FSU | CENTER FOR ADVANCED POWER SYSTEMS

Recent PHIL Testing at CAPS

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ATC
RTDS APPLICATIONS & TECHNOLOGY CONFERENCE

APPLICATIONS & TECHNOLOGY CONFERENCE 2025
CHICAGO, ILLINOIS, U.S.A.

RTDS Technologies
AMETEK

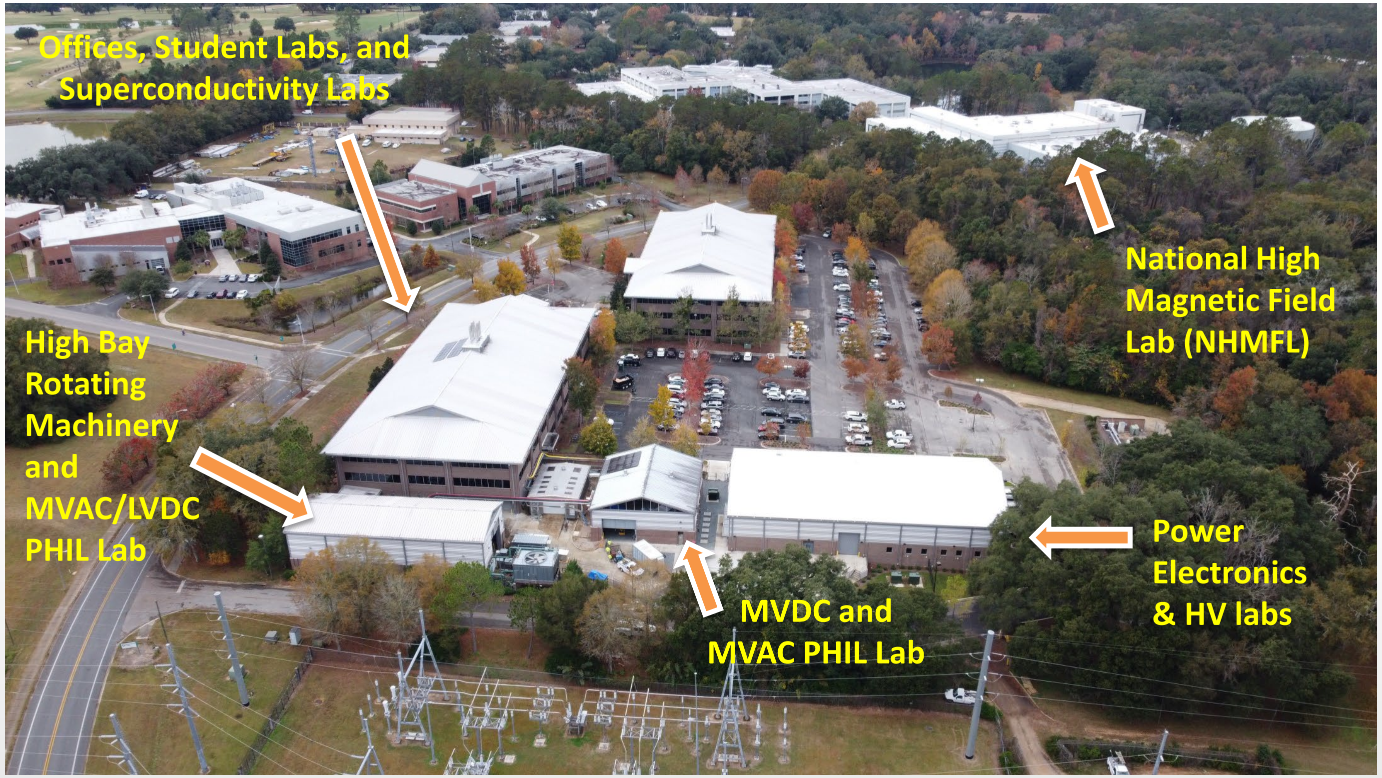
Outline

- CAPS Overview
- PHIL testing of
  - Diesel Generators
  - Energy Magazines
  - Islanded Microgrids

Center for Advanced Power Systems @ FSU

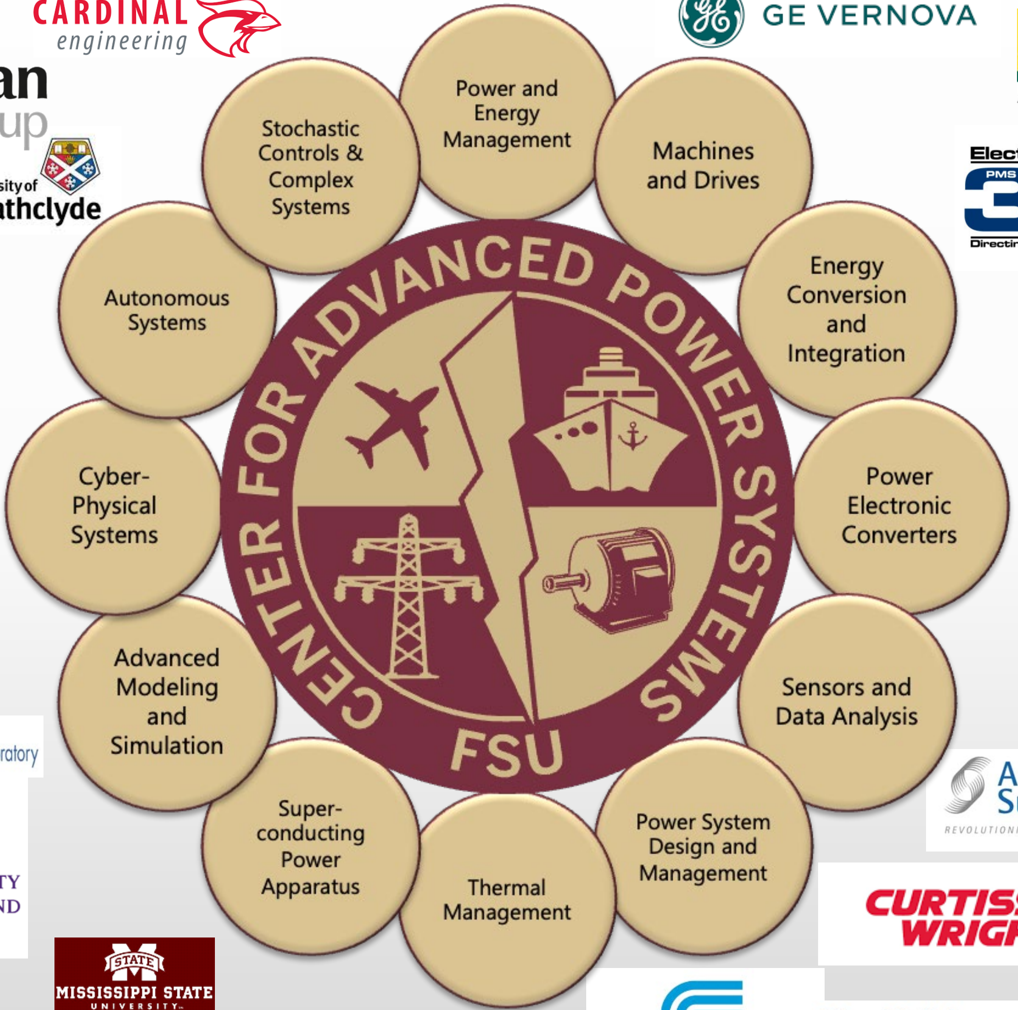
Established in 2000

- Spun off from **NHMFL** in **2000**
- **Research** and **education** related to application of new technologies to electric power systems
- Closely affiliated with **FAMU-FSU College of Engineering**
- 56,000 ft^2 laboratories/offices; CUI data **security compliant**
- Tenure/Non-tenure track **faculty, Ph.D./M.S./B.S. students, staff researchers and post-doctorial associates** and **facility support**



- Over **$105 million** specialized **power and energy capabilities** funded by ESO, ONR, DOE, NSF and Industry
- **Manager** of the ONR funded Electric Ship Research and Development Consortium **(ESRDC)**
- Contracted by **PEO Ships PMS460** to derisk the DDG(X) Power System and conduct HIL based demonstrations and DT&E of advanced P&E technologies supportive of multiple ship classes

Clients and Collaborators



- General Atomics
- Cardinal engineering
- GE Vernova
- 1SG Engineering Inc.
- Southern California Edison – An Edison International Company
- ARPA-E
- DDG(X) Guided Missile Destroyer PMS 460
- ONR – Department of the Navy Science & Technology
- Prysmian Group
- Virginia Tech
- University of Strathclyde
- Electric Ships Office PMS 320 – Directing the Future of Ships Power
- Bonneville Power Administration
- U.S. Department of Energy
- NAVSEA Naval Sea Systems Command
- Mitsubishi Heavy Industries
- Georgia Tech
- NSTIC
- RCT Systems
- National High Magnetic Field Laboratory
- Google
- NASA
- MSTIC – Maritime Sustainment Technology and Innovation Consortium
- University of South Carolina
- Johns Hopkins Applied Physics Laboratory
- ESRDC – Electric Ship Research & Development Consortium
- Leonardo DRS
- Massachusetts Institute of Technology
- INL Idaho National Laboratory
- Northrop Grumman
- GE Global Research
- American Superconductor – Revolutionizing the way the world uses electricity
- L3 Technologies
- Sandia National Laboratories
- Clarkson
- Purdue University
- The University of Queensland Australia
- Curtiss-Wright
- Eaton
- NAVSEA Warfare Centers Philadelphia
- The University of Texas at Austin
- University of Wisconsin Milwaukee
- Mississippi State University
- University of Texas Arlington
- conEdison
- City of Tallahassee – Your Own Utilities
- ABB
- Hepburn and Sons LLC
- KIT Karlsruhe Institute of Technology
- NPS
- University of Applied Sciences Upper Austria
- RTDS Technologies AMETEK

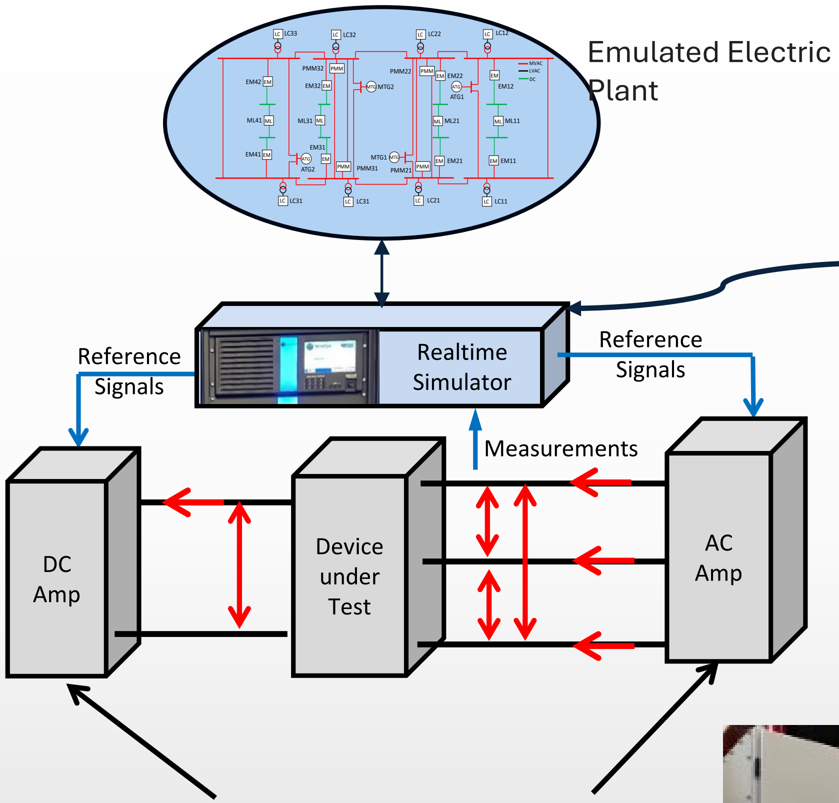
Power Hardware-in-the-Loop (PHIL) Simulation

Create a Virtual yet Realistic Environment to Rapidly Test and Demonstrate Equipment and Interfaces.

- Couple Device Under test (DUT) to a Real Time Computer Simulation using amplifiers and/or actuators, preserving natural coupling

Use of PHIL Simulation

- Testing in Realistic Environment
- Early integration testing
- Flexibility to quickly change surrounding system and conditions to test equipment performance envelope
- Validate System Specification & Interfaces
- Testing with yet unrealized system
- Test extreme conditions within controllable



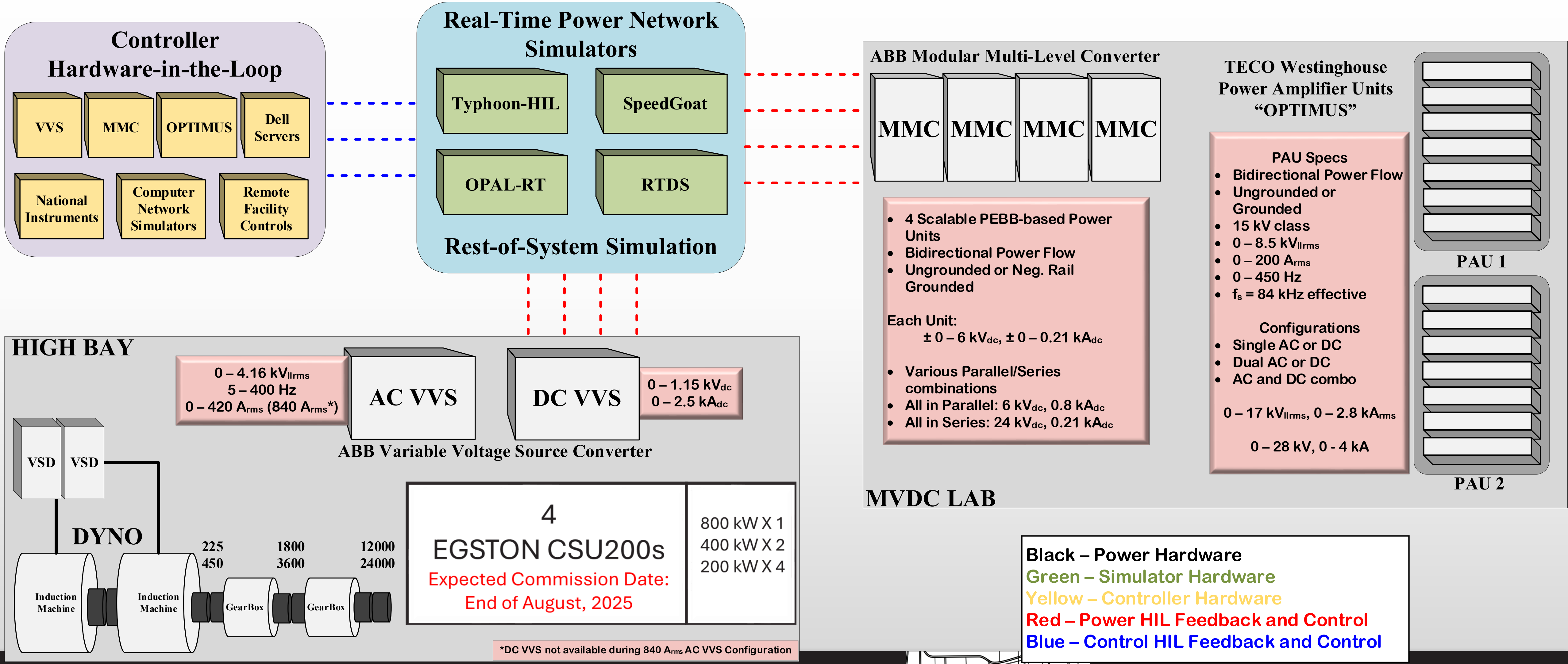
CAPS RT Simulators

- RTDS Novacore (9)
- SpeedGoat (2)
- Typhoon HIL (3)
- Opal-RT (2)

Variable Voltage Source

Optimus Power Units (2)

5 MW PHIL Facility Overview



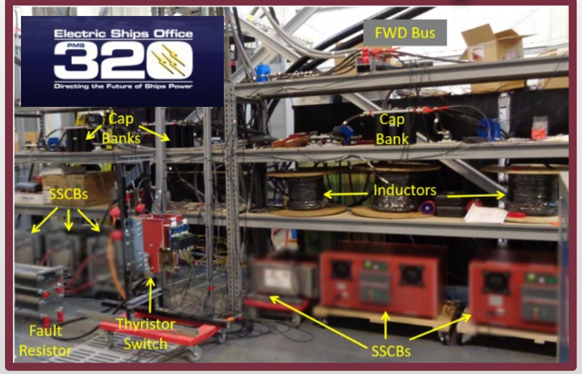
Recent PHIL Testing Highlights at FSU-CAPS

MITSUBISHI HEAVY INDUSTRIES
PHIL Exploration Projects

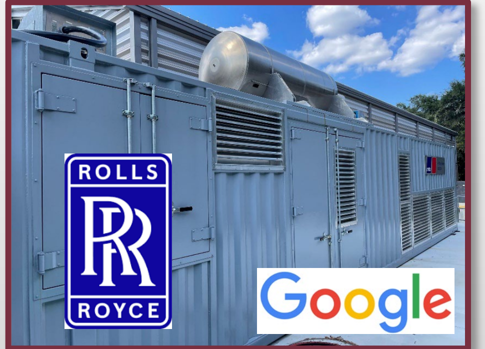
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
MV Power Converter

DEPARTMENT OF THE NAVY ONR Science & Technology
GUIDED MISSILE DESTROYER DDG(X) PMS 460
RCPC FNC
Robust Combat Power and Energy Controls
RCPC PHIL Demonstration with Energy Magazines

2020 | 2021 | 2022 | 2023 | 2024



Exploring Protection in MVDC Systems (Demo 5-2)

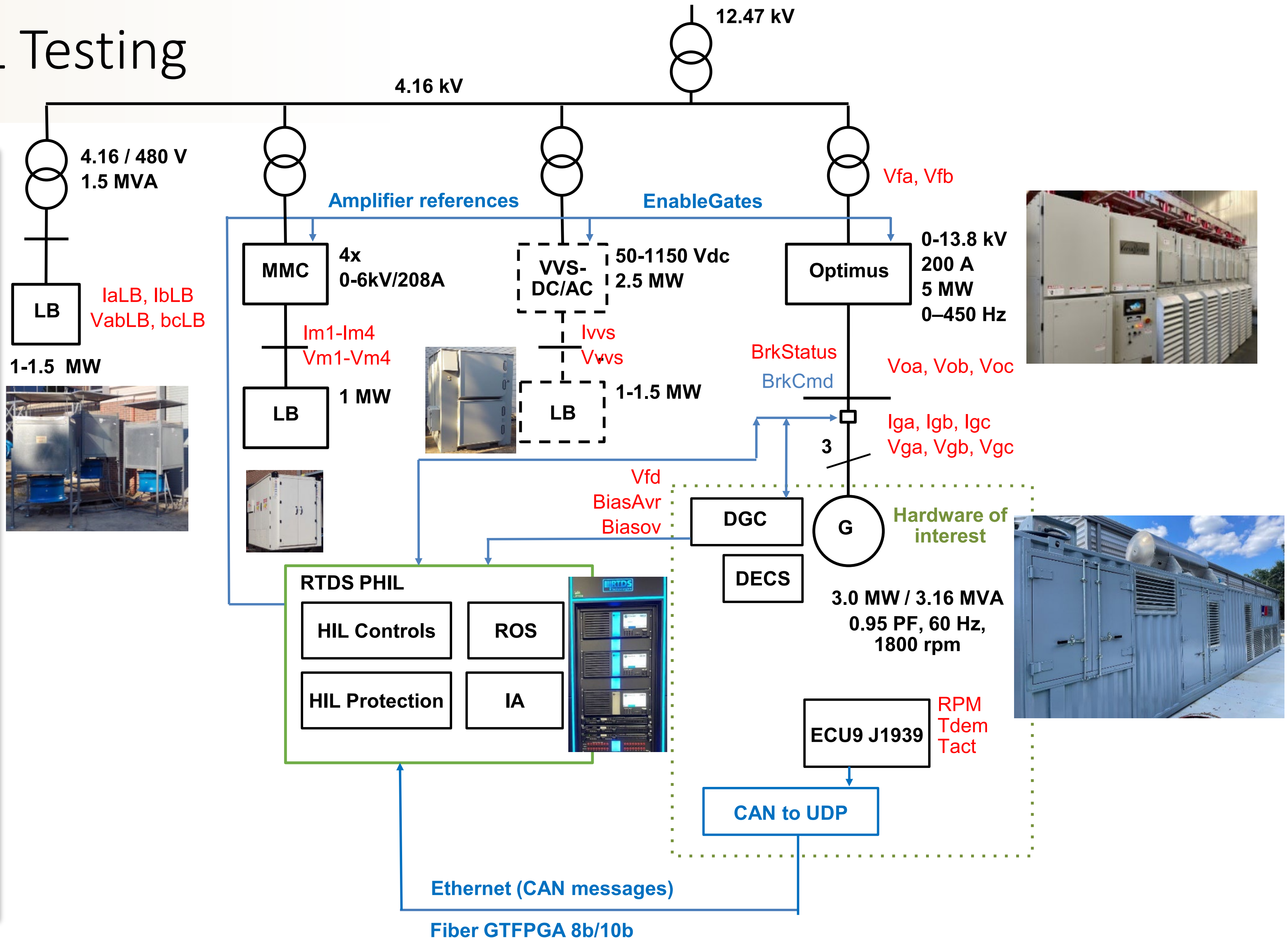


13.8 kV, 3 MW DG

660 kW EM-P

3 MW DG PHIL Testing

- Tested 3 MW, 13.8 kV DG
- PHIL Interface
  - DQ-frame DIM IA
  - Optimus amplifier configured for 13.8 kV AC, current control mode
- Use of load banks to dissipate power over 600 kW
- Multiple load interfaces using other PHIL amplifiers
- Testing of DG w.r.t
  - Increased power output
  - Unbalanced loading
  - Constant power load behavior



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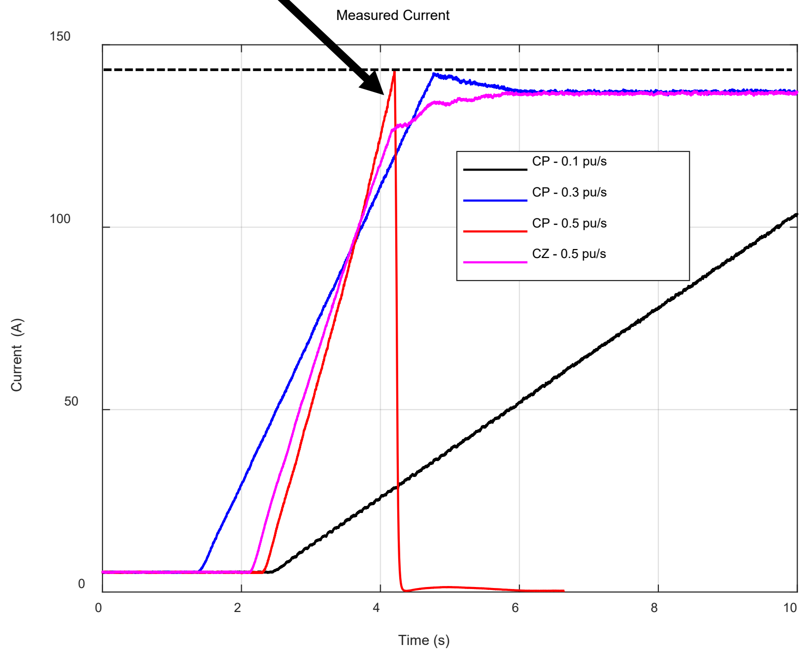
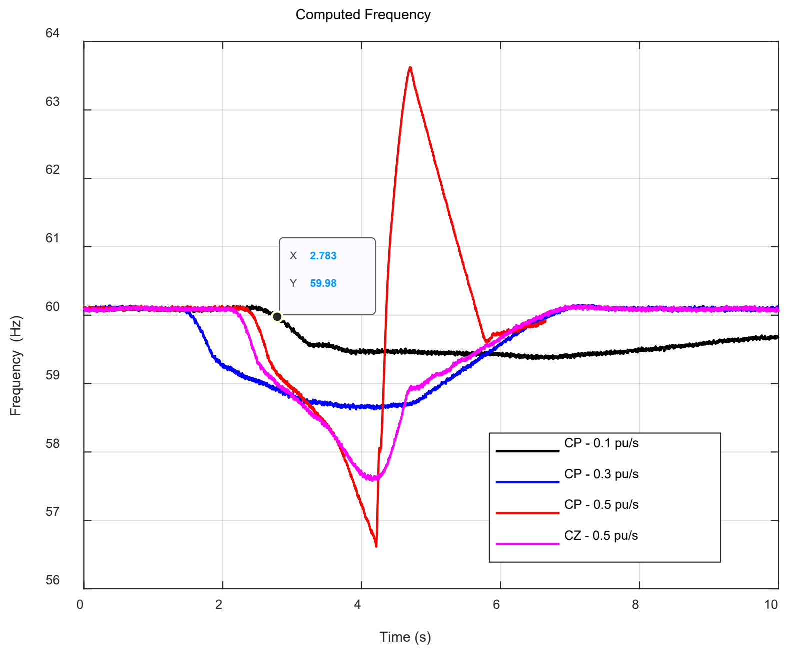
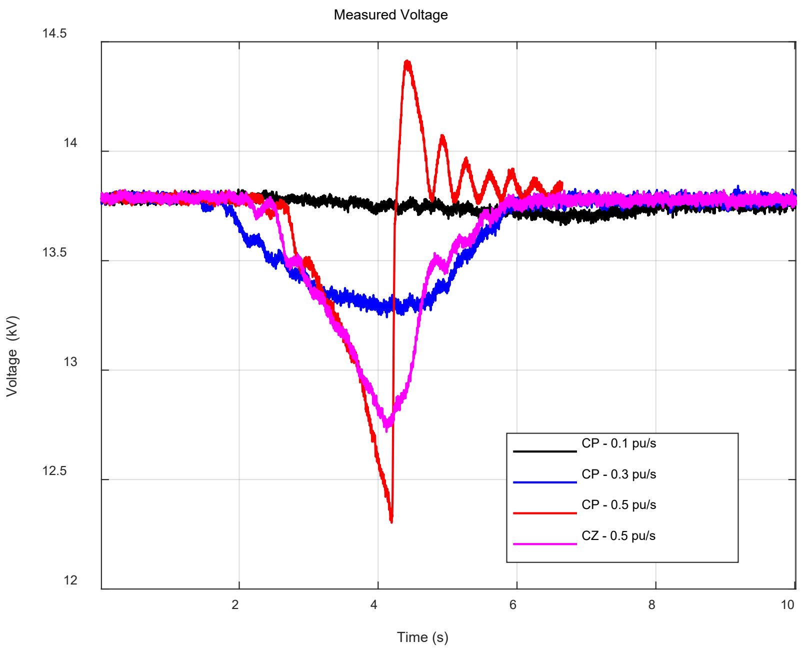
Load Ramp Tests

RTDS detected overcurrent and gracefully stopped the experiment



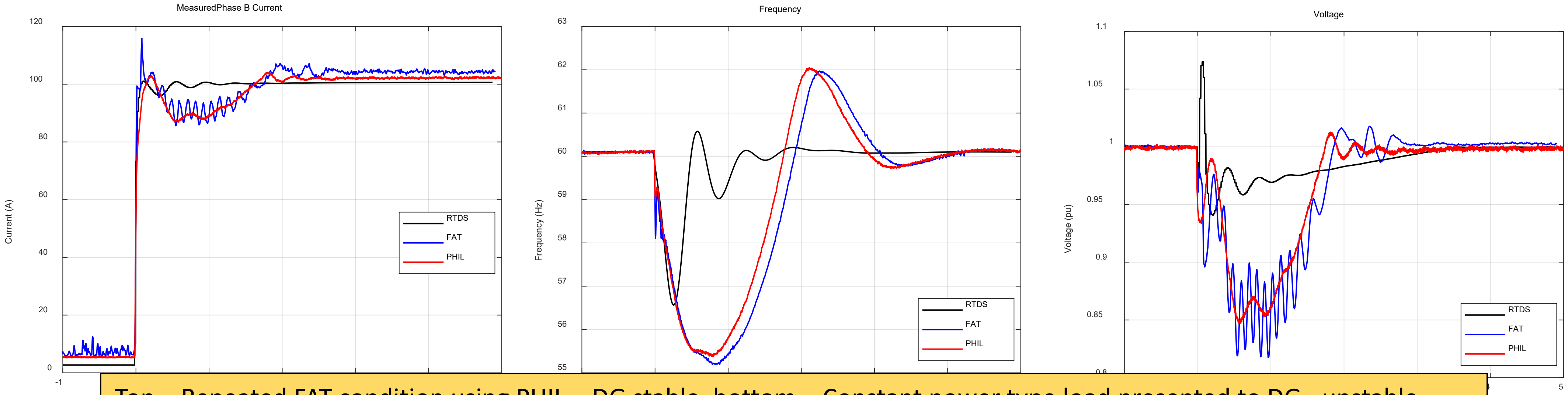




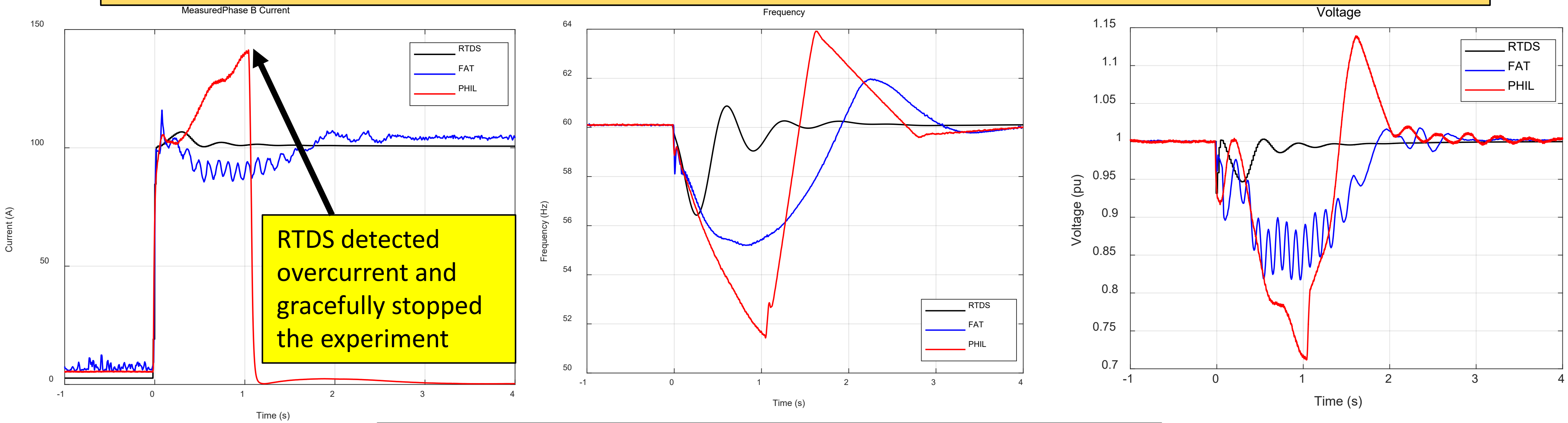
- Probing for limits: constant power load ramp rate of 0.5 pu/s caused by RTS based protection (current trip)
- Same setting feasible with constant impedance load

75% Block Load – Step Up

FAT (Constant Impedance) vs Constant Power



Top – Repeated FAT condition using PHIL – DG stable, bottom – Constant power type load presented to DG - unstable

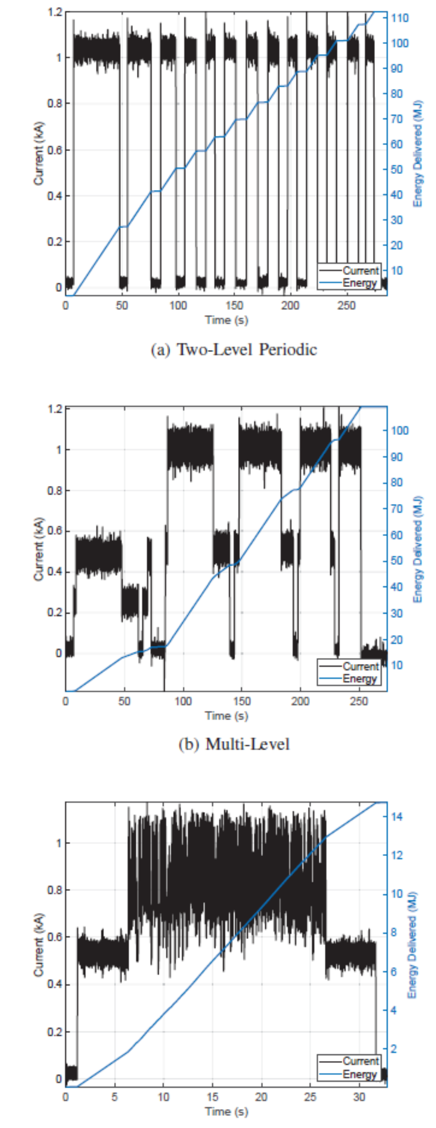


Load bank based testing inadequate to emulate data center loads

Testing 200 MJ Energy Magazine (EM) for Shipboard Systems

Electric Ships Office PMS 320 — Directing the Future of Ships Power
NAVSEA WARFARE CENTERS Philadelphia
LEONARDO DRS

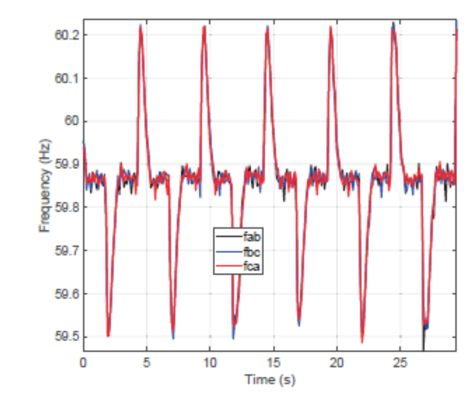
- DC PHIL Interface
  - Emulated pulsating mission loads and parallel PCM
  - DIM-IT IA
  - Used 2.5 MW, 1 kV DC amplifier
- AC PHIL Interface
  - Emulated generators and ship service loads
  - DQ-frame DIM-VT IA
  - Used 2.5 MW, 4.16 kV amplifier
- Studied voltage distortion, modulation, and disturbances in AC system
- Studied variety of DC load profiles (representing different types of loads)
- Gathered characterization data for modeling and model validation

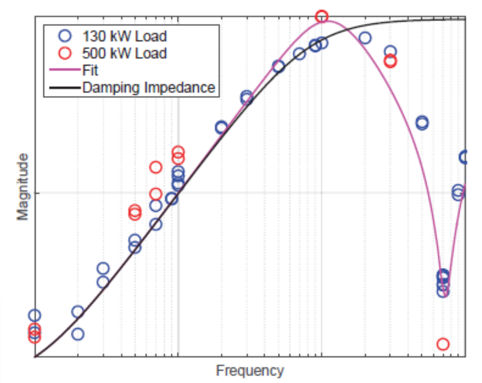


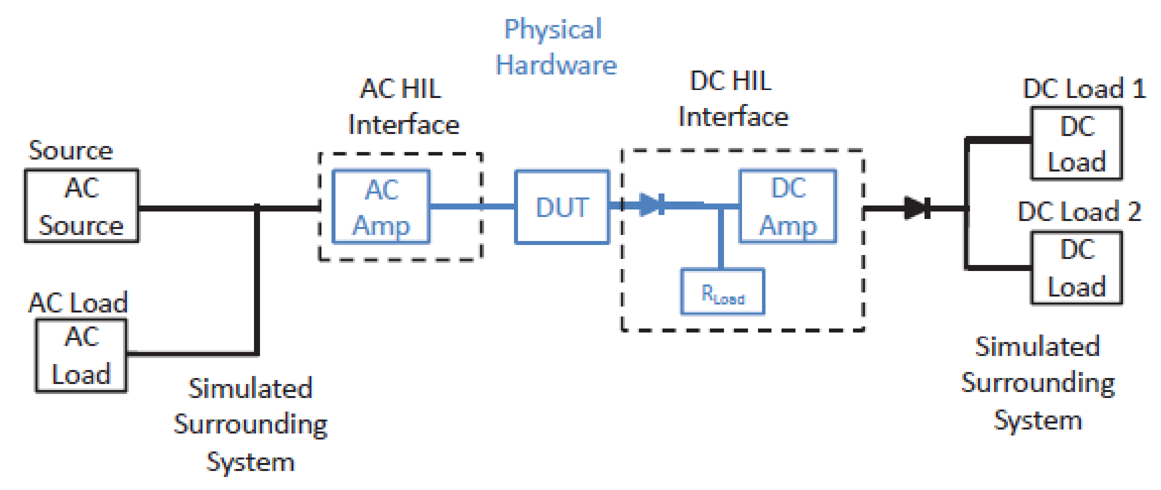
(a) Two-Level Periodic

(b) Multi-Level

(c) Base + Stochastic

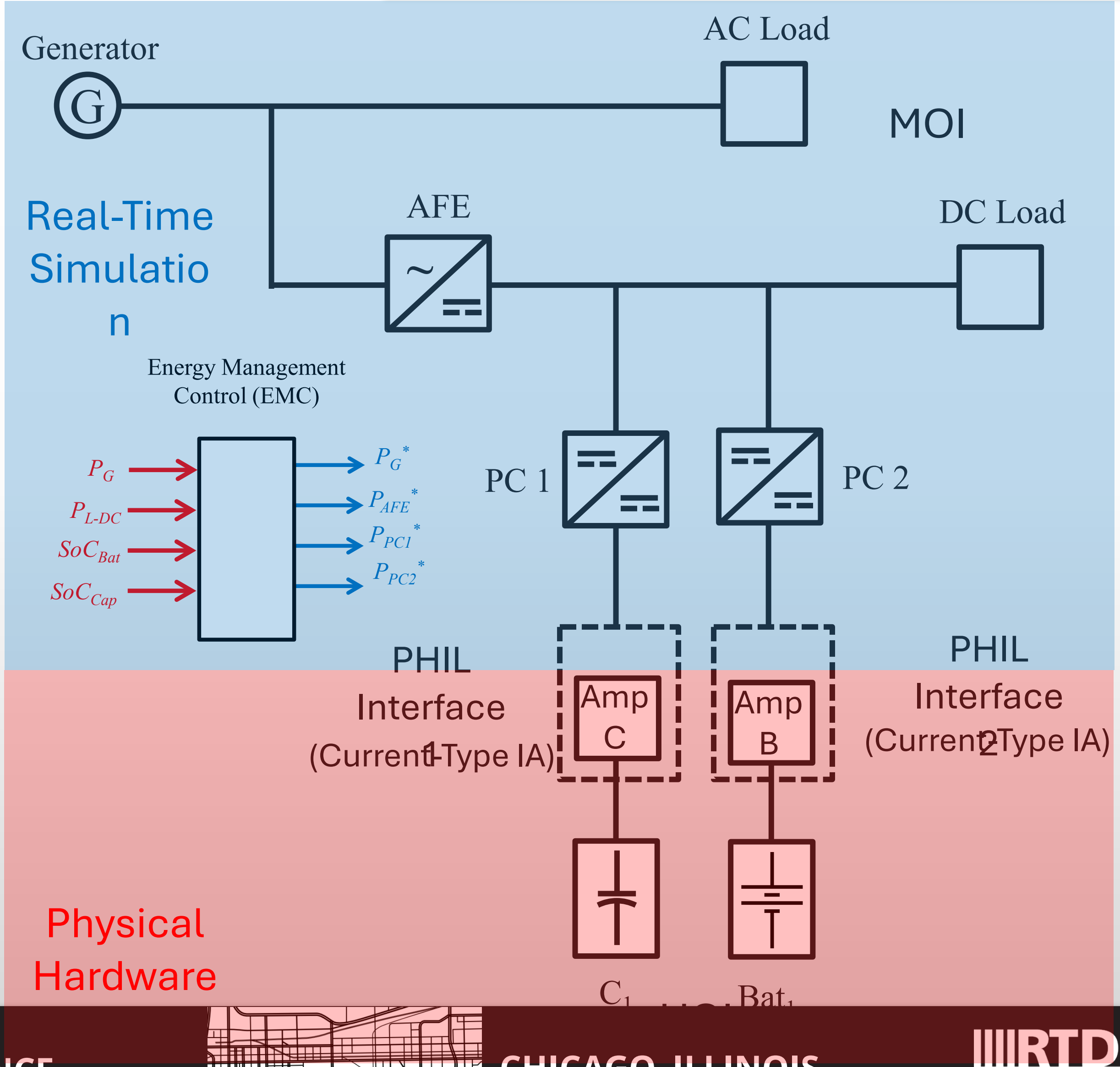






Testing of Energy Storage in Limited Inertia Systems

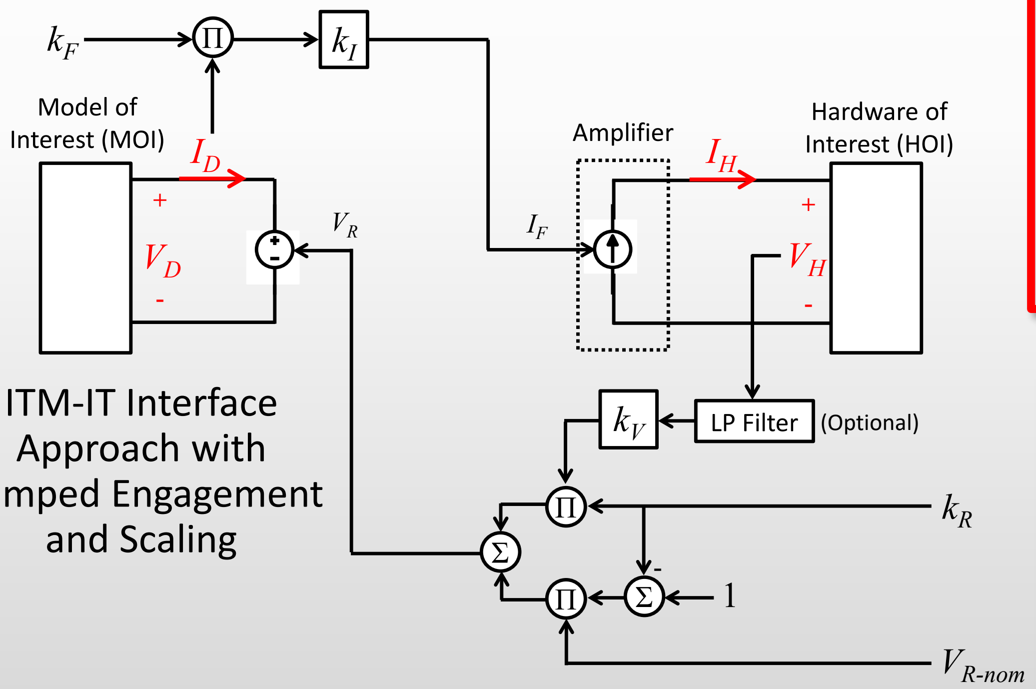
- Model of Interest (MOI)
  - All components and controls, excluding the energy storage media
  - Executed on real-time simulator using 50 µs time-step size
- Hardware of Interest (HOI)
  - Battery module
    - 45 Ah
    - Air cooled
    - 28 V nominal terminal voltage
  - Ultra-capacitor module
    - 53 F
    - Water-cooled
    - 170 V nominal voltage
- PHIL Interfaces



PHIL Interfaces

- Current-type Ideal Transformer Model (ITM-IT) Interface Approach
  - Gains for gradually engaging interface (k_F and k_R)
  - Scale factors for scaling current and voltage across the interface (k_I and k_V)
  - Low-pass filter on voltage feedback for stability and immunity to sensor noise (100 Hz cutoff frequency for battery interface)

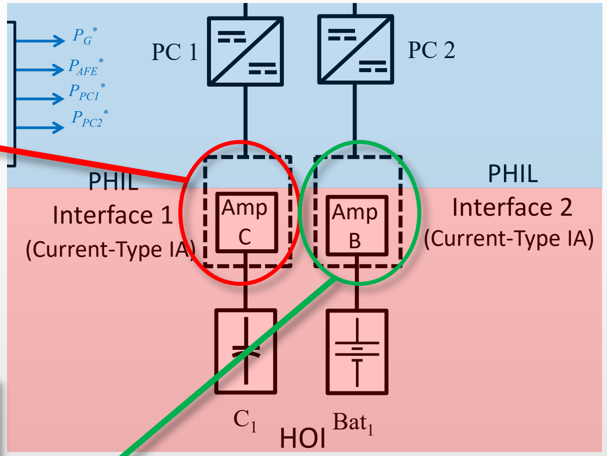
- Amplifiers
  - High bandwidth (> 5 kHz)
  - 750 V, 100 kW
  - Digital interface with RTS
  - Operated multiple amplifier units in parallel for each PHIL interface



ITM-IT Interface Approach with Ramped Engagement and Scaling

Interface to Capacitor Module

- 2 amplifier units in parallel (280 A)
- Single capacitor module scaled to represent 5s x 3p bank
  - k_I = 1/3
  - k_V = 5



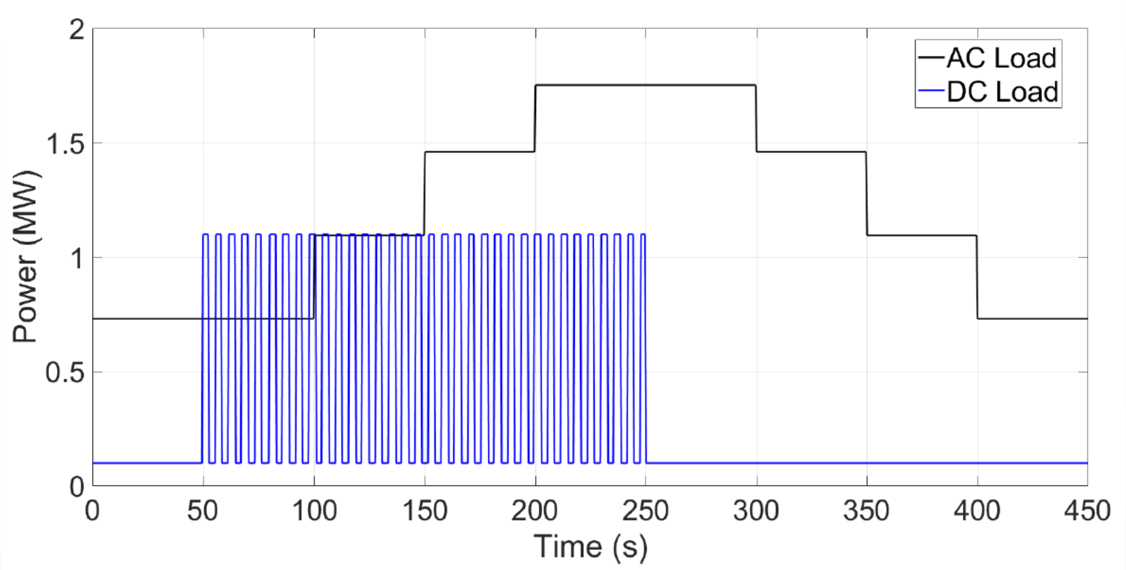
Interface to Battery Module

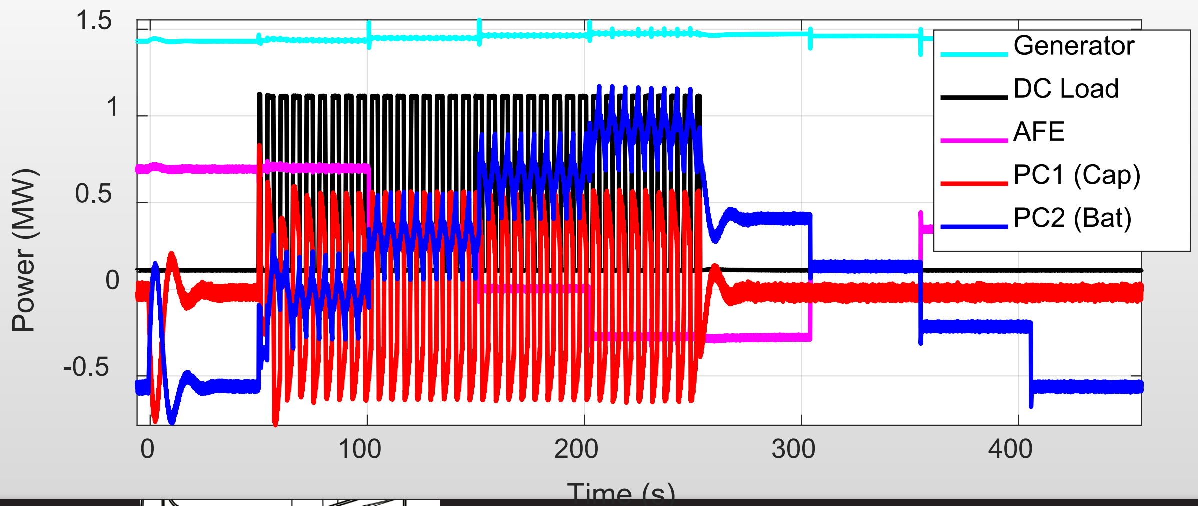
- 3 amplifier units in parallel (240 A*)
- Single battery module scaled to represent 28s x 7p bank
  - k_I = 1/7
  - k_V = 28

* Current limited by battery voltage, lower voltage limit of amplifiers, and voltage drop across series resistors used to facilitate current sharing between amplifiers

PHIL Simulation Experiments: Baseline Scenario

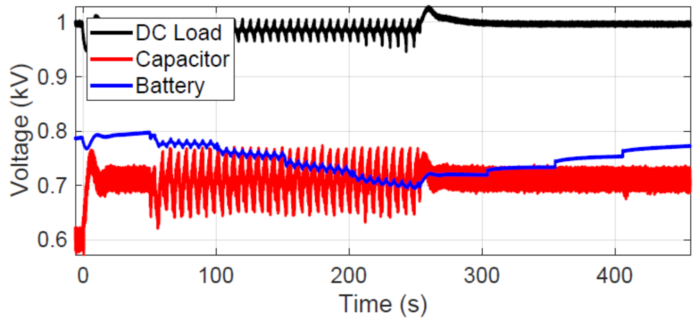
- Loading profile intended to test system in several modes of operation
- (0 s < t < 50 s) Base loading
- (50 s < t < 100 s) Pulse loading
  - Capacitor supplies load pulsations
- (100 s < t < 150 s) Battery supplements support of DC load
  - Total load exceeds generator capacity
- (150 s < t < 200 s) Battery fully supports DC load
  - AC load at generator capacity
- (200 s < t < 250 s) Battery supports DC load and supplements support of AC load
  - AC load at 120% of generator capacity
- (250 s < t < 300 s) Load pulsations cease
  - Battery supplied DC base load and supplements support of AC load
- (300 s < t < 350 s) Battery supports DC base load
- (350 s < t) Battery recharges



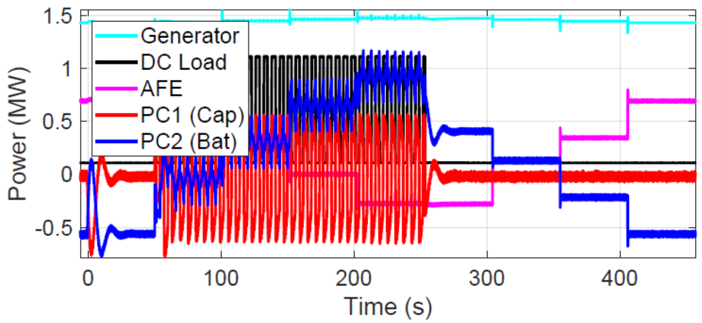


Results from PHIL Simulation Experiments

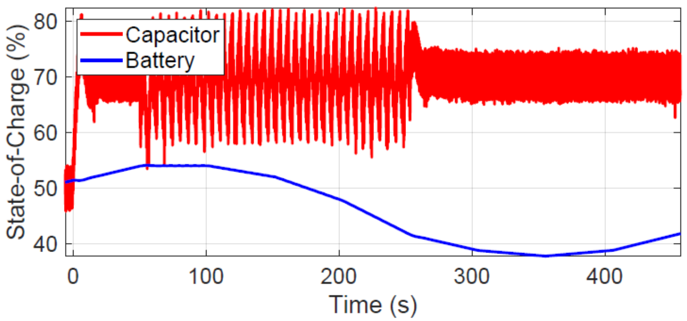
- Generator loading approximately held constant (near full load)
- Capacitor SoC generally maintained between 60% and 80%
- Voltage and current levels maintained within normal bounds



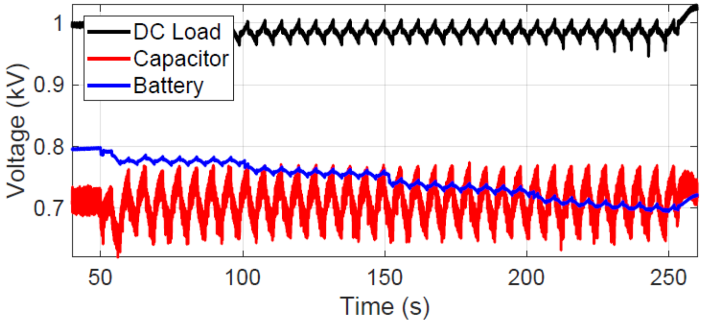
(a) Voltage



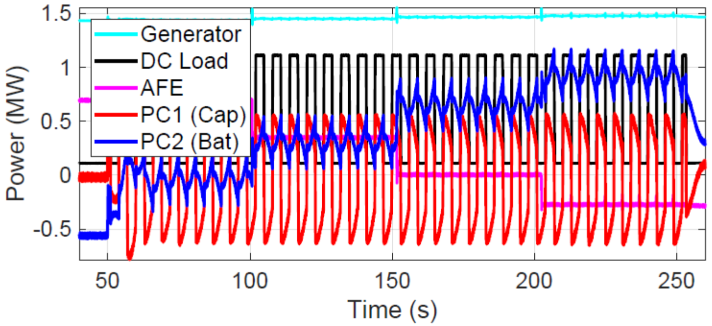
(b) Power



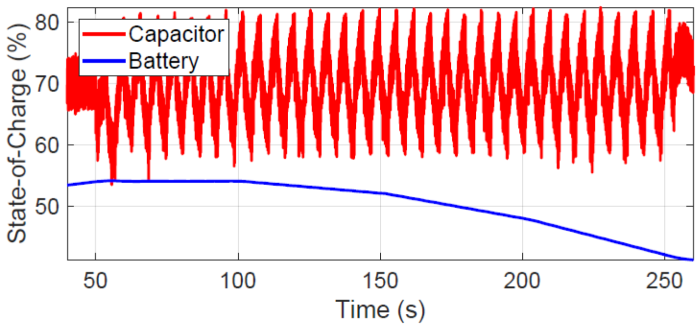
(c) State-of-Charge



(a) Voltage



(b) Power



(c) State-of-Charge

Thank You

Contributions: IEEE 2004-2025 Recommended Practice for Hardware-in-the-Loop Simulation

- **Michael "Mischa" Steurer** pioneered HIL and initiated IEEE WG P2004. Developed general linear formulation of PHIL experiment
- Collaboration**: PSRC WG CTF-33**; IEEE task force (TF) on "Real-Time Simulation of Power and Energy Systems", chaired by Dr. Omar Faruque, under **IEEE WG 15.08.09** (within the General System Subcommittee of the IEEE PES T&D Committee)
- Sponsor: **PELS,** Co-sponsor: **IAS, IES**
- CAPS led one of the chapters (Execution of PHIL Experiments)
- CAPS members made substantial contributions to multiple chapters and annexes

High Speed Generator for Air Force Application

- Tested 2 MW high speed generator
- Used 5 MW dynamometers and high speed gearbox for 14,000 rpm interface
- Used high-speed diode rectifier at AC terminals of generator
- DC PHIL interface
  - ITM-IT IA
  - 2.5 MW, 1 kV DC amplifier
- Verified operation of the generator at full power
- Tested with constant-current ramp loading

Langston, J., et al. “Megawatt Scale Hardware-in-the-Loop Testing of a High Speed Generator." *2012 ASNE*.