Project ID:ELT238 Award No:DE-EE0008450

Intelligent, Grid-Friendly, Modular Extreme Fast Charging System with Solid-State Direct-Current Protection

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ABB FREEDM SYSTEMS CENTER NEW YORK STATE OF OPPORTUNITY NY Power Authority NC STATE UNIVERSITY

Overview

Timeline

- Project Start Date: Oct. 2018
- Project End Date: July 2022
- Percent Complete: 60%

Barriers

- Integration to utility at medium voltage
- Protection
- System siting, integration and deployment

Budget

- Total Project Funding
  - DOE Share: $ 2,675,952
  - Contractor Share: $ 3,323,775
- Spending to Date (Q1 2021)
  - DOE Share: $ 1,417,909
  - Contractor Share: $ 2,257,136

Partners

- NCSU/FREEDM – Lead
- ABB Inc.
- New York Power Authority (NYPA)

Relevance

Objectives:

- Develop an electric vehicle (EV) extreme fast charging (XFC) station with direct connection to the medium voltage distribution network
- Develop a direct-current (DC) distribution network with solid-state protection to supply multiple EV charging ports

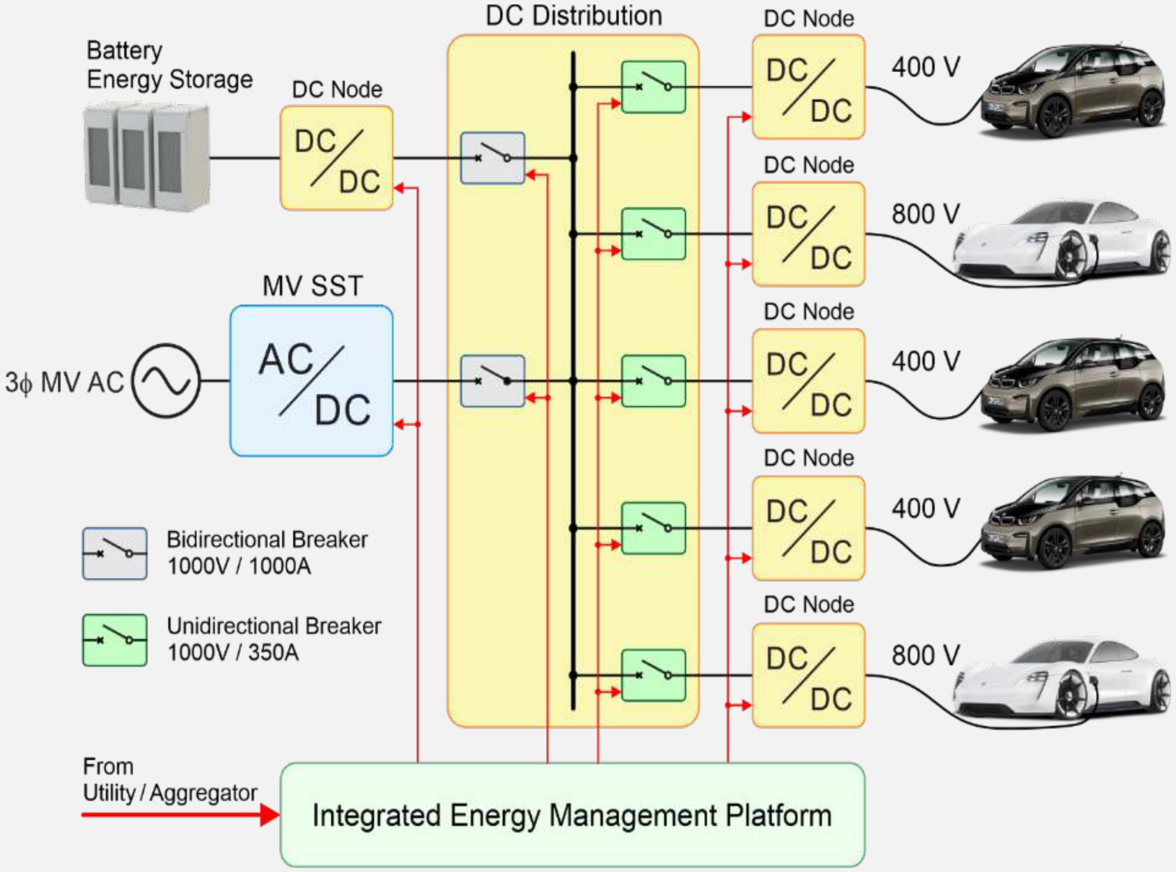
Project Impact:

- Framework for designing XFC stations to minimize installation and operating costs, manage grid impact, and provide design flexibility
- Field demonstration of novel technologies for future XFC installations
- Installation, operation and maintenance guidelines for deployment of XFC infrastructure with proposed unique architecture.

Approach

Develop and deploy a 1 MW medium voltage XFC station:

- Shared bi-directional Solid State Transformer (SST) connecting directly to the medium voltage (MV) distribution system
- DC distribution network with solid-state DC protection
- Energy management platform
- Head-ends for local isolation and DC/DC conversion



Milestones

System Development

BP1

- **Construct SST & DC node***
- Select site ✓
- Preliminary engineering diagrams ✓
- SST & DC nodes operational ✓
- Engineering diagrams complete ✓

10/1/2018 – 7/31/2020

System Integration

BP2

- **Complete system integration ***
- Site preparation complete ✓
- System integration
- Protection validated
- Safety evaluation ✓

8/1/2020 – 7/31/2021

System Deployment

BP3

- **Commission System**
- System transported and installed
- Use cases tested
- Data collection
- Public demonstration

8/1/2021 – 7/31/2022

* Denotes Go/No-Go Milestone

BP: Budget Period

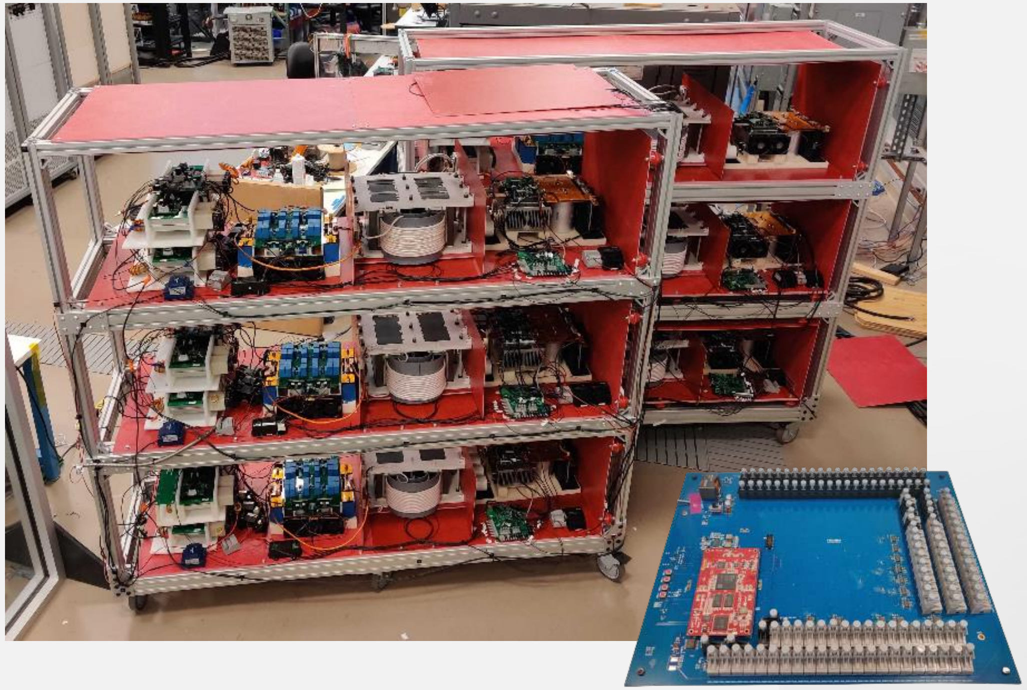
Technical Accomplishments & Progress

- Finalized site engineering drawings; deployment site construction started
- Developed charging infrastructure protection coordination; DC Solid State Breakers constructed
- Power Electronics:
  - Solid State Transformer (SST) lab prototype constructed and tested
  - Optimized SST module design; Field SST under construction
  - DC/DC stage design finalized; construction of first system underway

SST Design Approach

500kVA 4.16kV prototype

- Hardware validation/optimization
- Controls testbed
- Integration/protection validation

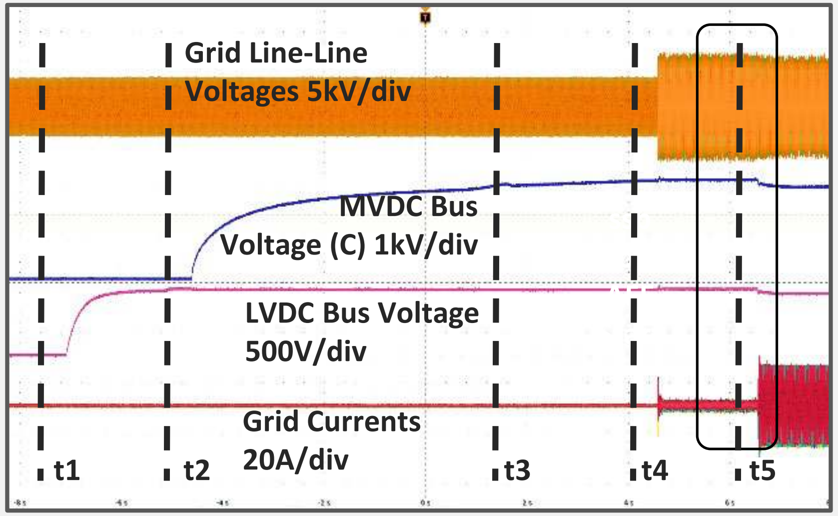


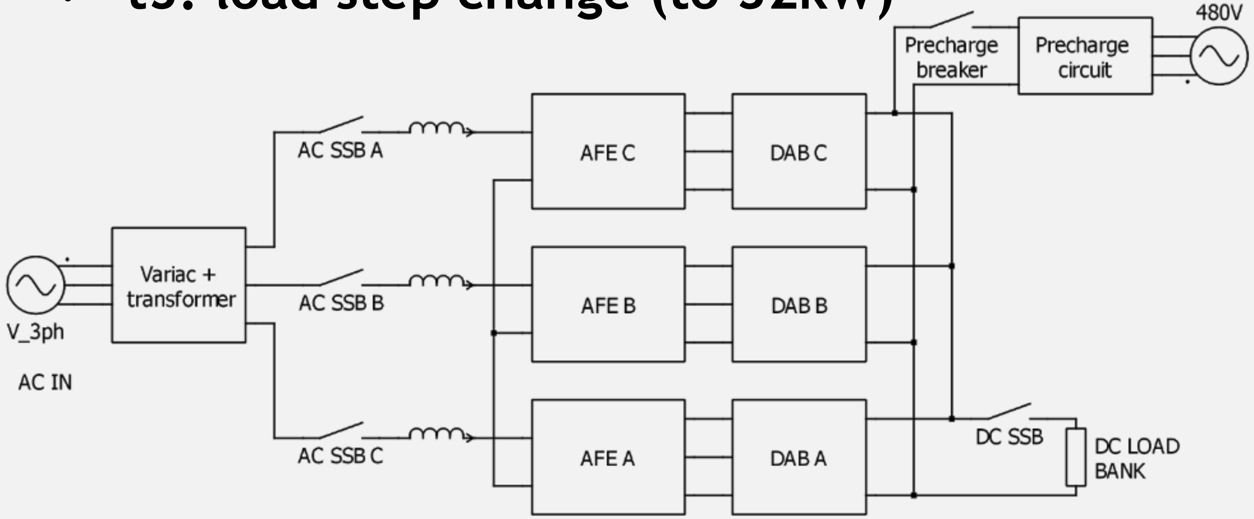
1,000kVA 13.2kV prototype

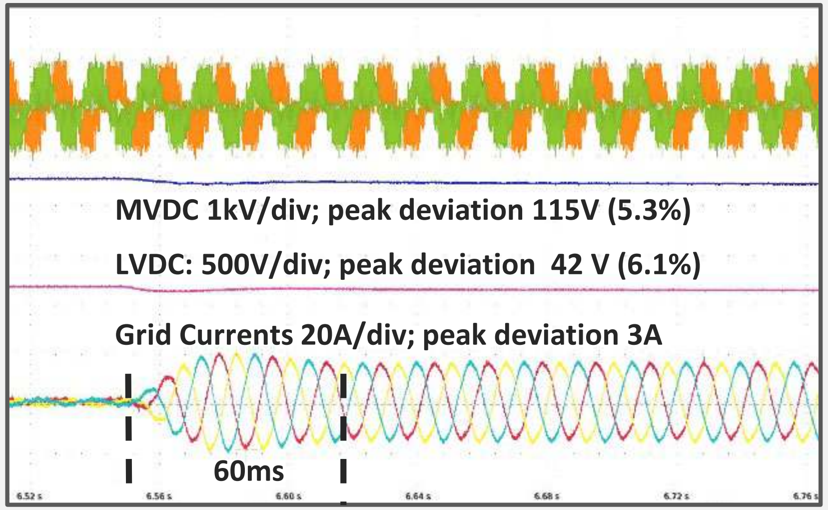
- Uses optimized and right-sized 500kVA components
- Field Deployment

500kVA Prototype Testing: Three Phase Startup and Load Change

- t1: Pre-charge circuit breaker closes
- t2: DAB charges MVDC bus in open loop
- t3: DAB control loop closes and regulates MVDC bus
- t4: AC and DC SSB close; pre-charge circuit disconnects; AFE starts
- **t5: load step change (to 32kW)**

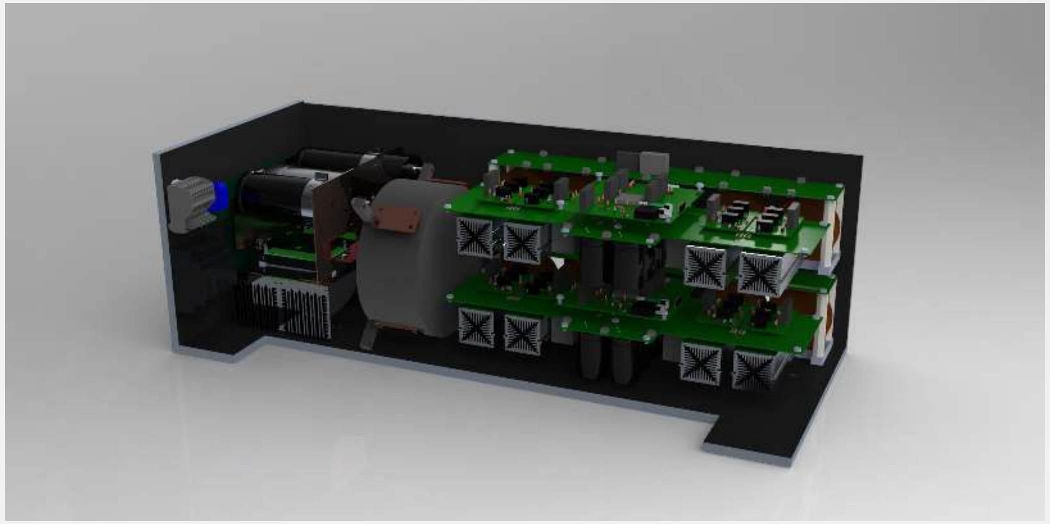






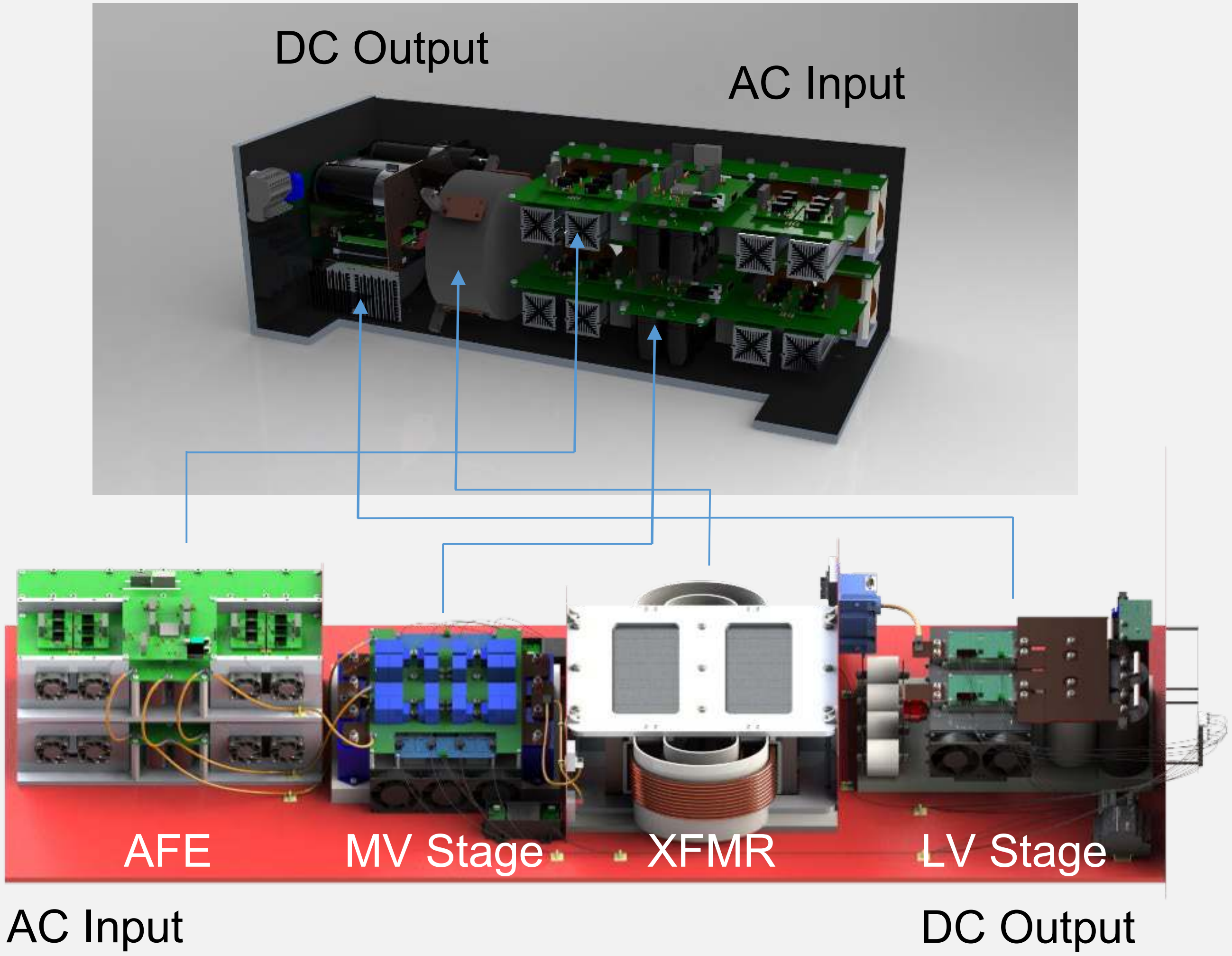
1,000kVA Prototype

- System made of 18 identical modules
- Each L-N phase made of 6 modules in a single rack
- SST dimensions 1x1.5x2m (3,000L)
- Weight is approximately 2,000kg
- Current focus on single module design construction and testing



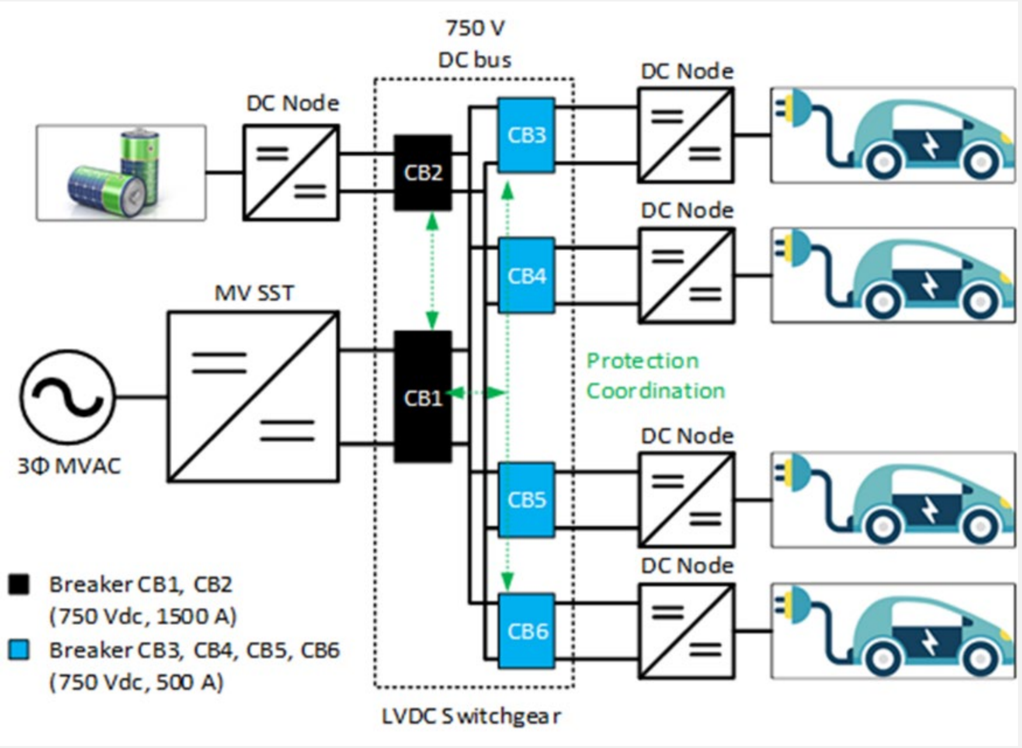
1,000kVA Prototype

- Builds on the lessons learned form 500kVA prototype
- Utilizes same validated low cost building block with TO-247 SiC Devices for AFC and MV Stage
- Module volume reduced from (6x18x5 dm3 = 540L) to (5x10x3dm=75L)



DC Distribution with Solid-State Protection

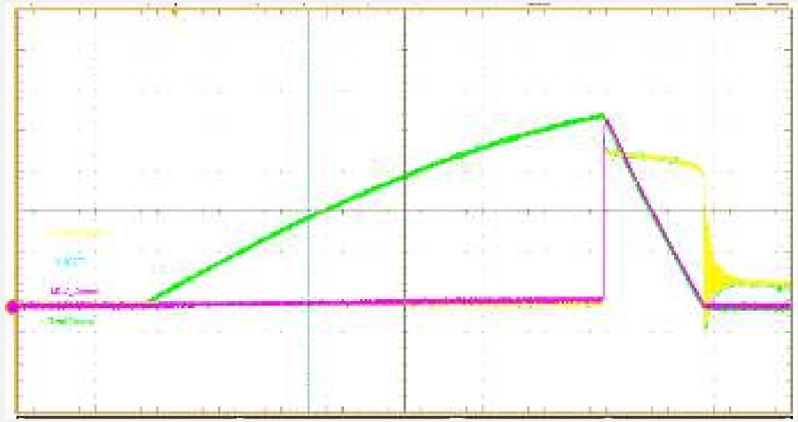
- High penetration of power converters requires fast system protection components and algorithms to be developed
- Commercially available DC breaker and fuses technology is not fast enough to guarantee protection coordination
- We are developing two classes of Solid State Circuit Breakers (1500 A and 500 A) and fast fault detection and coordination algorithms



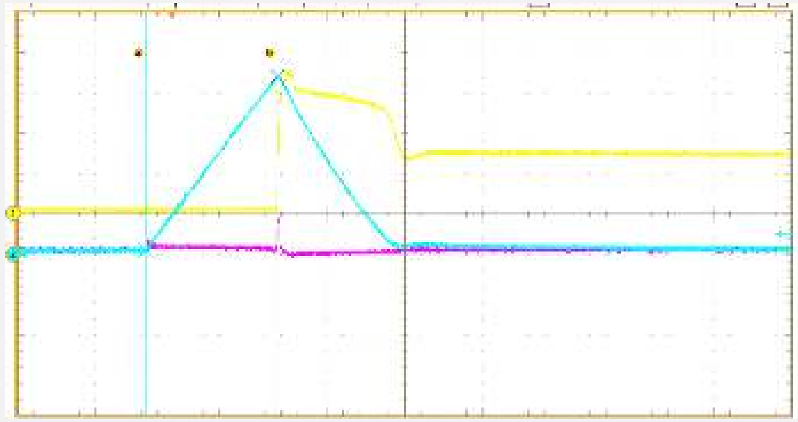
Testing of Breaker Prototypes

- Validation of short circuit performance of breaker B1/1500A
- Validation of short circuit performance of breaker B2/500A
- Validation of short circuit at very low inductance (< 5 uH)
- Validation of thermal performance at nominal rated current
- Validation of high performance trip unit

High Inductance Short Circuit Test



Low Inductance Short Circuit Test

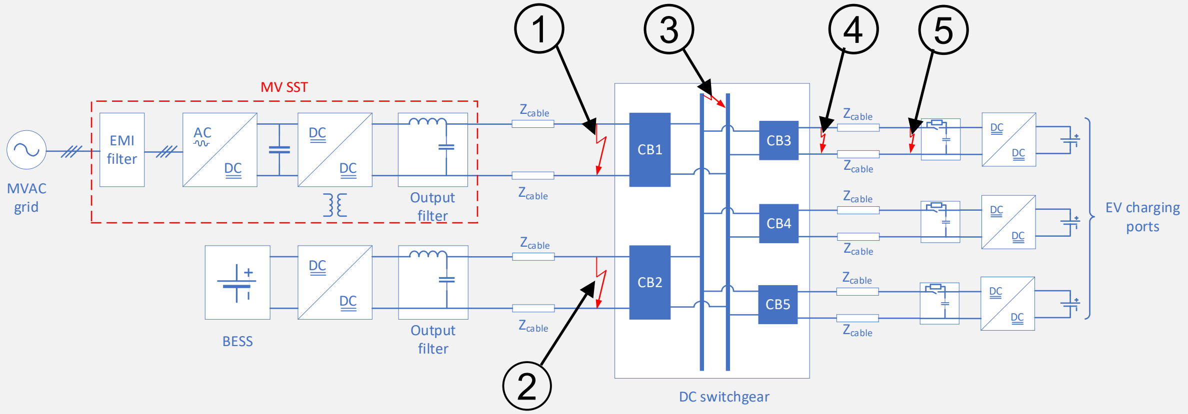


Representative Tests Passed (TRL6)

- Nominal rated current performance
  - Temperature rise test at 1500 A for B1/1500A (passed)
  - Temperature rise test at 500 A for B2/500A (passed)
- Short circuit performance
  - Current interruption test at -1500 A/+4500 A for B1/1500A (passed)
  - Current interruption test at +1500 A for B2/500A (passed)
- Validation of short circuit at very low inductance (< 5 uH) (passed)
- Validation of steady state voltage withstand at 1.1 kV (passed)
- Validation of remote control (ON / OFF / Reset) (to be done)

System Tests Passed

- Main DC bus faults
  - Tripping of both CB1 and CB3 (passed)
  - Isolation of faulty section (passed)
- Load Side faults
  - Charge point fault – coordination between CB1 and CB3 (passed)
  - Charge line fault – coordination between CB1 and CB3 (passed)
- Main Source Faults (to be done)
- BESS Source Faults (to be done)

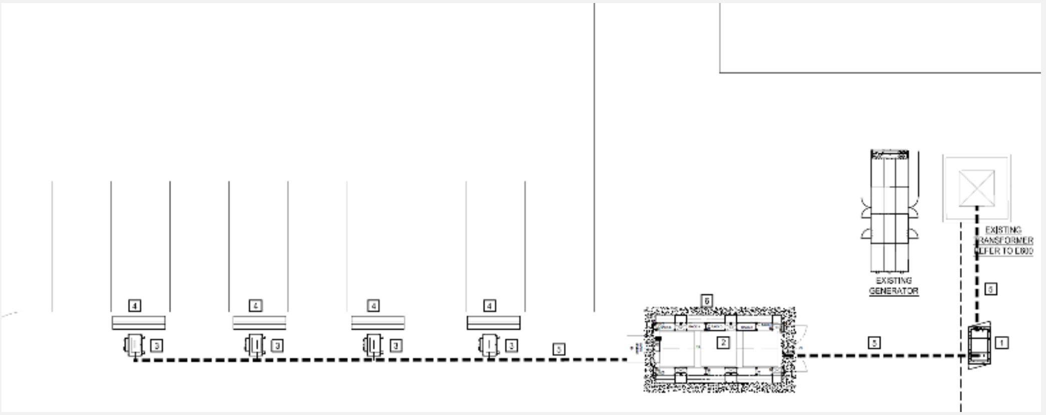


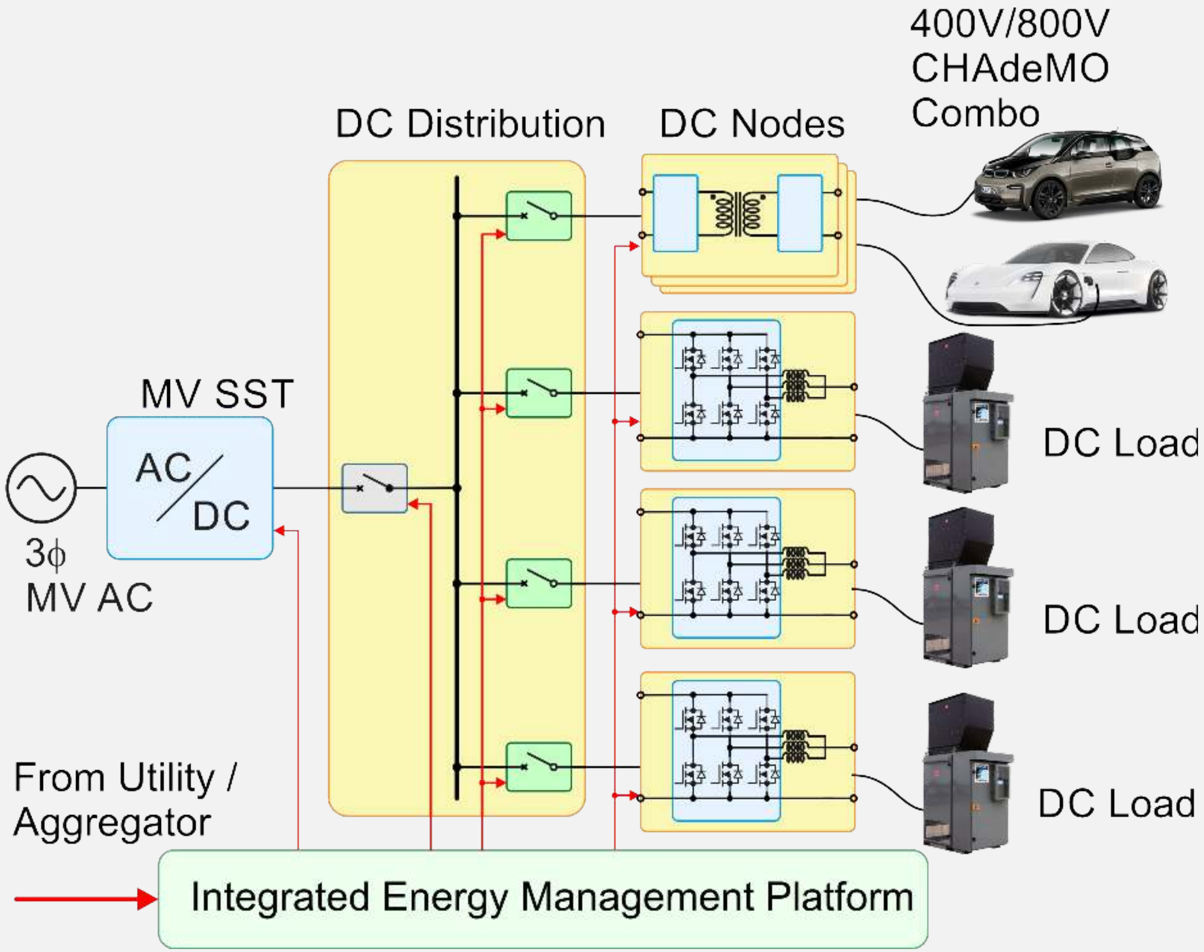
System Test Use Cases

Planned System Demonstration

Demonstration of key functionality:

- Vehicle charging
- System loading up to 1MVA
- DC protection scheme validation
- Reactive power control
- Demand response





System integration

Mechanical Breaker & Metering

MV AC Breaker

SST

DC Breaker

Site Layout (Marcy, NY)

Responses to Previous Year Reviewers' Comments

It would be helpful if the review explained the reasoning behind the 480 V versus high voltage—economic or technical benefits of this approach. It would also be helpful if the review clearly explained why a solid-state transformer was chosen or beneficial over conventional approach.

Power:	**720 kW**	40% more power	**1,000 kW**
Volume:	**12,910 L**	2x volume reduction	**6,000 L**
Mass:	**13,000 lb.**	3x mass reduction	**4,000 lb.**
Efficiency:	**92%**	4x loss reduction	**98%**
Concrete pad:	**177 sq. ft.**	2.5x footprint reduction	**75 sq. ft.**

Responses to Previous Year Reviewers' Comments (cont'd)

Coordination and communication across partners seem good, but a work breakdown structure or some type of system work plan would help communicate this (i.e., who is working on what piece).

See next slide

Collaboration & Coordination with Other Institutions

- **NCSU:** SST, DC Node (DC/DC converter) development; XFC system integration.
- **ABB:** development and testing of the solid-state breakers and system protection scheme. Help identify and source near-commercial DC/DC stage
- **NYPA:** system deployment and demonstration.

Remaining Challenges and Barriers

SST Stage:

Complete Assembly and testing of SST; contracting delays, component sourcing and covid-19 pandemic.

DC Protection:

Testing of breaker units for short circuit with very high di/dt typical of the proposed system architecture. Testing of coordination between upstream and downstream breakers with high di/dt short circuit fault scenarios.

Integration:

Managing logistics of component integration and deployment @ site

Proposed Future Work

Key Challenges

- Design of the SST stage, meeting key safety requirements
- Design and coordination of solid state protection
- Procuring vehicle loads capable of stressing the charger system
- System Integration

Future Work

- System Integration
- System Deployment

Any proposed future work is subject to change based on funding levels

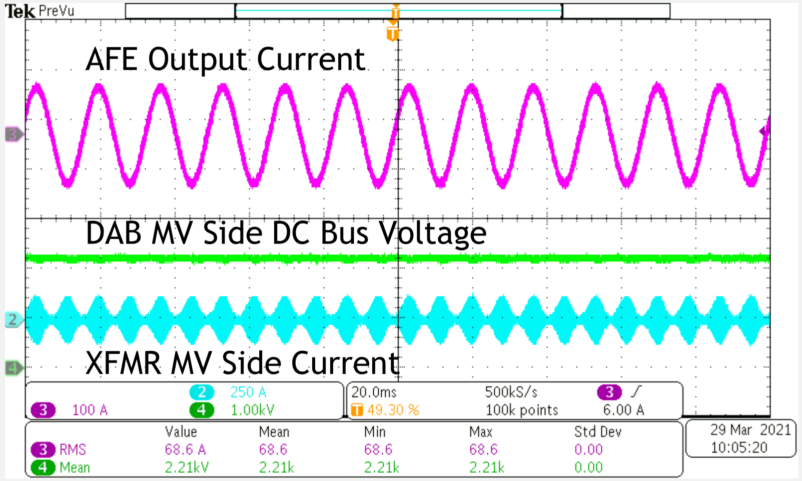
Summary

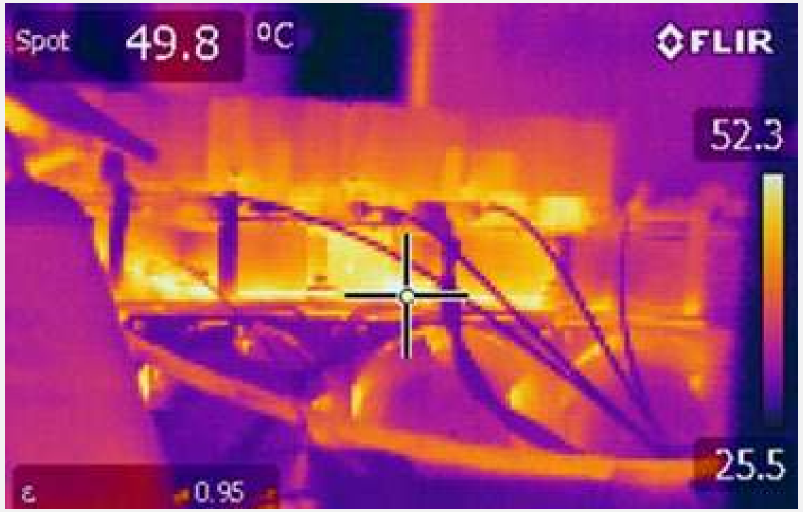
- Team on track to demonstrate a 1MVA XFC station with
  - A MV SST that connects directly to distribution grid
  - A shared DC bus that allows for local energy management to alleviate stress on the grid
- Three year project plan:
  - 2020: Component Validation
  - 2021: System validation
  - 2022: System Deployment and Data Collection

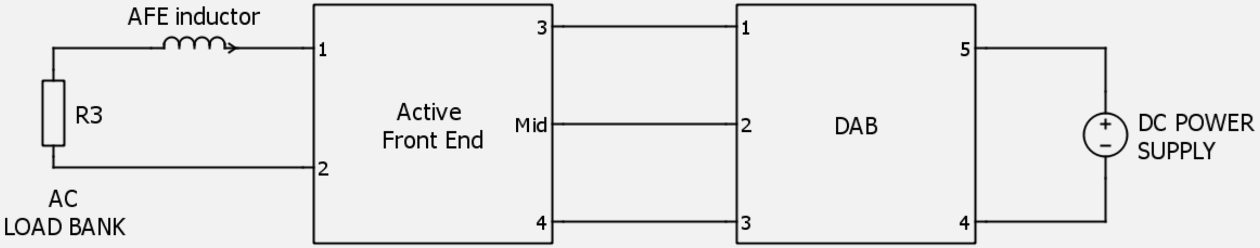
Technical Backup Slides

500kVA Prototype Single Module Testing & Thermal Validation

- Single module tested at 85 kW in DC to AC operation mode at rated voltage (750V DC in, 1200 Vrms AC out)
- Thermal capability verified at 85 kW; temperature rise under 40°C in steady state
- Repeated for each of the 6 modules.

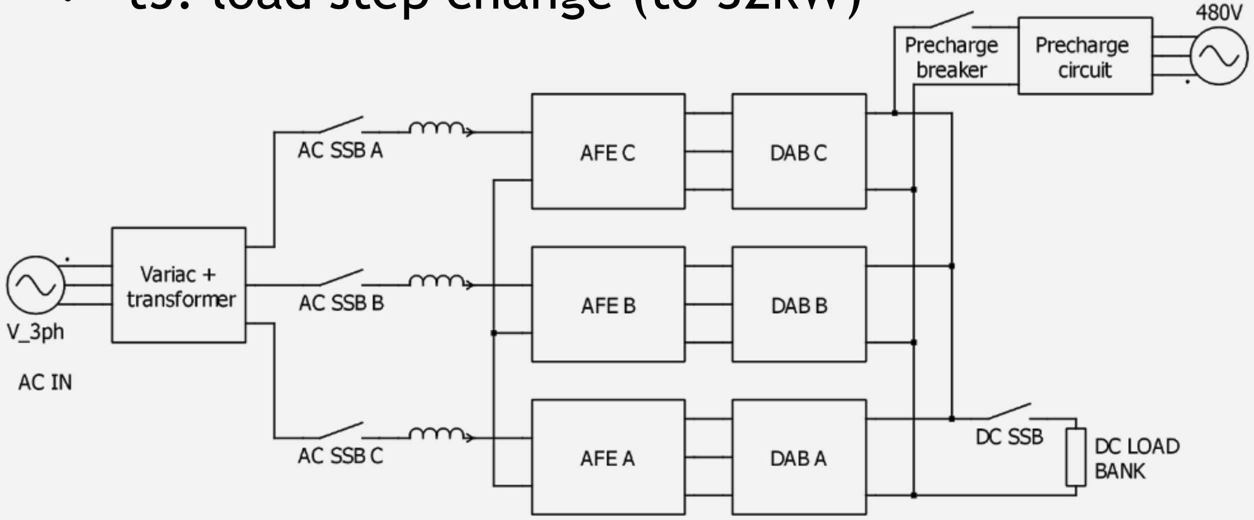


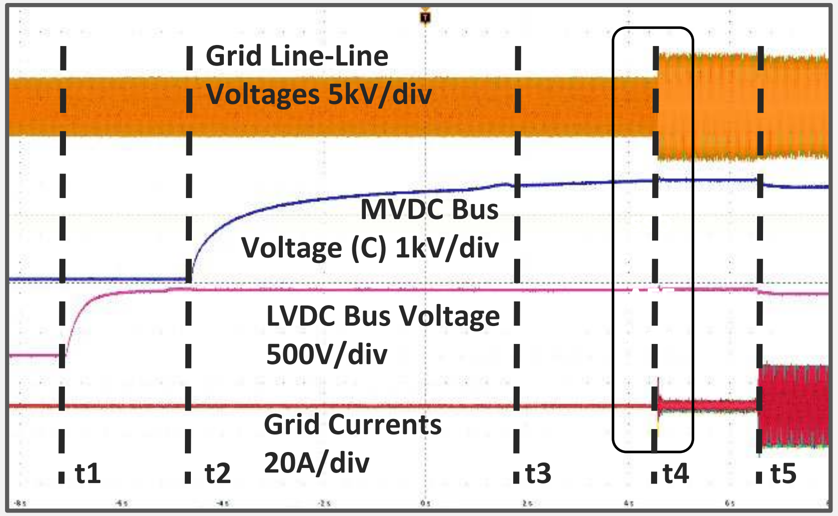


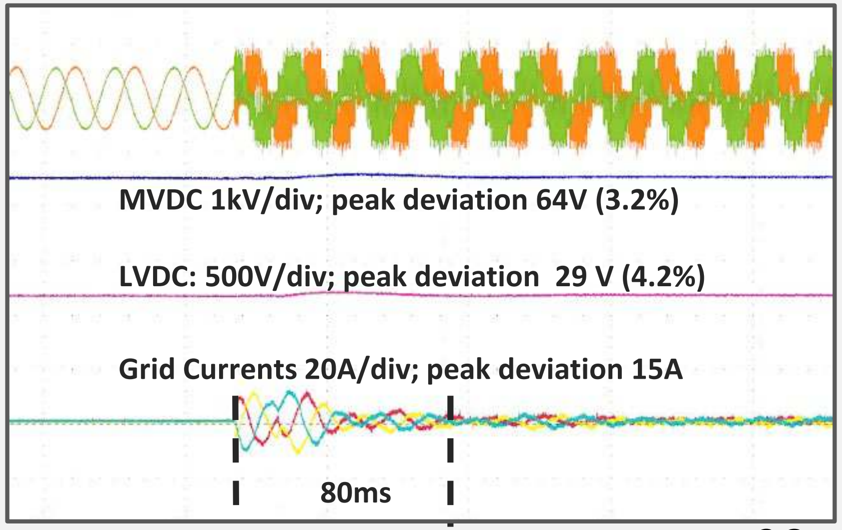


500kVA Prototype Testing: Three Phase Startup and Load Change

- t1: Pre-charge circuit breaker closes
- t2: DAB charges MVDC bus in open loop
- t3: DAB control loop closes and regulates MVDC bus
- **t4: AC and DC SSB close; pre-charge circuit disconnects; AFE starts**
- t5: load step change (to 32kW)





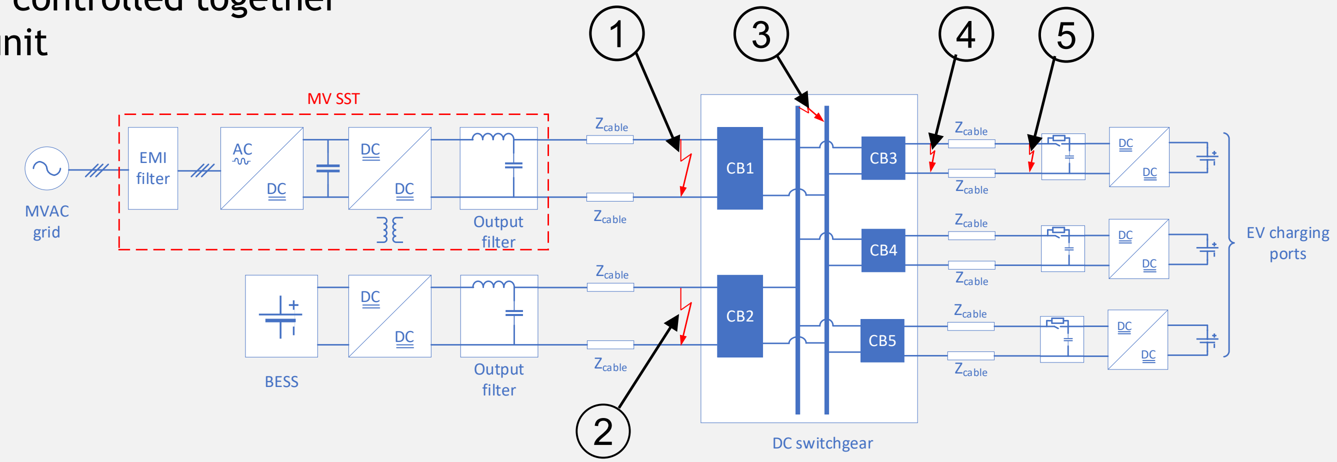


Coordination test details – Location 3

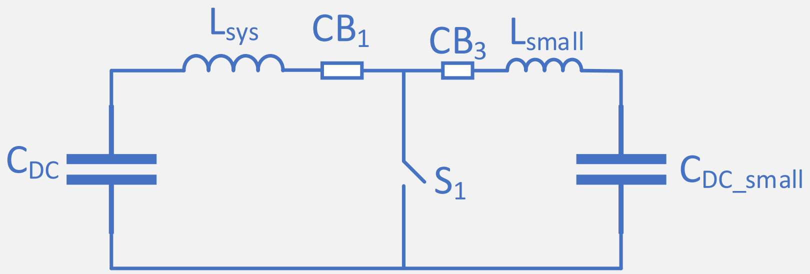
Testing conditions:
B1 and B2 breaker are connected in series

- Both poles of each breaker are connected in series and controlled together
- C_{DC_small} emulates input DC bus capacitor of a charger unit
- Trip thresholds:
  - CB1 – 4.5kA
  - CB3 – 1.5kA

System inductances tested: ~300 uH
Applied DC bus voltage: up to 1kV



Schematic representation of the test Circuit



System Inductance [µH]	Voltage	Peak Current [A]	di/dt [A/µs]	trip time [µs]	Peak Voltage [kV]	B1 Trip	B2 gated OFF
~300	200	1620	-	-	-	No	Yes
	300	-1300	-0.433	~3000	-	Yes	Yes
	500	~-1350	-0.86	~1600	-	Yes	Yes
	500	-1400	-0.93	~1500	-3.9	Yes	Yes
	750	4540	~2	~2300	4.54	Yes	Yes
	750	4500	~1.7	~2700	-	Yes	Yes
	1000	4540	2.84	~1600	4.46	Yes	Yes

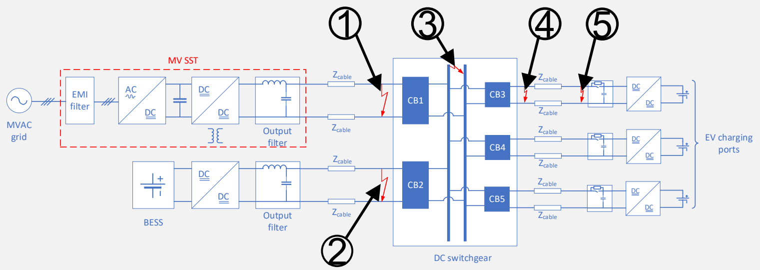
Coordination test details – Location 3

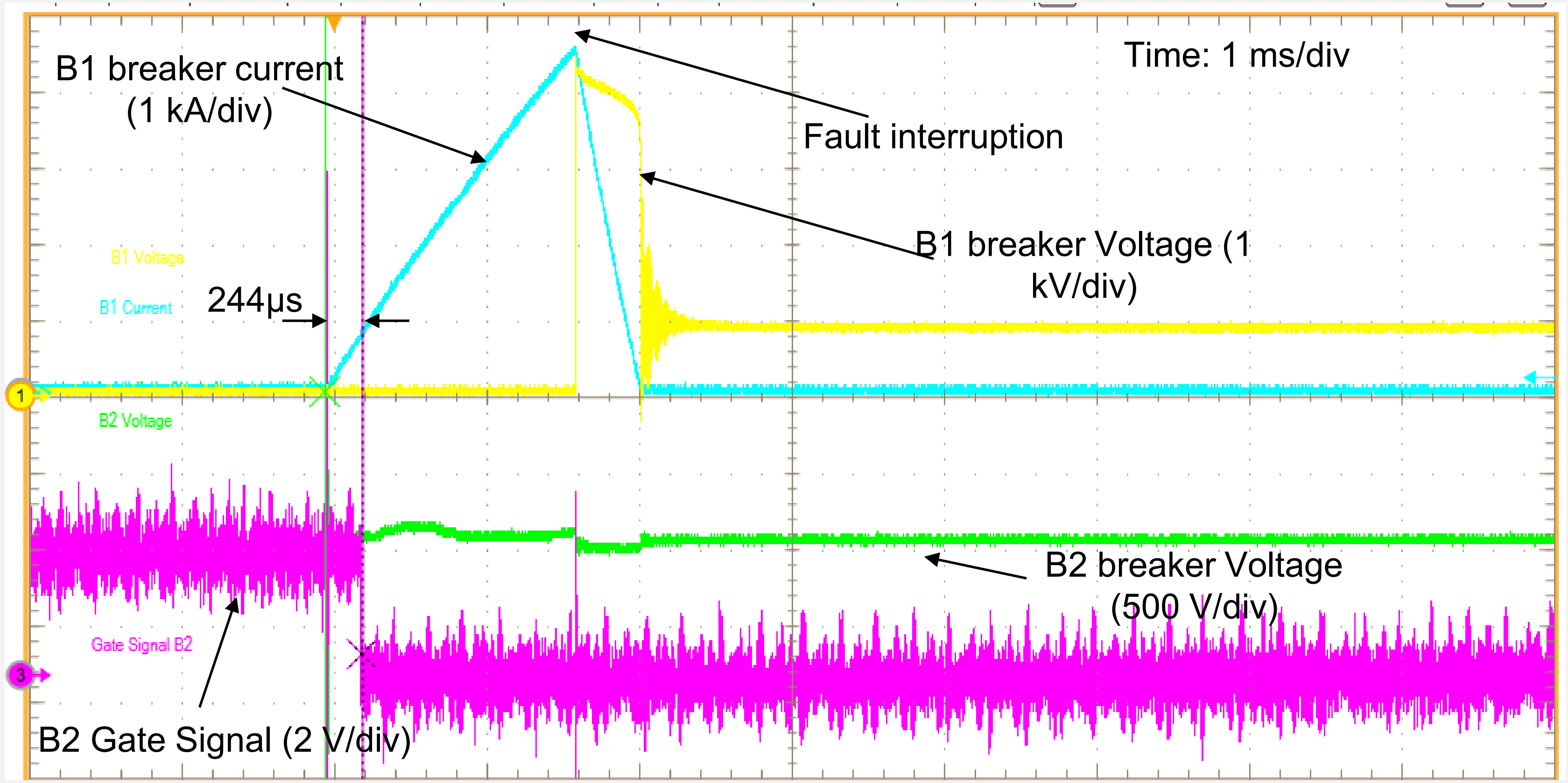
Test Conditions:

- DC Voltage= 1000 V
- B1 current threshold= 4.5 kA
- B2 current threshold= 1.5 kA
- System inductance = ~300 μH

Comments:

- B1 tripped
- B2 gate turned off
- Positive peak current: 4.54 kA
- Positive peak voltage: 4.46 kV
- Trip time: 1.6 ms





Successfully validated tripping/ turn-off of both breakers and fault isolation for a fault within switchgear cabinet

Reviewer-Only Slides

Publications & Presentations

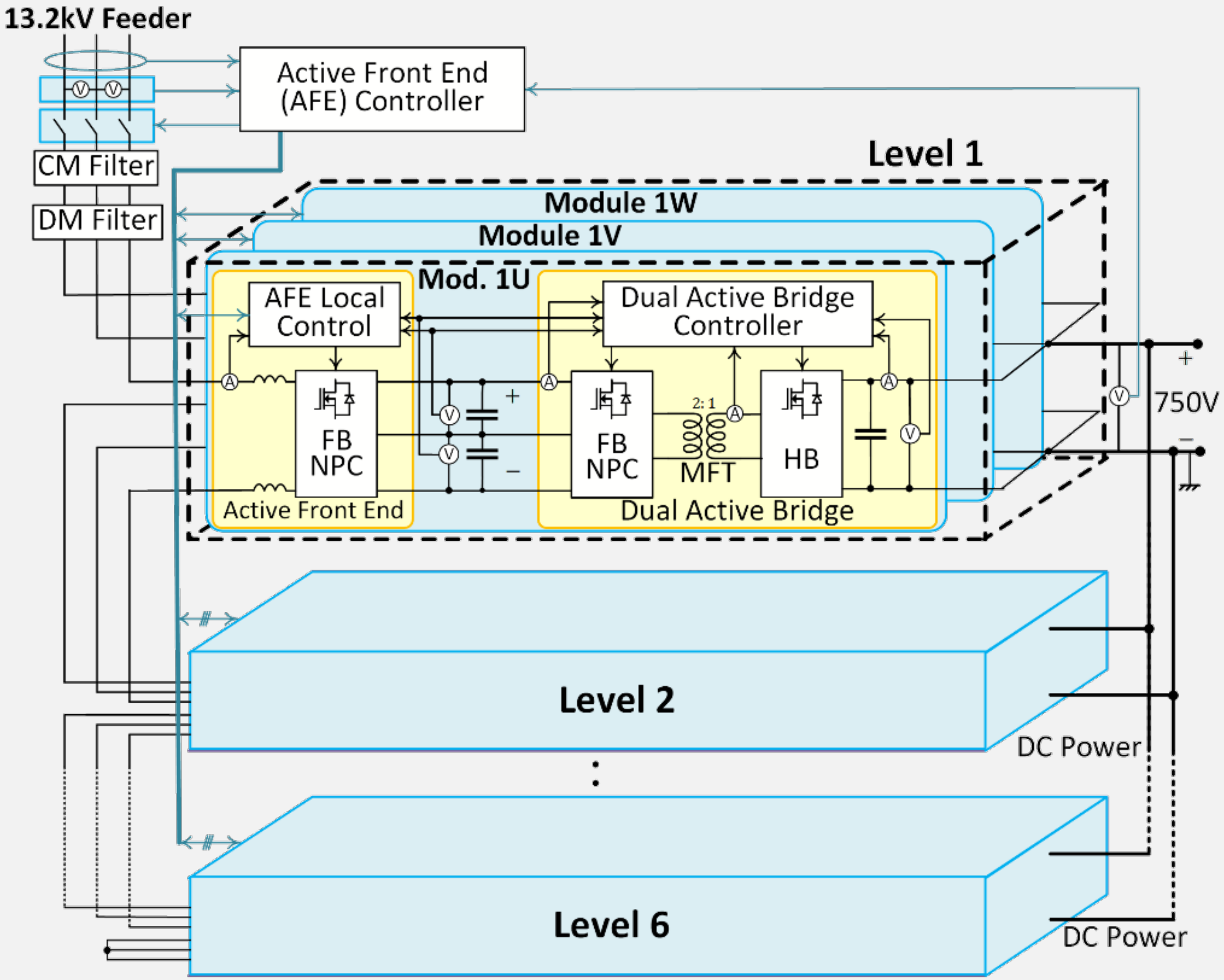
- H. Tu, H. Feng, S. Srdic and S. Lukic, "Extreme Fast Charging of Electric Vehicles: A Technology Overview," in *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 861-878, Dec. 2019.
- M.A. Awal, I Husain, Md R. H. Bipu, O. Montes, F. Teng, H. Feng, M. Khan, S. Lukic “Modular Medium Voltage AC to Low Voltage DC Converter for Extreme Fast Charging Applications”, arXiv preprint, submitted June 2020, arXiv:2007.04369
- M.A. Awal, Md. Bipu, O. Montes, H. Feng, I. Husain, W. Yu and S. M. Lukic, “Capacitor Voltage Balancing for Neutral Point Clamped Dual Active Bridge Converters”, in *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 11267-11276, Oct. 2020.
- L. Qi, P. Cairoli, Z. Pan, C. Tschida, Z. Wang, V. R. Ramanan, L. Raciti, A. Antoniazzi, “Solid-State Circuit Breaker Protection for DC Shipboard Power Systems: Breaker Design, Protection Scheme, Validation Testing” in *IEEE Transactions on Industry Applications*, Vol. 56, No. 2 , March-April 2020
- Dakai Wang and Wensong Yu, “Series Connection of SiC MOSFETs with Hybrid Active and Passive Clamping for Solid State Transformer Applications,” presented at *2019 IEEE 7th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Raleigh, NC, October 2019.
- S. Chen, M. Bipu, D. Wang and W. Yu, "Analysis and Solution of the Unbalanced Device Voltage Issue for SiC MOSFET Based Diode Neutral Point Clamped Converter," presented at *2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, New Orleans, LA, USA, March 2020
- MA Awal, Iqbal Husain, Md Rashed Hassan Bipu, Oscar Andreas Montes, Fei Teng, Hao Feng, Mehnaz Khan, Srdjan Lukic, “Modular Medium Voltage AC to Low Voltage DC Converter for Extreme Fast Charging Applications” *arXiv preprint* arXiv:2007.04369
- P. Cairoli, R. Rodrigues, U. Raheja, Y. Zhang, L. Raciti, A. Antoniazzi, “High Current Solid-State Circuit Breaker for safe, high efficiency DC systems in marine applications”, *2020 IEEE Transportation Electrification Conference and Expo (ITEC)*, 24-26 June 2020, Chicago, IL
- R. Rodrigues, U. Raheja, P. Cairoli, L. Raciti and A. Antoniazzi, "Accelerated aging test of Solid-State DC Circuit Breaker based on 2.5 kV Reverse Blocking IGCT," *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 6024-6029.
- Y. Zhang, U. Raheja, R. Rodrigues, P. Cairoli, L. Raciti and A. Antoniazzi, "Experimental Validation of Parallel Connection of RB-IGCTs for High Efficiency Solid State Circuit Breaker," 2020 I*EEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 6036-6042.
- R. Rodrigues, U. Raheja, Y. Zhang, P. Cairoli and A. Antoniazzi “Power loop busbars design and experimental validation of 1 kV, 5 kA Solid-State Circuit Breaker using parallel connected RB-IGCTs” *2020 IEEE IAS annual meeting*, October 2020
- R. Rodrigues, Y. Du, A. Antoniazzi, P. Cairoli, “A Review of Solid-State Circuit Breakers”, *IEEE Transactions on Power Electronics*, Vol. 36, No. 1, January 2021
- R. Rodrigues, U. Raheja, Y. Zhang, P. Cairoli, A. Antoniazzi, “Power loop busbars design and experimental validation of 1 kV, 5 kA Solid-State Circuit Breaker using parallel connected RB-IGCTs”, IEEE Transactions on Industry Applications, 26 February 2021

Critical Assumptions & Issues

- Availability of vehicle loads capable of stressing the charger system; use of resistive loads to emulate vehicle loads
- Covid-19 pandemic has affected the availability of components and services and the ability to access laboratory facilities to complete system assembly and testing; team has developed a plan to continue the work remotely as much as possible
- Availability of off-the-shelf sub-systems such as the DC/DC converter (ie. DC node), high frequency transformers, vehicle interfaces (CHAdeMO, Combo). To mitigate risks the team is actively developing these components if the off-the-shelf solutions do not meet the requirements or become unavailable due to supply chain issues.
- Testing of coordination between upstream and downstream breakers with high di/dt short circuit fault scenarios. Team will rely on high-fidelity simulations for initial validation.

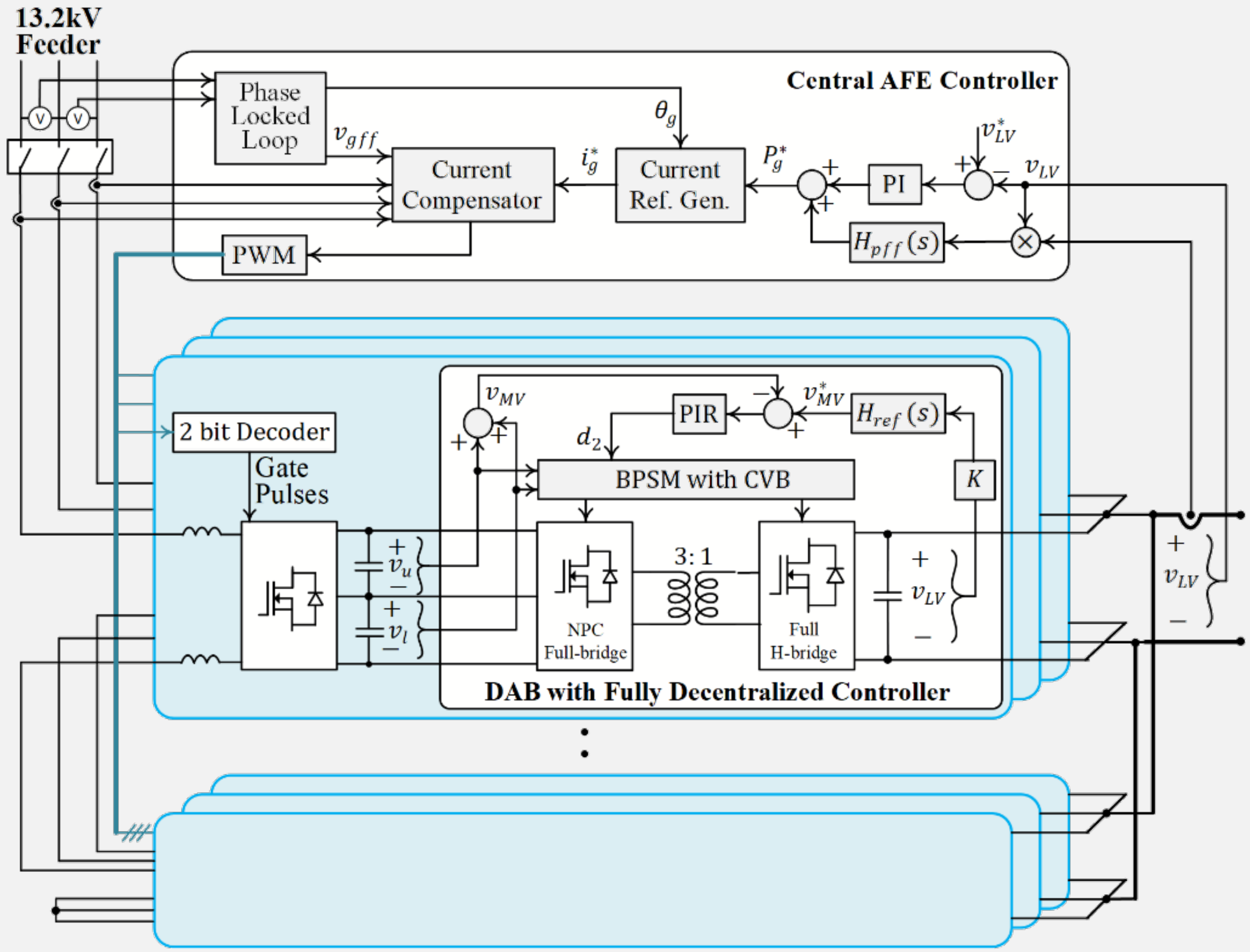
SST Architecture

- The SST connects to three-phase 13.2kV$_{LL}$ input and delivers 750V DC
- A total of 18 modules are arranged in 6 levels using input-series output-parallel configuration
- Each level is made up of three modules processing three-phase power on the input and delivering DC power at the output
- Each module consists of an active front end (AFE) and dual-active-bridge (DAB) isolated DC-DC stage



Design Approach & Control Architecture

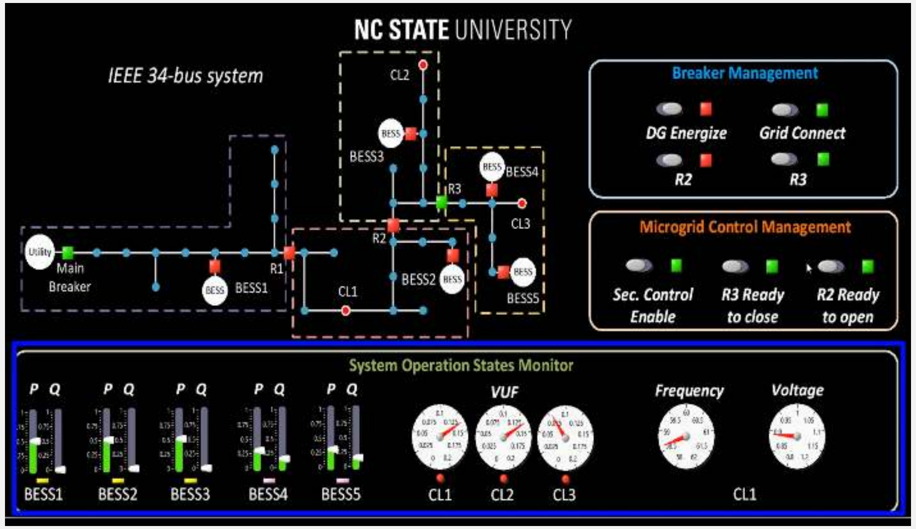
- Each Dual active bridge (DAB) autonomously regulates its medium voltage (MV) bus, minimizing communication requirements
- Centralized controller for all AFEs with local protection and decoding
- Interleaved modulation of AFEs and low voltage (LV) side bridges of DABs
- DABs designed for sinusoidal power flow, minimizing storage requirements on MV DC capacitors
- Solid-state protection on MV and LV



$H_{ref}(s)$ and $H_{pff}(s)$ are low-pass filters
PIR -- Proportional Resonant Integral Controller
BPSM with CVB -- Bidirectional phase-shift modulator with capacitor voltage balancing

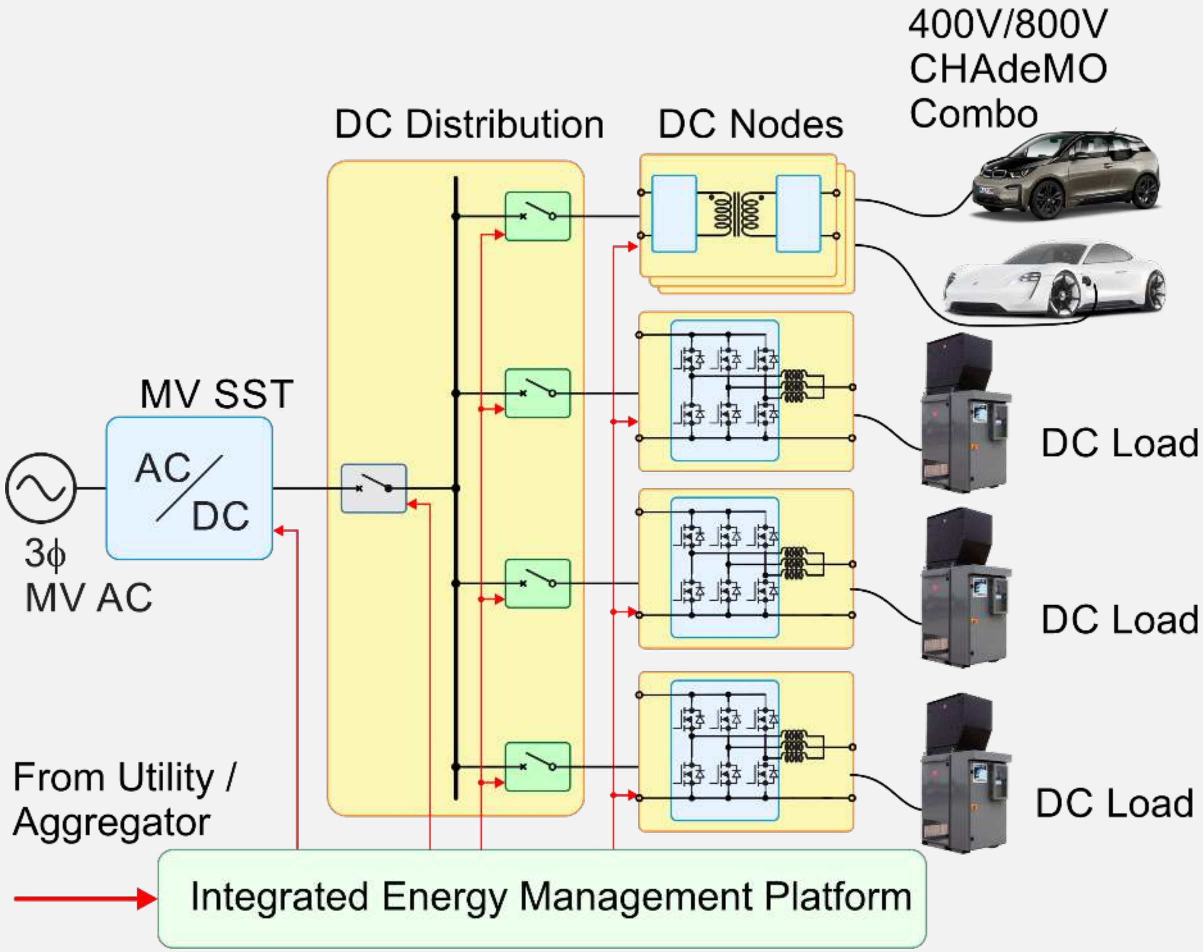
Energy Management Platform

- Developed for system demo; not the main focus
- Communicates to all system components
- Available remotely over secure link
- Based on RIAPS - Resilient Information Architecture Platform for the Smart Grid



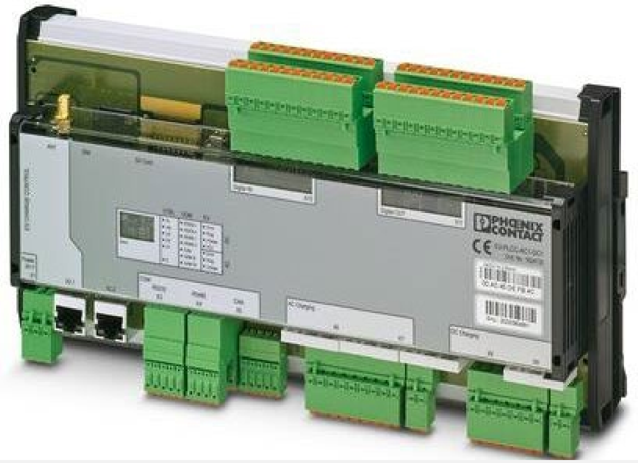
Example interface compatible with RIAPS* platform

*https://riaps.isis.vanderbilt.edu/

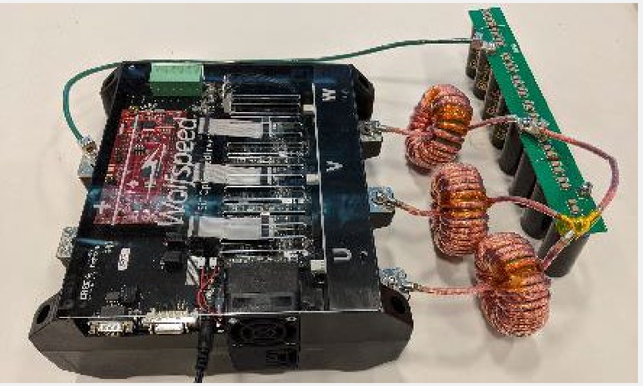


DC/DC Stage Implementation

- DC Head end unit will use an off-the-shelf Wolfspeed inverter (CRD300DA12E-XM3) to deliver 300kW per unit to the load or vehicle
- Non-isolated interleaved buck converter for interface to load (single CRD300DA12E-XM3)
- Isolated DAB followed by buck used for design that interfaces to vehicle (isolated design uses three CRD300DA12E-XM3)
- Phoenix CHARGEX module for communication to the vehicle.



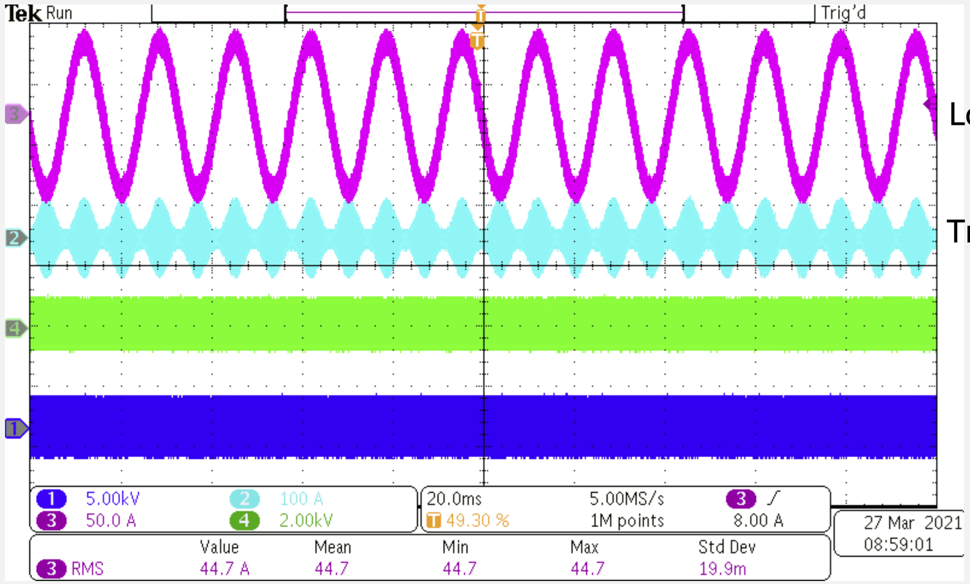
Phoenix CHARGEX module for communication



Non-isolated interleaved buck prototype

Transformer Testing

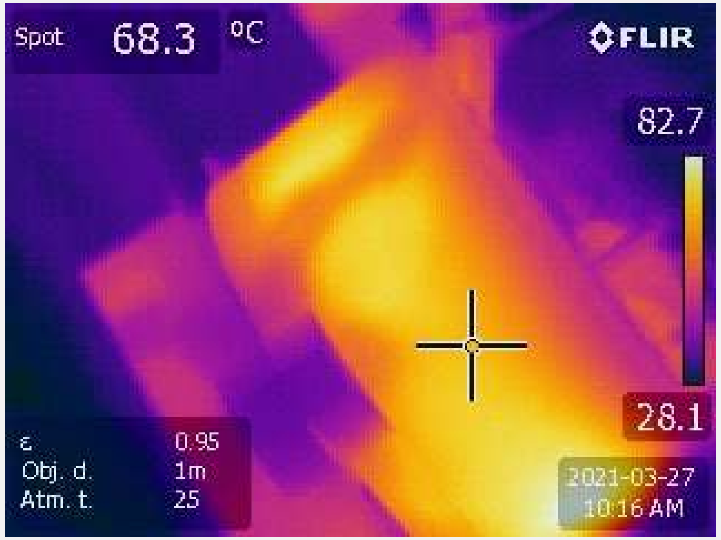
- Transformer presents the most heat-dense component
- Each transformer comprehensively tested before insertion into system:
  - Electrical performance(inductance, coupling capacitance)
  - Thermal performance
  - Partial discharge



Load Output Current

Transformer current
HV side

Detail of transformer



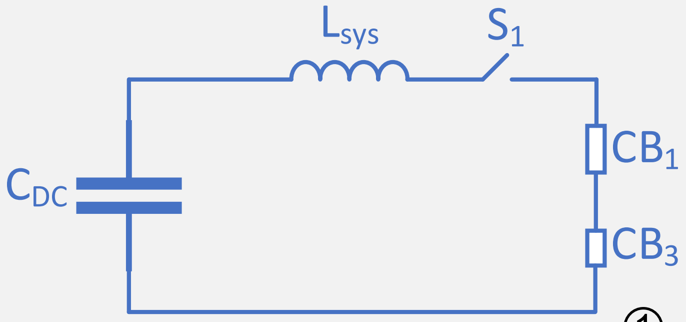
Thermal verification of transformer

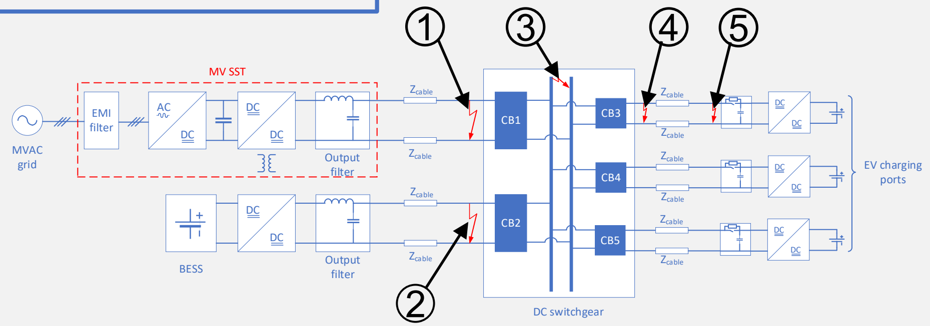
Breaker Coordination test details – Location 4 & 5

Testing conditions:
B1 and B2 breaker are connected in series.

- Both poles of each breaker are connected in series and controlled together
- Trip thresholds:
  CB1 – 4.5kA
  CB3 – 1.5kA

System inductances tested: ~300 uH, 60 uH, 40 uH
Applied DC bus voltage: up to 1kV





Summary of tests conducted

System Inductance [µH]	Voltage	Peak Current [A]	di/dt [A/µs]	trip time [µs]	Peak Voltage [kV]	B1 Trip	B2 Trip
~300	200	1450	0.495	3900	-	no	Yes
	200	1460	0.473	3980	3.76	no	Yes
	300	1460	0.71	2020	3.76	no	Yes
	500	1480	1.28	1112	3.76	no	Yes
	750	1500	2.14	698	3.8	no	Yes
	750	1500	2.14	696	3.76	no	Yes
	750	1480	2.05	696	3.8	no	Yes
	1000	1500	2.83	507	3.8	no	Yes
	1000	1500	2.8	503	3.8	no	Yes
	1000	1500	2.91	498	3.8	no	Yes
~60	100	1460	1.39	1438	3.64	no	Yes
	200	1500	2.75	708	3.68	no	Yes
	500	1540	7.37	206	3.72	no	Yes
	750	1600	11.3	136	3.72	no	Yes
	750	1600	11.31	136	3.76	no	Yes
	750	1600	11.31	136	3.76	no	Yes
	1000	1640	16.34	102.6	3.76	no	Yes
	1000	1640	15.1	102.6	3.72	no	Yes
	1000	1620	15.2	101	3.76	no	Yes
~40	100	1500			3500	no	Yes
	200	1520	2.98	480	3560	no	Yes
	500	1600	10.22	148	3640	no	Yes
	500	1600	10.82	144	3680	no	Yes
	750	1660	16.89	96.2	3640	no	Yes
	750	1640	16.14	98.4	3640	no	Yes
	750	1680	16.14	97.2	3680	no	Yes
	1000	1720			3720	no	Yes
	1000	1700	21.7	73.8	3720	no	Yes
	1000	1680	22.22	73.6	3720	no	Yes
	1000	1680	23.077	73.6	3720	no	Yes

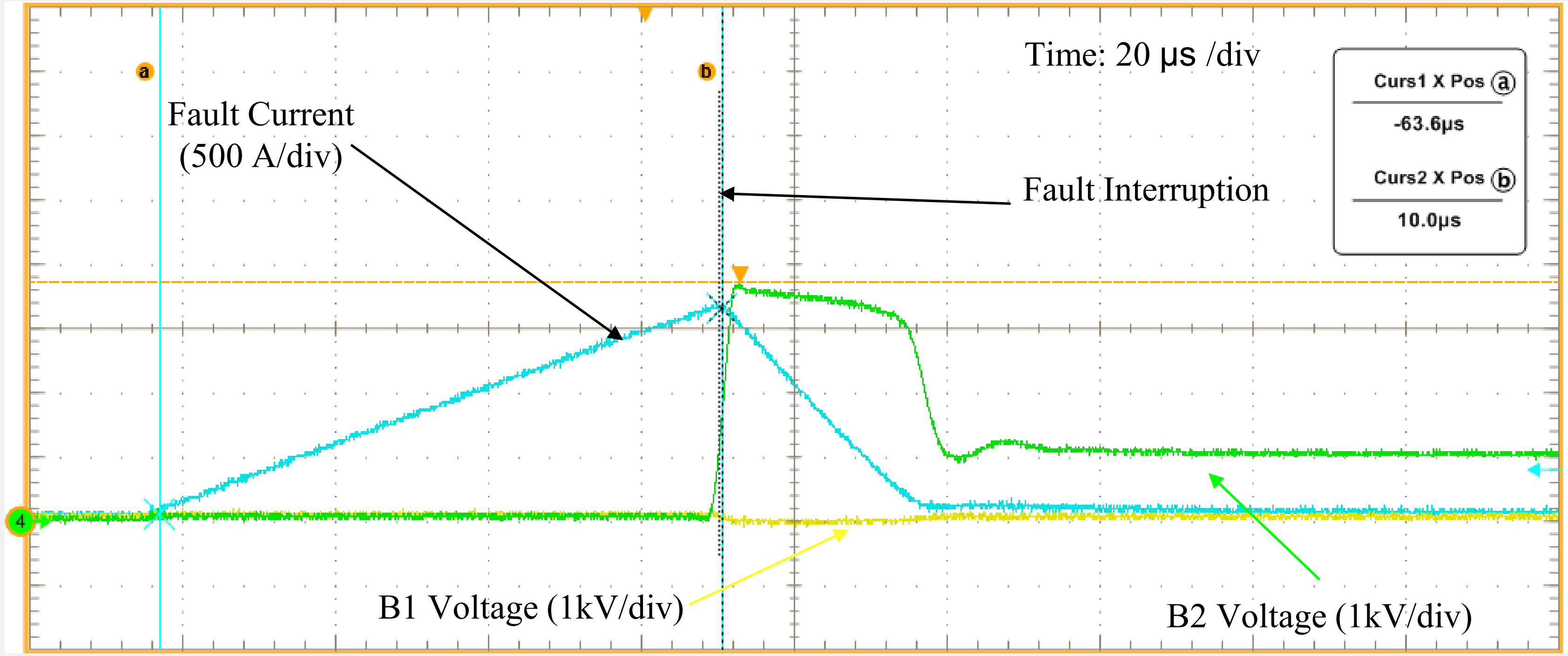
Breaker Coordination test details – Location 4 & 5

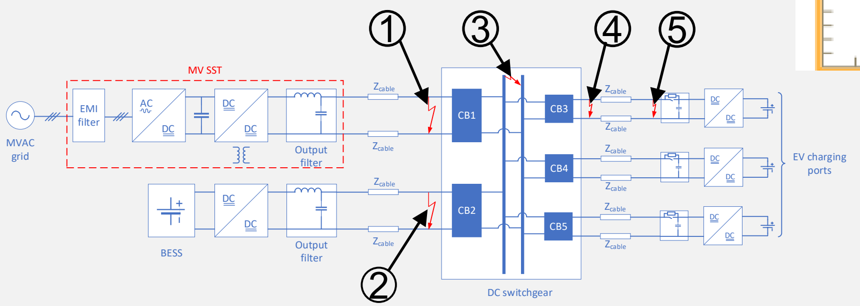
Test Conditions:

- DC Voltage= 1000 V
- B1 current threshold= 4.5 kA
- B2 current threshold= 1.5 kA
- System inductance = ~40 μH

Comments:

- B2 tripped
- Positive peak current: 1.68 kA
- Positive peak voltage: 3.72 kV
- di/dt: 23.1 kA/μs
- Trip time: 73.6 μs





V_{DC} = 1000V; L_{sys} = ~40μH

Fault coordination between upstream and downstream breaker validated successfully for a downstream fault

Switchgear design and assembly

Overall system dimension:

- 1600W 1200D 2000H

Switchgear composition:

- 1 main source breaker 1500 A
- 1 BESS breaker up to 1500 A
- 4 charger breakers 500 A each

Forced air ventilation for heat removal

Distribution bus structure

Off the shelf components

Forced air DC switchgear for solid state circuit breakers