FSU-CAPS Experiences with Large Scale Power Hardware-in-the-Loop (PHIL) Testing

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1st International Workshop on
Grid Simulator Testing of Wind Turbine Drivetrains

June 13, 2013, Boulder, CO

FSU Center for Advanced Power Systems

- Established at Florida State University in 2000 under a grant from the Office of Naval Research
- Organized under FSU VP for Research
- Affiliated with FAMU-FSU College of Engineering
- Lead Member of ONR Electric Ship R&D Consortium
- Focusing on research and education related to application of new technologies to electric power systems
- ~$8 million annual research funding from ONR, DOE, Industry
- DOD cleared facility at Secret level

Research Groups

- Electric Power Systems
- Advanced Modeling and Simulation
- Advanced Control Systems
- Power Electronics Integration and Controls
- Thermal management
- High Temperature Superconductivity
- Electrical Insulation/Dielectrics

Staffing

Employing 102, including

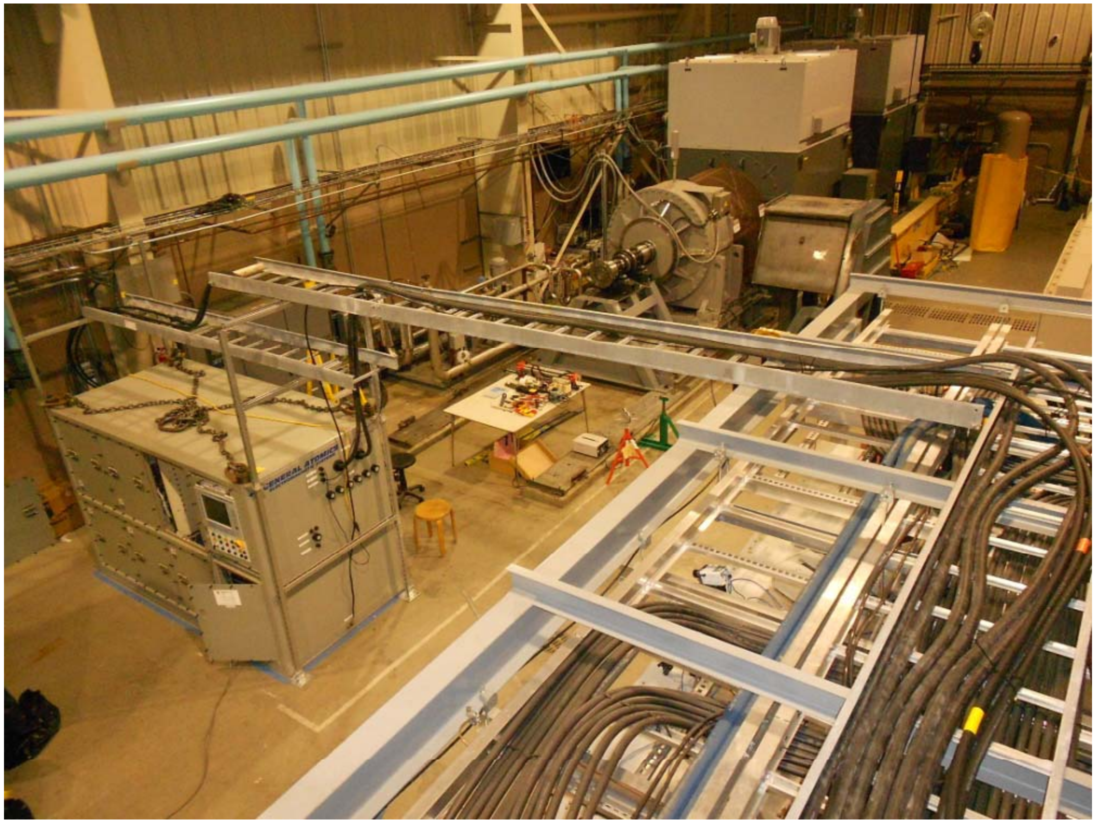
- 54 Full-time staff of scientists, engineers and technicians, post-doc.'s and supporting personnel
- 6 FAMU-FSU College of Engineering faculty
- 41 Students

Facility

- 44,000 square feet, laboratories and offices, located in Innovation Park, Tallahassee;
- Over $35 million specialized power and energy capabilities funded by ONR, DOE

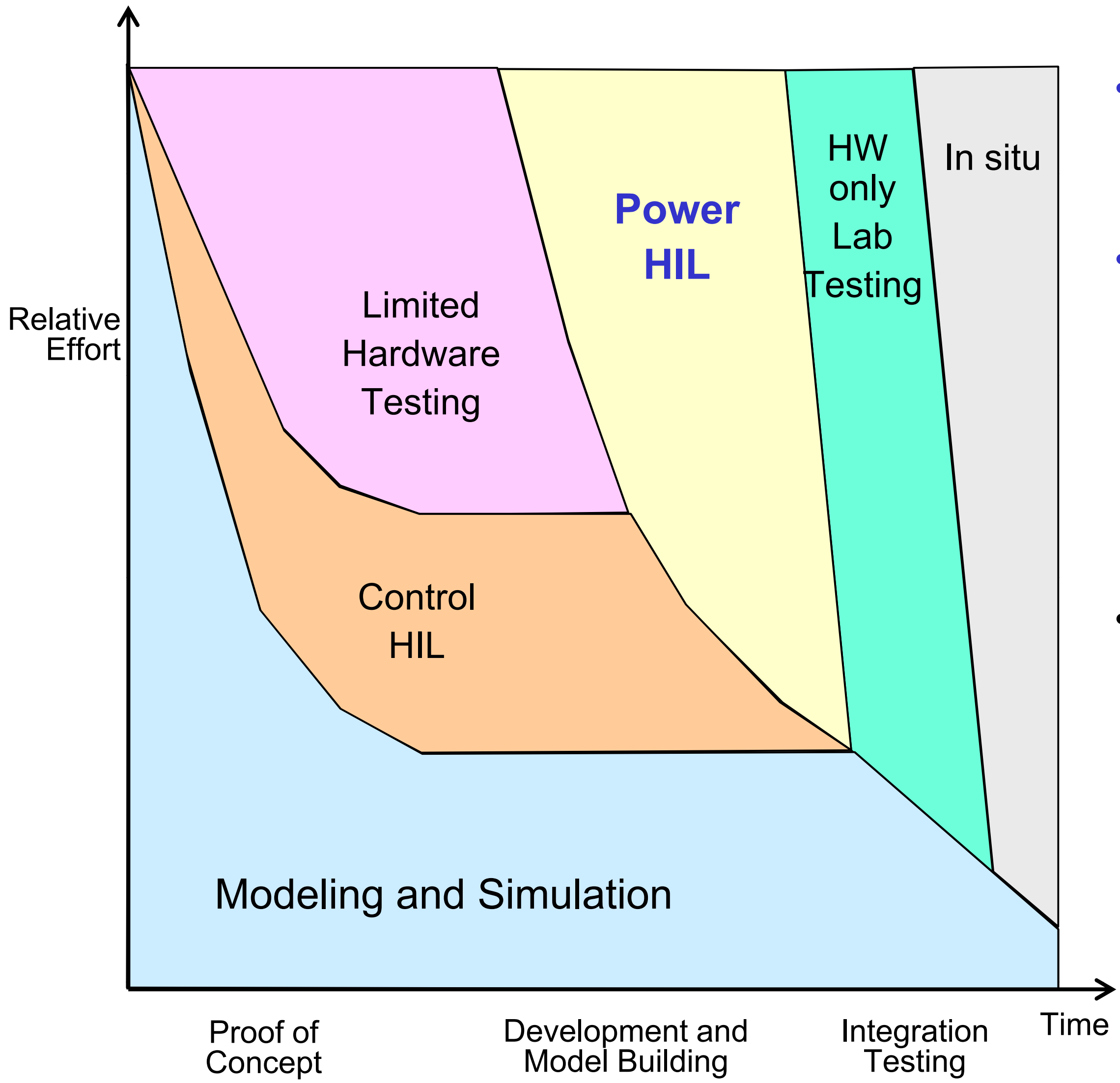
Overview

- FSU-CAPS 5 MW PHIL test facility
  - 0…4.16 kV AC "amplifier"
  - 0…1.1 kV DC "amplifier"
- De-risking of PHIL experiments
  - Controller HIL of "amplifier"
  - Protection elements in RT simulator
- Past and future PHIL experiments
  - Superconducting fault current limiter
  - High speed generator
  - 500 kW PV converter
  - Active rectifier for Naval applications



FSU-CAPS High Bay PHIL Lab

Potential Role of HIL Simulation: Stages of Development

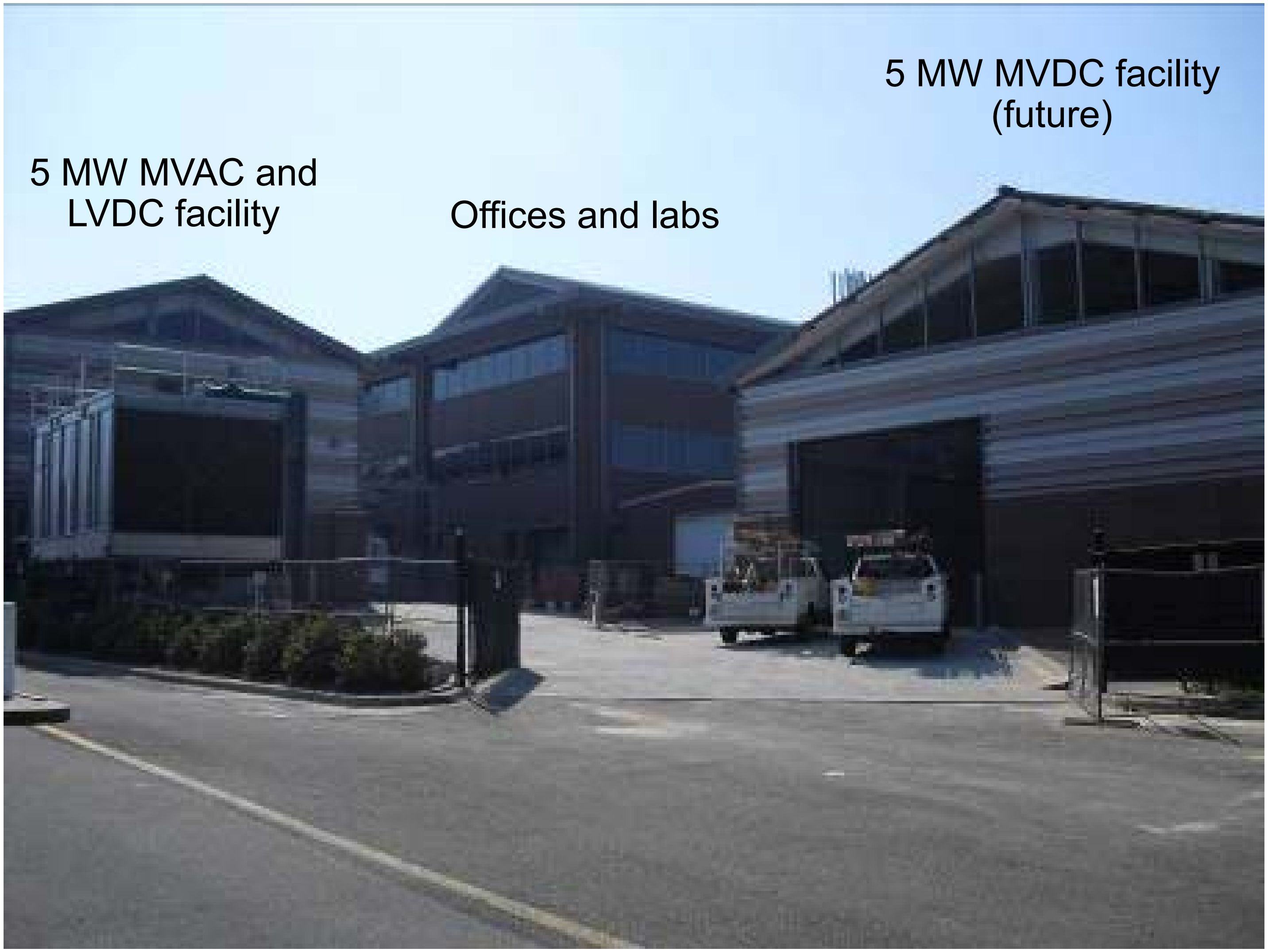


- Modeling and Simulation dominates the entire process
- CHIL contributes heavily from proof of concept through PHIL testing
  - De-risk early development of
    - Hardware (fast) controller
    - Application (slow) controller
  - De-risking PHIL experiments
- PHIL supports model building and integration phases
  - Experimental data for model construction and validation
  - Stimulation of component through controlled transients
  - Integration testing through emulation of the target environment(s)

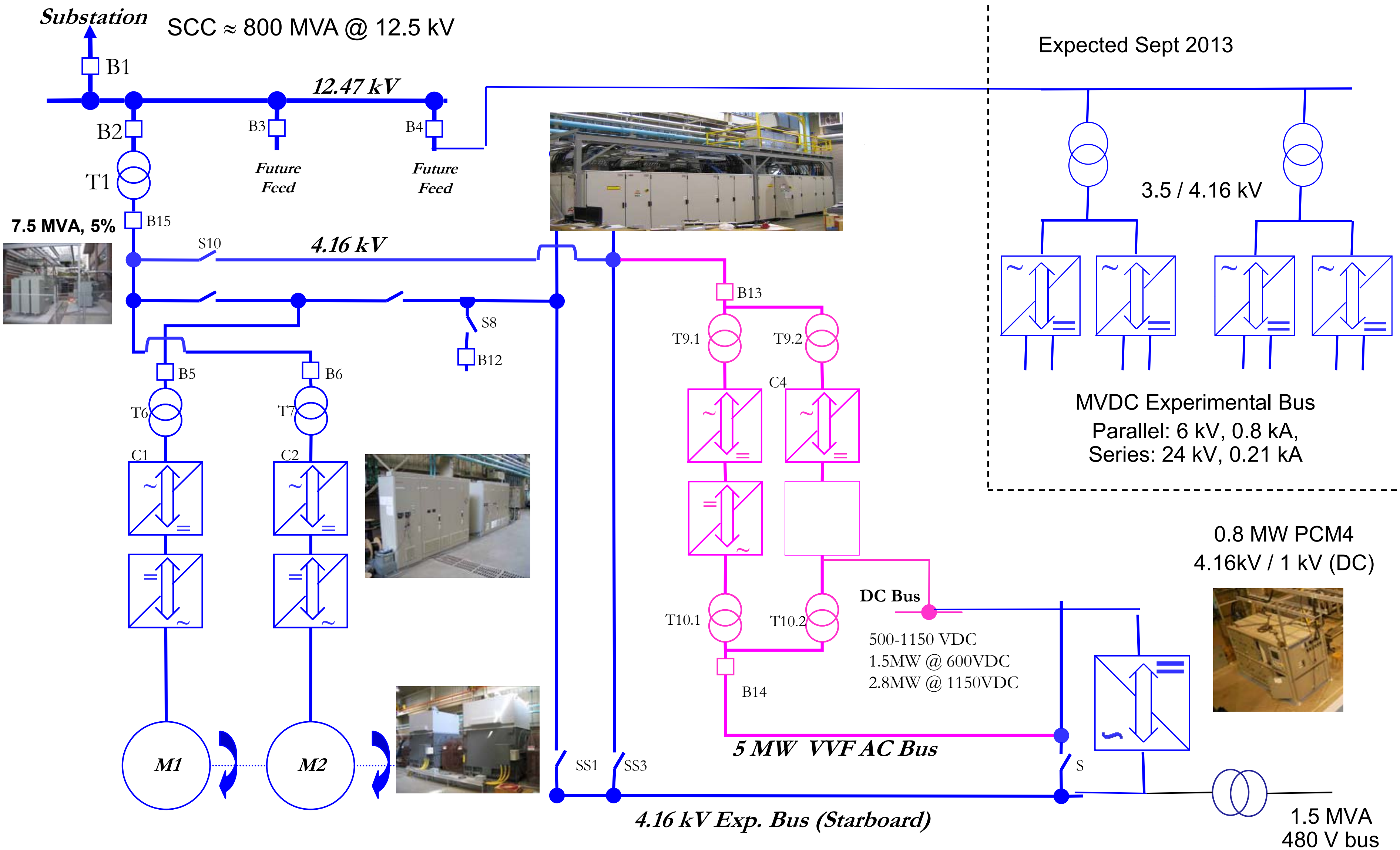
CAPS 5 MW PHIL Test Facility

- Real Time Simulator (RTDS, OPAL-RT)
  - Electromagnetic transient simulator
  - Typical time step: 50 μs and 2 μs (RTDS dual)
  - 756 electrical nodes (RTDS)
  - Hundreds of control and other simulation blocks
  - Numerous analog and digital Input/Outputs (RTDS)
  - Communication interfaces (RTDS: IEC 61850, DNP3, MODBUS, custom)
- 5MW variable voltage source (VVS) converter
  - VVS operates at 4.16 kV, 45-65 (240) Hz, bandwidth of 1 kHz
  - Can be split into a 2.5 MW AC unit and a 2.5 MW DC unit (both bi-directional)
  - The DC output is up to 1.15 kV
  - VVS can be dynamically controlled by sending reference voltage (current) from the RTDS
- 2 X 2.5 MW dynamometer set
  - Rated for 450 rpm, two-stage gearbox allows operation up to 3600 rpm and 24,000 rpm
  - Dynamically controlled from RTDS
- 5 MW, 24 kV MVDC Amplifier (Sep 2013)

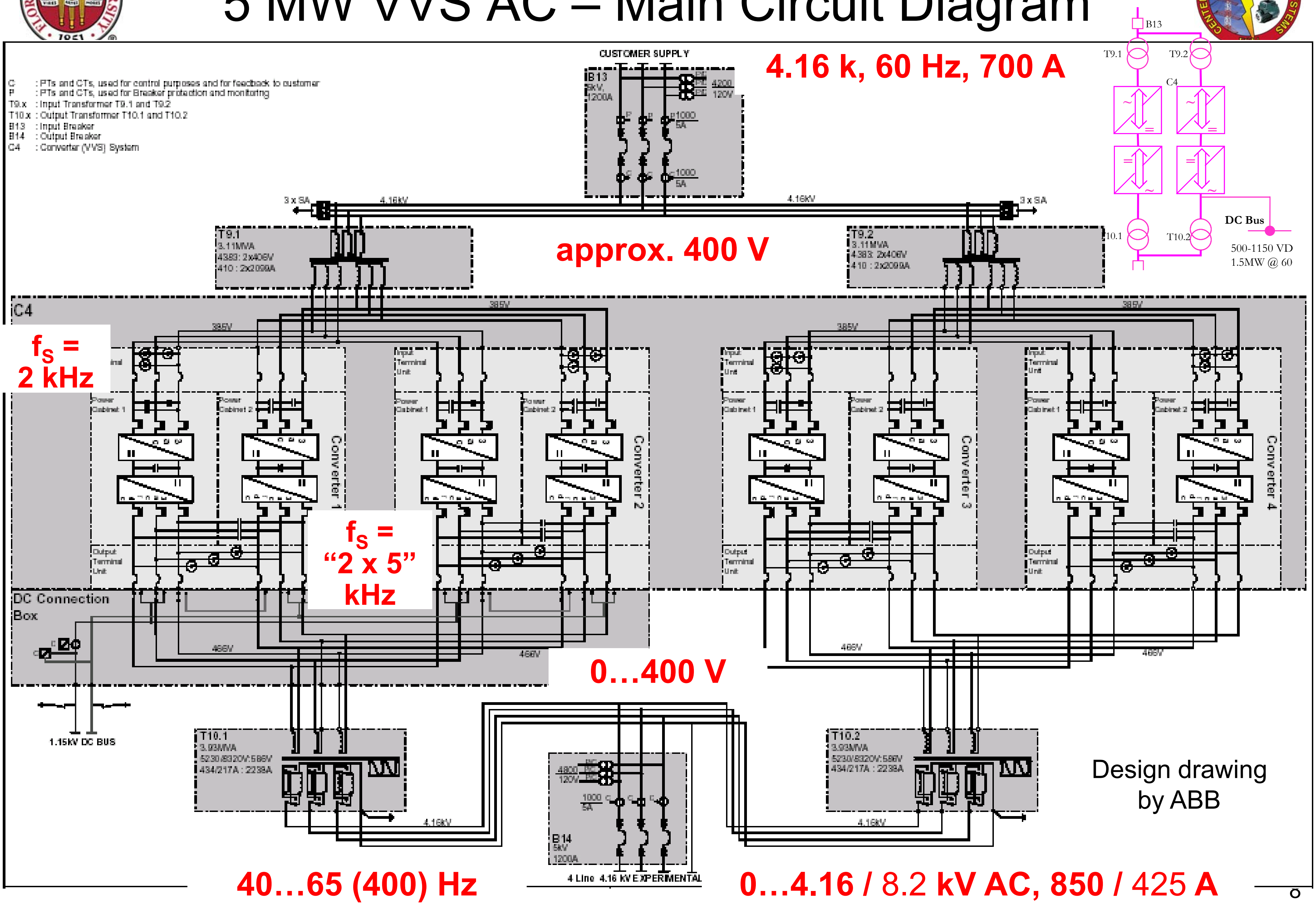
FSU-CAPS Power Testing Facility



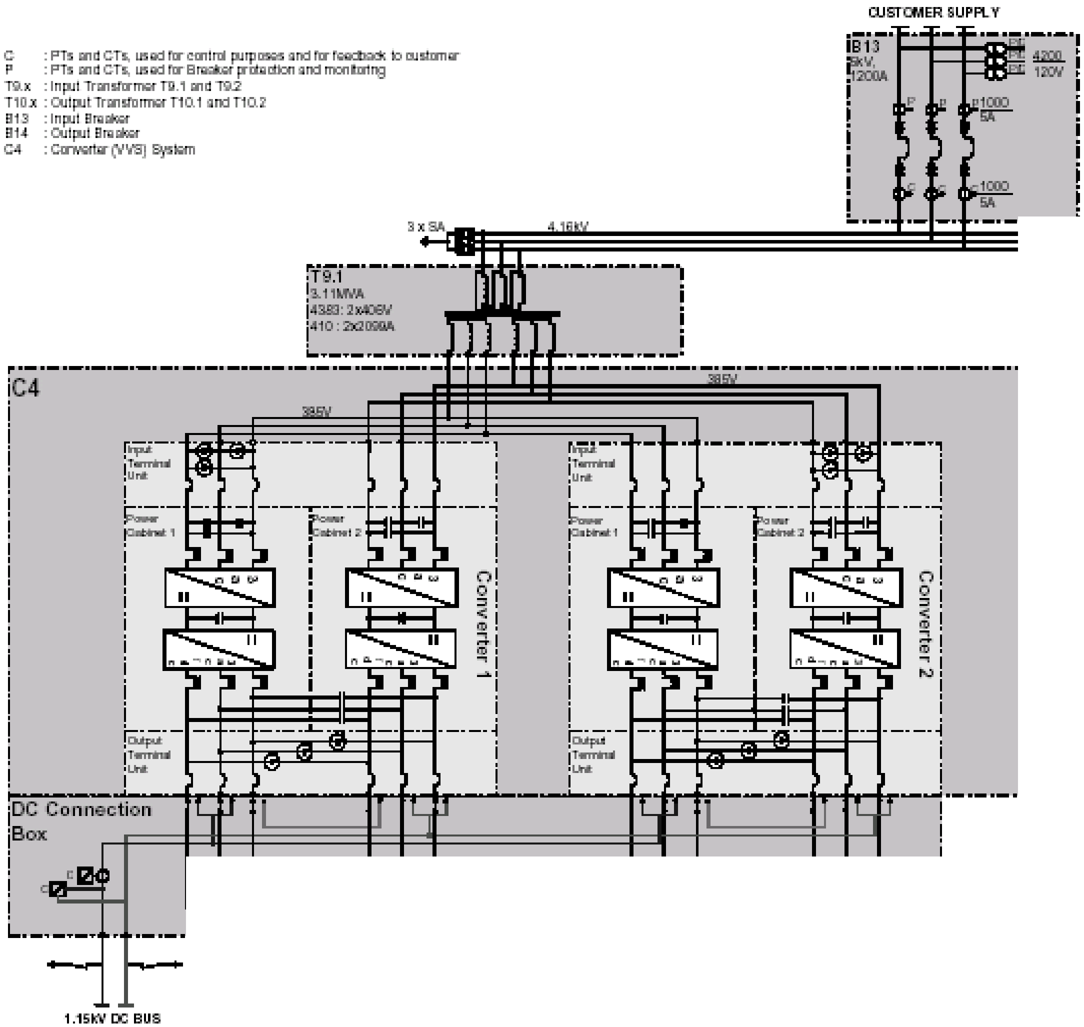
CAPS Facility Layout



5 MW VVS AC – Main Circuit Diagram



2.5 MW VVS DC – Main Circuit Diagram

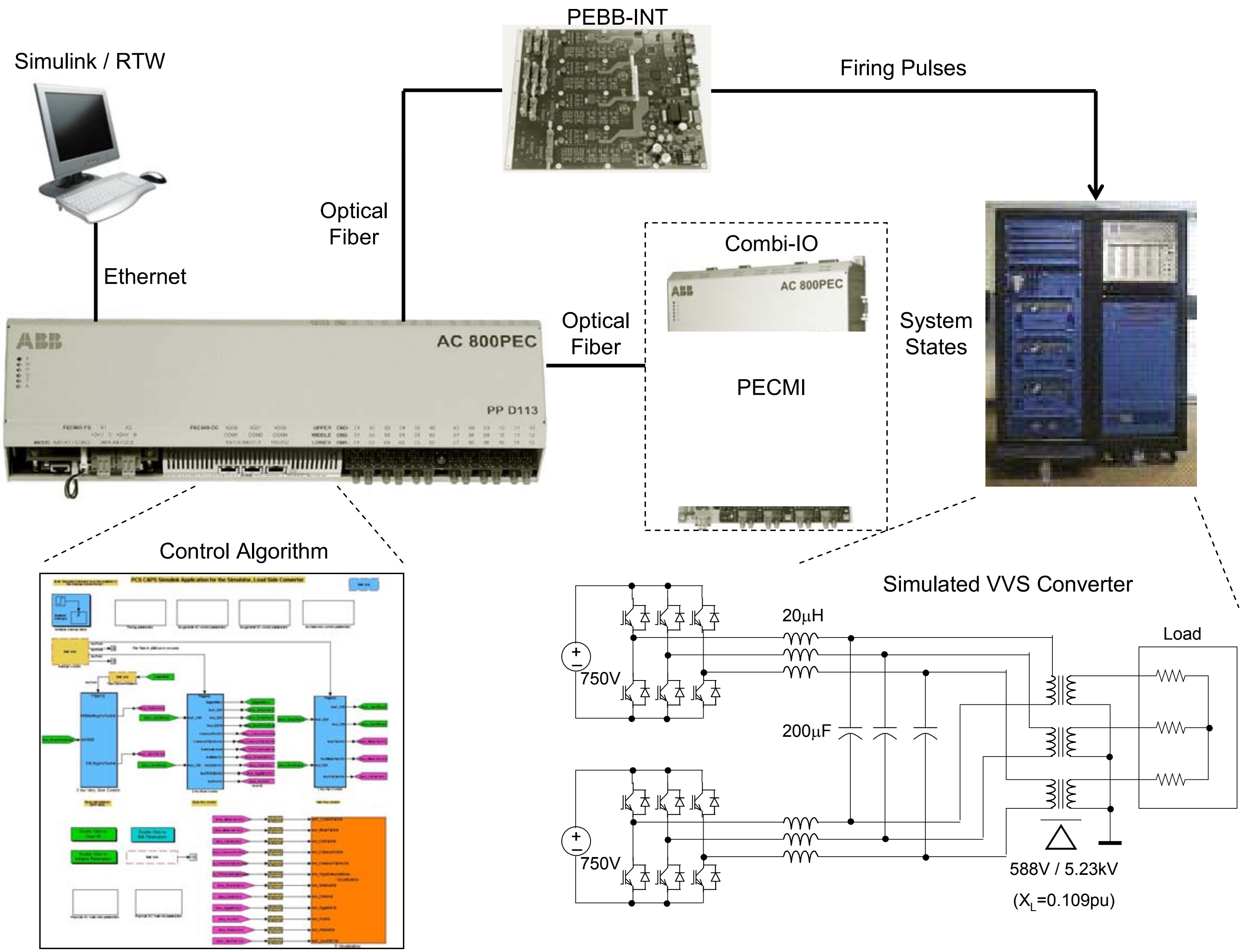


0.05…1.1 kV

0…2500 A

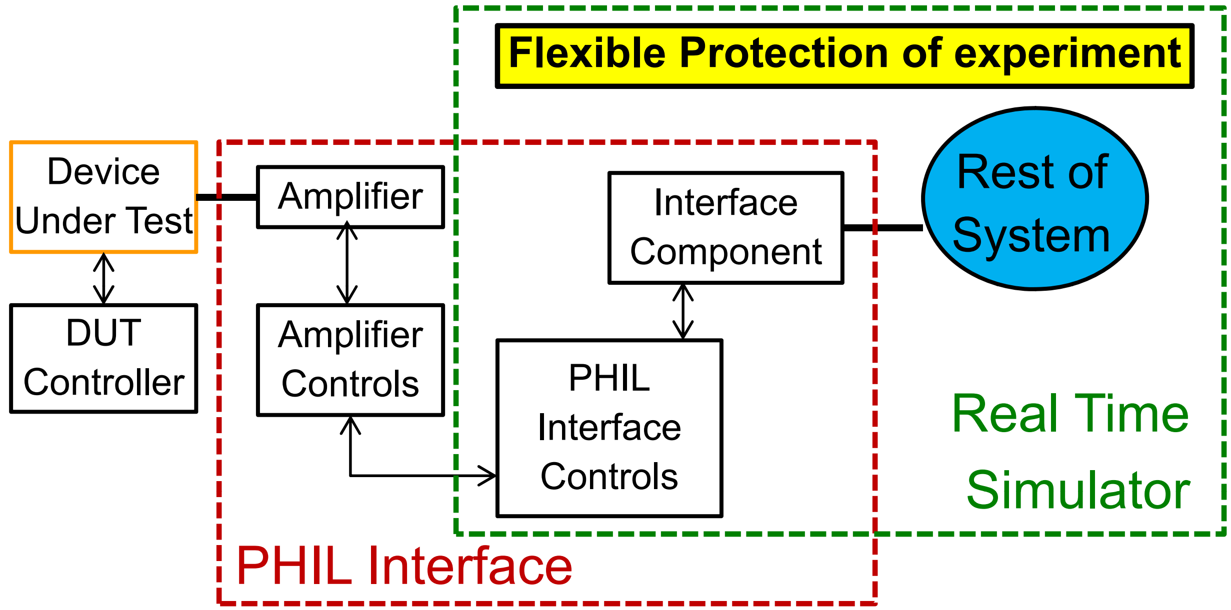
DC "ungrounded"

CHIL Simulation of VVS



Challenges: Accuracy, Stability, Protection

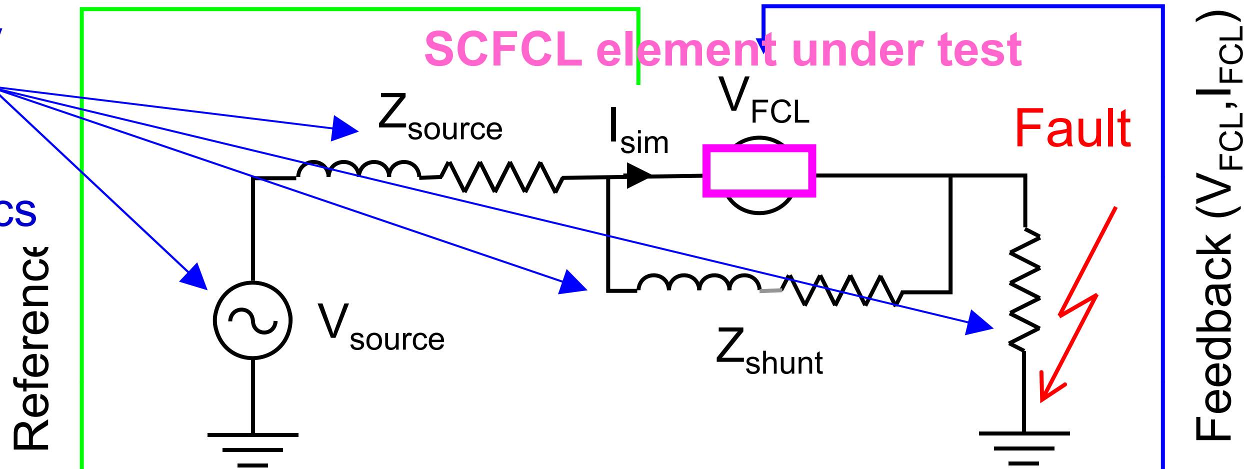
- Interfaces
  - Time delays
    - Input/Output
    - Controllers
  - Limited bandwidth of amplifiers and actuators
- Real-time simulation
  - Fixed time-step with minimum achievable time-step size
  - Limitations on the size and complexity of simulated systems
  - Protection of experiment



- Amplifiers and actuators
- Maximum power, torque, speed, etc.
- Assessment of the impact of HIL interfaces
- Accuracy of models used for surroundings
  - Common issue – establishing confidence in the models

PHIL for Fault Current Limiter (FCL) Testing

Need to vary system and device c…stics



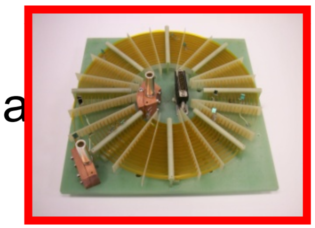
Real Hardware

- Test of FCL modules/elements
  - under different grid conditions (1-ph or 3-ph faults)
  - system parameter uncertainties (variance in source impeda…
- Modification of FCL configuration/design (e.g. parallel shunt)

…es with traditional hardware testing setups

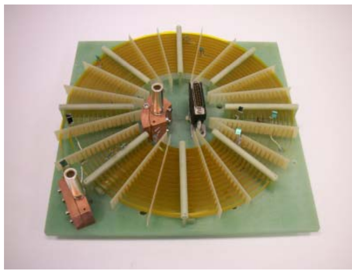
…nvironments are costly and setup is time intensive

…m conditions are difficult to reproduce (e.g. reclosing)



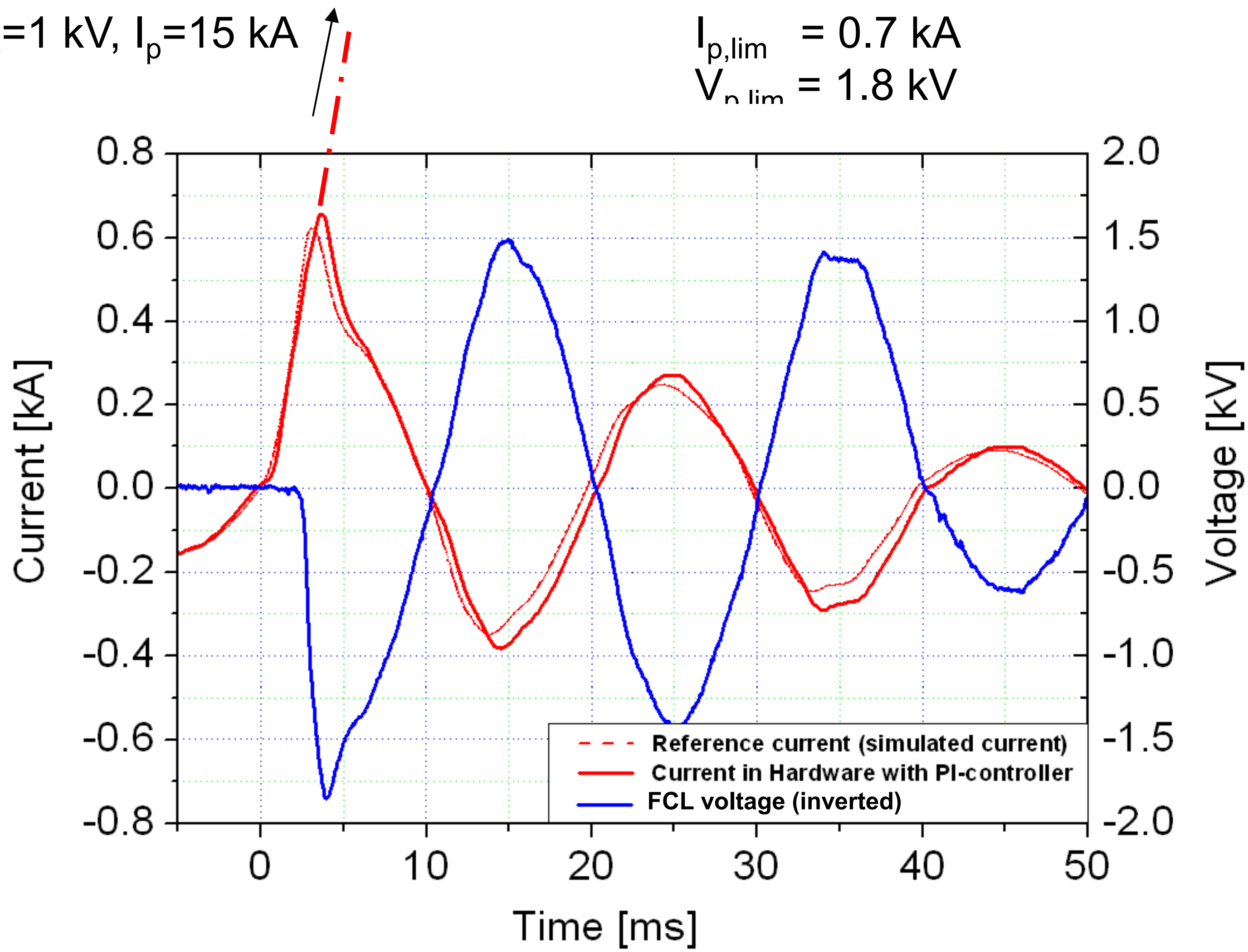
- Fast and inexpensive changes of test conditions within virtual test circuit
- „Faults“ only occur in virtual environment

Results from PHIL Experiment with FCL



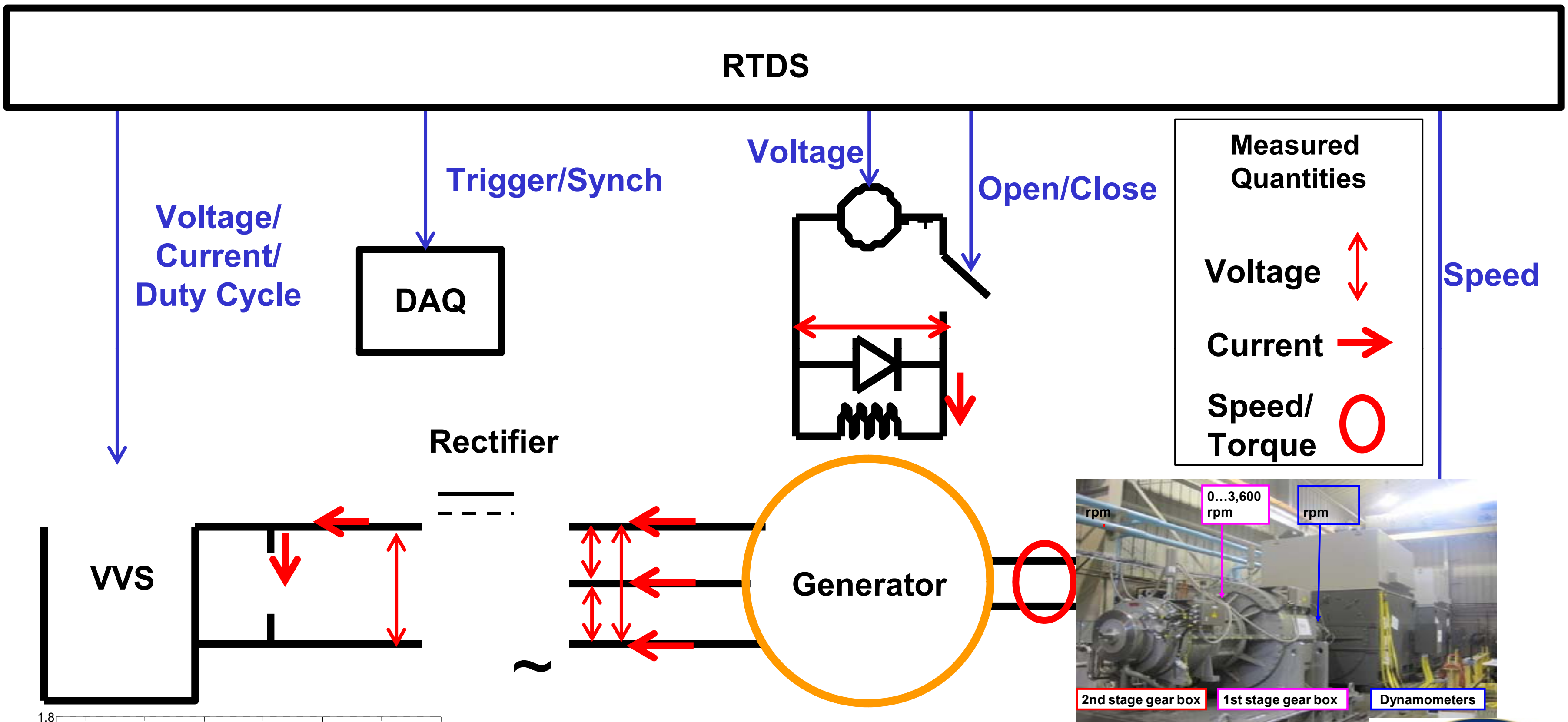
FCL

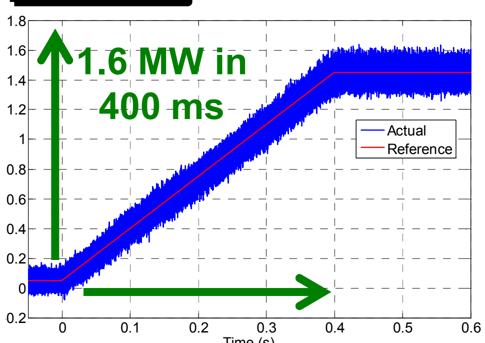
Cryostat (77K)



C. Schacherer, J. Langston, M. Steurer, M. Noe, *"Power Hardware-in-the-Loop Testing of a YBCO Coated Conductor Fault Current Limiting Module",* IEEE Trans. on Applied Superconductivity, Volume 19, Issue 3, Part 2, June 2009 Page(s):1801 - 1805

Megawatt Scale High-Speed Generator





Moved from Model to CHIL to full-scale PHIL
- Offline models used nano-second time step
- Startup, shutdown procedure
- Steady-state and dynamic loading (ramping)

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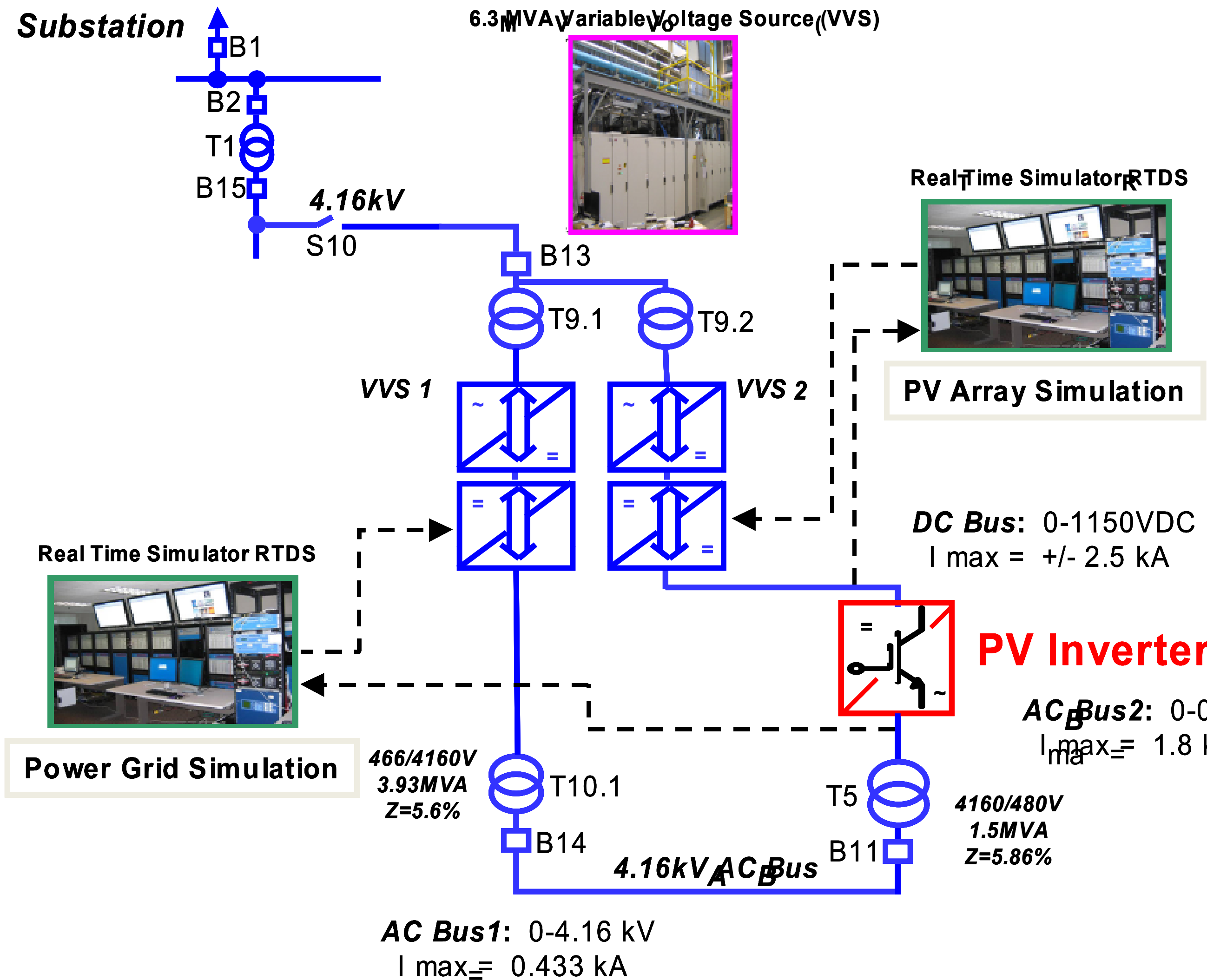
Dynamic HIL Testing of Large Inverters



PHIL testing of MW-scale converters is possible today!

Low voltage ride through
Fault current contribution
Unbalanced voltage
Anti-islanding

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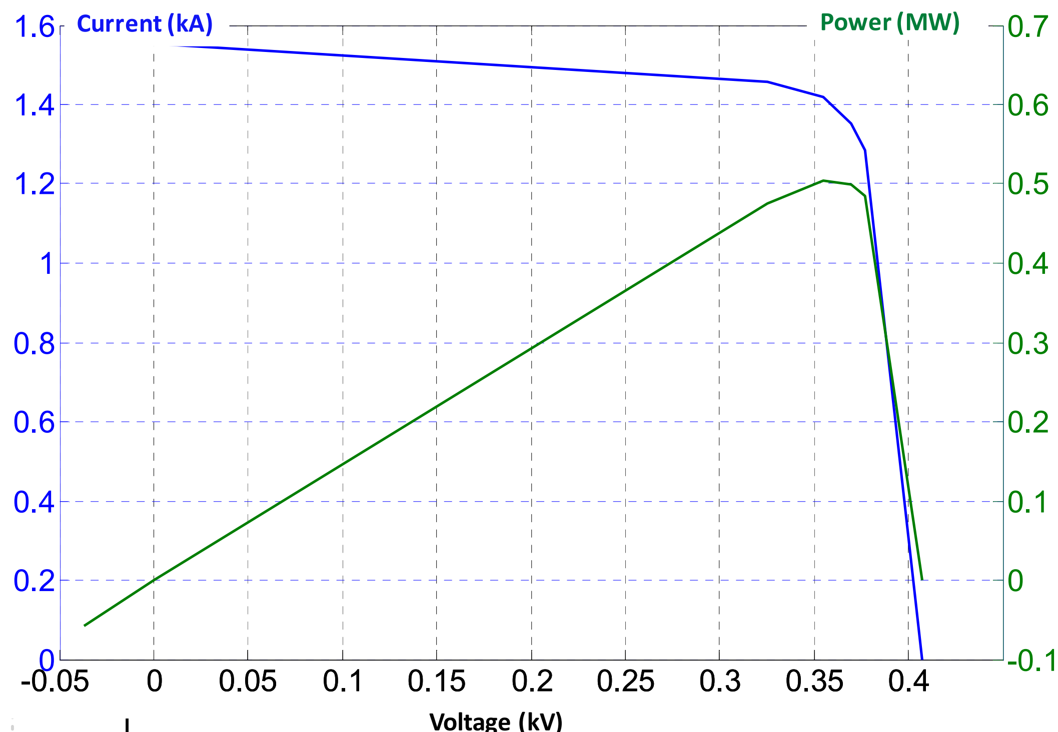
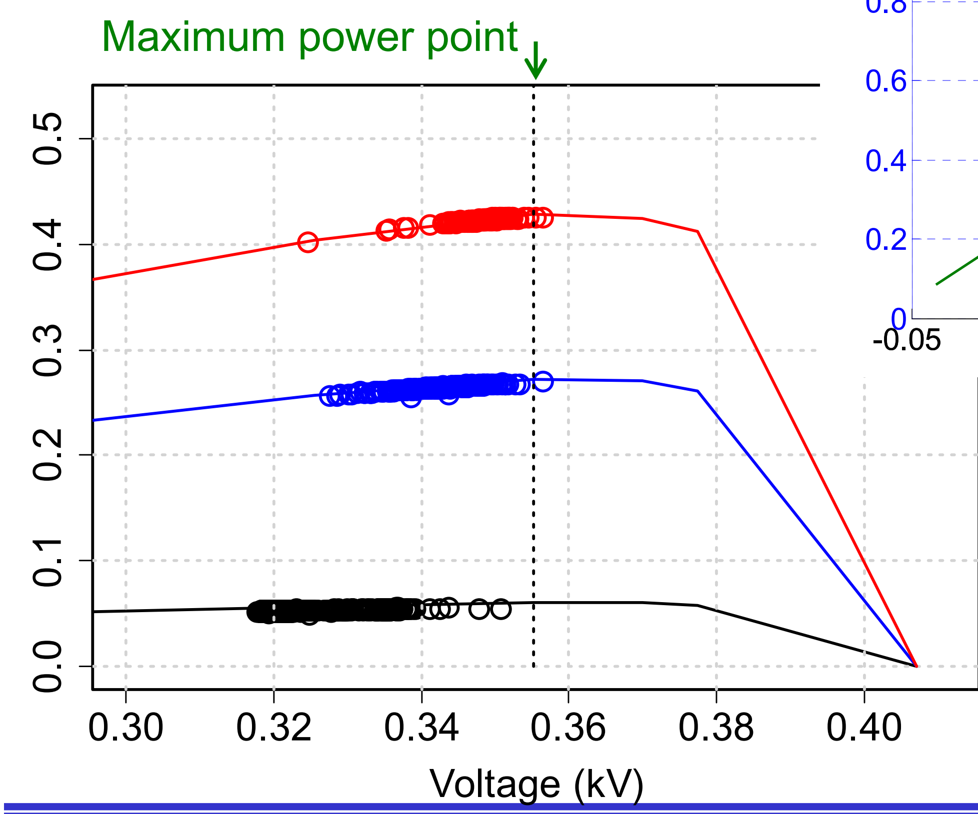
DC-side: Photovoltaic Emulation





Ensure that DC-amplifier controls allow PV-emulation in conjunction with PV inverter dynamics.

Full PHIL Testing of 500 kW PV Inverter

- Collaboration between Quanta Technology, Satcon, SCE and FSU CAPS sponsored by NREL.
- Test and evaluate the capability of inverter implementing advanced functions (PF control, volt/Var control)
  - Simulate PV array **<u>and utility grid</u>**
- Quantify in a laboratory setting the mitigation of high-penetration PV impacts using advanced inverter functions.
- A possible operational issue with VAr fold-back control was identified.
- Constant PF control worked flawlessly.

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QUANTA TECHNOLOGY

500 kW PV converter in FSU-CAPS lab

Challenges: Grounding can be tricky…

- PHIL testing of a 500 kW solar inverter
- RTDS + VVS simulates solar ungrounded panels
- Inverter grounds the DC rail through a 10 A fuse
- **Fuse blew when VVS was energized (w/o DUT energized)**

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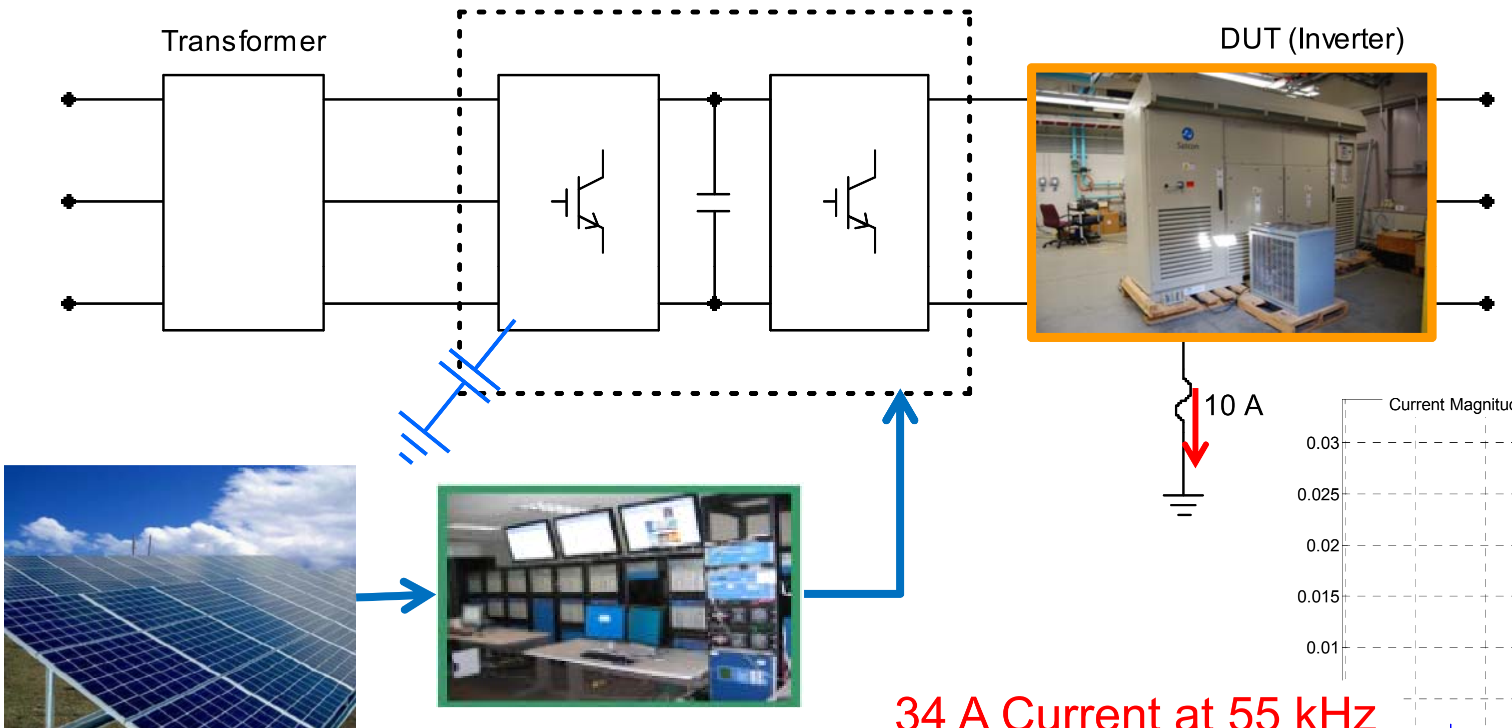
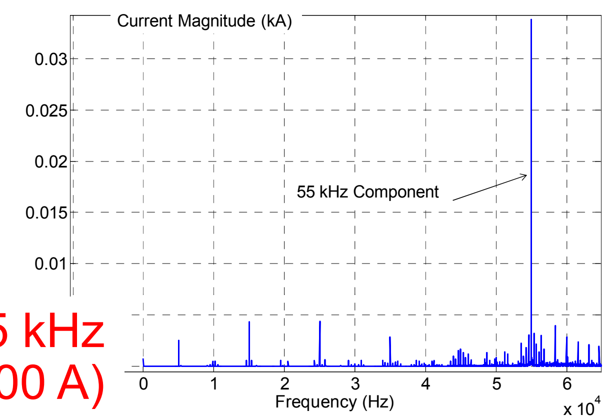
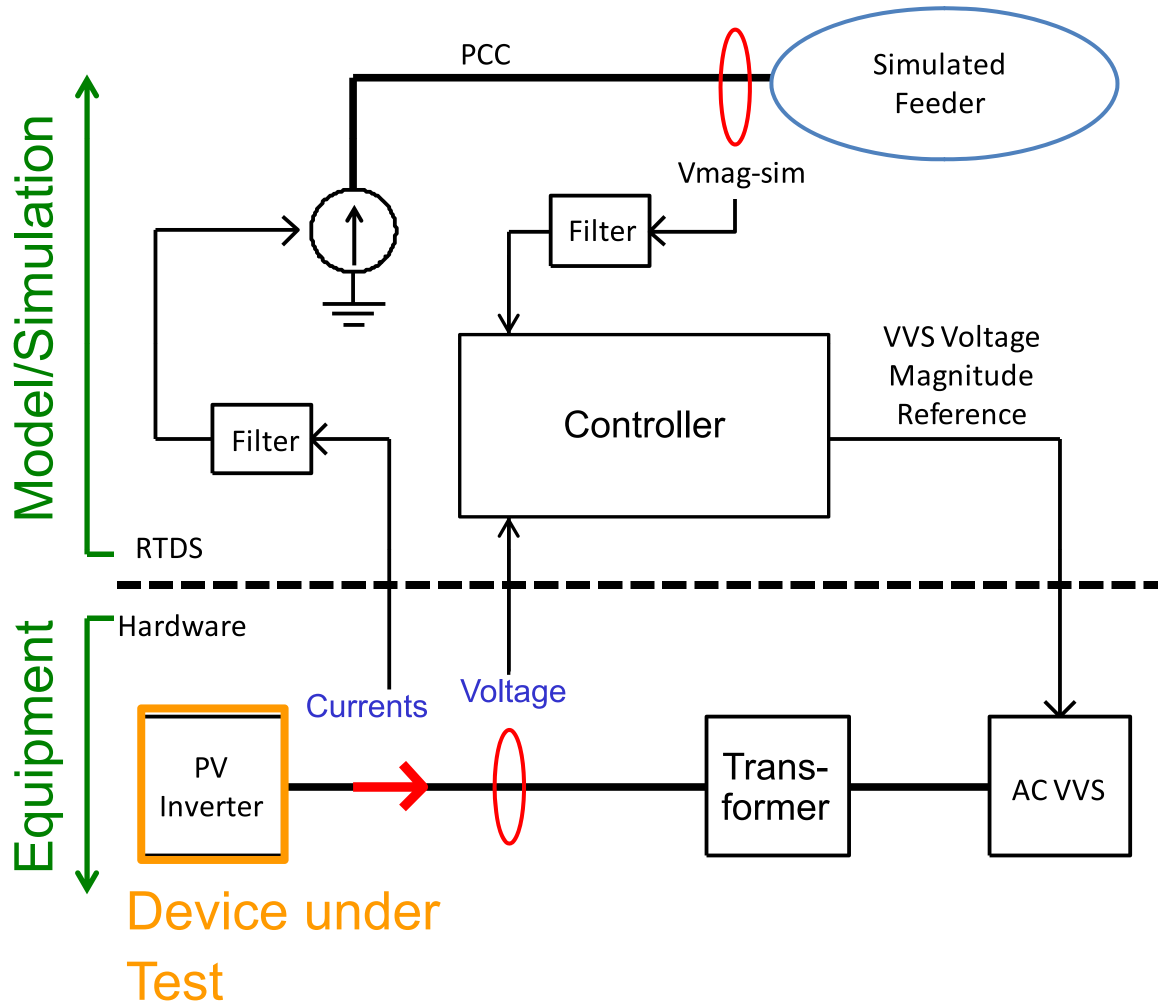




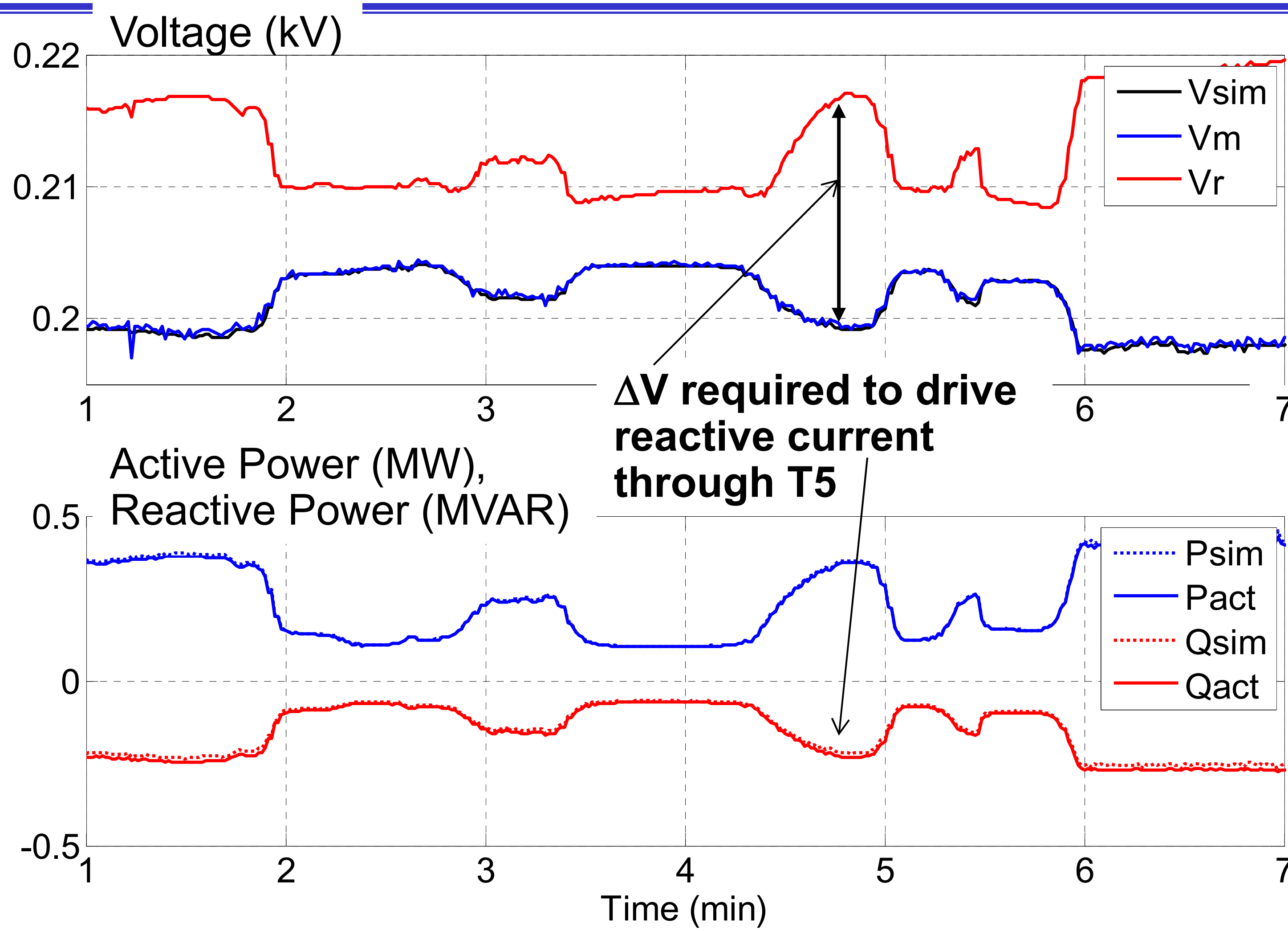
34 A Current at 55 kHz
(1.4% of 2500 A)

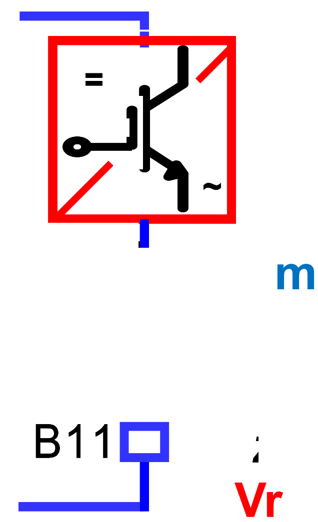
Grid-side PHIL Interface



- Choice:
  Voltage ←→ Current,
  but impacts stability
- Know your limits:
  Filters for bandwidth adjustment
- Protect:
  Open loop operation through feedback gain adjustment

Inverter with 0.8 PF lagging

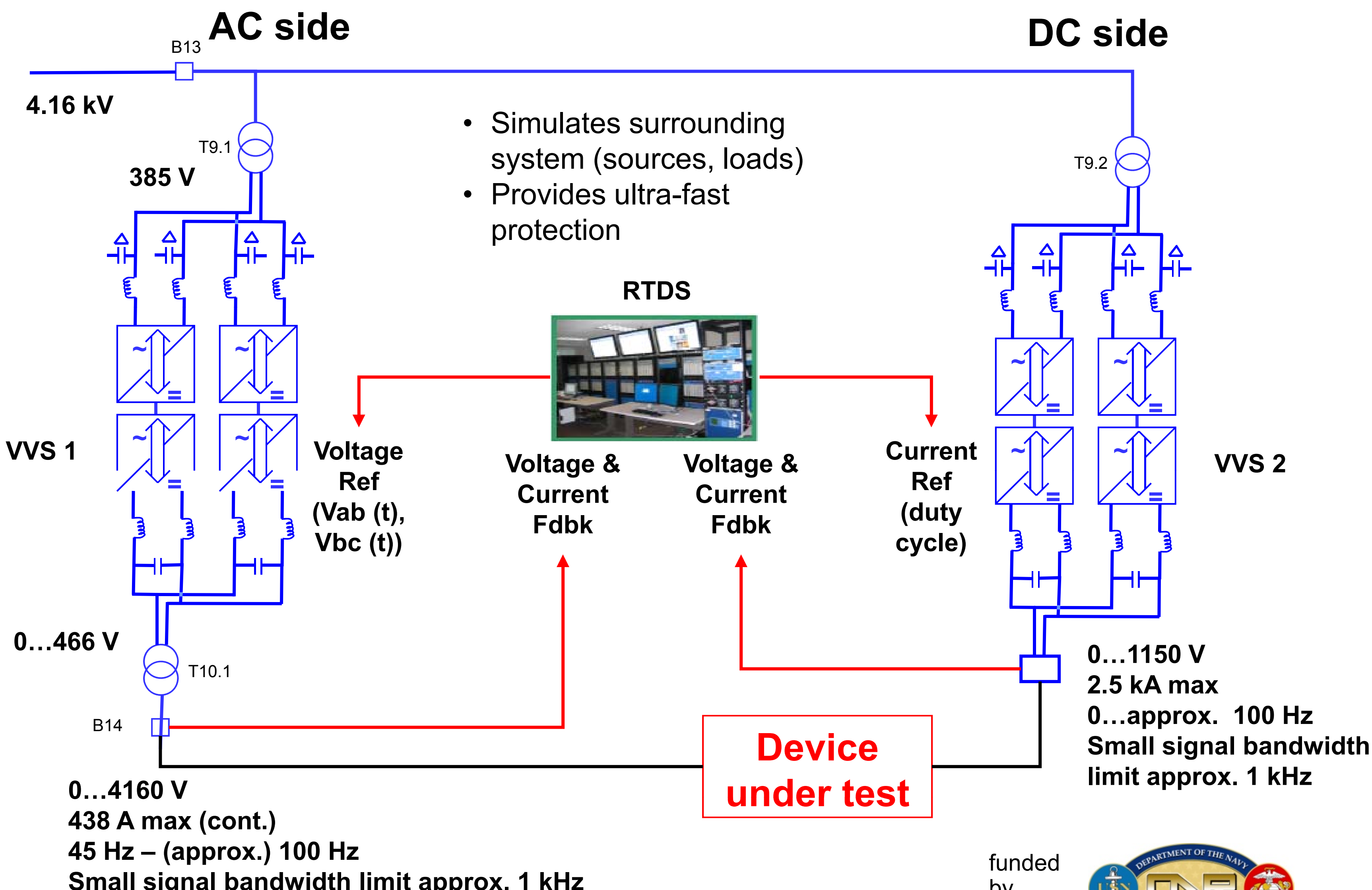




Simulated grid impedance $X < X_{T5}$

See J. Langston, et al. "*Power Hardware-in-the-Loop Testing of a 500 kW Photovoltaic Array Inverter*", in Proc. of IECON, Montreal, Canada, 2012

PHIL testing of SiC converter
4.16 kV_{AC}-1 kV_{DC}



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Concluding Remarks

- PHIL testing is advancing rapidly
  - A tool to address several challenges associated with transitioning technology (de-risking)
  - Emulate a wide range of surroundings and scenarios, simulate yet unrealized systems

Team at work in FSU-CAPS control room

- Impact of PHIL interface more pronounced at MW scale experiments
  - Aim for close coupling between reference and amplifier
  - Faster switching amplifiers
  - Real time simulation of models

500 kW PV converter in FSU-CAPS lab

- Simulation based preparation of MW scale experiments save time and money
  - Improve development cycle

    Discover hidden issues early
  - Model construction and validation

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