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PHIL Validation of Ultracapacitor Storage for Black Start Application*

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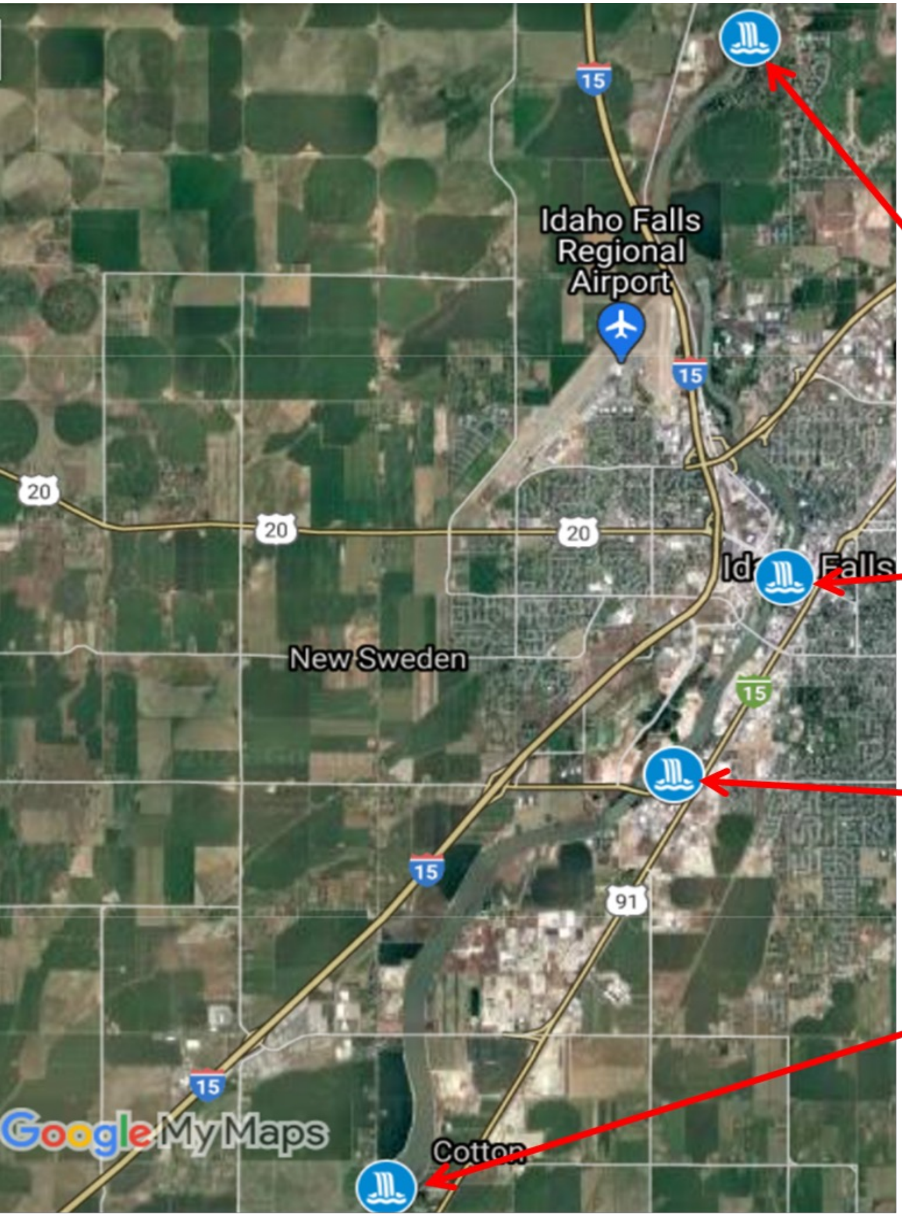
INL/CON-22-70130

Idaho National Laboratory

Disclaimer

Idaho Falls Power is municipal utility with five ROR hydropower plants on upper Snake River



- Plants all connected to city's distribution and sub-transmission system.
- Under normal conditions, plants are operated for maximum efficiency. Balancing is performed by Rocky Mountain Power.

8.9 MVA Upper Plant (ROR, Horizontal Kaplan Bulb)

8.9 MVA City Plant (ROR, Horizontal Kaplan Bulb)

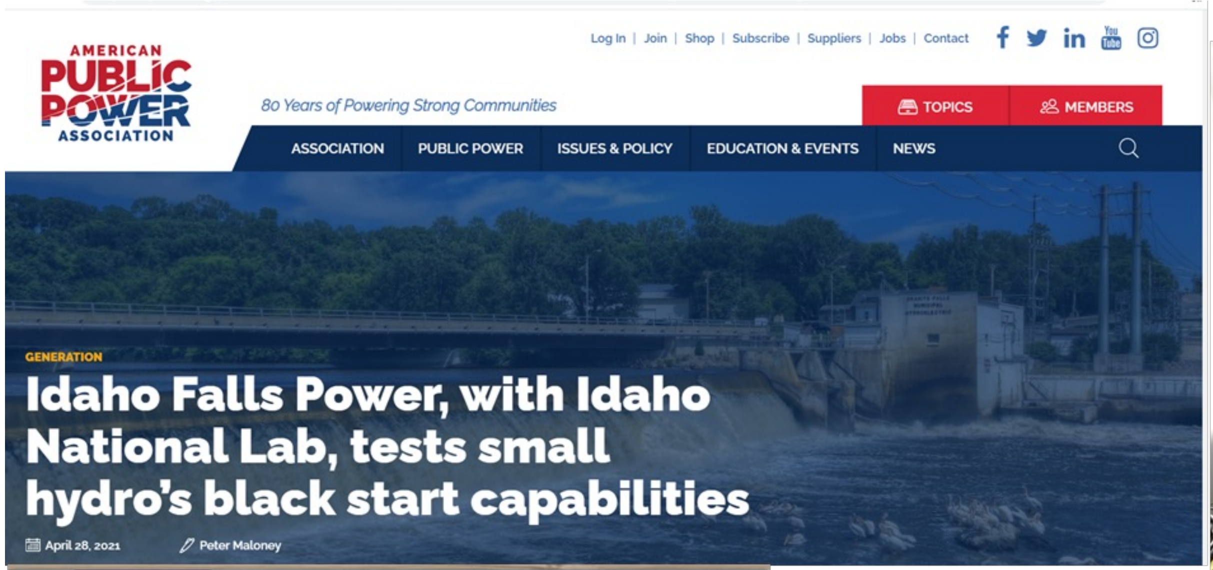
Blackstart Field Demonstration

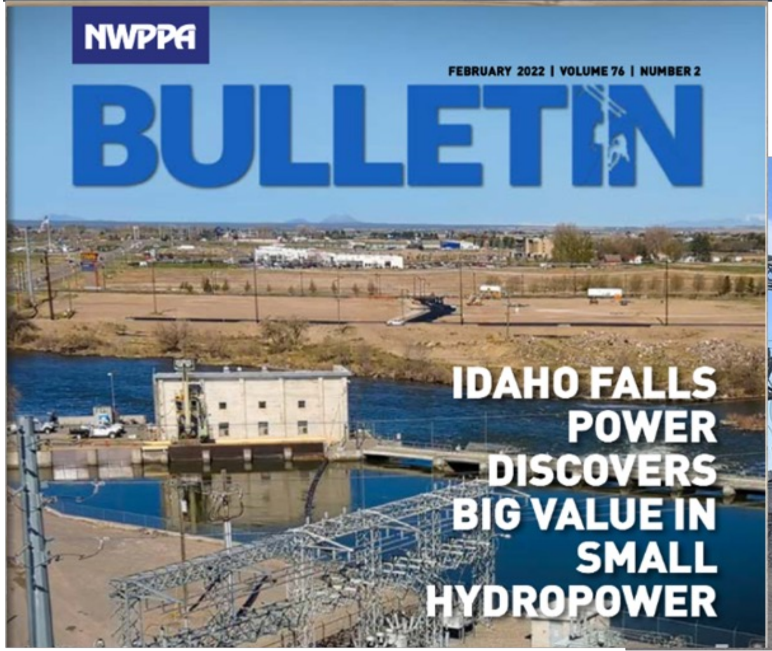
8.9 MVA Lower Plant (ROR, Horizontal Kaplan Bulb)
2 x 1.8 MVA Old Lower Plant (ROR, Vertical Francis)

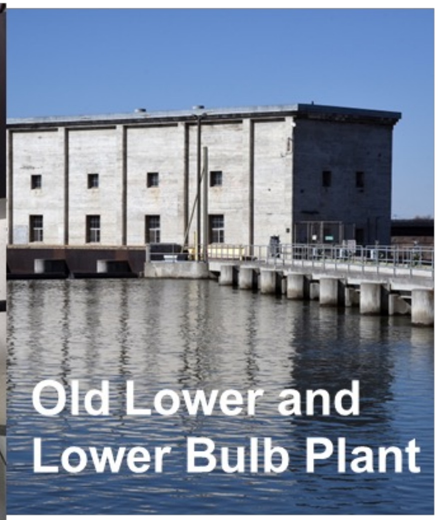
22.6 MVA Gem State Plant, (Vertical Kaplan)

Additional Info: https://www.ifpower.org/

Islanded Distribution Grid Black start: Successful Field Demonstration with Idaho Falls Power



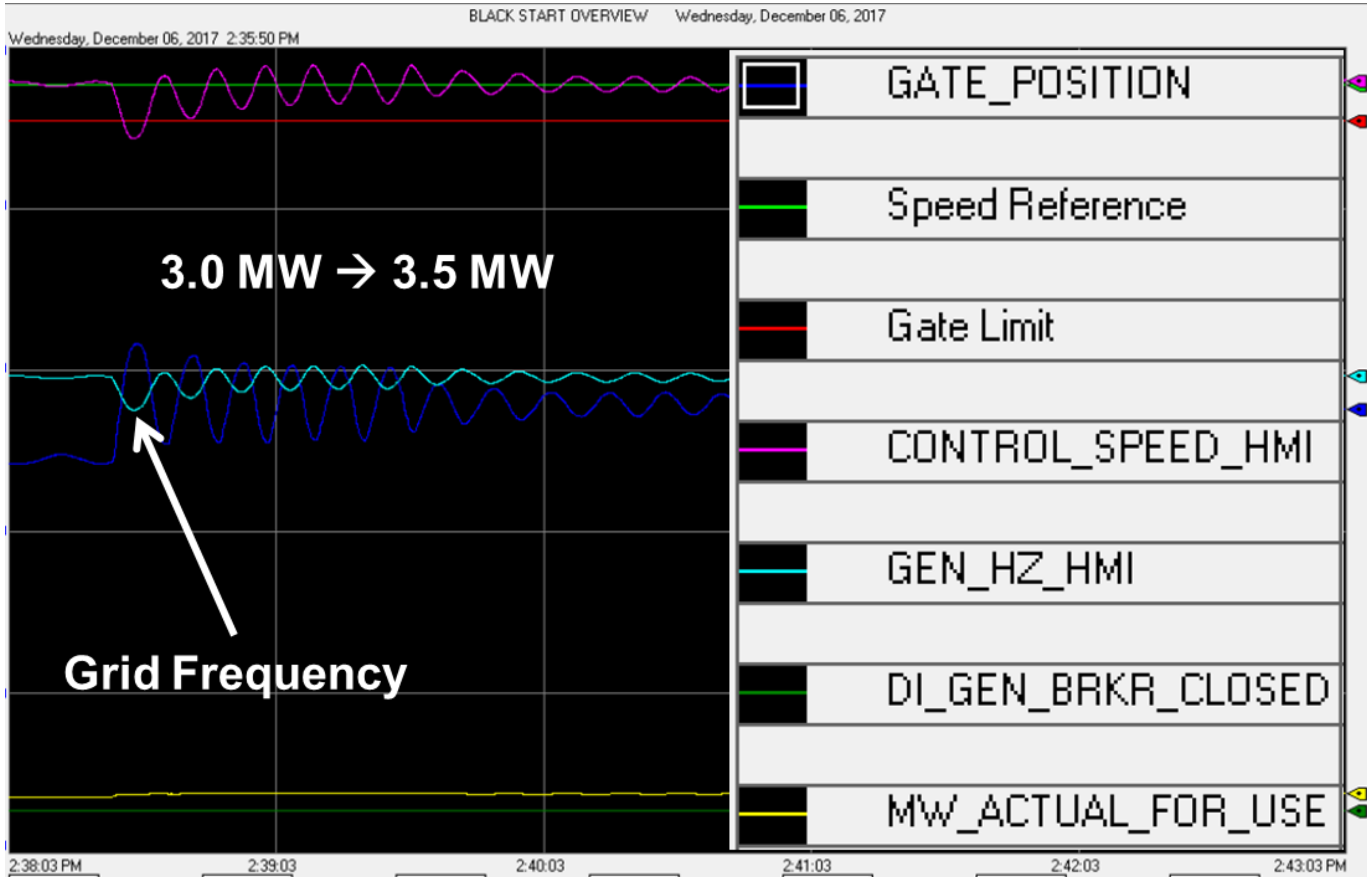




Islanded black start with ROR hydropower

From the December 2017 Field Test

- Load stepping causes frequency stability issues
  - Potential trip off during black start
  - Critical load carrying capability is limited
- Hydrogovernor and frequency protection settings need adjustment



Can energy storage integration demonstrate improvement?

Energy Storage

- Ultracapacitor
  - High power density
  - Small form factor
  - Enables mobility

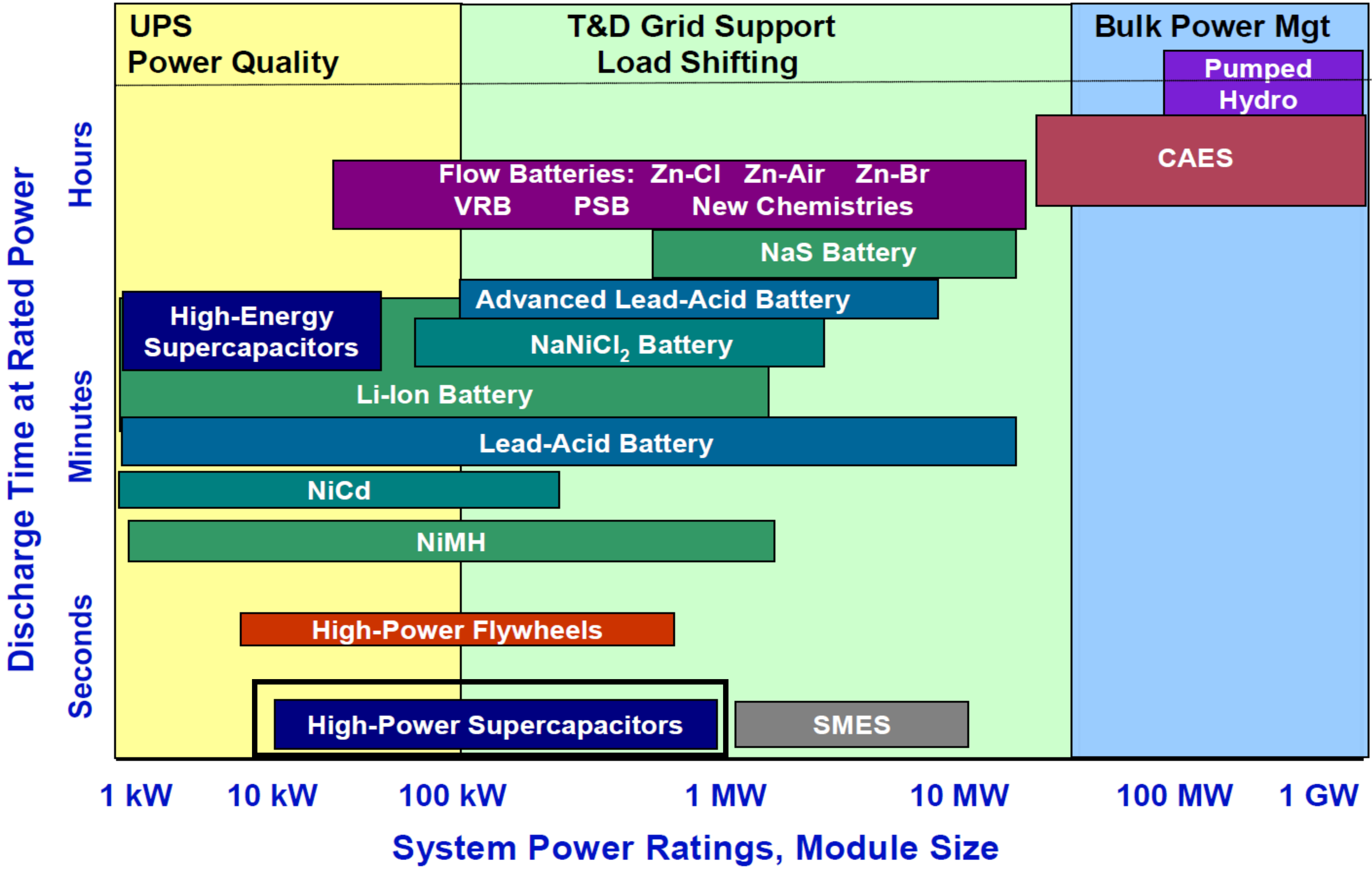


Image Source: Akhil et. Al. (2015), "DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA".

Steps to de-risk the field demonstration

Modeling

- Collect hydrogovernor data in grid connected mode of operation
- Develop hydrogovernor model for ROR hydropower on Simulink

Simulation

- Set hydrogovernor in islanded mode
- Analyze response to load step change on Simulink
  - Without UCAP
  - With UCAP

Test

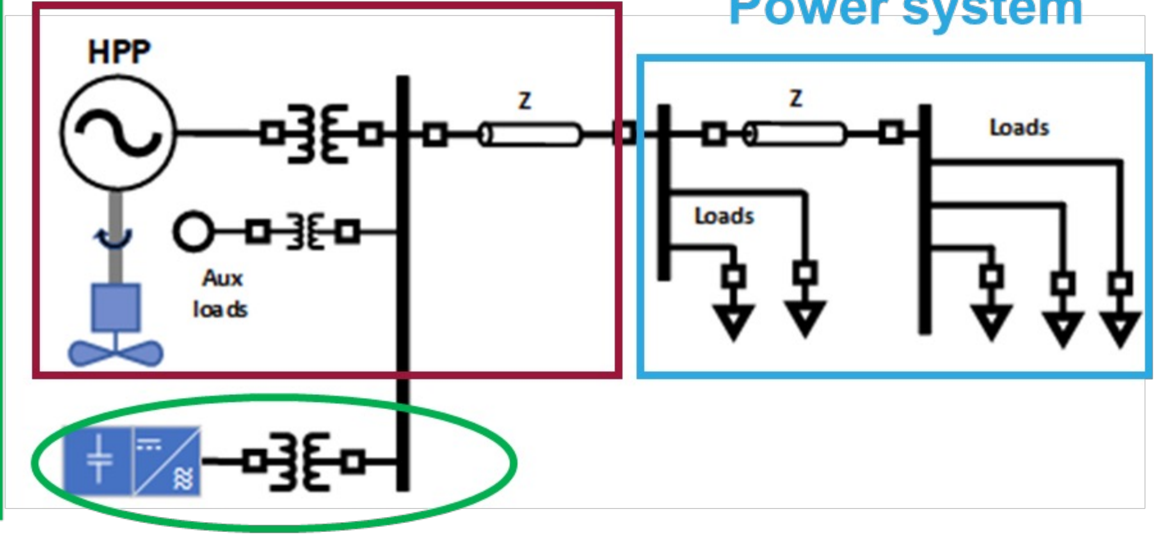
- Develop RSCAD model for digital real-time simulation (DRTS)
- Conduct power hardware-in-the-loop (PHIL) test

RSCAD modeling for digital real-time simulation

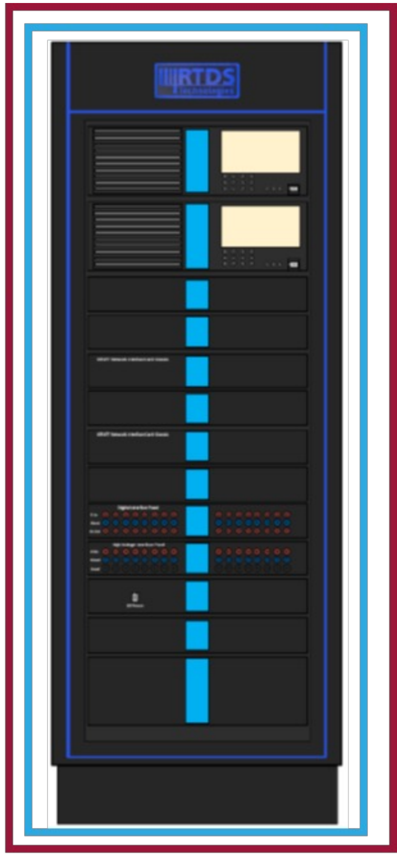
Maxwell TECHNOLOGIES Enabling Energy's Future™ epcpower

Bulb-style hydropower plant

Critical loads on Idaho Falls Power system



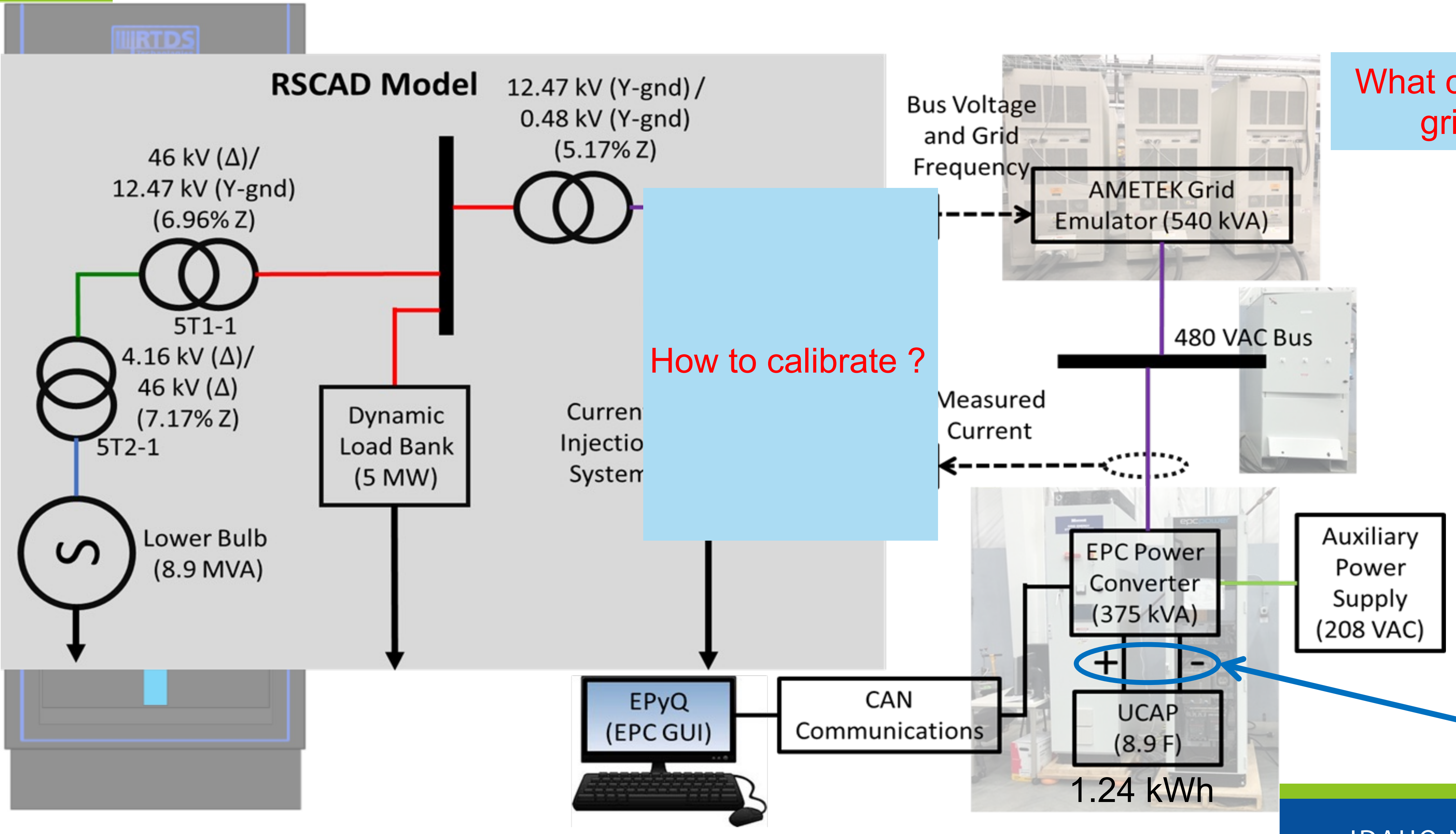
Ultracapacitor (UCAP) system



AMETEK 540 kVA Grid Emulator

Tektronix Current Probing Assembly

“Closed-loop” Power Hardware In-the-Loop Testing



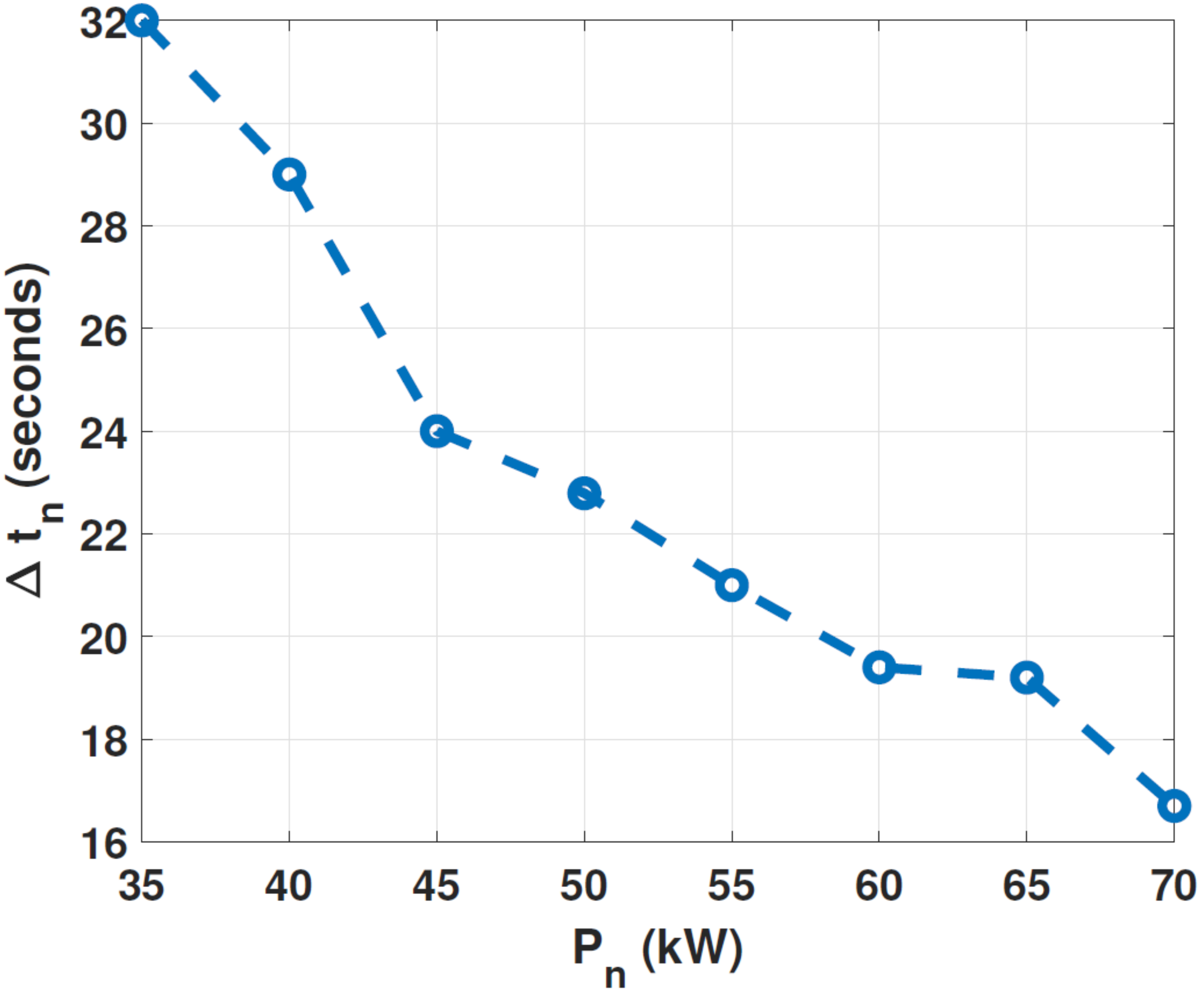
What capacitance does the grid emulator see?

710 – 1000 VDC,
Trips at 650 VDC

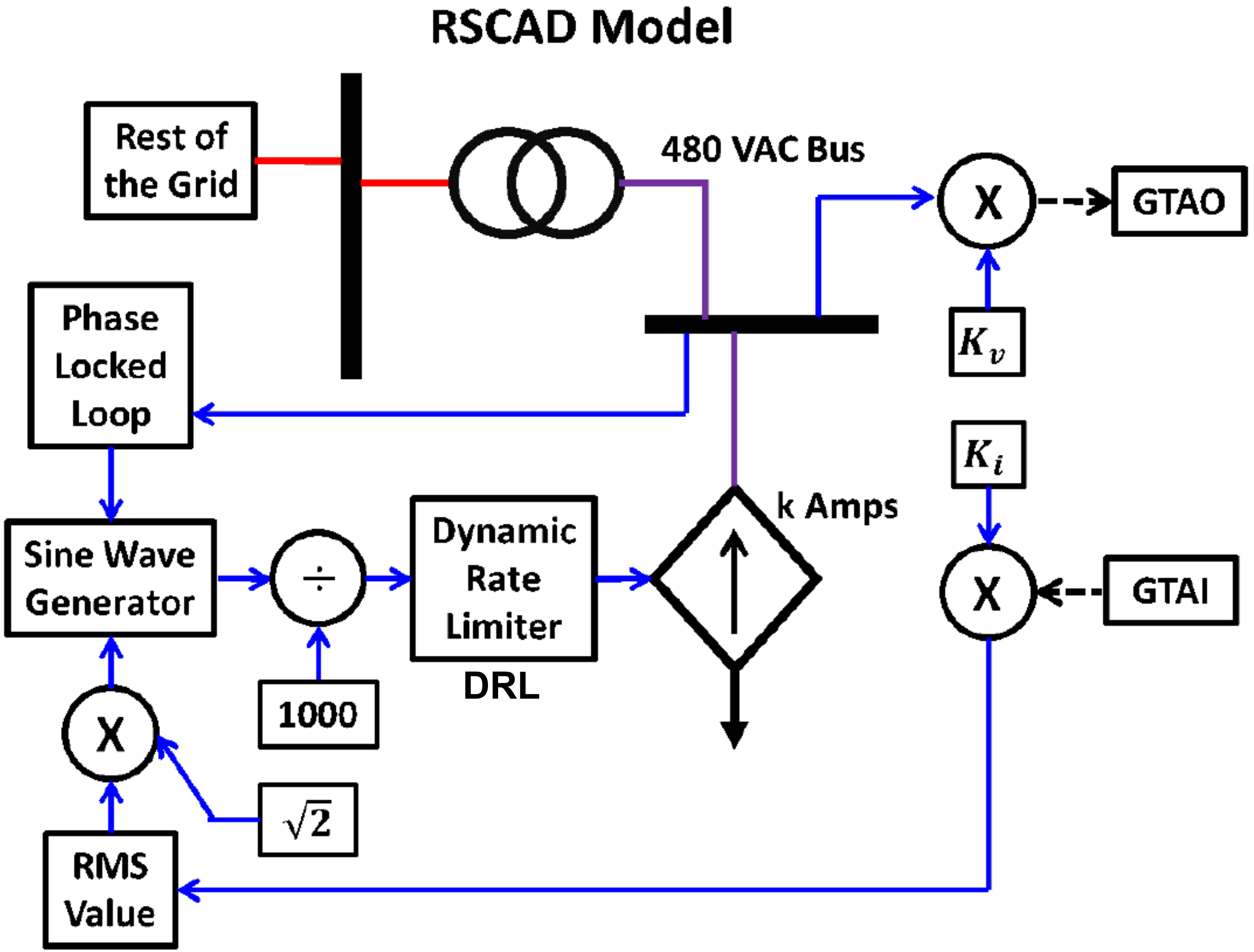
Ultracapacitor Characterization

$$C_{480\text{VAC}} = \frac{2 \times 1000}{N_c(950^2 - 750^2)} \sum_{n=1}^{N_c} P_n[\text{kW}] \times \Delta t_n$$

- $C_{480VAC} = 6.7\ F$

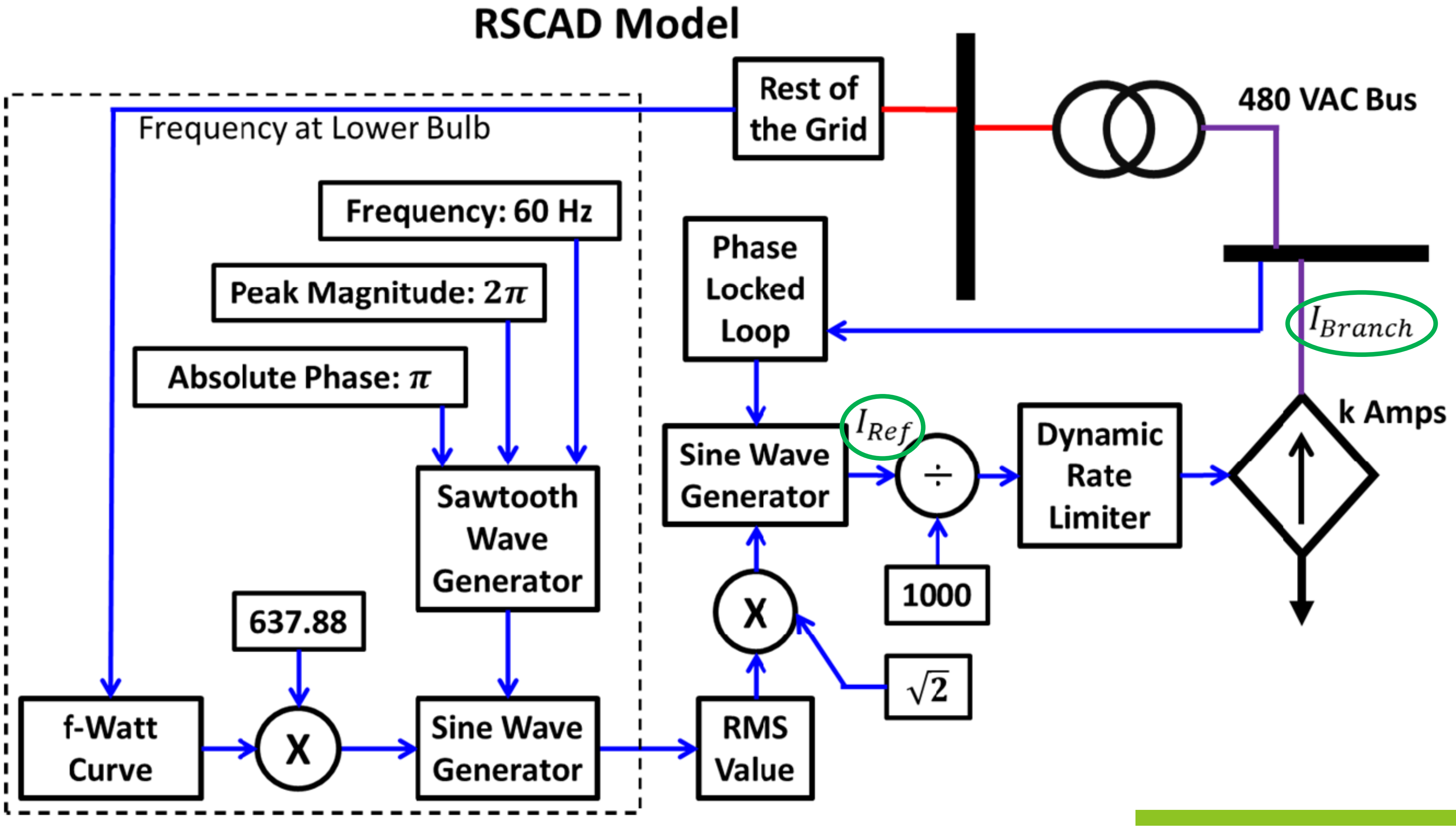


Current Injection System

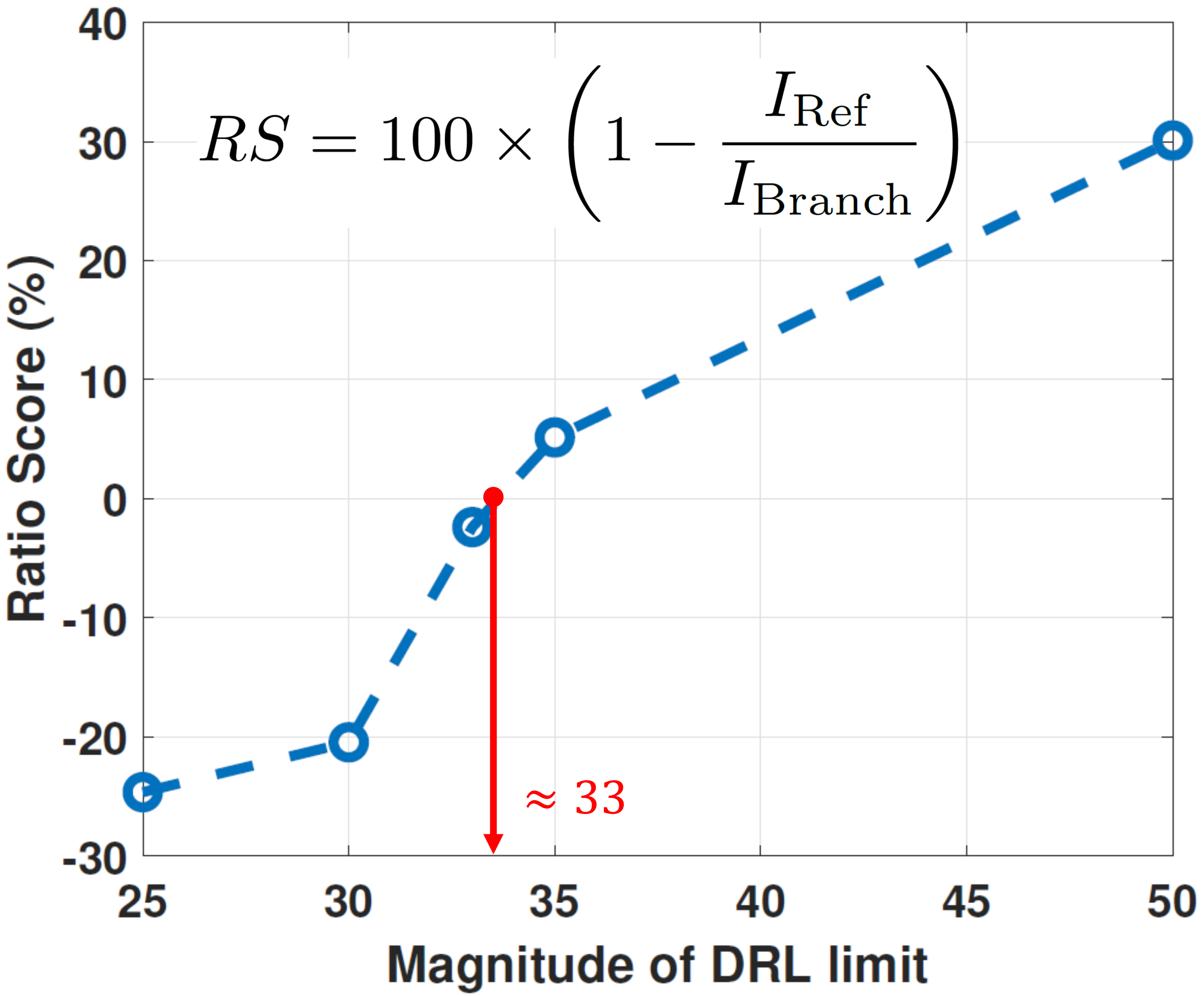


How to set DRL, K_v, and K_i?

Analyze DRL Sensitivity through f-Watt Responsive Current Synthesis



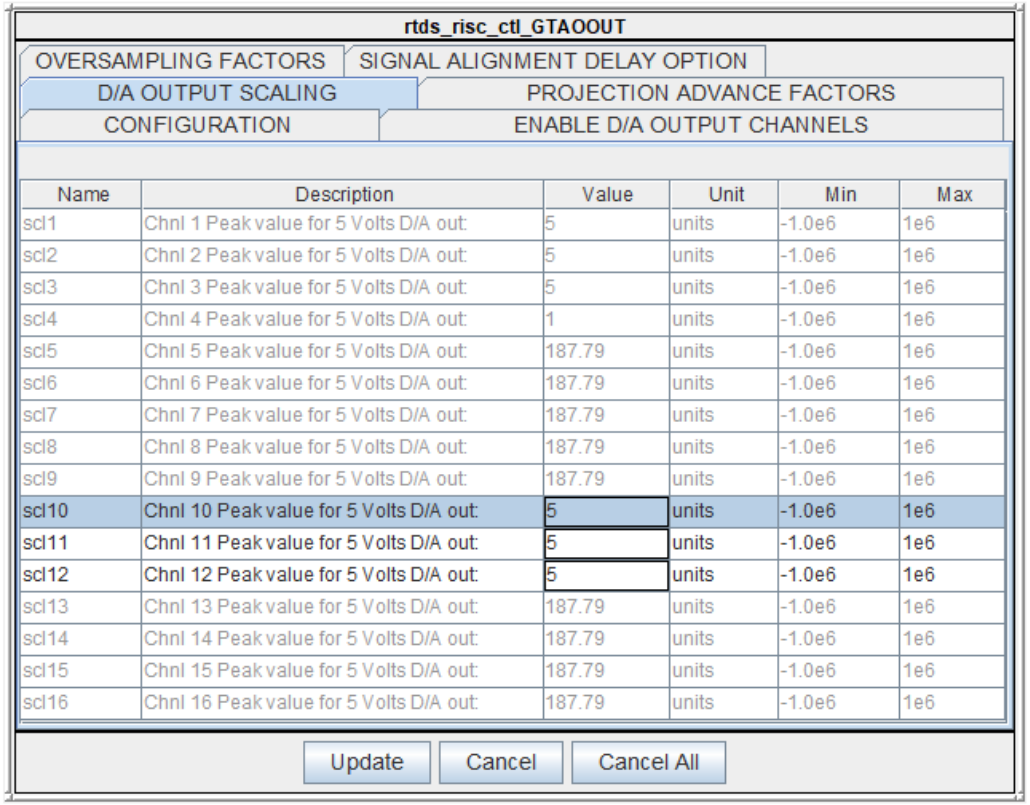
Set DRL



$$RS = 100 \times \left(1 - \frac{I_{\mathrm{Ref}}}{I_{\mathrm{Branch}}}\right)$$
Ratio Score (%)
40
30
20
10
0
-10
-20
-30
25
30
35
40
45
50
Magnitude of DRL limit
≈ 33

Set K_v

- Peak analog input to AMETEK grid emulator: 10 V
- Grid emulator's line-to-neutral amplification factor: 40
- Line-to-neutral peak value at 480 VAC bus ≈ 0.4 kV
- $0.4 \times K_v = 10$
- $K_v = 25$



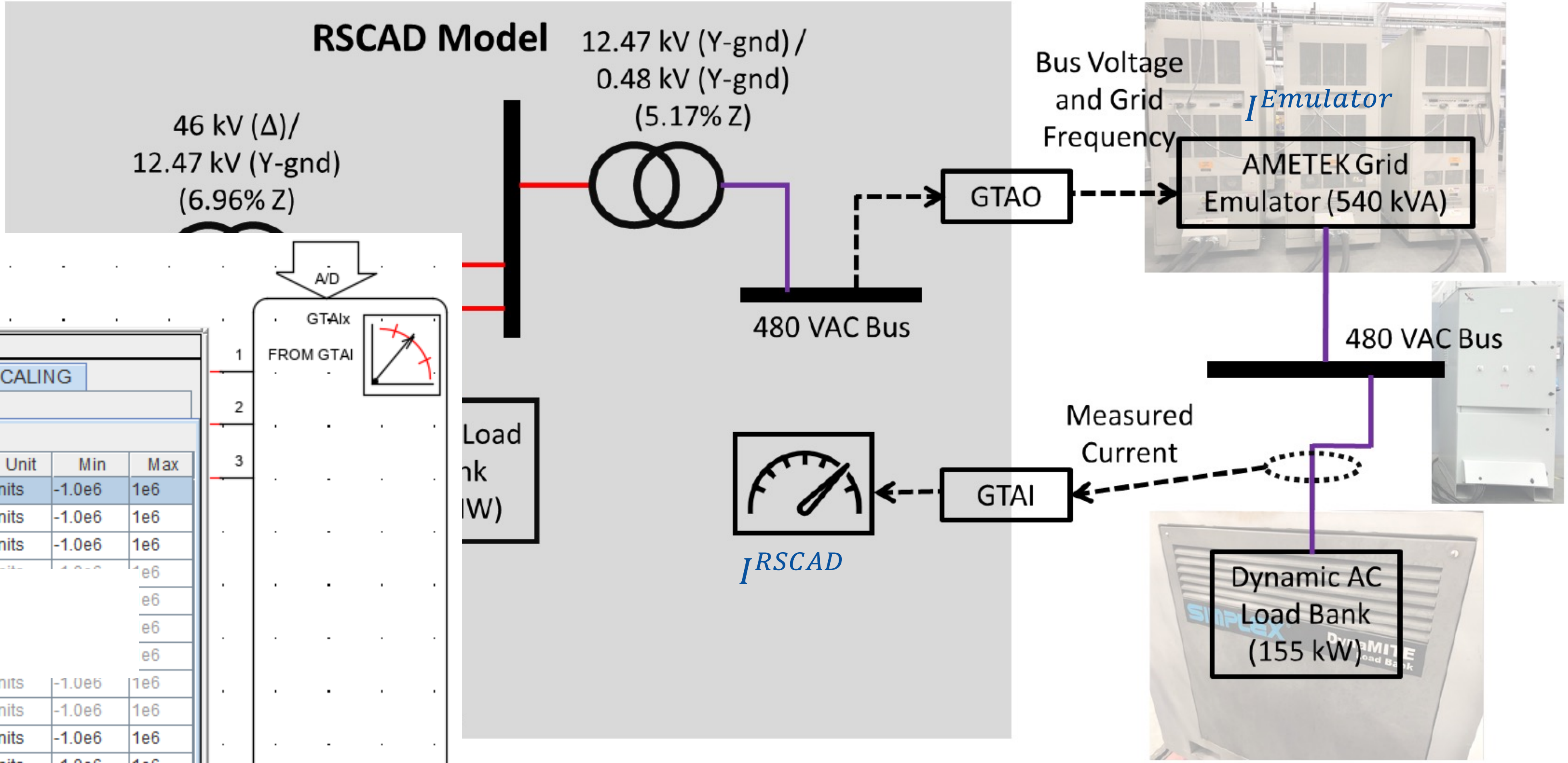
rtds_risc_ctl_GTAOOUT

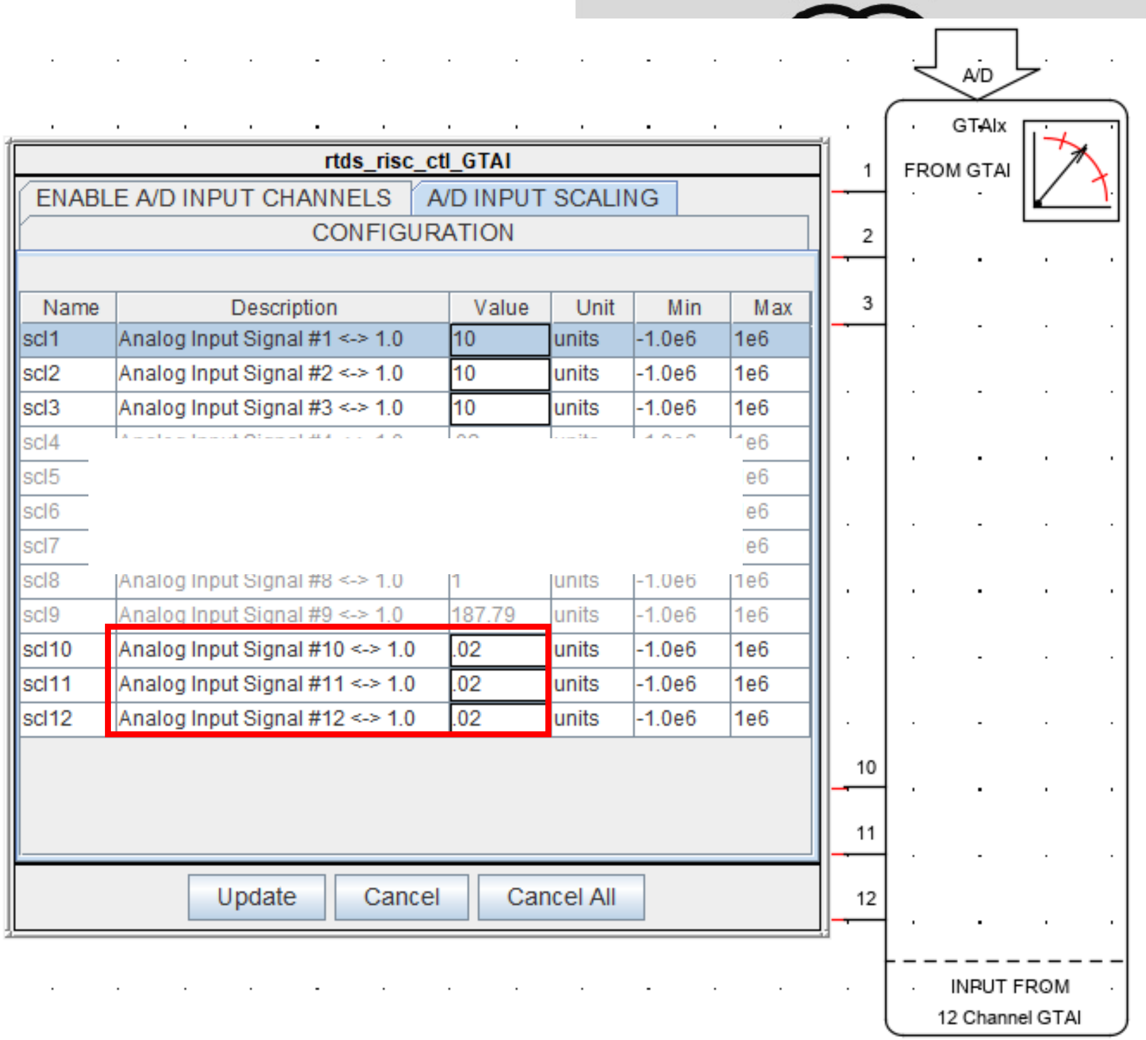
OVERSAMPLING FACTORS | SIGNAL ALIGNMENT DELAY OPTION
D/A OUTPUT SCALING | PROJECTION ADVANCE FACTORS
CONFIGURATION | ENABLE D/A OUTPUT CHANNELS

Name	Description	Value	Unit	Min	Max
scl1	Chnl 1 Peak value for 5 Volts D/A out:	5	units	-1.0e6	1e6
scl2	Chnl 2 Peak value for 5 Volts D/A out:	5	units	-1.0e6	1e6
scl3	Chnl 3 Peak value for 5 Volts D/A out:	5	units	-1.0e6	1e6
scl4	Chnl 4 Peak value for 5 Volts D/A out:	1	units	-1.0e6	1e6
scl5	Chnl 5 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl6	Chnl 6 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl7	Chnl 7 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl8	Chnl 8 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl9	Chnl 9 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl10	Chnl 10 Peak value for 5 Volts D/A out:	5	units	-1.0e6	1e6
scl11	Chnl 11 Peak value for 5 Volts D/A out:	5	units	-1.0e6	1e6
scl12	Chnl 12 Peak value for 5 Volts D/A out:	5	units	-1.0e6	1e6
scl13	Chnl 13 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl14	Chnl 14 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl15	Chnl 15 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6
scl16	Chnl 16 Peak value for 5 Volts D/A out:	187.79	units	-1.0e6	1e6

Update | Cancel | Cancel All

Set K_i





Name	Description	Value	Unit	Min	Max
scl1	Analog Input Signal #1 <-> 1.0	10	units	-1.0e6	1e6
scl2	Analog Input Signal #2 <-> 1.0	10	units	-1.0e6	1e6
scl3	Analog Input Signal #3 <-> 1.0	10	units	-1.0e6	1e6
scl4					e6
scl5					e6
scl6					e6
scl7					e6
scl8	Analog Input Signal #8 <-> 1.0	1	units	-1.0e6	1e6
scl9	Analog Input Signal #9 <-> 1.0	187.79	units	-1.0e6	1e6
scl10	Analog Input Signal #10 <-> 1.0	.02	units	-1.0e6	1e6
scl11	Analog Input Signal #11 <-> 1.0	.02	units	-1.0e6	1e6
scl12	Analog Input Signal #12 <-> 1.0	.02	units	-1.0e6	1e6

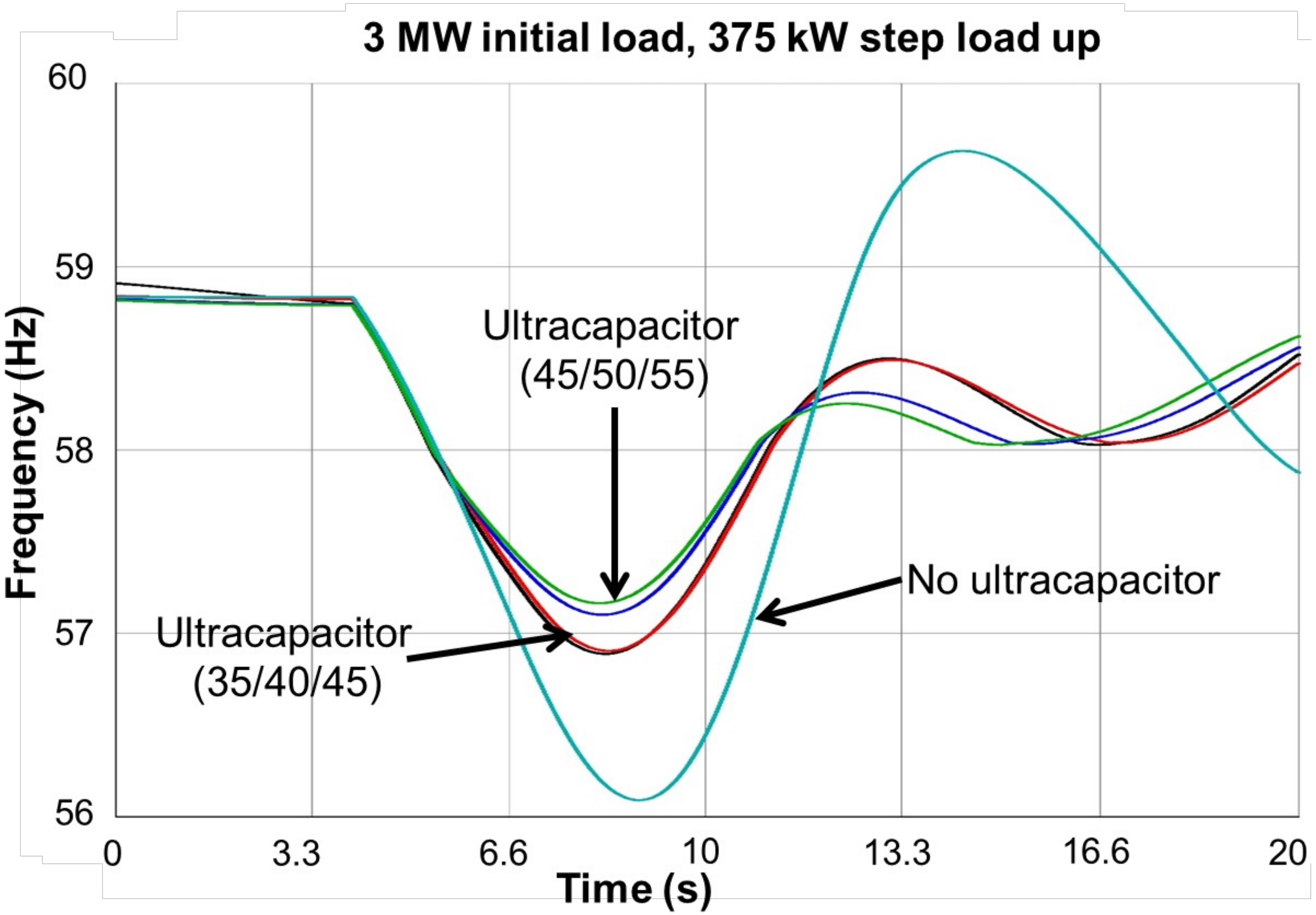
$K_i = 78$ from

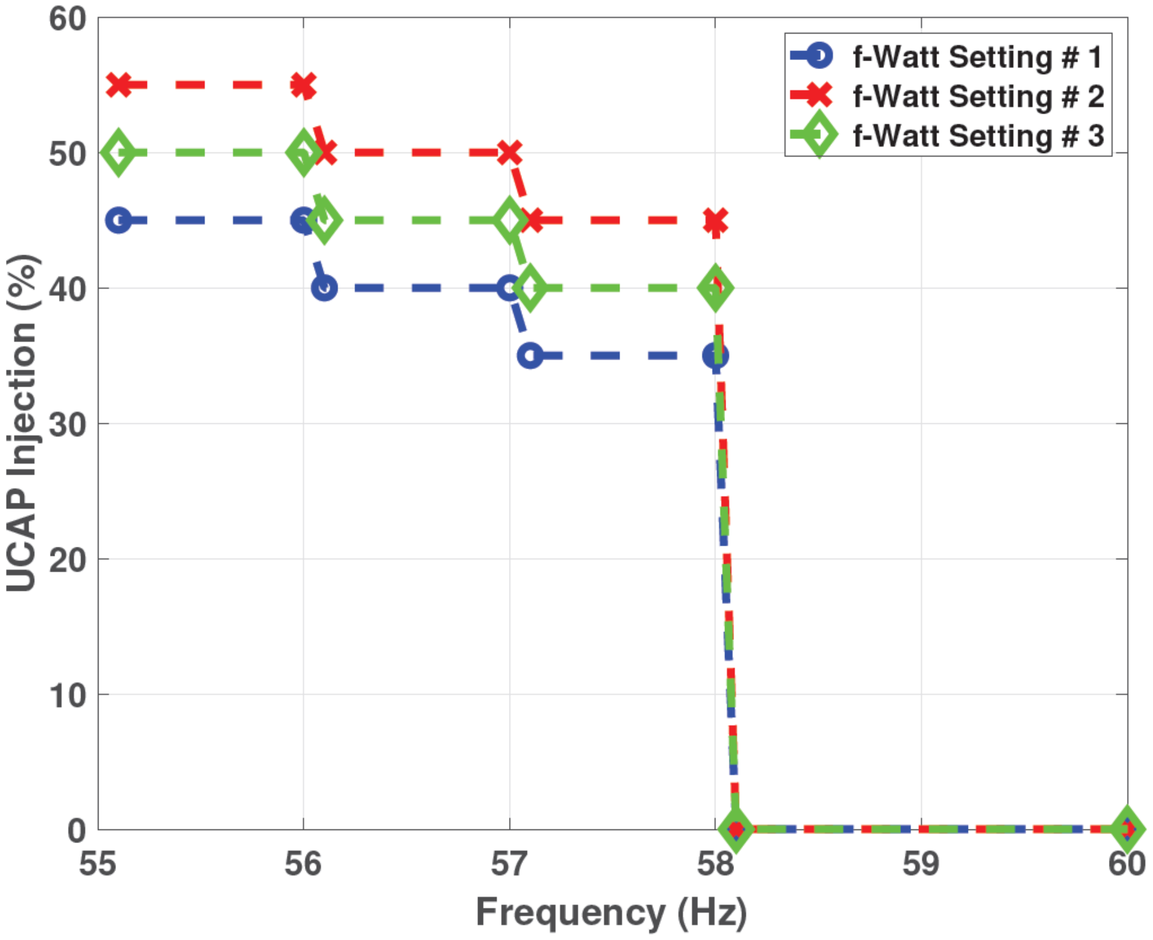
$$K_i = \frac{1}{N_L} \sum_{n=1}^{N_L} \frac{I_n^{\text{Emulator}}}{I_n^{\text{RSCAD}}}$$

Test Sequence

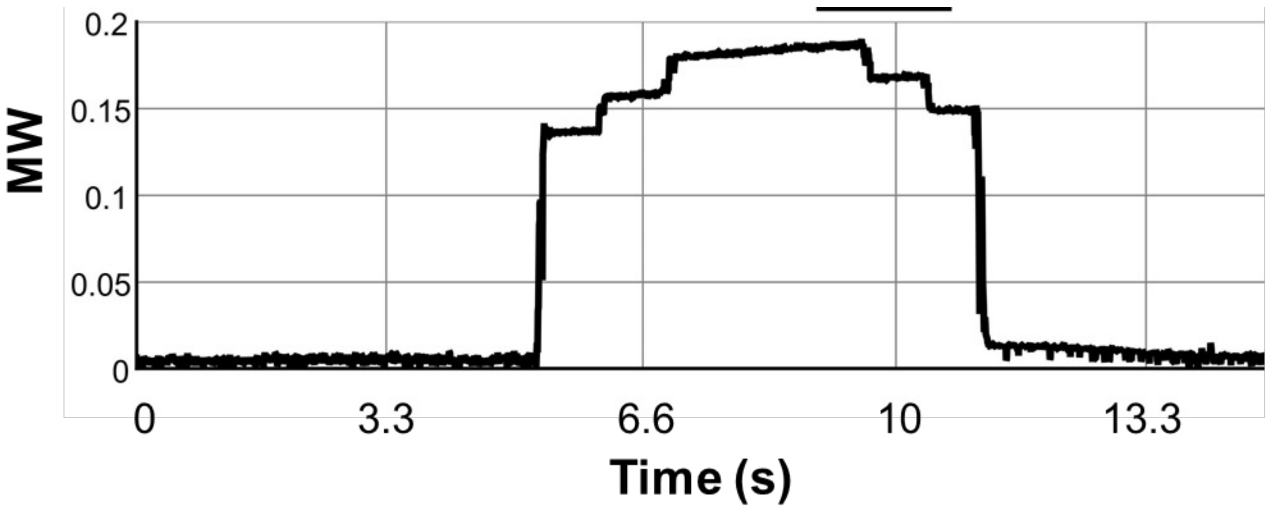
Event Number	Event Description
E1	UCAP ESS: Disable inverter operation. Current injection model: ’Disable’
E2	“Lower Bulb” Unit: Set “Initial Mode of Lock/FreeSwitch” to “Lock” under “Mechanical Data and Con-figuration”.
E3	Dynamic Load Bank”: Set the desired value for steady-state load.
E4	Run load flow and initialize hydrgovernor turbine settings according to [6], [7]. This step must be repeated for each steady-state electric loading and prior to stepload change.
E5	Compile the draft file and load to RUNTIME.
E6	Start simulation and “unlock” the “Lower Bulb Unit” from E2.
E7	Apply a desired step load change on the “Dynamic Load Bank” and observe frequency and other variables of interest.
E8	Stop the simulation.
E9	EPC converter: Load the desired f-Watt setting via the EPyQ GUI. Enable inverter operation and current injection system from E1. Repeat E2 - E8.

Test UCAP system injection rates

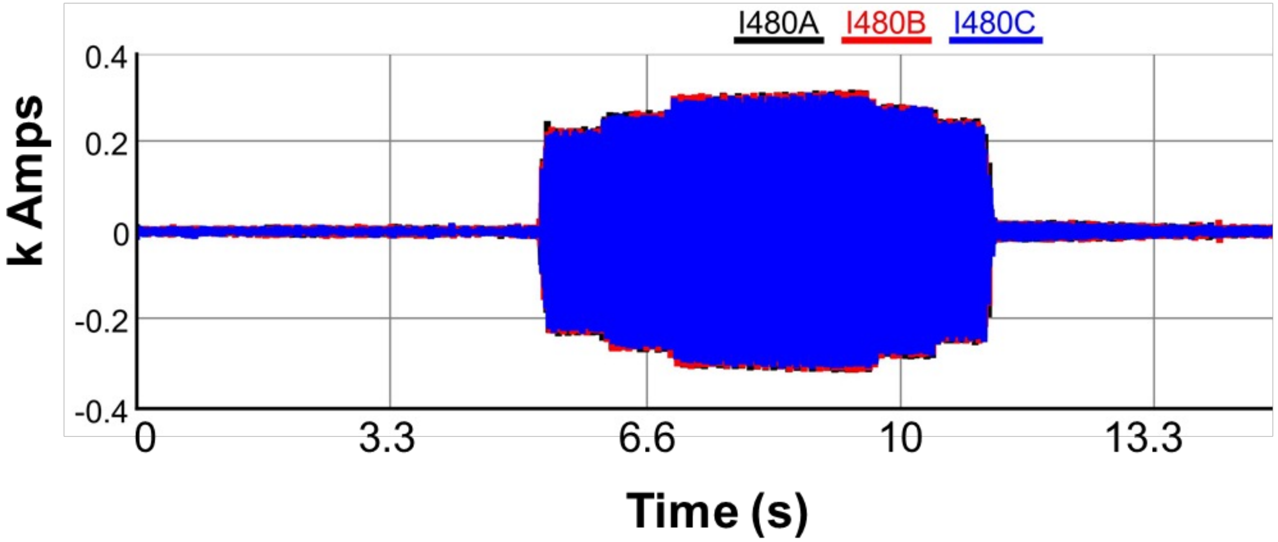




Observe UCAP response

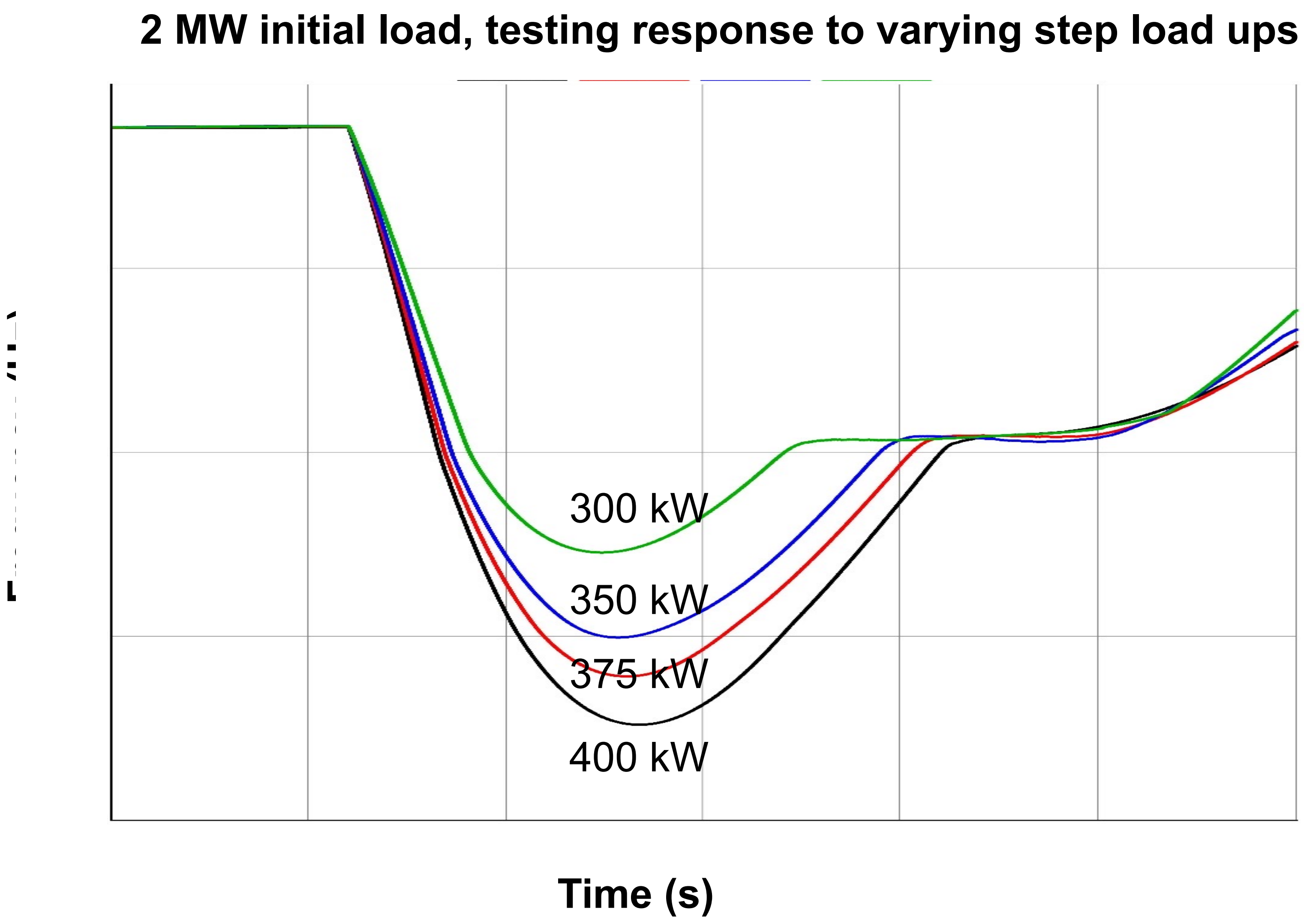


Power Injection from UCAP



Instantaneous Current Injection at 480 VAC Bus

Test maximum step load size



Conclusions

- **RSCAD Model is Publicly Available on GitHub**
  - https://github.com/IdahoLabResearch/Hydropower_Unit_Models
- **Key findings**
  - Pre-characterization of energy storage response drives the inverter control design.
  - A systematic approach to real-time simulation model calibration with hardware response can reduce effort and cost for PHIL preparation.
- **Next steps**
  - Develop operational-mode-aware-coordination scheme between hydrogovernor and inverter control for transient stability.
  - Explore inverter integration beyond grid following mode operation and frequency droop-based control to further improve islanded operation stability (e.g., lower the ROCOF, dampen oscillation).

Questions & Feedback

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Reference: Alam et al. 2022 “Enhancing Local Grid Resilience with Small Hydropower Hybrids: Proving the concept through demonstration, simulation, and analysis with Idaho Falls Power”, INL/RPT-22-69038.
DOI: https://doi.org/10.2172/1891110

Reference: Alam et al. 2022 “Power Hardware-In-the-Loop Hydropower and Ultracapacitor Hybrid Testbed”, IEEE PES GM 2022.
DOI: https://doi.org/10.1109/PESGM48719.2022.9917167

Reference: Panwar et al. 2019 “Experiences from Field Testing for Black Start of a Run-of-the-river Hydropower Plant in Idaho Falls Power Distribution Grid”, INL/CON-19-54888.
Link

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