Fast Grid Frequency Support from Distributed Inverter-based Resources

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PV Systems Symposium

Motivation

- Hawaii has more distributed PV (as percentage of load) than any other U.S. state.
  - Oahu: ~400 MW of distributed PV on a ~1000 MW system
  - No connections to neighboring systems
  - Instantaneous penetration of non-synchronous generation can exceed 70%
  - Grid operators have no visibility or control of distributed PV
- State RPS goal: 100% renewables by 2045
- Current levels of PV result in both steady-state and dynamic voltage and frequency issues
- Communication to DERs typically non-existent or proprietary
- Near-term solution: *autonomous* inverter-based grid support
  - E.g. ride-through, volt-var, volt-watt, frequency-watt (droop)

Acknowledgements

Partners

- Hawaii Electric
- Sandia National Laboratories
- Enphase Energy
- Fronius USA

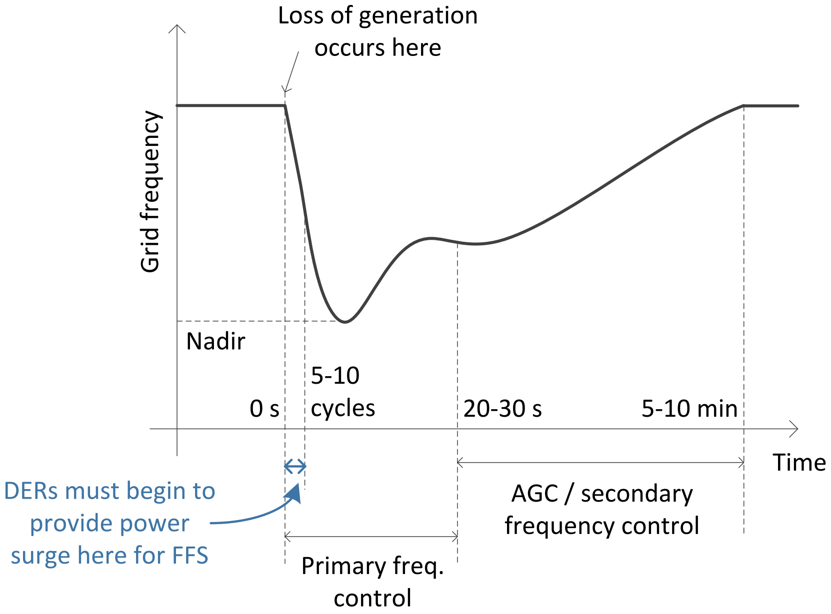
Sponsor

- U.S. Department of Energy Grid Modernization Laboratory Consortium (GMLC)

Objectives

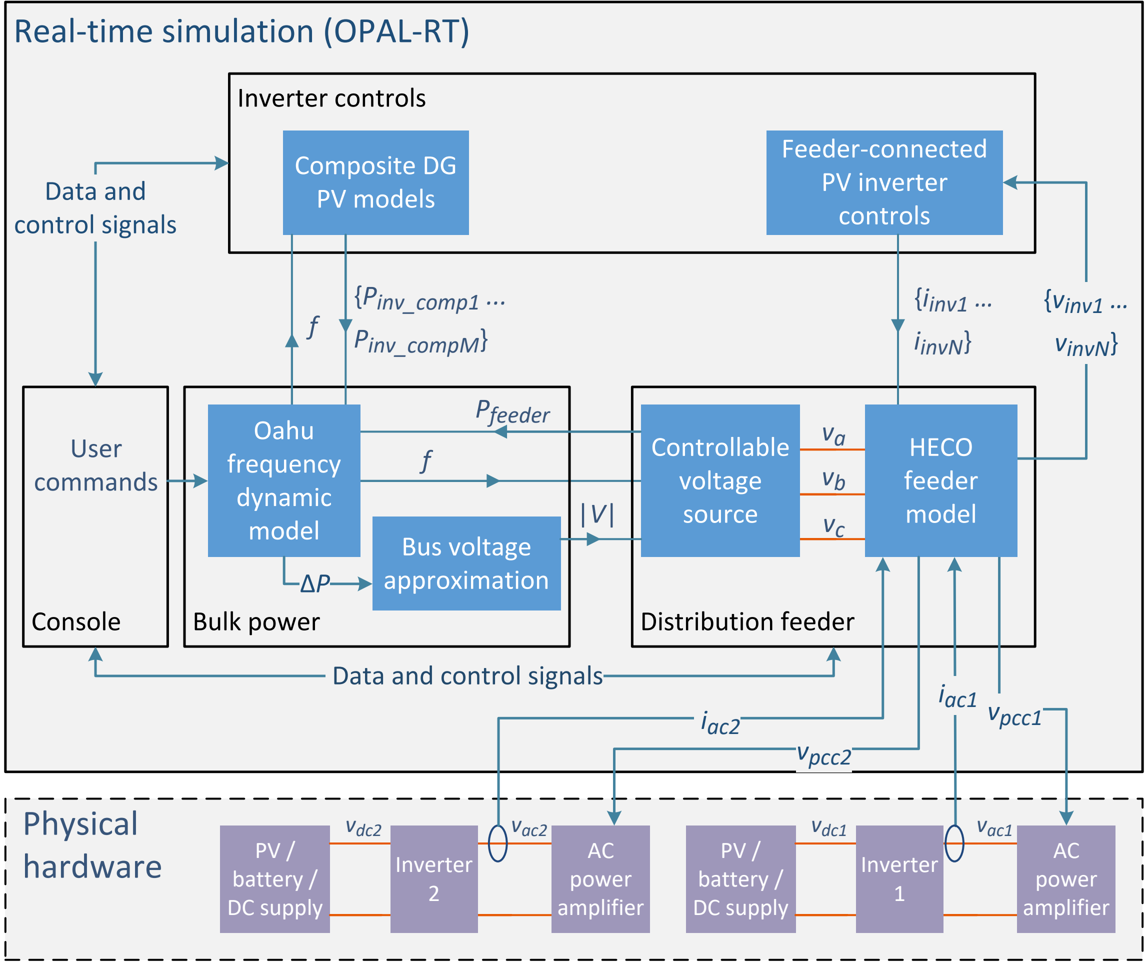
- Validate grid support settings of hardware inverters in an environment that mimics the relevant dynamics of the Oahu power system
- Include both distribution system and bulk grid dynamics
- Identify challenges and risks associated with DER grid support

Example: DER frequency support on inertial time-scale:

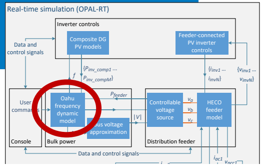


Island-wide real-time hybrid model for PHIL:

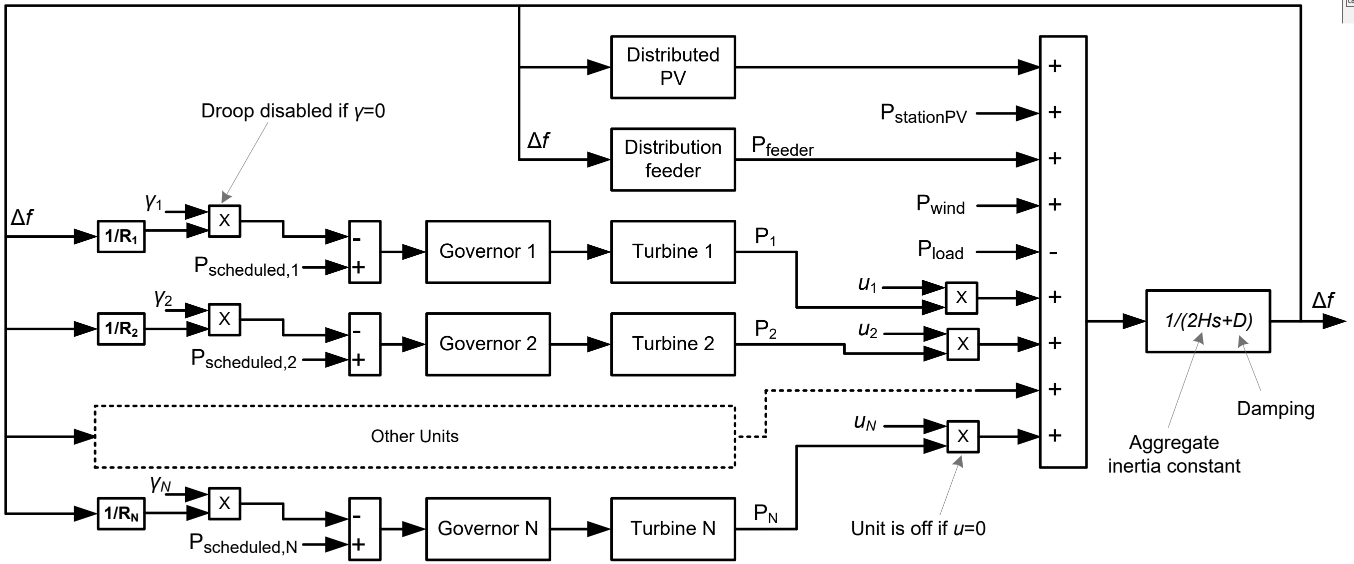
- Real-time Oahu frequency dynamic model simulates contingency events; tuned to match PSSE simulations performed by Sandia team
- Bulk system model drives frequency of voltage waveforms in distribution system simulation
- Hardware inverter is connected to AC supply driven by simulated PCC voltage
- Many more inverters simulated with various controls, both on distribution feeder and in bulk system model
- Approximation of feeder bus voltage changes during frequency events



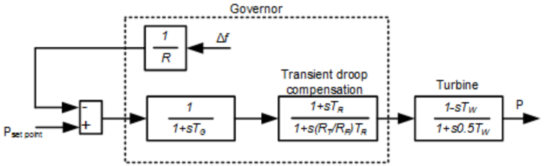
Bulk system governor-only model overview



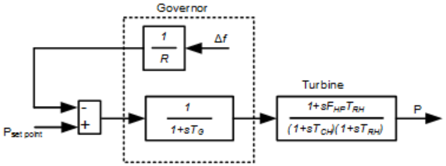
Island frequency time-domain model



Examples of governor models

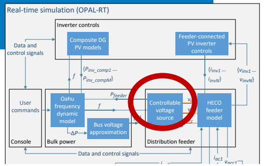


$T_G = 0.2$ s, $T_R = 5.0$ s, $T_W = 1.0$ s, $R_T = 0.38$

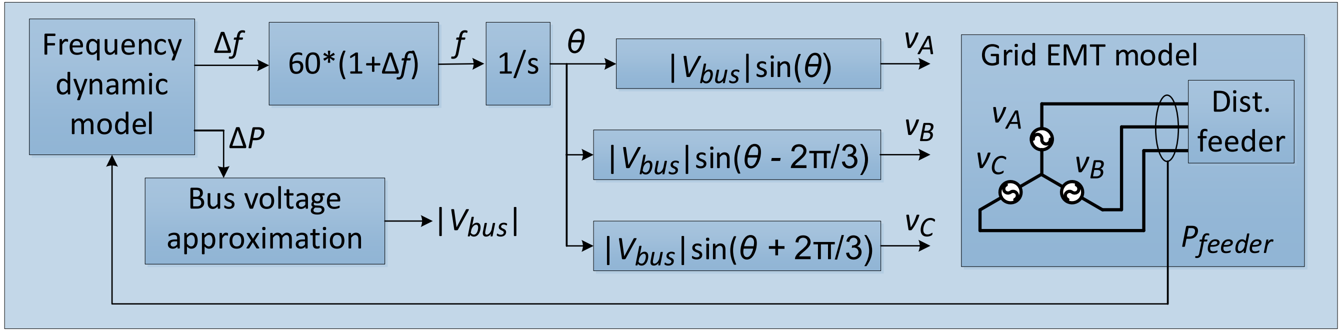


$T_G = 0.2$ s, $T_{CH} = 0.3$ s, $T_{RH} = 7.0$ s, $F_{HP} = 0.3$

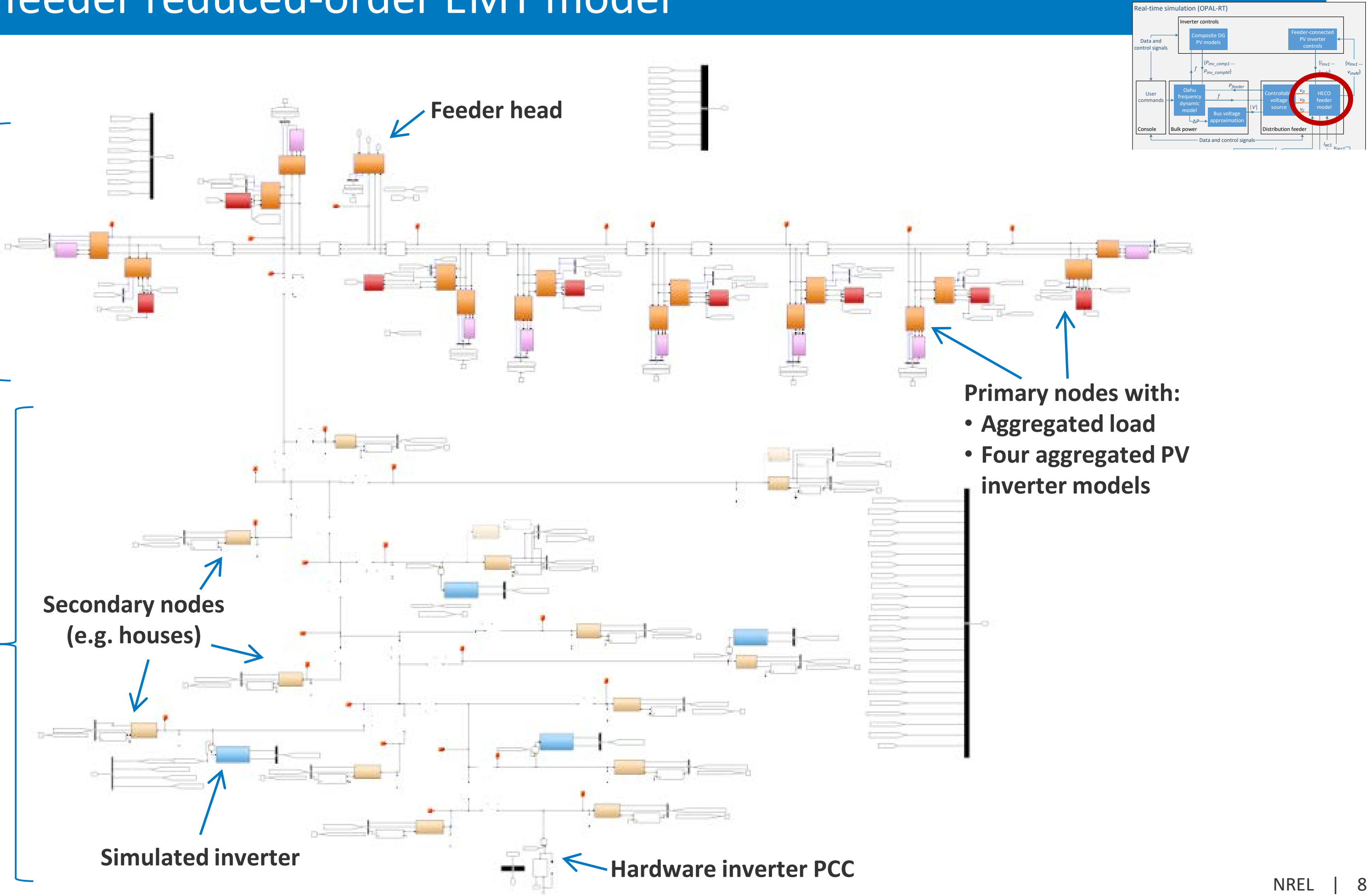
Transmission-distribution interface



- Frequency and voltage magnitude from bulk system model converted to individual phase voltages at feeder head (46 kV level).
- Frequency is integrated to produce voltage phase angle, θ
- Phase voltage balance assumed. (Not entirely accurate)
- Feeder model includes source impedance
- Voltage magnitude at feeder source constant except during transients



Distribution feeder reduced-order EMT model



Feeder head

Reduced-order feeder primary

Primary nodes with:
- Aggregated load
- Four aggregated PV inverter models

Selected secondary circuit

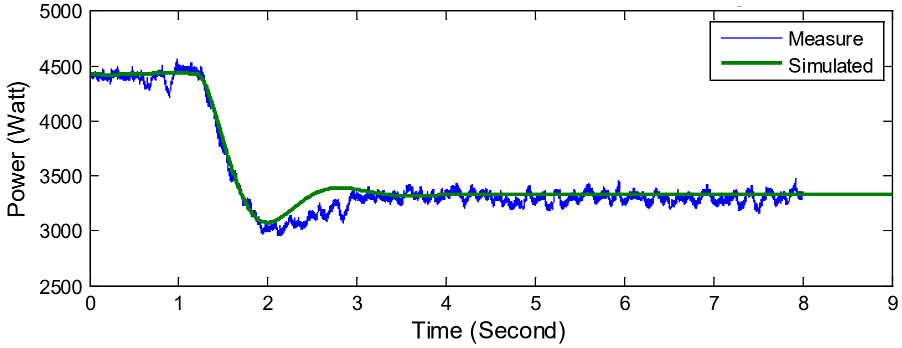
Secondary nodes (e.g. houses)

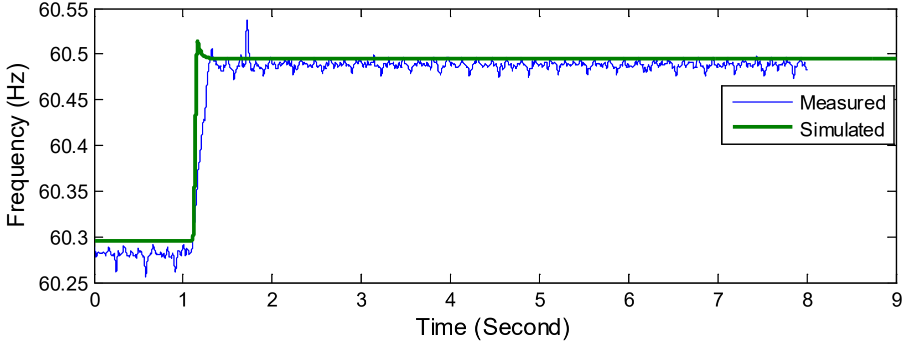
Simulated inverter

Hardware inverter PCC

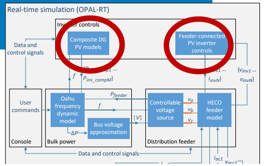
Commercially available PV inverter overfrequency response

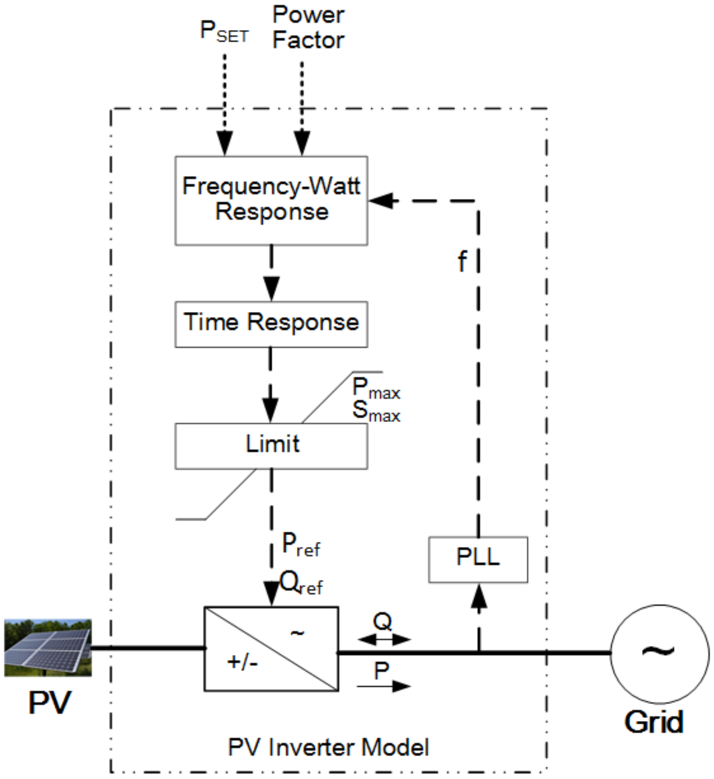
- Shown: Mild undershoot (~second-order response)
- Other inverters tested had ~first-order response
- All three inverters tested in this project had fast (sub-second) response times
- Quantifying exact response time is challenging as the frequency measurement instrument itself has a finite time response
- Response on frequency recovery varies between inverters
- Responses will likely become more uniform in response to IEEE 1547-2018

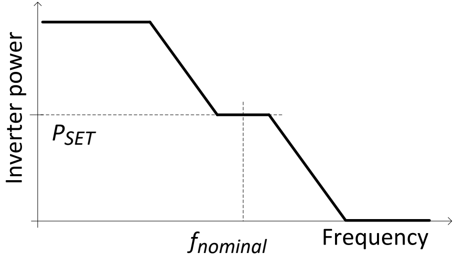




PV inverter model overview





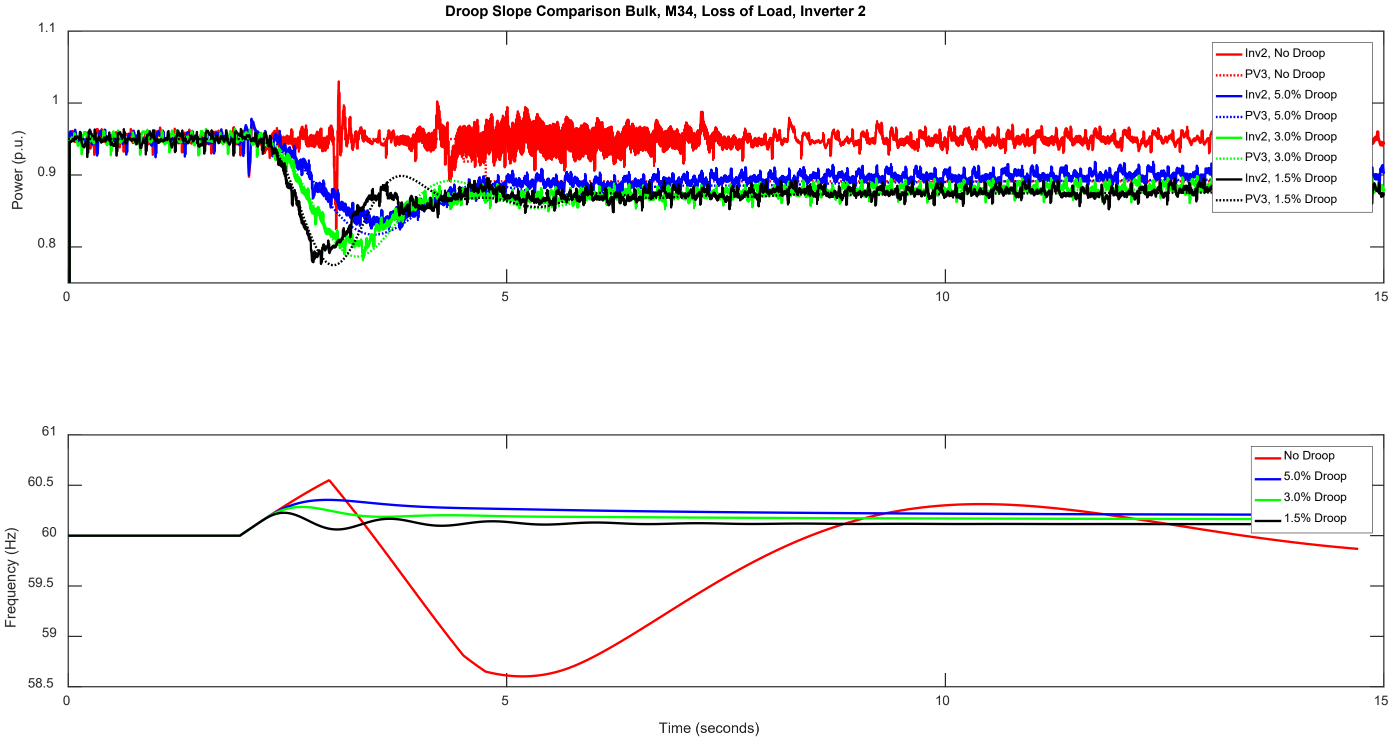


Frequency-Watt Response

- Four types of inverters modeled:
    - Legacy Enphase
    - Advanced Enphase
    - Legacy Fronius
    - Advanced Fronius
- f-W response tuned to match hardware tests
- Ride-through capability matches field inverters
- Each connected on bulk system and at 8 locations on distribution system

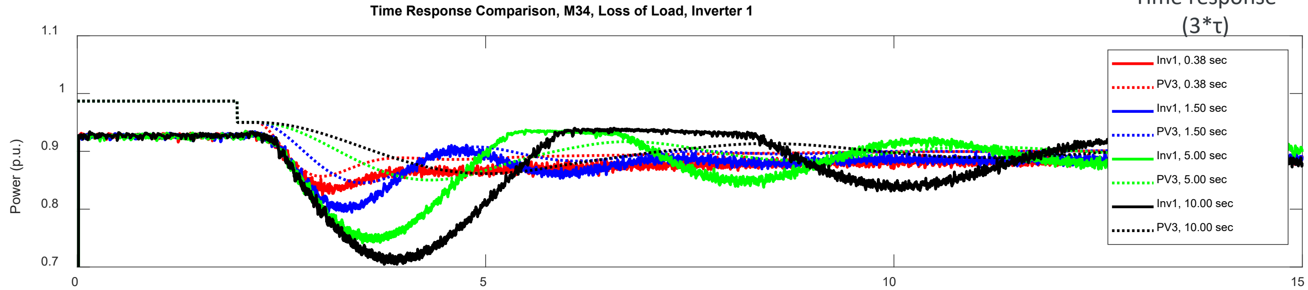
PHIL test: Worst case 2019 overfrequency event

- Event run multiple times with varying droop slope. Each color represents one test.
- Dotted lines are modeled inverters, solid lines are hardware.
- "2nd order" hardware inverter response shown

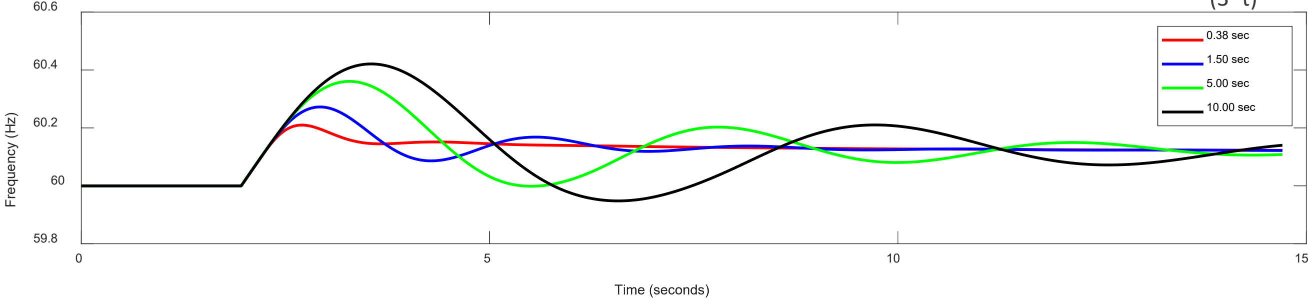


PHIL test: Worst case 2019 overfrequency event

- Same event, varying time response (speed) of 1st order inverters in PHIL model



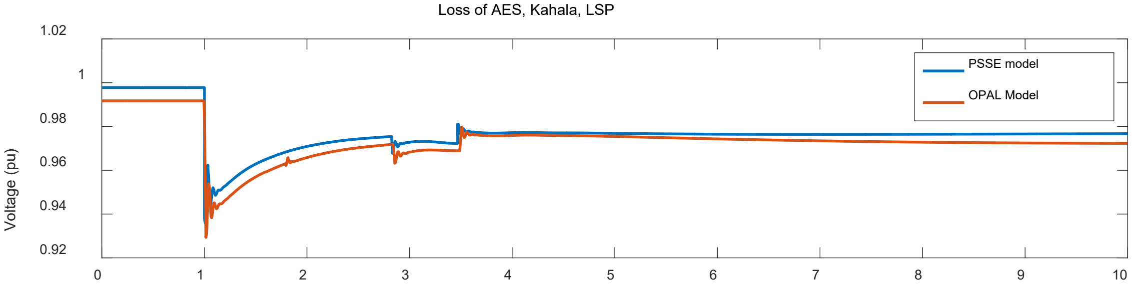
Time response (3*τ)



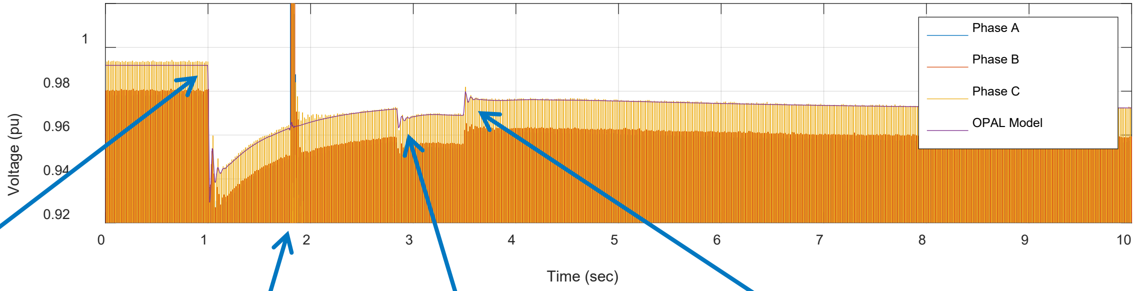
Time response (3*τ)

Test result: Inverters ride through remote and local events

- Worst case PSSE voltage profile input to PHIL models (loss of AES)
- Verified that:
  - Grid simulator could replicate voltage profile
  - Inverters ride through voltage event
- Additional voltage transient occurs during legacy PV trip event



Hardware voltage measurements and RMS command



Voltage transient due to initial bulk generator trip

Local feeder legacy PV trips on underfrequency, causing local voltage transient

Legacy PV trip on rest of system

Voltage transient due to load shed

Conclusions

- Inverter-coupled generation can provide very fast primary reserve, which is advantageous in low-inertia power systems.
    - The response can also be slowed down for larger power systems if desired
- Several variables are critical:
    - Amount of PV responding
    - Speed of response
    - Droop curve (slope and deadband)
    - Inverter dynamic response
- Some challenges and points of caution:
    - Fast response could cause undesired interactions (SSTI, frequency oscillations, or others
    - Knowing how much DPV is online at any time is difficult (little/no communications)
    - Dynamics of individual inverters (and load) vary. Models must make many simplifications and assumptions.
    - Each power system is different. This work has focused on Oahu. Smaller islands may need faster response.
- Many distributed-scale battery inverters don’t yet include upward response capability (but capability will be required as 1547-2018 is rolled out)
- To build up a base of f-W enabled inverters and avoid stability issues, it is necessary to start soon. Initially the function will have little/no impact until many MW of DPV are installed.

Impacts

- Developed **first island-wide PHIL platform** including bulk grid and distribution dynamics.
- Hawaii PUC approved **system-wide activation of f-W** following the curve recommended by the project team
  - HECO’s UL 1741 SA Source Requirements Document (SRD) calls for f-W; the spec is in line with IEEE 1547-2018.
  - All distributed inverters are now required to provide f-W droop (downward response only)
- California PUC expected to approve f-W soon as well
- Newly published **IEEE 1547-2018 allows for fast (sub-second) f-W response** based on technical recommendations from the project team
  - Initially, the 1547 Working Group was hesitant to allow sub-second responses
  - Must be coordinated with the “regional reliability coordinator” (e.g. ISO or RTO)

Thank you

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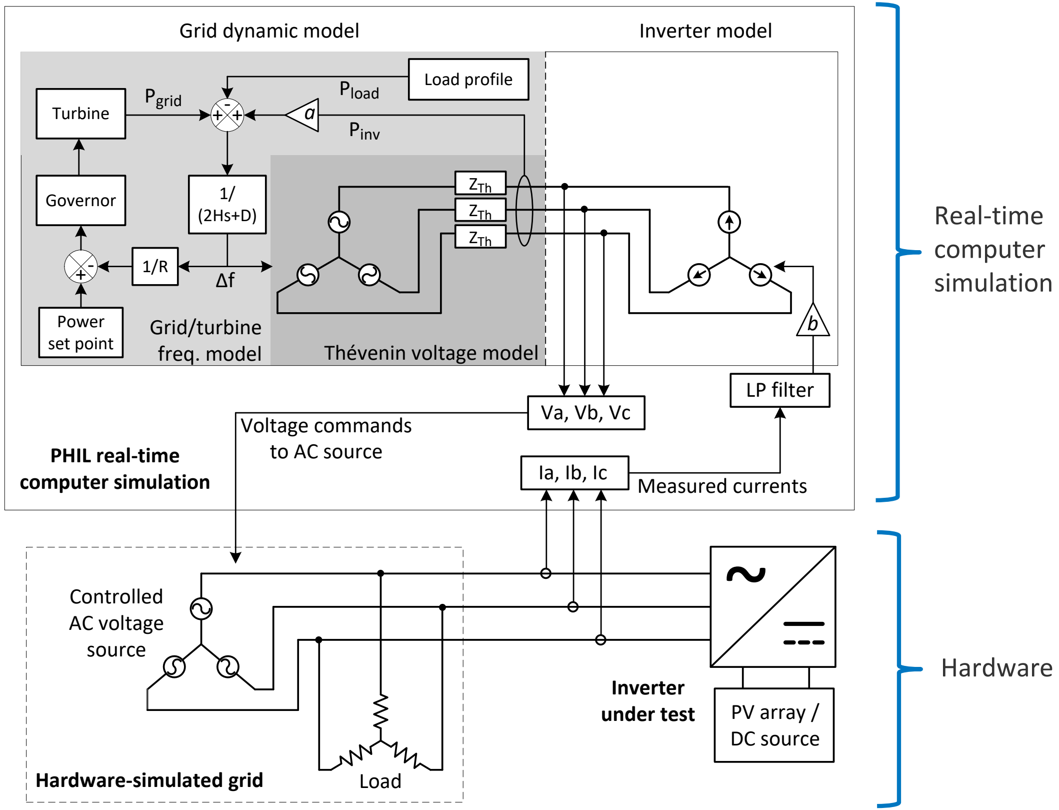
Backup slides

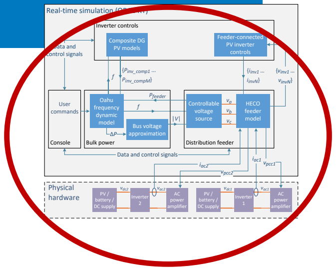
Simple generic real-time hybrid model for PHIL:

- This model shows a very simple power hardware-in-the-loop system capturing:
    - Bulk-system frequency dynamics
    - Distribution system EMT dynamics
- Intended for time-scales from sub-cycle to several seconds
- A similar but more detailed model was developed for the Oahu power system

A. Hoke, S. Chakraborty, T. Basso, "A Power Hardware-in-the-loop Framework for Advanced Grid-interactive Inverter Testing", *2015 IEEE Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC



Full system PHIL tests



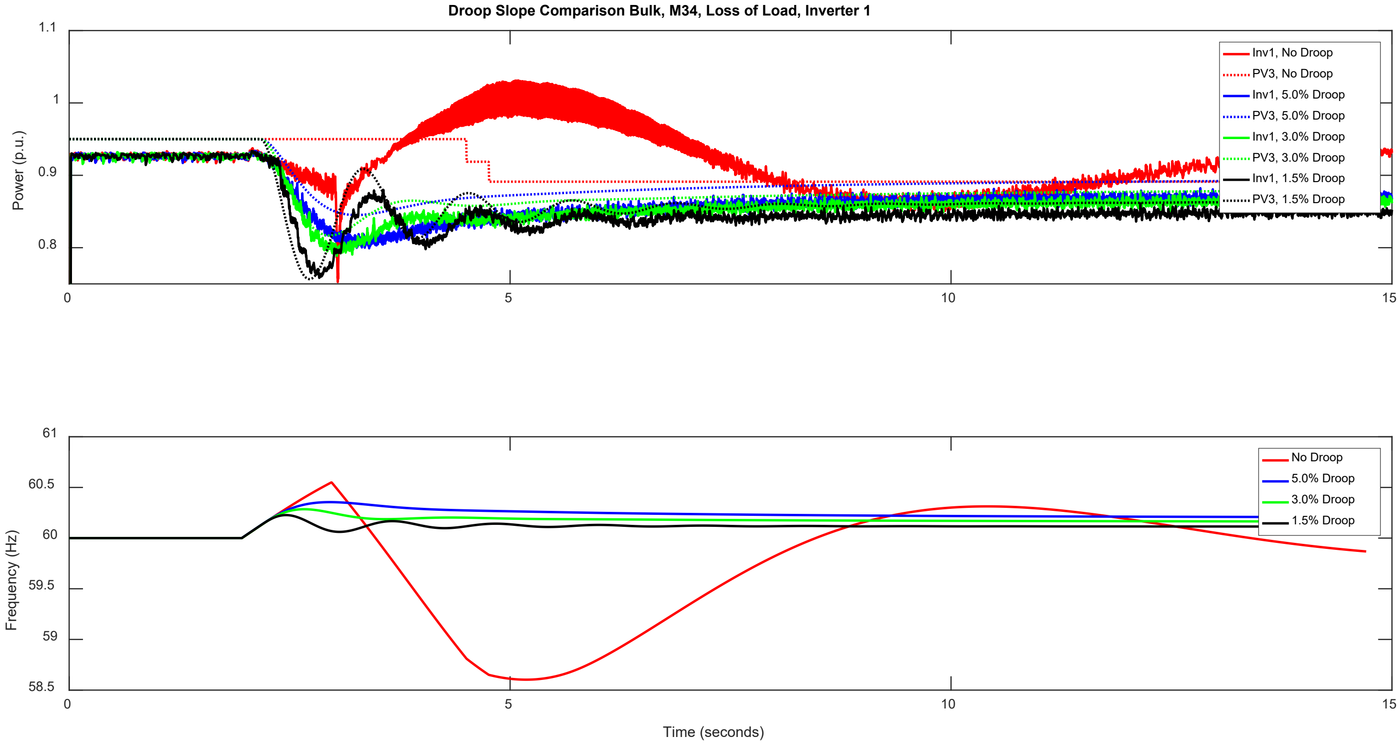
- Two hardware inverters connected to neighboring points on distribution secondary
- Primarily tested underfrequency events
- 2019 Light Spring case
- Worst-case loss-of-load contingency: 63 MW load loss due to breaker failure

Inverter Type	f-W Capable?	Power Factor	Underfrequency Trip Setting	Overfrequency Trip Setting	f-W response dynamic	Aggregate rating in base case (MW)
DGPV Type 1	No	1.00	<59.3 Hz for 105 ms*	>60.5 Hz for 105 ms*	NA	48.38
DGPV Type 2	No	1.00	<57.0 Hz for 110 ms*	>60.5 Hz for 110 ms*	NA	93.02
DGPV Type 3	Yes	-0.95	<57.0 Hz for 20.5 sec	>63.0 Hz for 20.5 sec	1st order	325.20
DGPV Type 4	Yes	-0.95	<57.0 Hz for 20.5 sec	>63.0 Hz for 20.5 sec	2nd order	8.00
Station/Utility	Yes	-0.95	<57.0 Hz for 20.5 sec	>63.0 Hz for 20.5 sec	1st order	134.7

*Trip times tuned to actual inverter behavior based on test data; up to 160 ms allowed by IEEE 1547-2003.

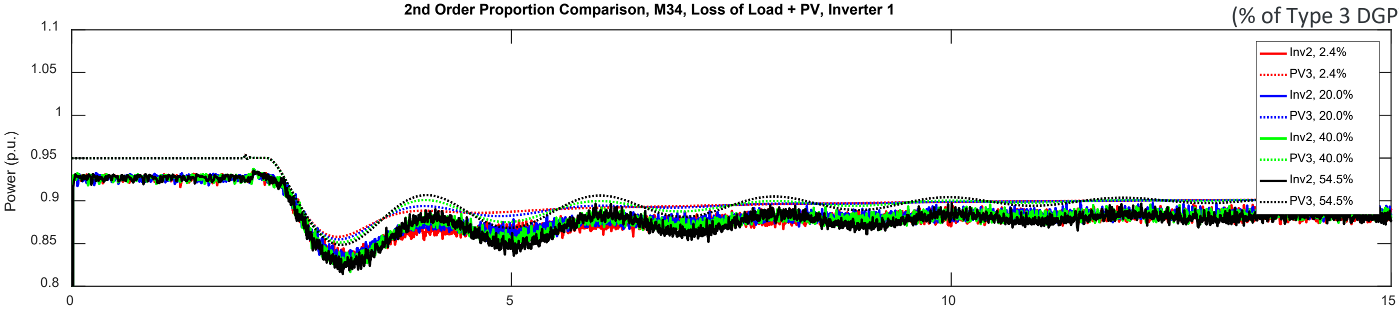
PHIL test: Worst case 2019 overfrequency event

- Event run multiple times with varying droop slope. Each color represents one test.
- Dotted lines are modeled inverters, solid lines are hardware.
- “1^{st} order” hardware inverter response shown

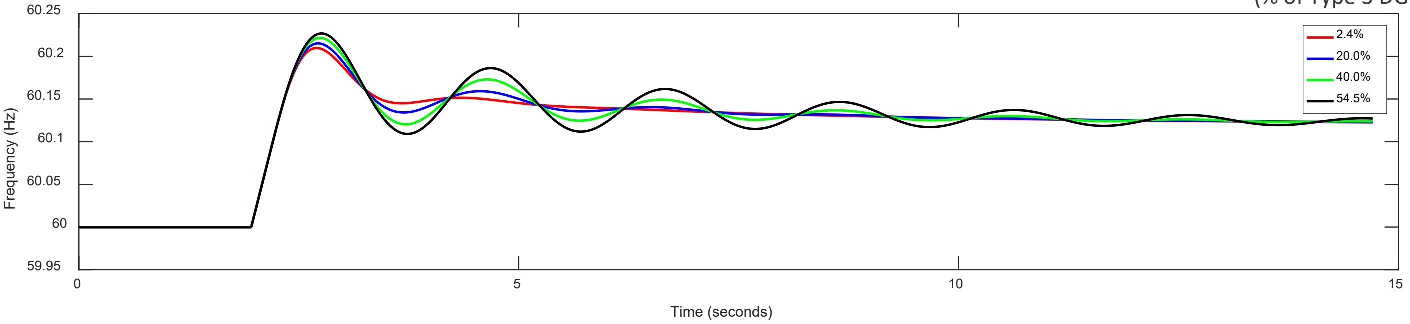


PHIL test: Worst case 2019 overfrequency event

- Same event, varying proportion of 2nd order to 1st order inverters in PHIL model



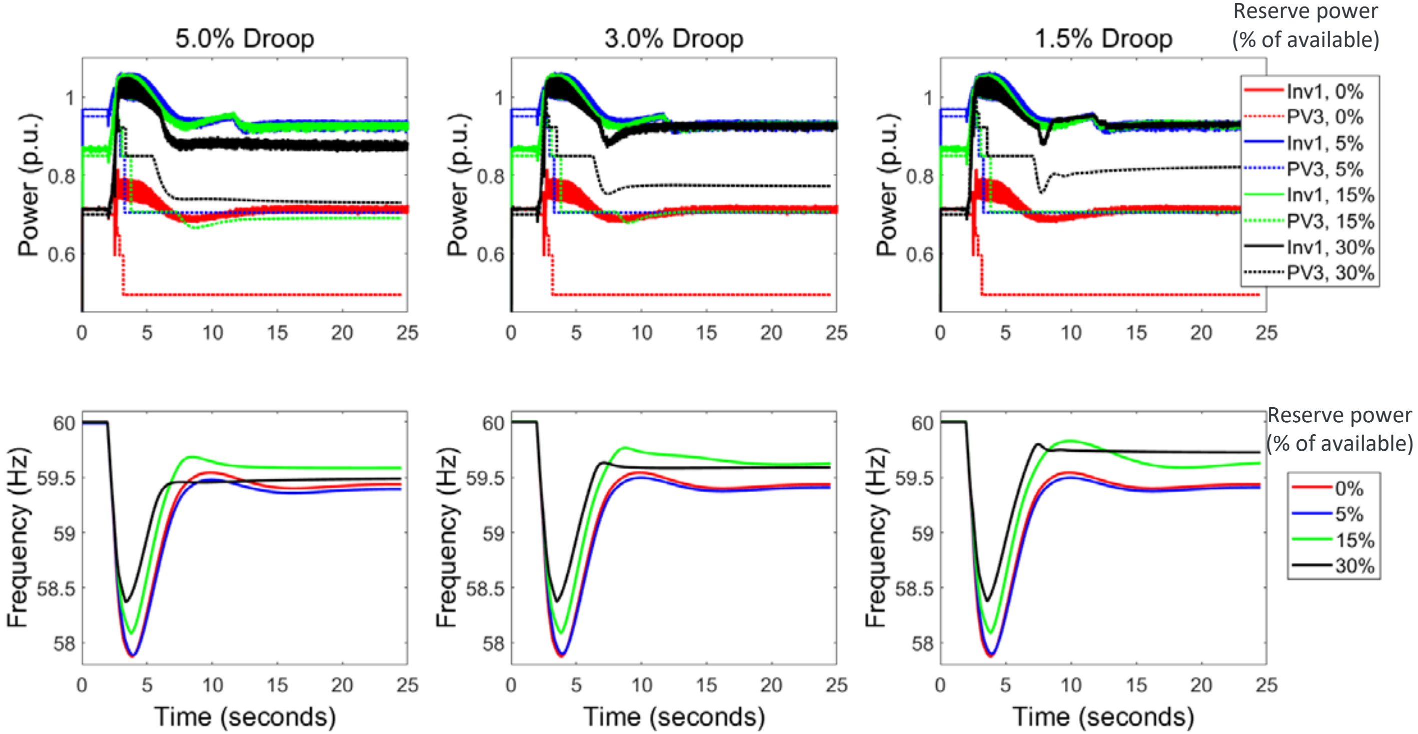
Inverters with 2nd-order response (% of Type 3 DGPV)



Inverters with 2nd-order response (% of Type 3 DGPV)

PHIL test: Worst case 2019 *underfrequency* event

- Loss of AES (190 MW); heavy summer load case
- Assumes PV operating with reserve, capable of autonomous upward response



Challenges:

- Linking of bulk grid and distribution grid simulations
- PHIL stability
- How to account for HIL phase delay when:
  - Frequency and DUT power are not constant
  - Non-fundamental frequency components are present
- Validation and debugging of complex model
- Balance between model fidelity vs. computation time

Publications

- A. Hoke, M. Elkhatib, A. Nelson, J. Tan, V. Gevorgian, J. Johnson, J. Neely, C. Antonio, D. Arakawa, “The Frequency-Watt Function: Simulation and Testing for the Hawaiian Electric Companies,” NREL/TP-5D00-68884, July 2017.
- A. Nagarajan, et al., “Network Reduction Algorithm for Developing Distribution Feeders for Real-time Simulators,” *IEEE Power and Energy Society General Meeting*, 2017.
- A. Nelson, et al., “Power Hardware-in-the-Loop Evaluation of PV Inverter Grid Support on Hawaiian Electric Feeders,” 2017 *IEEE Innovative Smart Grid Technologies Conference (ISGT)*, April 2017.
- Others to appear