Nanocrystalline Soft Magnetics Workshop 2023

Solid State Transformer: From Concept to Pilot Demonstration in a Decade enabled by HV SiC 10-15kV IGBTs and MOSFETs

Magnetics Requirements

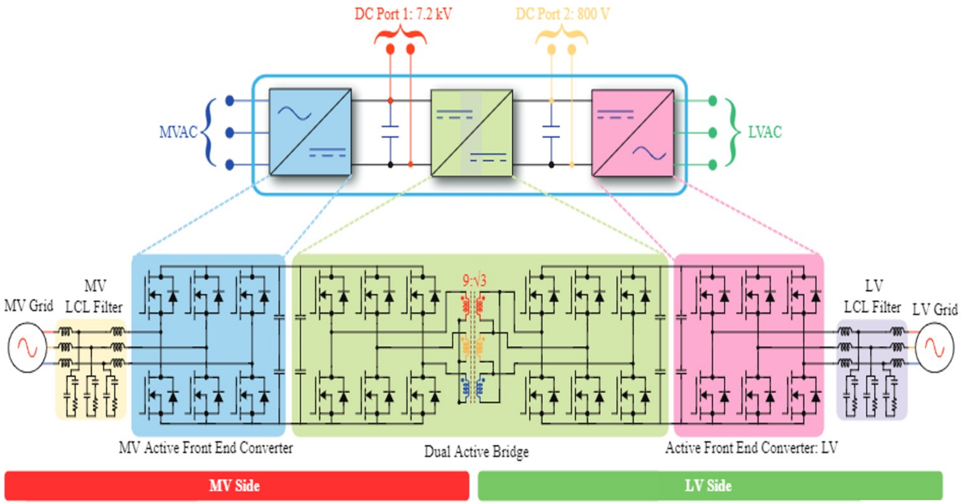
August 17th, 2023

Subhashish Bhattacharya, AMPED Director (NCSU)

NC STATE UNIVERSITY | PowerAmerica | FREEDM SYSTEMS CENTER

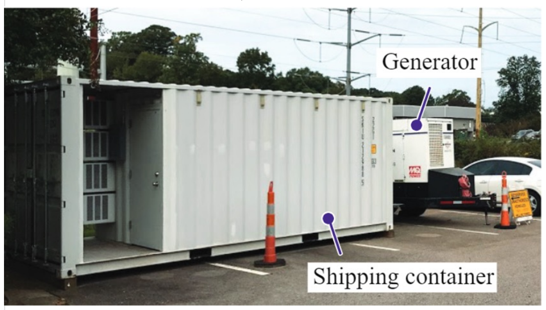
Solid State Transformer installed at Naval Base [Port Heuneme, CA]

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



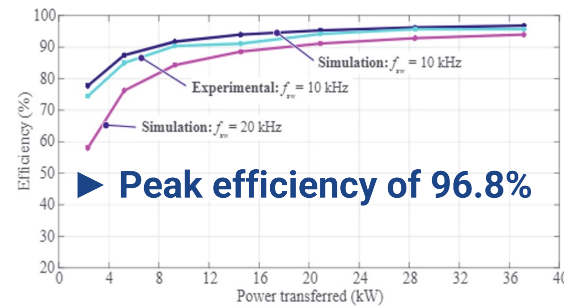
MV Side Device used:
10 kV SiC MOSFET module
XHV-6/XHV-9 half-bridge modules

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



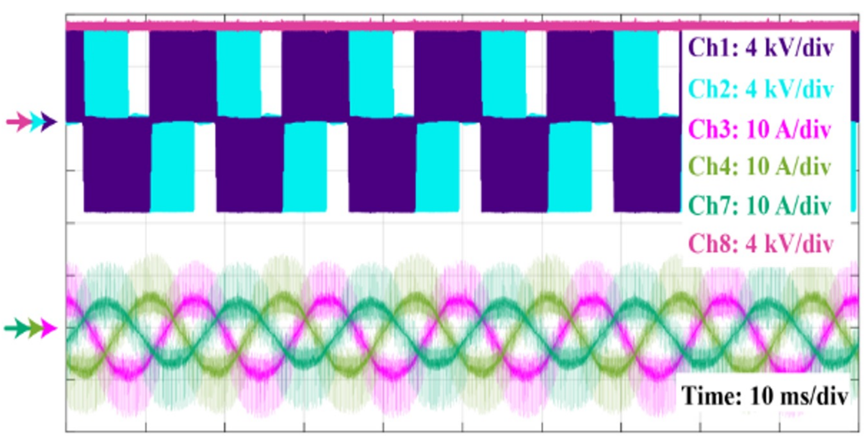
MUSE SST system container system

Internal dimensions: 4.4 m x 2.33 m x 2.33 m

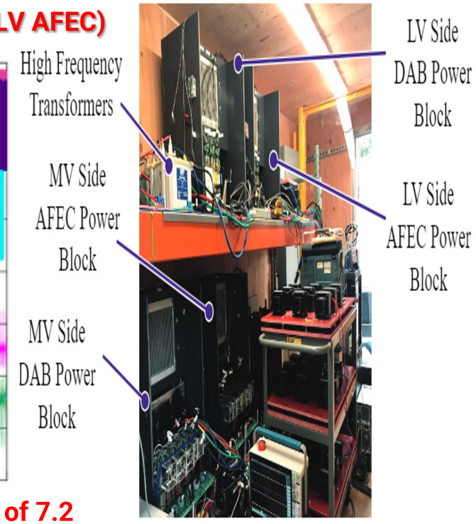


Efficiency of the MVac/MVdc system

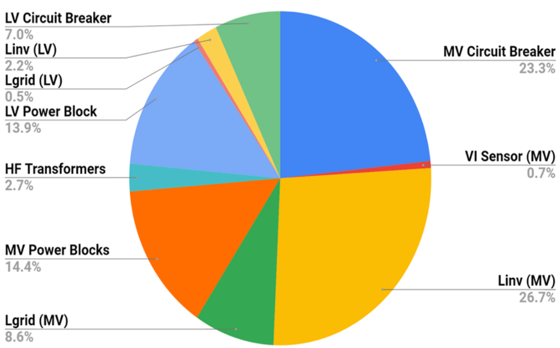
SST switching frequency: 10kHz (MV AFEC); 20kHz (DAB); 20kHz (LV AFEC)



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

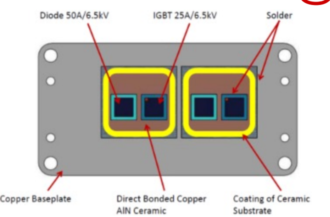


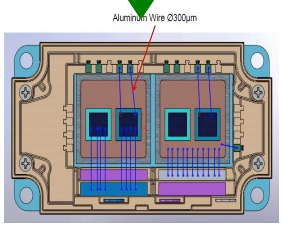
Power Density of MUSE SST

Gen-I SST: Topology & Prototype – 6.5kV Si-IGBT capabilities & challenges

Si-IGBT die: Vces- 6500V; Ice-25A

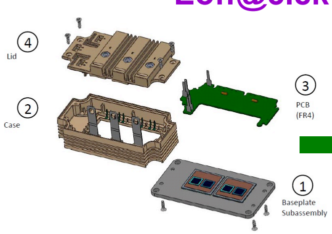
Vf = 4.2V / 5.4V @ 25ºC/125ºC





Eon@3.8kV, 10A, 25ºC : 64.4mJ

Eoff@3.8kV, 10A, 25ºC : 32.7mJ



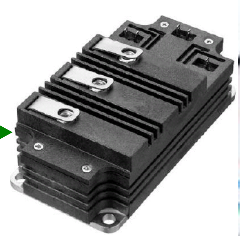
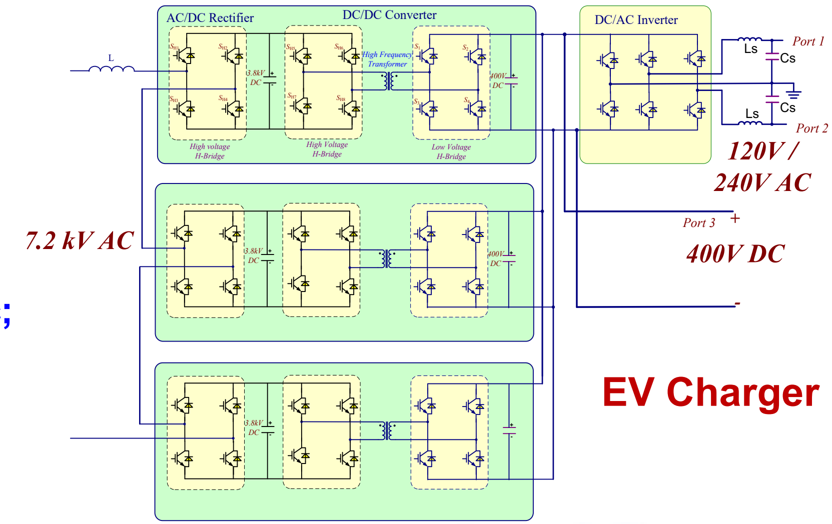
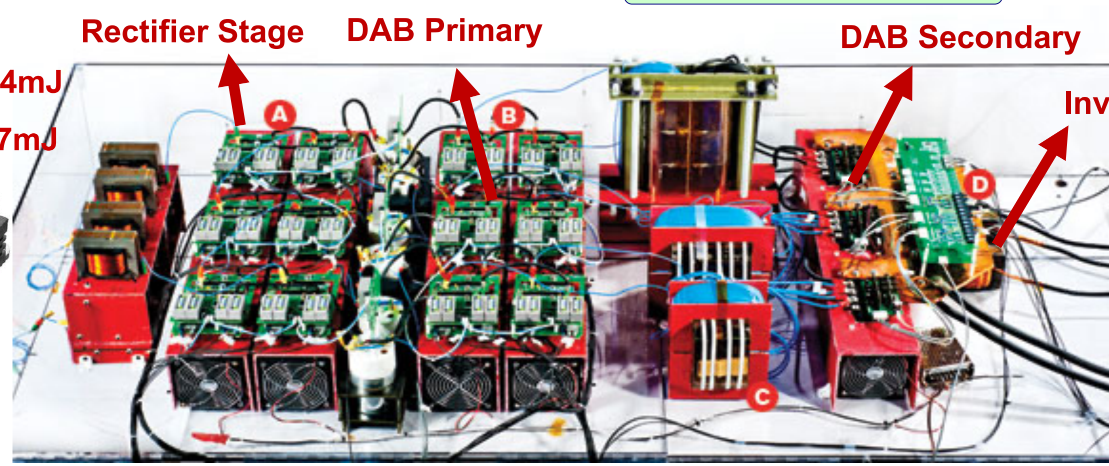


ABB & POWEREX

Specifications:

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





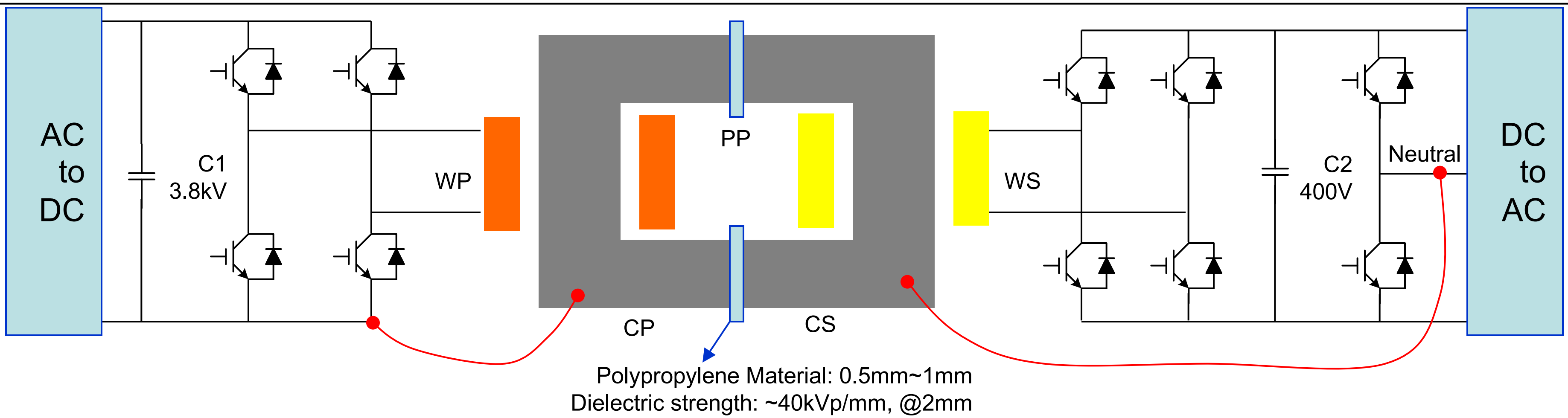
Magnetics for SST

Magnetic materials

Material	Composition	Loss(w/kg) (10kHz, 0.2T)	Saturation B_{max}[mT]	Permeability (50Hz)	Max working Tem[°C]
Grain oriented silicon steel	$Fe_{97}Si_3$	>1000	2000	2k-35k	120
Fe-amorphous alloy	$Fe_{76}(Si.B)_{24}$	18	1560	6.5K-8K	150
High performance ferrite	MnZn	17	500	1.5K-15K	100/120
Nanocrystalline alloys	FeCuNbSiB	4.0	1230	20K-200K	120/180

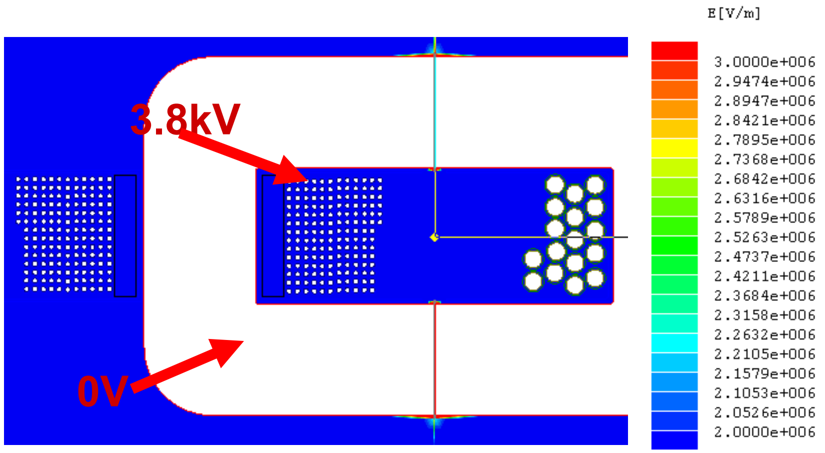
- Critical parameters are high saturation flux density and low losses

Challenges: HV - HF Magnetics and Transformer design



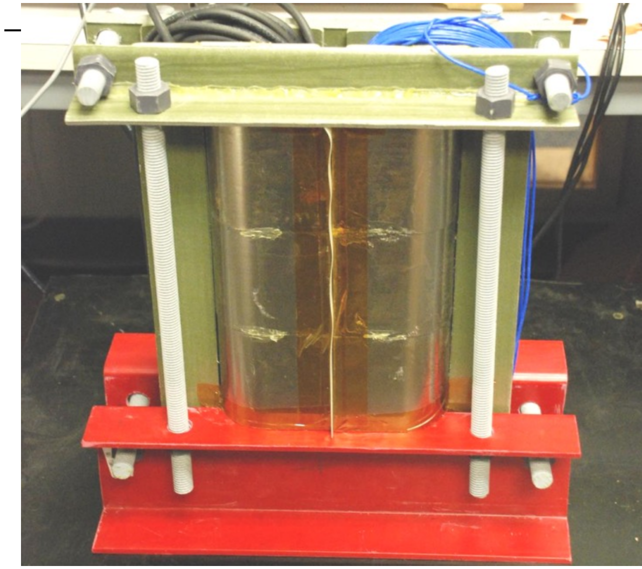
Specifications and design parameters:

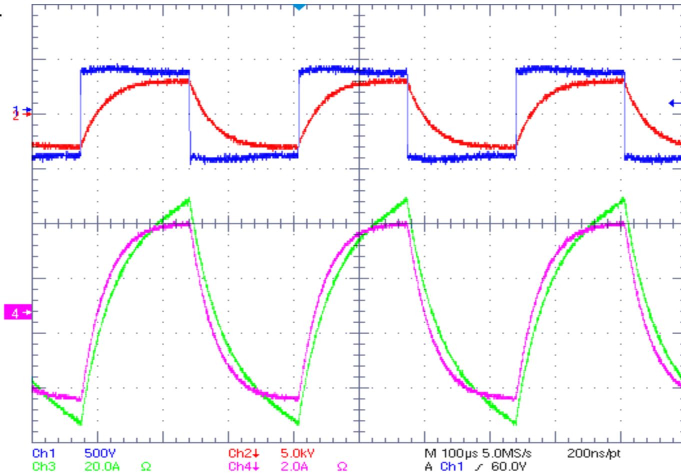
- Frequency: 3 kHz
- High voltage DC-link: 3.8kV
- Low voltage DC-link: 400V
- Power rating: 20/3=6.7kVA
- Turns ratio: 9.5
- Insulation: 15kV
- Number of primary turns:190
- Number of secondary turns:20
- Magnetizing Inductance: 235mH
- Leakage Inductance: 36mH



Electric field distribution (Winding voltage is evenly distributed to each wire in order)

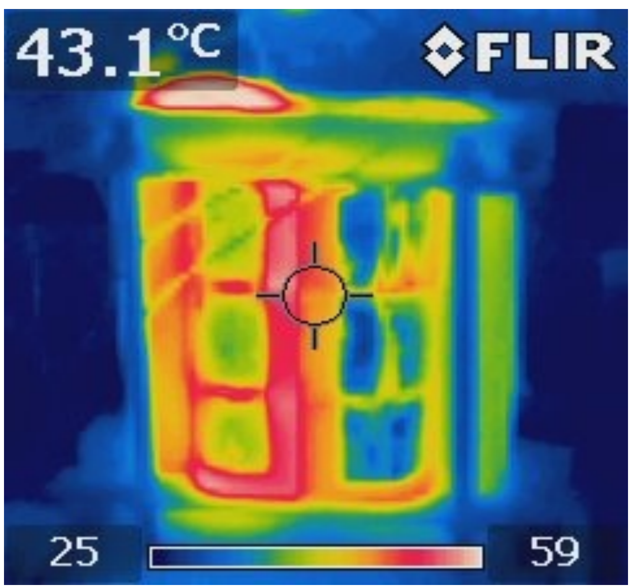
Challenge 3: HV-HF Magnetics -Transformer test





Ch1=Vac_low side;
Ch2=Vac_high side;
Ch3= Iac_low side;
Ch4=Iac_High side,

Test Waveforms



	3.9KW	7.0KW
CORE LOSS (W)	80.6	80.6
HV WINDING LOSS (W)	16.4	62.1
WINDING LOSS (W)	28.7	85.4
TOTAL (W)	126	228
EFFICIENCY	96.9%	96.8%

Efficiency

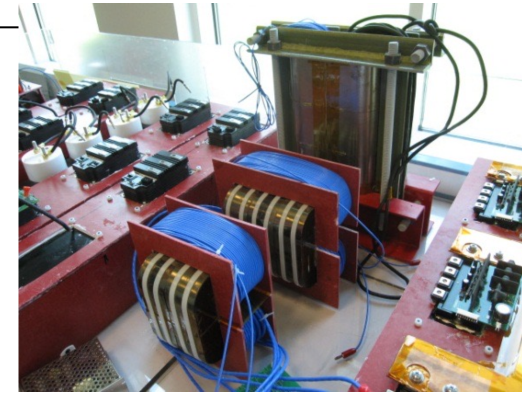
VOLTAGE (KV)	LEAKAGE CURRENT (nA)
10	3.6
15	5.8
20	10.5
25	16

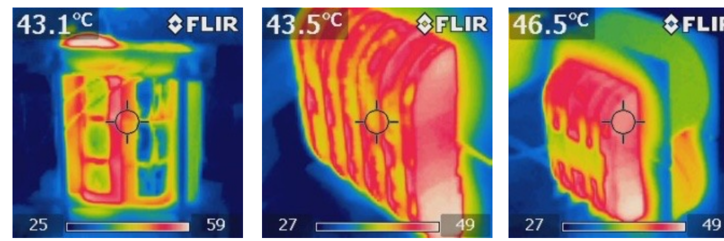
Insulation Capability

Specification of transformers

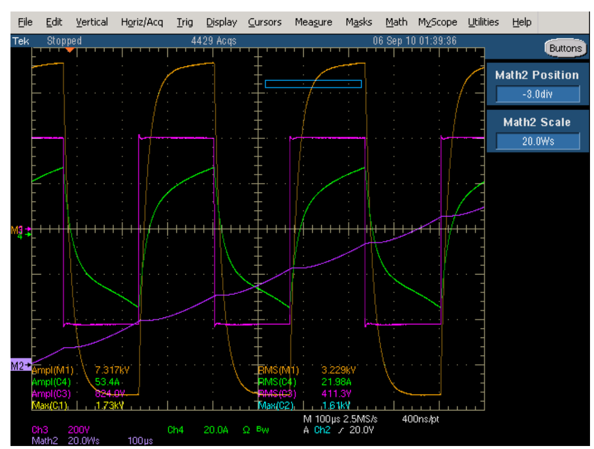
SST gen-1

	prototype-1	prototype-2	prototype-3
Core material	Metglas SA2605SA1	Metglas SA2605SA1	Metglas SA2605SA1
Operating freq.	3 kHz		
Pin	7 kW		
kVA	10 kVA		
Pri. Volt.	3800 V		
Sec. Volt.	400 V		
Pri. Amp	2.6 A		
Sec. Amp	25 A		
Turns ratio [n:1]	9.5 : 1		
Bac	0.25 T	0.26 T	0.35 T
Ac [cm^2]	69	60	40
Window area [cm^2]	42	56.25	56.25
Core volume [cm^3]	3472	2706	1804
Core mass [kg]	24.9	19.4	13.0
# of pri. turns	190	207	228
# of sec. turns	20	22	24
Airgap [mm]	0.5 (each side)		
Mag. Ind. [mH]	235	468.9	341.2
Leak. Ind. [mH]	36	30.3	29.7
Excitation current on pri. side	0.85 A	0.44 A	0.59 A
Core loss	80 W	100 W	118 W
Winding loss	147 W	94 W	81 W
Total loss	227 W	194 W	199 W
Efficiency	96.76 %	97.3 %	97.16
Hot spot temp. on the surface with natural convection	43.1 °C	43.5 °C	46.5 °C





prototype-1 (Top), prototype-2 (middle), prototype-3 (bottom)



LV-side voltage (purple,200V/div), HV-side Voltage (orange, 1kV/div) and current (green, 20A/div), Time (100us/div) of Prototype. 3 10kVA HV-HF Transformer

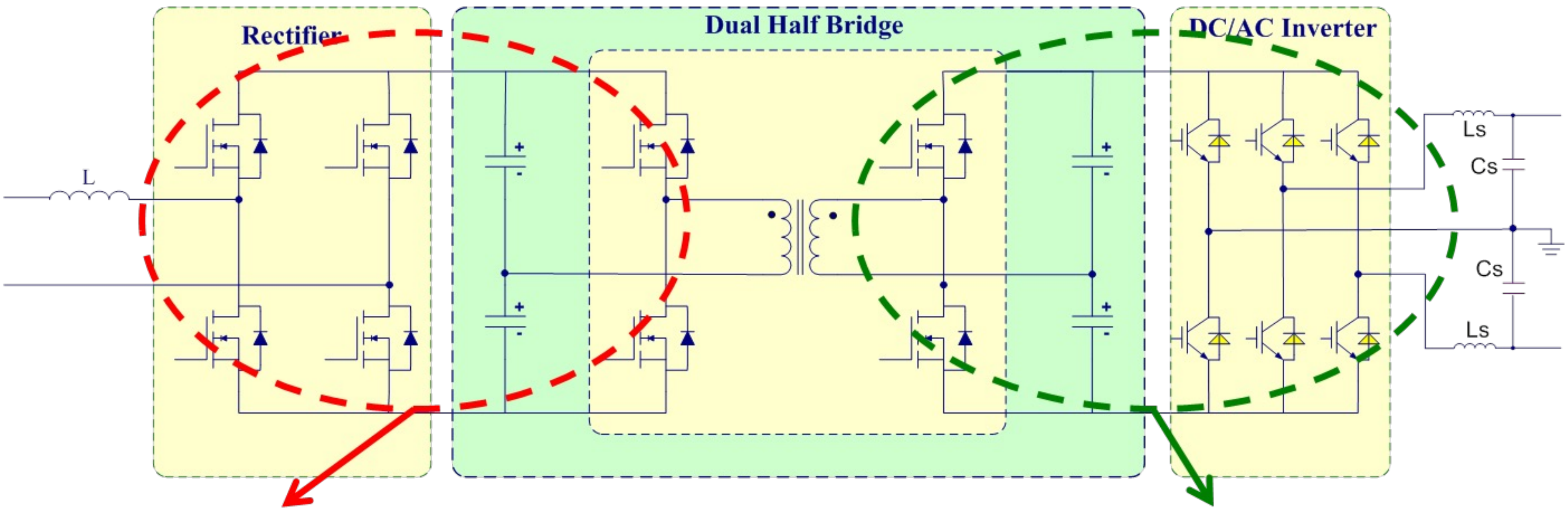
Gen-II SST: Topology – single stage enabled by SiC 15kV MOSFET

Specifications:

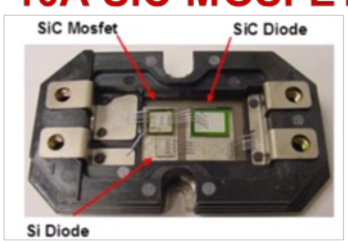
- Input: 7.2kVac
- Output: 240Vac/120Vac; 400Vdc
- Power rating: 20kVA

Tested:

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

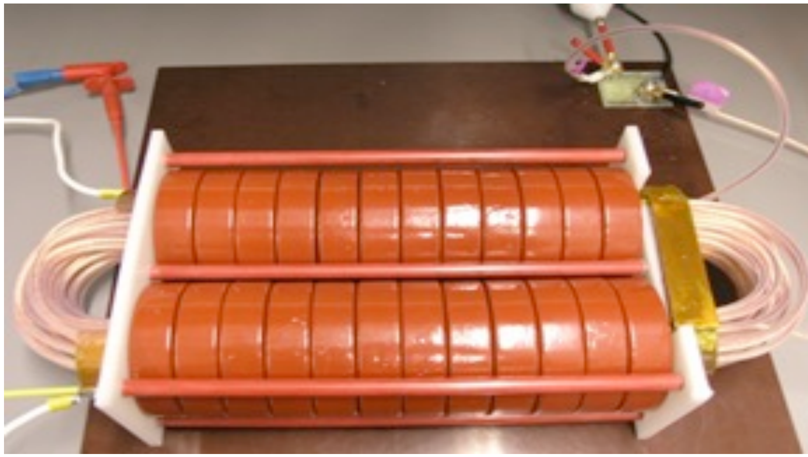


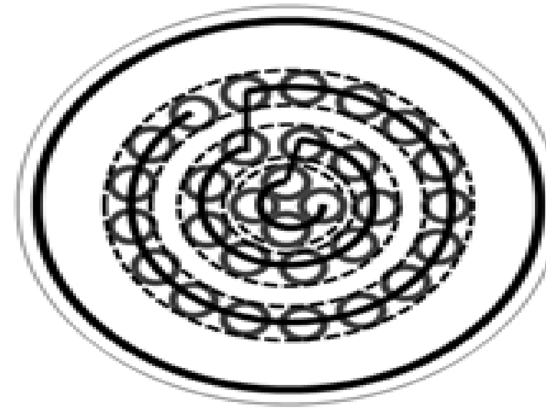
15kV 10A SiC MOSFET



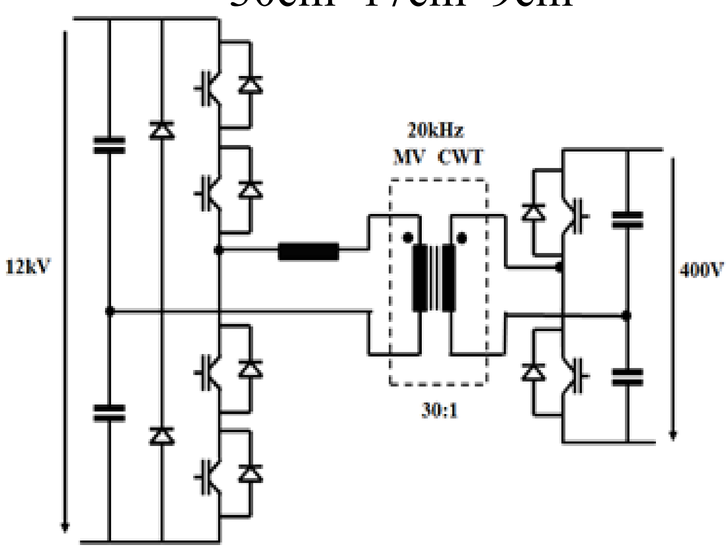
1200V 100A SiC MOSFET

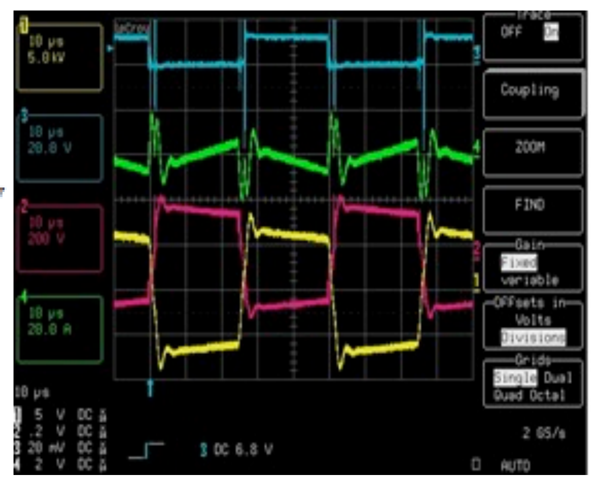
Gen-II SST: High Frequency Co-Axial Winding (CWT) Transformer - Design & Test at 20kHz, 30kW, 12kV/400V

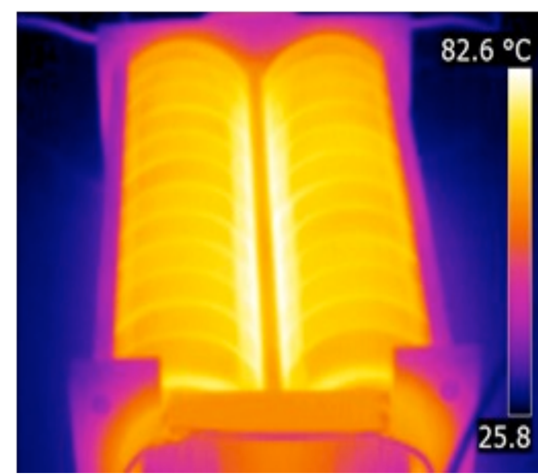




30cm*17cm*9cm



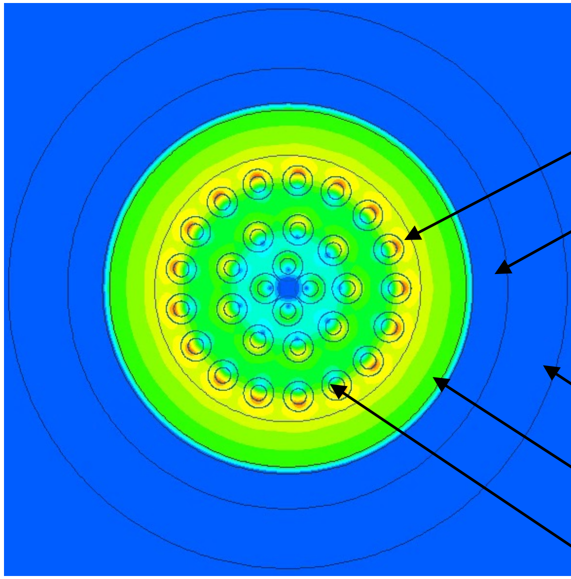




DC-DC converter of the SST; 30kVA, 20 kHz CWT test - Yellow (Vo) 5kV/div, pink (Vi) 200V/div, green (Imag) 20A/div; Heat distribution after 90 min operation

Equivalent Circuit Modeling

Magnetic field distribution and inductance calculation



Magnetic field intensity in 2D
(the same amount of current on each winding on the opposite direction)

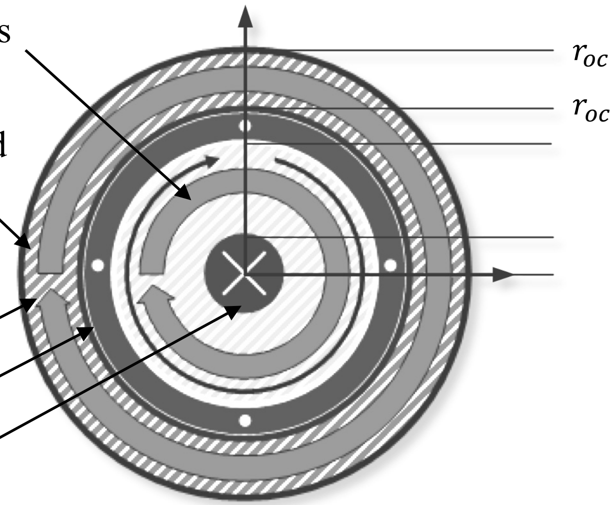
Leakage inductance $B_{leak\,\phi}$ is only on the inner winding

Mutual flux $B_{m\,\phi}$ is located outside outer winding

Magnetic cores

Outer winding (LV)

Inner winding (HV)

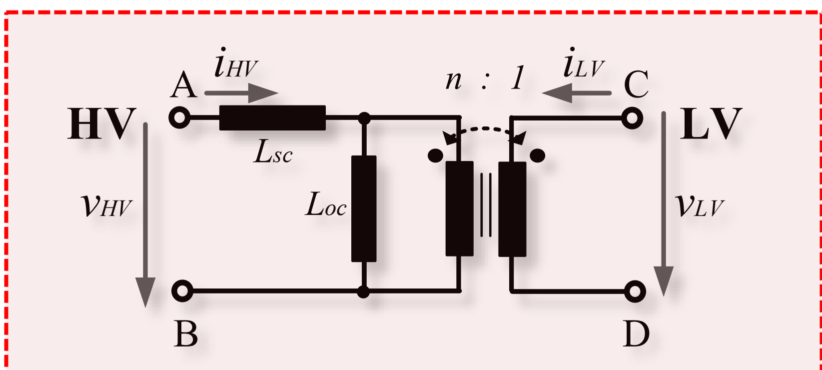


$$B_{leak\,\phi} = \frac{\mu_o \mu_{r\,i}\, N_i\, i_i}{2\pi r}$$

$$B_{m\,\phi} = \frac{\mu_o \mu_{r\,o}\,(N_i\, i_i - N_o\, i_o)}{2\pi r}$$

$$L_{oc} = L_m = \int B_{m\,\phi}\, dr\ [H/m]$$

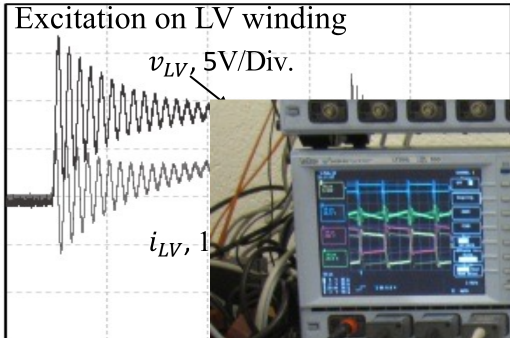
$$L_{sc} = L_{leak} = \int B_{leak\,\phi}\, dr dr\ [H/m]$$

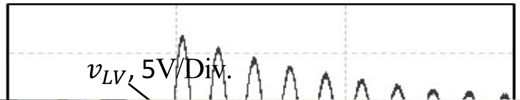


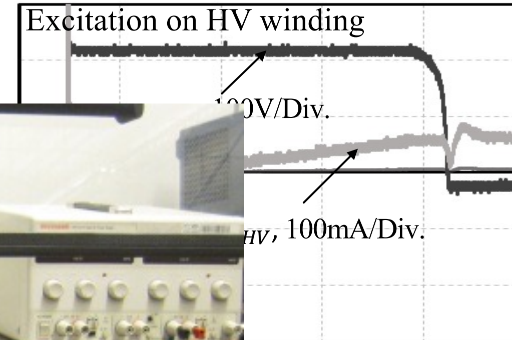
Co-Axial Winding Transformer (CWT) prototype

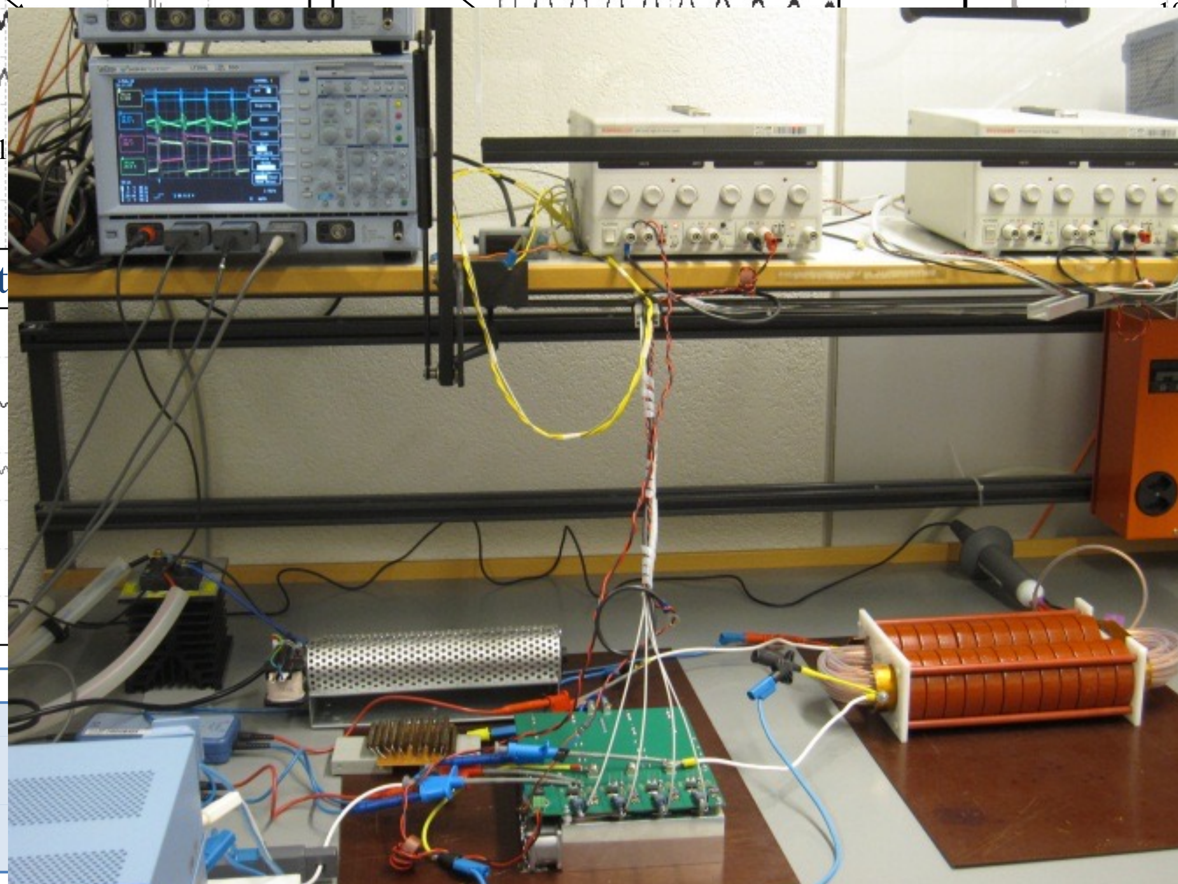
- Switching response -

Measurement

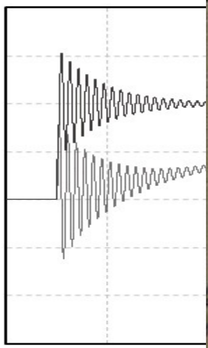


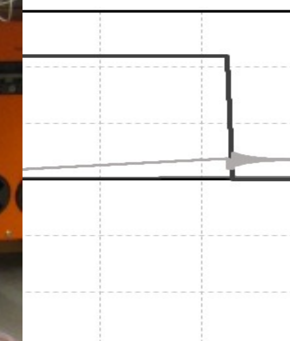






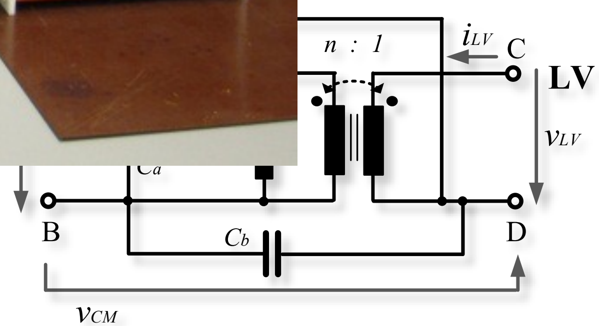
Ckt. Simulation on t



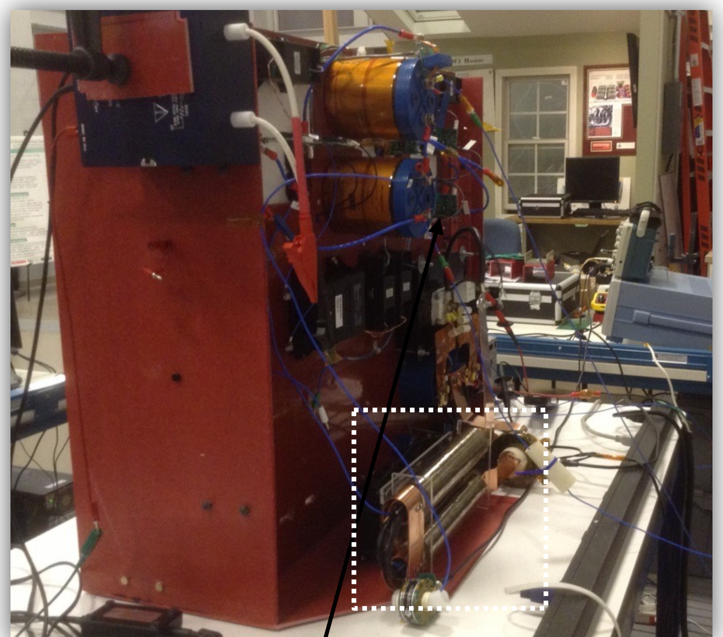


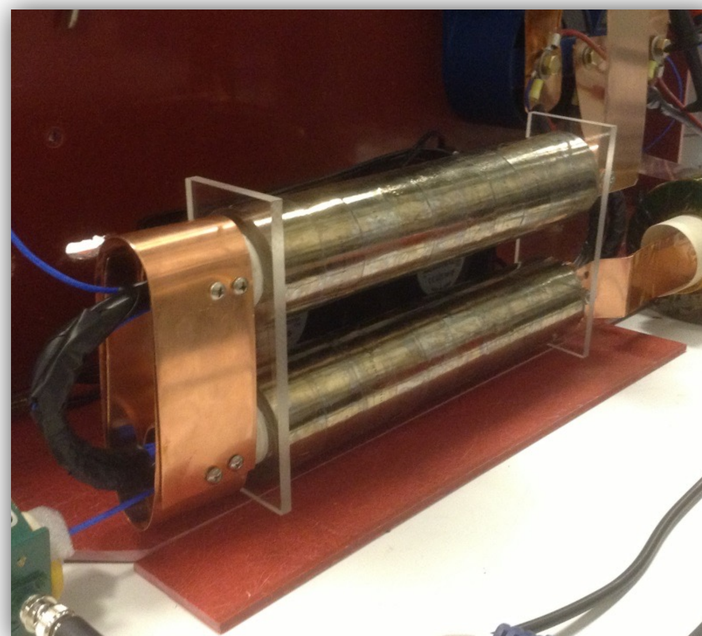
Calculation in 2D
2D FEM
3D FEM
Measurements

	Common-mode	Ca	Cb	Cc
Calculation in 2D	125pF	13pF	79pF	47pF
2D FEM	128pF	2pF	89pF	39F
3D FEM	137pF	15pf	97pF	40pF
Measurements	138pF	16pF	93pF	45pF

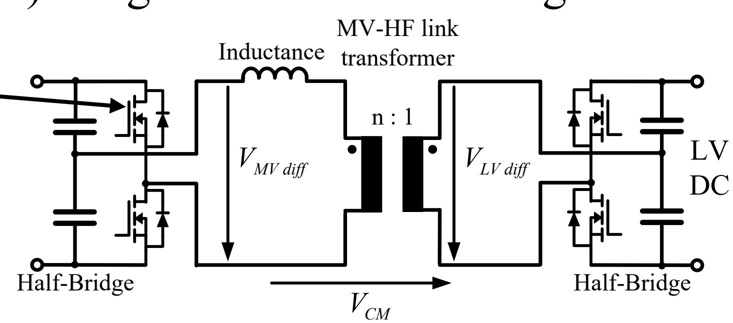


Integrated CWT based SST





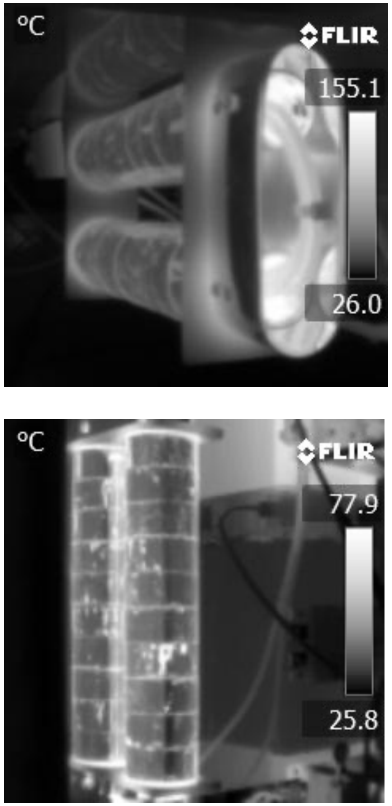
13kV SiC MOSFET based SST with Inductor (4mH) integrated coaxial winding transformer



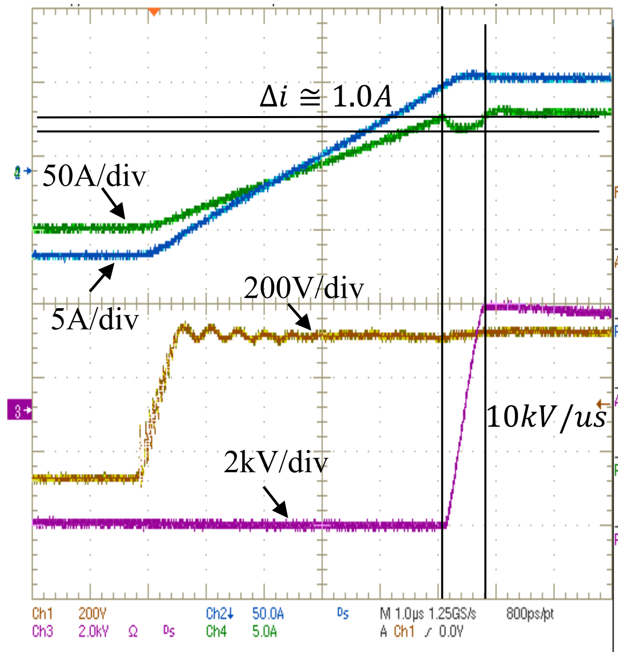
Freq.	VA	n	MVDC	LVDC	I_p	I_s
20 kHz	10kVA	15:1	6kV	400V	3.3Arms	50Arms

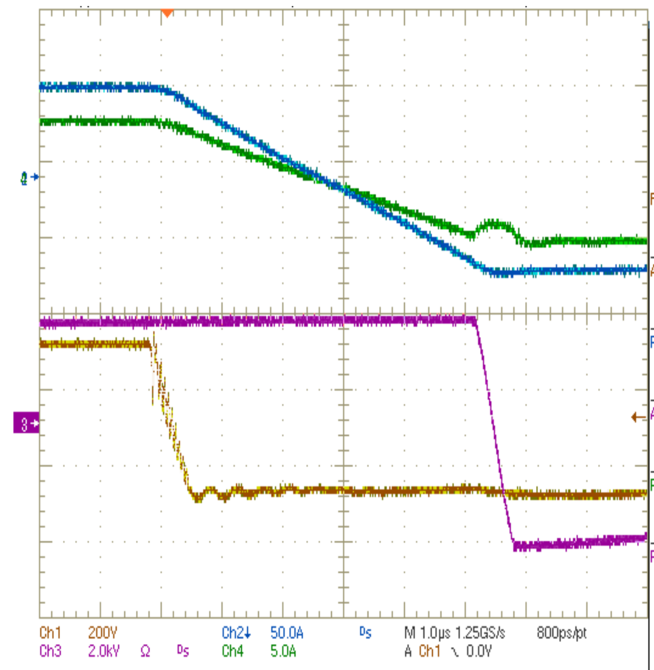
ICWT operation with 6kVdc-400Vdc dc/dc stage of SST

- Waveforms and temperature rise at 6.5kVA-

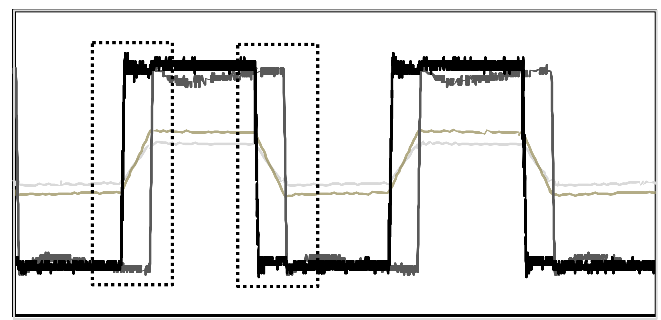


Heat distribution at 6.5kVA power transfer without an active cooling method after 70 minute operation





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

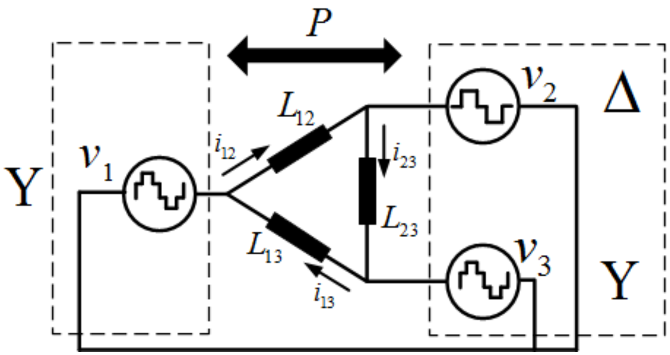


Hot spot temperature :170 °C after 70 minutes operation with 6.5kVA without active cooling method in dry-type

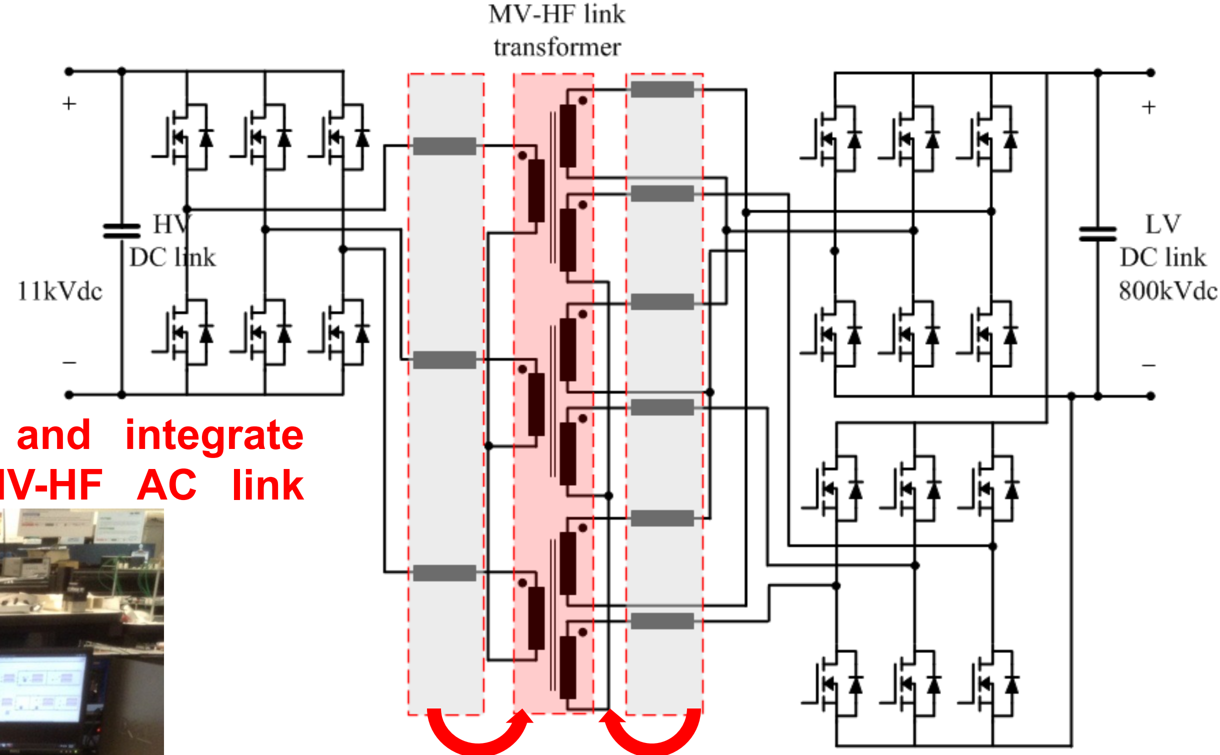
-The upper temperature limit of wire insulation material, PFA (Perfluoroalkoxy), is 260°C

Gen-II 3-phase SST

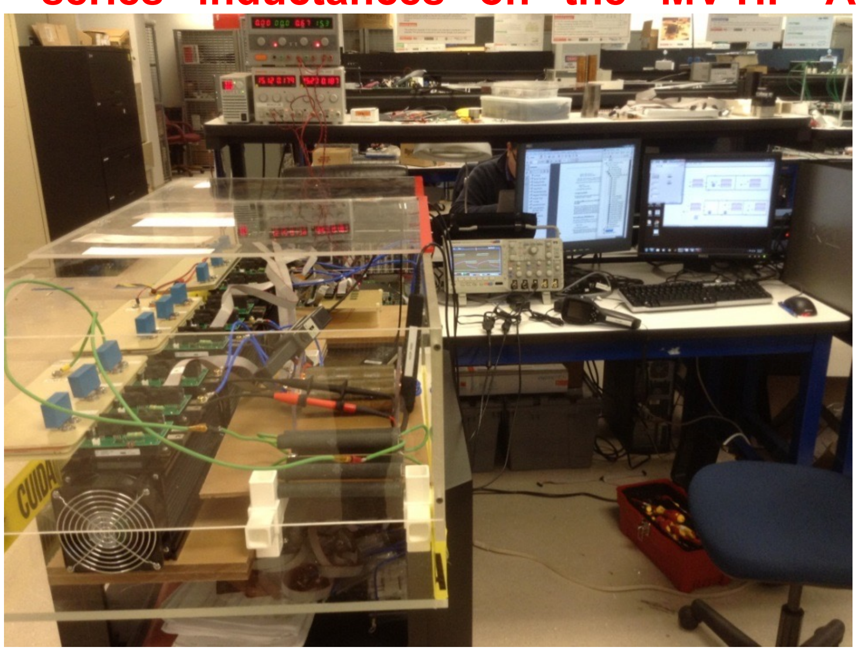
High-Frequency 10kHz Multi-Terminal Planar Transformer

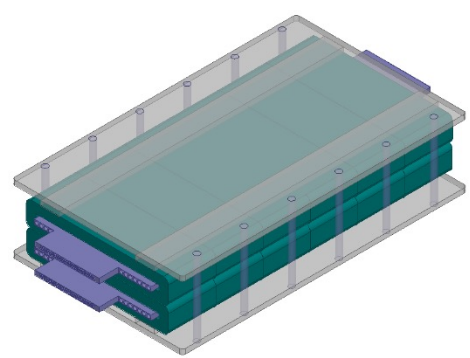


Simplified eq. circuit model



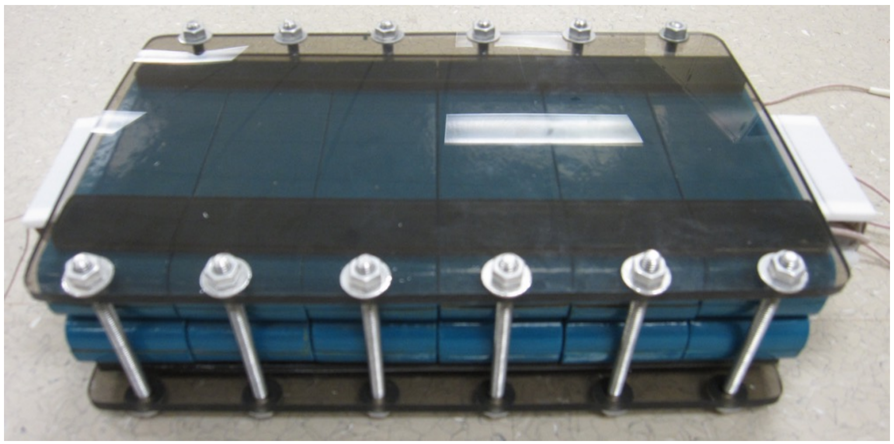
Design to analytically utilize and integrate series inductances on the MV-HF AC link

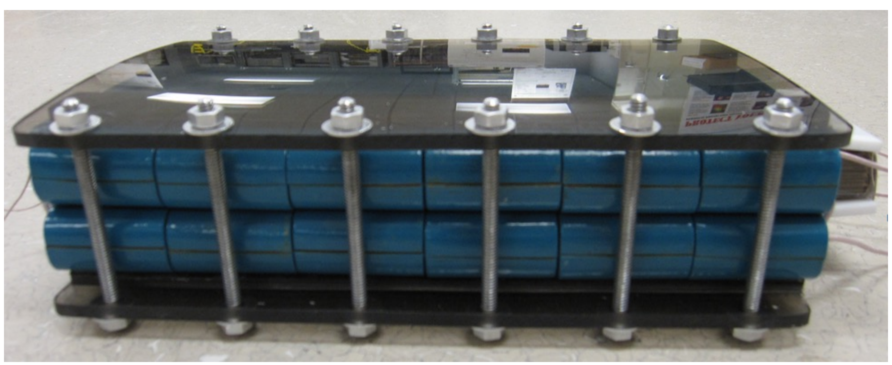


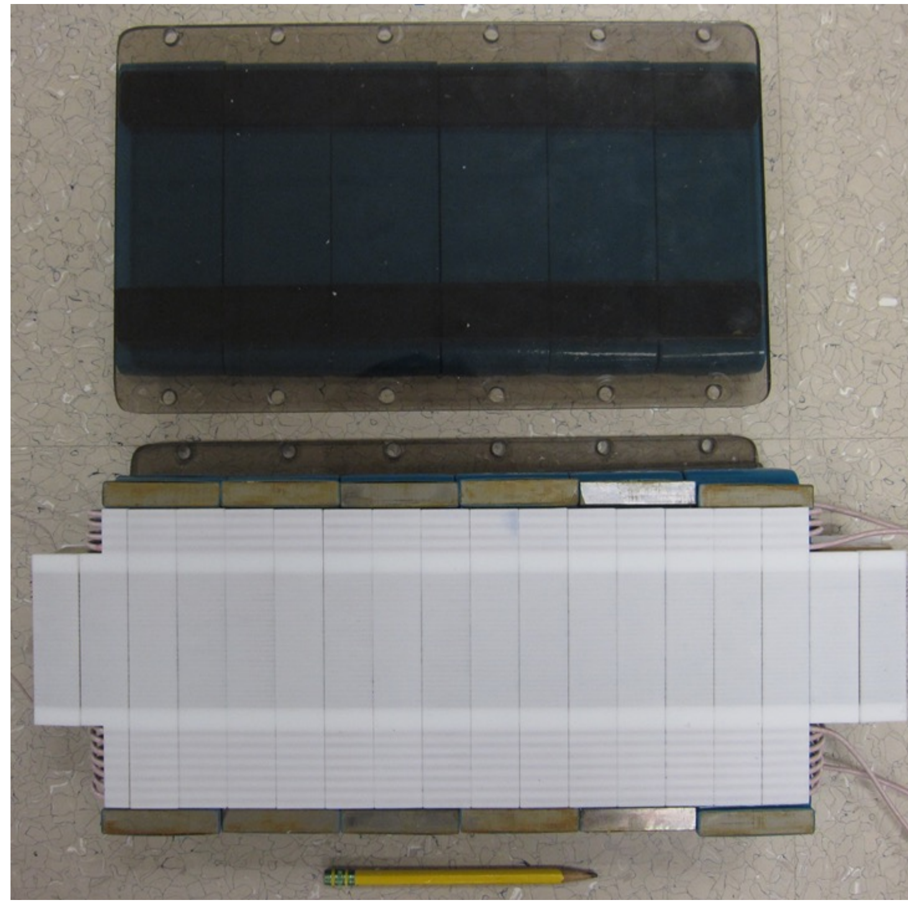


- No additional parasitic elements
- No additional space and cost.
- Light and compact.

Gen-II 3-phase SST
High-Frequency 10kHz Multi-Terminal Planar Transformer

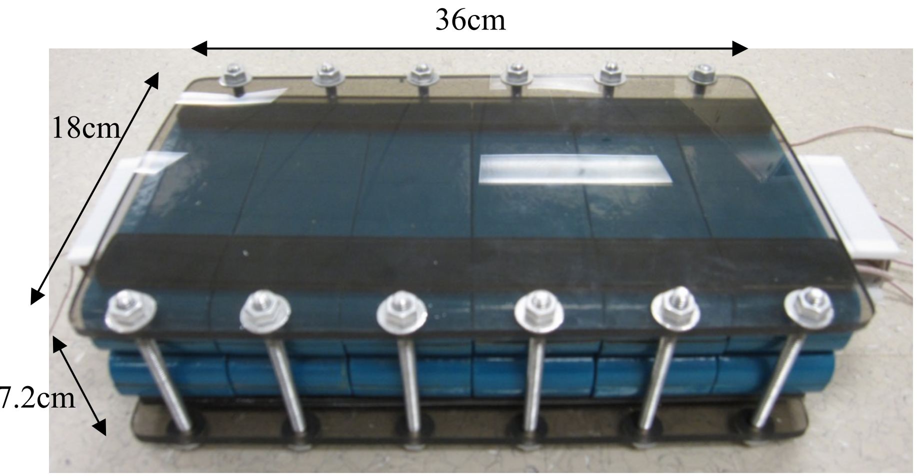






Proposed shell-type low-profile MF/MV transformer

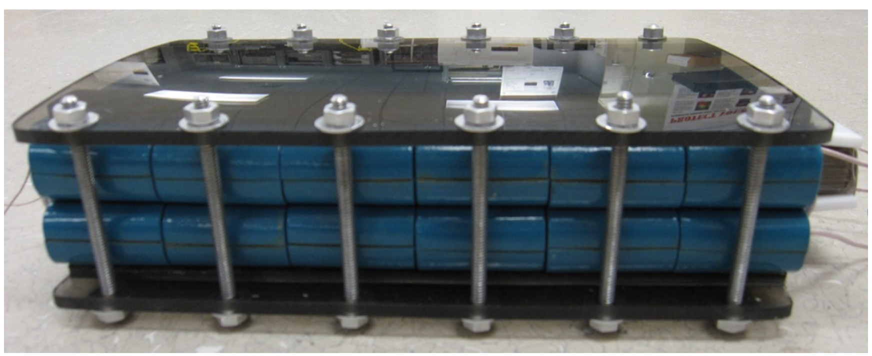
- Prototype-



Freq.	$V_{dc\,1}$	$V_{dc\,2}$	kVA_{phase}
10kHz	5500V	400V	5.5kVA

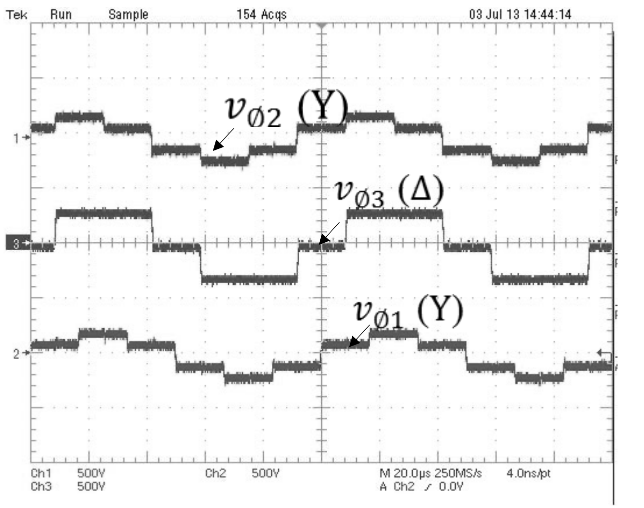
$N_1:N_2:N_3$ $(Y:Y:\Delta)$	V_{phase}	B_{ac}
55: 7: 4	2.6kV	0.28T

No load loss (Open circuit)	Load loss (Short circuit)	Total loss
40W	78 W	118W

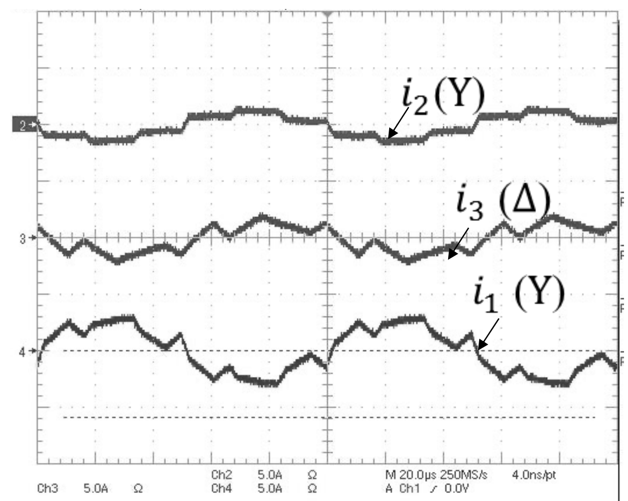


Experimental results

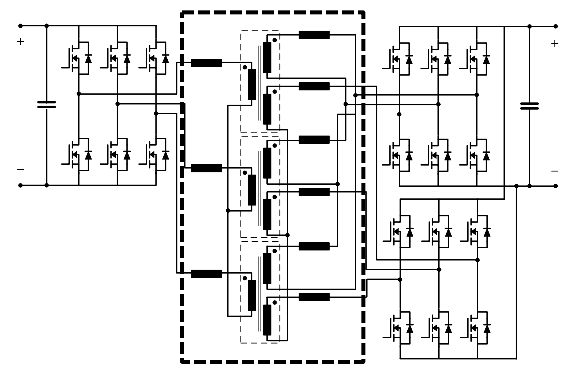
- Operation test, waveforms -

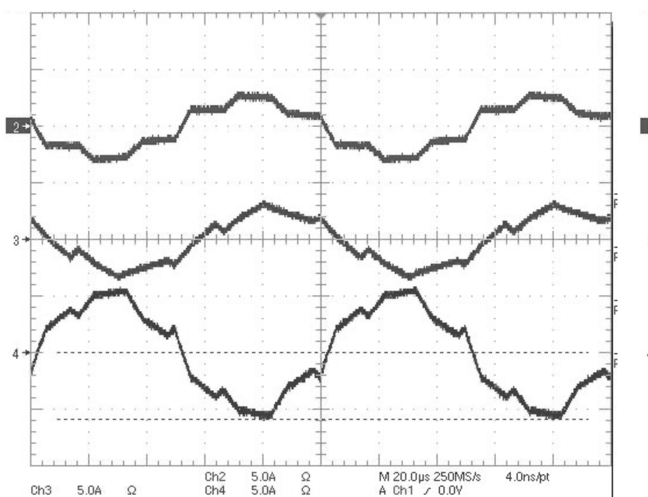


Voltage waveforms on each winding with $\theta_{ps} = 30°$

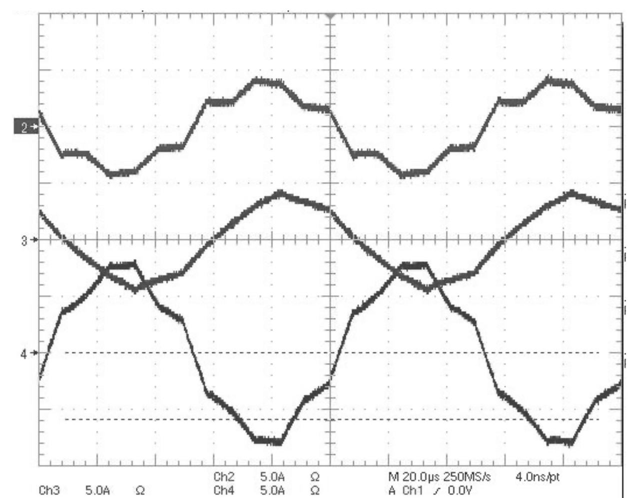


Line current waveform with $\theta_{ps} = 10°$

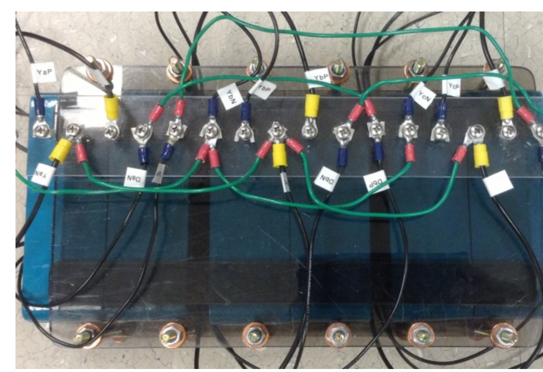




Line current waveform with $\theta_{ps} = 20°$



Line current waveform with $\theta_{ps} = 30°$

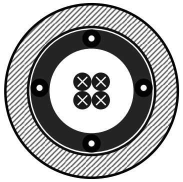


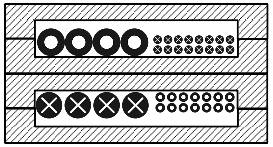
3 of 1/3 size prototype

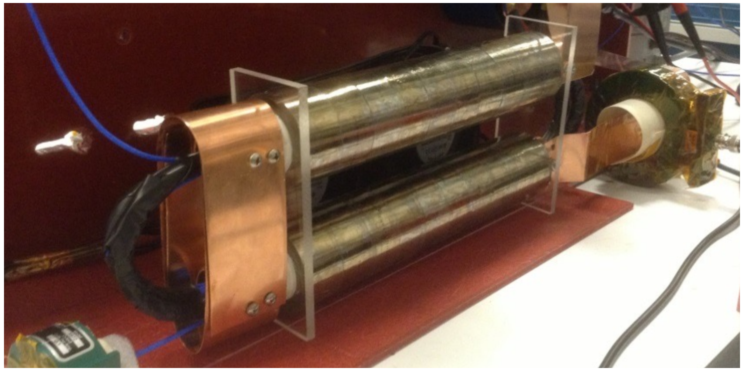
Waveforms (500V/Div, 5A/Div, 20us/Div)

Introduction

- Transformers -





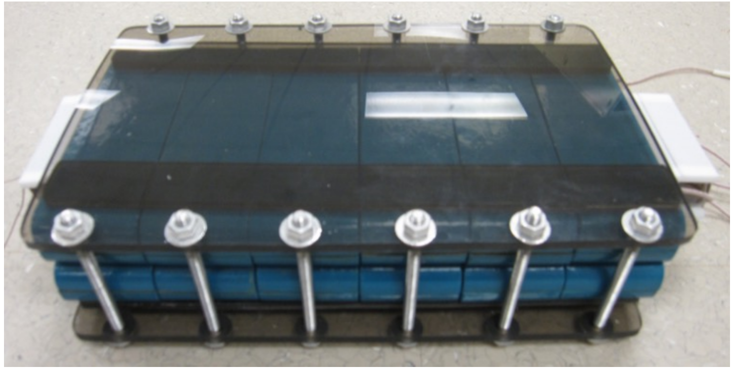


1. The best known geometry regarding LC characteristics!

2. Ideal geometry with no electric, magnetic field and heat congestion.

3. Low parasitic elements

4. Electrically and magnetically well shielded.



1. Easy utilization of leakage inductance by geometric factor !

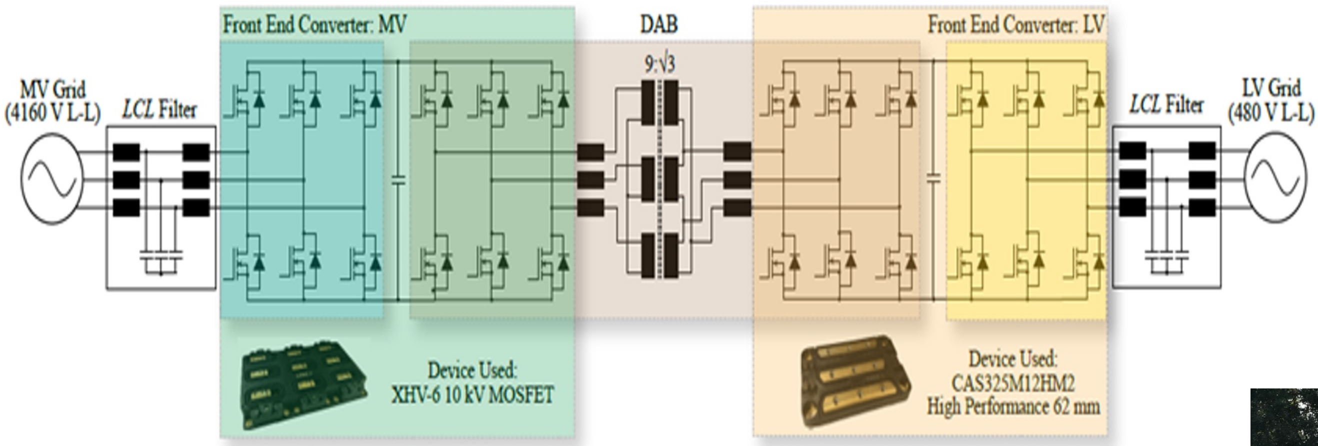
$$\frac{w \cdot l}{h}$$

w=width of window area
h=height of window area
l = length of window area

2. Electrically and magnetically well shielded.

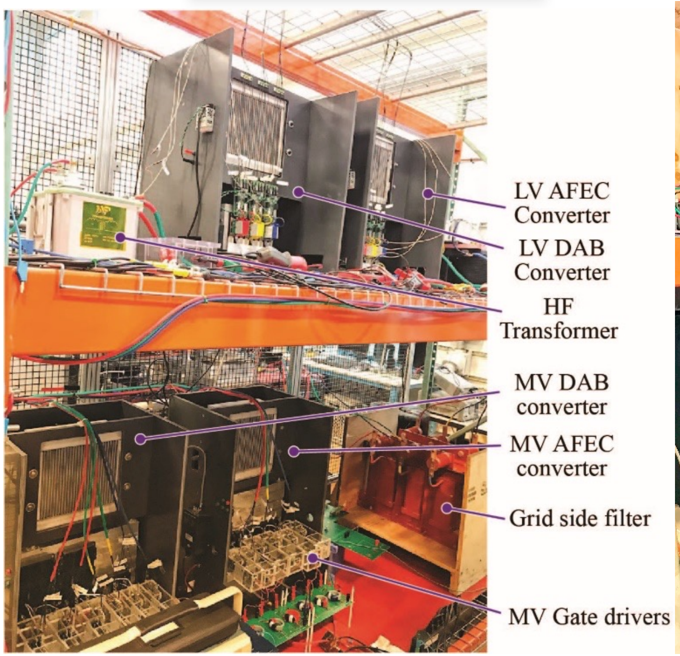
3. Simple geometry.

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



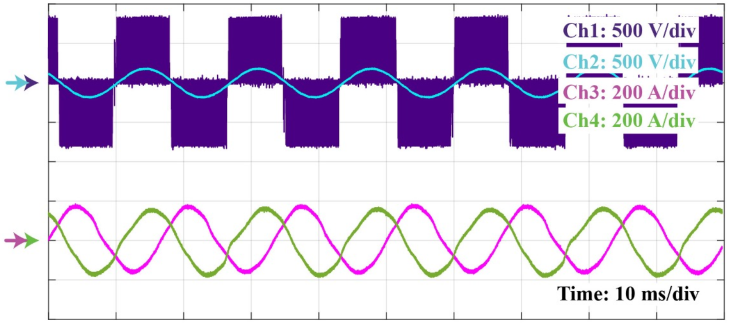
Photograph of the entire MUSE-SST system in the laboratory

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

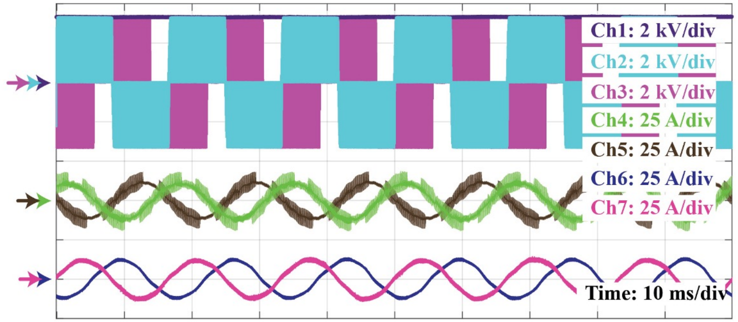
Demonstration of the entire MUSE-SST system in the mobile container

Final Operation of the Entire MUSE-SST System

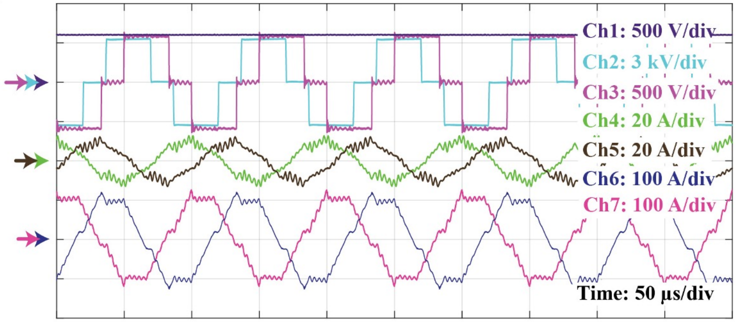
- ► Operation at **3.5 kV MVDC; 600 V LVDC and an active power of 28 kW**



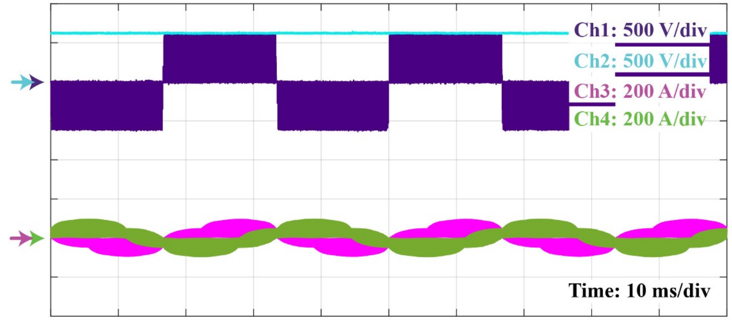
Ch1: LV pole voltage (VRY); Ch2: LV voltage across filter capacitor (VRY-cap); Ch3: Current through LV R-phase; Ch4: Current through LV Y-phase.



Ch1: MV DC-link voltage (Vdc-MV); Ch2/Ch3: MV pole voltage (VRY/VYB); Ch4/Ch5: Inverter current through MV R/Y-phase; Ch6/Ch7: Grid current through MV R/Y-phase.



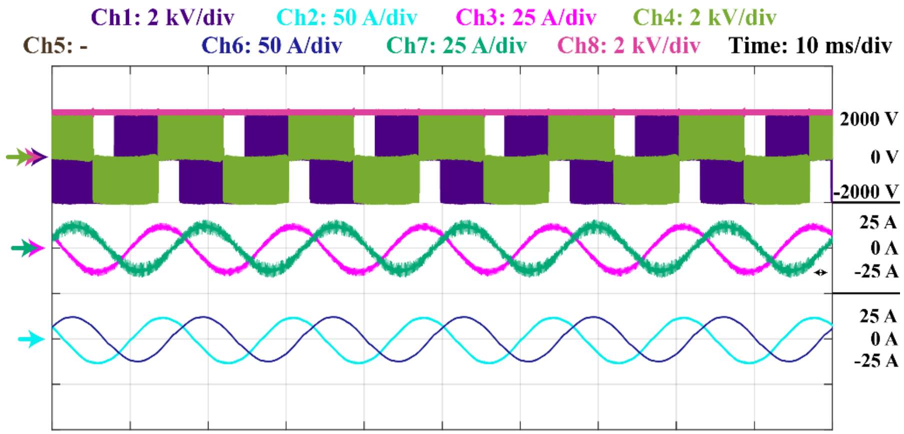
Ch1: LV DC-link voltage (Vdc-LV); Ch2: MV pole voltage (VRY-MV); Ch3: LV pole voltage (VRY-LV); Ch4/Ch5: Current through MV R/Y-phase; Ch6/Ch7: Current through LV R/Y-phase.



Ch1: LV pole voltage (VRY); Ch2: DC-link voltage across inverter; Ch3: Current through LV R-phase; Ch4: Current through LV Y-phase.

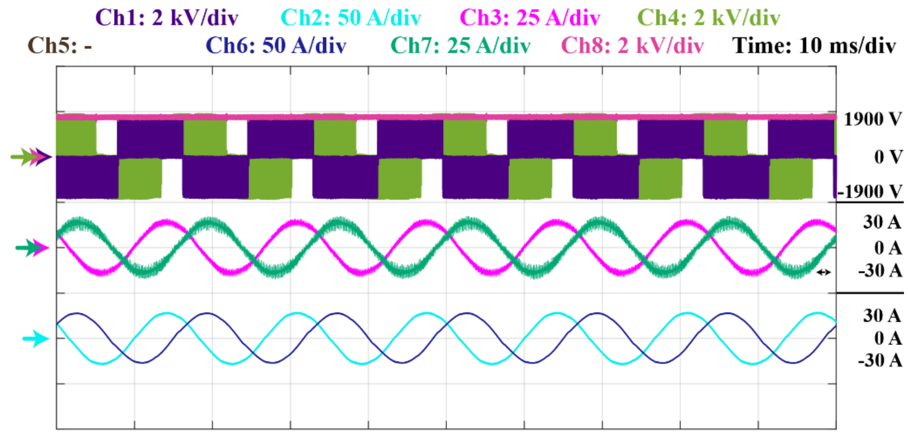
Final Operation of the Entire MUSE-SST System

► 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.

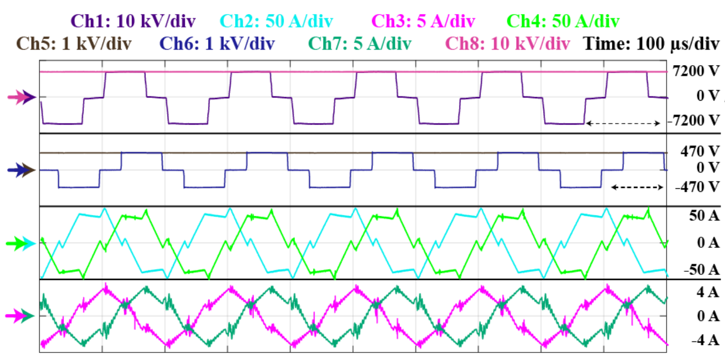
(Ch1/Ch4: MV pole voltage (V-RY/V-YB); Ch2: Grid current through R-phase; Ch3/Ch7: Inverter current through MV R/Y-phase; Ch8: MV DC-link voltage



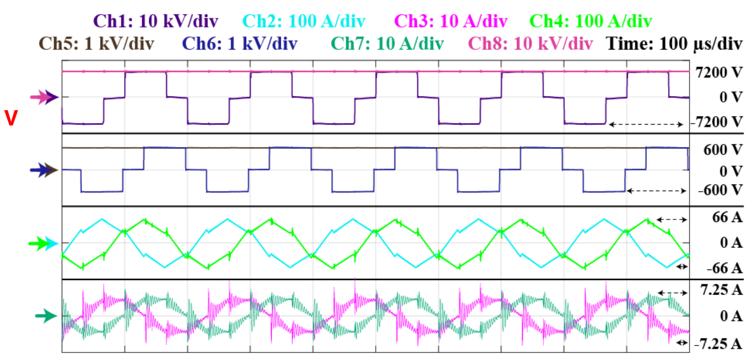
MV-AFEC system for a peak current of 30 A.

(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



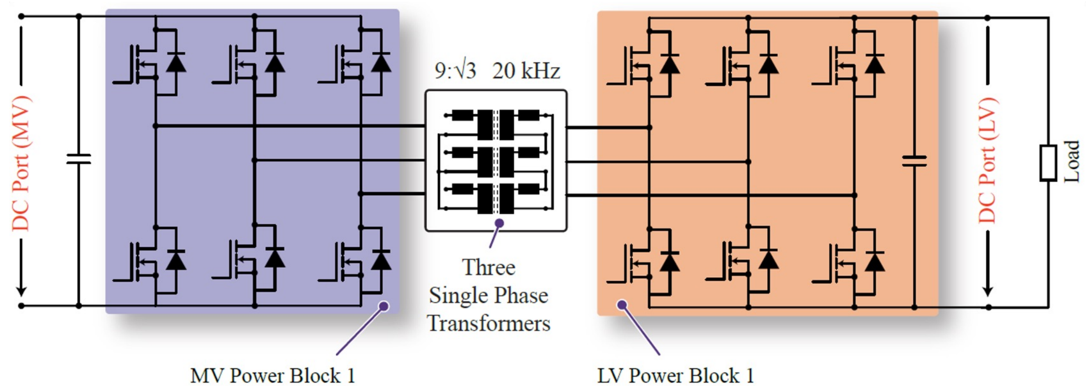
Phase shift: 30°
R load: 12.5 Ω
Input voltage: 7200 V
Power transfer: 30.5 kW

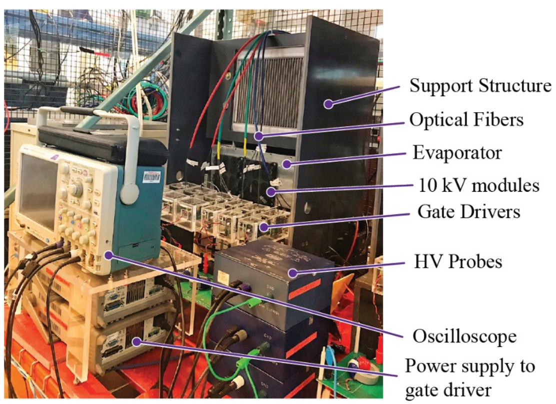
(Ch1/Ch6: Line-to-line voltage of MV/LV side (VRY); Ch2/Ch4: R/Y-phase LV side current; Ch3/Ch7: R/Y-phase MV side current; Ch5/Ch8: MV/LV side DC-link voltage)

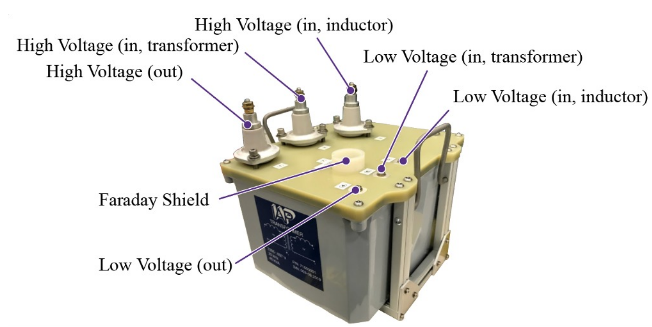
High Frequency Transformers Design and Characterization

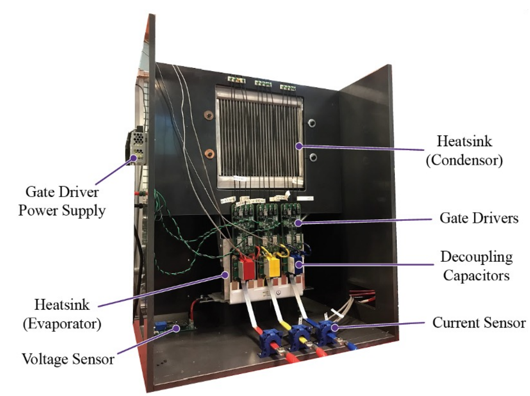
DAB Converter System

- ▶ **Dual Active Bridge (Power flow from MV side to LV side)**







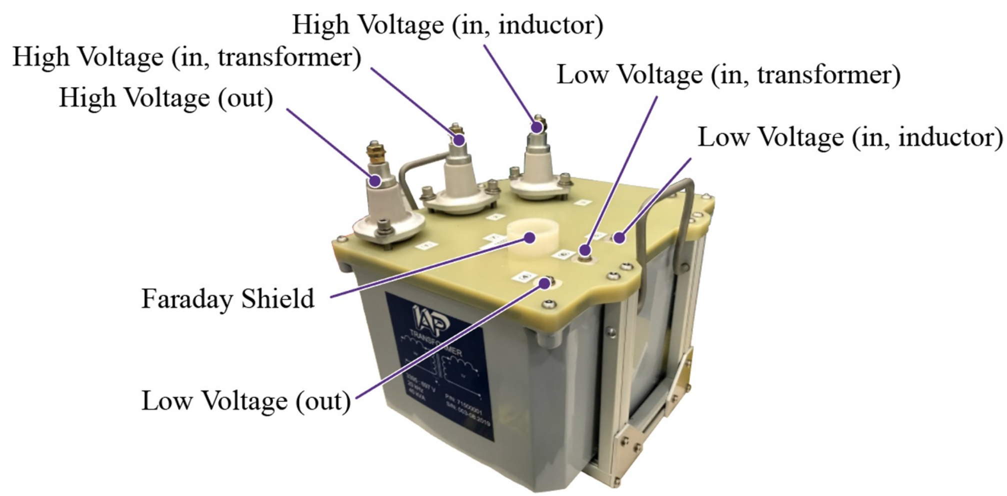


Testing the High Frequency Transformer

- ▶ **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

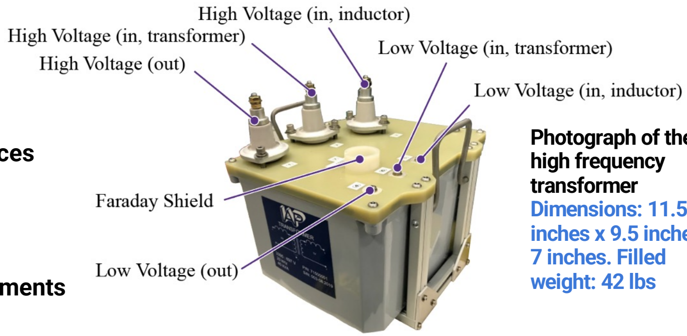


Photograph of the HFT used in the Dual Active Bridge converter system. Dimensions: 11.5 inches x 9.5 inches x 7 inches. Filled weight: 42 lbs

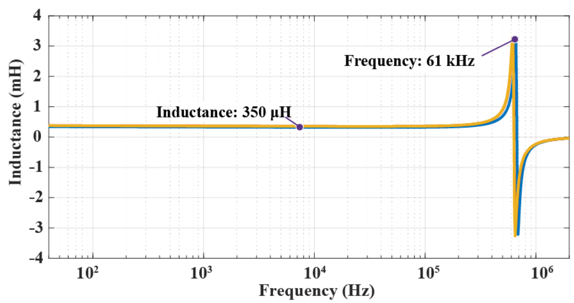
- ▶ Insulation tested up to 15kV
- ▶ Core material : nanocrystalline
- ▶ Filled with oil to achieve the required insulation level and thermal cooling
- ▶ Transformer design is very challenging to meet size, minimal parasitics and high magnetizing inductances

High Frequency Transformer Characterization and Modeling

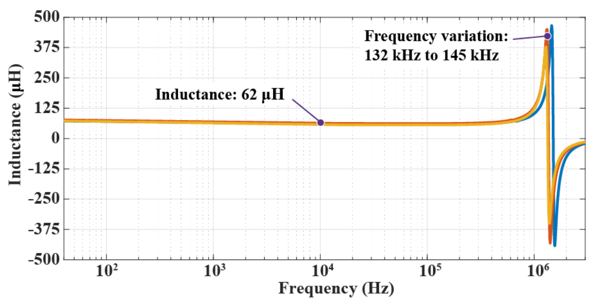
- ► Three high-frequency transformers (Operating frequency 20 kHz)
  - ► Manufactured using nanocrystalline core
  - ► Insulation and thermal management is provided by transformer oil
  - ► Small hole is provided on top to monitor and replace the transformer oil when necessary
  - ► Transformer houses 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



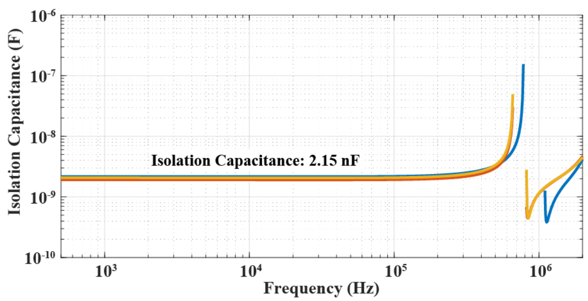
Photograph of the high frequency transformer
Dimensions: 11.5 inches x 9.5 inches x 7 inches. Filled weight: 42 lbs



Inductance measurement curves of MV side inductor



Inductance measurement curves of LV side inductor



Isolation capacitance of the primary to secondary winding

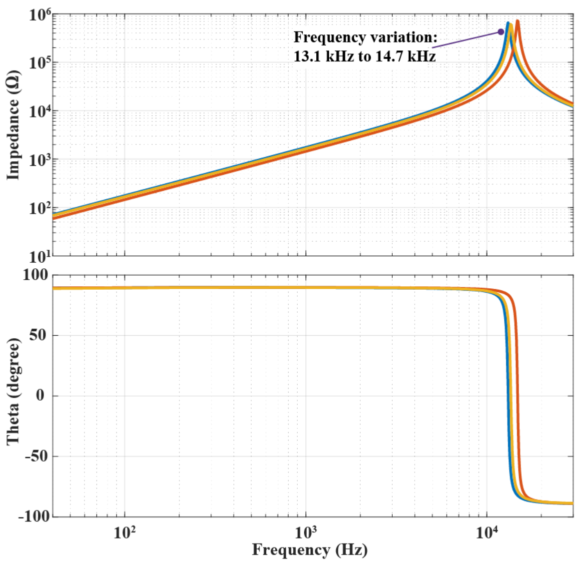
[1] A. Anurag, S. Acharya, S. Bhattacharya, T. R. Weatherford and A. Parker, "A Gen-3 10 kV SiC MOSFETs based Medium Voltage Three-Phase Dual Active Bridge Converter Enabling a Mobile Utility Support Equipment Solid State Transformer (MUSE-SST)," in IEEE Journal of Emerging and Selected Topics in Power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

NC STATE UNIVERSITY

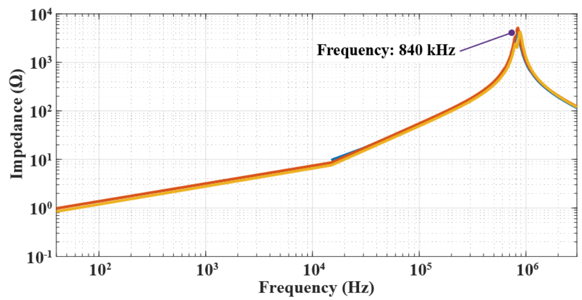
FREEDM SYSTEMS CENTER

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

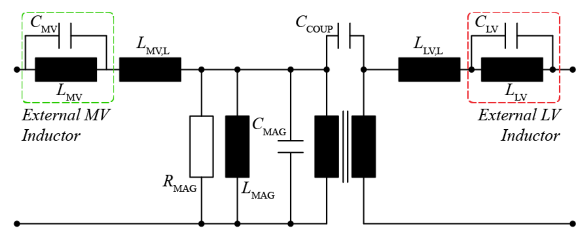


Impedance curves of primary winding with secondary side shorted

- ► Calculate the respective capacitance and inductance using:

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

Equivalent model of the high frequency transformer

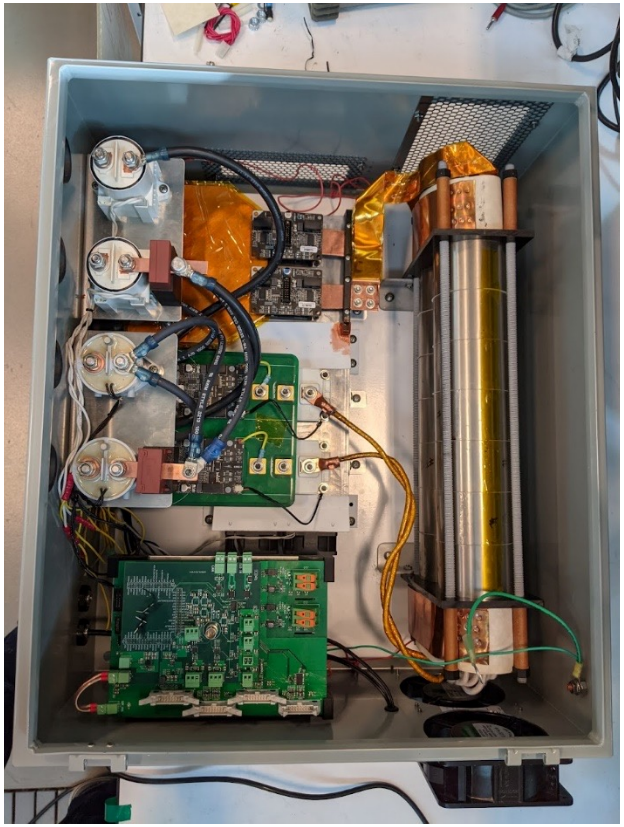


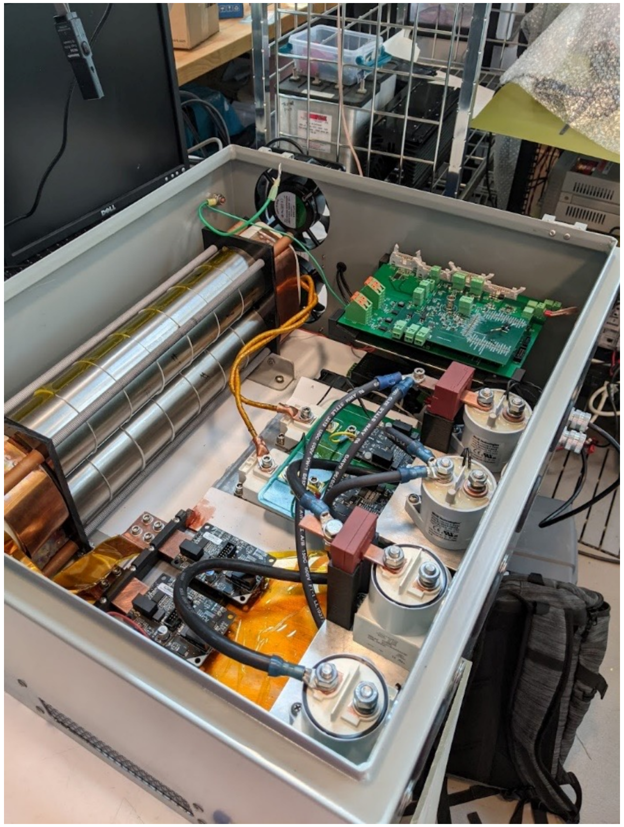
Key parameters of the high frequency transformer

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
$L_{\mathrm{MV,L}}$	40 µH
$L_{\mathrm{LV,L}}$	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.

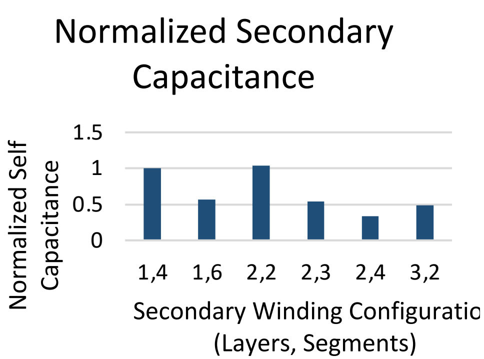
50kW DC-DC Dual Active Bridge [DAB] Converter [400V: 1000V]

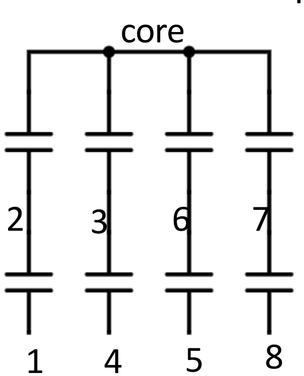




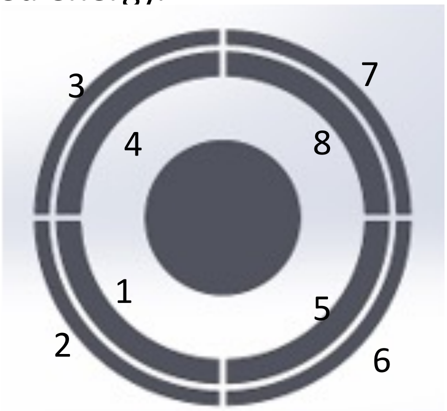
Coaxial Transformer: Tubular Winding Capacitance

- Layered secondary windings have increased self capacitance, but careful winding selection can minimize capacitive stored energy.
- Assume:
  - Flat plate capacitance is dominant.
  - Layer-to-layer and layer-to-core capacitance is the same.
- Capacitive shielding of inner winding layers results in minimal capacitive stored energy.





Capacitance model of optimal 8-turn, 2 layer winding



Winding order of optimal 8-turn, 2 layer winding

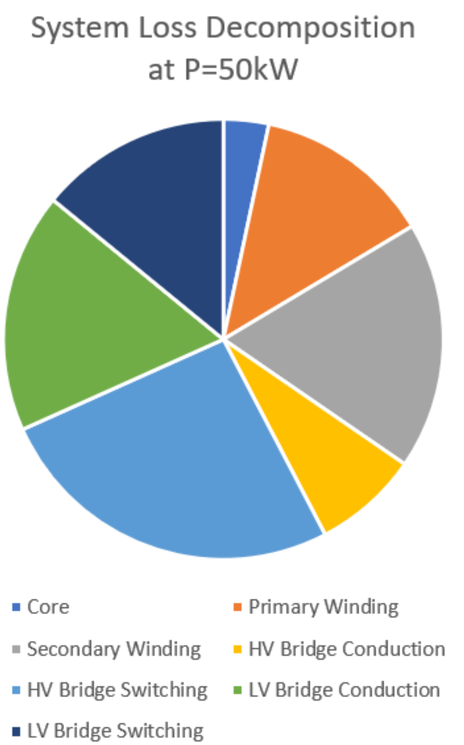
Optimal Co-Design of DAB: 50kW results

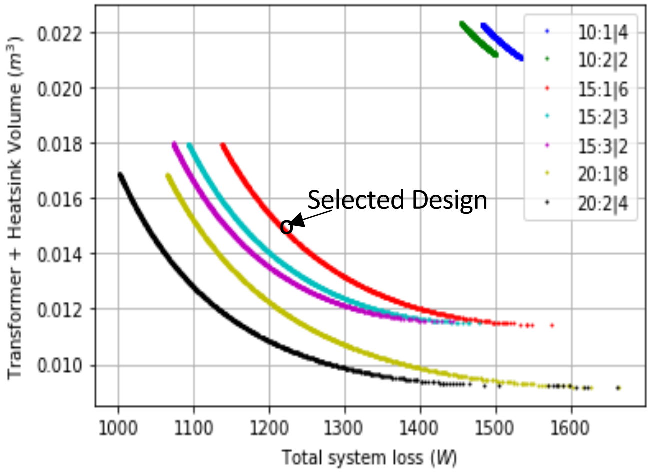
Rated Power	50 kW
Maximum Phase Shift	30 deg
Switching Frequency	40 kHz
HV Bus Voltage	1000 V
LV Bus Voltage	400 V
HV Modules	Wolfspeed CAS300M17BM2
LV Modules	Wolfspeed CAB425M12XM3
LV Capacitance	200 µF
HV Capacitance	80 µF
Transformer Turns	15:6
Transformer Leakage Inductance	34.7 µH
Transformer Magnetizing Inductance	30.0 mH

System Parameters

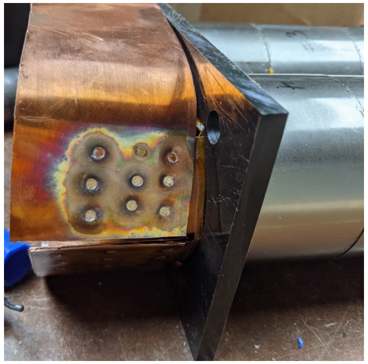
Primary Turns	15
Primary Conductor	1650x38 ga Litz
Secondary Turns	6
Secondary Layers	2
Secondary Layer 1 Conductor	10 mil copper foil
Secondary Layer 2 Conductor	20 mil copper foil
Core Inner Diameter	70 mm
Core Outer Diameter	73 mm
Core Total Length	700 mm
Core Mass	1.68 kg

Transformer Build Details



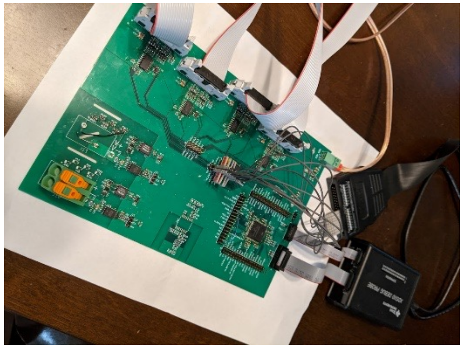


System Build



Welded foil end connections resulted in winding resistance only 15% higher than ideal

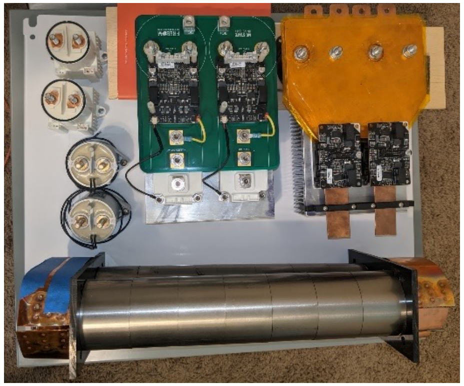
Detail of foil end connections, insulation, and primary Litz winding



Controller communications and fault response testing

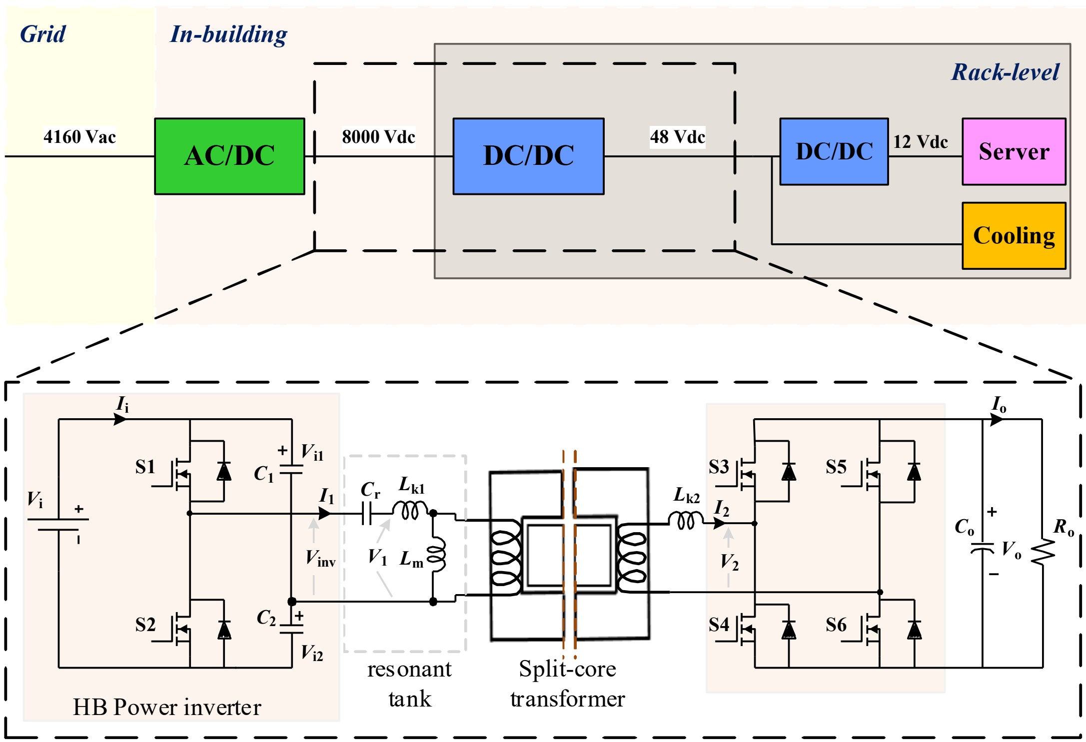
Composite winding tube has direct copper-air cooling

Second composite tube prior to transformer assembly



System components (except controller) on build plate

1000V/ 20kW MVDC Contactless Power Supply



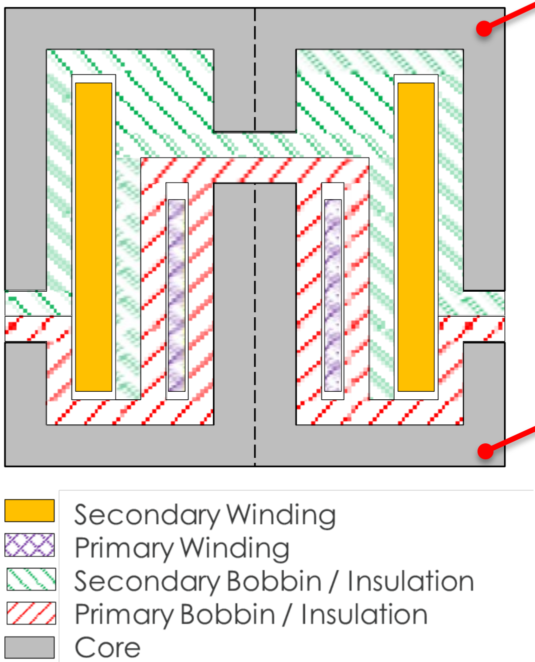
Specification	Value
Nominal Input Voltage	1000V
Nominal Output Voltage	48V
Nominal Output Current	400A
Rated Power	20kW
Efficiency Target	95% @ 50% Load 91% 100% Load 90% @ 200% Load

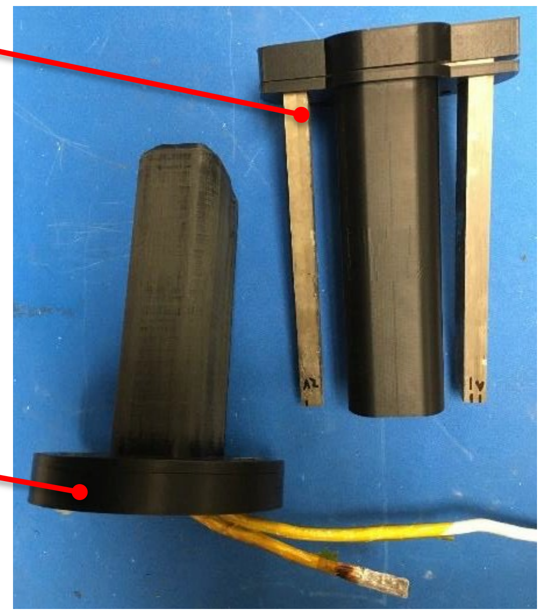
- 1000V chosen for validation phase
- Opens the pathway to 2000V, 4000V, 8000V

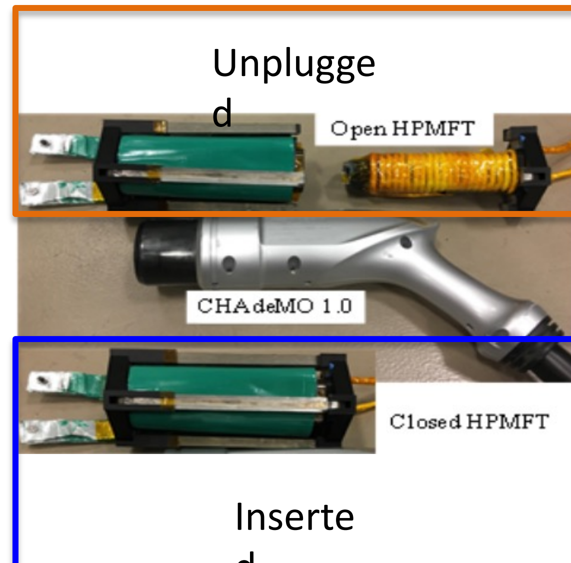
Gapped Transformer Design Overview

LV Side Assembly

HV Side Assembly

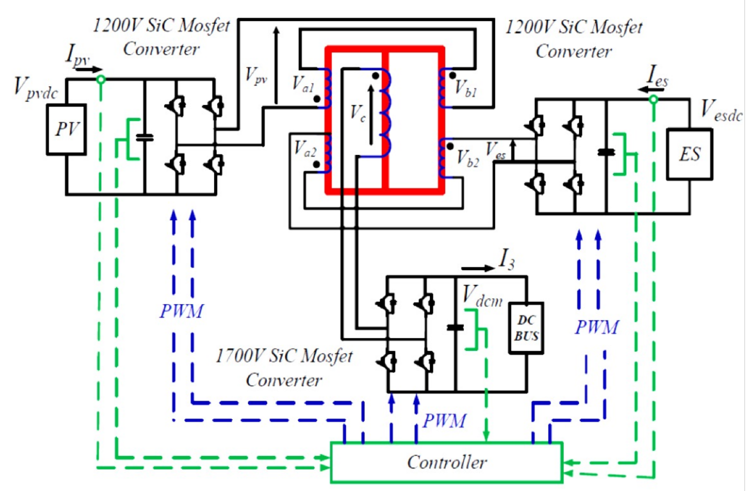


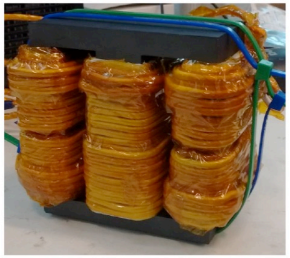




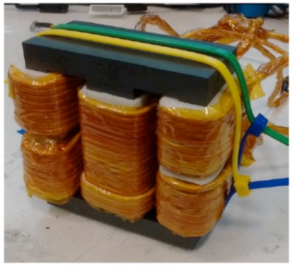
Integration of PV and ESS using TAB

- **Three-Limb split winding transformer.**
  - PV and ESS windings are split into two equal halves on the side two limbs.
  - Two equal halves have same number of turns and the geometric dimension of the limbs are also same.
  - Transformer design is optimized based on the loss-volume using a leakage inductance and parasitic capacitance model.
  - Two laboratory prototypes were built for 50kHz and 100kHz switching frequency.

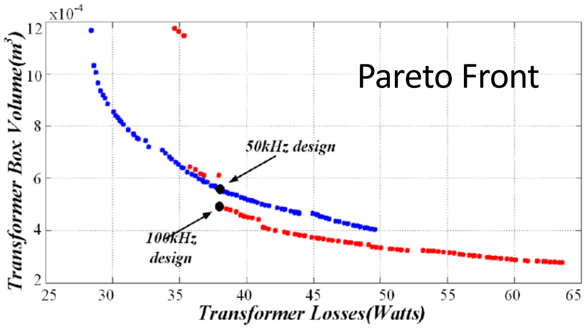




50 kHz prototype

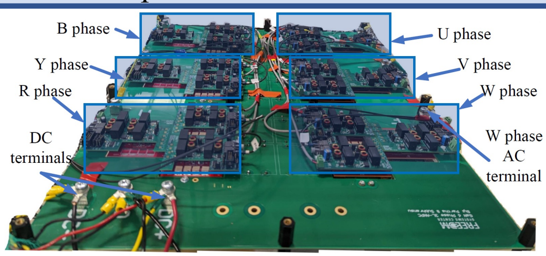


100 kHz prototype

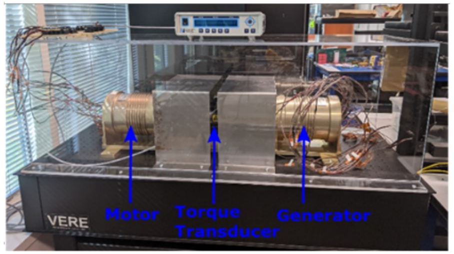


4.2 Inverter-fed High-Speed Motor Drive Efficiency Evaluation (In Progress)

Six-phase 3L-ANPC inverter



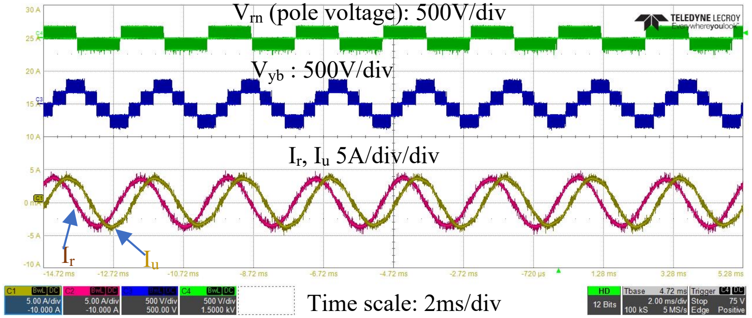
High-speed PMSM setup



Motor details

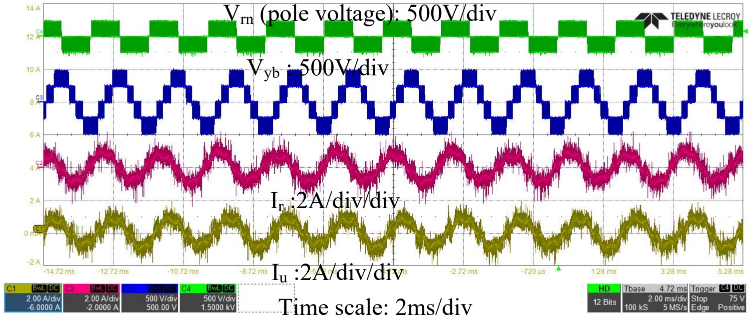
Power	10kW
Voltage (L-L)	565V (Open winding, 3ph and 6ph M-G set). One HSM is 3-phase and other 6-phase. 3-phase motor is configurable for 1130V.
Poles	8
Speed	21,000 rpm
Fundamental frequency	1400 Hz

Motor drive test result at 6000 RPM 0.7PU load



- V_{dc}: 350V
- Fundamental frequency: 400Hz
- Six-phase input ≈ 1kVA

Motor drive test result at 9000 RPM no load

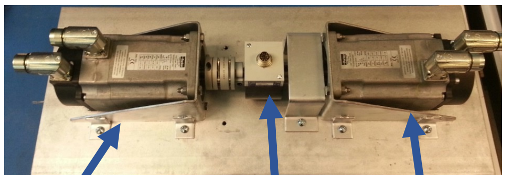


- V_{dc}: 450V
- Fundamental frequency: 600Hz

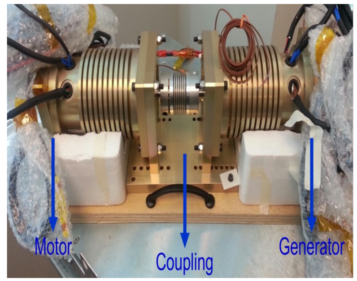
- Test results are with Six-phase 3L-ANPC inverter (1dev/switch)
- Switching frequency: 50kHz
- Six-phase PMSM is controlled using dual three phase-based vector control [4].
- Control algorithm is implemented is TI DSP F28379D.

[4] P. P. Das, S. Satpathy, S. Bhattacharya and V. Veliadis, "Generalized Control Technique for Three-Level Inverter Fed Six-Phase Permanent Magnet Synchronous Machines Under Fault Conditions," *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2022, pp. 1-8, doi: 10.1109/ECCE50734.2022.9947672.

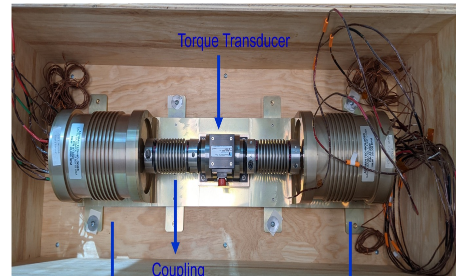
High speed machine (HSM) testbeds



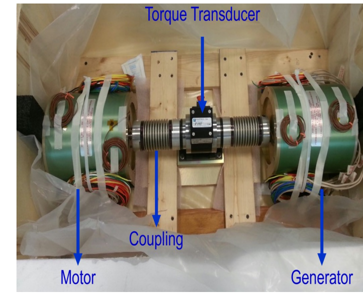
LV HSM-1



LV HSM-2



LV HSM-3

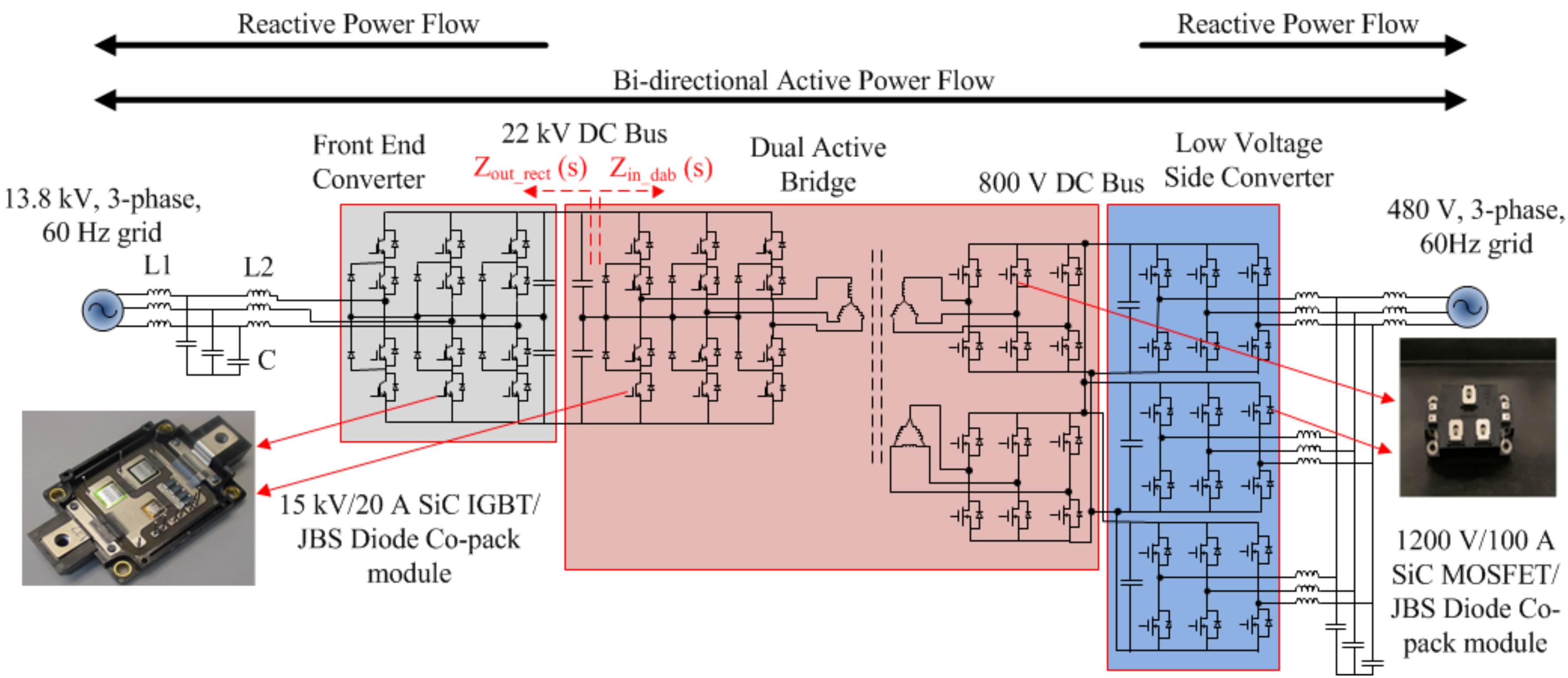


MV HSM-4

	LV HSM-1 Testbed 1	LV HSM-2 Testbed 2	LV HSM-3 Testbed 3	MV HSM-4 Testbed
Power	1.39kW	5kW	10kW	15kW
Voltage (L-L)	400V (3ph-3ph M-G set)	560V (3ph-3ph M-G set)	565V (Open winding, 3ph and 6ph M-G set); one HSM is 3-phase and other 6-phase	1100V (Open winding, 3ph-3ph M-G set)
Poles	10	4	8	6
Speed	14,000rpm	30,000rpm	21,000 rpm	25,000 rpm
Fundamental frequency	1167Hz	1000Hz	1400 Hz	1250Hz

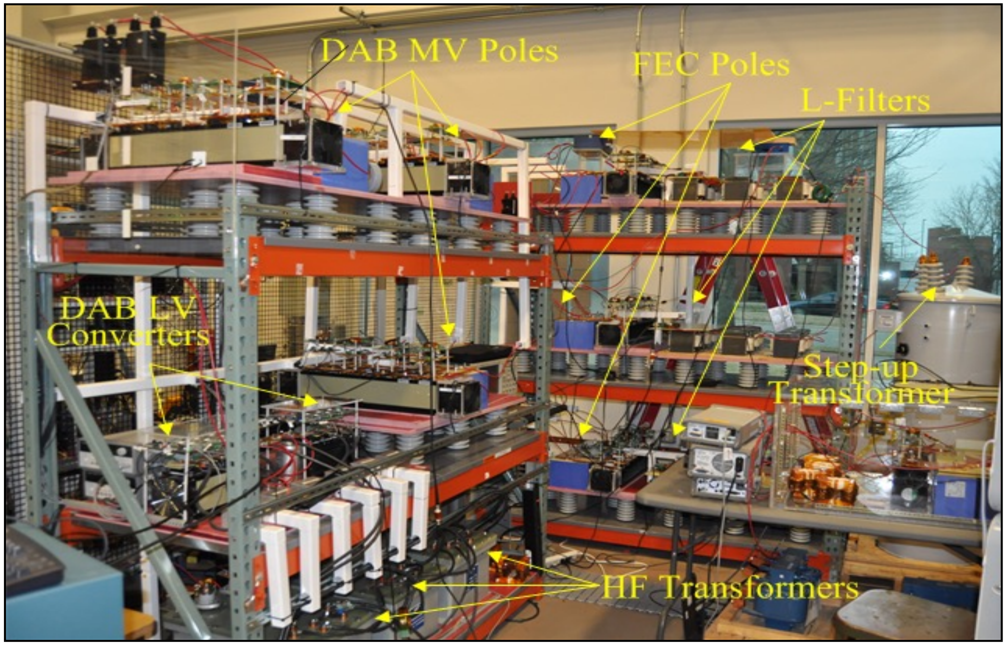
FREEDM systems center | PowerAmerica | ece NC STATE UNIVERSITY Electrical & Computer Engineering

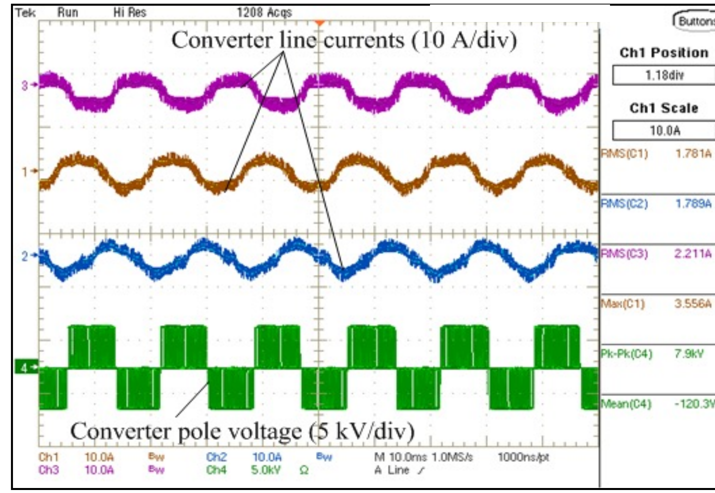
15kV SiC IGBT based 3-phase SST with 13.8kV MV AC grid tie: Transformerless Intelligent Power Substation (TIPS)



- 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

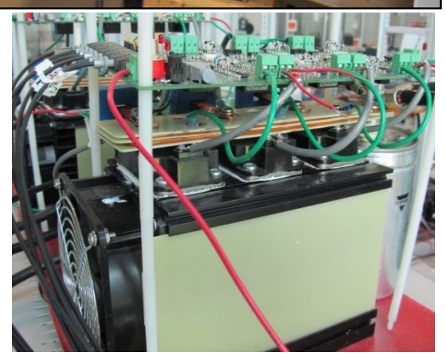
TIPS Converter Laboratory Demonstration: AFEC waveforms for 4.16 kV MV AC grid tie operation with 8 kV MV dc bus and 9.6 kW load



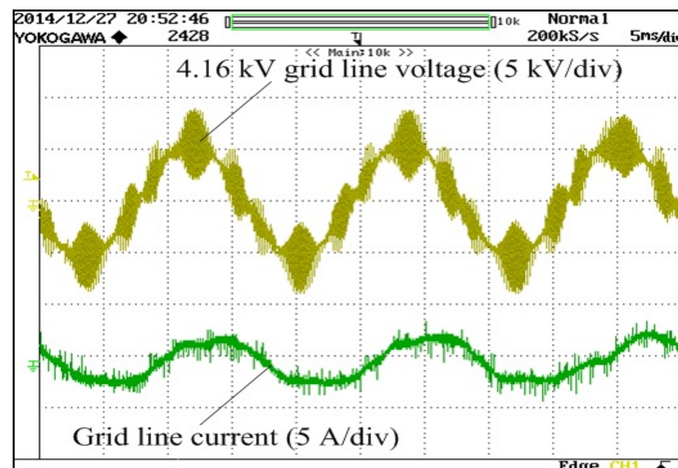


FEC grid currents and R-phase pole-voltage

70kVA, 10kHz, 22kV/11kV/800V Transformer

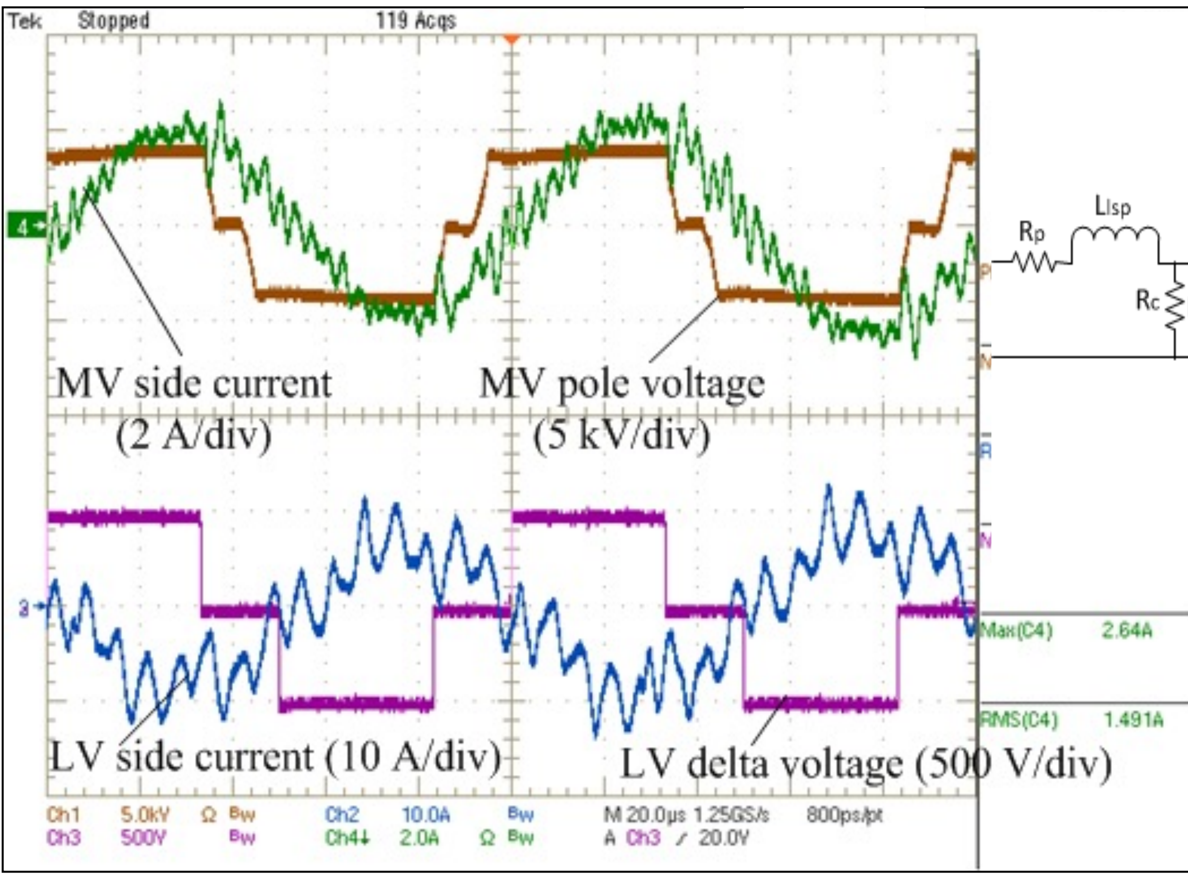


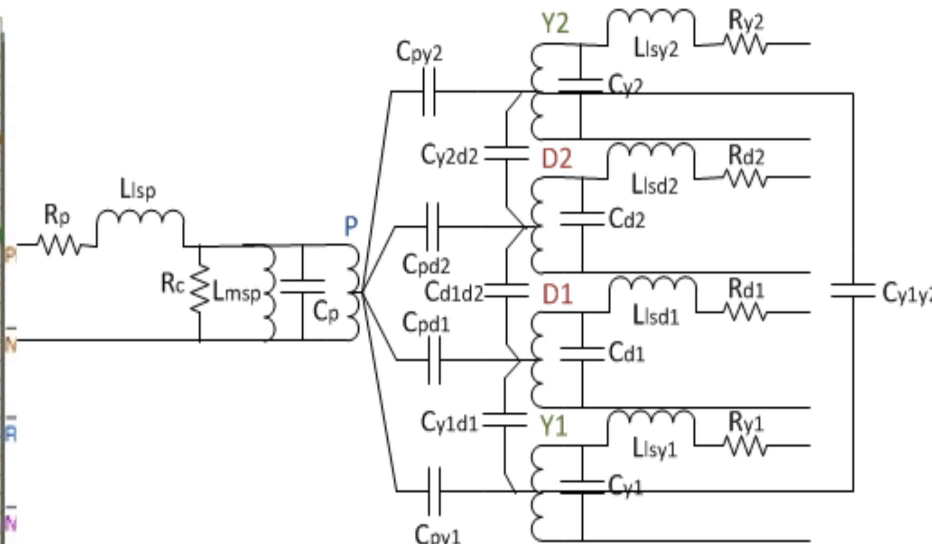
1200V SiC MOSFET LV Side Converter



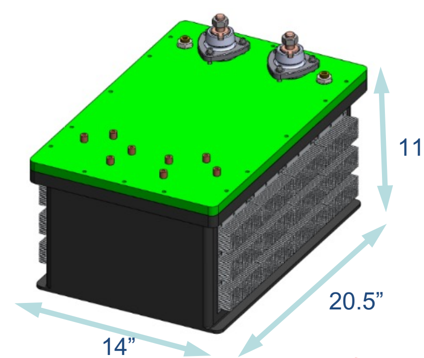
RY-grid voltage and R-phase grid current

TIPS Converter Laboratory Demonstration: DAB waveforms for 4.16 kV MV ac grid tie operation with 8 kV MV dc bus, 480 V LV dc bus voltage and 9.6 kW load





HF Transformer Equivalent Circuit Parameters with Parasitic Capacitors



65 kg dry
95 kg oil filled

70kVA, 10kHz, 22kV/11kV/800V Transformer

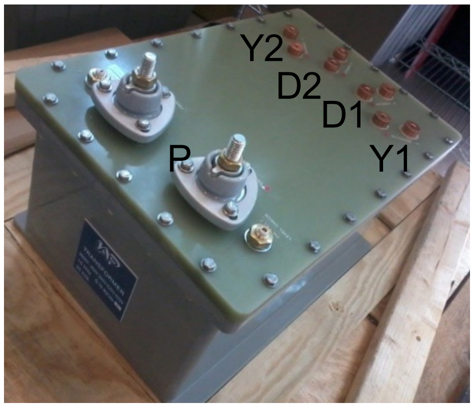
- All waveforms captured at the HF transformer terminals
- Ripple in the DAB currents is due to the HF transformer parasitics

MV – Medium Frequency Transformer Specifications

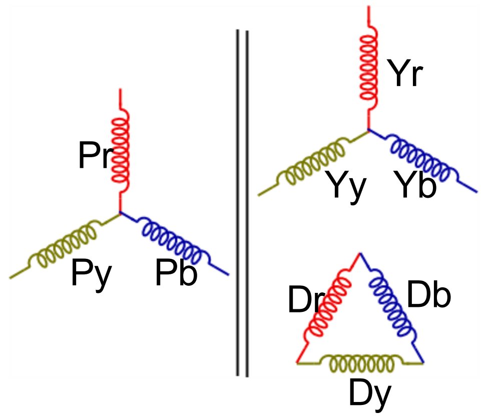
Parameter	Values
Power	35/70 kVA,11 kV/22 kV dual mode
Primary	9.6 kV RMS, 16.6 kV peak,8 A RMS, 12A peak
Secondary – Y winding 1 ,2	360 V RMS , 605 V peak,52 A RMS, 83 A peak
Secondary – Delta winding 1 ,2	625 V RMS , 1050 V peak,31 A RMS, 46 A peak
Frequency	10 kHz
Leakage inductance	80 μH (from secondary side)
Magnetization inductance	280 mH (from primary side), Max. magnetizing current 15% of full load current
Parasitic capacitance (inter turn from primary)	<500 pF
Isolation primary to secondary	100 kV RMS
Cooling	Oil cooling
Efficiency	>99%

- Turns ratio, switching frequency, leakage inductance are selected for optimum operation of DAB

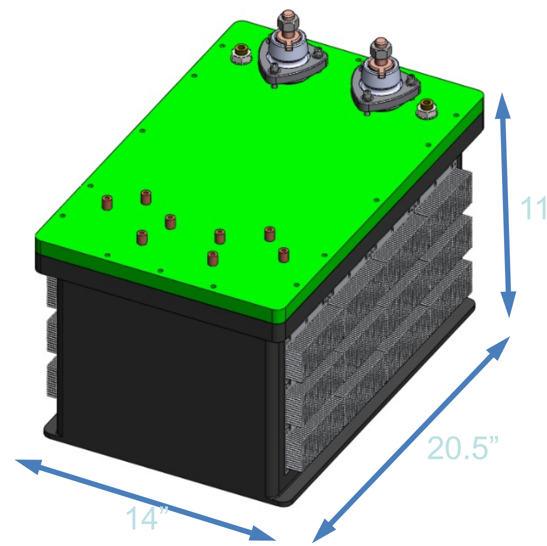
Medium Frequency Transformer for DAB



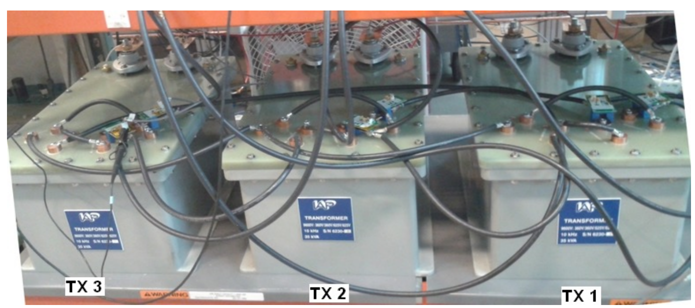
22/11 kV, 10 kHz, 70 kVA 1-Φ Transformer



Transformer Connections

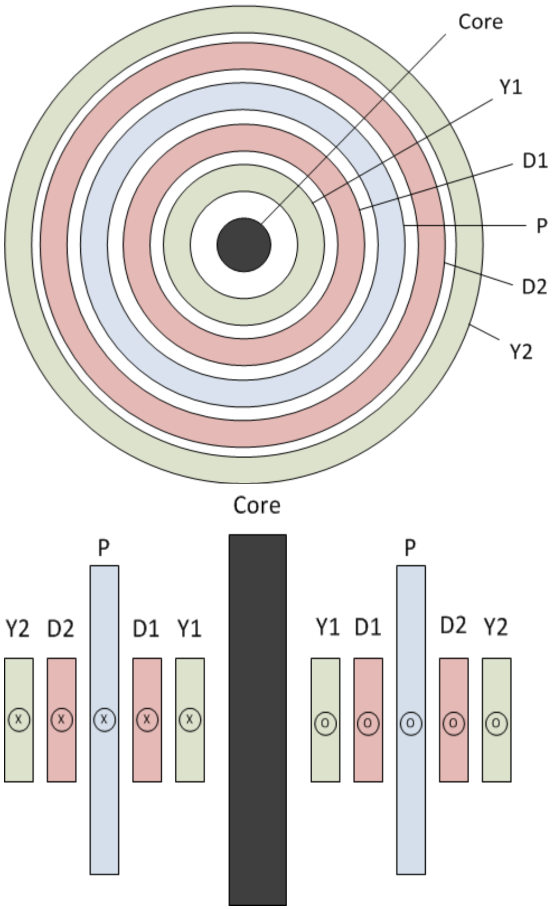


- Insulation tested up to 22kV
- Oil filled transformer
- Three 1-Φ transformers are connected in Y/Y-Δ for 3-Φ DAB

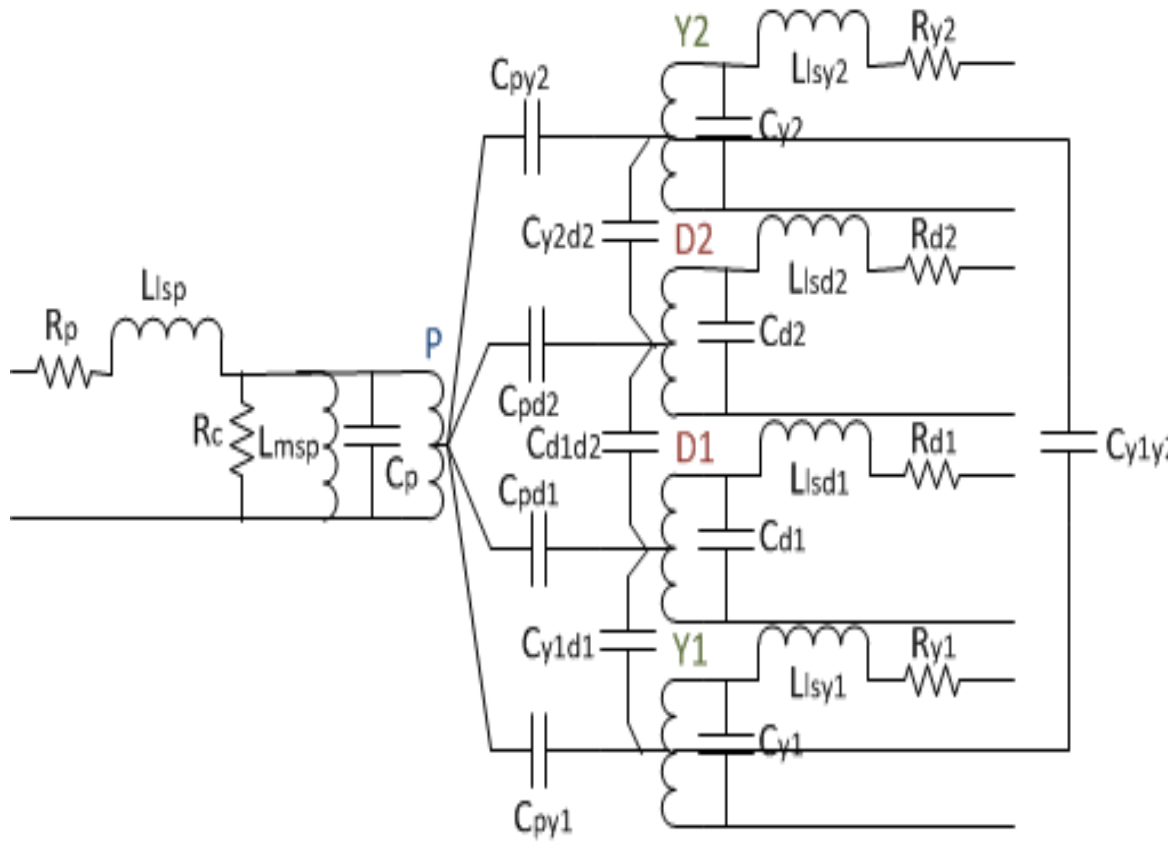


65 kg dry
95 kg oil filled

Transformer Winding Arrangement and Equivalent Circuit with Parasitics



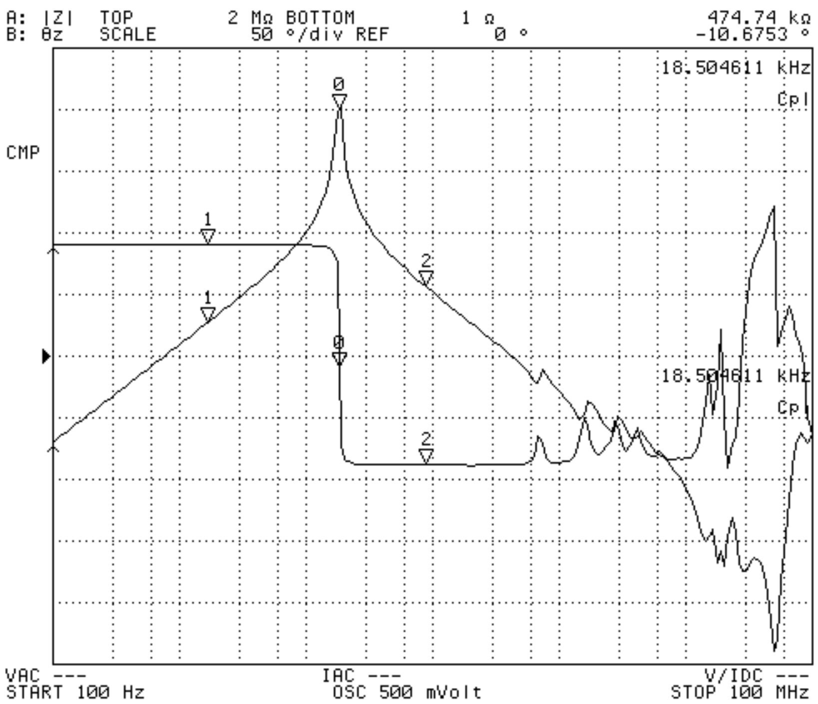
Transformer Winding Arrangement



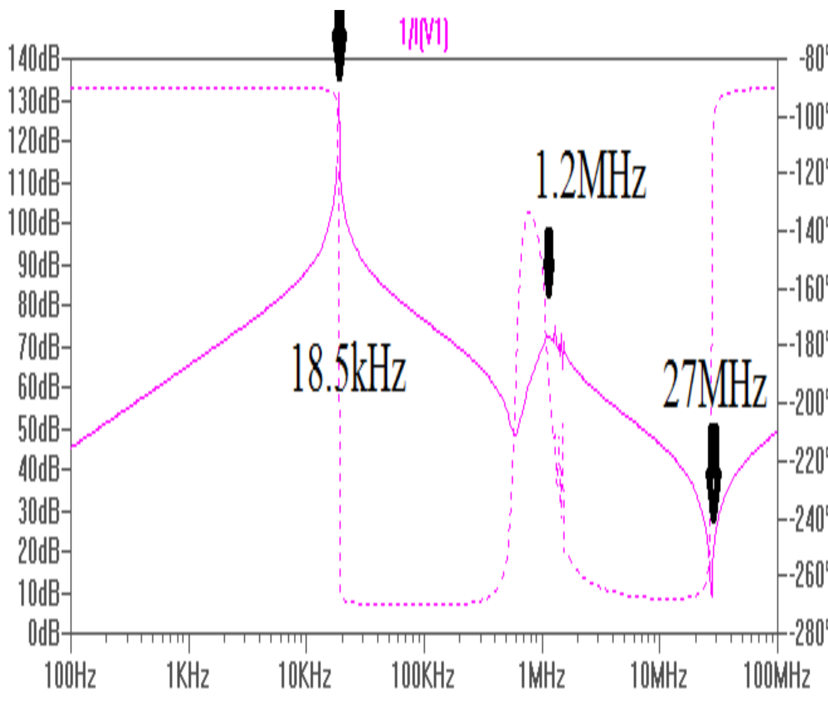
HF Transformer Equivalent Circuit Parameters with Parasitic Capacitors

Verification of Measured Equivalent Circuit using Spice Simulation

Open Circuit Secondaries



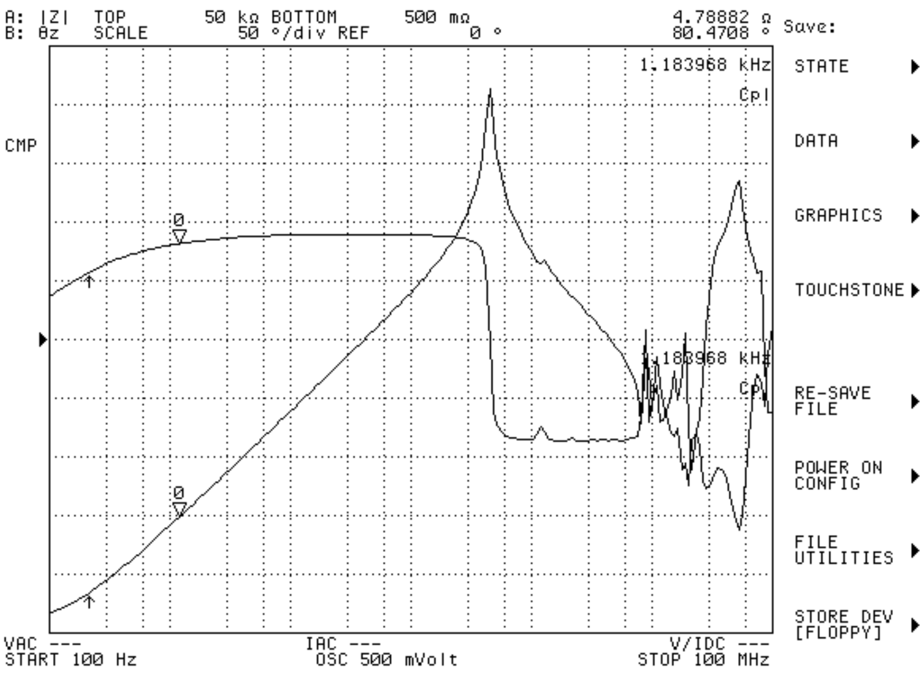
Actual Impedance Plot using Impedance Analyzer



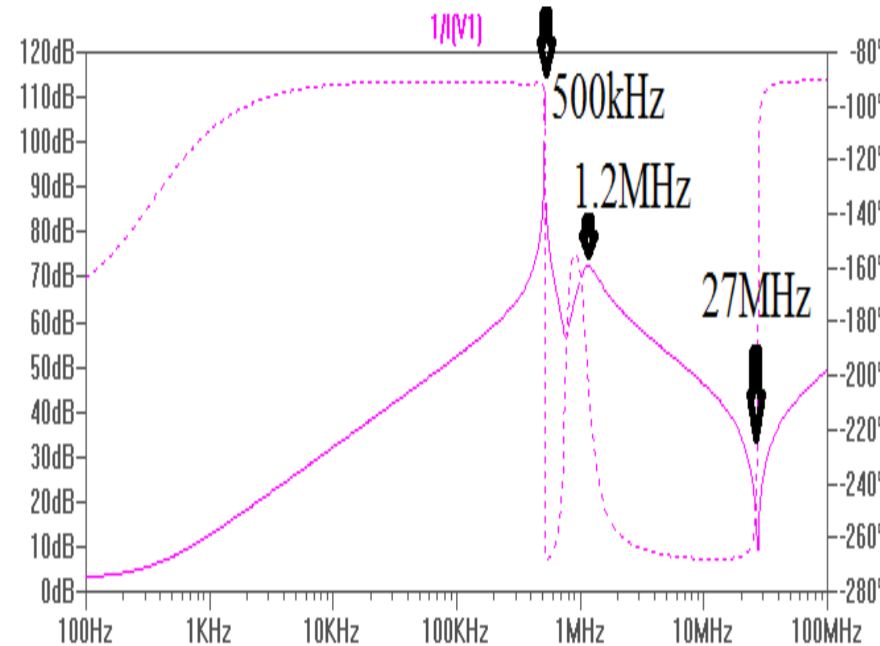
Impedance Plot using Spice Simulation

Verification of Measured Equivalent Circuit using Spice Simulation

Short Circuit Secondaries

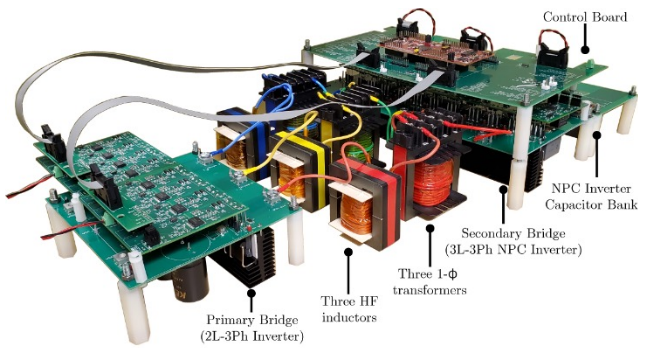


Actual Impedance Plot using Impedance Analyzer



Impedance Plot using spice Simulation

Hardware Demonstration

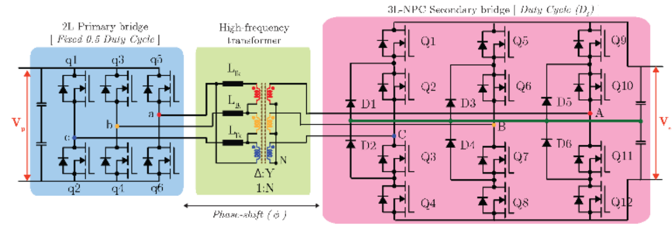


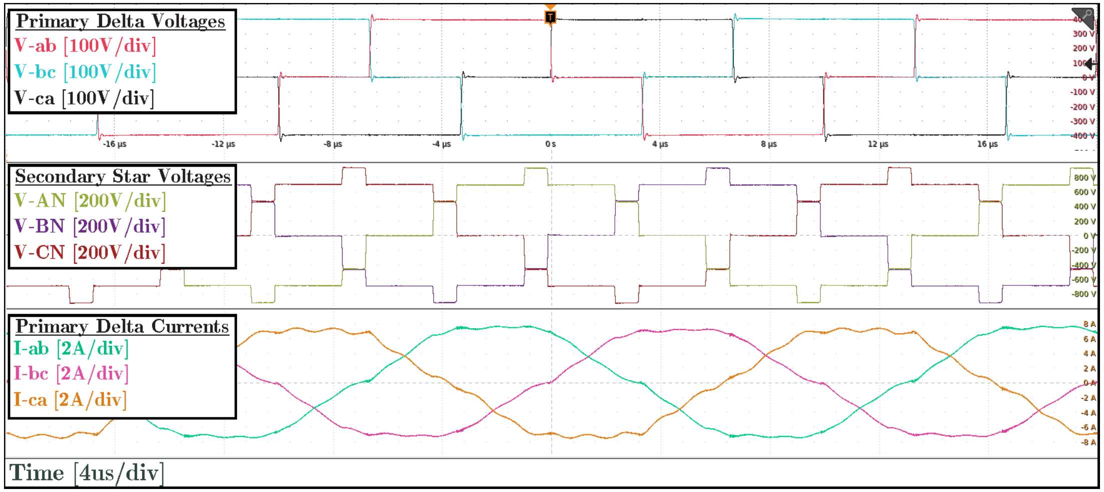
Hardware prototype of the ΔY connected 2L-3L DAB3 converter

Table: Specifications for the Hardware Setup

Parameter	Value (Unit)
Rated Power, P	5 (kW)
Primary DC-link Voltage, V_p	400 (V)
Secondary DC-link Voltage, V_s	1500 (V)
Switching frequency, f_s	50 (kHz)
Primary DC-link Capacitance, C_p	180 (μF)
Secondary DC-link Capacitance, C_s	12 (μF)
Turns Ratio, N	1.88
Inductance, L_{lk1}	140 (μH)
HFT Leakage Inductance, L_{lk2}	10 (μH)
HFT Magnetizing Inductance, L_m	3.18 (mH)

*Balancing Resistors of 50 kOhm are implemented on the secondary side.



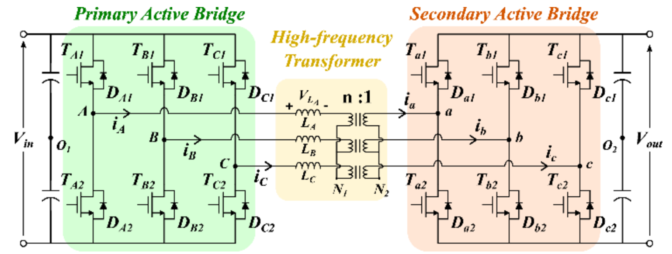


Steady-state waveforms of ΔY connected Two-level to Three-level Three Phase Dual Active Bridge (2L-3L DAB3) at a rated power of 5 kW and the operating point (D2, φ) = (0.34, 23.8°).

Open-circuit Fault in DAB3

Causes volt-sec imbalance across phase inductors

- Produces DC bias in AC phase currents (i_A, i_B, i_C)
- Effect of primary side fault >> secondary side fault



- All the results shown here are experimental results.

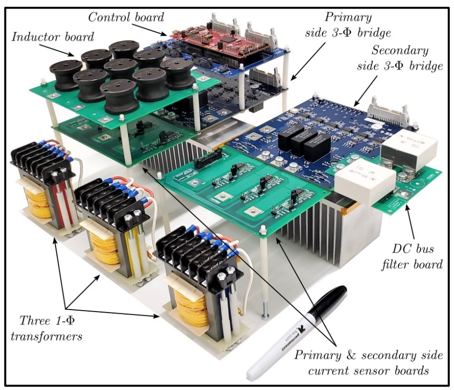
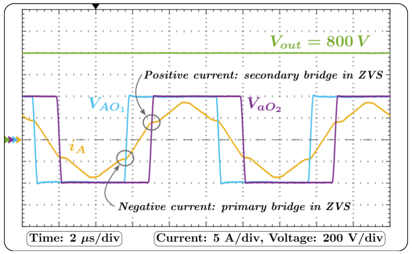


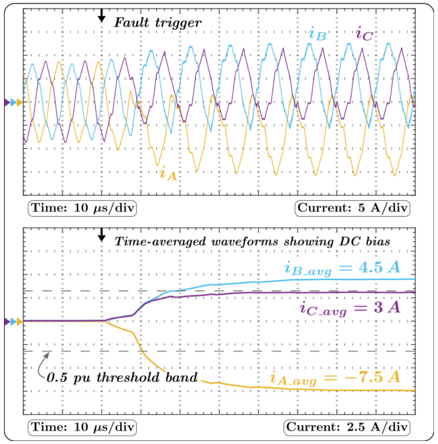
TABLE
OPERATING PARAMETERS

Parameter	Symbol	Value
Rated Power	P	5.5 kW
Input Voltage	V_{in}	800 V
Output Voltage	V_{out}	1000 V/ 800 V/ 600 V
Turns Ratio	n	1
Switching frequency	f_s	100 kHz
Phase Inductance	L_X	78 µH
Magnetizing Inductance	L_{mX}	2.5 mH

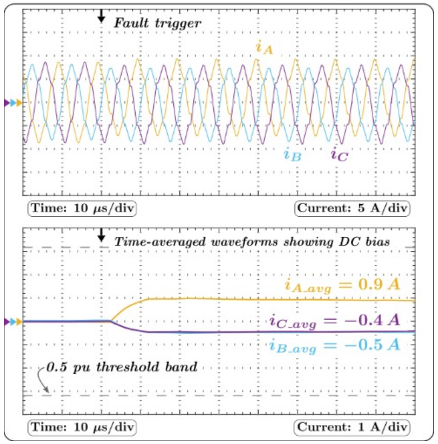
800 V - 800 V: Normal mode (ZVS) operation



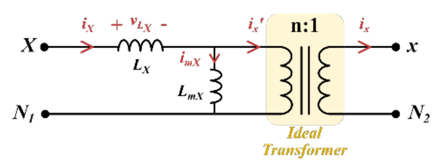
800 V - 800 V: Primary fault (T_{A1})



800 V - 800 V: Secondary fault (T_{a1})



Effect of Open-circuit Fault on the Transformer



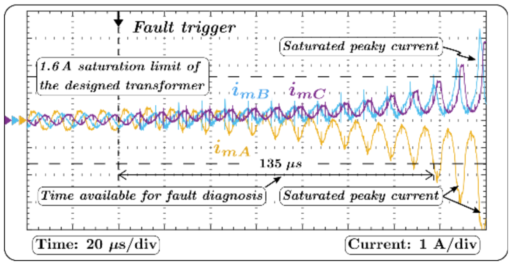
$$n \cdot (i_X - i_{mX}) = i_x$$

$$\Rightarrow i_{mX} = i_X - \frac{i_x}{n} = i_X - i_x'$$

where,

$X \in \{A, B, C\}$, and $x \in \{a, b, c\}$.

Primary fault (T_{A1}) - Magnetization currents



$$time\_available = -\tau \times \ln\left(1 - \frac{i_{sat} - i_{mA\_pk(nor)}}{I_{DC}}\right)$$

$$i_{mX\_avg} = I_{DC}(1 - e^{-t/\tau})$$

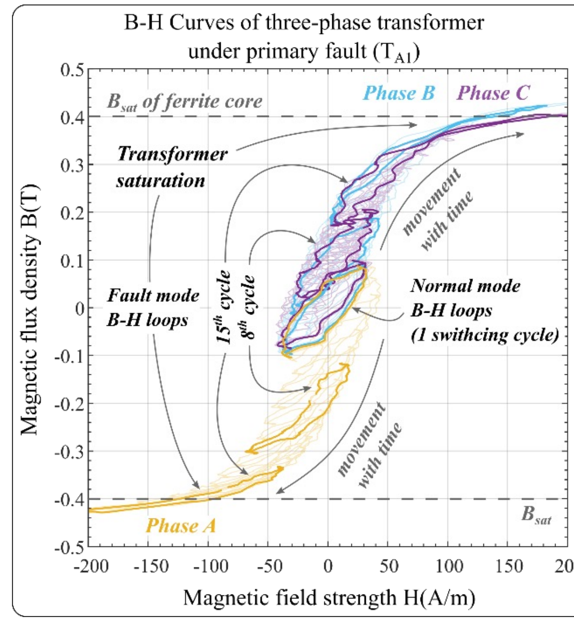
Non-trivial relationship $\left(\tau \neq \frac{L_{mX}}{R_{winding}}\right)$ $\tau = f\left(\phi, \frac{L_{mag}}{L_{leak}}, Dead\ time\right)$

No-fault mode

- No dc bias
- Balanced around (0,0)
- BH loops overlap

Fault mode

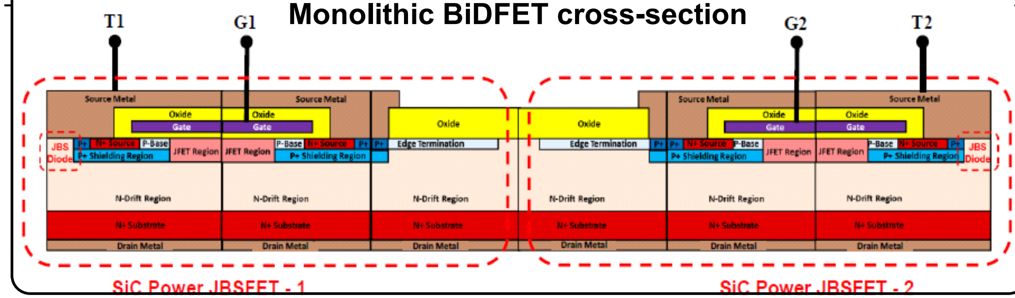
- DC bias
- Movement away from (0,0)
- Saturation!



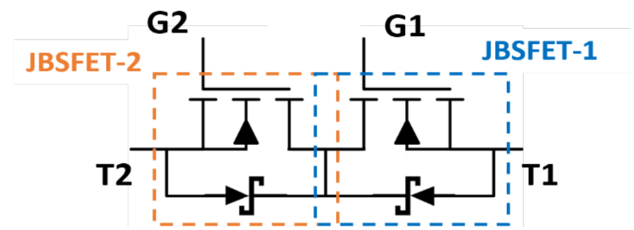
First of its kind study for isolated dc-dc converters!

Monolithic SiC-based Bidirectional FET (BiDFET) Switch: 1200V, 20A DIE

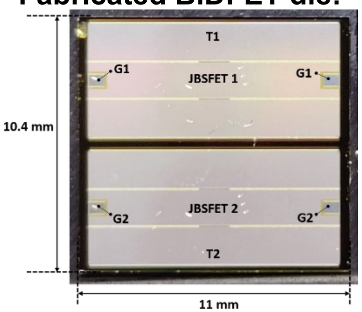
Monolithic BiDFET cross-section

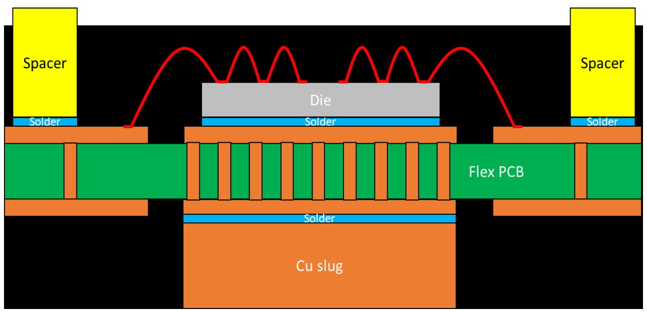


4-terminal Monolithic BiDFET circuit schematic

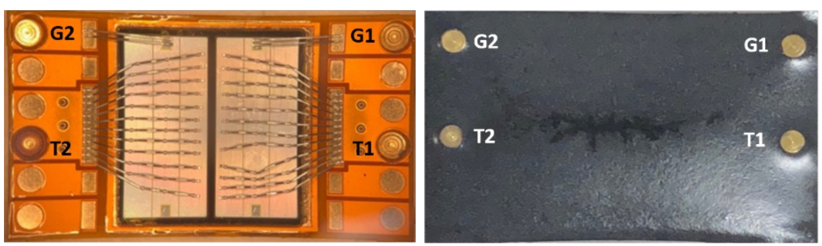


Fabricated BiDFET die:





Custom-made 4-terminal package for the BiDFET:



Comparison of fabricated 1.2 kV 20 A BiDFET with previous bidirectional switch implementations

Switch Configuration	Description	Number of components	On-State Voltage Drop (V)	Switching Loss
D1, D3, Q1, D2, D4	Diode Bridge + Asymmetric IGBT Neft & Schauder, IEEE Trans. Ind. Appl., vol. 28, pp. 546-551, 1992	5	8.6 [2 diodes + 1 IGBT]	High
Q1, Q2, D1, D2	Asymmetric IGBTs + Freewheeling diodes Moghe et al., ECCE, pp. 3848-3855, 2012	4	5.8 [1 diode + 1 IGBT]	High
Q1, D2, D1, Q2	Back-to-back symmetric IGBTs Takei et al., ISPSD, pp. 413-416, 2001	2	2.2 [1 symmetric IGBT]	Very High
Q1, Q2, D1, D2	SiC Power MOSFETs + JBS diodes Safari et al., IEEE Trans. Power Electron., vol. 29, no. 5, pp. 2584-2596, 2014	4	3.1 [1 diode + 1 MOSFET]	Low
D1, Q1, D2, D3, D4, Q2	Back-to-back SiC Power MOSFETs + antiparallel and series JBS diodes Ahmed et al., IEEE Trans. Power Electron., vol. 32, pp. 1232-1244, 2017	6	3.1 [1 diode + 1 MOSFET]	Low
	Four-terminal SiC Monolithic BiDFET	1	1.0 [1 BiDFET]	Low

Monolithic SiC BiDFET enabled grid-connected power conversion system for PV

- *Cyclo-converter based 1-phase and 3-phase grid connected PV inverter enabled by Monolithically integrated SiC 4-QPS at 1200V, 10-25A*

** Advanced packaging of single switch module and half-bridge switch module*

- **Elimination of DC electrolytic capacitors**
- Capacitors required are filter capacitors which are film capacitors (small VA rated, available for high ripple current with low ESR)
- All switches shown can be SiC 4-QPS – hence standardized modules

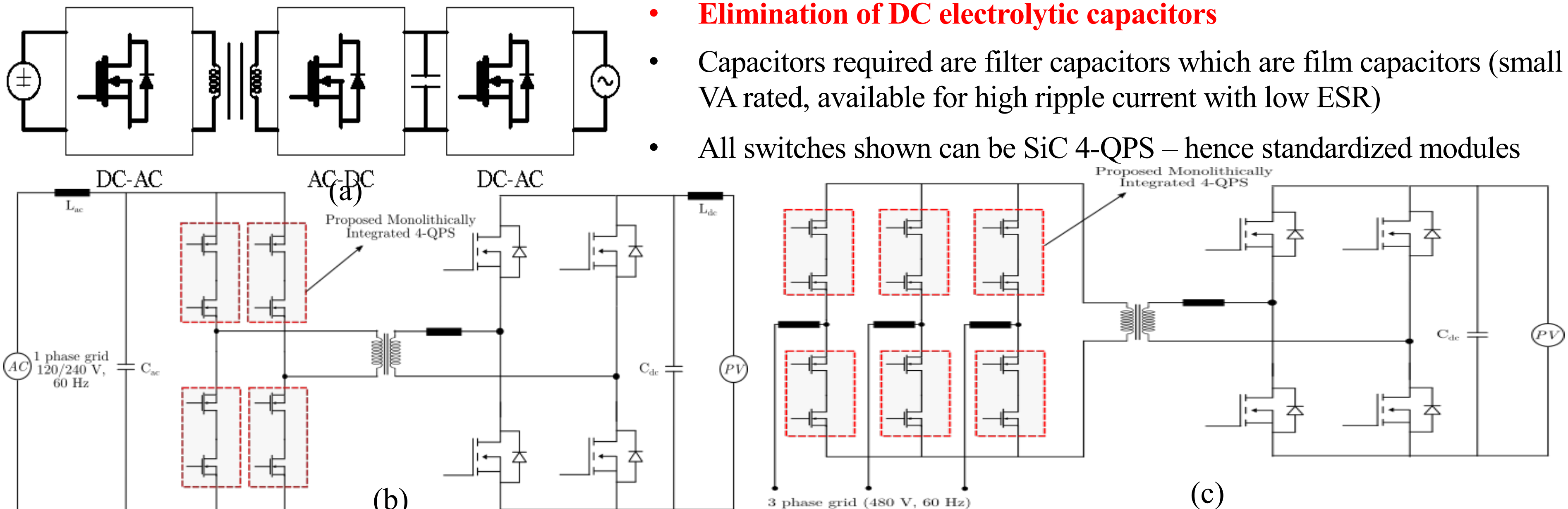
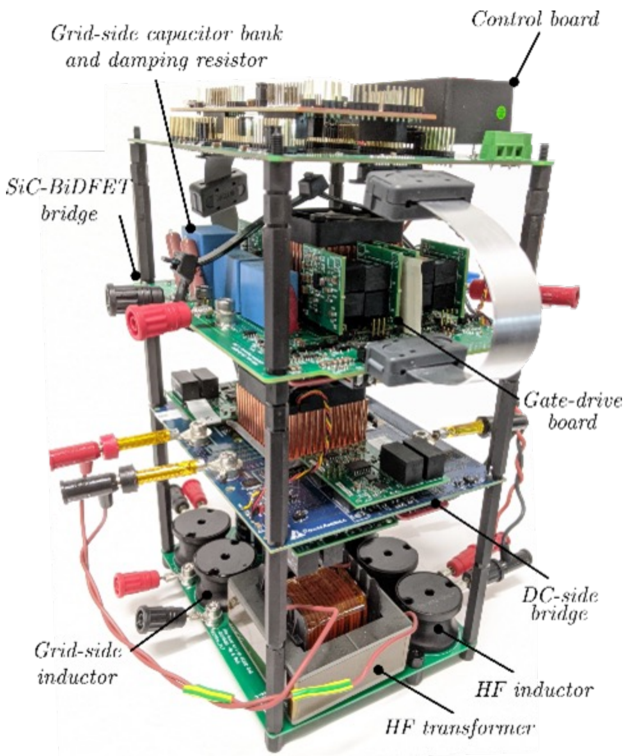
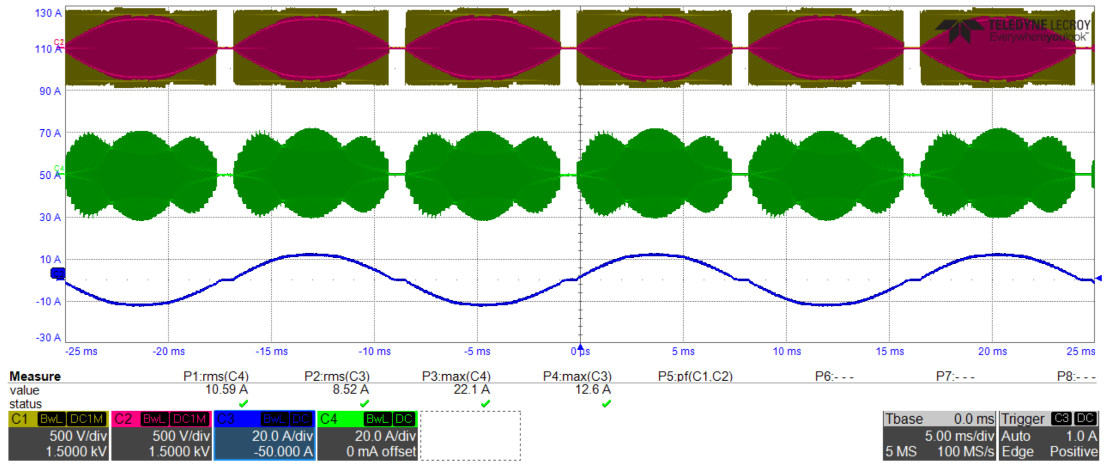


Figure 1: (a) Conventional power architecture for DC-AC conversion, (b) High-frequency link single phase inverter using 4-QPS enabled cyclo-converter (c) High-frequency link 3-phase inverter using 4-QPS enabled cyclo-converter.

2.1 kW, 1-ph grid connected converter prototype enabled by 1200V, 20A SiC BiDFET



Hardware prototype of the AC/DC DAB converter



High frequency transformer voltages/current and grid side current at 100% load at 240 V AC voltage.

- Full load operation at 400V input, 240V RMS output at 2.1 kW
- Total harmonic distortion in grid-side current: 4.8%
- Power factor: 0.9998

BiDFET (or 4-QPS) based AC-DC converter development

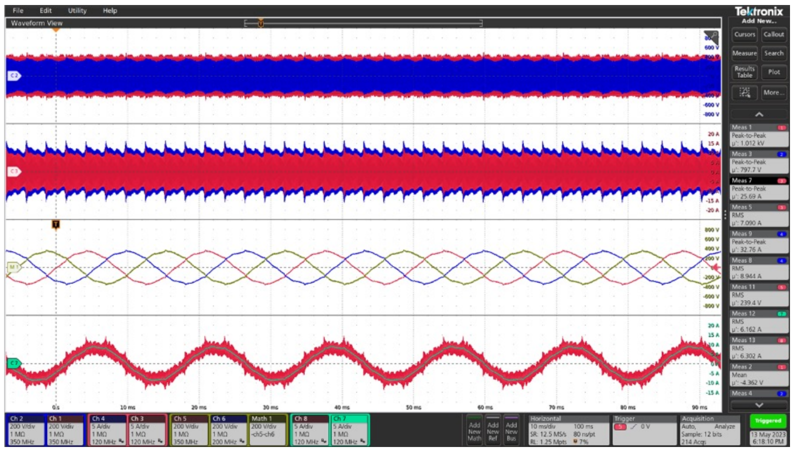
10 kW, 3-ph PV inverter prototype enabled by 1200V, 20A BiDFET half-bridge module

DC side transformer voltage
AC side transformer voltage

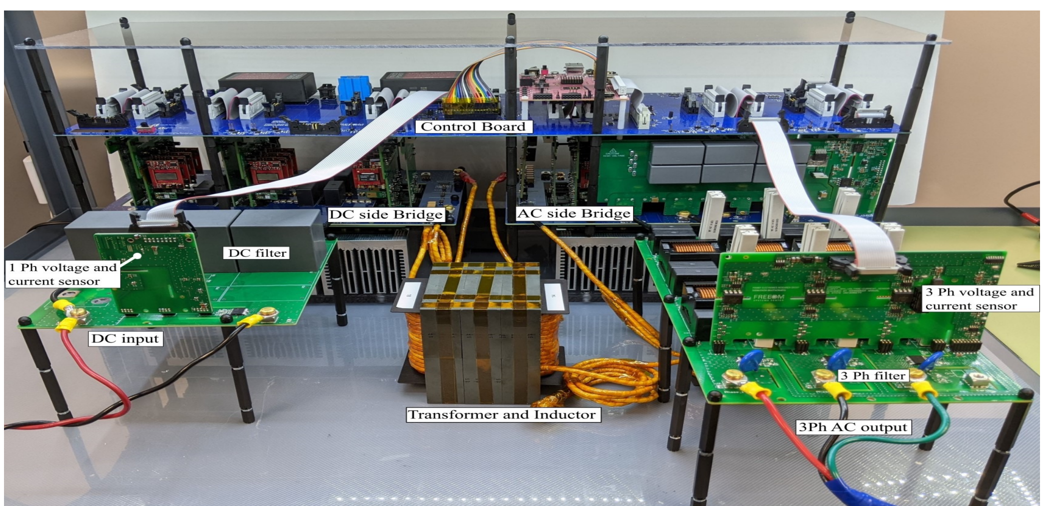
DC side transformer current
AC side transformer current

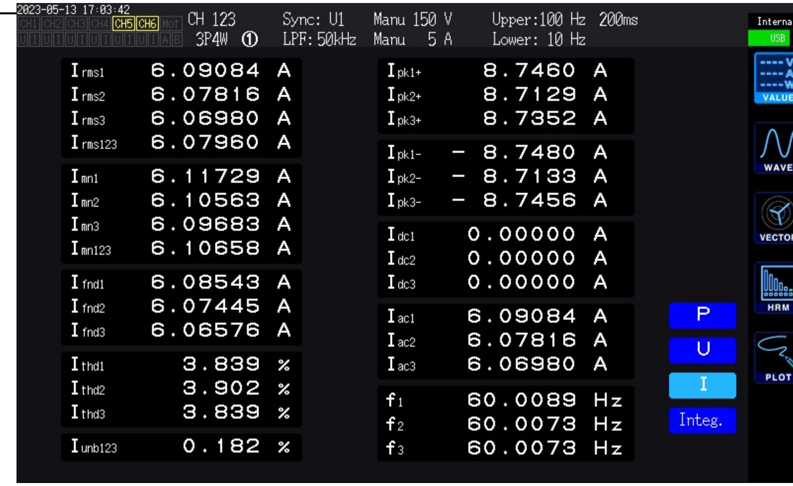
V_{AB}
V_{BC}
V_{CA}

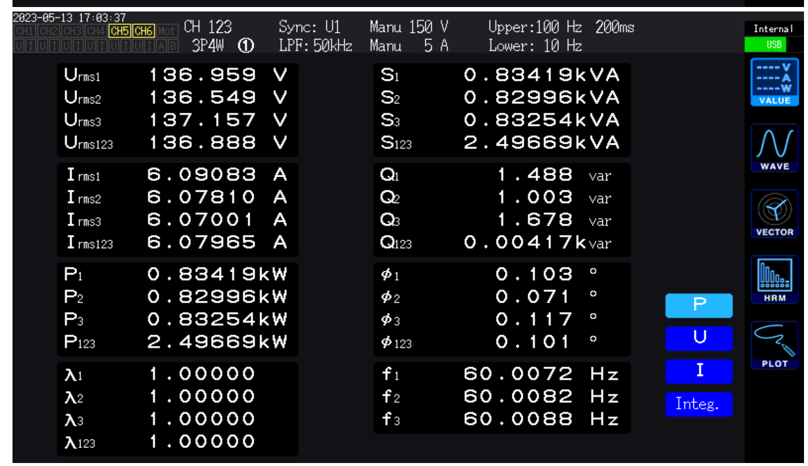
i_A before EMI filter
i_A after EMI filter



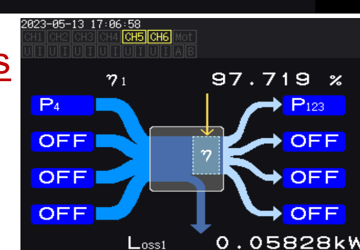
Operating waveforms at 240 V, 2.5 kW AC output with 400 V DC input.
(AC current THD = 3.9%)
[BiDFET module based phase-leg PCB]







Efficiency and AC currents THD as measured using Hioki Power Analyzer PW6001.



BiDFET (or 4-QPS) based AC-DC converter development

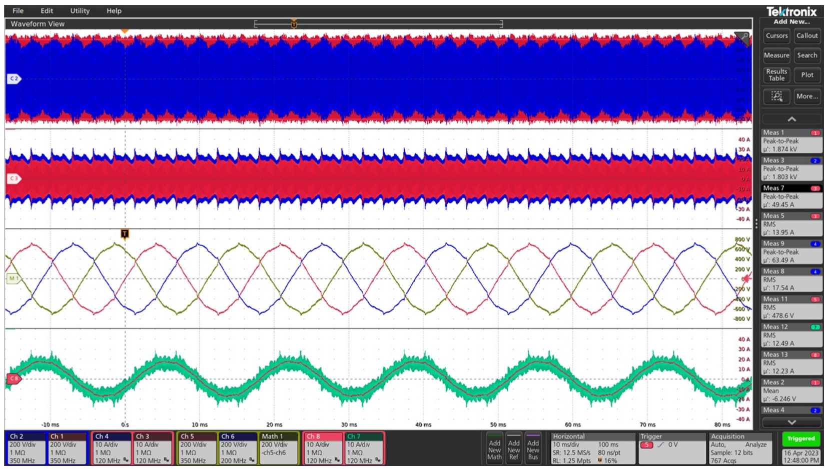
10 kW, 3-ph PV inverter prototype enabled by 1200V, 20A BiDFET half-bridge module

DC side transformer voltage
AC side transformer voltage

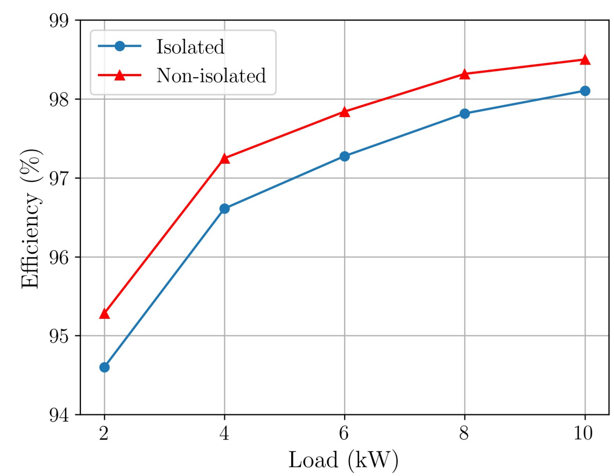
DC side transformer current
AC side transformer current

V_{AB}
V_{BC}
V_{CA}

i_A before EMI filter
i_A after EMI filter

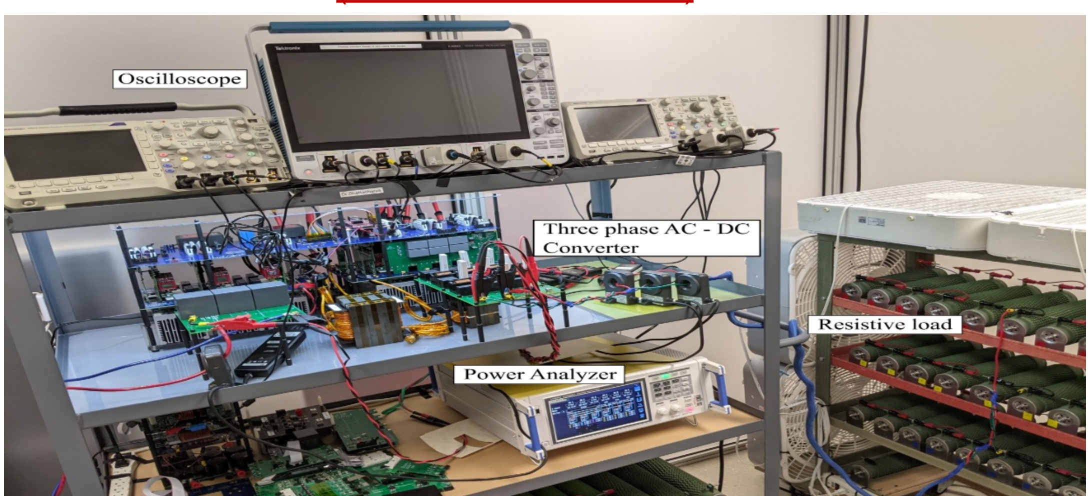


Operating waveforms at 480 V, 10 kW AC output with 800 V DC input. (AC current THD = 3.5%)



Efficiency variation with load.

Around 0.4% efficiency is forgone to achieve isolation.



- **Collaboration with industry – please join AMPED**
- **Reference designs for different applications**
- **Applications: EV Charging, EMI filters, CMC filters, DC-DC converters, Server power supplies for Data Centers**

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

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

Email: sbhatta4@ncsu.edu

Thank You!!!

Questions

- Ack to all my PhD students, UG Research students and Post-Doctoral Scholars in my group