DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Multi-Port Modular Medium-Voltage (M3) Transactive Power Electronics Energy Hub

PRINCIPAL INVESTIGATOR

Dr. Madhu Chinthavali, ORNL

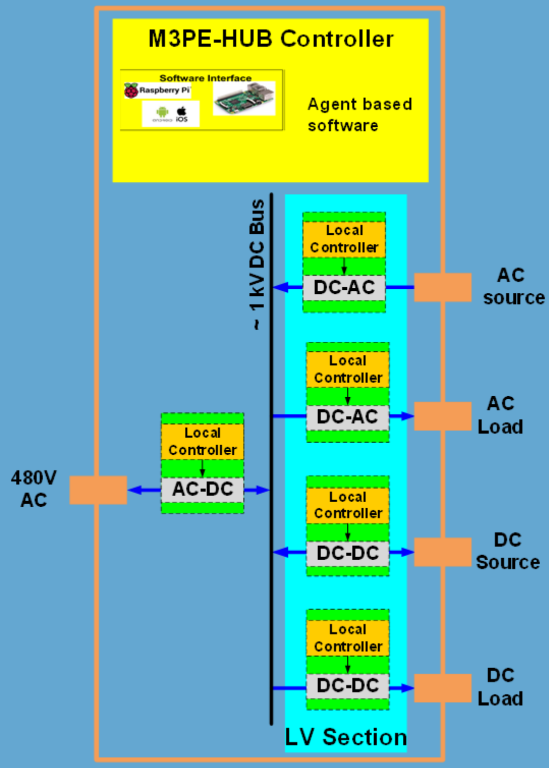
PROJECT SUMMARY

The goal for this project is to design, develop, and demonstrate foundational technologies and capabilities for multiport power electronics energy hubs (a.k.a. HUB) that can serve as intelligent devices to coordinate and control several different sources and loads

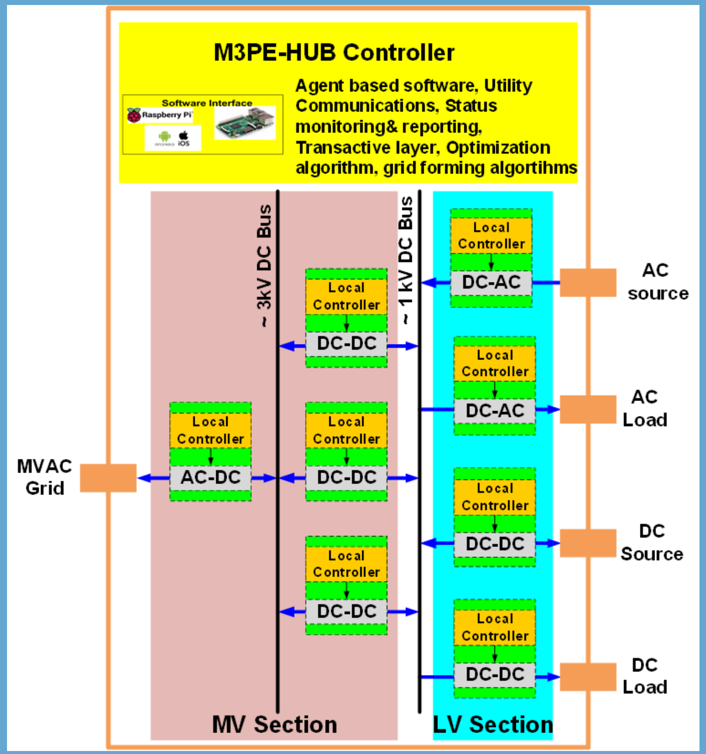
Objective 1: Design and build a modular, grid-tied integrated three-phase, minimum **three port 480 V ac power electronic hardware prototype** with open-source controls, communication, protection and intelligence to demonstrate the value of the HUB concept.

Objective 2: Develop **CHIL** interface connected with a **real-time feeder model** for the evaluation of a **single M3PE-HUB** suitable for multi-time scale CHIL simulations, and scaling efforts to include multiple HUBs.

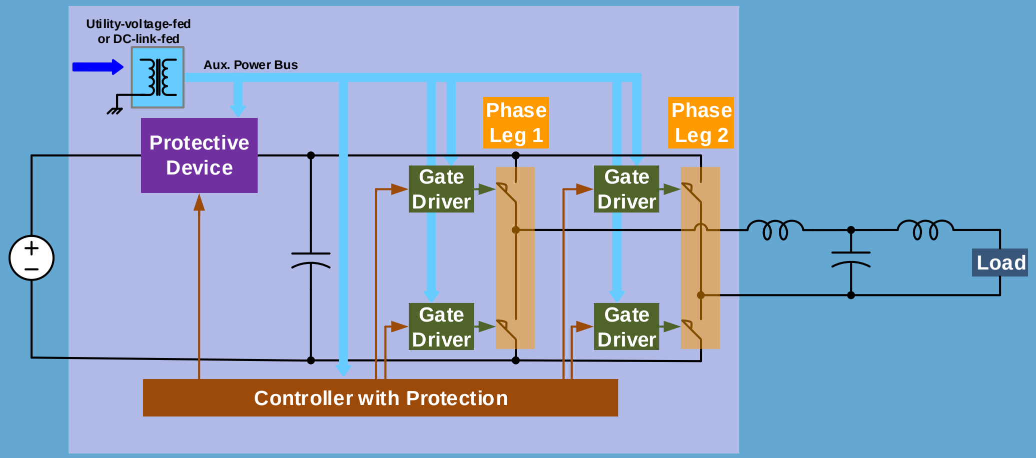
Objective 3: Develop medium voltage power stage building blocks with advanced device packages to address critical technology gaps for direct grid-tied medium voltage power electronic converter systems.



Low Voltage HUB



Medium Voltage HUB



Medium Voltage H-Bridge Power Stage

The Numbers

DOE PROGRAM OFFICE:
OE – Transformer Resilience and Advanced Components (TRAC)

FUNDING OPPORTUNITY:
GMLC Lab Call

LOCATION:
Knoxville, Tennessee

PROJECT TERM:
02/15/2020 to 2/15/2023

PROJECT STATUS:
Incomplete

AWARD AMOUNT (DOE CONTRIBUTION):
$5.3 M

AWARDEE CONTRIBUTION (COST SHARE):
$1.3 M

PARTNERS:
Industry and University Partners

University Partners

Laboratories

Laboratory	Focus
Oak Ridge National Laboratory	• High voltage packaging, hardware prototype and smart software interface development • Magnetics Hardware Development
NREL Transforming ENERGY	• System level grid controller development and CHIL
Pacific Northwest NATIONAL LABORATORY	• Transactive coordination and grid-forming inverter control strategies development

Partners		
Industry Vendors	SEMIKRON innovation+service, MICROCHIP, POWERAMERICA, FLEXPOWER	Semikron, Microchip, Power America, Flex Power
University	CURENT, NC STATE UNIVERSITY	CURENT (UTK), NCSU
Utilities	Southern Company, NRECA America's Electric Cooperatives, Southern California EDISON Energy for What's Ahead	Southern Company, NRECA, SCE

Team - ORNL

Madhu Chinthavali
Power Electronics Systems Architecture

Brian Rowden
Hardware design and prototyping

Michael Starke, PhD
Systems and Software Architect

Steven Campbell
System Integration & Testing

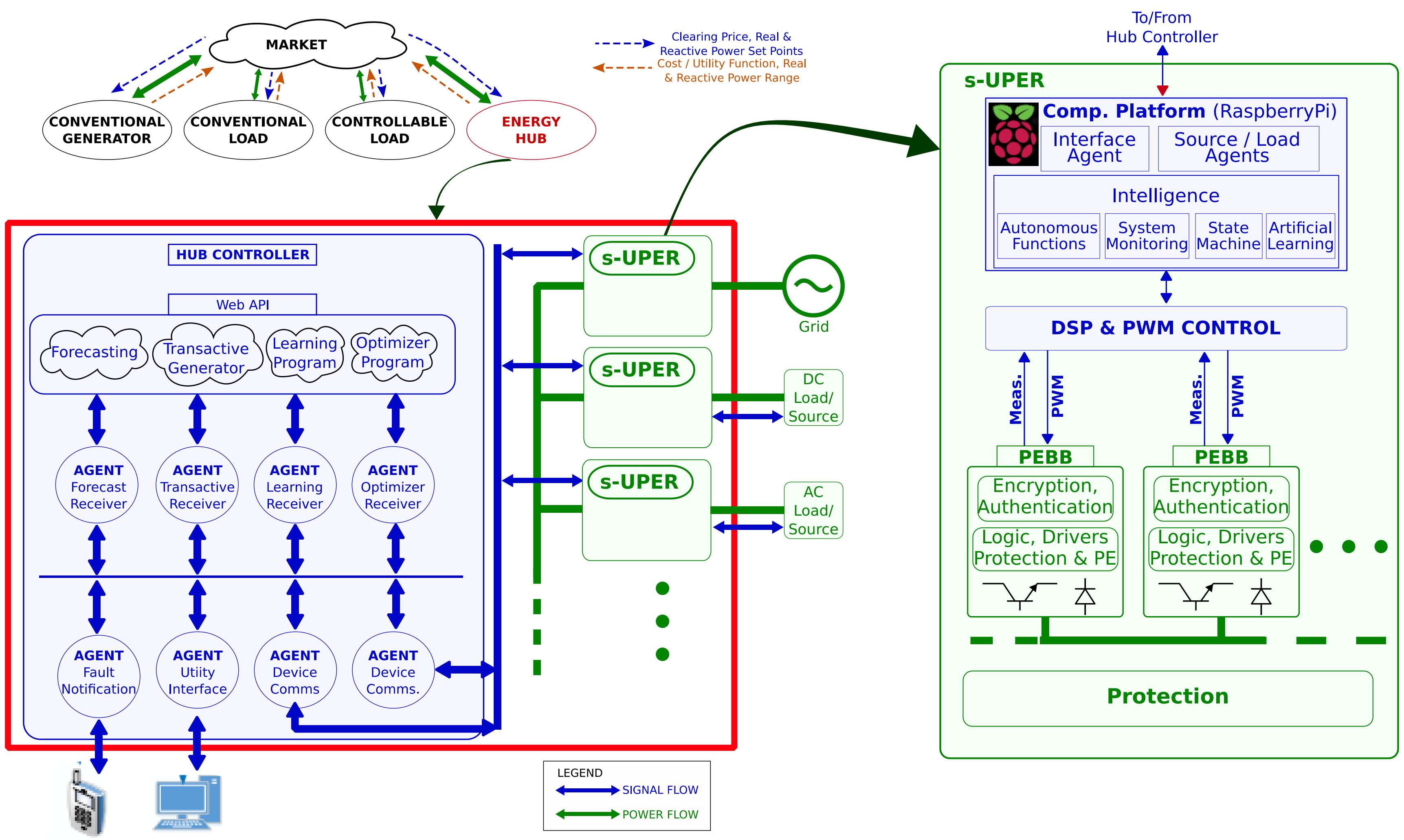
Jonathan Harter
Hardware development

Aswad Adib
Topology simulation

Rafal Wojda
Magnetics Design

Innovation: HUB Architecture

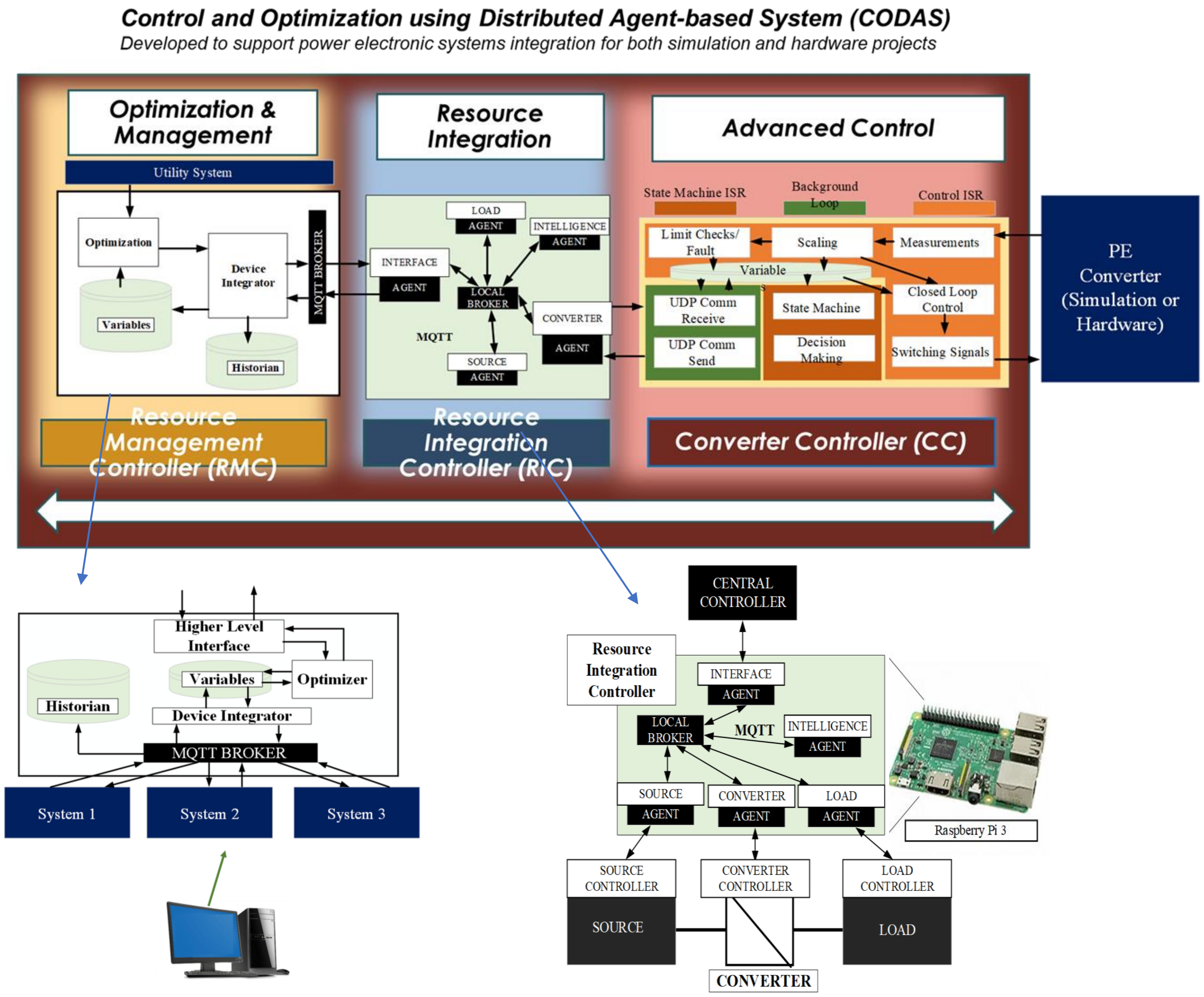
System-level Control



Features of the Modular Multiport Medium Voltage PE HUB (M3PE-HUB) platform

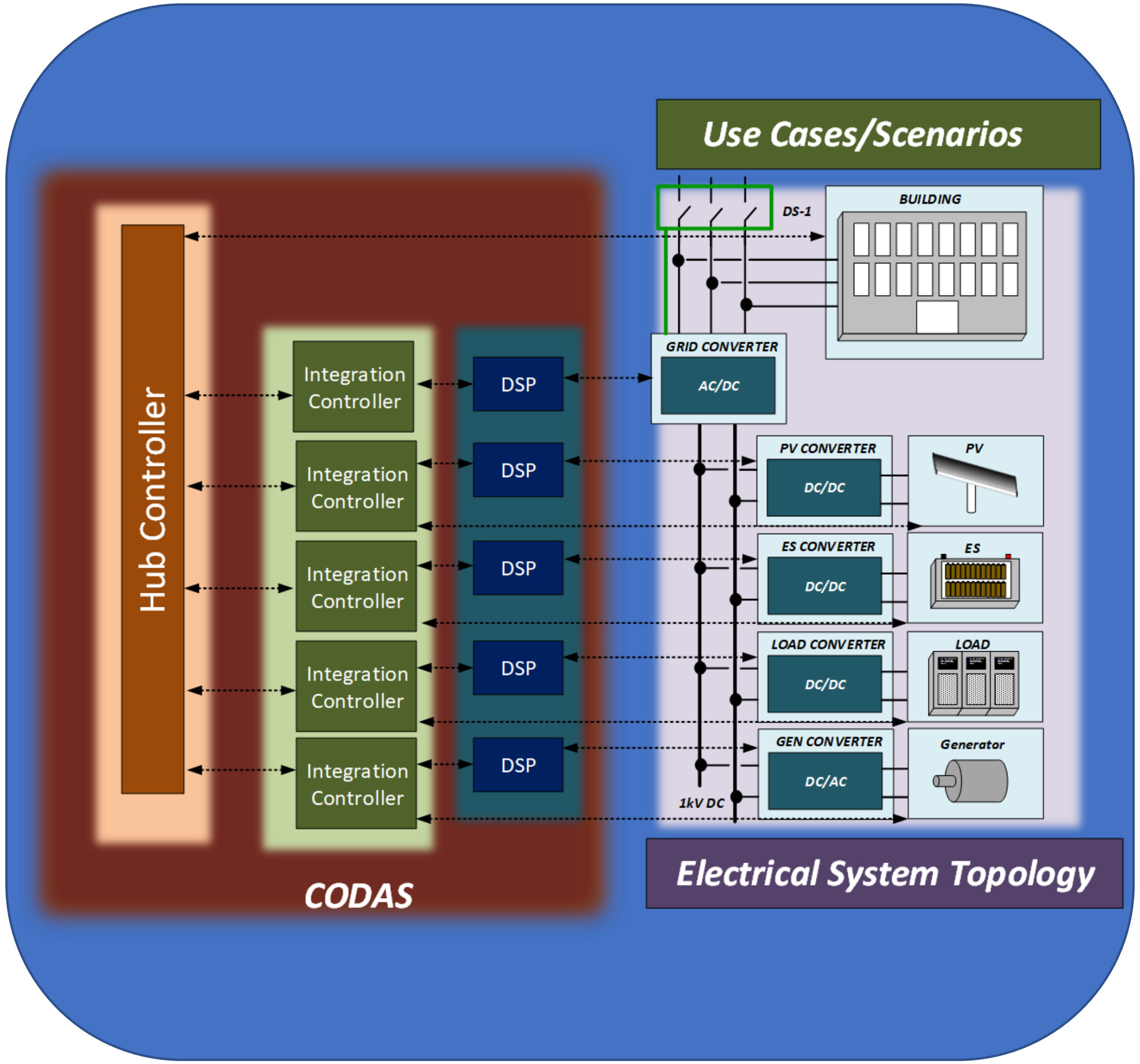
- **Automation of energy flow** between multiple sources and loads with on-line optimization
- **Single transactive node** that enables market participation or integration into large centralized systems
- **Grid services:** harmonic distortion management, unbalance management, voltage support, outage restoration support and ride-through etc. based on the HUB location on the feeder.
- Increase in grid reliability and resilience: enabling advanced **de-centralized grid control architecture**
- **Interoperable/Vendor agnostic**: minimizing the number of DER interfaces, single point of communication for utility management systems
- **Modular and scalable agent-based software platform** with real-time dynamic control of device systems to support the grid

Innovation : HUB Controller Architecture



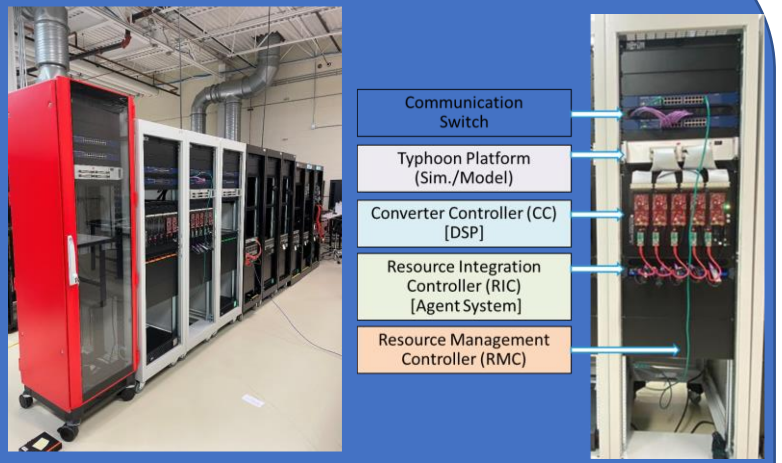
- Devices support multiple levels of hierarchy.
- Simulations represent full switching models of power electronic devices and auxiliary equip
- Physical control is performed by DSP/FPGA controllers interfacing an integration computation node.
- Computer node integrates other components (sources and loads) with power electronic system via communications and agent system.
- Central controller registers devices with automatic configuration system
- System configuration is driven by converter system capabilities and interconnected resources (AUTOMATIC through Plug-and-Play Communication Framework)

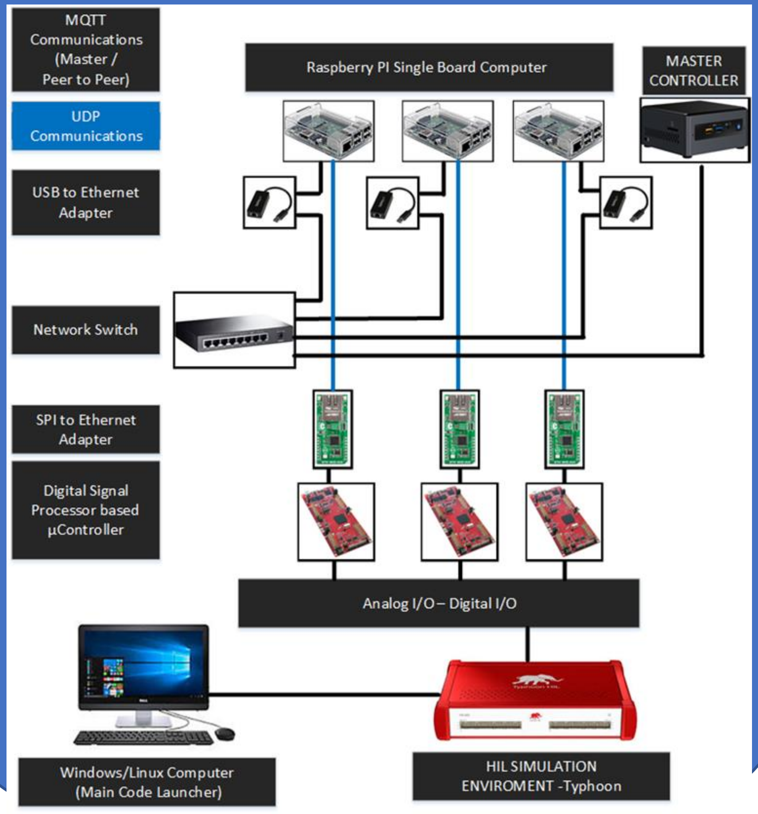
Innovation Update: Simulation Framework for LV-HUB



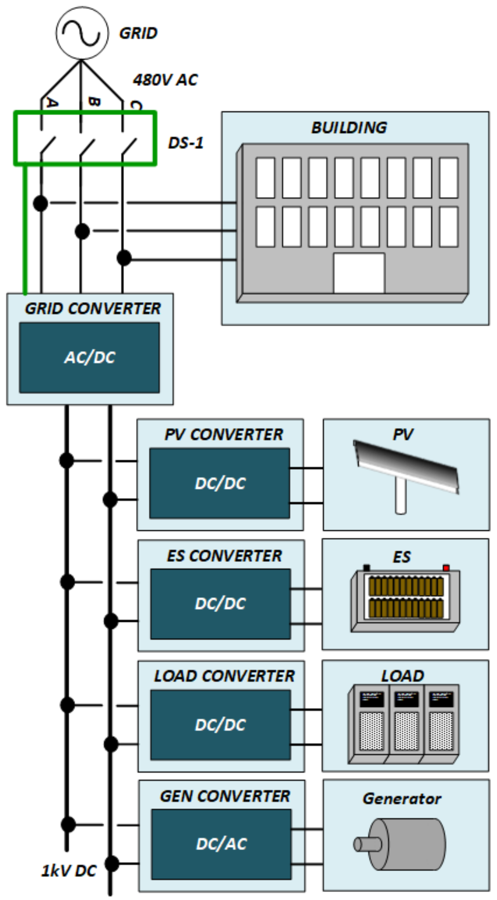
- Multi port LV HUB: Grid inverter with 3 50 kW DC-DC converters.
- Same controller hardware and communication framework as applied to hardware testing.
- Used in early development stages to verify stability of optimization, controls, communications, and systems integration.
- All hardware systems are modeled including pre-charge and contactor circuitry to ensure start-up and shutdown sequences and protection systems are validated.

CHIL Validation in GRID-C @ORNL



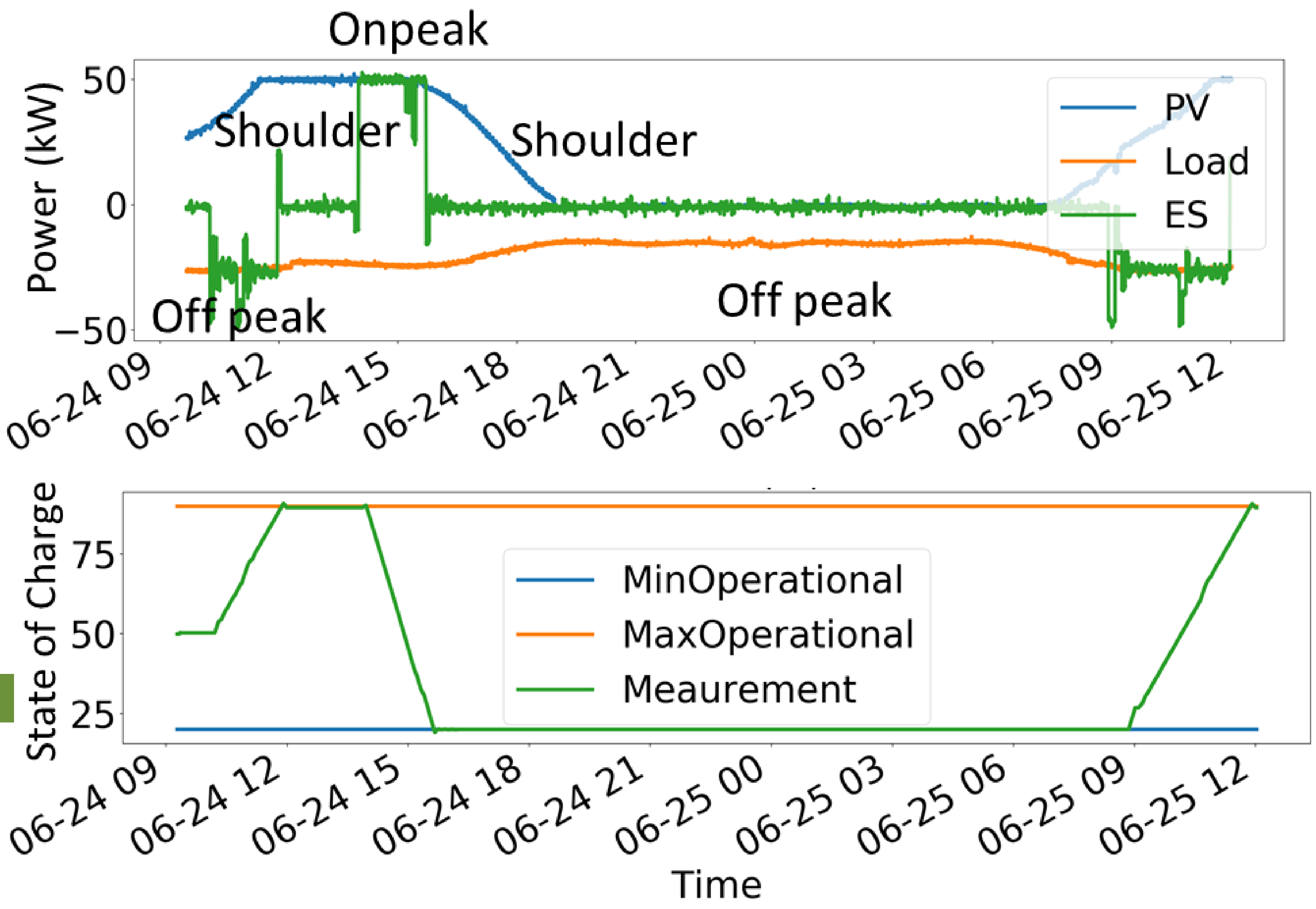


Innovation Update: Use Case Simulation in CHIL platform



LV-HUB Use Case Architecture

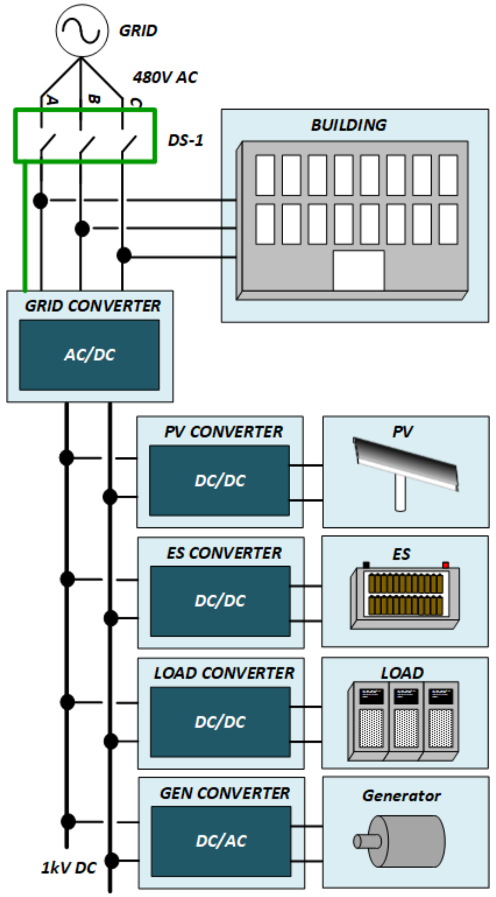
ONGRID Normal Operations



System Configuration	DSP Control Option	
	Input	Output
Grid Converter (DC/AC)	Vdcreg	Grid Following Q, ~~Grid Forming (V/F)~~
PV Converter (DC/DC)	MPPT	
ES Converter (DC/DC)		P, ~~Vdcreg~~
Load Converter (DC/DC)	Vdcreg	

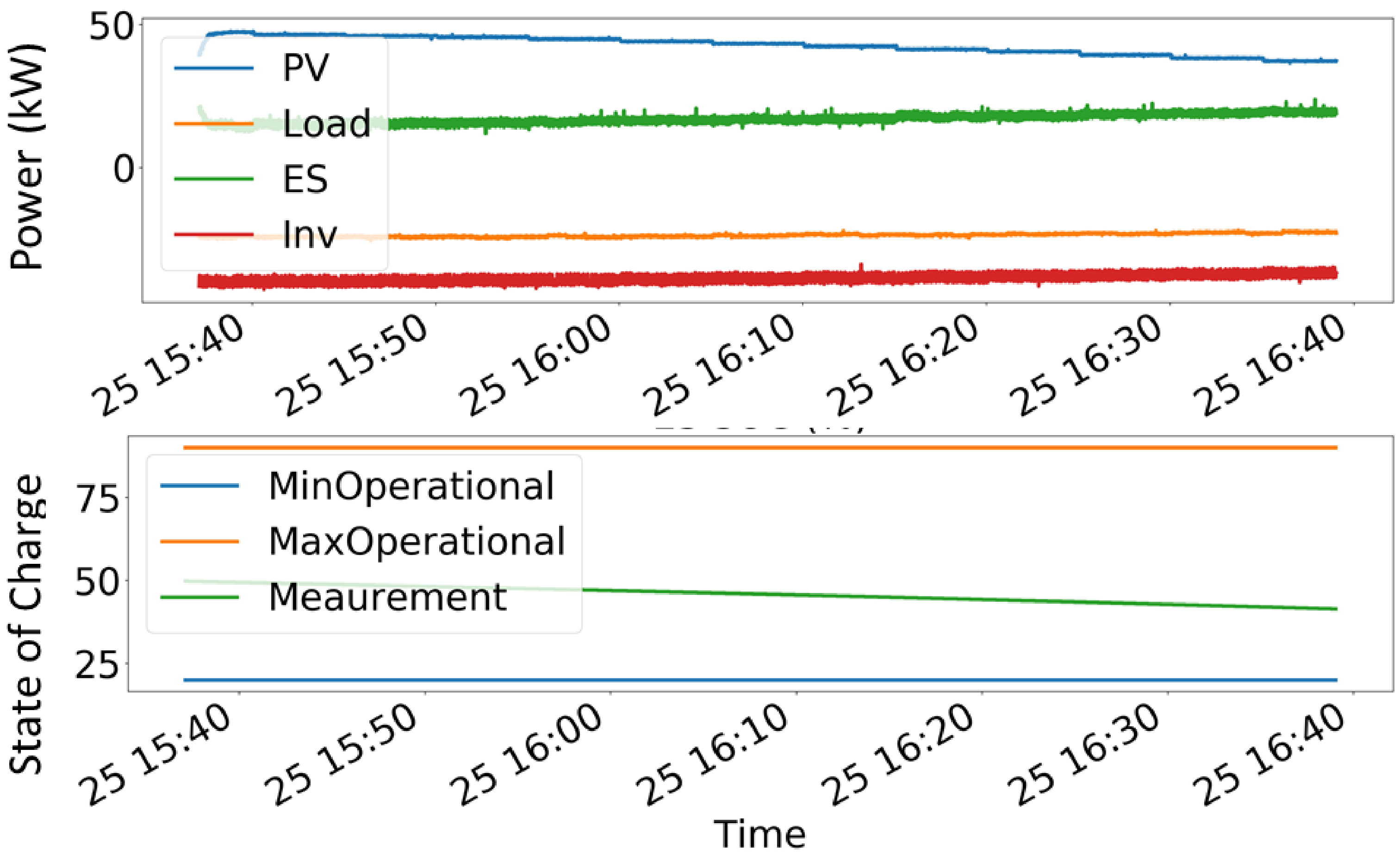
	Price	Time
On Peak	\$0.122/kwh	3PM-8PM
Shoulder	\$0.0625/kwh	1PM-3PM, 8PM-10PM
Off Peak	\$0.0235/kwh	10PM-1PM

Innovation Update: Use Case Simulation in CHIL platform



LV-HUB Use Case Architecture

OFF GRID Normal Operations



System Configuration	DSP Control Option	
	Input	Output
Grid Converter (DC/AC)	~~Vdcreg~~	~~Grid Following~~ ~~Q~~, Grid Forming (V/F)
PV Converter (DC/DC)	MPPT	
ES Converter (DC/DC)		~~P~~, Vdcreg
Load Converter (DC/DC)	Vdcreg	

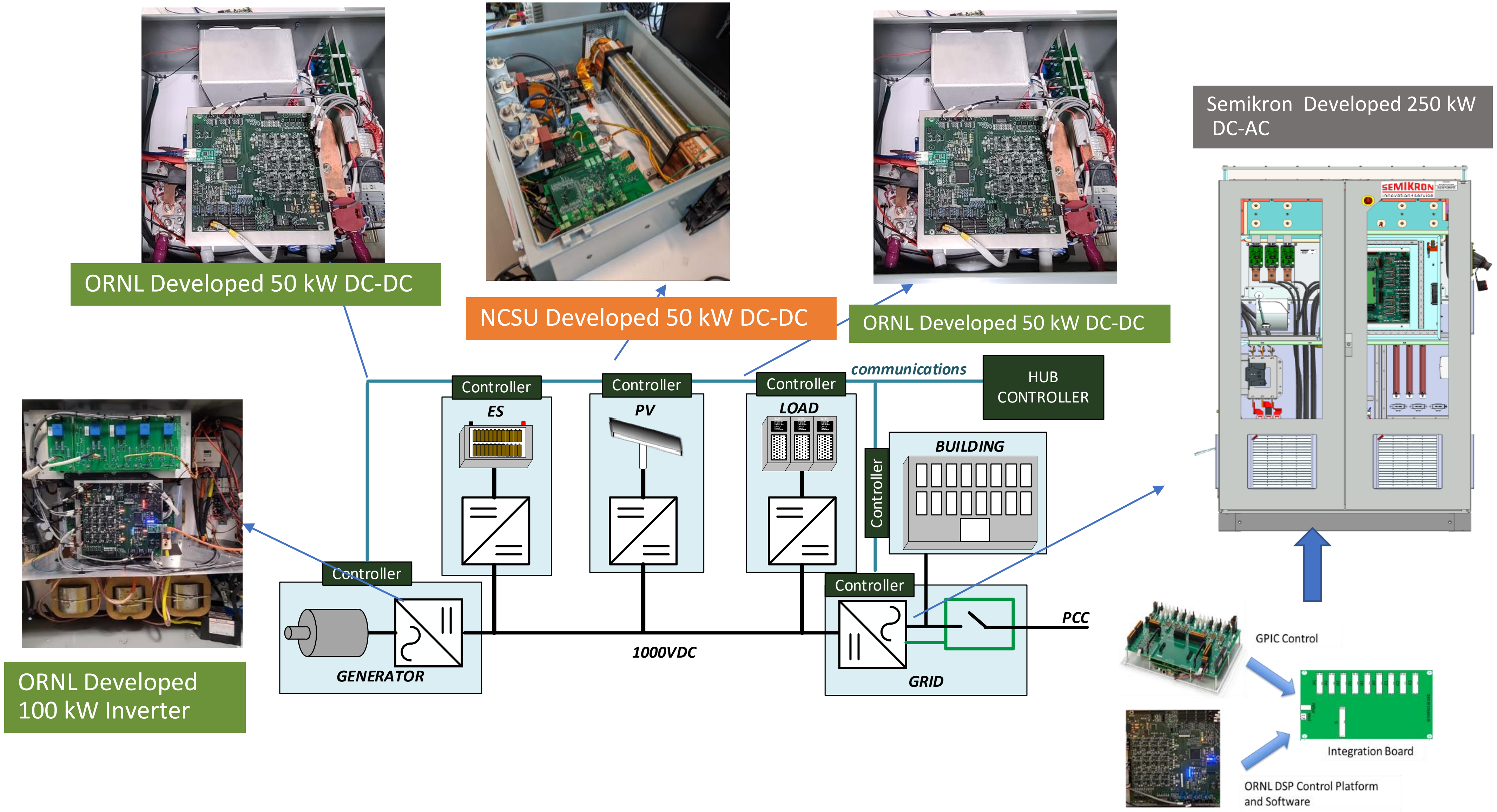
Innovation Update : Hardware Prototypes

<u>PE Hardware baseline LV HUB Hardware:</u>

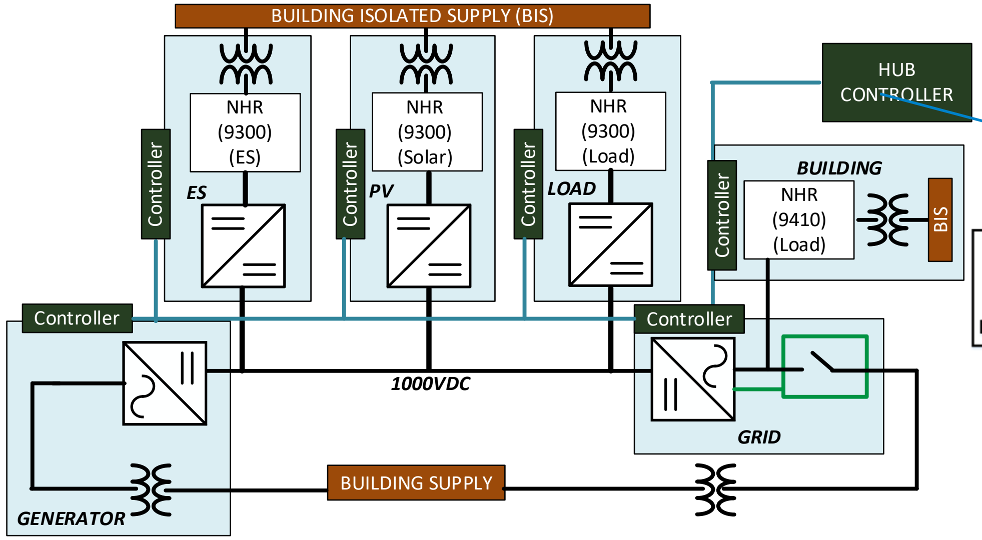
- 3 x 50kW DC/DC Converters (ORNL)
- 1 Grid Inverter 100 kW(ORNL)

<u>Final LV HUB Hardware</u>

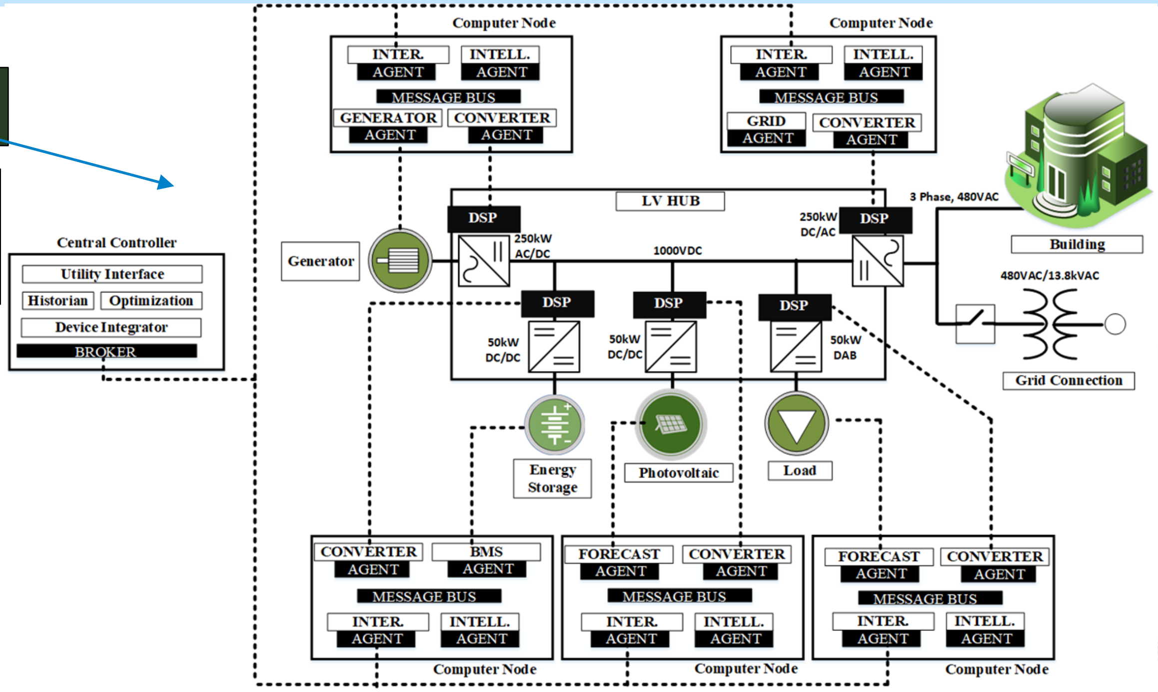
- 2 x 50kW DC/DC Converters (ORNL)
- 1 x 50kW DC/DC(DAB) Converter (NCSU)
- 1x 250kW AC/DC Inverters (Semikron)



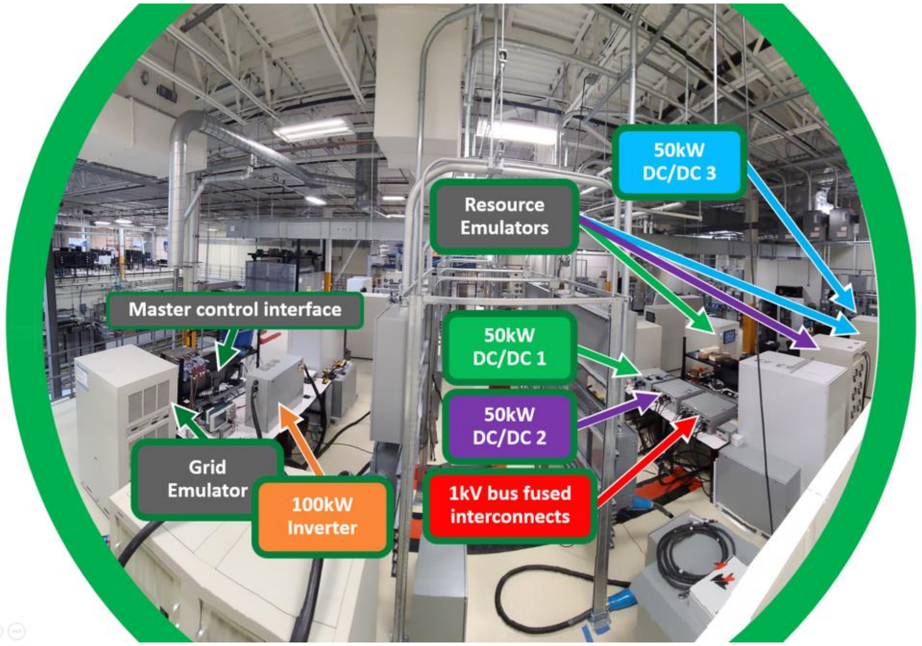
Innovation Update : Hardware Testbed in GRID-C @ ORNL

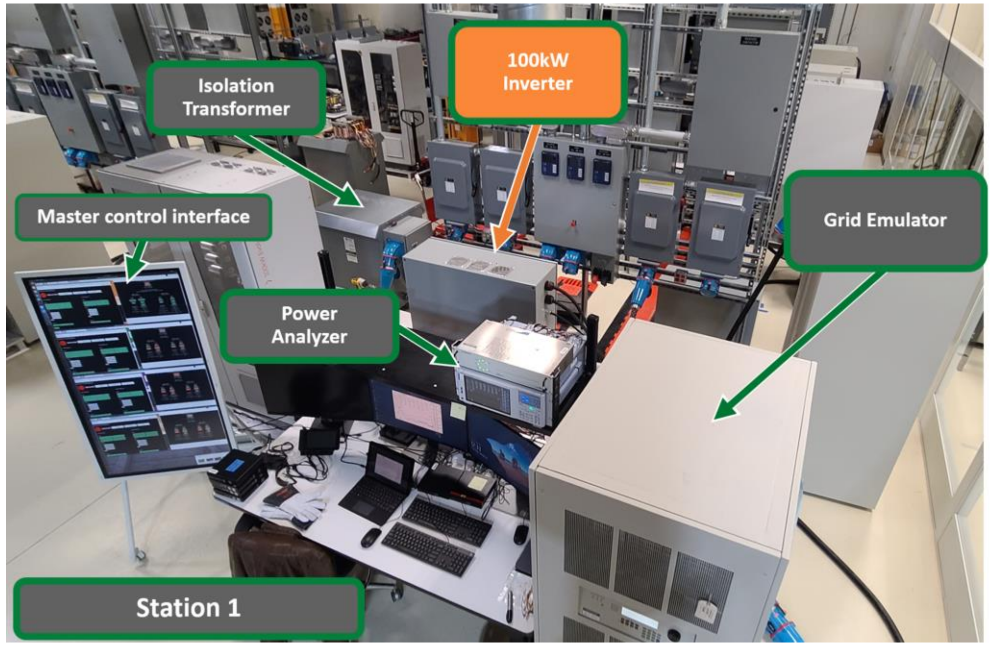


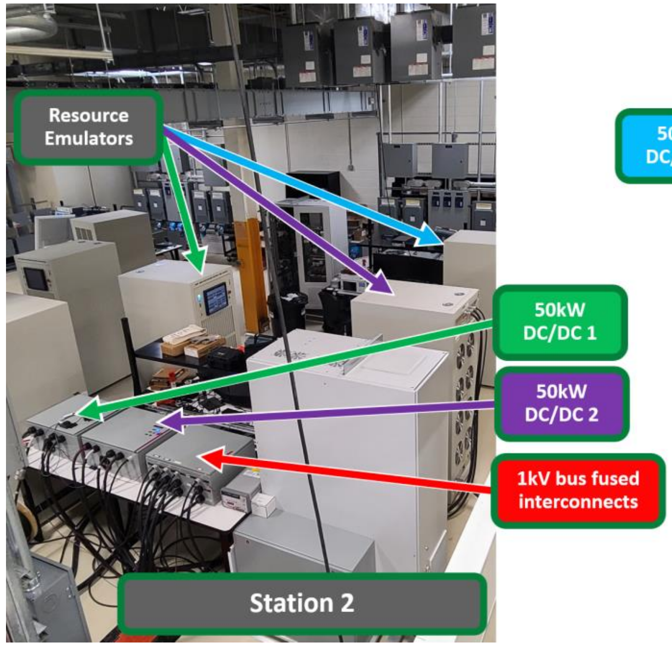
LV-HUB Test Bed Architecture

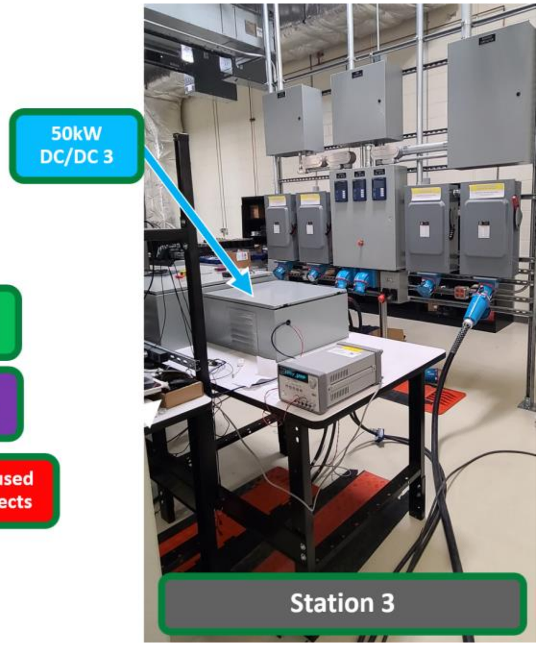


LV-HUB Controller Platform



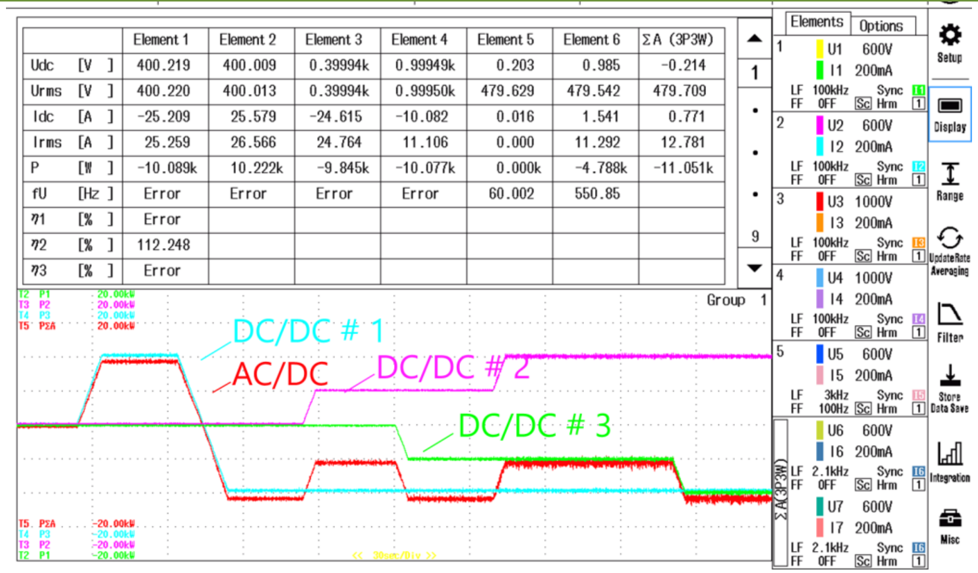




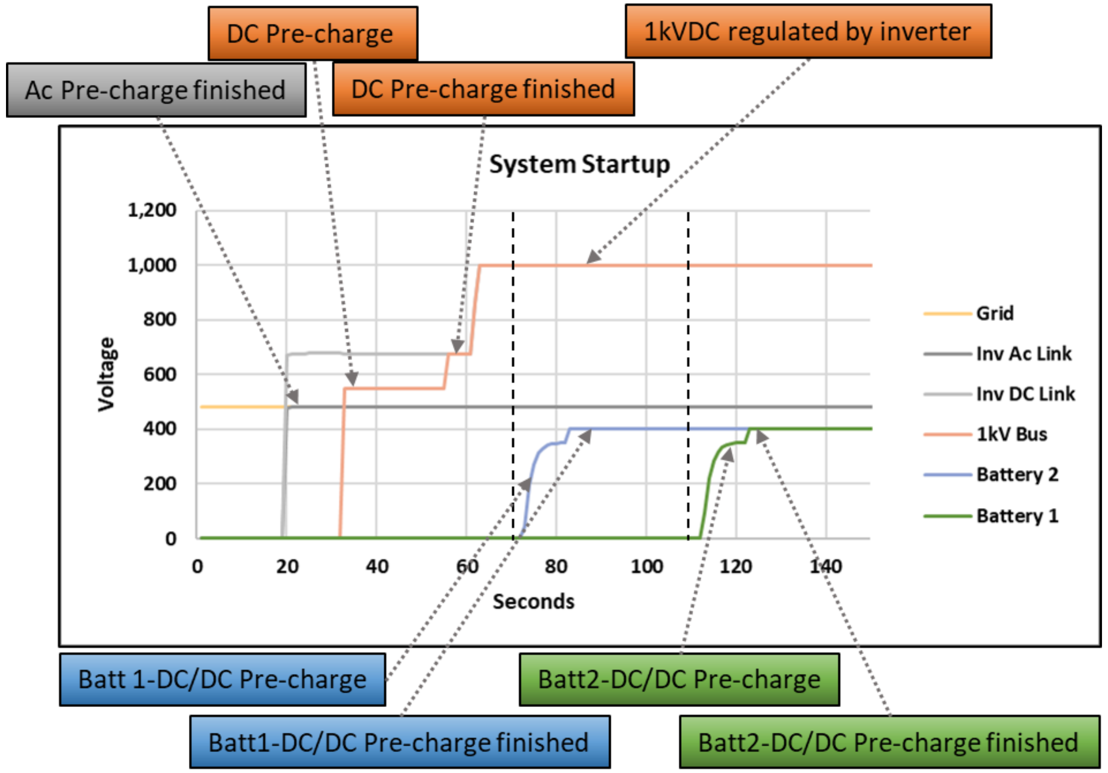


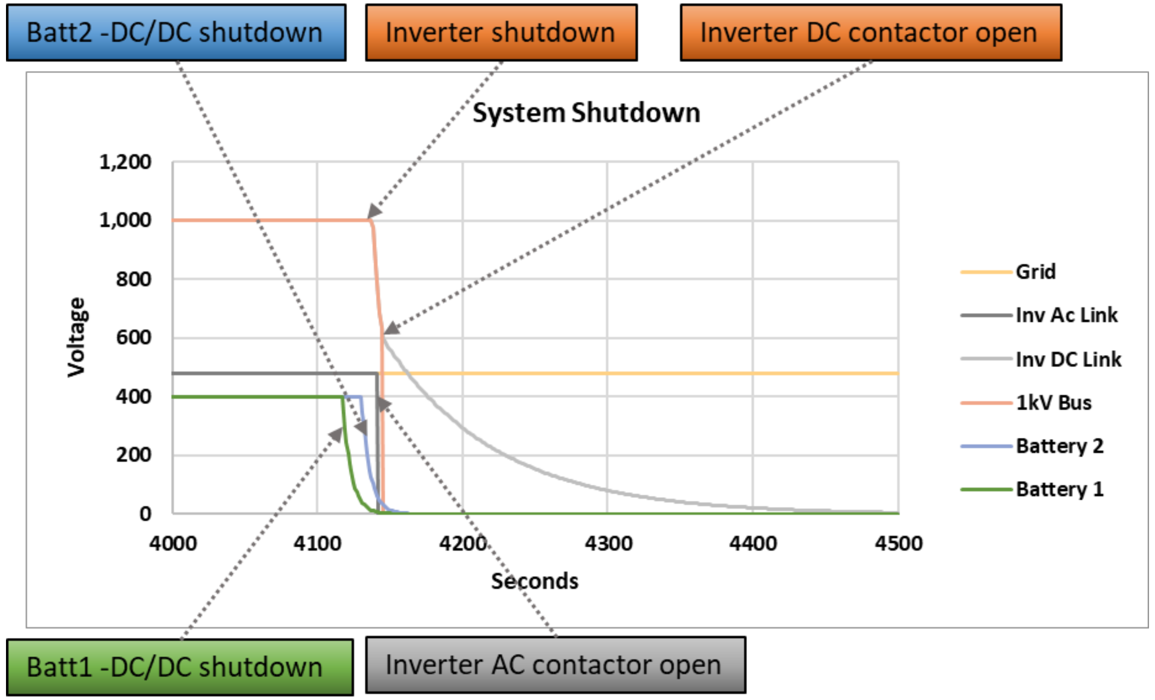
Innovation Update : Transient Operation of LV-HUB

Transient operation of the LV-HUB, 1 kV DC and 480 VAC: 3 DC-DC Converters, 1 DC-AC



	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6	ΣA (3P3W)
Udc [V]	400.219	400.009	0.39994k	0.99949k	0.203	0.985	-0.214
Urms [V]	400.220	400.013	0.39994k	0.99950k	479.629	479.542	479.709
Idc [A]	-25.209	25.579	-24.615	-10.082	0.016	1.541	0.771
Irms [A]	25.259	26.566	24.764	11.106	0.000	11.292	12.781
P [W]	-10.089k	10.222k	-9.845k	-10.077k	0.000k	-4.788k	-11.051k
fU [Hz]	Error	Error	Error	Error	60.002	550.85	
$\eta 1$ [%]	Error						
$\eta 2$ [%]	112.248						
$\eta 3$ [%]	Error						



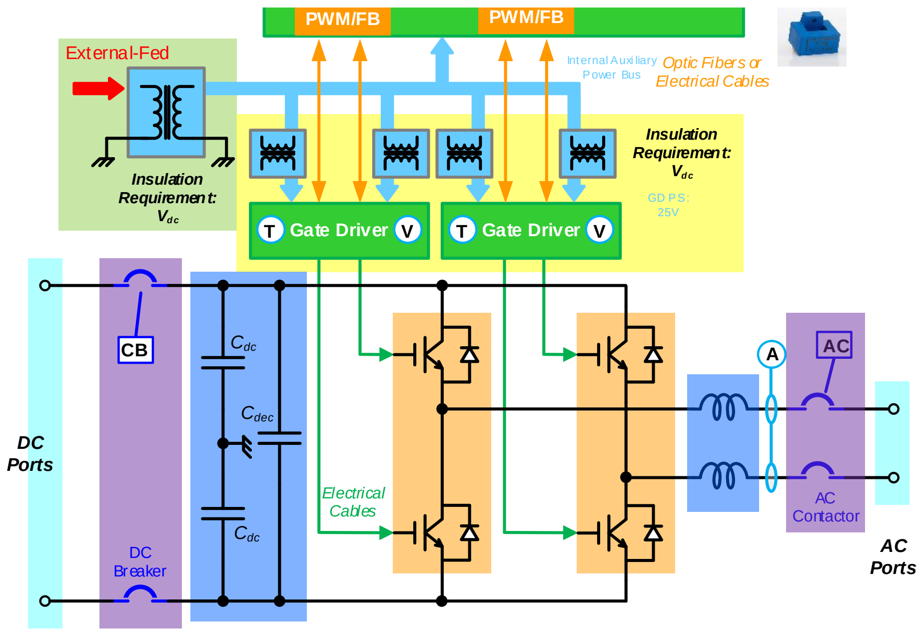


Development and evaluation of 10 kV SiC DC-DC Converter

Specifications for 10 kV H-bridge:

- Input voltage (DC): 6 - 7 kV
- Current rating (DC): 10 A
- Output voltage (DC): < 3 kV
- Switching frequency region: 1 – 5 kHz
- Test configuration: Buck mode
- Cooling: forced convention
- Ambient temperature: up to 40 °C

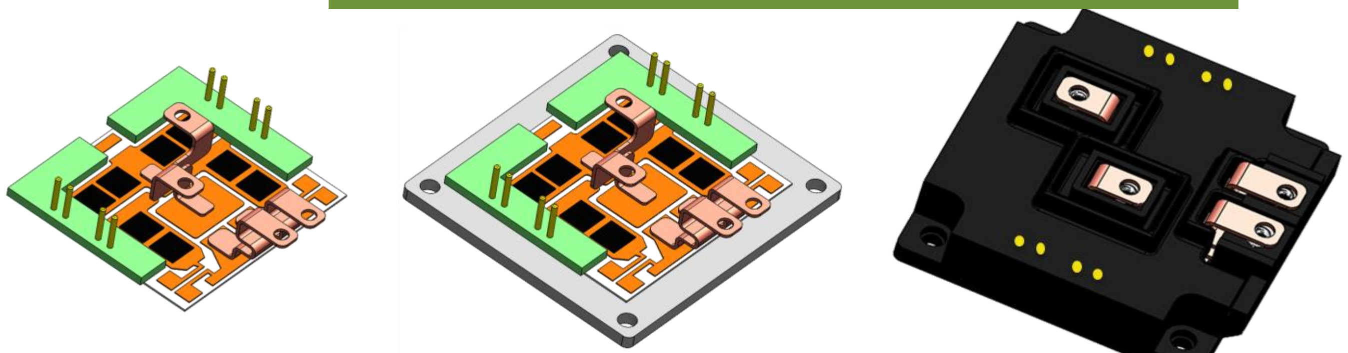
10 kV DC-DC Converter Architecture



3.3kV and 10kV Power module platform

- Evaluation of novel gate-source configuration for low inductance parallel device integration
- Can support 2 x 3.3-10kV (8mm devices) per switch position or 3 x 1.2-1.7kV devices (5mm devices)
- Configurable as Full bridge or Half Bridge Configuration internally

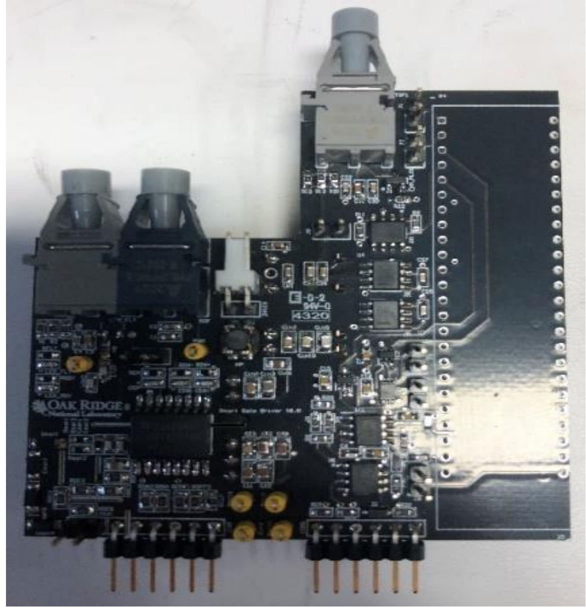
ORNL Medium Voltage Power Module : up to 10 kV



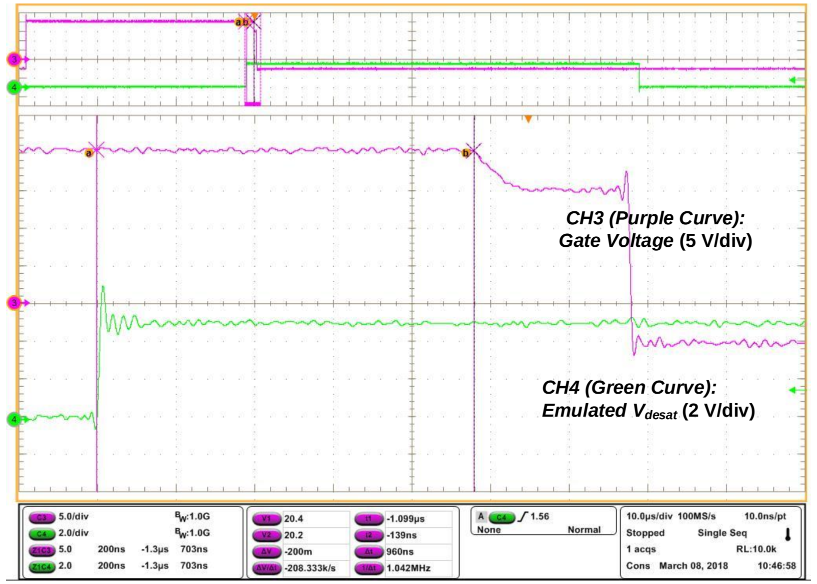
Device Packaging facility: clean room in GRID-C @ ORNL

Development and evaluation of 10 kV SiC H-bridge integrated module and power stage

- Medium Voltage Smart Gate Driver (ORNL)
  - Design, manufacture, and test of initial single switch medium voltage prototype
    - Included fiber optic interfacing
    - Onboard device level sensing features
    - Two level soft turn-off
  - Signal level testing completed
    - Test with Microchip 3.3kV TO-247-4 lead packaged devices for DPT board function
  - Scale voltage to 10 kV for module level multi-position configuration to support full bridge module design

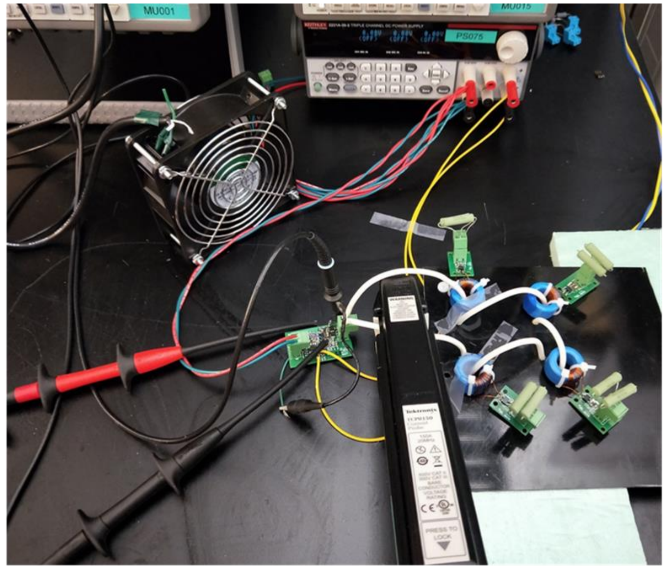


Smart gate driver : 3.3 kV rated module

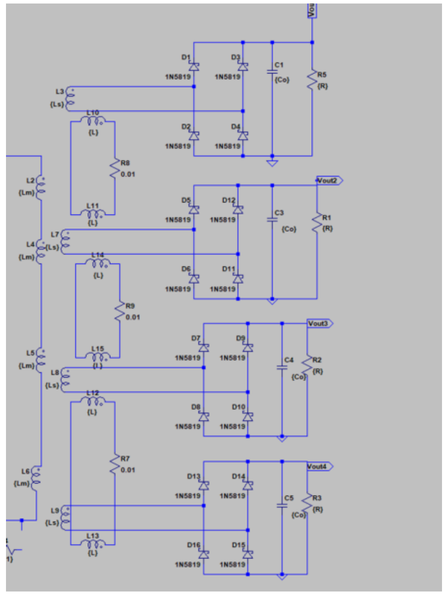


Gate driver transient operation: Gate voltage and Desat protection

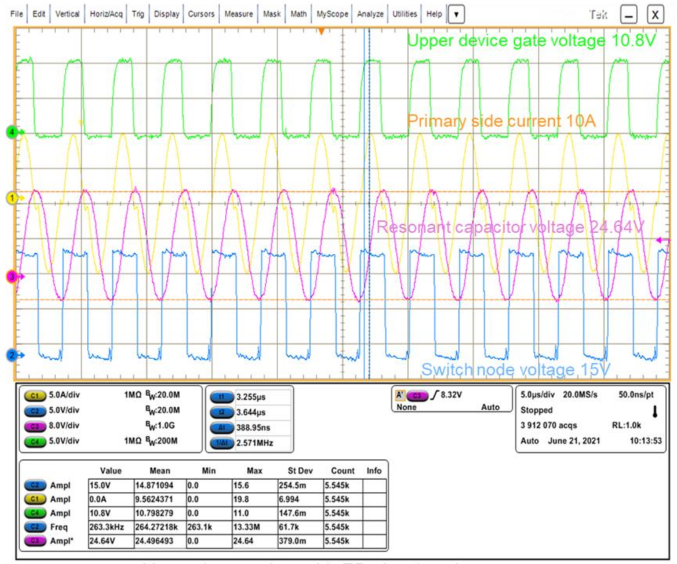
Auxiliary Power Supply: 20kV peak voltage, 14.14kV RMS voltage (UTK)



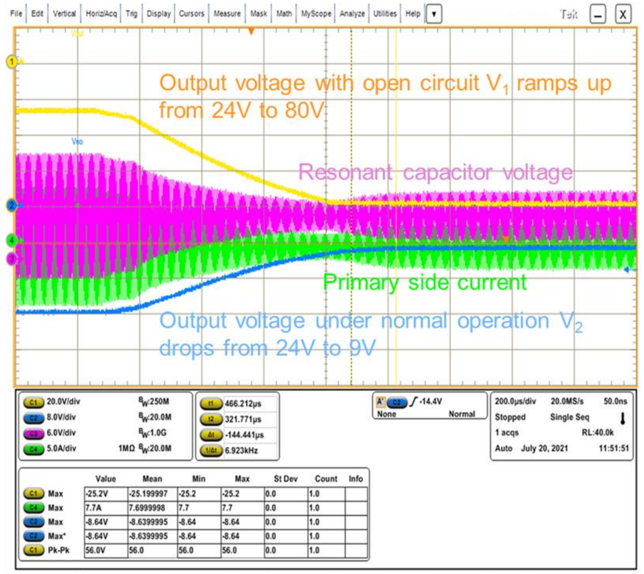
Auxiliary Power Supply upto 10 kV (UTK)



Auxiliary Power Supply Topology



Normal operation with 75Ω load resistor



One output open circuit operation with 75Ω load resistor

Auxiliary Power Supply Transient Operation

Development and evaluation of 10 kV SiC H-bridge integrated module and power stage

D=0.1			
VI	3000	6500	10000
VO	300	650	1000
Imax	275	126.92	82.5
L	0.54	2.535	6
N	9	20	30
Acu	55	25.385	16.5
d	8.3683	5.6851	4.5835

D=0.2			
VI	3000	6500	10000
VO	600	1300	2000
Imax	137.5	63.462	41.25
L	1.92	9.0133	21.333
N	18	40	61
Acu	27.5	12.692	8.25
d	5.9173	4.02	3.241

D=0.3			
VI	3000	6500	10000
VO	900	1950	3000
Imax	91.667	42.308	27.5
L	3.78	17.745	42
N	27	59	91
Acu	18.333	8.4615	5.5
d	4.8314	3.2823	2.6463

D=0.4			
VI	3000	6500	10000
VO	1200	2600	4000
Imax	68.75	31.731	20.625
L	5.76	27.04	64
N	37	79	122
Acu	13.75	6.3462	4.125
d	4.1841	2.8426	2.2917

D=0.5			
VI	3000	6500	10000
VO	1500	3250	5000
Imax	55	25.385	16.5
L	7.5	35.208	83.333
N	46	99	152
Acu	11	5.0769	3.3
d	3.7424	2.5425	2.0498

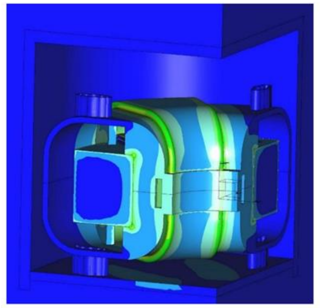
D=0.6			
VI	3000	6500	10000
VO	1800	3900	6000
Imax	45.833	21.154	13.75
L	8.64	40.56	96
N	55	119	183
Acu	9.1667	4.2308	2.75
d	3.4163	2.3209	1.8712

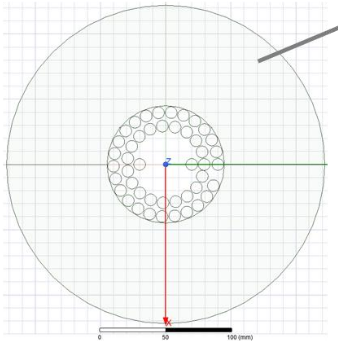
D=0.7			
VI	3000	6500	10000
VO	2100	4550	7000
Imax	39.286	18.132	11.786
L	8.82	41.405	98
N	64	138	213
Acu	7.8571	3.6264	2.3571
d	3.1629	2.1488	1.7324

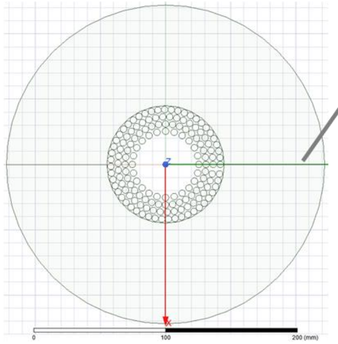
D=0.8			
VI	3000	6500	10000
VO	2400	5200	8000
Imax	34.375	15.865	10.313
L	7.68	36.053	85.333
N	73	158	243
Acu	6.875	3.1731	2.0625
d	2.9586	2.01	1.6205

D=0.9			
VI	3000	6500	10000
VO	2700	5850	9000
Imax	30.556	14.103	9.1667
L	4.86	22.815	54
N	82	178	274
Acu	6.1111	2.8205	1.8333
d	2.7894	1.895	1.5278

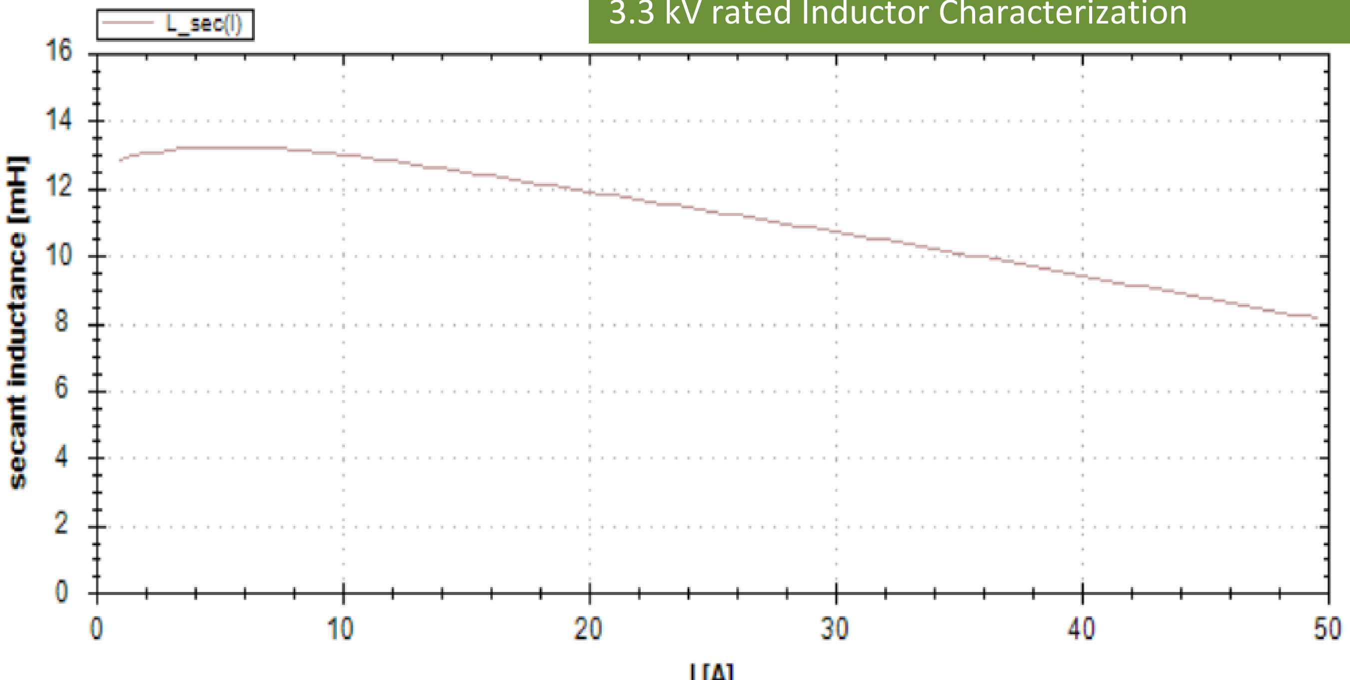
D=1			
VI	3000	6500	10000
VO	3000	6500	10000
Imax	27.5	12.692	8.25
L	0	0	0
N	91	198	304
Acu	5.5	2.5385	1.65
d	2.6463	1.7978	1.4494



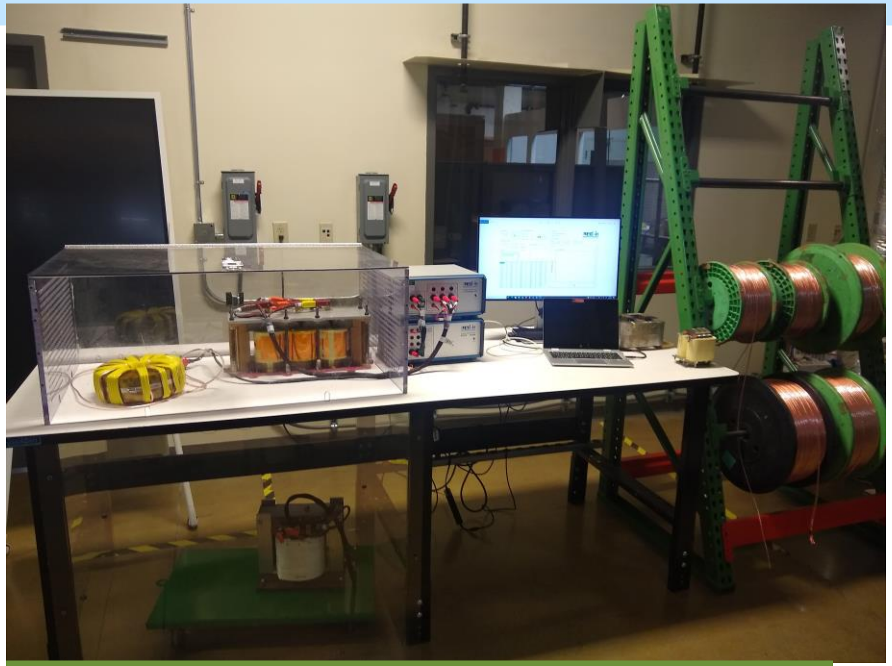




3.3 kV rated Inductor Characterization



D=0.5			
VI	3000	6500	10000
VO	1500	3250	5000
Imax	55	25.385	16.5
L (mH)	7.5	35.208	83.333
N	46	99	152
Acu	11	5.0769	3.3
d	3.7424	2.5425	2.0498

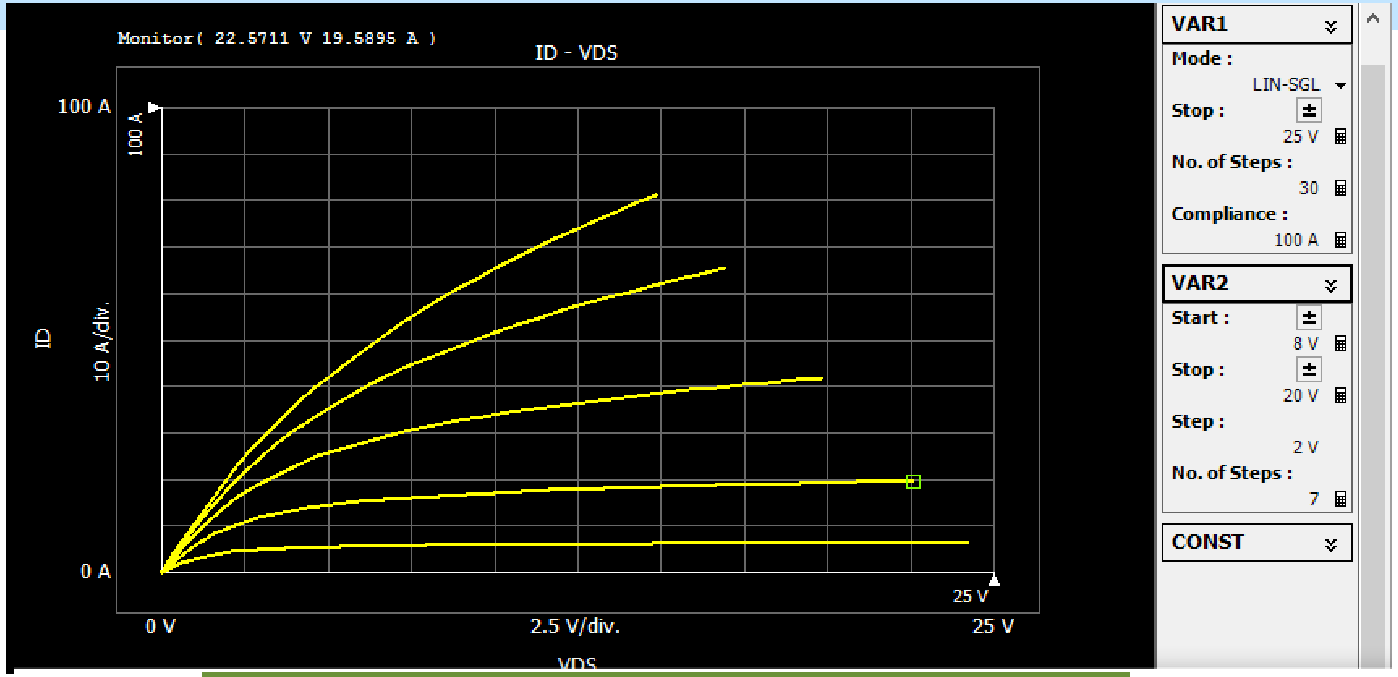


Magnetics Build and Test Setup in GRID-C @ ORNL

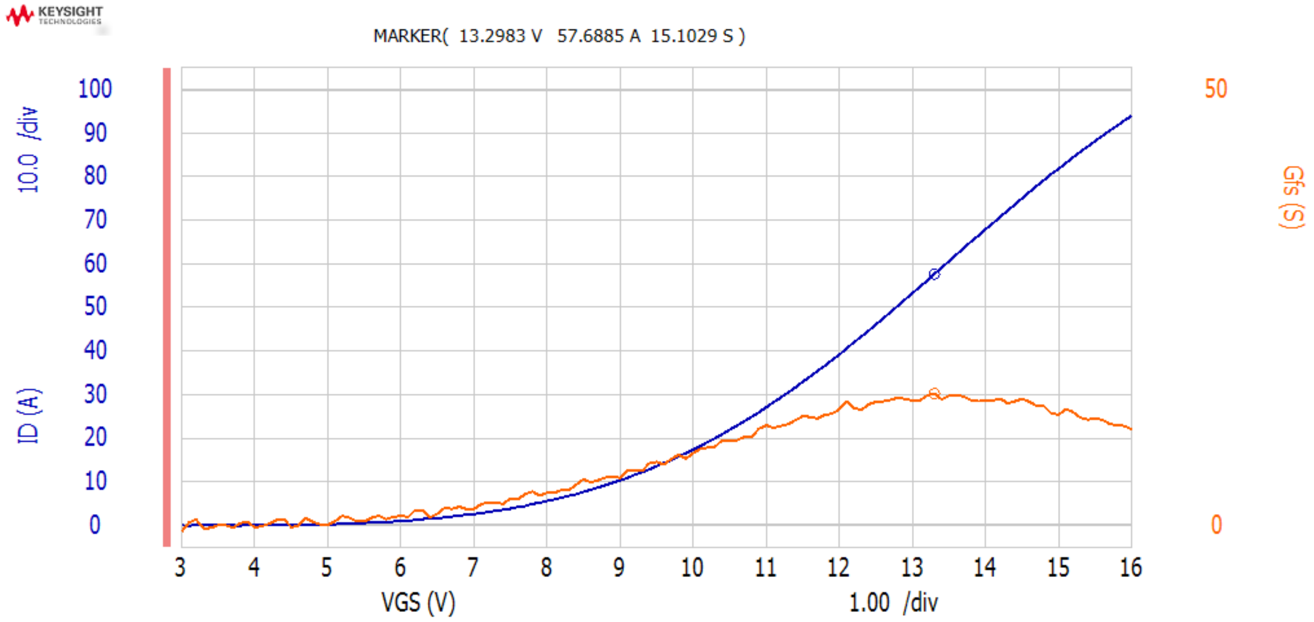
3.3 kV rated Inductor for DC-DC Converter built @ ORNL

Evaluation of Power Devices : Static Characterization in GRID-C @ORNL

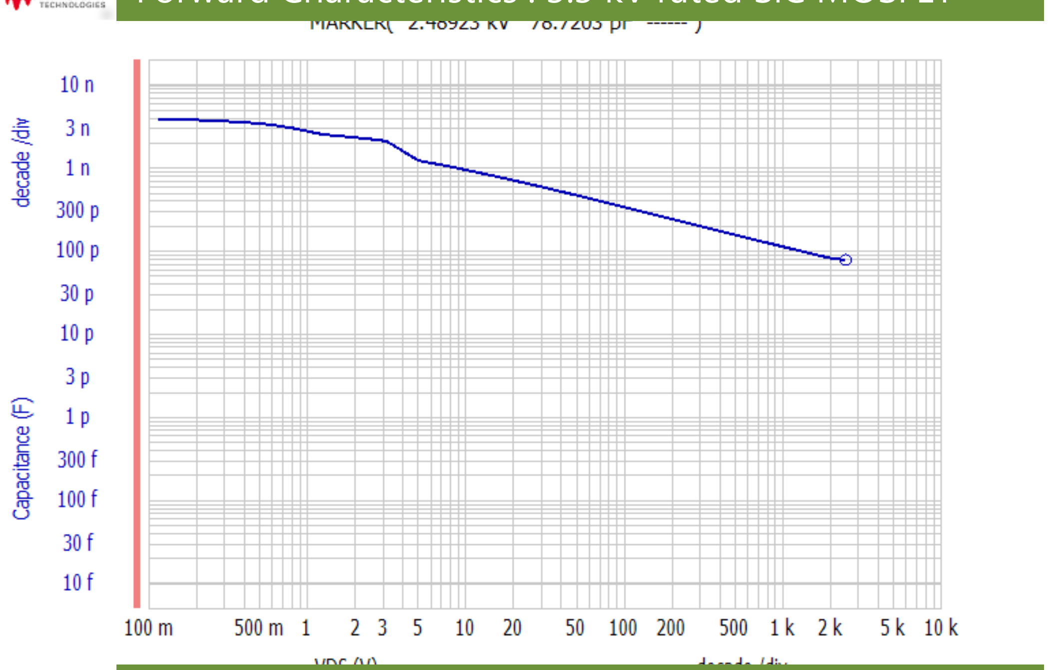
Static Characterization Test Setup in GRID-C @ ORNL



Forward Characteristics : 3.3 kV rated SiC MOSFET

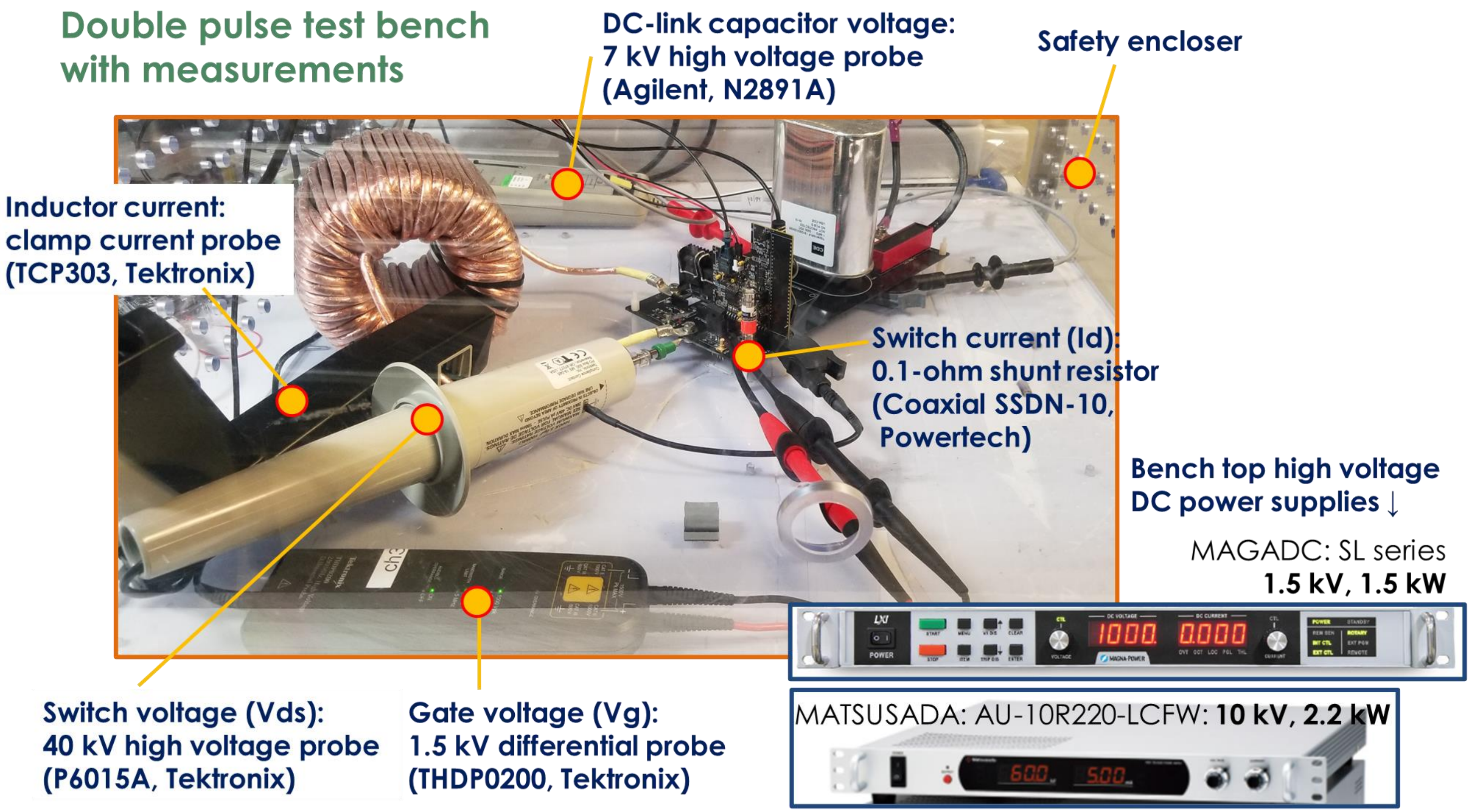


Transfer Characteristics : 3.3 kV rated SiC MOSFET

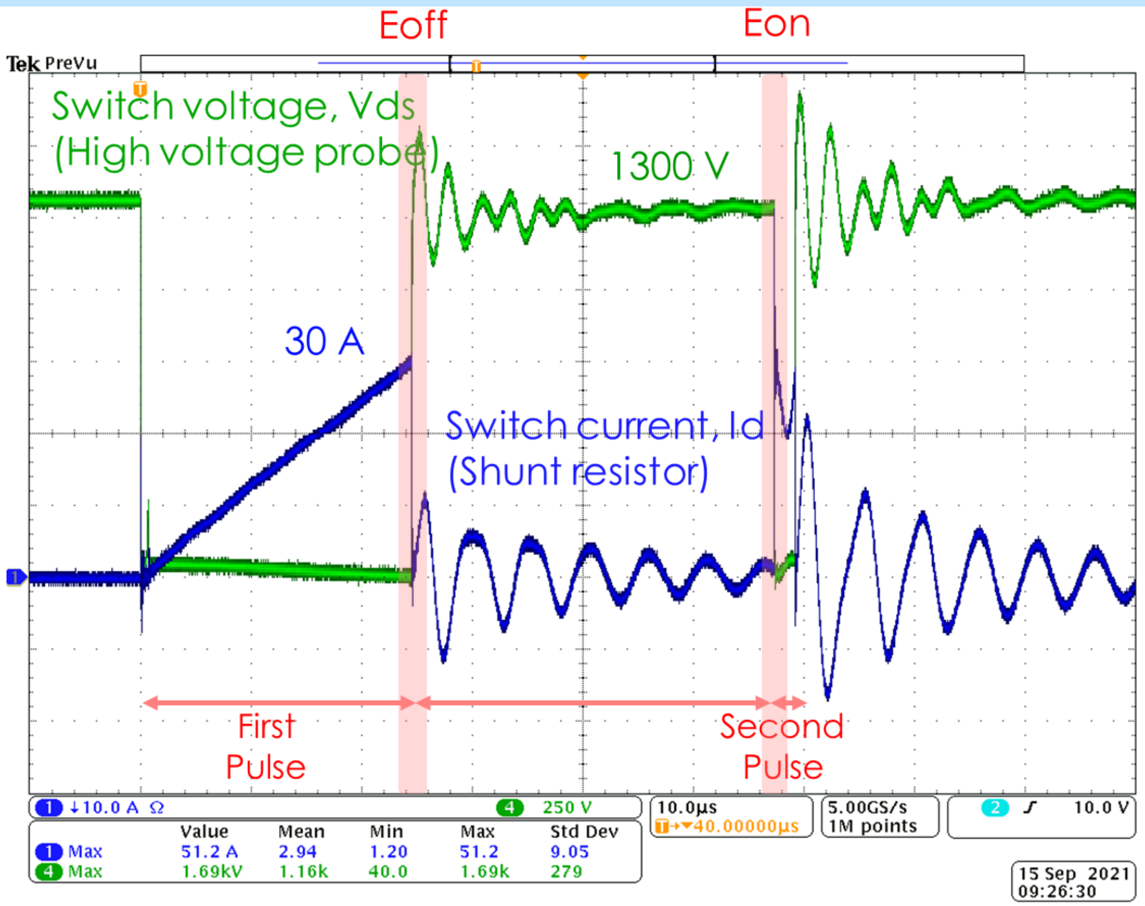


Output Capacitance : 3.3 kV rated SiC MOSFET

Evaluation of Power Devices : Dynamic Characterization in GRID-C @ORNL



Dynamic Characterization Test Setup in GRID-C @ ORNL



Switching Characteristics : 3.3 kV rated SiC MOSFET, 30 A @ 1300 V

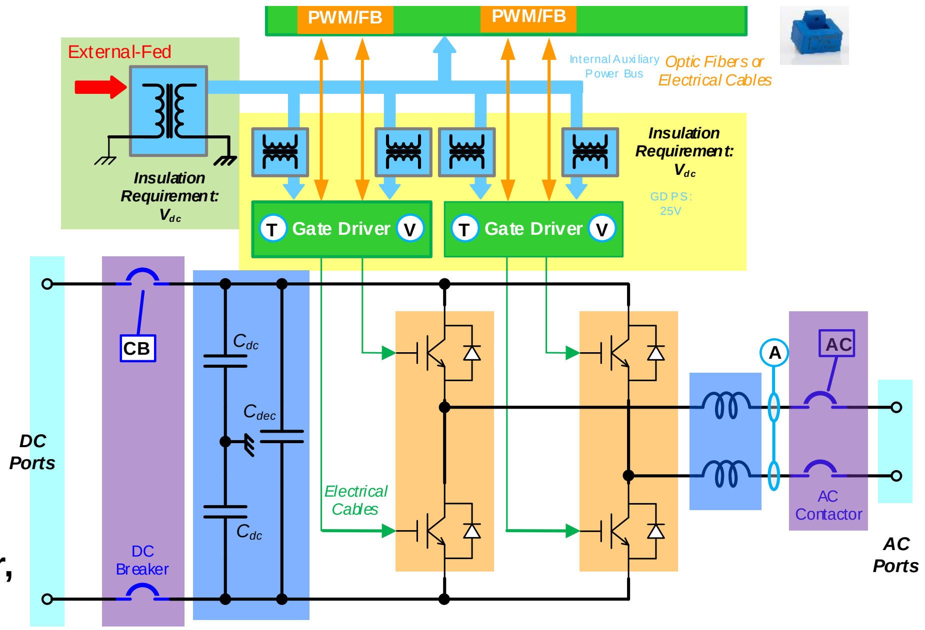
- ☆ 1300 V, 30A, 156 uJ (Eoff), 908 uJ (Eon)
- ☆ 1000 V, 30A, 121 uJ (Eoff), 619 uJ (Eon)
- ☆ 500 V, 30A, 66.4 uJ (Eoff), 167 uJ (Eon)
- △ 1300 V, 40A, 221 uJ (Eoff), 1244 uJ (Eon)
- △ 1000 V, 40A, 168 uJ (Eoff), 842 uJ (Eon)
- △ 500 V, 40A, 115 uJ (Eoff), 228 uJ (Eon)
- O 1300 V, 50A, 312 uJ (Eoff), 1686 uJ (Eon)
- O 1000 V, 50A, 254 uJ (Eoff), 1155 uJ (Eon)
- O 500 V, 50A, 187 uJ (Eoff), 311 uJ (Eon)

Development and evaluation of 10 kV SiC H-bridge integrated module and power stage

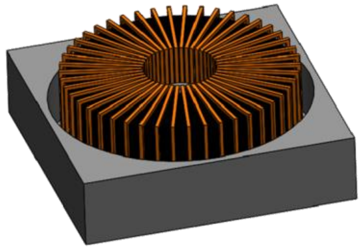
Design for the 10kV integration with scalability for power to support testing at 3.3kV transition from power modules and magnetics

Auxiliary Power Supply

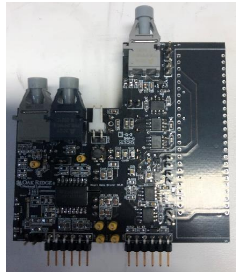
DC link capacitor, decoupling capacitor, Busbar (ORNL)



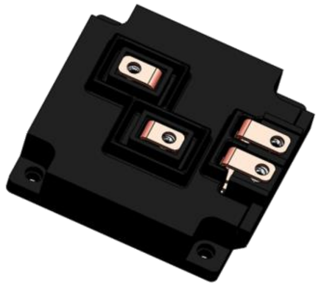
Sensors (ORNL)



Magnetic Component (ORNL)

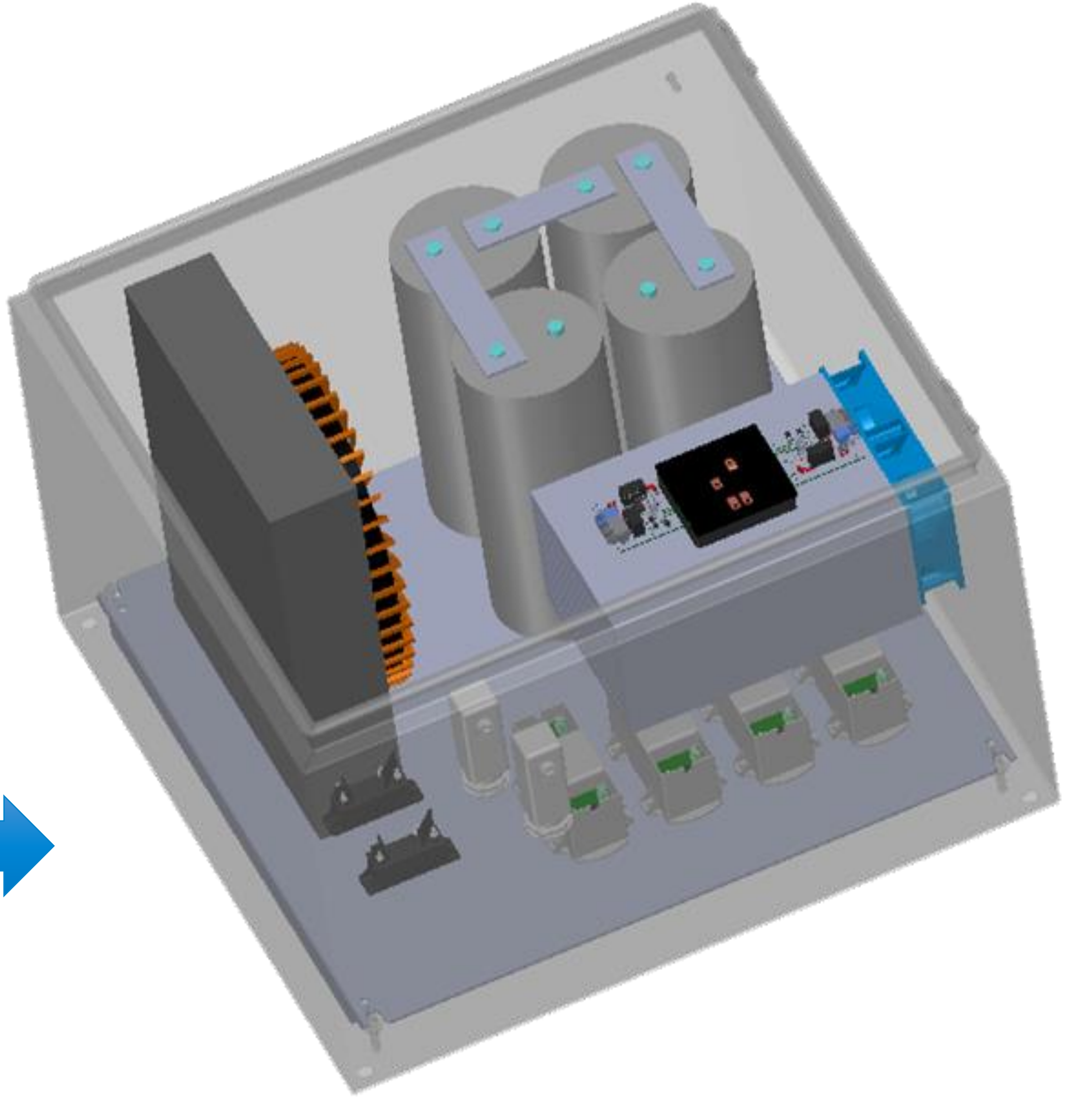


Gate Driver (ORNL)



Integrated Module (ORNL)

AC/DC Relays(ORNL)



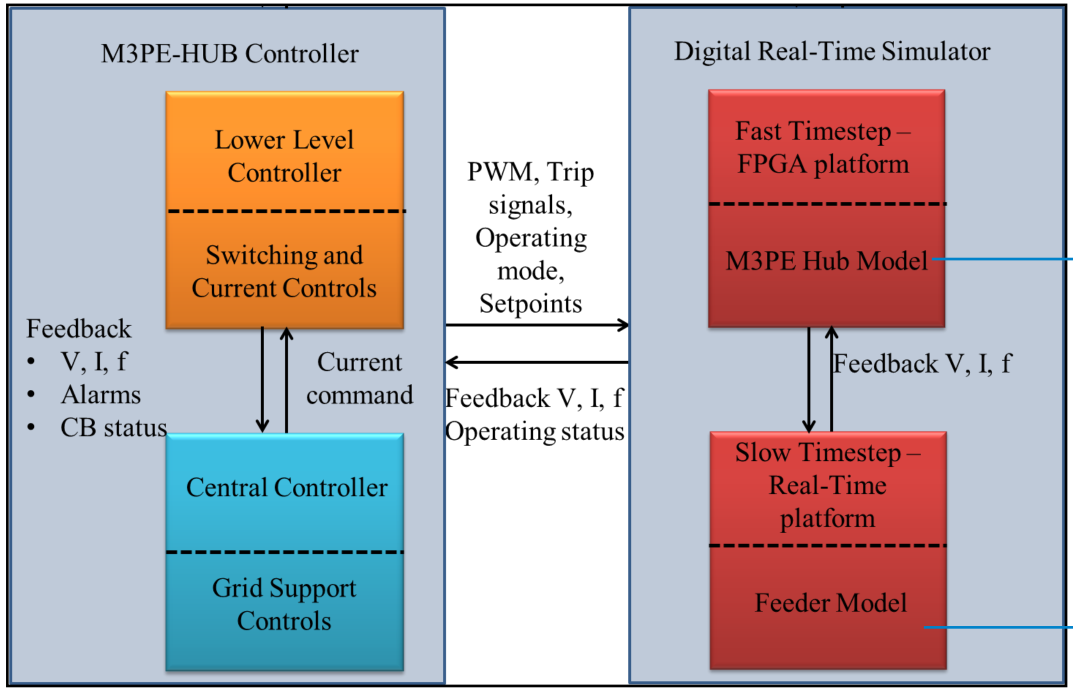
24”x24”x12” DC-DC Converter (ORNL)

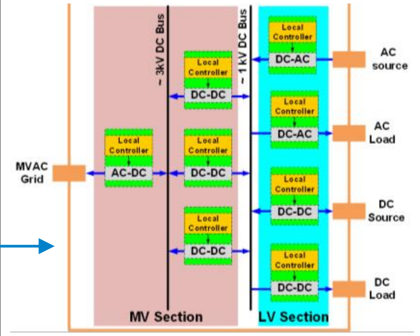
HIL Validation of Multi-Port HUB

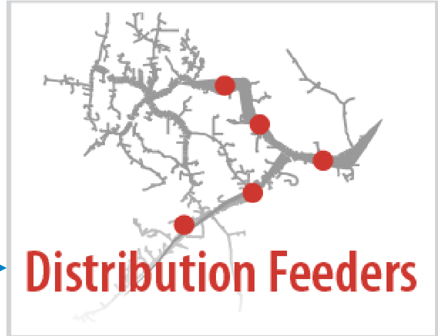
Block Diagram for multi-timestep single node CHIL for M3PE-HUB

Domains	Test Functions
Voltage Functions	Volt-VAR
	Volt-Watt
	High/Low Voltage Ride-through
	Dynamic Voltage Support
	Power Factor
Frequency Functions	Frequency Watt
	High/Low Frequency Ride-through
Others	Normal and Delayed Ramp Rate Control

Controller (3555 RTAC)





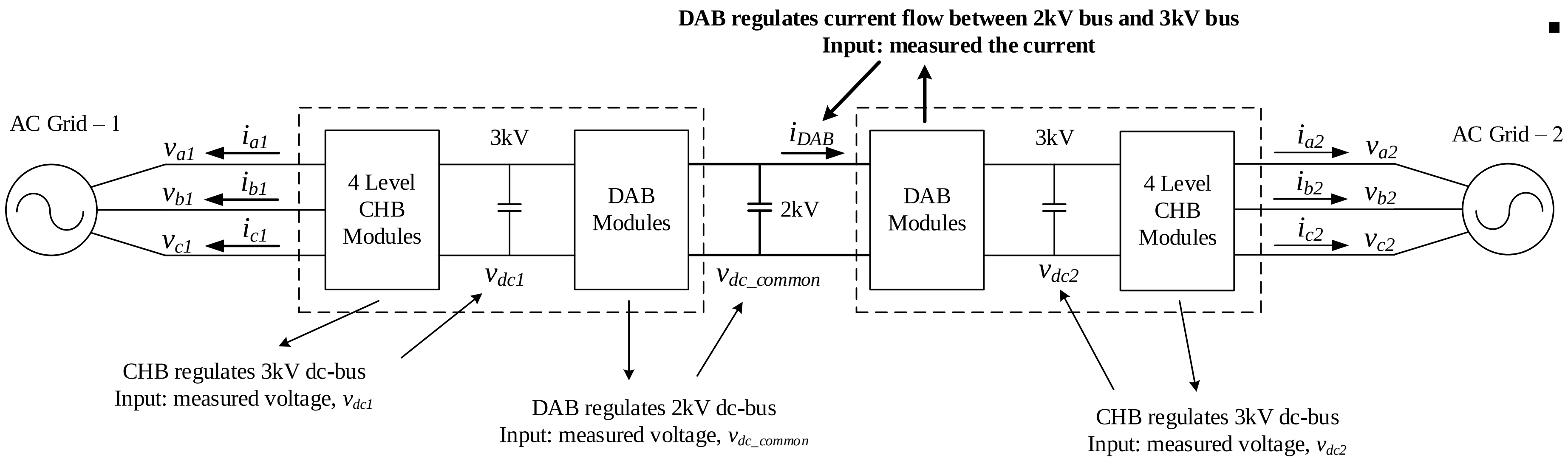


RTDS

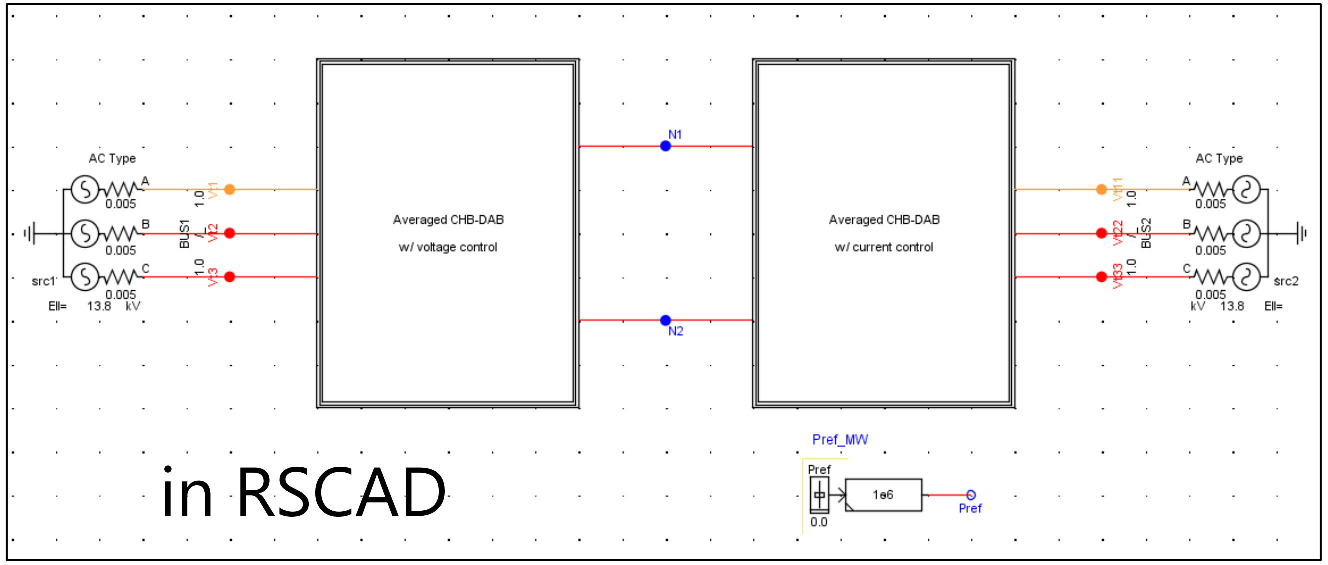
EtherCAT, DNP3 or IEC 61850

- The CHIL system will be developed to host both the M3PE-HUB model and the interconnected feeder model on a digital real-time simulator (DRTS) platform
- Multi-timestep implementation, to capture the dynamics and steady-state operation accurately
- Assessment of single transactive node for grid services such as: harmonic distorsion management, un-balance management, voltage support, etc., based on location of the M3PE-HUB on the feeder

Back-to-back Configured MV-Energy Hub: Model Development



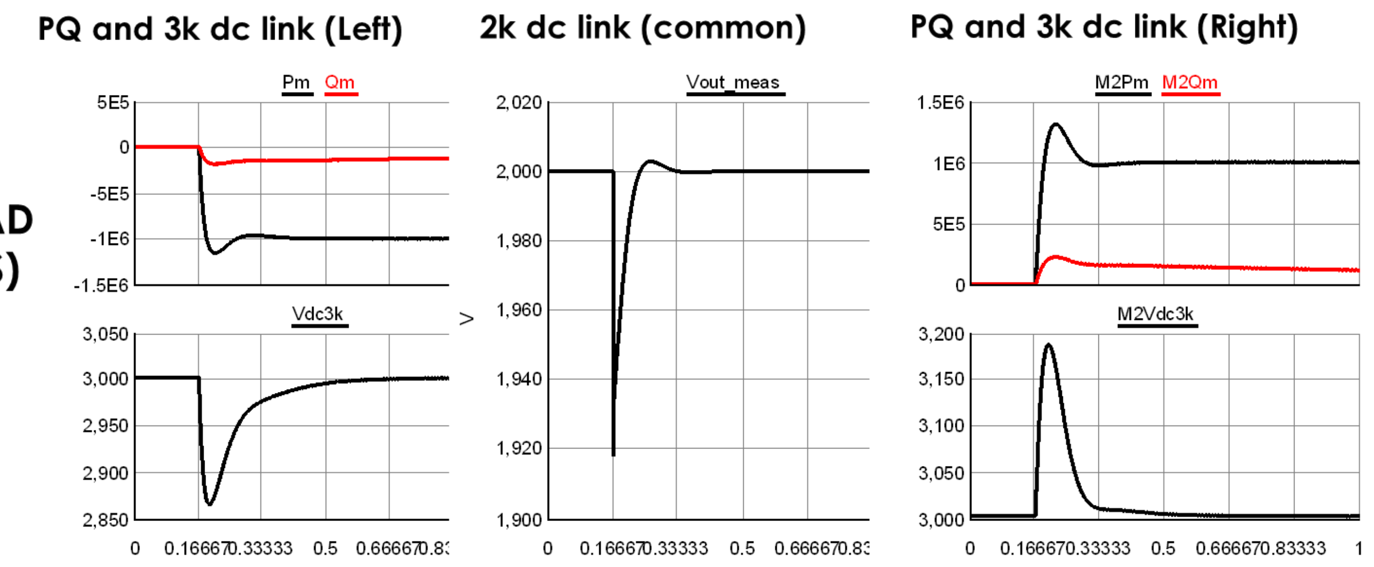
Back-to-back configuration (CHB-DAB-DAB-CHB)



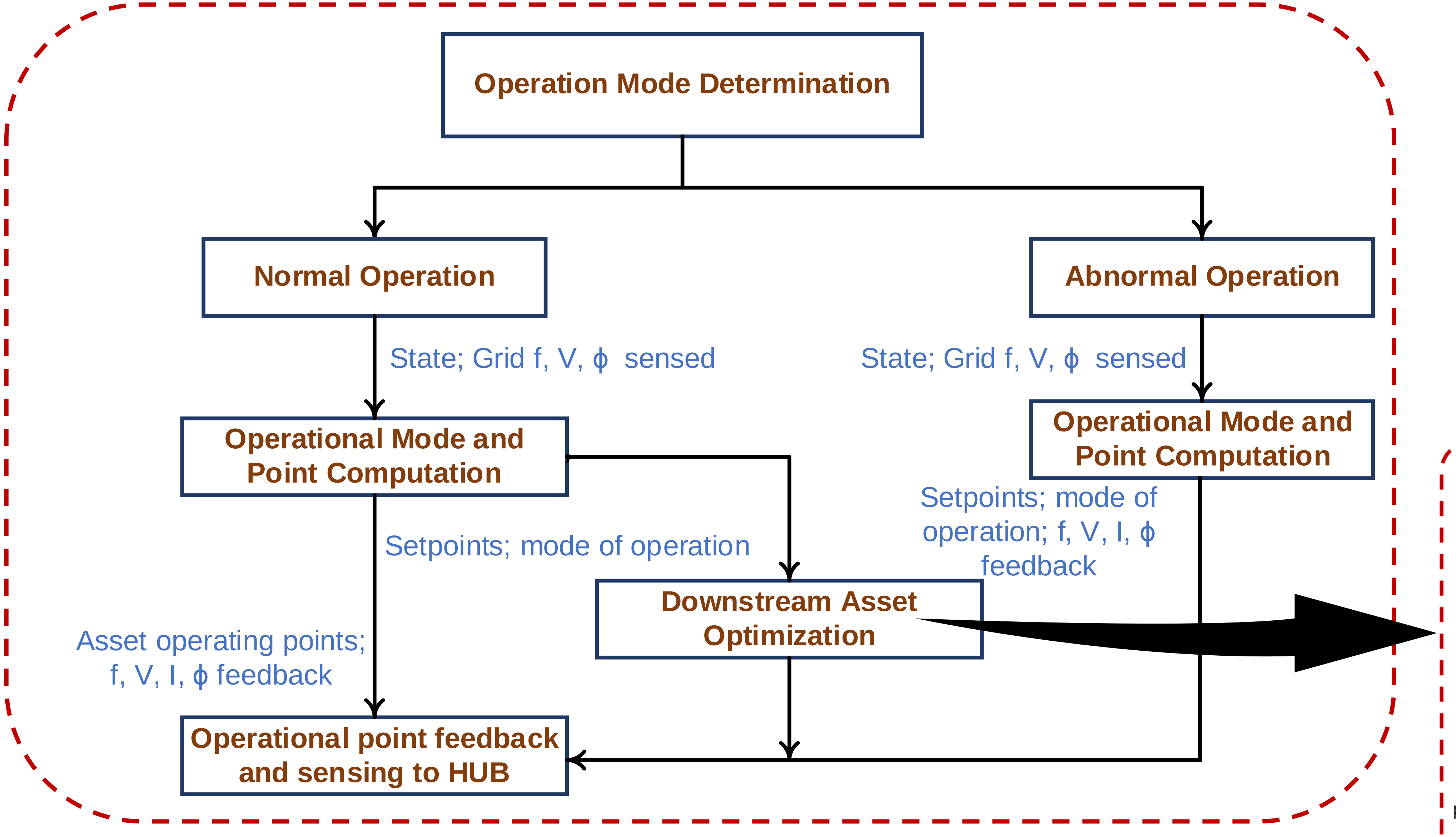
- **CHB-DAB blocks-based MV-Energy hub**
  - CHB module (both 3kV voltage control)
    - AC side: AC medium voltage (13.8 kV)
    - DC side: DC 3kV
  - DAB module (Left: 2kV voltage control, Right: current control)
    - Primary side: CHB side DC 3kV
    - Secondary side: Common DC 2kV

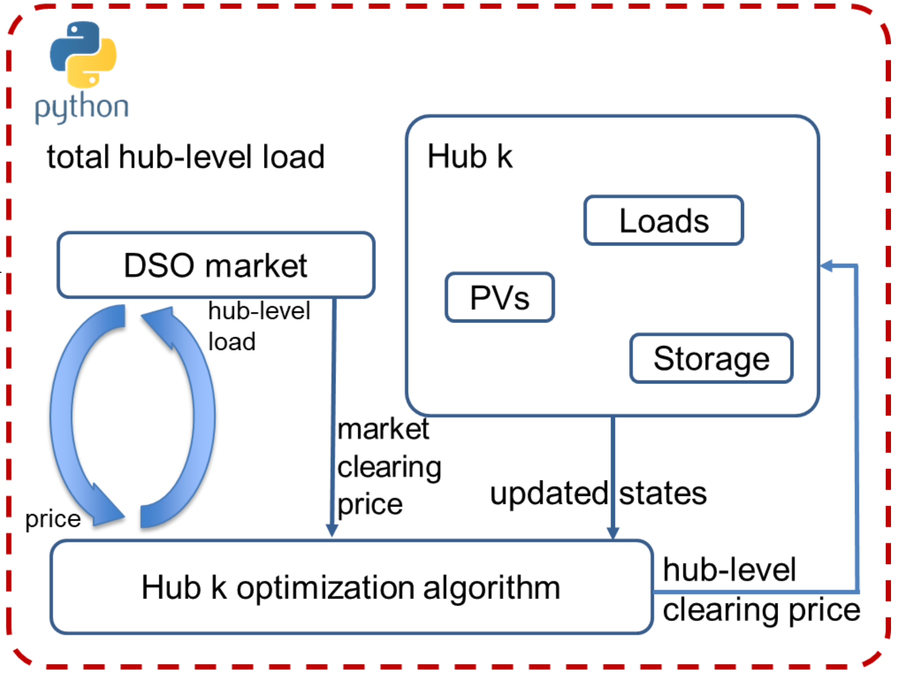
P_{ref} change from 0 MW to 1 MW

RSCAD (RTDS)



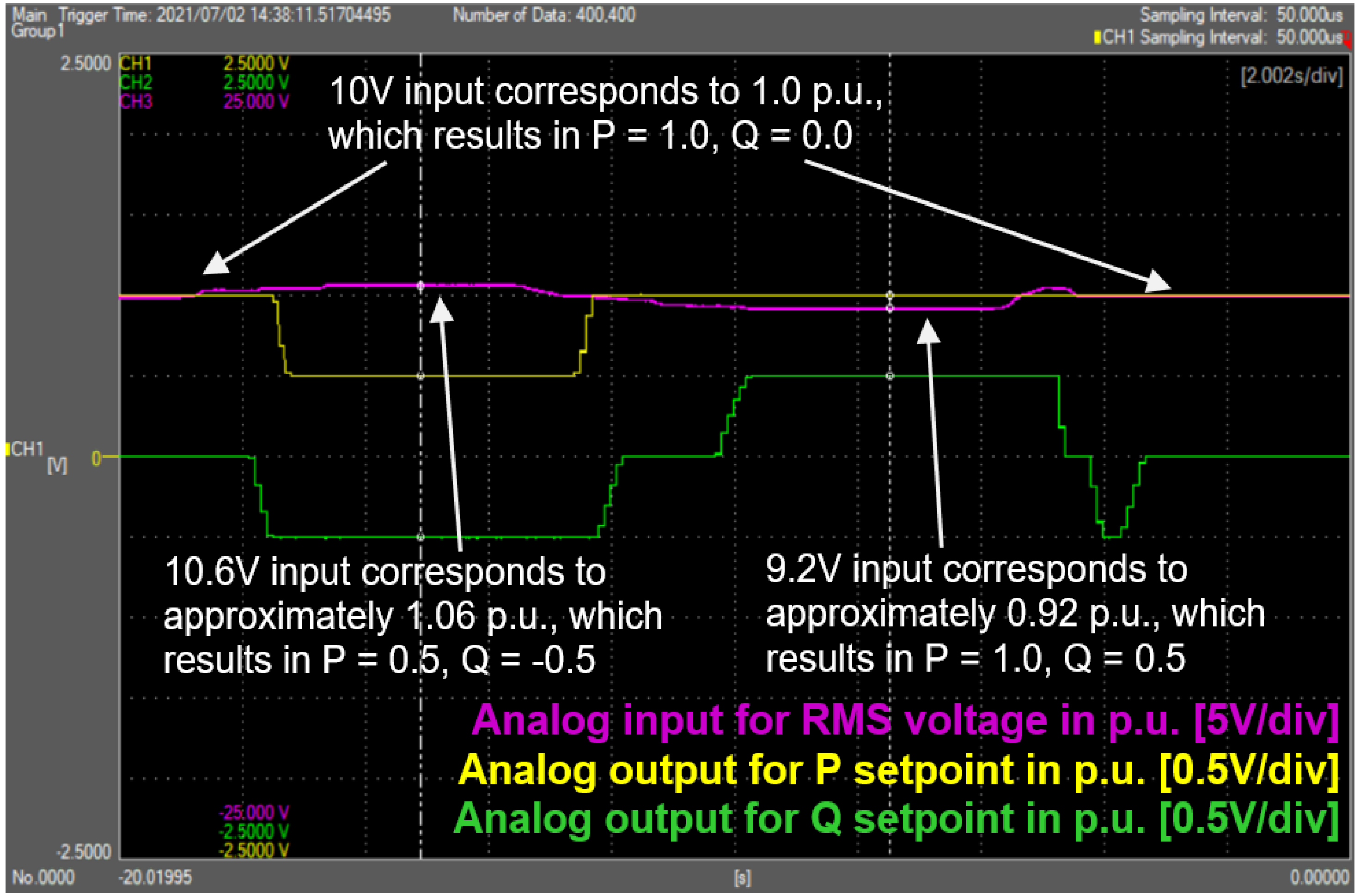
Controls and Optimization Integration

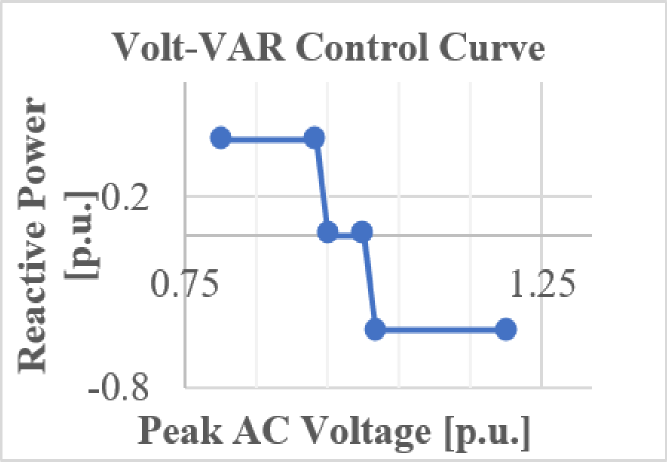


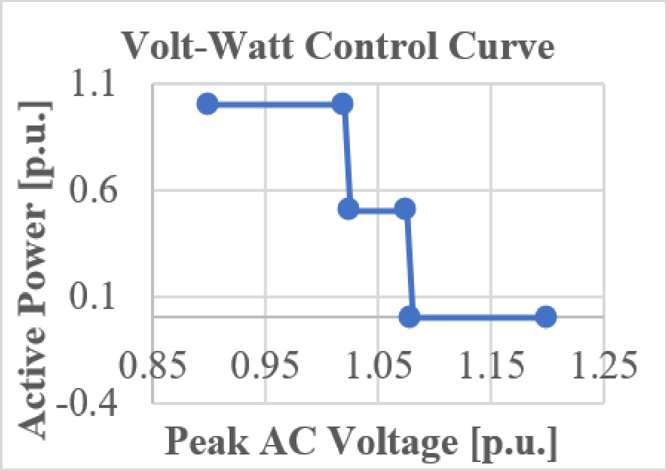


Operating Modes of the HUB- Controller

Controller validation using CHIL Setup – Voltage Regulation

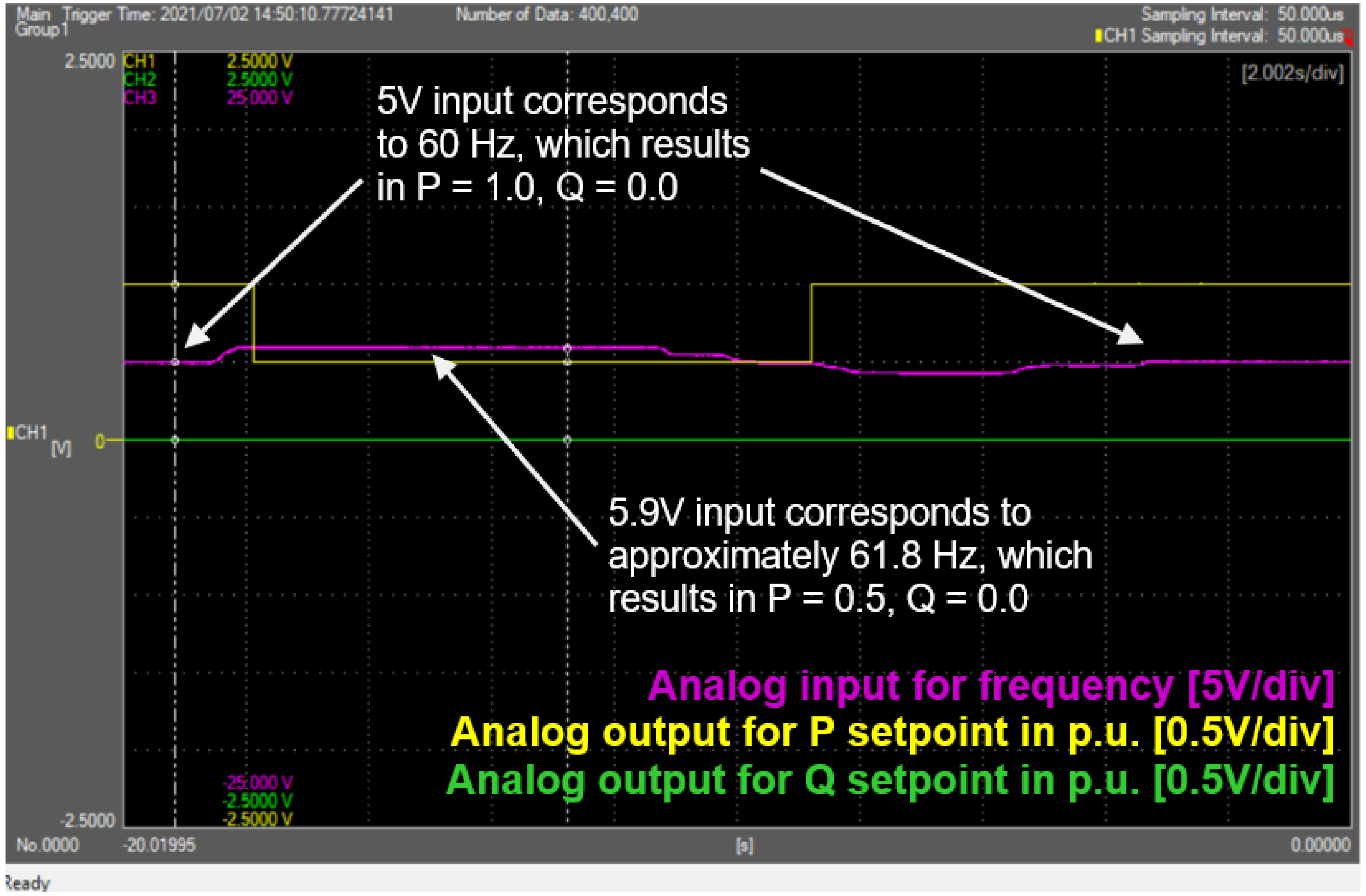


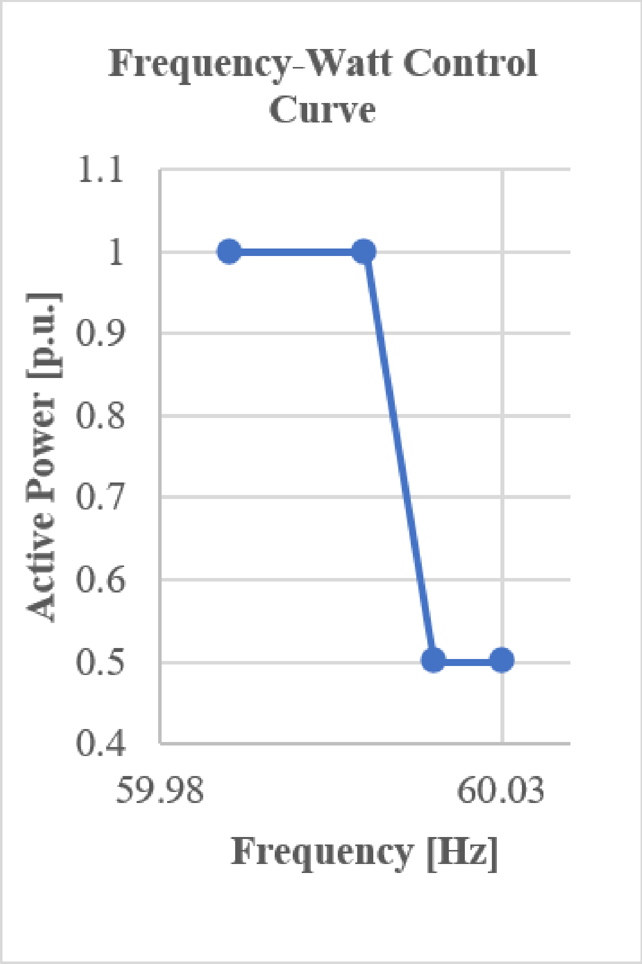




- Input from DRTS – scaled rms grid voltage
- Voltage varied at constant frequency
- P and Q setpoints governed by implemented VV and VW functions
- Voltage variation was within normal operation range of ride-through settings

Controller validation using CHIL Setup – Frequency Regulation





- Input from DRTS – scaled grid frequency
- Frequency varied at constant voltage
- P setpoints governed by implemented FW function
- Frequency variation was within normal operation range of ride-through settings
- Functions will be used for Hub use-case assessments

Innovation Update

Milestone Update

Milestone Description	Scheduled Due Date	% Completion	Completion Date
Year 1			
Design the smart interface and the agent-based software for the low voltage vendor hardware	1/15/2021	100%	1/10/2021
Duplicate, Test, and Integrate SuNLaMP Multi-Port PE Hardware and Controls [Go/No-Go]	1/15/2021	100%	10/30/2021
Development of the controller firmware and hardware	1/15/2021	100%	1/10/2021
Complete the simulation transactive control algorithms with multiple M3PE-HUB	1/15/2021	100%	1/10/2021
Year 2			
Complete the integration of LV multi-port HUB and demonstrate functionality [Go/No-Go]	2/15/2022	90%	
Complete the design and build of the evaluation of 3.3 kV H-bridge based power stage	2/15/2022	50%	
Validate and test the proposed control strategies for energy hubs	2/15/2022	80 %	
Development and testing of CHIL for the single M3PE-HUB in a real-time feeder model	2/15/2022	80%	

Innovation Update

Risks

- ❑ Anticipated delays in 3.3 kV H-bridge power stage
- ❑ Anticipated delays in the integration of prototypes from partners due to supply chain issues.

Future Work

- ❑ Complete the integration of prototypes for final LV-HUB demonstrations.
- ❑ Develop and evaluate the 10 kV dc-dc prototype in collaboration with the partners
- ❑ Complete the CHIL implementation of the medium voltage HUB and show the impact of the HUB concept with use cases.

Impact/Commercialization

Invention Disclosures Filed:

- M. Starke, B. Xiao, M. Chinthavali “A Low Voltage DC Power Electronic Hub to Support Buildings,” IEEE International Conference on DC Microgrids (IDCM), July 2021

THANK YOU

Acronyms

Insert any acronyms used and the associated definition here

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