PHIL Testing of Integrated Supercapacitor Energy Storage System for Providing Blackstart and Wide-Area Stability Services through DER Plants

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Introduction

- Creating and maintaining a black-start strategy is a requirement for utilities
- A successful strategy starts with identifying feasible cranking paths which requires blackstart capable power sources
- Having more choices for power sources increases the flexibility, effectiveness and reliability of the strategy
- DER's by themselves are not suitable for blackstart
- Supercapacitor Energy Storage Systems (SESS) with their fast response time are ideally suited to provide cost competitive Watt-Hz support to existing DER plants to enable them to be blackstart candidates
- Idaho National Lab in partnership with Maxwell Technologies initiated a DoE project to evaluate this technology. A field pilot was part of the validation plan
- Being the first of its kind application, real-time PHIL testing was considered a prudent intermediate step to validate the strategy to de-risk the investment in a field pilot
- This presentation discusses the PHIL test setup with the SESS power hardware interfaced with a candidate DER plant modeled in RTDS.
- Presentation also includes some background on Supercapacitors

Project Team

Idaho National Laboratory	Principal Investigator, Implementation of pilot
Maxwell Technologies	Supercapacitor Energy Storage System (SESS)
Nayak Corporation	RTDS Modeling Support

Thank You to

RTDS Technologies Inc.	Provided a NovaCor to test the SESS at the factory

Nayak Corporation

Nayak's role in this project:

- Nayak provided both remote and onsite technical support in the RSCAD simulation and PHIL interface

About Nayak

- Nayak Corporation established in 1999, has unique combination of power system simulation knowhow and industry application experience
- We are the representatives for RTDS, PSCAD, SPS amplifiers and DesignBase in the US
- We provide technical support, training, consulting services related to these power system simulation tools
- www.nayakcorp.com

Idaho National Lab HIL Capabilities

Idaho National Laboratory

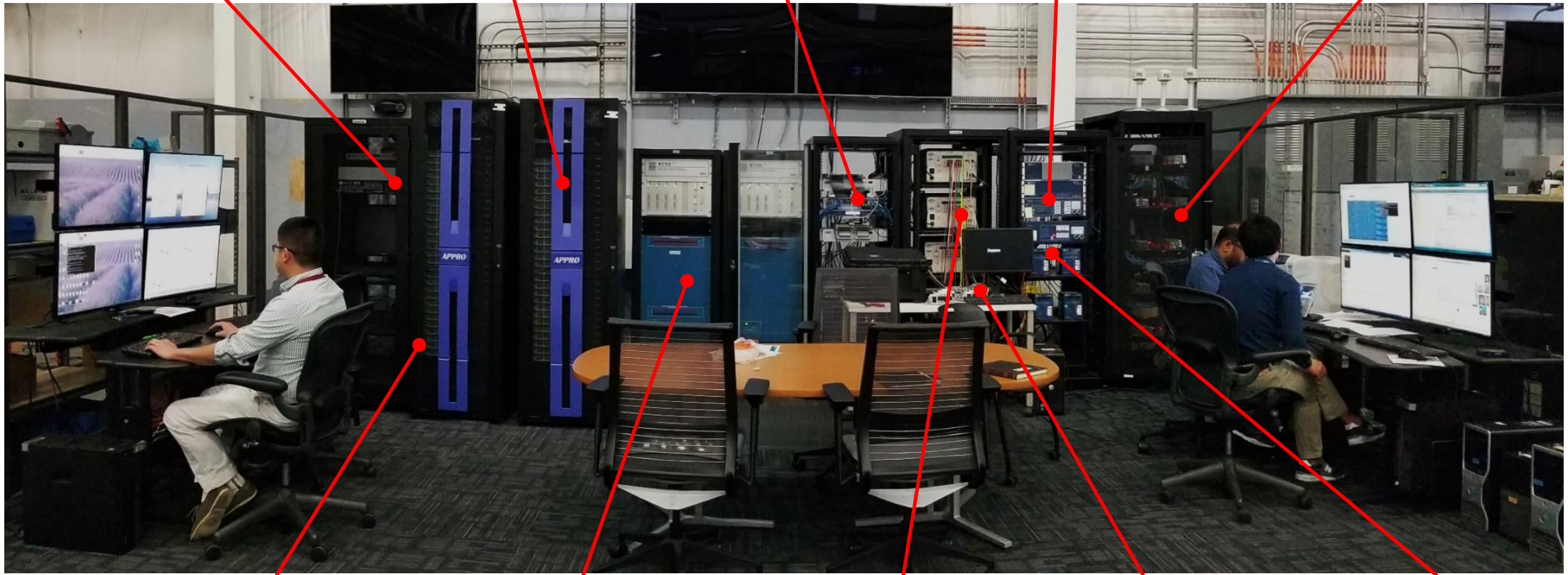
Opal RT, FPGA Development Environment
(IEEE 1394 and MIL 1553)

High Performance Computing
(~1800 compute nodes)

Typhoon HIL
for Testing Advanced Power Electronics

Controllers
(Siemens, SEL RTAC)

100+ RISC-based programmable cards for emulating hardware devices
(Electric Vehicles, Wind Turbines)



Linux Servers for communication layer, Real-time Data Analytics

Real-Time Digital Simulator

Programmable V & I-Amplifiers

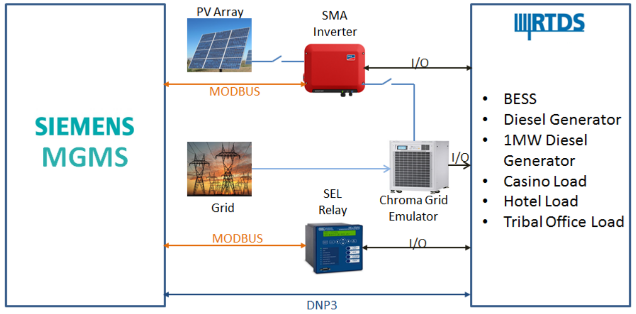
Micro-PMUs

Protection Relays

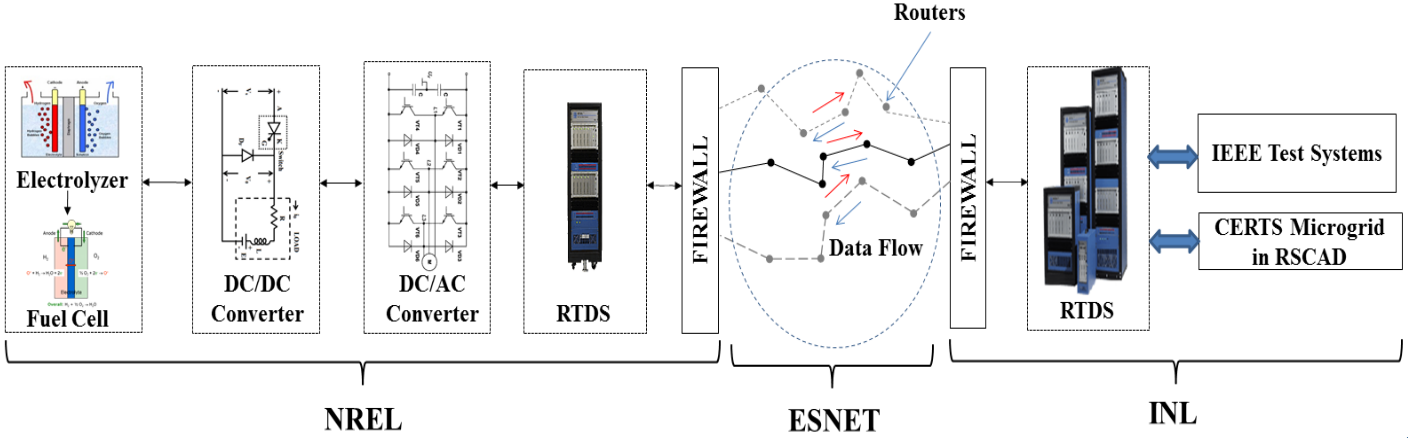
Contact Mayank.Panwar@inl.gov for more information

INL's Recent Realtime HIL Projects

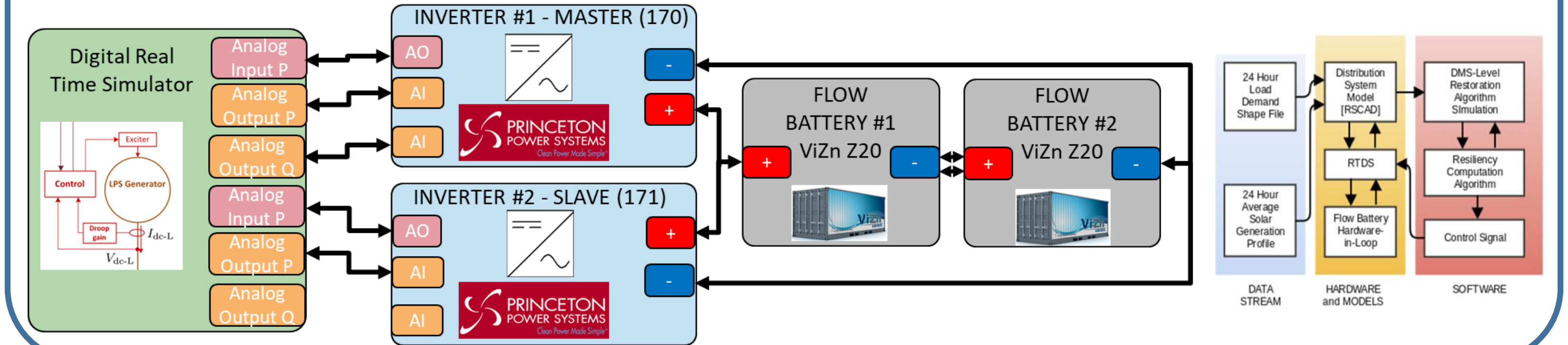
California Energy Commission's Blue Lake Rancheria Microgrid



Hydrogen Electrolyzer – Experimental Setup for Remote HIL



Digital Real Time Testing for Flow Batteries



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Maxwell Technologies

Maxwell Technologies
Enabling Energy's Future™

Business Highlights

Overview

- **Founded 1965**
- Headquarters: San Diego, CA
- IPO 1983 (NASDAQ: MXWL)
- Advanced energy storage & power delivery solutions
- Locations: San Diego, Phoenix, Germany, S. Korea, China

Product Lines

Energy Storage

- Grid and Microgrid Energy Storage
- Utility Distribution Grid Storage
- Advanced Automotive Electrification
- Light and Heavy Rail
- Industrial – Customer Side of Meter

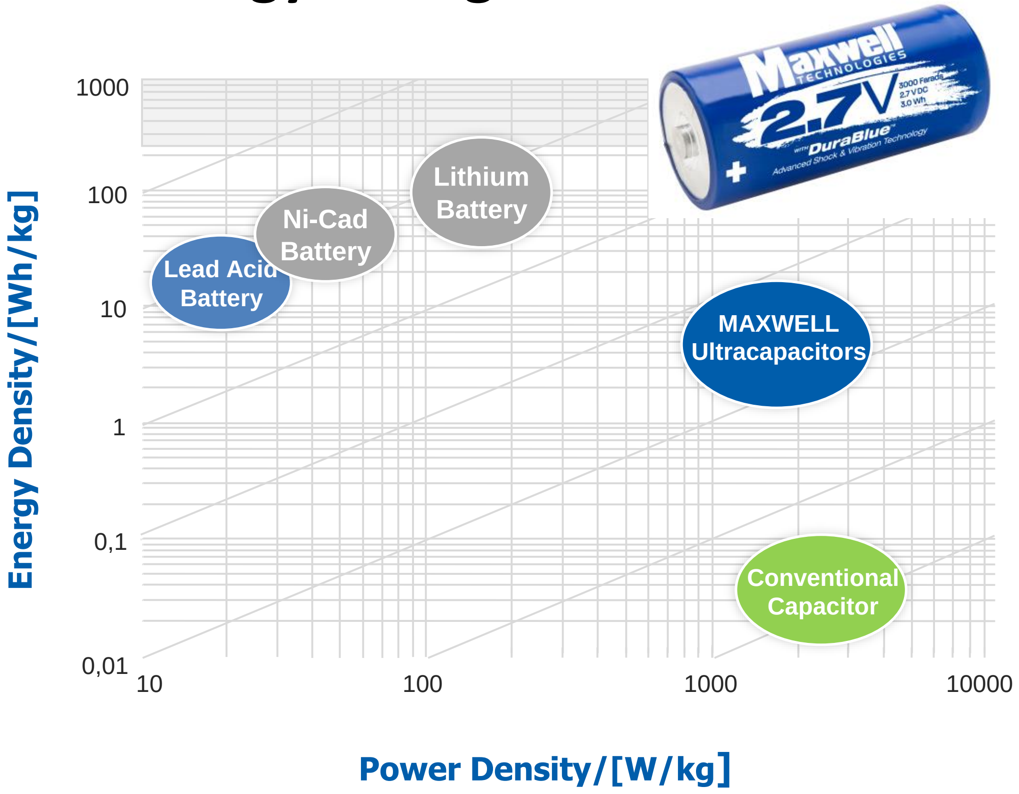
Next-Gen, Building Block Technologies

- Lithium-ion Ultracapacitor
- Li-ion Battery Electrode

Some Background on Ultracapacitors

❖ Ultracapacitors are High Power DC Energy Storage Devices

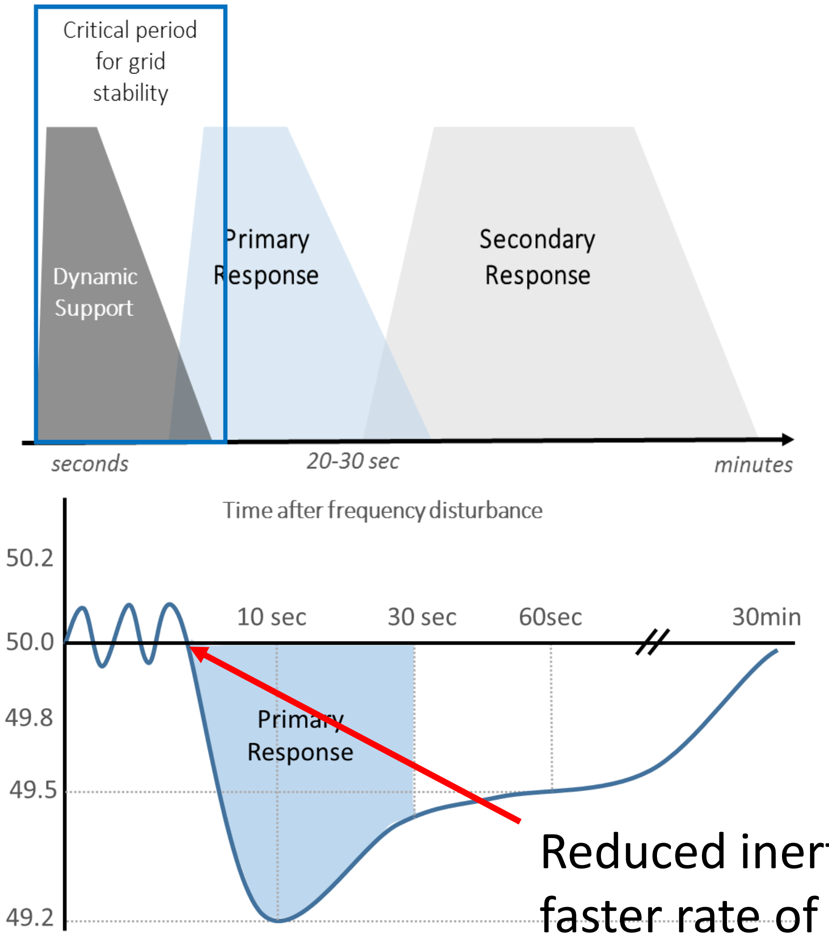
- Provide peak power from **sub-seconds to minutes,** with **millisecond response times**
- **Long lifetime:** 1M cycle life, 12-15 year lifetime* electrostatic (not electro-chemical)
- **Low to zero maintenance over the asset lifetime**
- **Compact form factor for power delivery**
- **Scalable:** commercially deployed at kW through MW
- **Safety & Environment:** does not contain lithium, metal oxides, rare earths or lead. Thermal runaway not possible
- **-40 to 65°C** operating temp window
- Deep discharge capability to 99% under repetitive cycling conditions



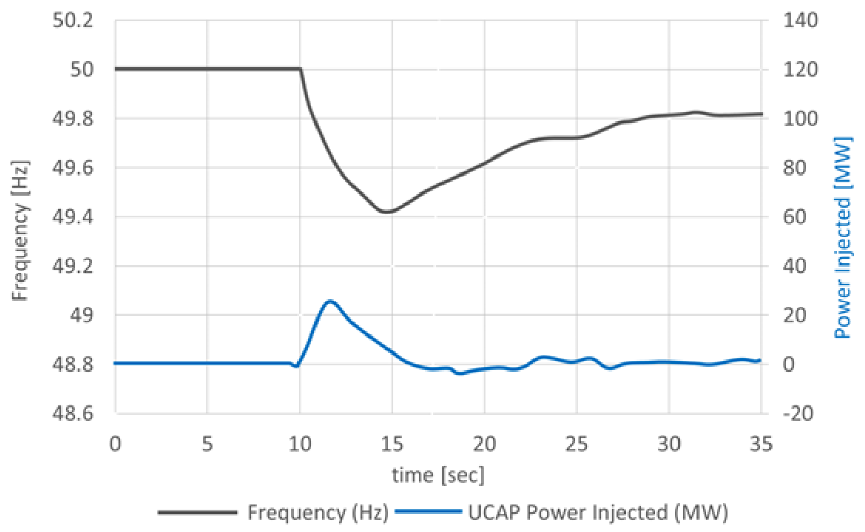
*Ultracapacitors are also known as **Supercapacitors** or **Electric Double Layer Capacitors** (EDLCs)*

*Results may vary, additional terms and conditions include limited warranty, apply at the time of purchase. See the data sheet and warranty details for applicable operating end user requirements.

Ultracaps: FFR and Synthetic Inertia



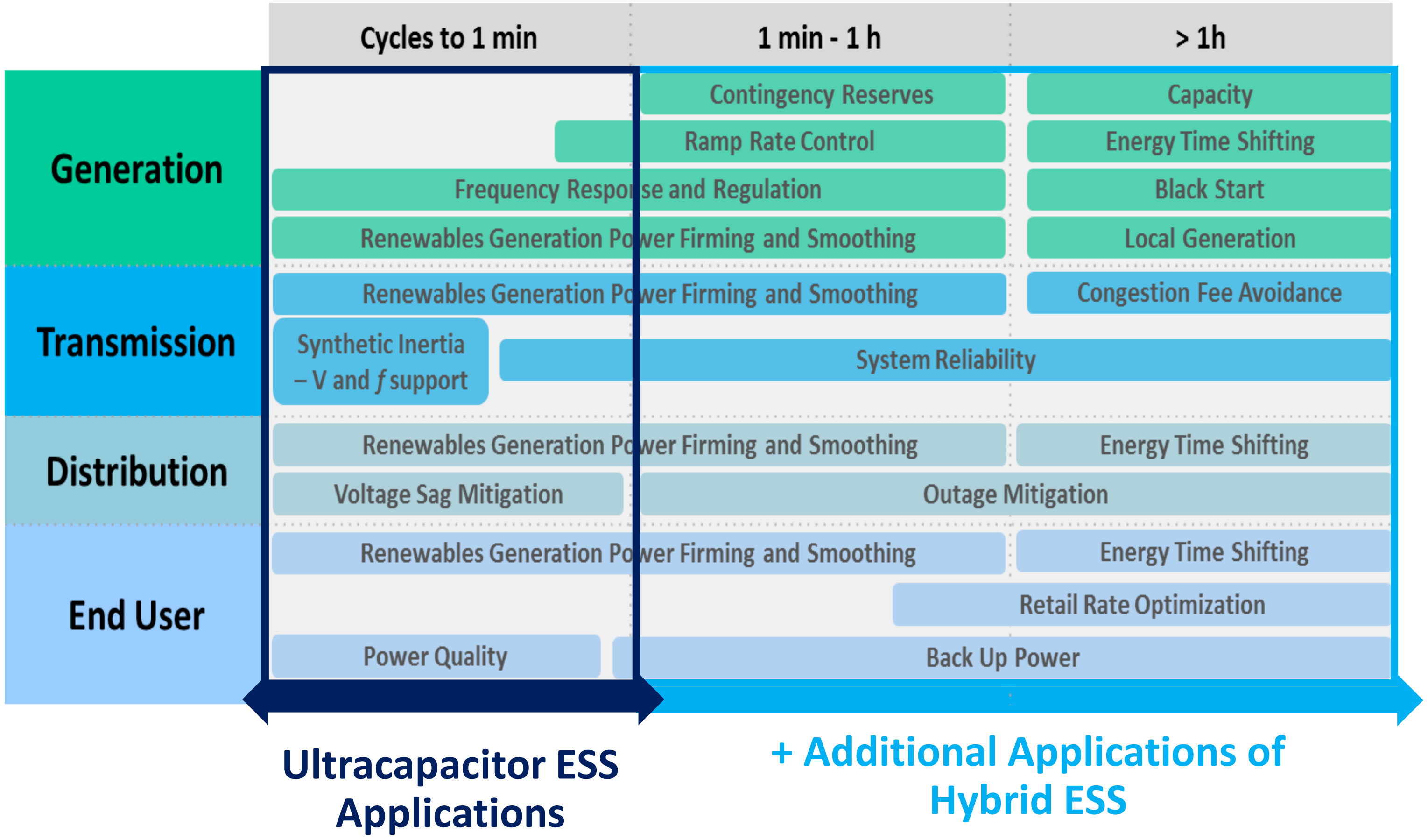
Ultracapacitor devices rapidly inject power in the millisecond timeframe. **Integrated power system response is sub-cycle.** Power delivery duration times are scalable.



Reduced inertia in the grid due to more renewable generation causing faster rate of change of frequency (RoCoF) events

Ultracapacitors and Hybrid Systems

❖ Singular or Stacked Benefits Spanning Milliseconds to Hours



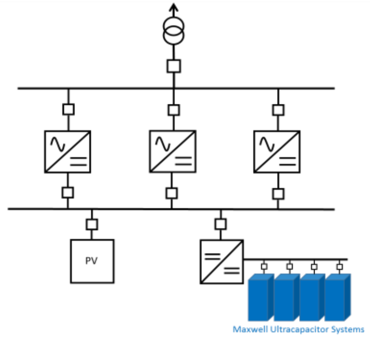
- At the system level, ultracapacitors may also be combined with other storage (such as Li-ion batteries) to deliver "stacked" services spanning msec to hours to **optimize benefit-to-cost ratio's, project CAPEX and OPEX**
- **Examples:**
  - ✓ Wind and PV Power Firming + Energy Shifting
  - ✓ Fast Frequency Response + Stacked Services
  - ✓ Fast "Distribution Level" Voltage Sag Mitigation + Peak Shaving + Resource Adequacy

Renewables Power Firming

Issue and UCAP Solution

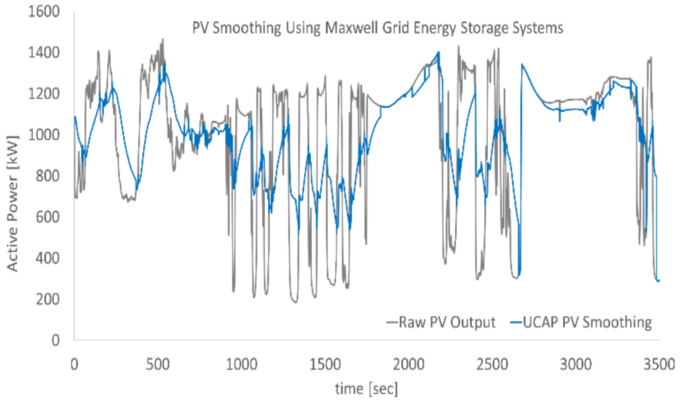
- Renewables power intermittency creating voltage fluctuations on a long distribution feeder
- Desire for storage to provide "stacked" services – time shifting + power firming to improve business case, B/C ratio

Example System Architecture



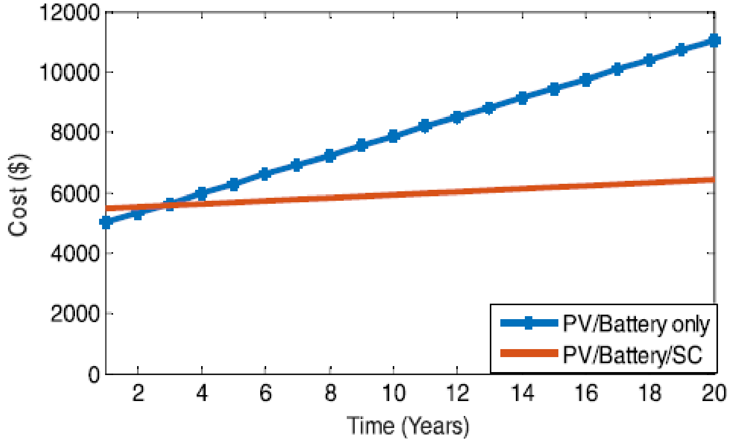
- Ultracapacitors DC coupled
- AC configurations also possible
- Battery may be DC or AC coupled

Technical Fit



UCAPS damp power fluctuation

Economics



J. Renewable Sustainable Energy 10, 013503 (2018)

Power	Stacked Functionality	**Energy**

UCAPs:
- V, *f* stabilization
- PV Smoothing
- Support Peak Power

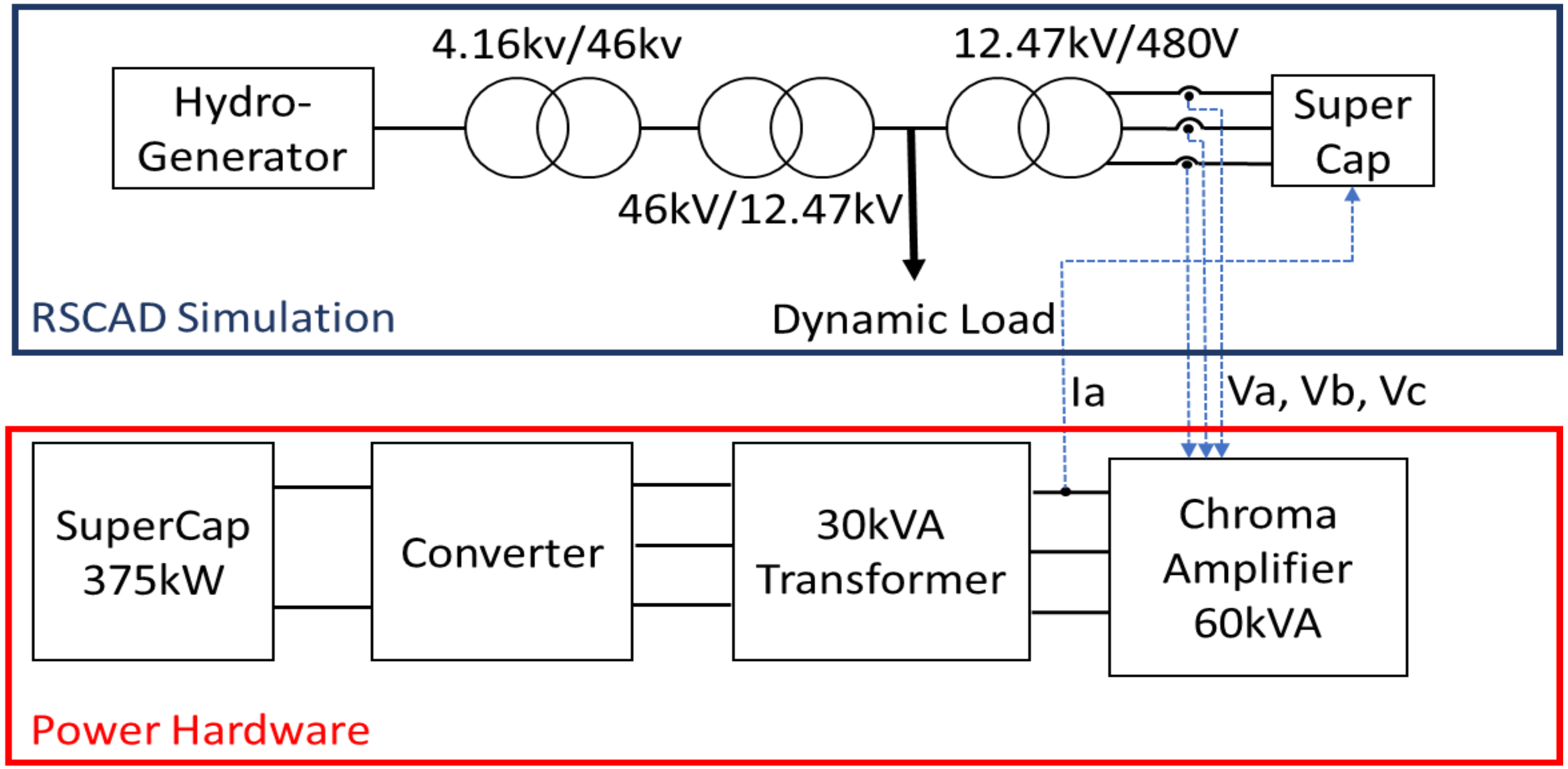
Batteries:
- PV Smoothing
- Ramping
- Time shifting

High power and cycling requirement removed from battery and placed on UCAPS to maximize total asset lifetime

40% battery lifetime improvement →
58% reduction in LCC

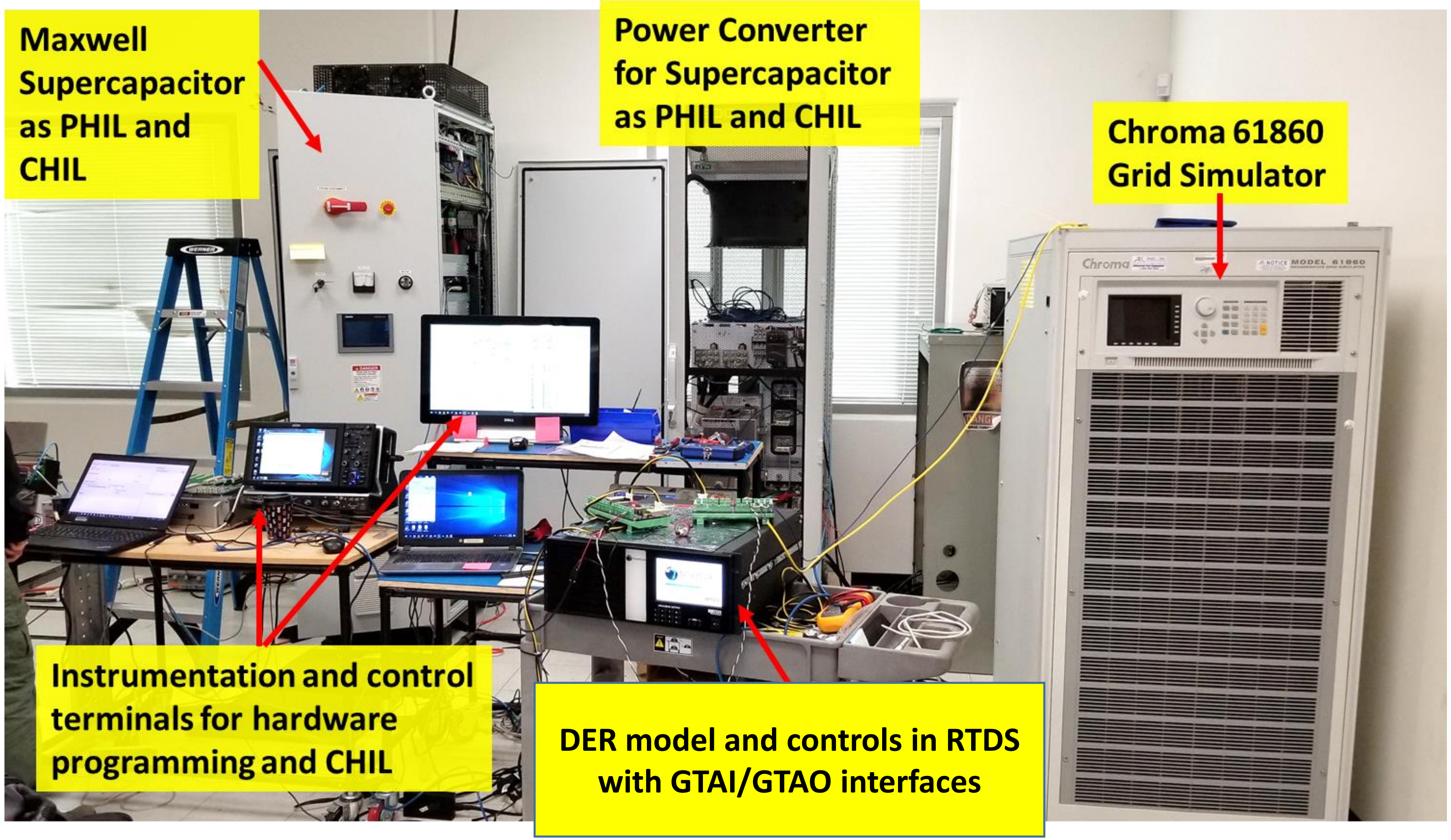
SESS PHIL Setup Overview

- **RSCAD Model:** Power plant, transformers, breakers
- **Power Hardware:** Supercapacitor, converter, transformer
- **PHIL Interface:** RTDS simulation interfaced to the physical power hardware via a 4-quadrant power amplifier



PHIL Setup: Power Hardware

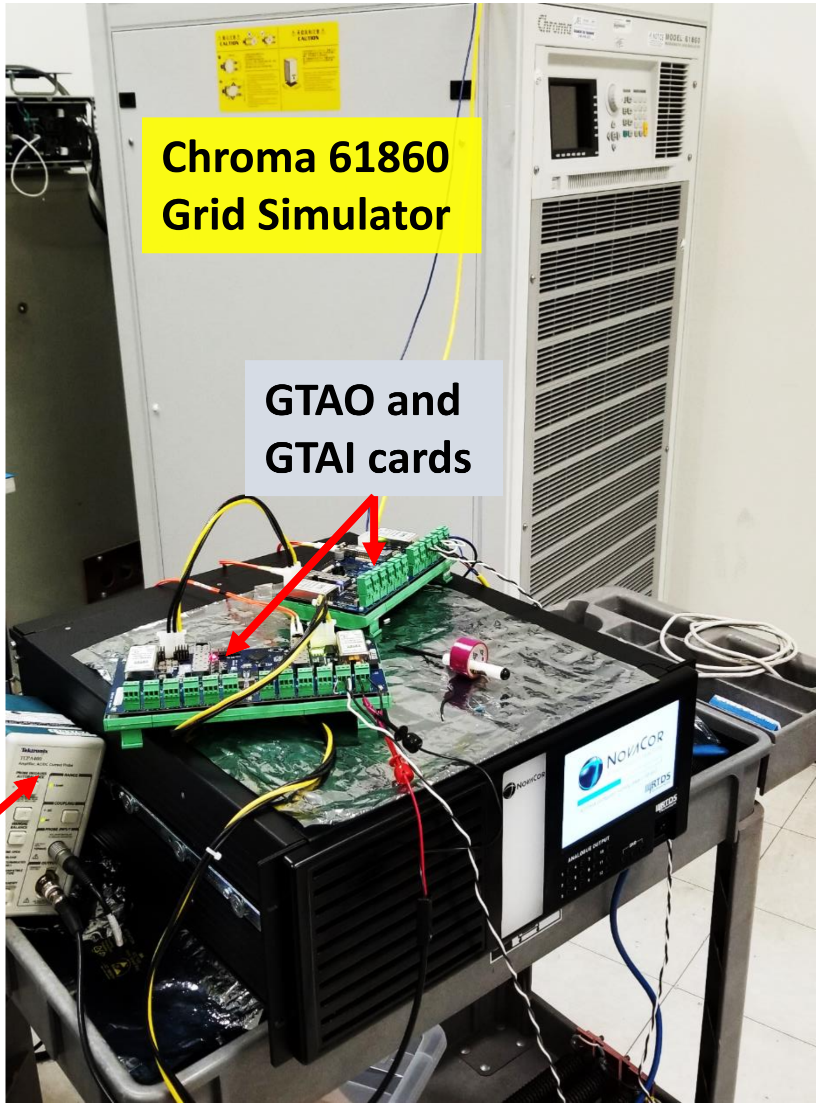
- Supercapacitors: 1kWh
- EPC Power converter: 375kVA (limited to 60kVA)
- Transformer: 30kVA
- Chroma 61860 amplifier: 60kVA (4 Quad operation)
- Current probe: Tektronix TCPA 400 AC/DC (1A=1mV conversion) to GTAI



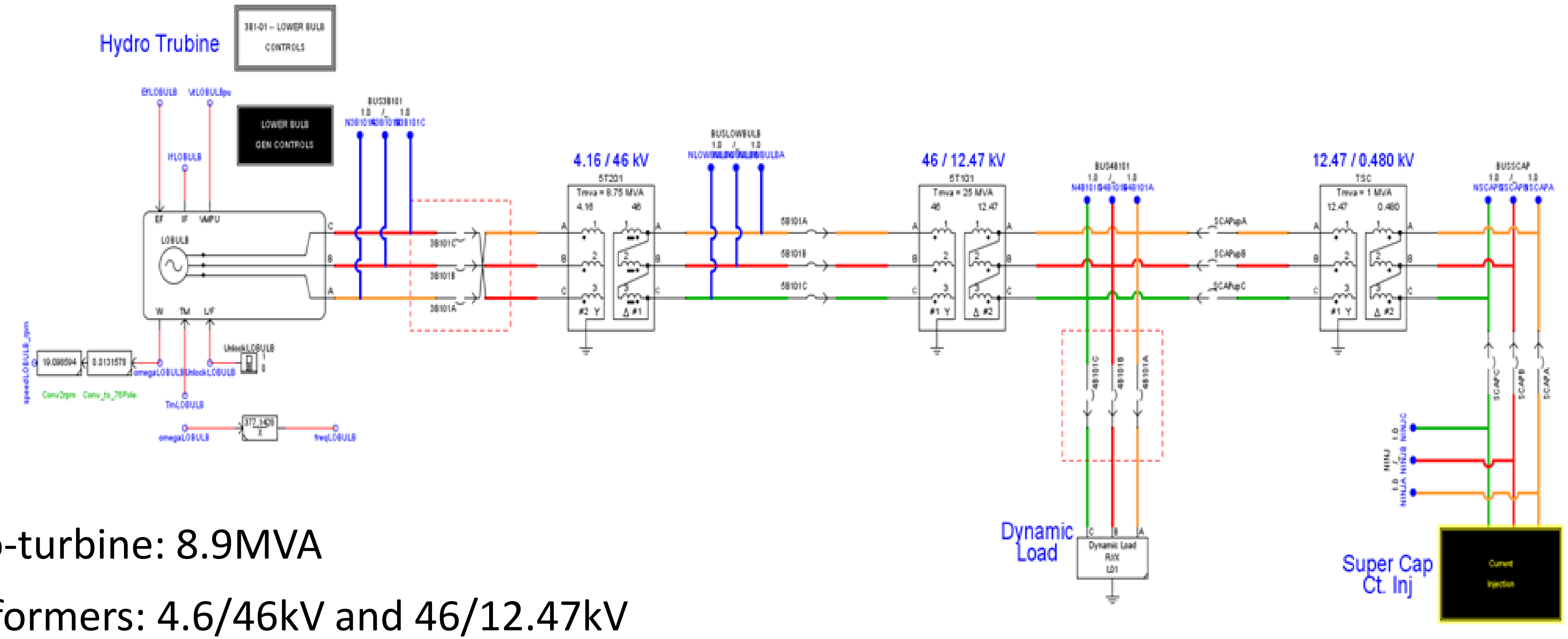
PHIL Interface

- The grid voltage was measured in RTDS and Chroma emulated the AC load bus where SESS was connected
- Current from AC bus was transduced into RTDS for HIL
- Using RMS value of input current and simulated PLL tracking the grid voltage, current injection for the SESS is generated

Yes, there were issues with interface delays and instability and some on-the-spot improvisation, trial and error had to be done. We can discuss that separately if anybody is interested in those aspects of the experiment

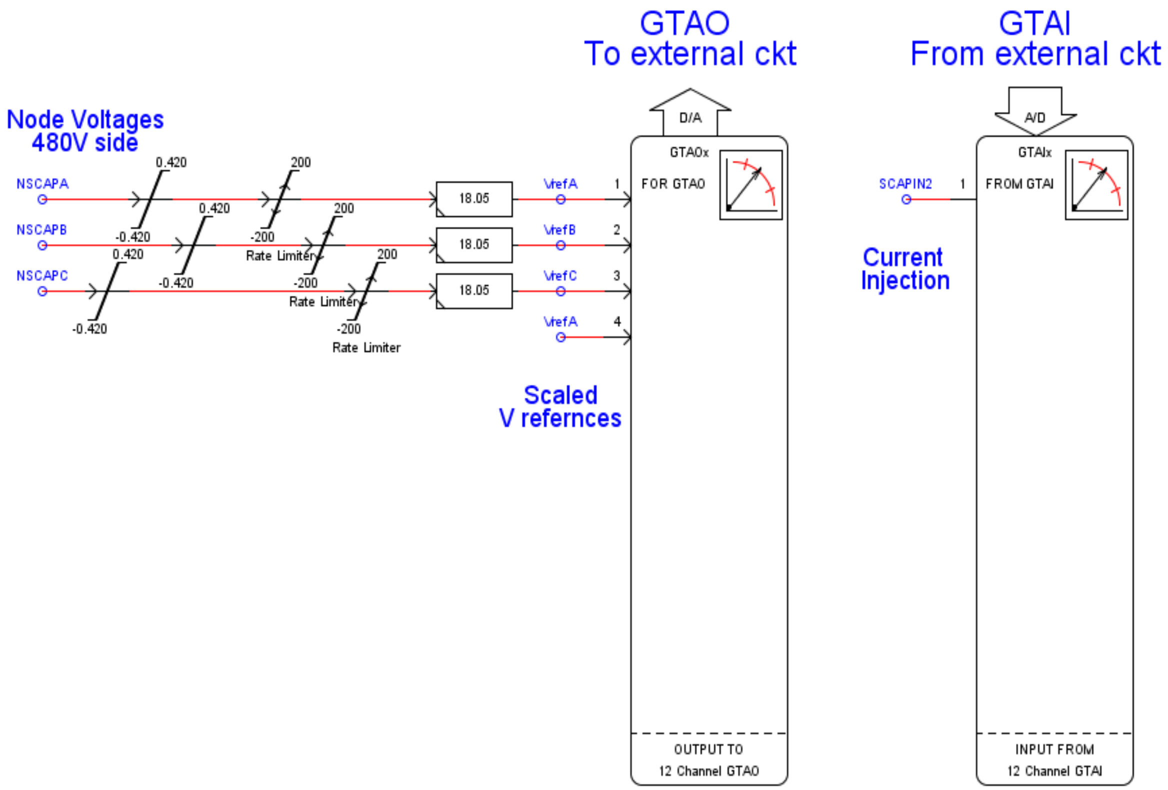


RSCAD Model



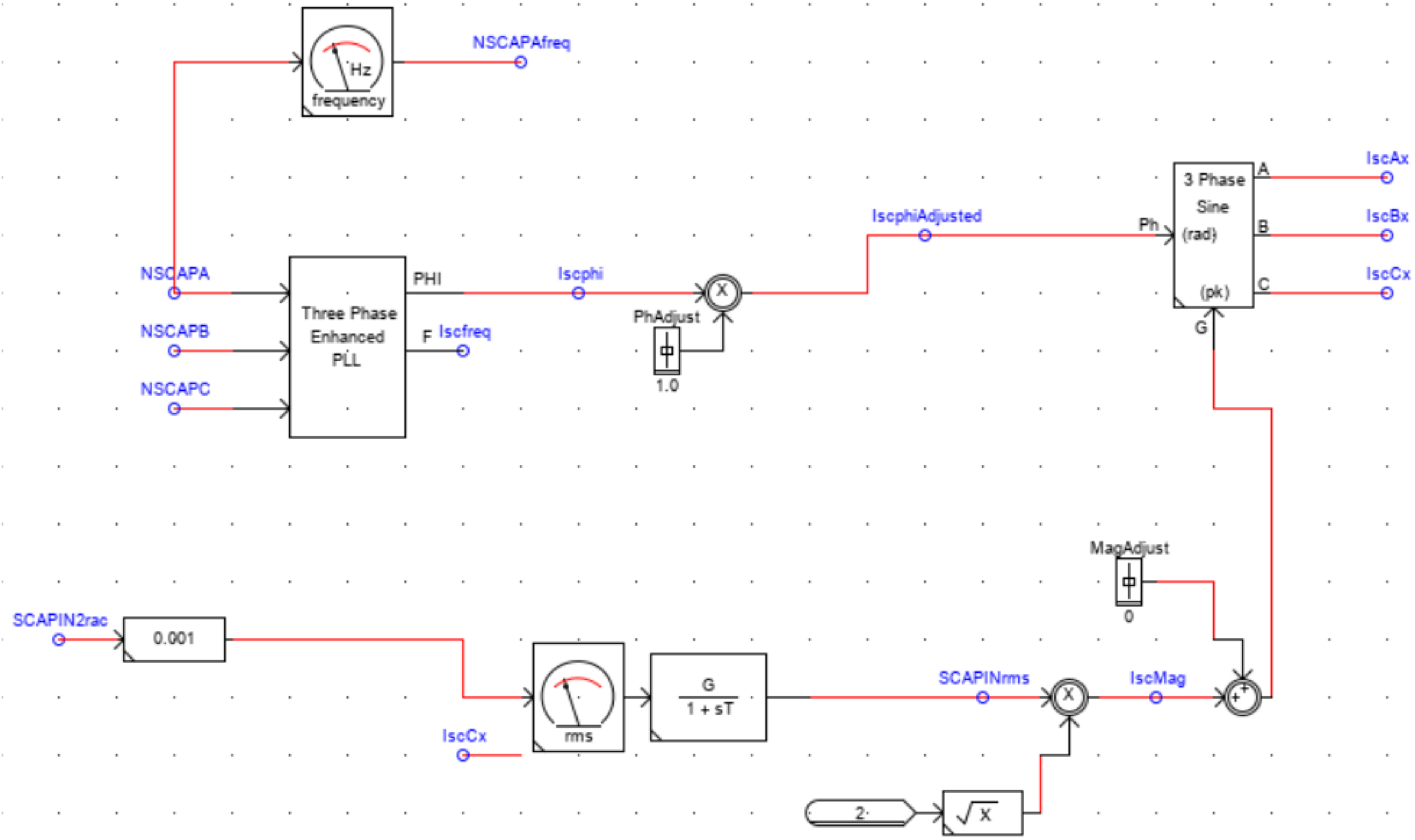
- Hydro-turbine: 8.9MVA
- Transformers: 4.6/46kV and 46/12.47kV
- Supercapacitor: 3-phase current injection at 12.47kV load bus
- Chroma Amplifier is the interface between RSCAD simulation and power hardware

RTDS IO



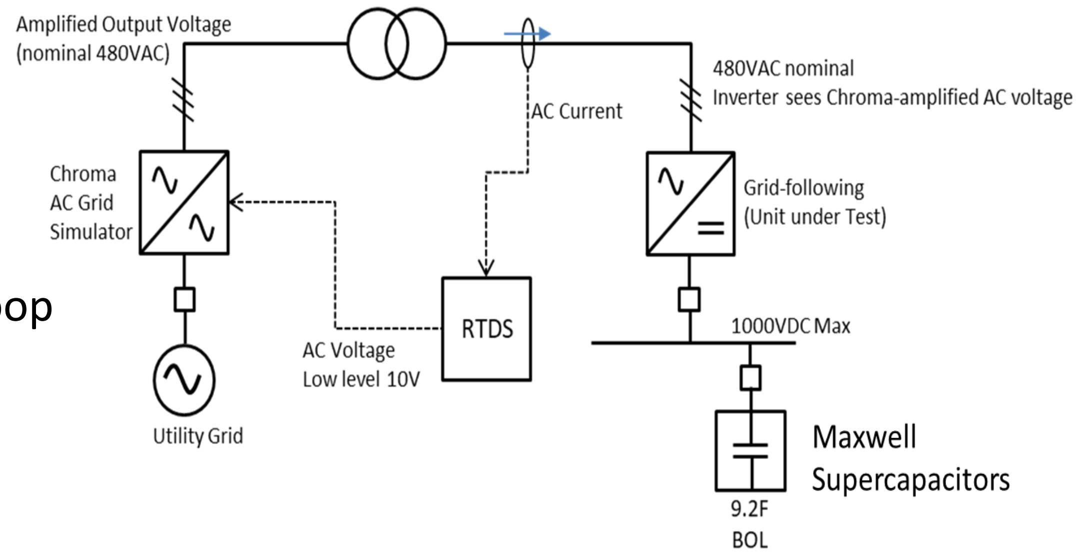
- GTAO: Node voltages measured at 480V bus in RSCAD are scaled and fed to Chroma amplifier
- GTAI: Actual currents measured at the output of the amplifier are fed back to RTDS

Current Injection Calculation



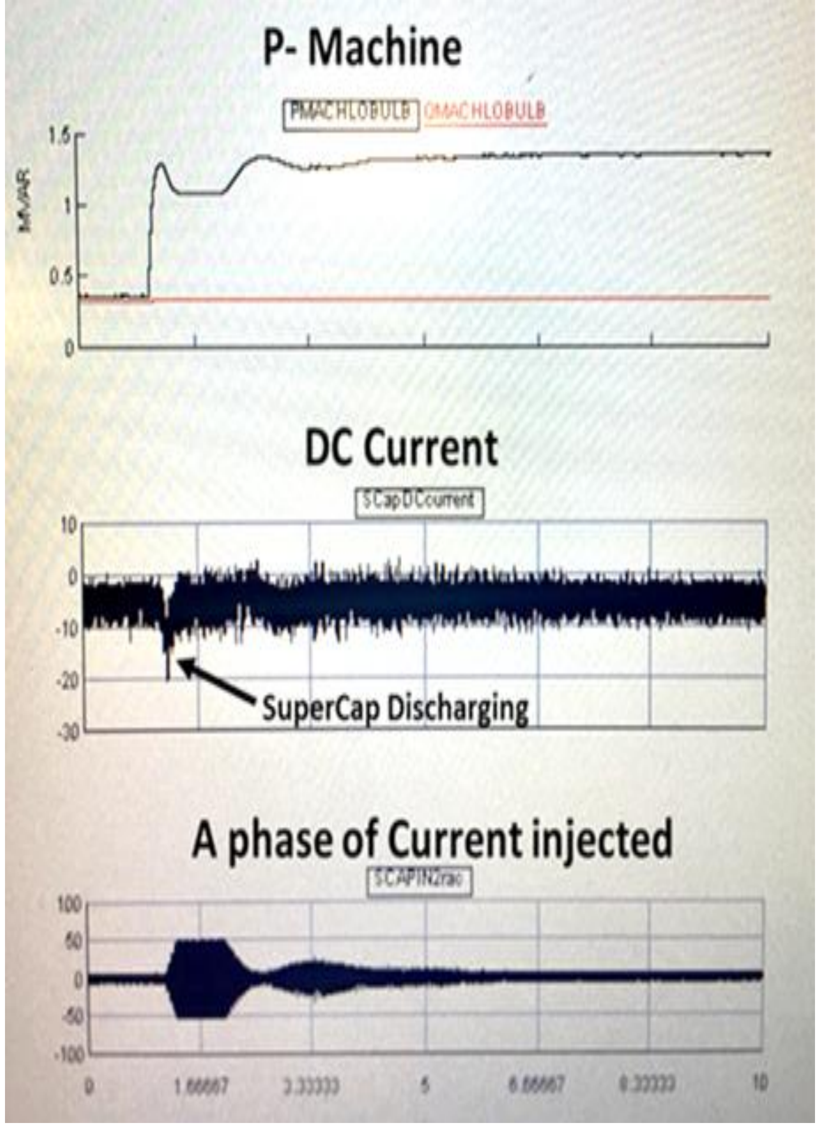
HIL Tests

- HIL tests were designed to show the ability of SESS to provide stability during blackstart
- Several tests including the following tests were conducted
  - Autonomous response of EPC converter
    - Load drop and step load change
    - Frequency-Watt (f-W) response for frequency changes
    - Volt-Var (V-Var) for grid voltage changes (open loop only)
  - Safety and functionality tests
    - Supercapacitor (SC) charging and discharging procedure was verified
    - Safety trips and interlocks were tested



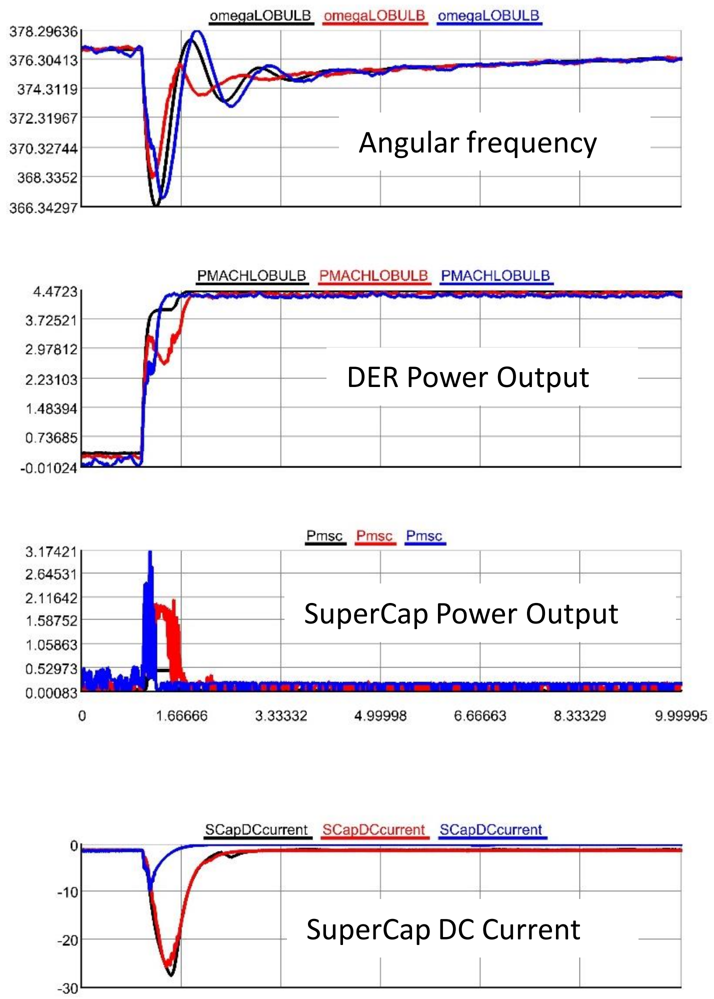
Test Results

- Supercapacitor enables better frequency response during dynamic load variation
- Capacitor is (dis)charged accordingly to address the frequency change

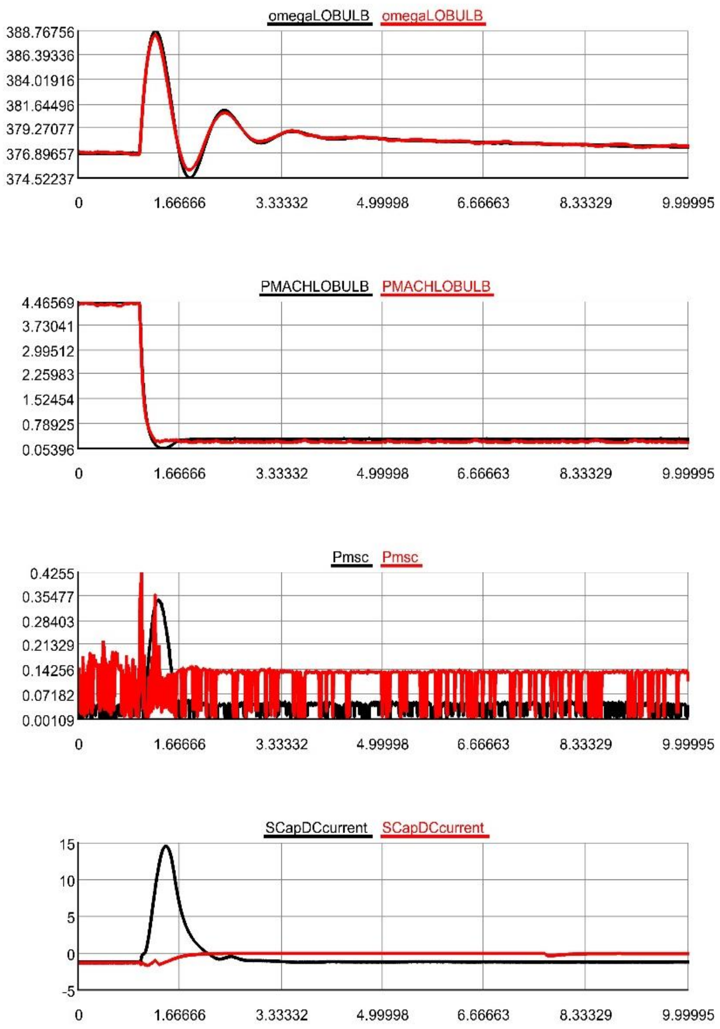


Test Results – Scaled Input as % of Load

Case - 1 (black), 3 (red), 5 (blue - df/dt trip



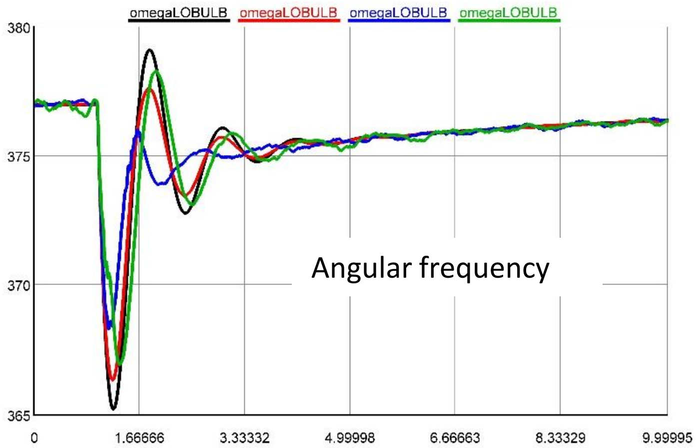
Case - 2 (black), 4 (red)

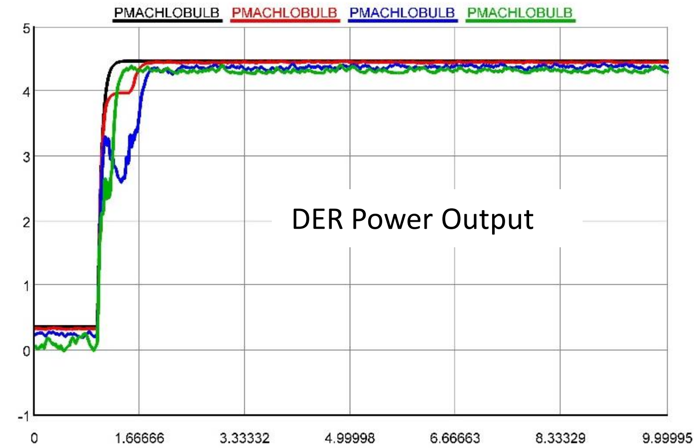


Case #	Damping [pu/pu]	Droop [pu]	Load [MW]	UCAP Pwr [% of Load]	UCAP Pwr [kW]	UCAP Pwr [Scale)
1	10	0.01	4	12.5%	500	16.67
2	10	0.01	-4	13%	500	16.67
3	10	0.01	4	50%	2000	66.67
4	10	0.01	-4	50%	2000	66.67
5	10	0.01	4	75%	3000	100.00
6	10	0.01	4	100%	4000	133.33

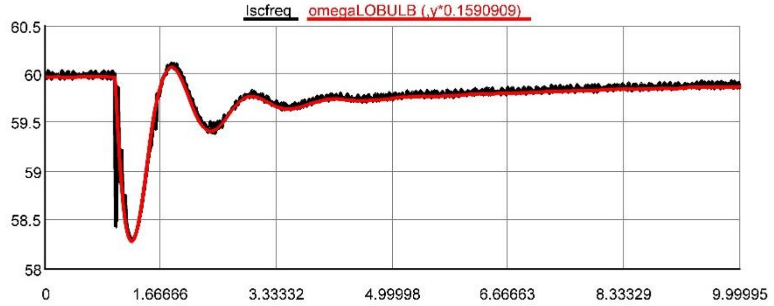
Test Results – Case#1, 2, 3

Black: No Supercap; **red**: Case#1; **blue**: Case#2; **green**: Case#3

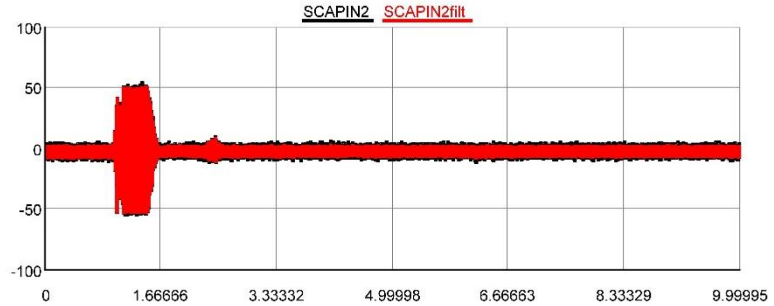




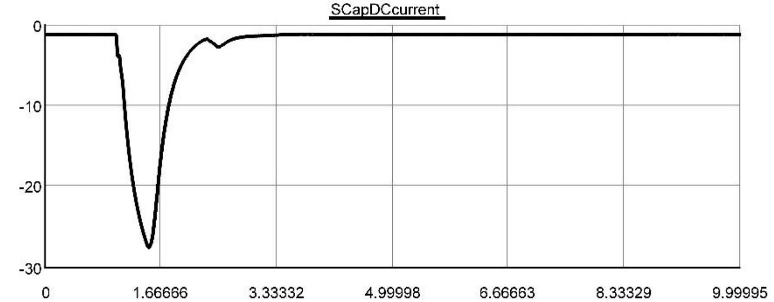
black: Estimated frequency in RSCAD at POI of Supercapacitor
red: DER angular frequency in RSCAD



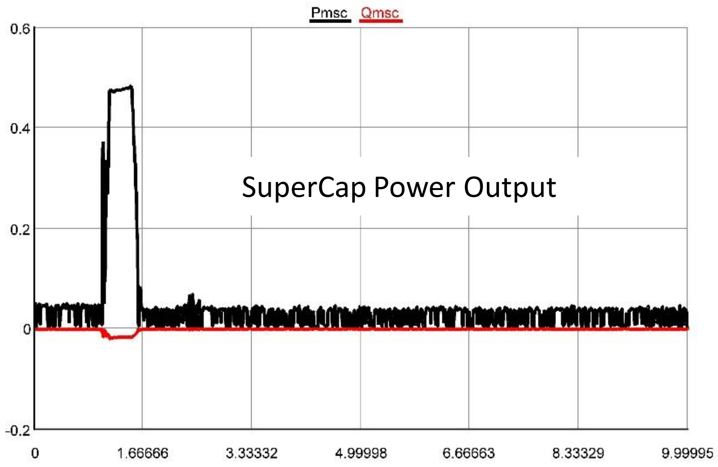
Measured AC current
black: from GTAI
red: filtered

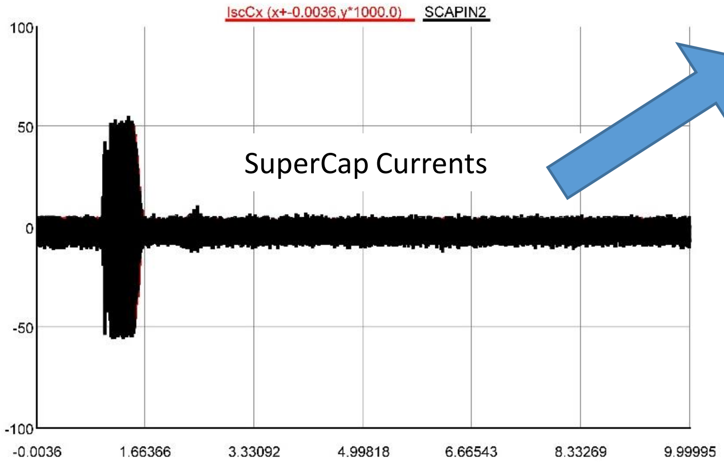


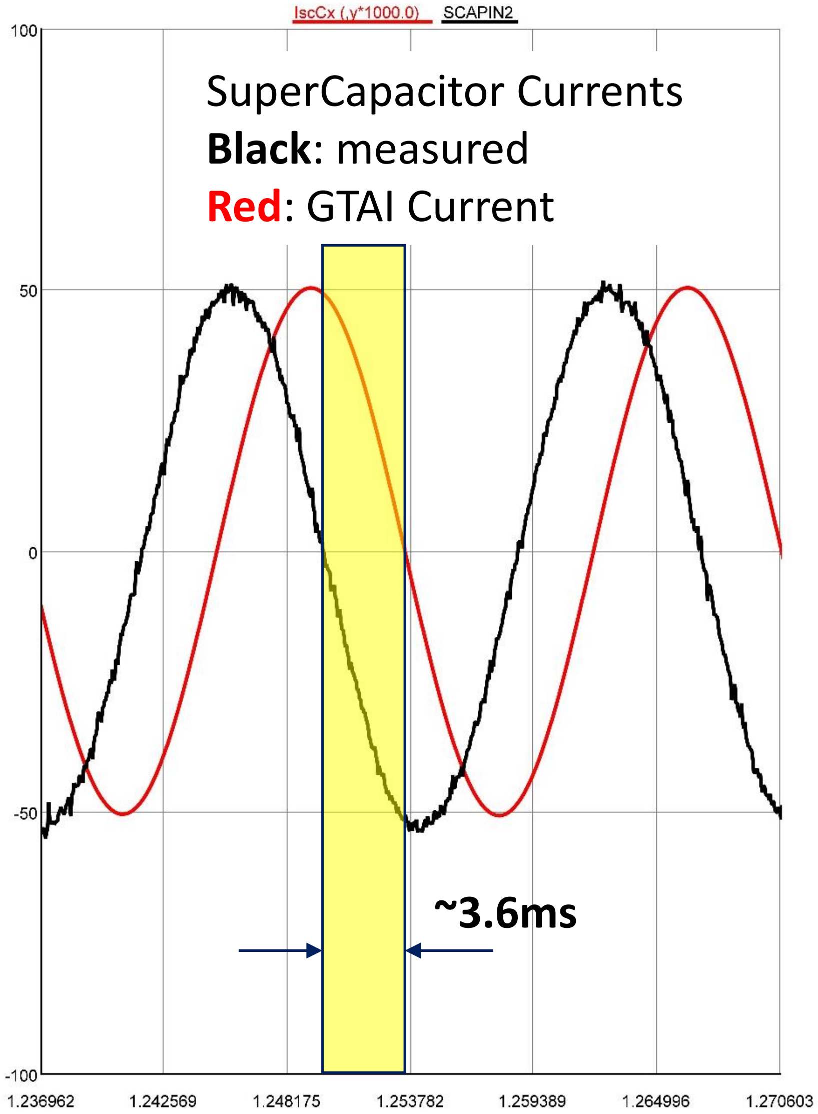
Measured DC current
black: from GTAI

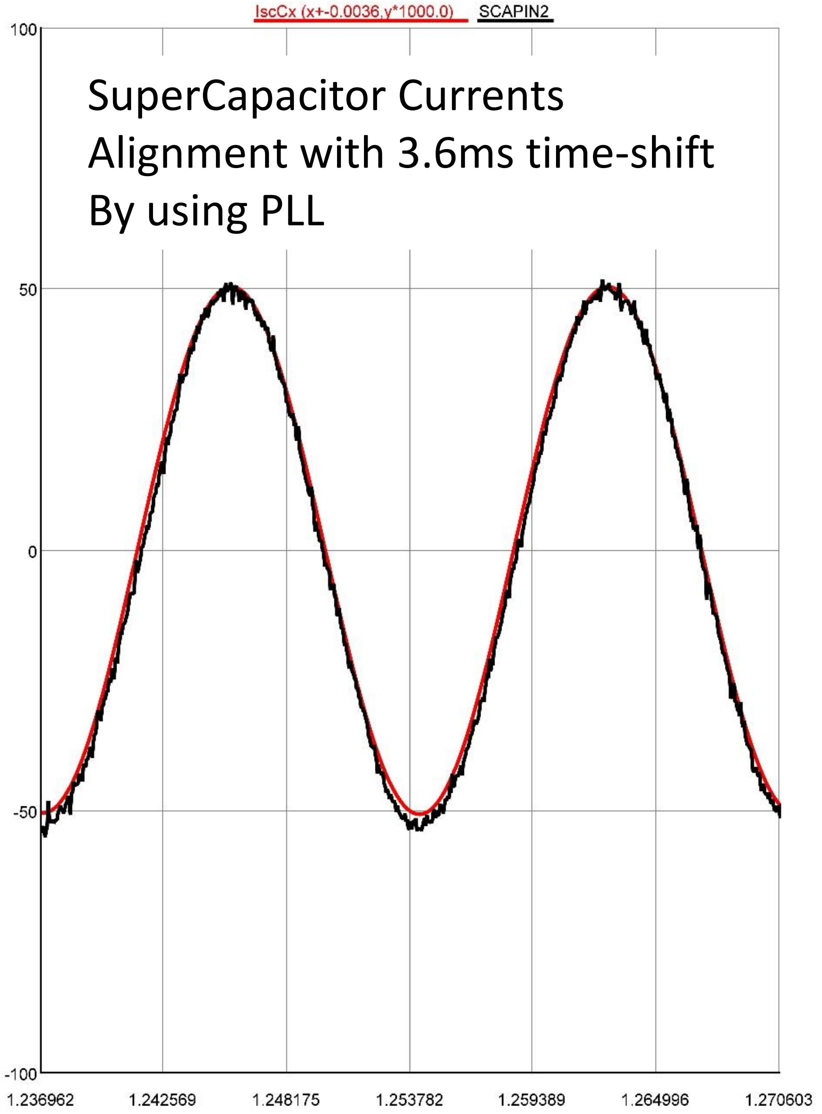


HIL Delays – Current Measurement

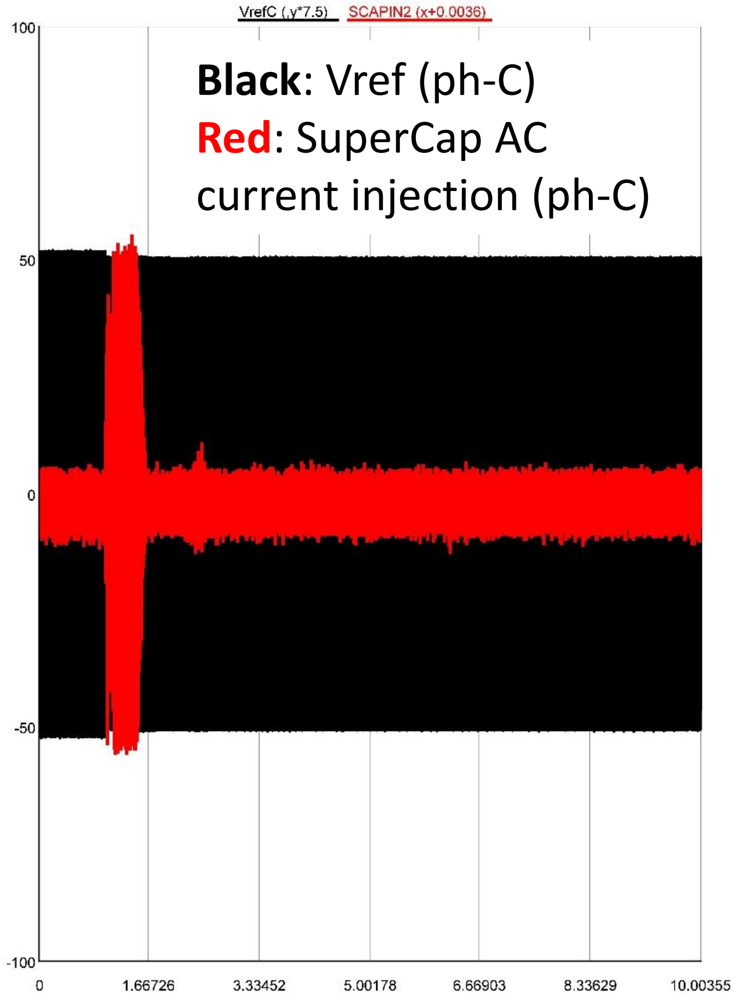


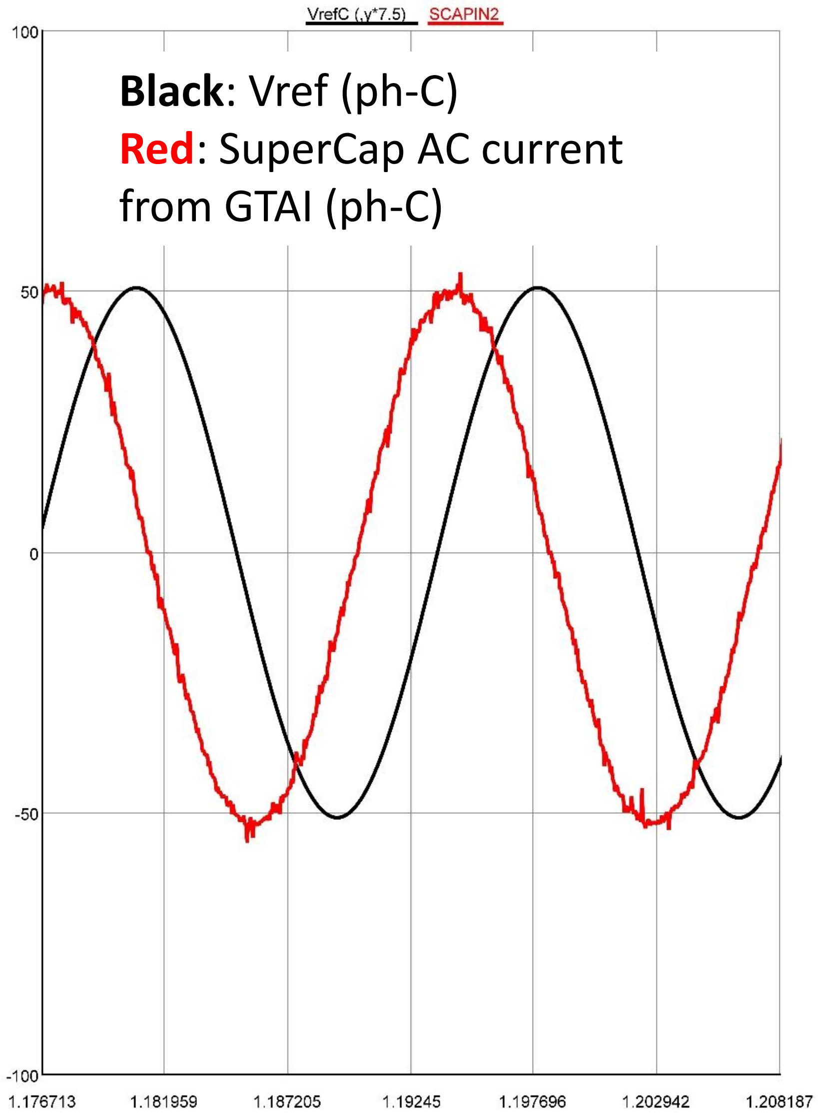


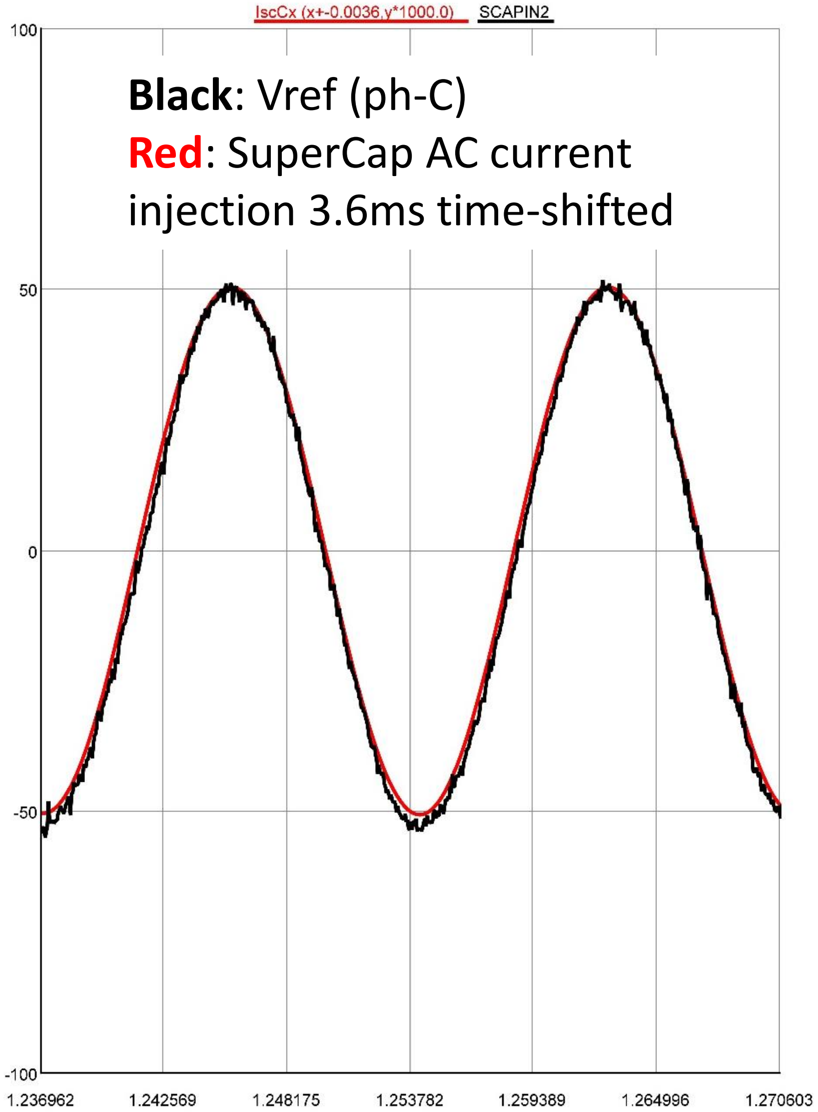




HIL Delays – Current Injection and Vref







Conclusions and Future Work

- Conclusions:
  - Test demonstrated the feasibility of the hybrid-technology for enabling a small-hydro power plant to be a black start power source by integrating it with a supercapacitor energy storage system
  - A decision to recommend a field implementation was supported.
- Future Work:
  - Further Volt/VAR response testing in closed-loop
  - Support for field pilot commissioning

Thank you!