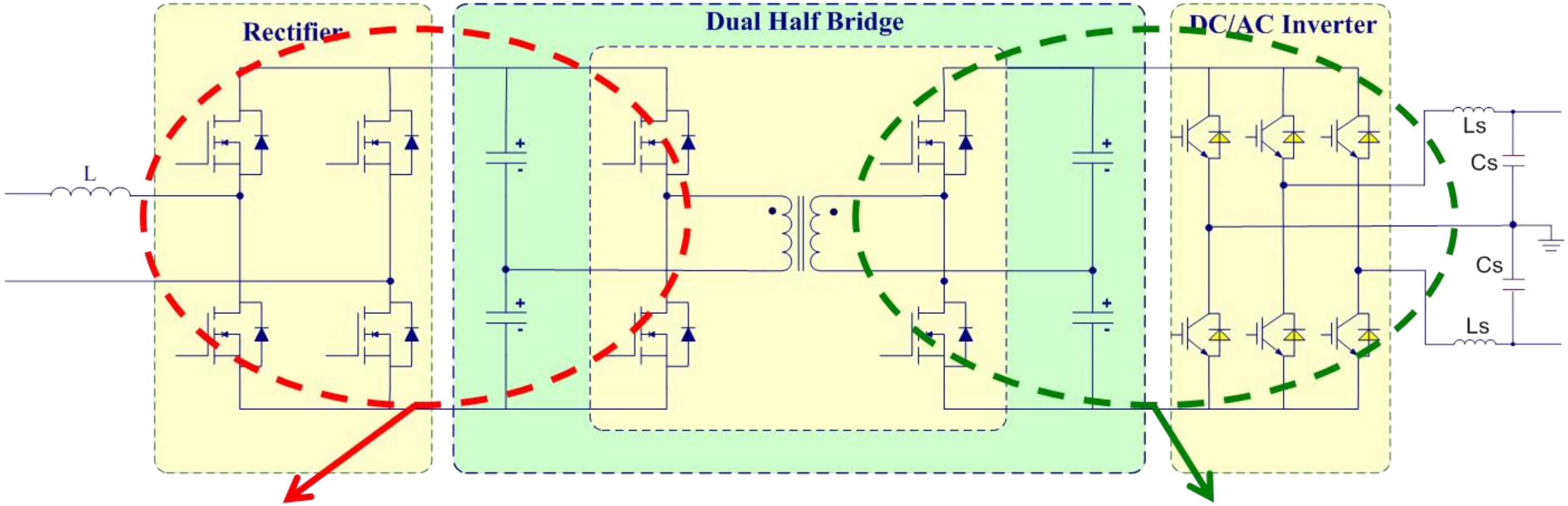




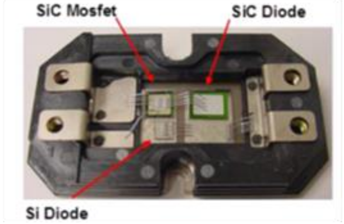
Gen-II SST: Topology – single stage enabled by SiC 15kV MOSFET

Specifications:
- Input: 7.2kVac
- Output: 240Vac/120Vac; 400Vdc
- Power rating: 20kVA

Tested:
- Input: 3.6kVac
- Output: 240Vac; 400Vdc
- Power rating: 10kVA

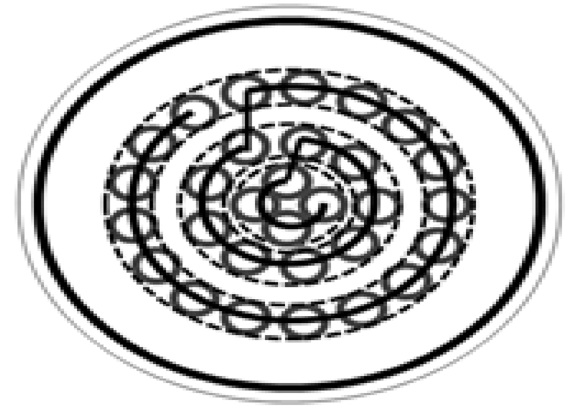


15kV 10A SiC MOSFET

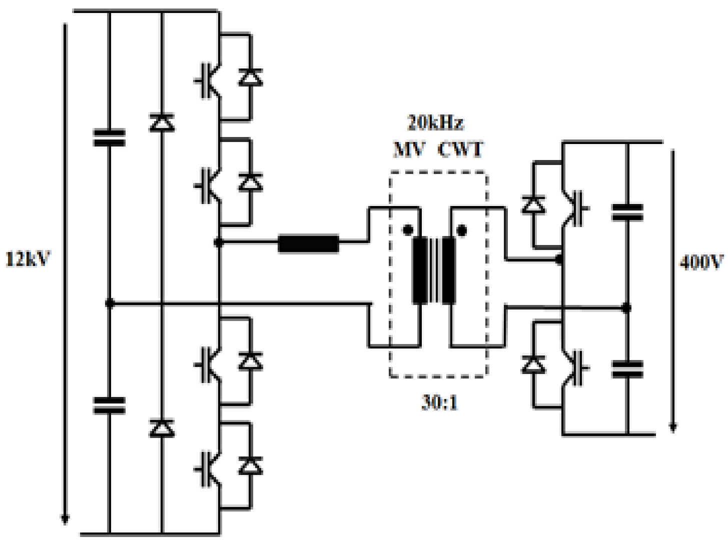


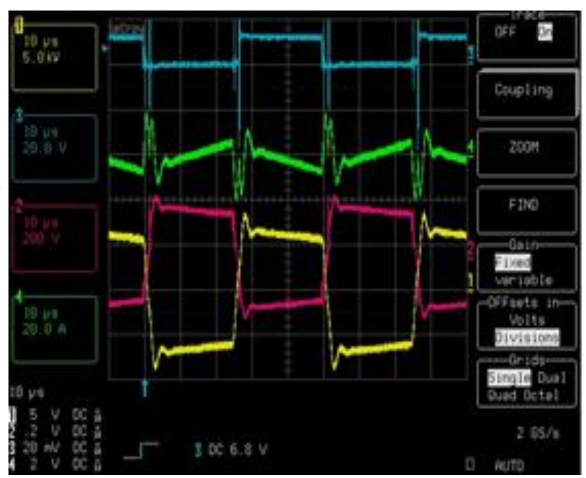
1200V 100A SiC MOSFET

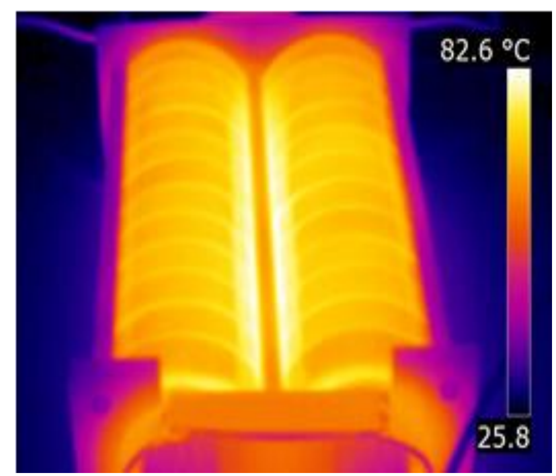
Gen-II SST: High Frequency Co-Axial Winding (CWT) Transformer - Design & Test at 20kHz, 30kW, 12kV/400V



30cm*17cm*9cm

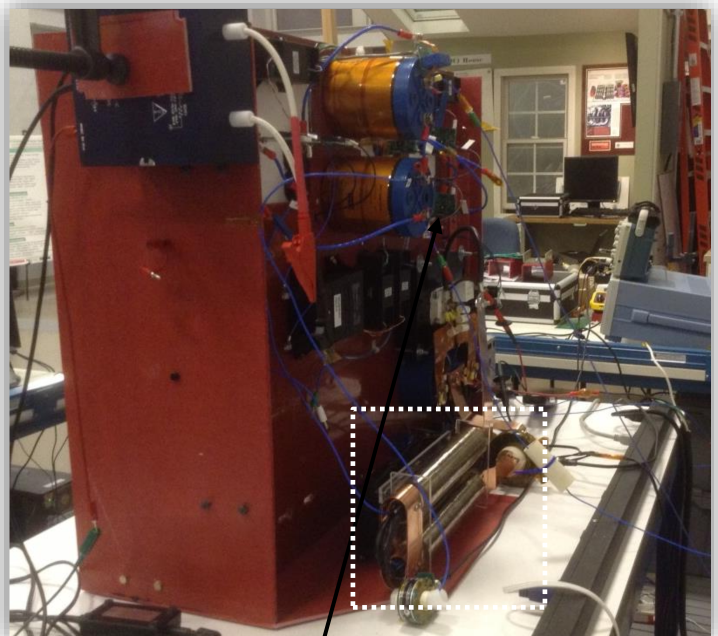




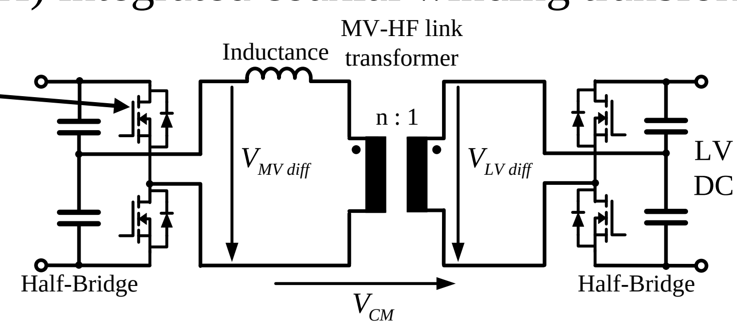


DC-DC converter of the SST; 30kVA, 20 kHz CWT test - Yellow (Vo) 5kV/div, pink (Vi) 200V/div, green (Imag) 20A/div; Heat distribution after 90 min operation

Integrated CWT based SST



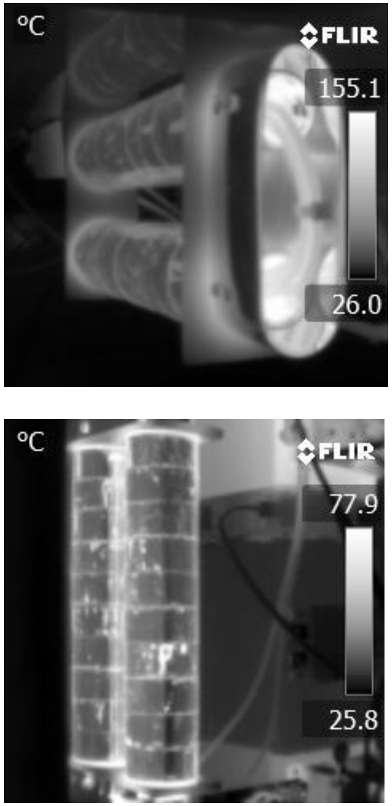
13kV SiC MOSFET based SST with Inductor (4mH) integrated coaxial winding transformer

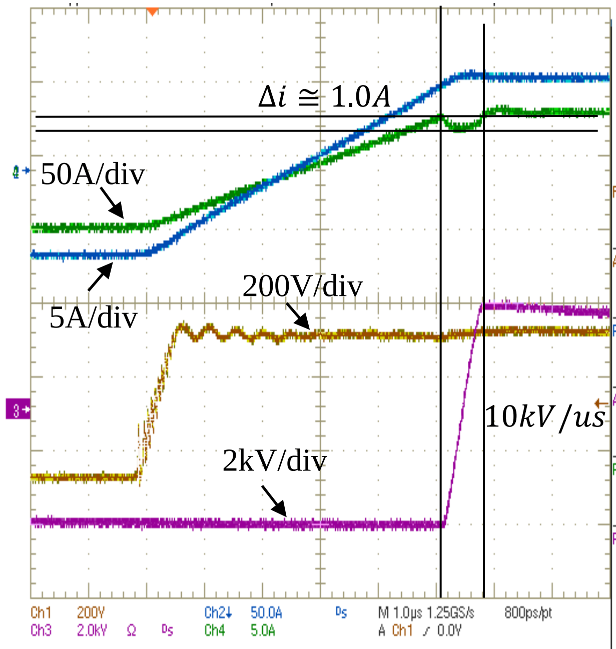


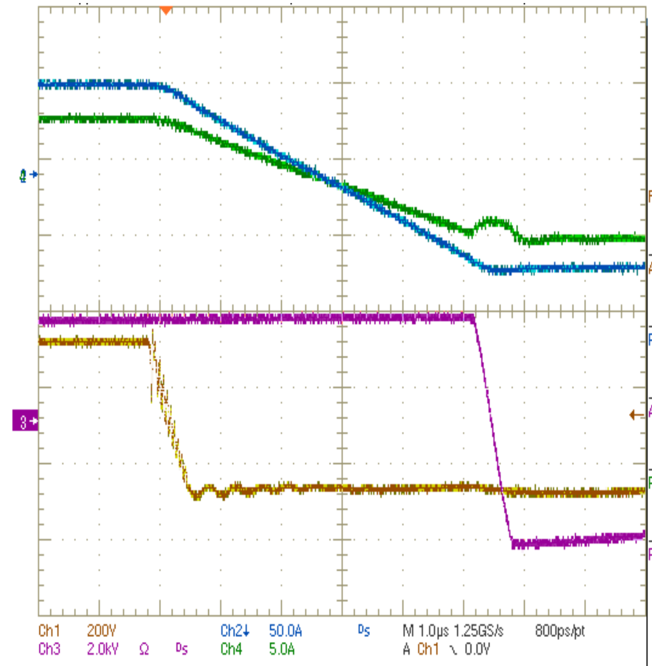
Freq.	VA	n	MVDC	LVDC	I_p	I_s
20 kHz	10kVA	15:1	6kV	400V	3.3Arms	50Arms

ICWT operation with 6kVdc-400Vdc dc/dc stage of SST

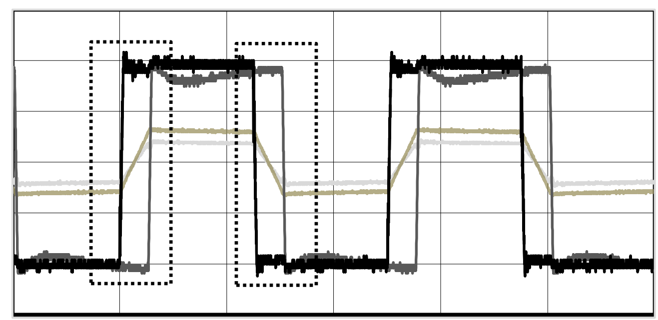
- Waveforms and temperature rise at 6.5kVA-







Waveforms of 6kVdc-400Vdc dc-dc conversion operation at 20kHz.



Heat distribution at 6.5kVA power transfer without an active cooling method after 70 minute operation

Hot spot temperature :170 ℃ after 70 minutes operation with 6.5kVA without active cooling method in dry-type

-The upper temperature limit of wire insulation material, PFA (Perfluoroalkoxy), is 260℃

Acknowledgements

- To all my PhD students, UG Research students and Post-Doctoral Scholars in my group over the last many years

- This work made use of FREEDM ERC shared facilities supported by National Science Foundation under award no. EEC-0812121.

https://research.ece.ncsu.edu/bhattacharya/

https://ece.ncsu.edu/people/sbhatta4/

Email: sbhatta4@ncsu.edu

Thank You!!!

Questions

Acknowledgements:
FREEDM Systems Center, PowerAmerica
ARPA-E, DOE, Navy
Dept. of ECE, NC State University