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Hawaiian Electric Advanced Inverter Test Plan – Result Summary

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Context – Recent and ongoing NREL-HECO work

1. HECO-SolarCity-NREL collaboration (2014-2016, complete)
   - Transient and temporary overvoltage evaluation
   - Anti-islanding with advanced inverters in multi-inverter, multi-point islands
   - Impacts of coordinated volt-var control on power quality and conservation voltage reduction
2. HECO advanced inverter test plan (2016 – Focus of this presentation)
   - Baseline testing
   - Circuit-level PHIL testing
3. DOE GMLC – Hawaii regional partnership, DOE funded (2016-2017 – Next presentation)
   - Focus is on fast grid frequency support from DERs (including, but not limited to, frequency-Watt function)
   - Modeling, simulation, and controls development
   - Hardware testing
   - Field deployment
4. Simulation of inverter-based voltage regulation (2016-2017 – Started September 2016)
   - Simulate 3 HECO circuits with volt-var, volt-watt, fixed PF (and combinations), plus legacy inverters
   - Variables: PV penetration, portion of legacy inverters, PV system DC:AC ratio
   - Quantify effects on annual feeder voltage profiles and on PV kWh production loss
   - Extension of advanced inverter test plan

Note: Other work not covered here: PSIP support, work prior to 2015, etc

Advanced Inverter Test Plan Team

- NREL: Andy Hoke, Austin Nelson, Kumar Prabakar, Adarsh Nagarajan, Shaili Nepal, Rasel Mahmud – NREL
- Hawaiian Electric Companies: Earle Ifuku, Marc Asano, Reid Ueda, Jon Shindo, Kandice Kubojiri, Riley Ceria, Justin Goza
- Inverter manufacturer participants:
  - Apparent
  - Enphase Energy
  - SMA
  - SolarEdge
- Smart Inverter Technical Working Group

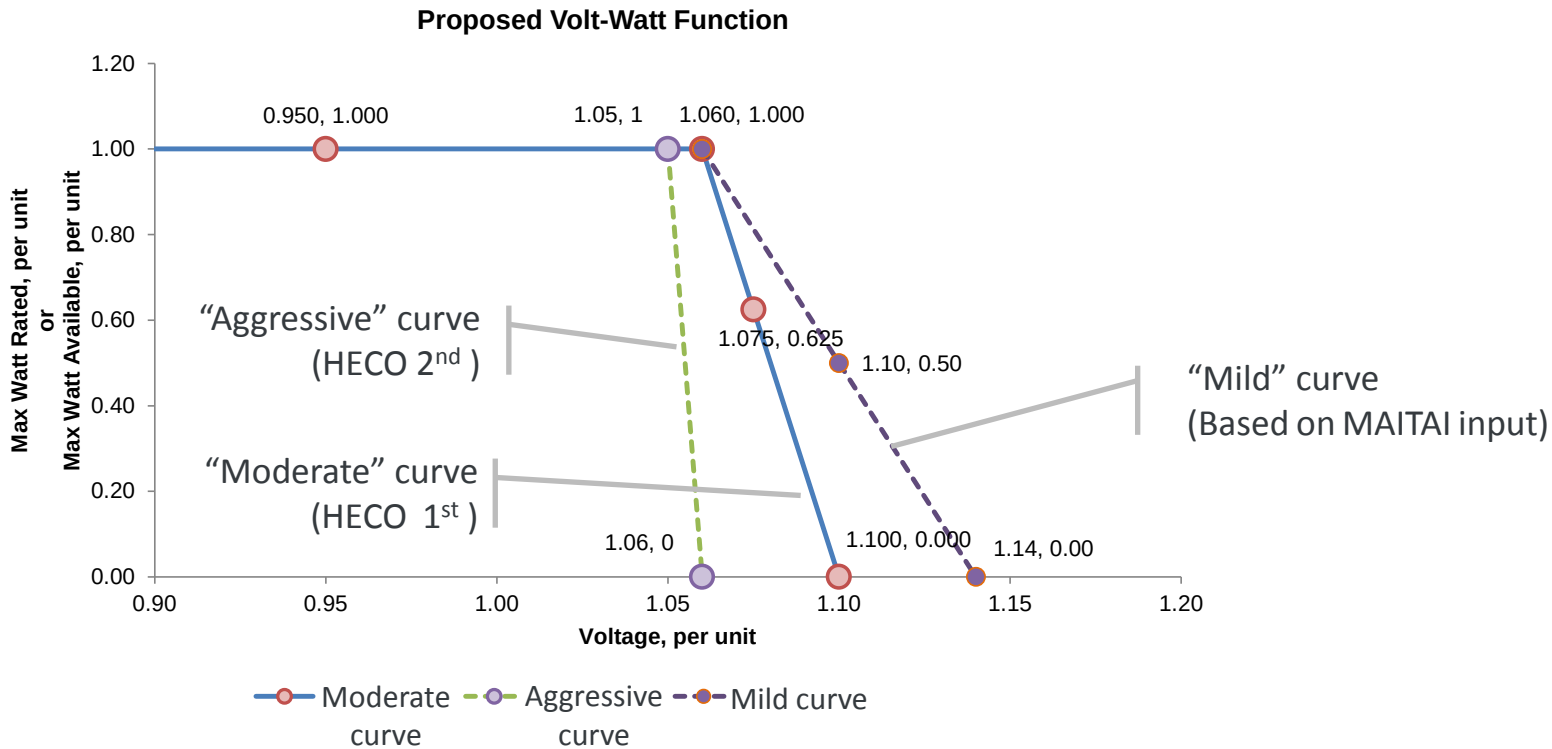
Statement of Work

Focus of presentation

1. Define test details (test scenarios) – Complete ☑
2. Baseline testing – Complete ☑
   - Evaluate each inverter's ability to perform selected advanced functions
   - Results used to develop simple model of each inverter
   - Based on draft UL 1741 SA (but will not qualify for or impact UL certification)
   - Volt-Watt, FPF, VRT, FRT, ramp rate, soft start
   - Volt-var added later. (Baseline testing only – no PHIL testing)
3. PHIL testing – Complete ☑
   - Use PHIL to test inverters as if connected to high penetration HECO circuits
   - One/two inverters in hardware, many more simulated in real time
   - Compare tests with/without various advanced functions active
   - Vary advanced function control parameters
4. Result dissemination to stakeholders (ongoing, including today) ☐
5. Final Report to PUC – December 15 ☐
6. Follow-up project – Recently started ☐
   - NREL-HECO CRADA: Voltage Regulation Operational Strategies (VROS)
   - Long-term simulation of various PV voltage regulation functions on HECO feeders

Baseline testing: Volt-Watt

- Based on draft UL 1741 SA volt-watt test
- Three volt-watt curves tested



- Snapshot mode ("0") and P_{max} mode ("1") on 2/4 inverters
- Varying time responses
- Varying levels of available PV power (irradiance)
- 33 test series, 495 total points tested
- All inverters capable; responses as expected

Proprietary data and preliminary results
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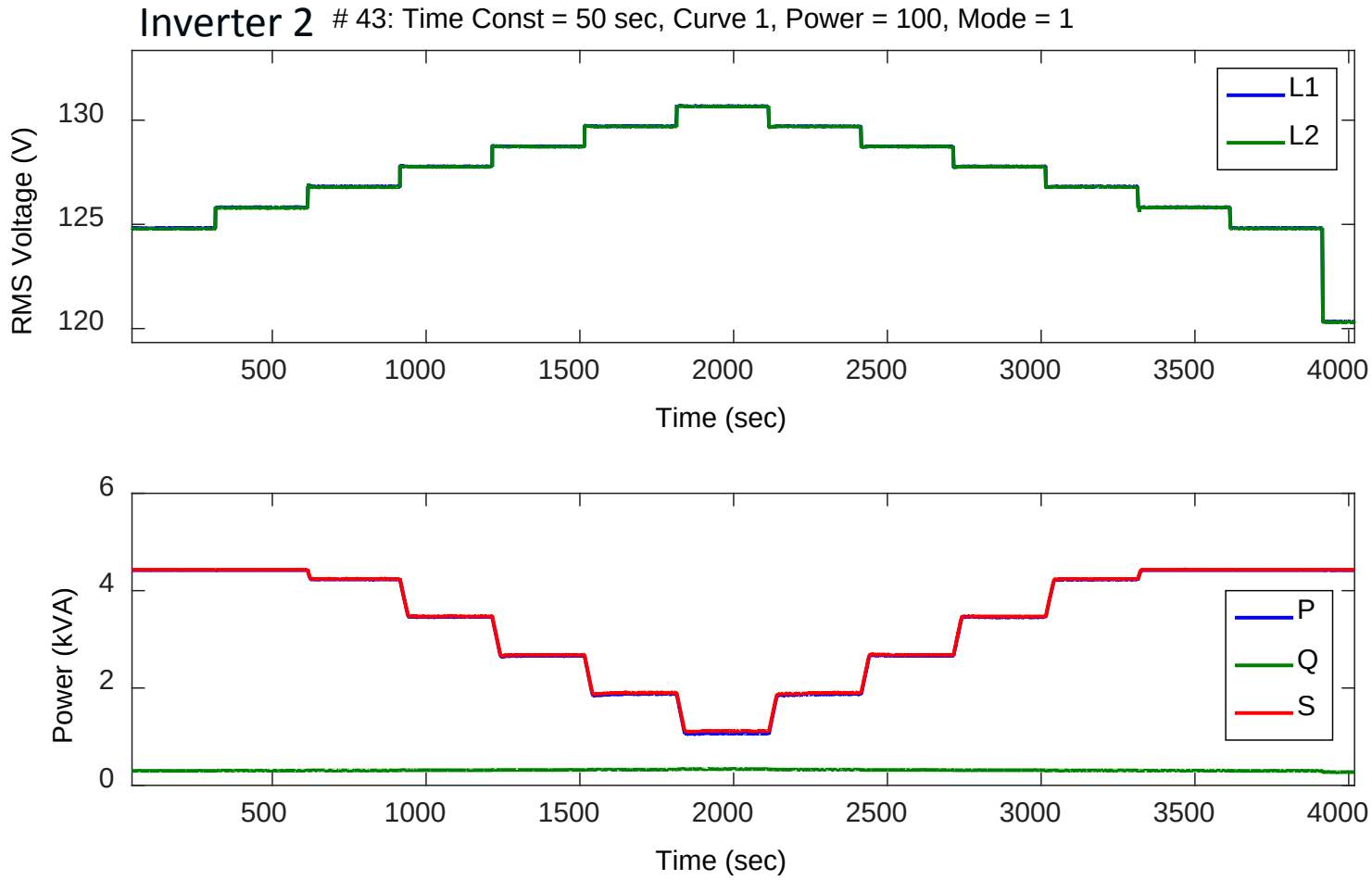
Volt-Watt example

Moderate curve



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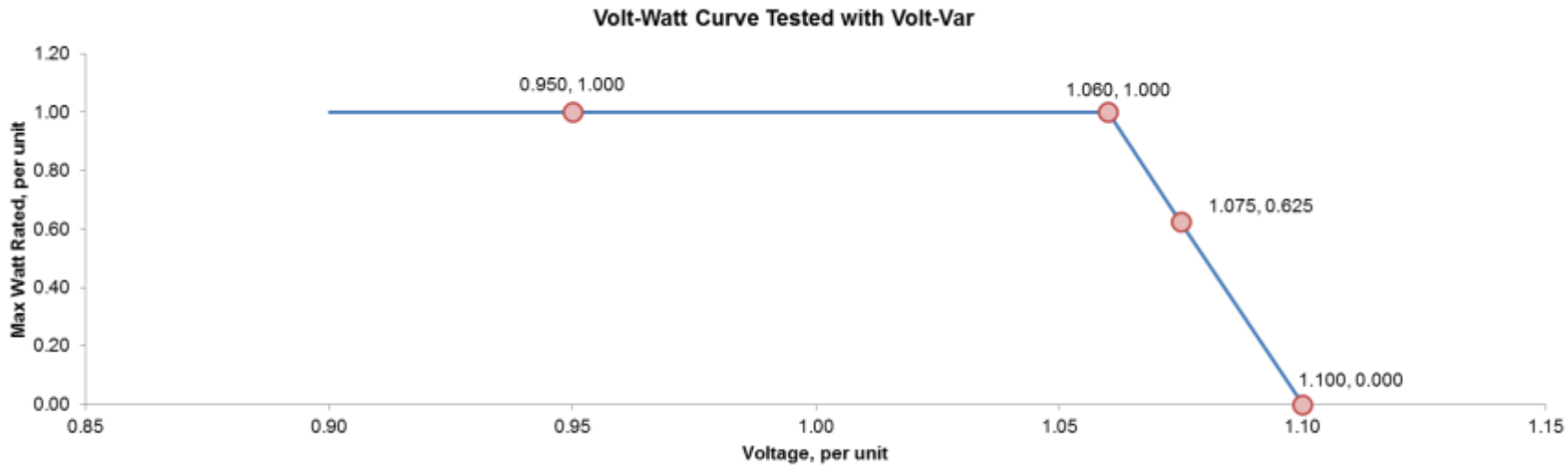
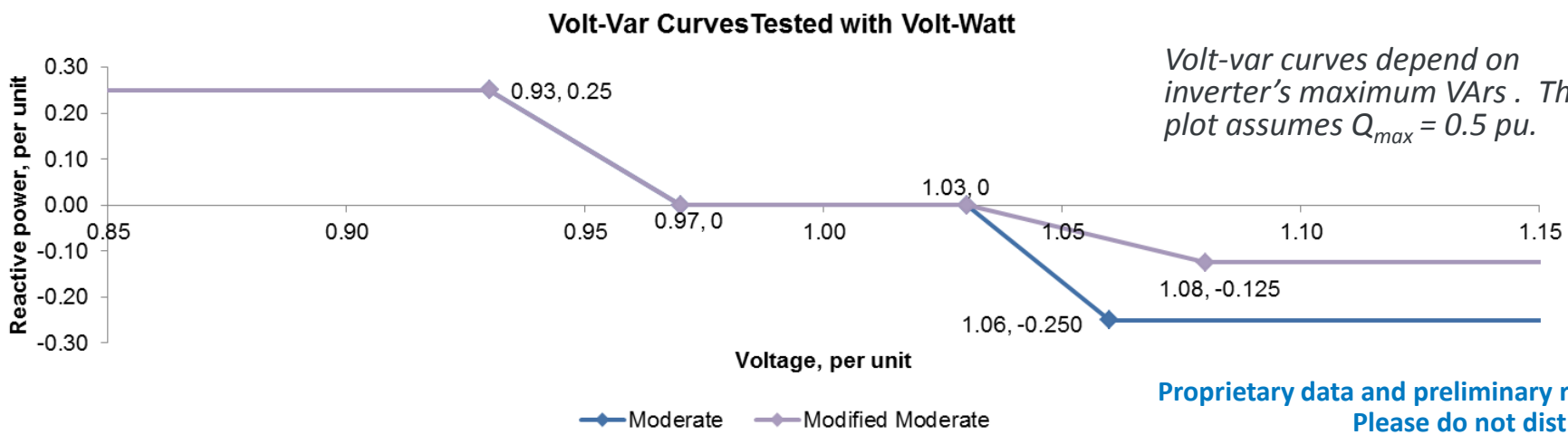
Baseline testing: Simultaneous volt-var and volt-watt

Only 2 inverters capable; 2 curve combinations; 4 test series, 108 total test points

Can be activated under Rule 14H by mutual agreement, per HECO





Volt-var curves depend on inverter's maximum VArs . This plot assumes Q_{max} = 0.5 pu.

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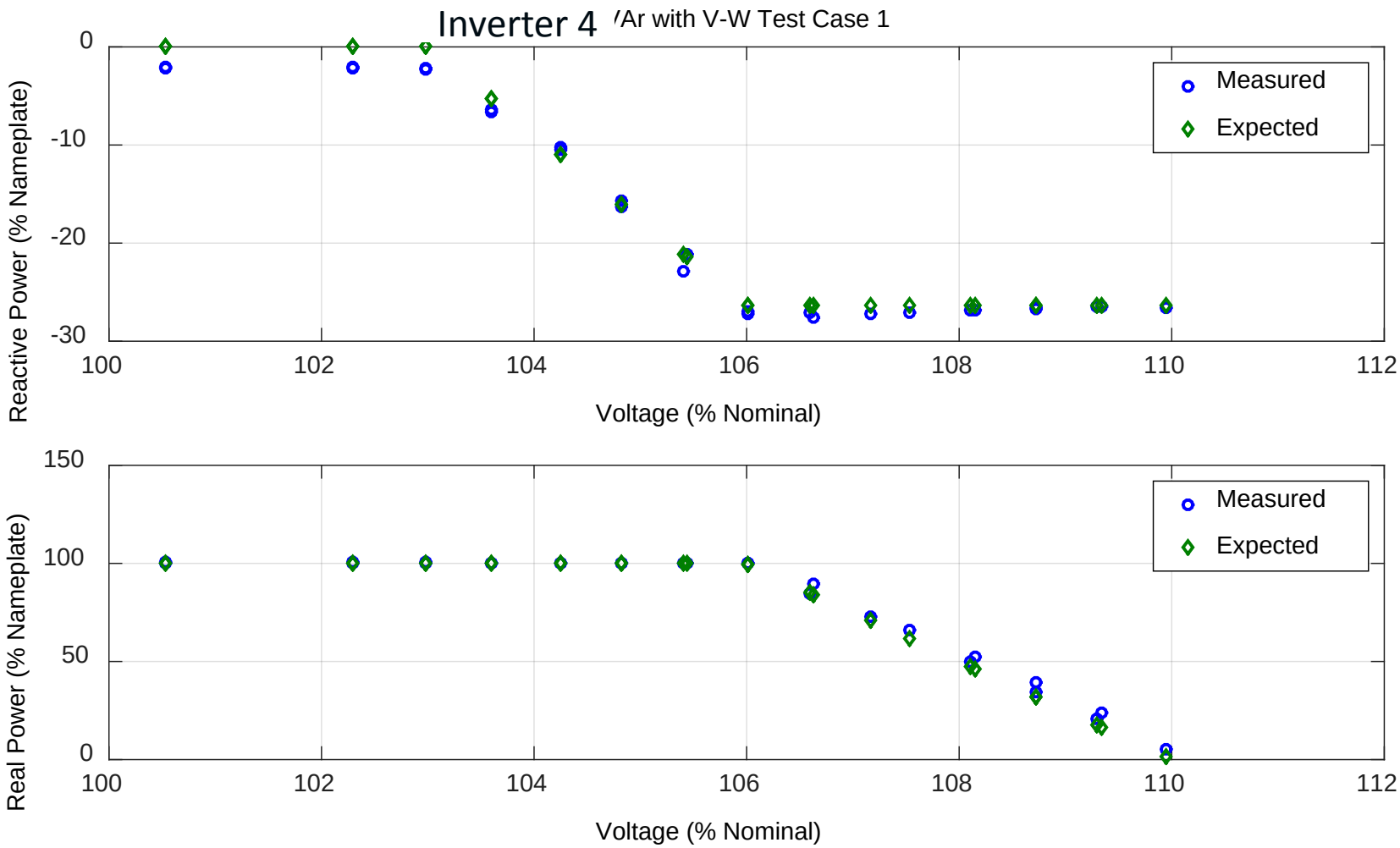
Volt-var with volt-watt example



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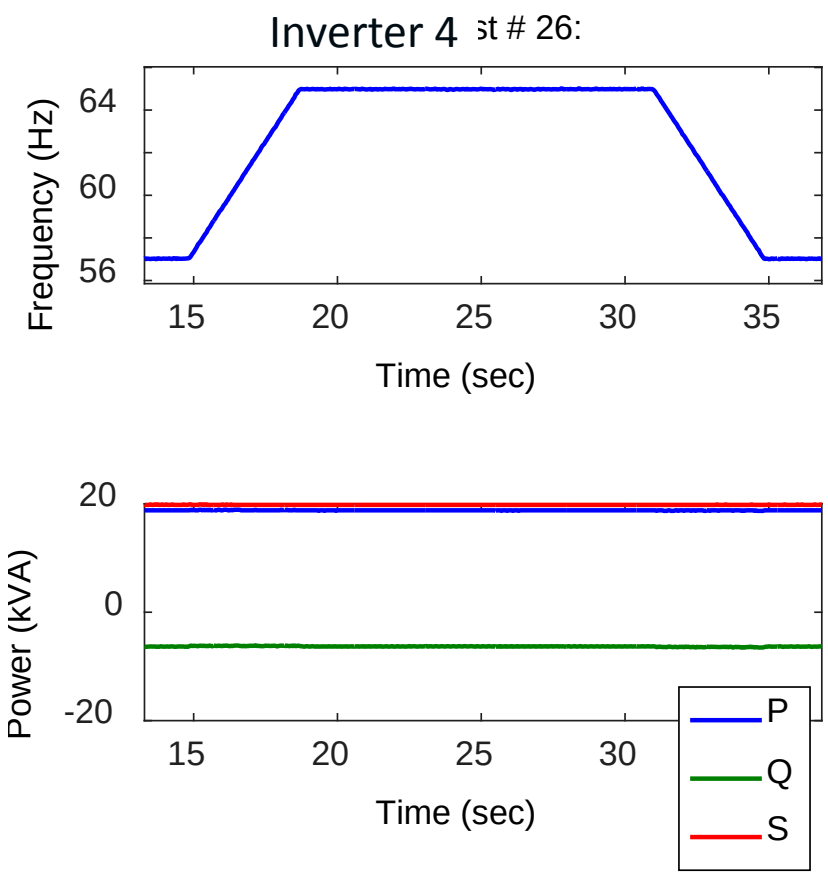
Baseline testing: Voltage and frequency ride-through

- Based on draft UL 1741 SA ride-through tests
- Tested using Oahu country/profile (as in field)
- VRT: 3 UVR levels, 2 OVR levels (per 14H)
  - UVR2 tested at two adjustable time settings (per 14H)
  - 56 total tests
- FRT: 2 UFR levels, 2 OFR levels (per 14H)
  - UFR1 tested at two adjustable time settings (per 14H)
  - 56 total tests
- Each test repeated at 20% and 100% power levels
- Legacy Enphase (i.e., M-Series) inverters also tested
- All inverters capable of meeting Rule 14H, but slope of ride-through test profile in draft test was too steep for one – product is being updated based on recently-published 1741 SA

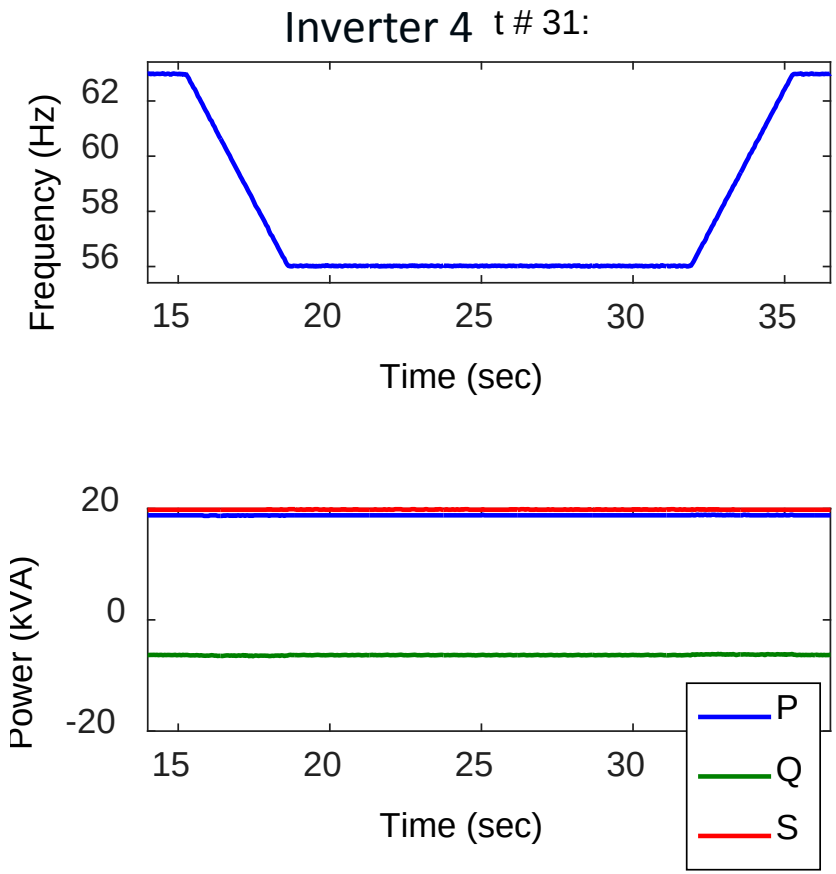
Frequency ride-through examples

OFR1: 63 < f < 65 Hz for 20 s

(high end of 14H range of adjustability)



OFR1: 57 < f < 56 Hz for 20 s



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Baseline testing summary

All inverters "passed" all tests, but some tests required interaction with manufacturer:

- Some IMs had not seen draft UL 1741 SA in advance (or had seen an old version), so some test details were a surprise, requiring slight test modifications
- Functions (or combinations of functions) not required in another grid code were not supported in all inverters:
  - Ramp-rate control
  - Simultaneous volt-watt and volt-var
- All IMs expected to be able to pass UL 1741 SA in next 12 months – timing and selection of functions is up to each manufacturer
- Configuring functions manually is time-consuming and error-prone. Engineering and firmware development of pre-configured function profiles (aka "country settings") will be needed for commercial field deployment.

Recommendations from baseline testing

- Some areas of Rule 14H would benefit from clarification. Work is underway between Hawaiian Electric and NREL to address gaps:
  - Volt-var requirements need to be defined in detail
    - Pay attention to var capability (rectangular vs triangular; vars at max P)
  - Volt-watt requirements need to be defined in detail
  - Clarify how response times are defined
  - Where possible, align with Rule 21 and/or IEEE P1547 (draft, near-final)
    - Some variation in settings from other codes *should* be okay
  - If simultaneous operation of various voltage regulation functions is required, that should be specified.
- Where function details not yet specified, unclear if manufacturers will make Hawaii-specific functions available in 12 months
  - Recommend continued discussions with stakeholders on the near-term, high-priority voltage regulation functions

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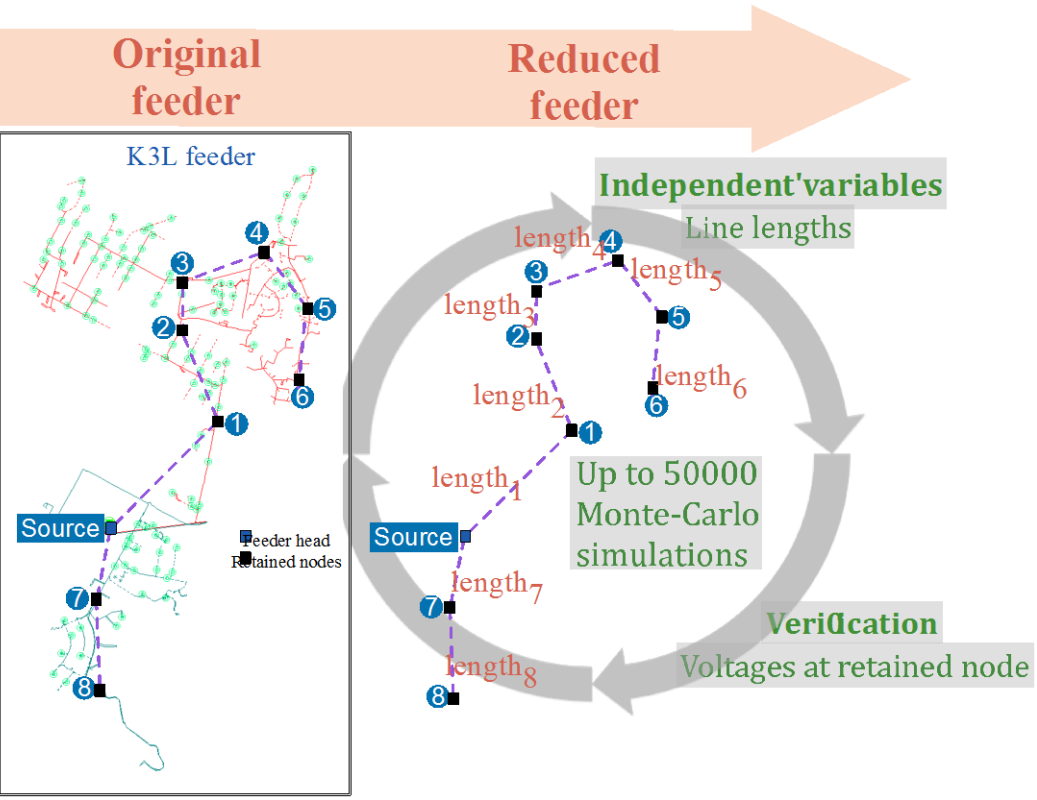
Circuit-level Power Hardware-in-the-Loop Testing

PHIL test introduction

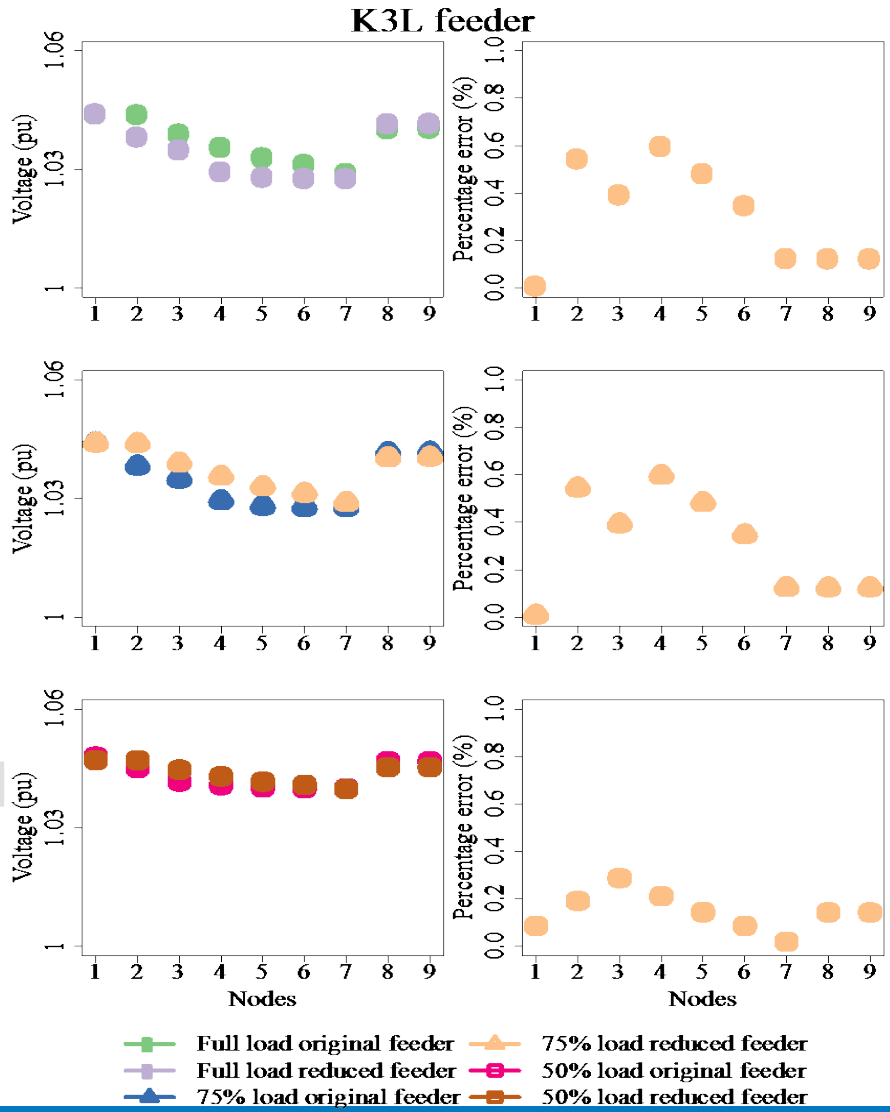
- Goal: Test inverters as if connected to real HECO circuits
- Method: Run real-time dynamic simulation of HECO circuit in parallel with, and interacting dynamically with, hardware inverter test. (Power hardware-in-the-loop, PHIL)
- To capture fast dynamics, real-time feeder simulation solves circuit over 4000 times per second.
- Feeder model detail must be reduced to allow fast computation.
- Feeder reduction overview:
  1. Convert from Synergi to OpenDSS and validate
  2. Select nodes to retain
  3. Reduce feeder (process depicted on next slide)
  4. Validate voltages by simulating at multiple load levels (100%, 75%, 50%)
  5. Translate reduced model from OpenDSS (quasistatic) to SimPowerSystems (electromagnetic transient) and re-validate
  6. Add aggregated PV models
  7. Add selected distribution secondary circuit(s)

Feeder reduction process

Reduction



Validation



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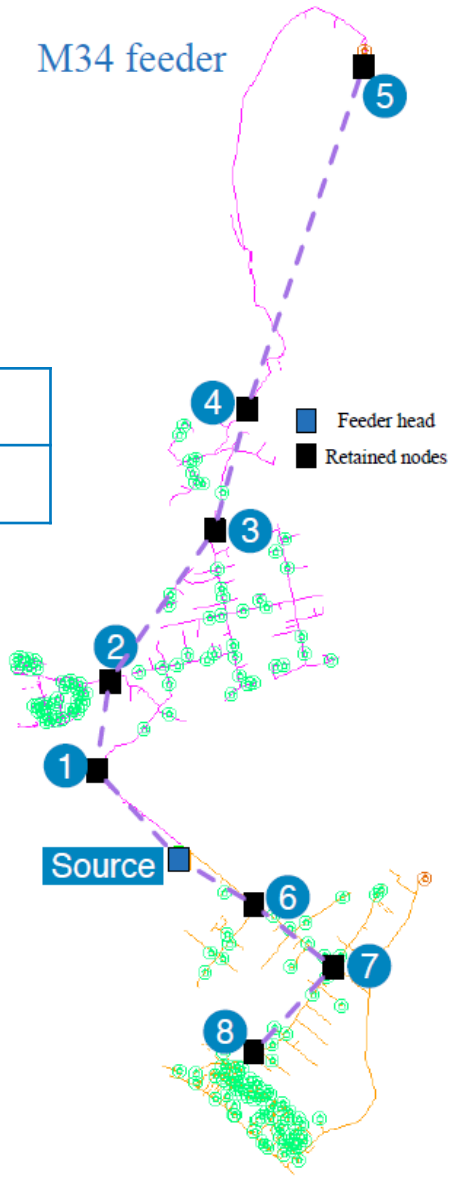
PHIL test summary

- Two circuits (K3L and M34) adapted from full HECO Synergi models:
  - Synergi → OpenDSS → reduced OpenDSS → SimPowerSystems
  - 8 primary nodes retained, voltages validated
  - 4 aggregated inverter types at each node → 32 modeled inverters:

Legacy Enphase	Advanced function capable Enphase
Legacy non-Enphase	Advanced function capable non-Enphase

  - Inverter capacities based on detailed data on existing PV systems and projections of future inverters provided by HECO
  - Capacity and settings of each type of inverter at each node vary between tests
- Both circuits contain a detailed single-phase secondary model in one location, provided by HECO. Single-phase hardware inverters are connected here. Three-phase hardware inverter (#4) connected to a simple fabricated secondary far from the feeder head.
- Secondary impedances not modeled elsewhere.



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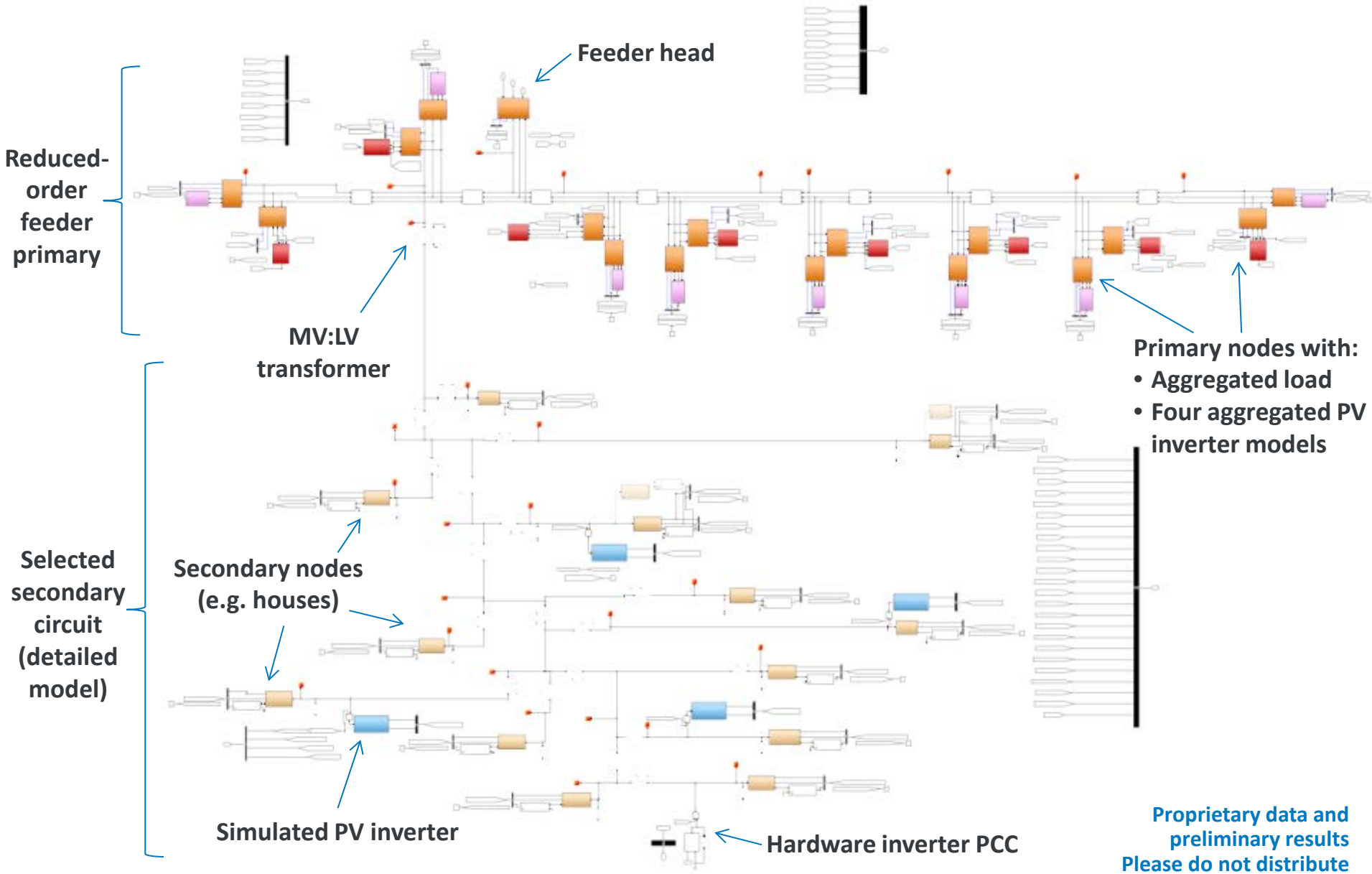
Reduced-order distribution feeder model (one of two)



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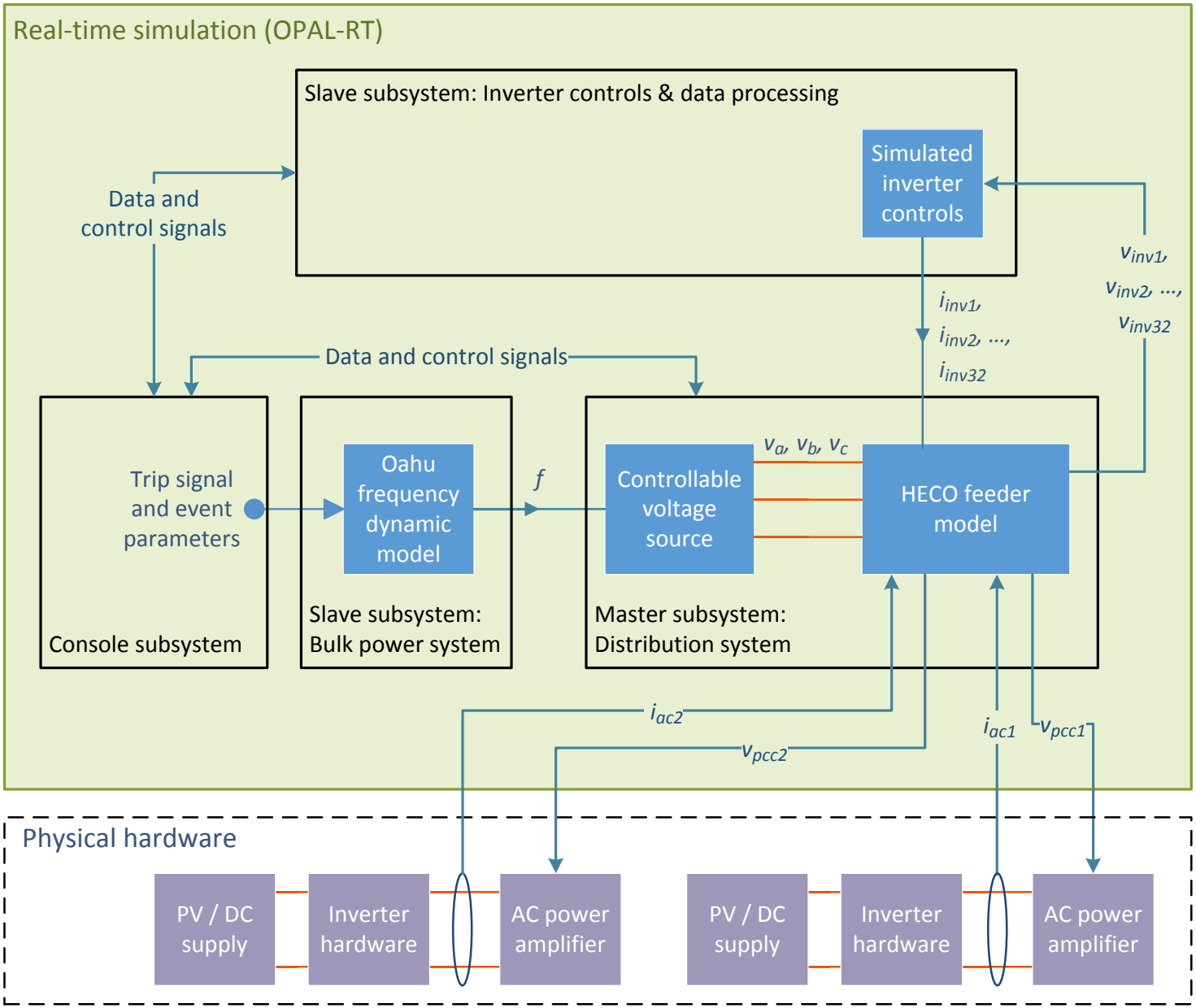
Real-time model for PHIL

- Real-time HECO feeder model contains two PCCs for hardware inverters
- Hardware inverters are connected to AC supply driven by simulated PCC voltage
- Many more inverters simulated with various controls in distribution feeder model



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PHIL test scenario overview

- Each PHIL test focuses on a single event lasting few minutes in time
- Summary of test scenario matrix developed by NREL and HECO, vetted by SITWG:
  - 180 volt-watt tests (details on next slide)
  - 24 VRT tests:
    - Distant event (simulated) reduces voltage at inverter terminals, then recovers within required ride-through time. Voltage event designed to cover multiple VRT levels
  - 24 FRT tests:
    - Bulk system conditions cause temporary frequency event. Frequency recovers within required ride-through time. Event designed to cover multiple FRT levels
  - 18 ramp-rate tests:
    - PV output low due to low irradiance. Irradiance rises (200 $W/m^2 \rightarrow$ 1000 W/m^2)
  - 18 soft-start tests:
    - Inverter comes online following voltage event and ramps to full power

Volt-watt PHIL test scenarios

- General scenario: POI voltage near top of ANSI Range A (1.05 pu). PV output low due to low irradiance. Irradiance rises (e.g. 200 W/m^2 → 1000 W/m^2 in 40 seconds).
  - Record voltages and powers at inverter POI and other key locations on circuit.
  - Load set low (MDL), feeder head voltage set high, and legacy PV added to secondary to produce interesting test cases
- Volt-watt test variables
  - 3 volt-watt curves, plus baseline with volt-watt off
  - 2 volt-watt styles: snapshot, P_{max}
  - 3 fixed PF settings (0.98, 0.95, 0.90), plus baseline with unity PF
  - 2 retrofit proportions for legacy inverters: (25%, 50%), plus baseline with no retrofit
  - Present and future (2021) PV penetration cases
    - All "future" inverters assumed to be capable of V-W and non-unity PF
- Inverter 1 and Inverter 4 tested independently
- Inverters 2 and 3 tested simultaneously (neighboring locations on same secondary)
- Different subset of variable combinations tested for each inverter to maximize the number of variables covered within time available

Simulated inverters – volt-watt test scenarios

Total PV inverter ratings

- M34 circuit:

Year	Portion of PV inverters retrofitted	Legacy PV (MW)	Advanced PV (MW)	Total PV (MW)
2016	None	3.9	0	3.9
	25%	2.9	1.0	3.9
	50%	1.9	1.9	3.9
2019	None	3.9	11.2	15.1
	25%	2.9	12.1	15.1
	50%	1.9	13.1	15.1

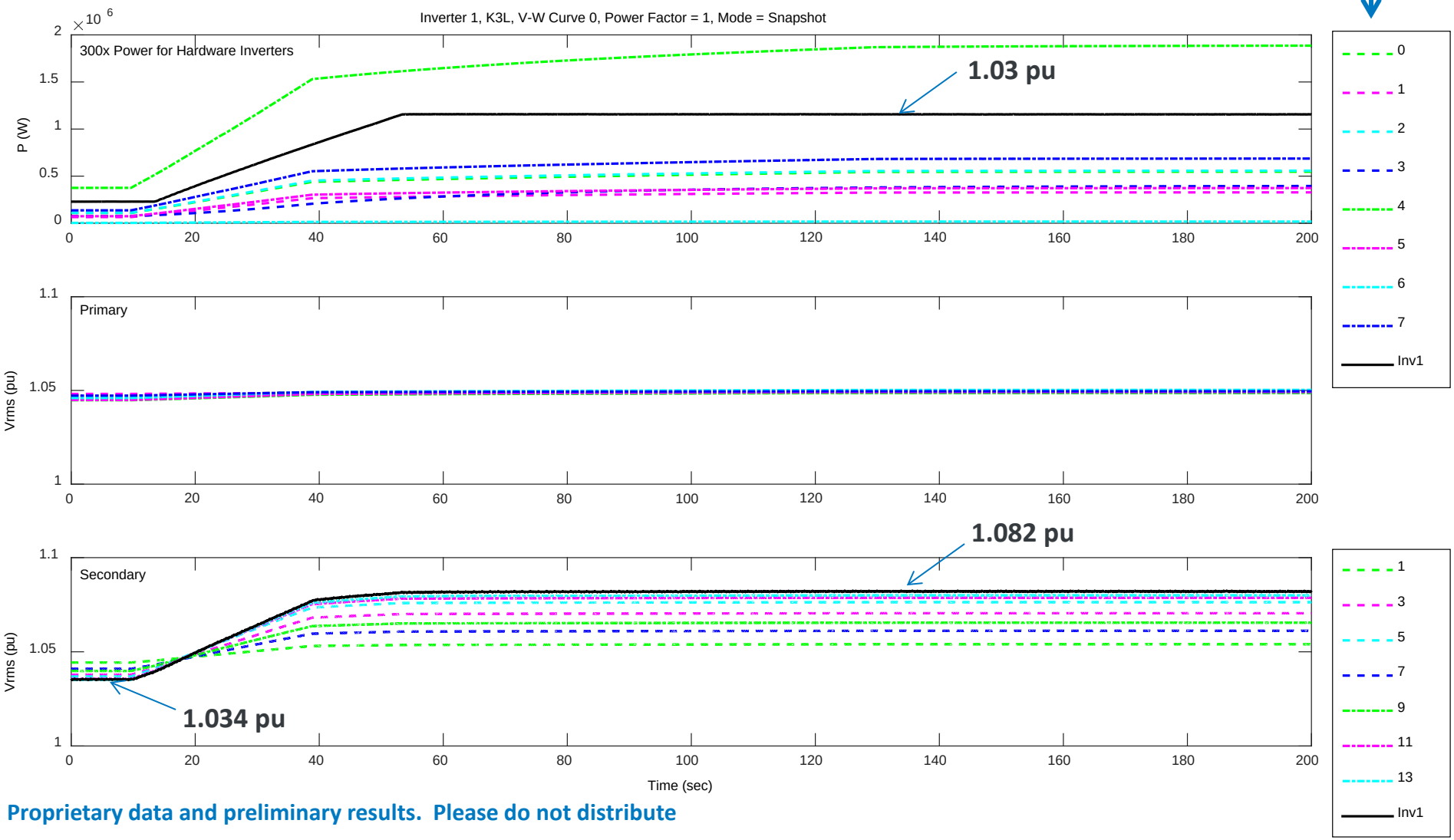
- K3L circuit:

Year	Portion of PV inverters retrofitted	Legacy PV (MW)	Advanced PV (MW)	Total PV (MW)
2016	None	3.0	0	3.0
	25%	2.3	0.8	3.0
	50%	1.5	1.5	3.0
2019	None	3.0	1.8	4.8
	25%	2.3	2.5	4.8
	50%	1.5	3.3	4.8

Volt-watt PHIL test example

Inverter 1, volt-watt disabled, unity PF, year 2021, no retrofit

Dashed lines show total power at each node from all four types of modeled inverters



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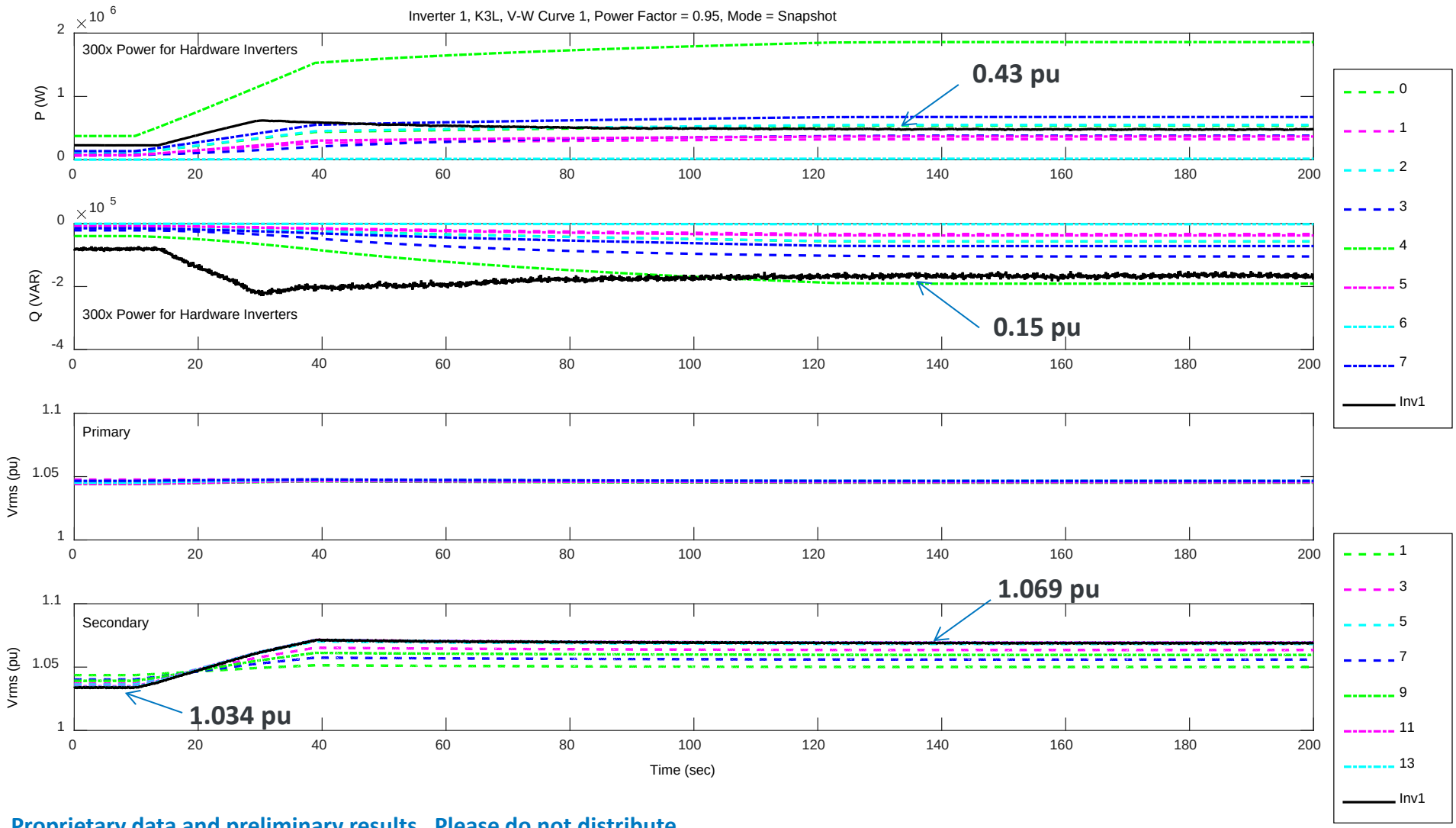
Volt-watt PHIL test example

- Inverter 1, moderate volt-watt, 0.95 PF, year 2021, no retrofit



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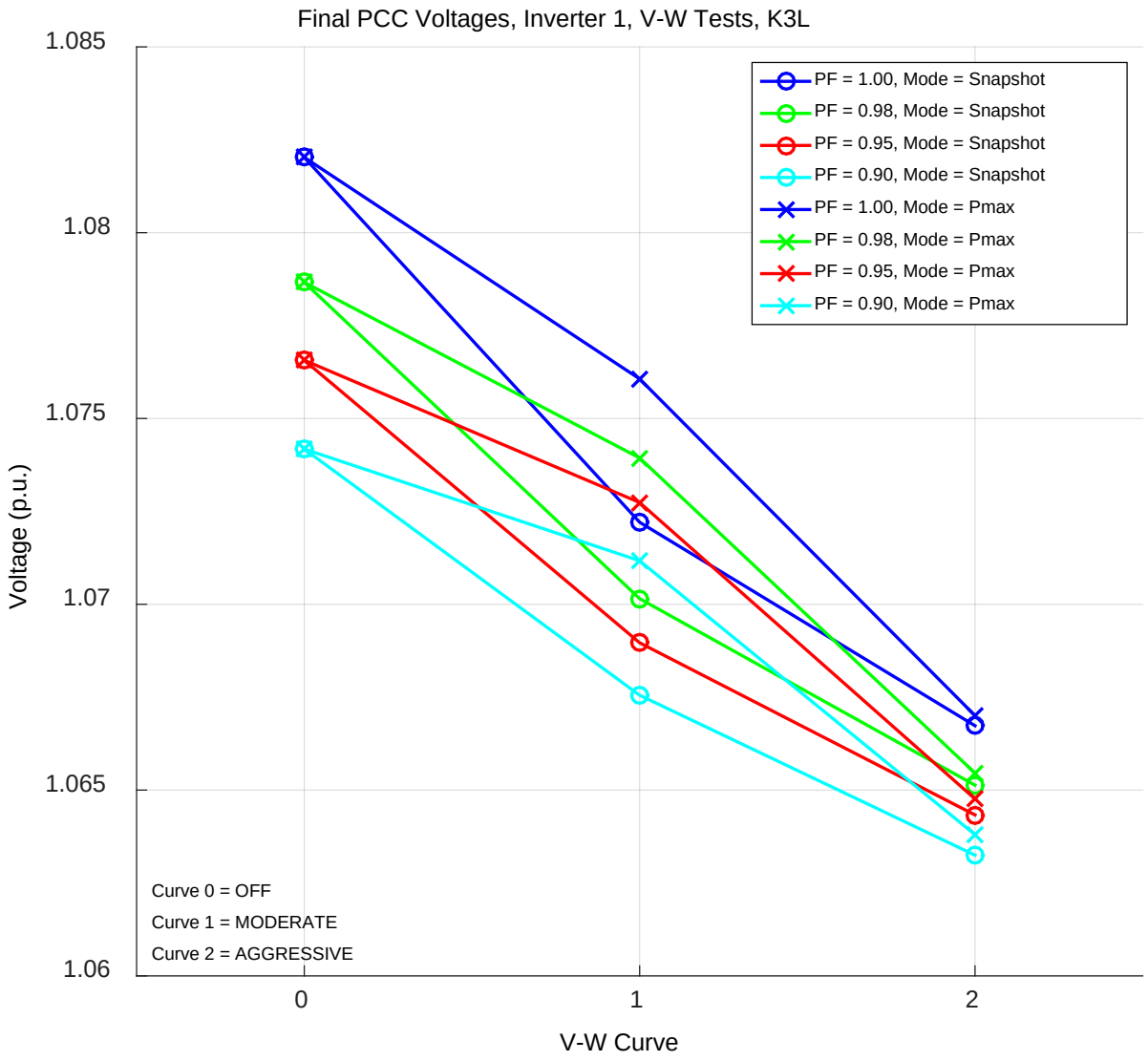
Summary of Inverter 1 volt-watt tests, K3L circuit

All Inverter 1 tests:

- Year 2021
- No retrofitting (but all post-2015 PV assumed capable of V-W and Fixed PF)



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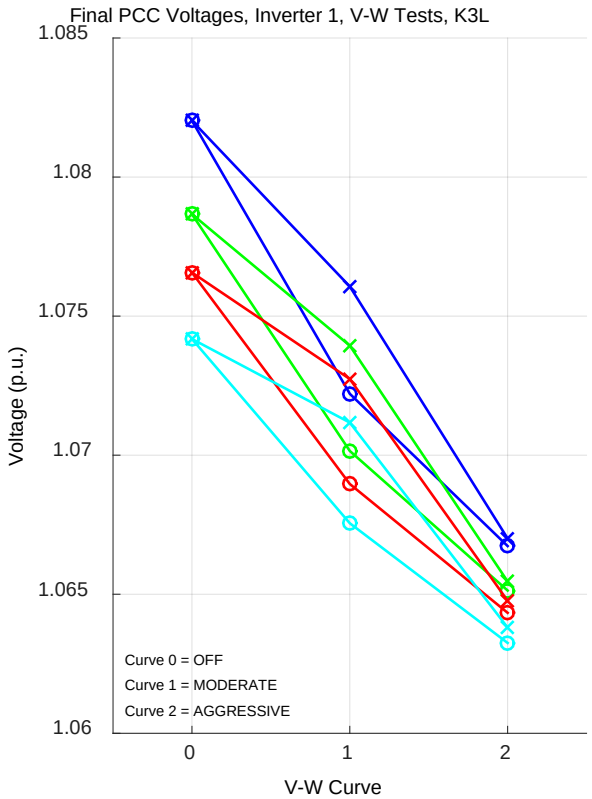
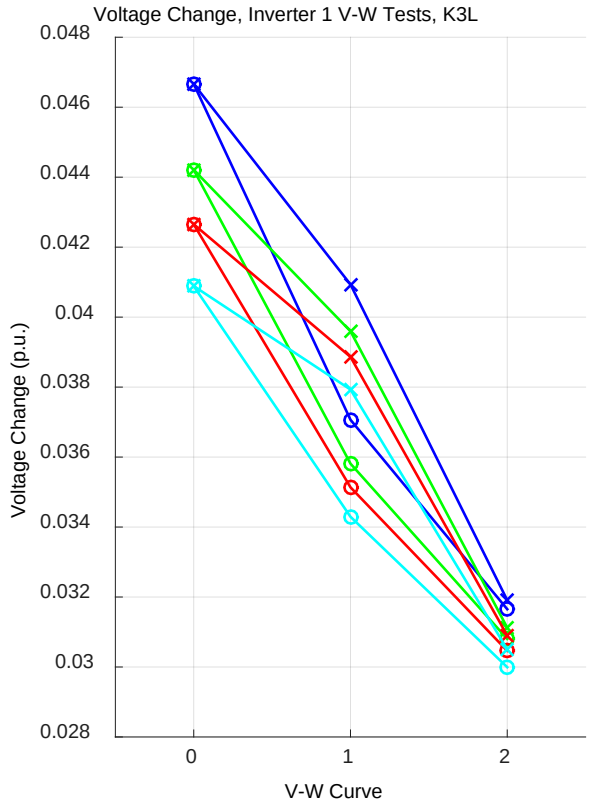
Summary of Inverter 1 volt-watt tests, K3L circuit

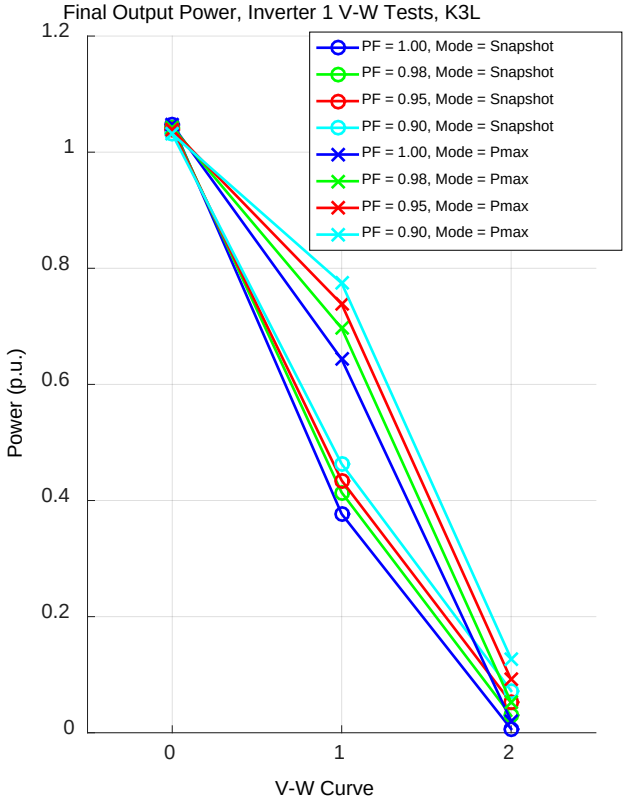
Same plot as previous slide:



PCC voltage change from beginning of test till end:



Effect on hardware PV power output:



- In this case, both V-W and FPF have significant impacts on voltage

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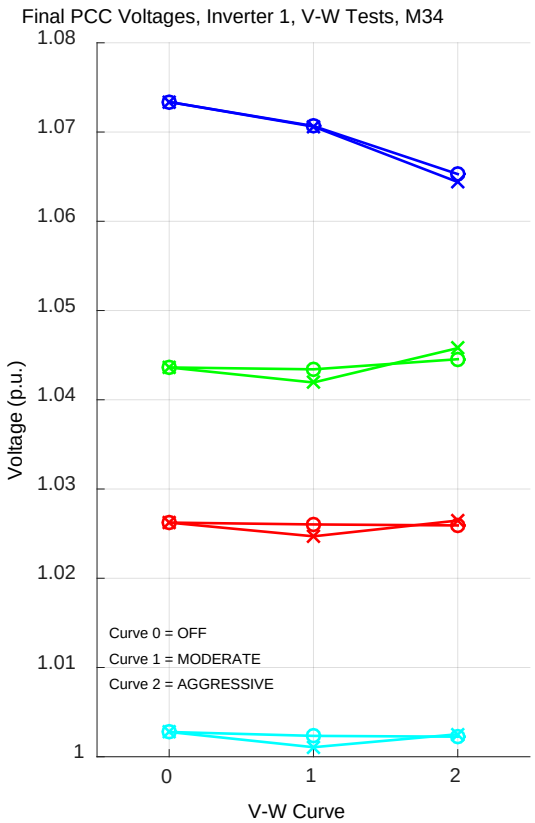
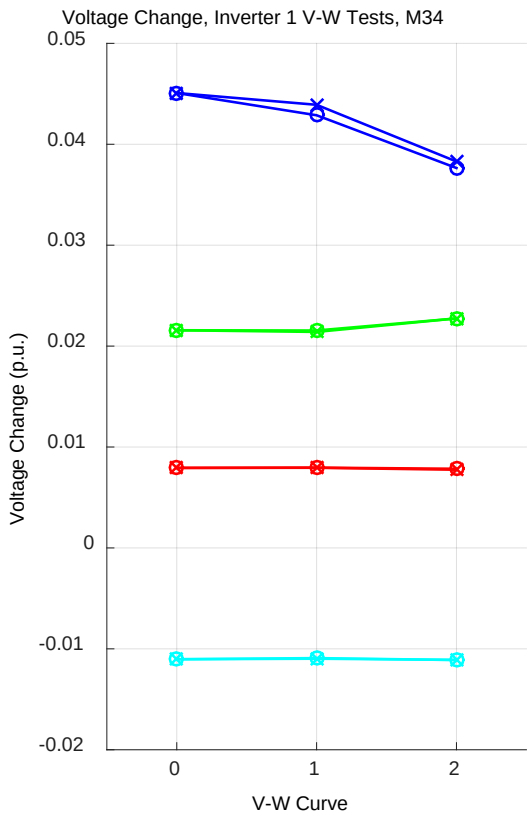
Summary of Inverter 1 volt-watt tests, M34 circuit

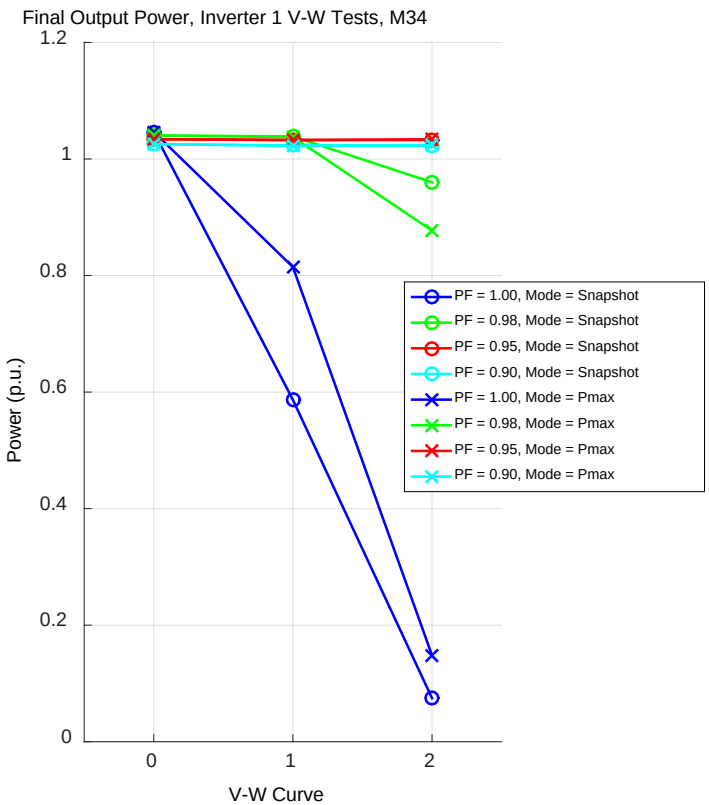
Final hardware inverter PCC voltage:



PCC voltage change from beginning of test till end:



Effect on hardware PV power output:



- In this case, Fixed PF impacts voltage strongly; V-W has comparatively little impact
- Reason: much more future PV on this circuit (11 MW on M34 vs 1.8 MW on K3L)

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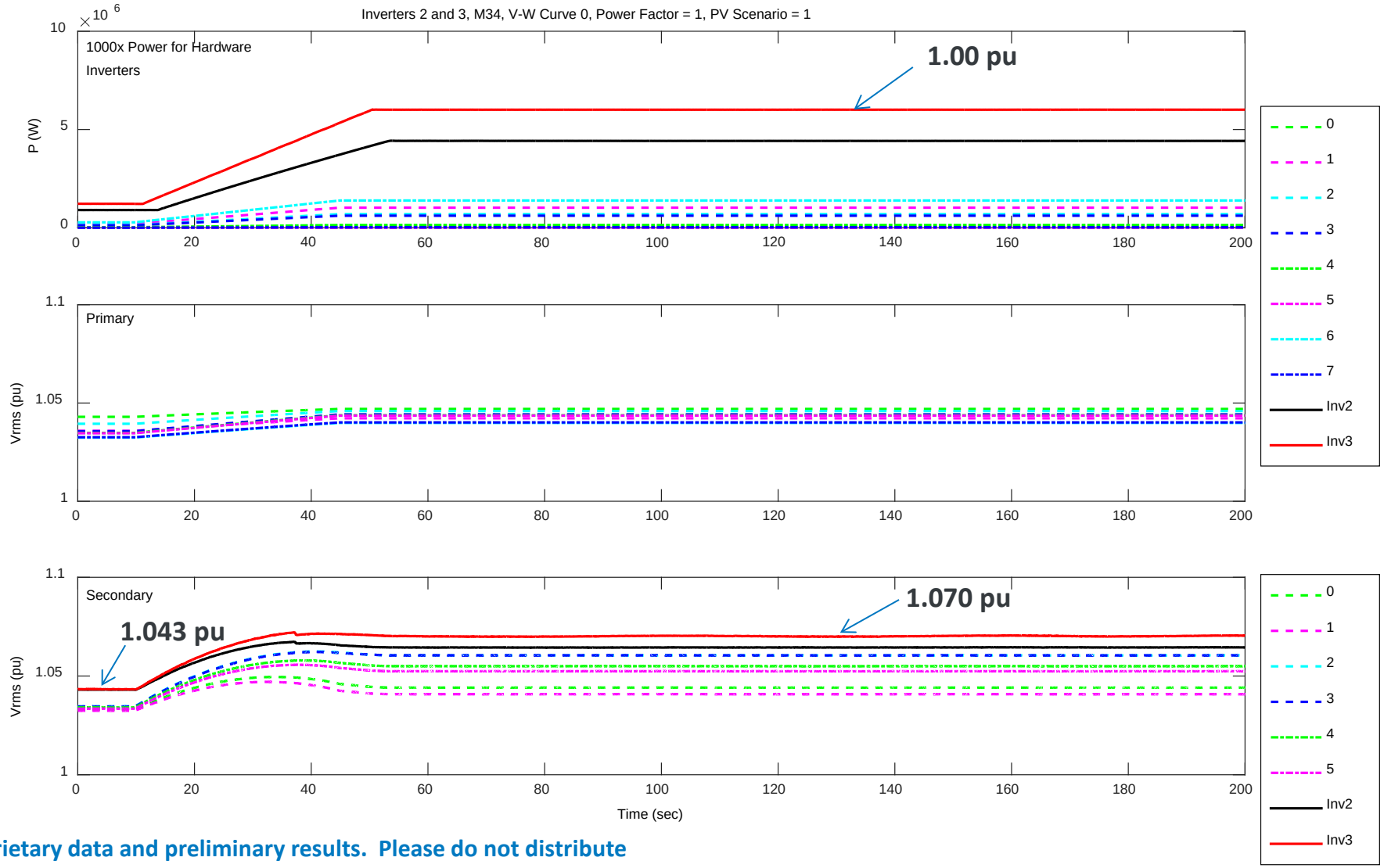
Volt-watt test example, Inverter 2&3, M34 circuit

Year 2016, no retrofit, no V-W, unity PF, (baseline test)



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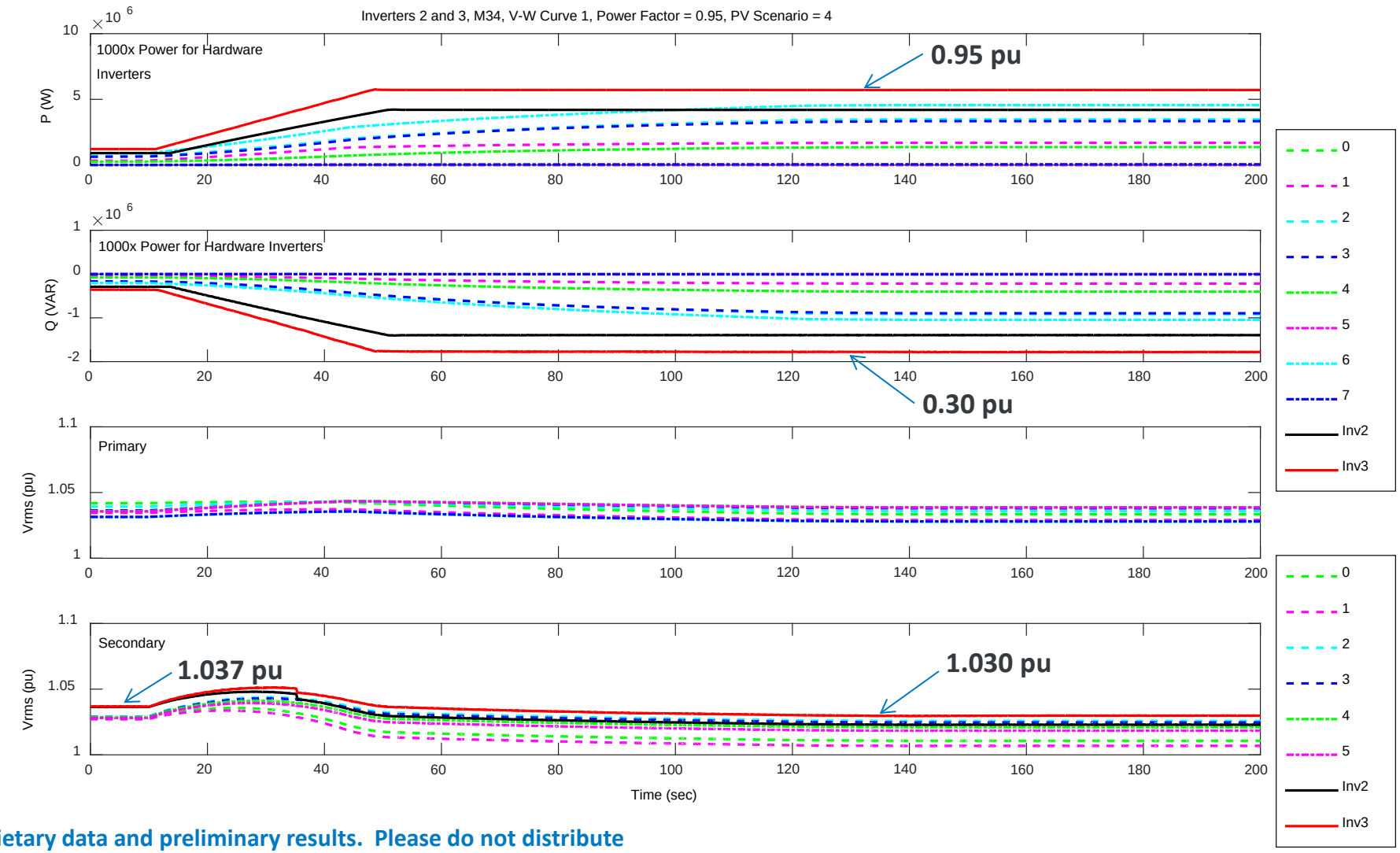
Volt-watt test example, Inverter 2&3, M34 circuit

Year 2019, no retrofit, moderate V-W (P_{max} mode), 0.95 PF



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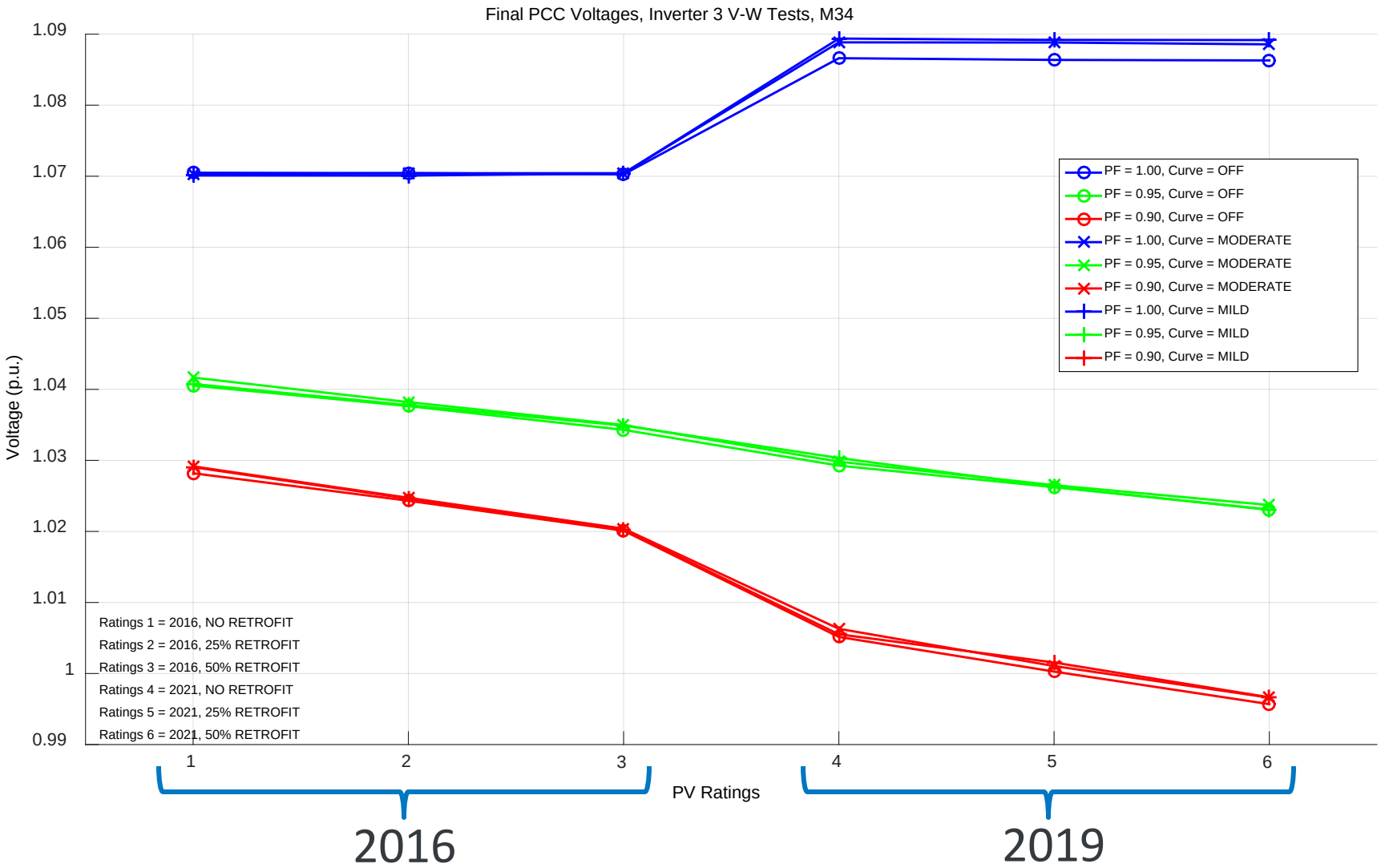
Summary of Inverter 2&3 volt-watt tests, M34 circuit



Fixed PF has the dominant impact for this circuit.

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Summary of Inverter 2&3 volt-watt tests, K3L circuit

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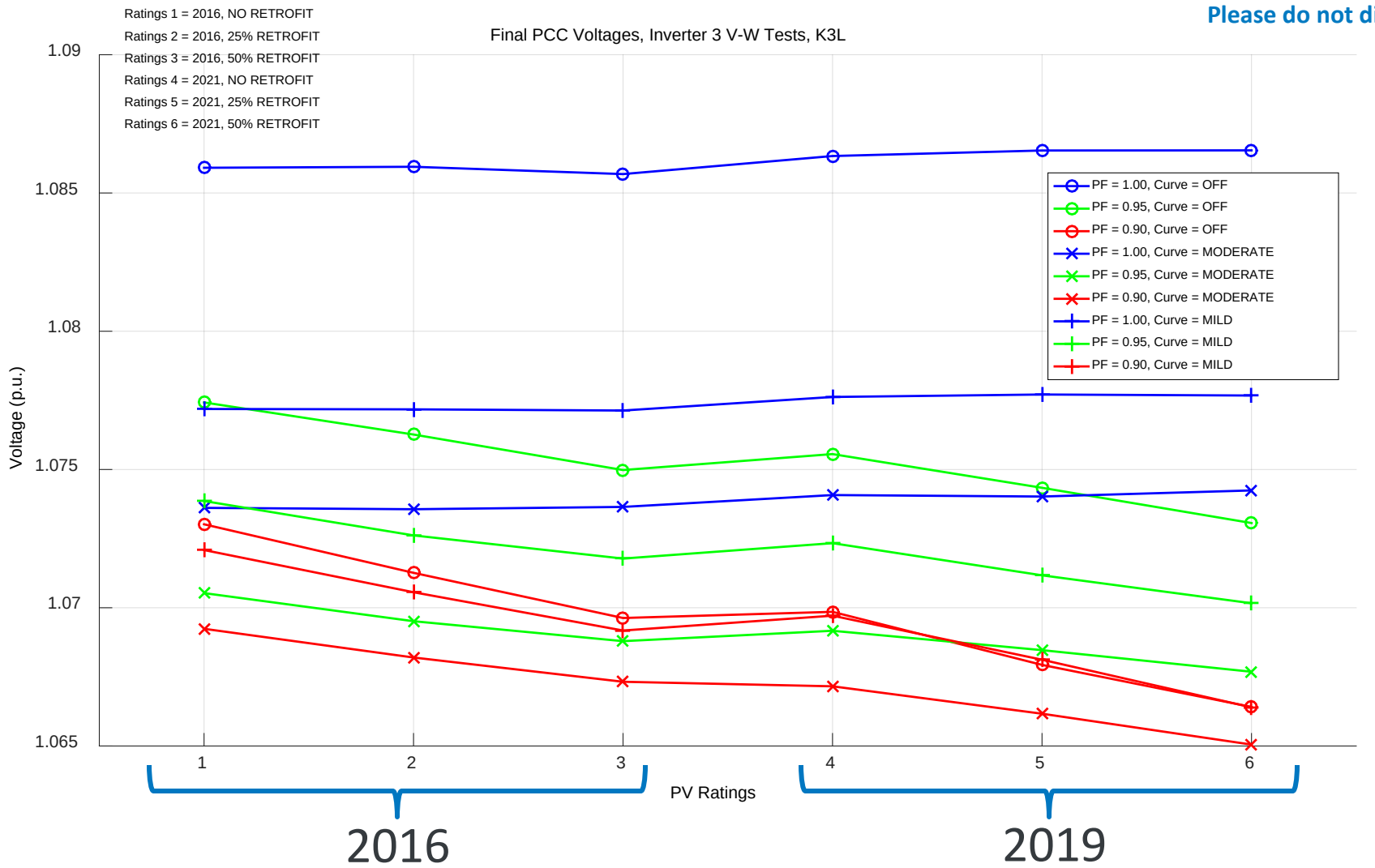
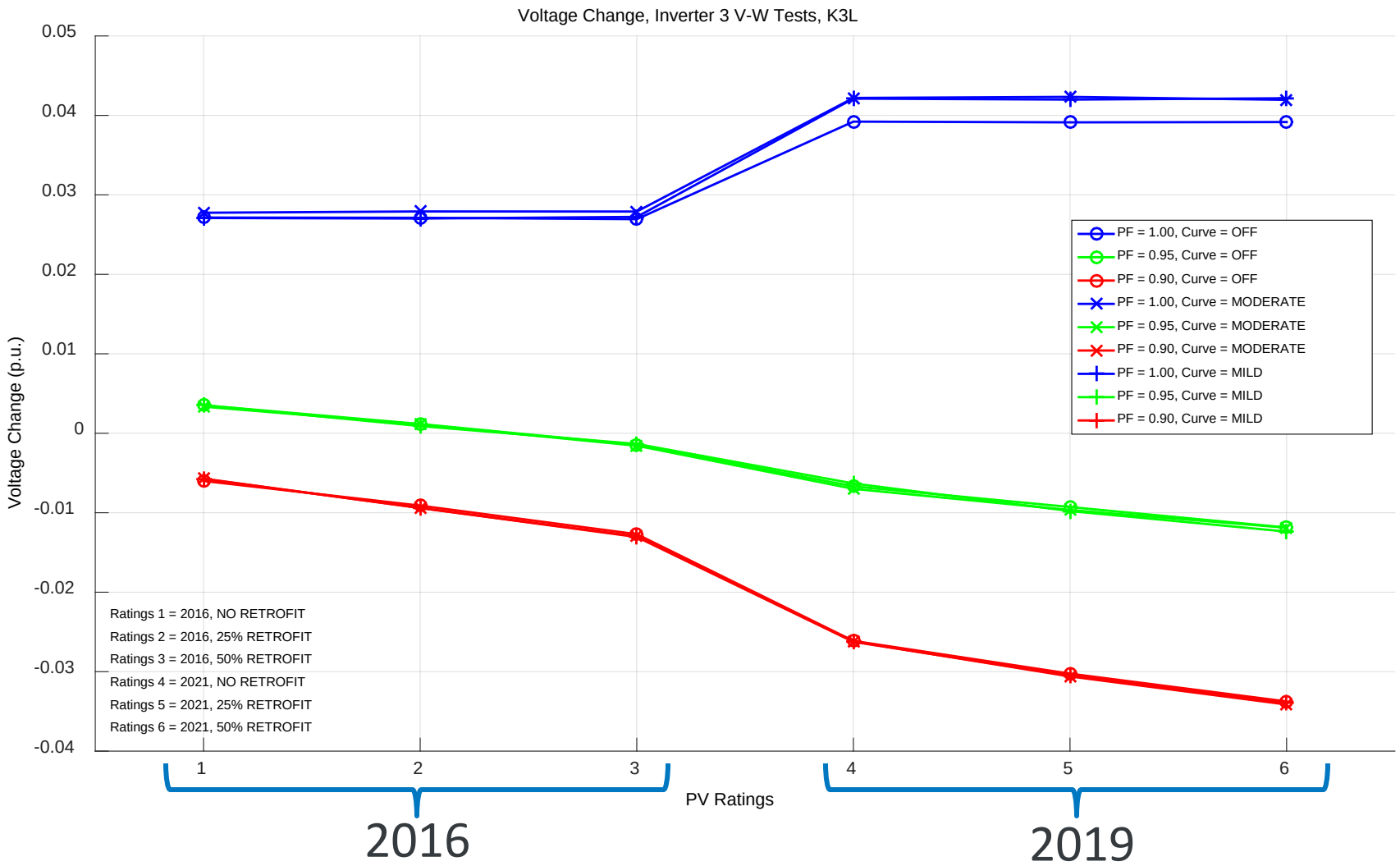


For K3L, both V-W and fixed PF have significant impact, but…

Summary of Inverter 2&3 volt-watt tests, K3L circuit – Voltage change

Voltage change from beginning till end of test:



Fixed PF has dominant impact on *voltage change*.

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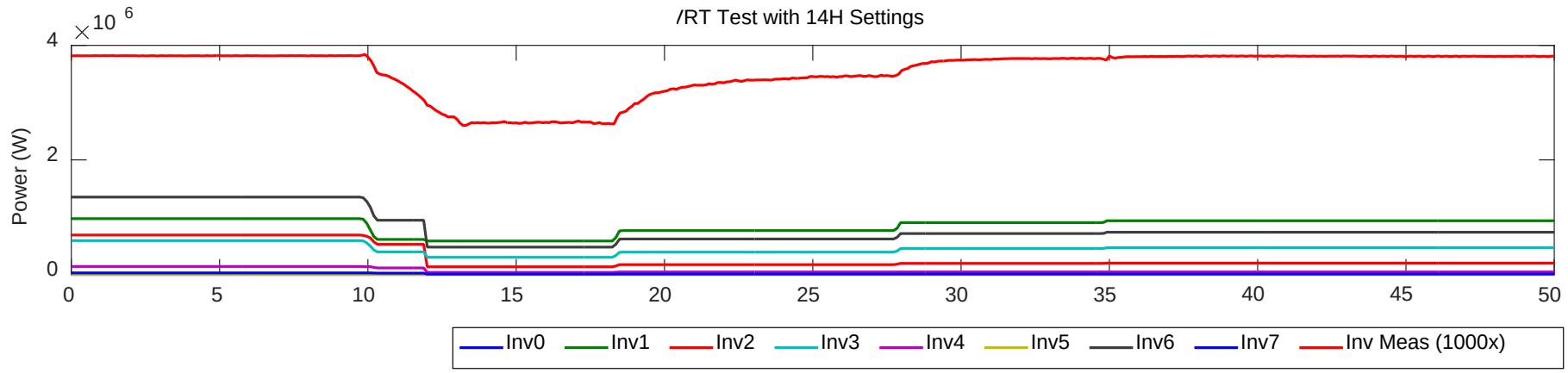
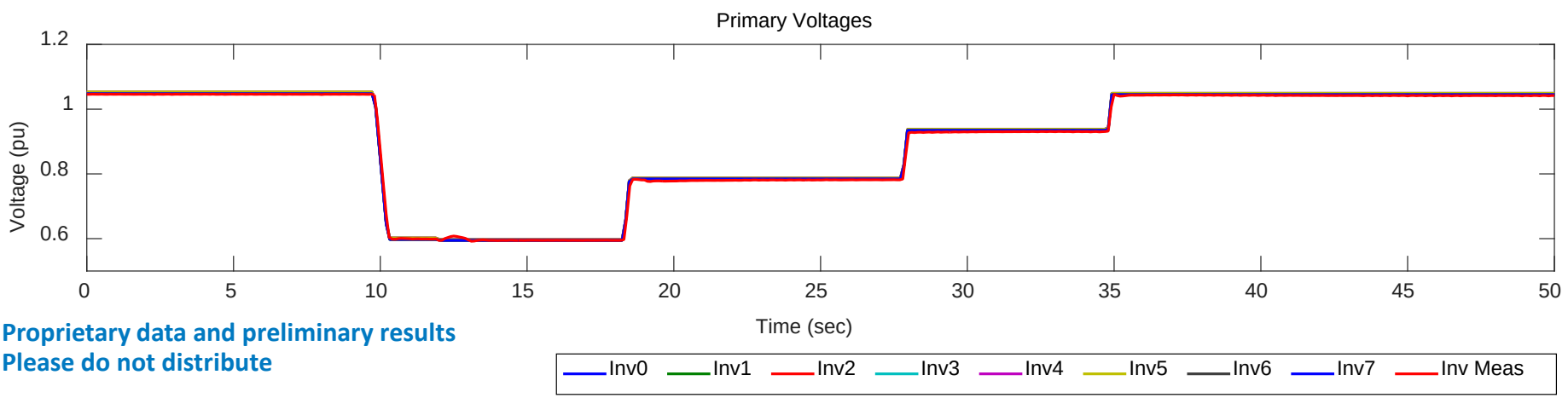
Voltage ride-through PHIL test example (Inverter 1)

- Event tests all LVRT levels
- Hardware inverter stays online. Modeled legacy inverters trip





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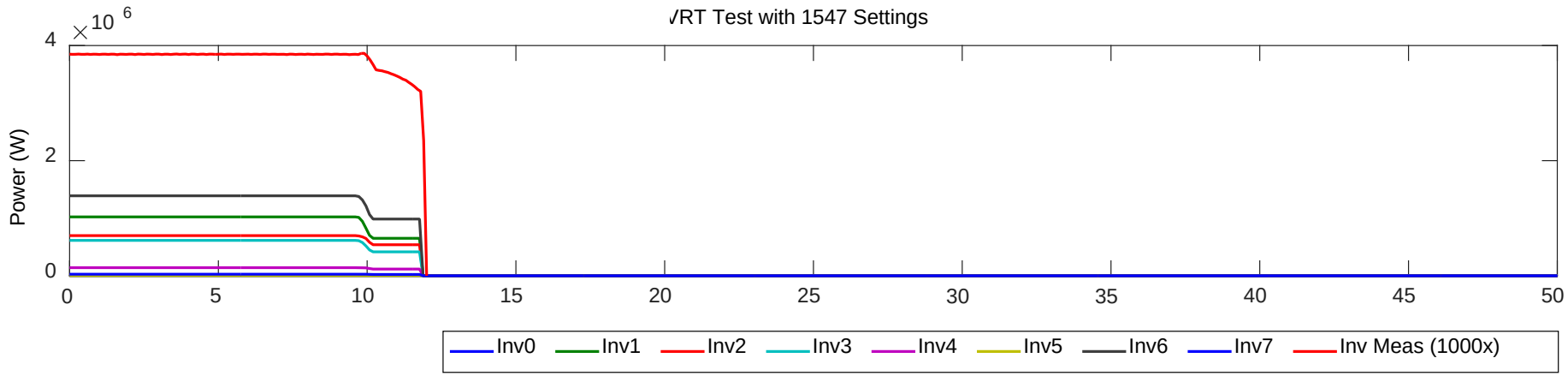
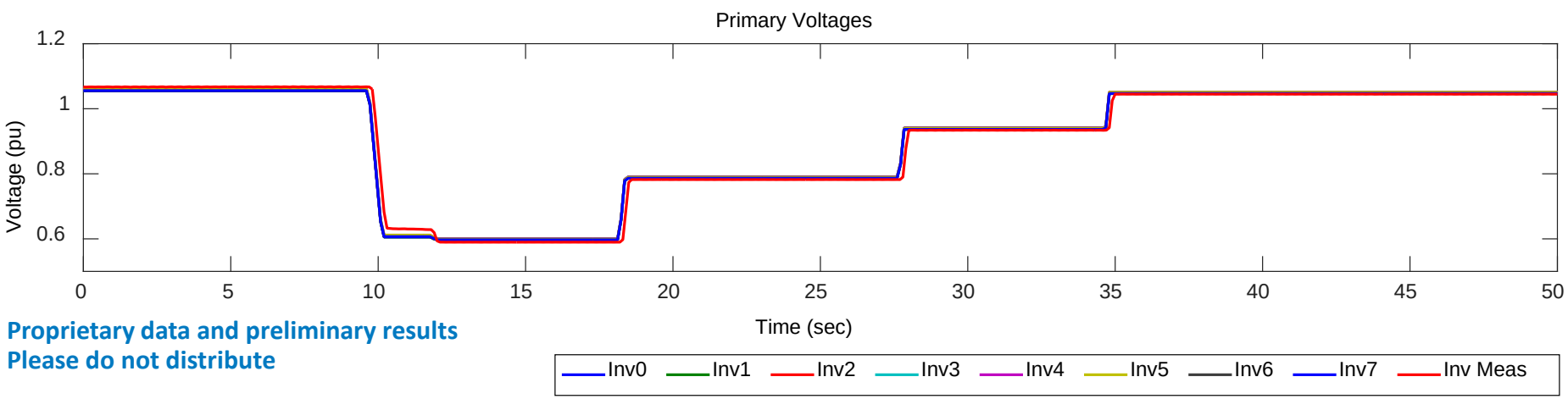
Voltage ride-through disabled

- Same event
- All inverters trip





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Conclusions: Volt-watt and fixed PF

- All inverters were capable of simultaneous V-W and fixed PF
- PHIL tests showed V-W has significant impact on voltage in some cases, but fixed PF tended to have a larger impact.
  - However, non-unity PF may increase system losses, and requires vars to be sourced by utility (even if voltages are not high).
- A moderate V-W curve had substantial impact on voltage, especially when combined with 0.95 PF.
- The impact of both V-W and fixed PF is highly dependent on the proportion of total inverters participating.
- High feeder head voltages were typically needed to produce high secondary voltages. => Adjusting LTC controls *may* help

The fine print:

- Volt-watt tests were intentionally designed to create high voltages. Actual feeder voltages will vary.
- These tests focused on one specific secondary per feeder. Results at other locations will vary. (See VROS CRADA)

Proprietary data and preliminary results
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Next steps

- Advanced inverter test plan:
  - NREL deliver final report to HECO
  - HECO deliver to PUC by Dec 15
- Voltage regulation operational strategies (VROS) study
  - Design simulation scenarios and collect data
  - Conduct simulations to select combinations of volt-watt, volt-var, and fixed PF
  - Quantify impacts of selected combinations on annual PV kWh production and feeder voltage profiles
  - Complete in Spring 2017
- DOE GMLC work
  - Simulation and testing of frequency-watt (both presently available function and possible future advancements)
  - Complete in Fall 2017

Thank you!

Questions welcome

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Extra Slides

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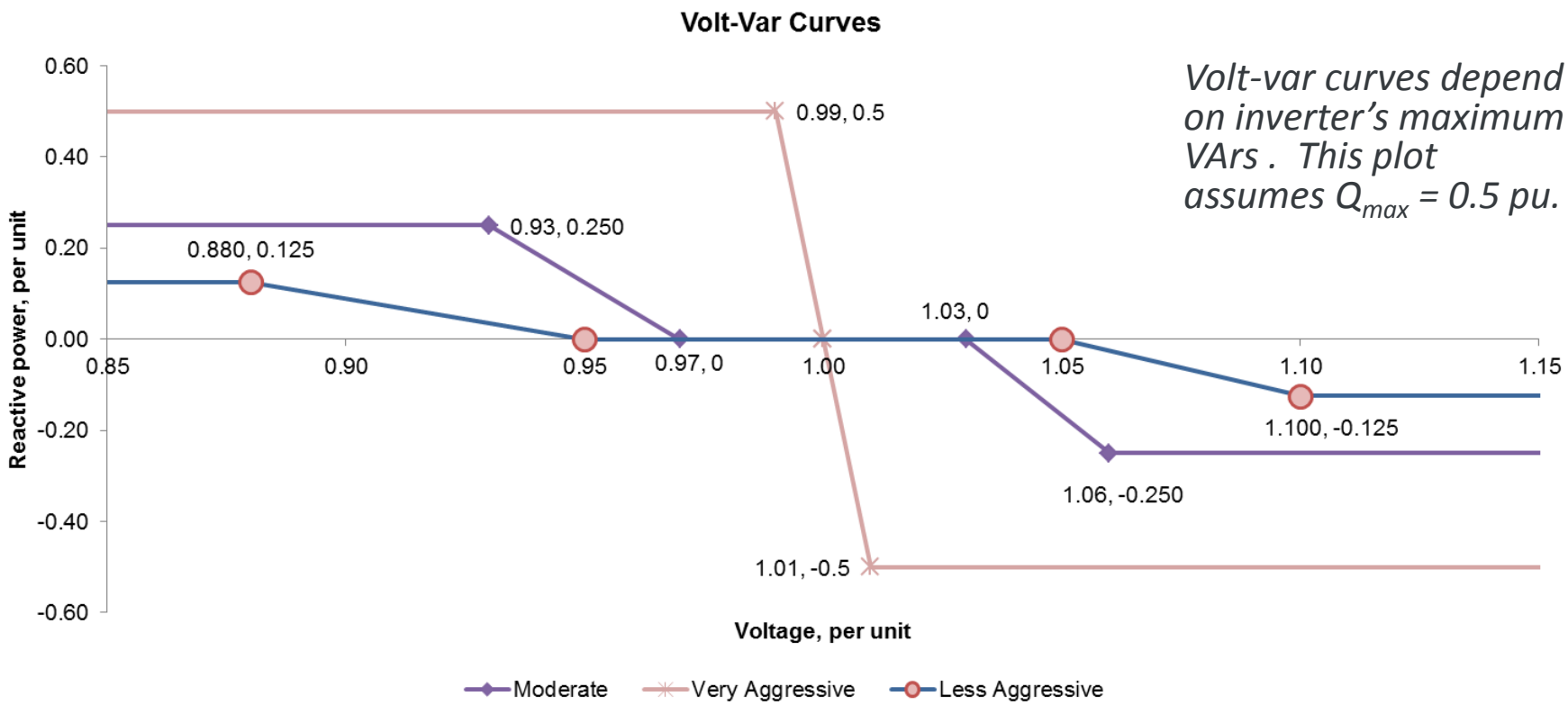
Baseline testing: Volt-var

- Based on UL 1741 SA volt-var test
- Three curves tested, plus inductive and capacitive offsets:

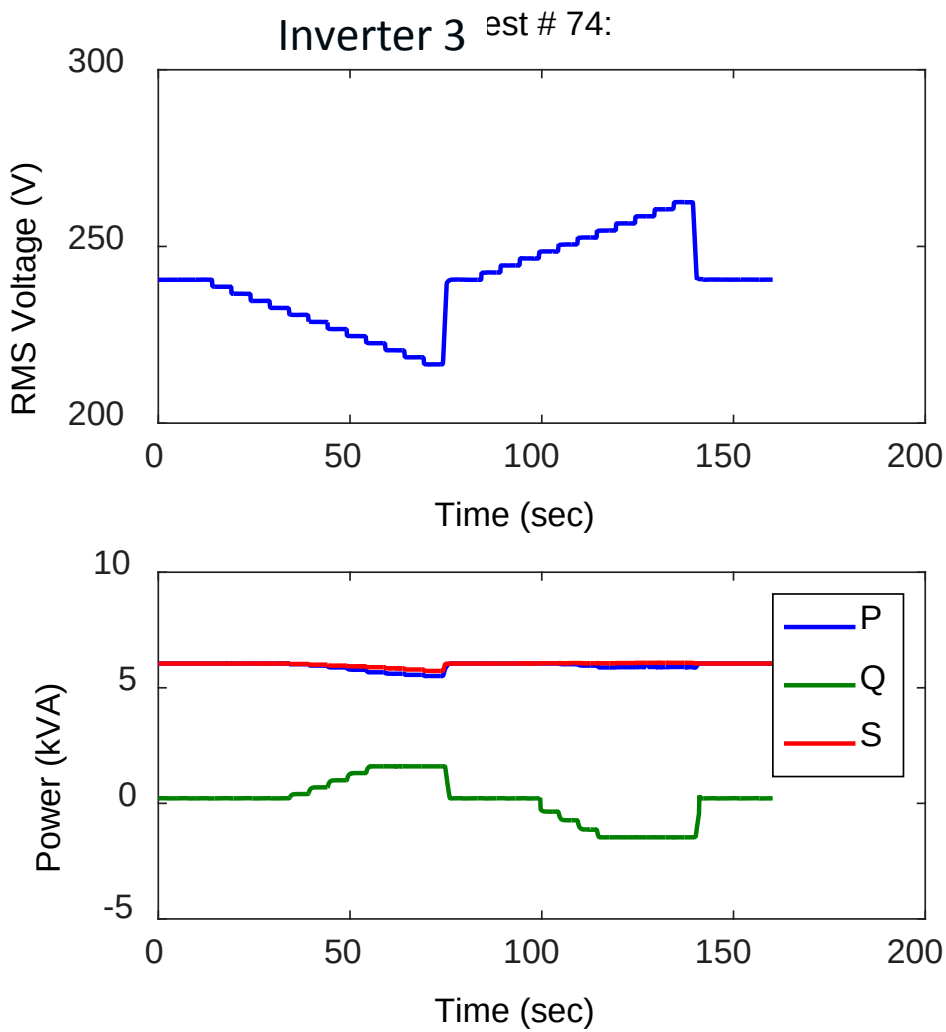


Volt-var curves depend on inverter's maximum VArs . This plot assumes Q_{max} = 0.5 pu.

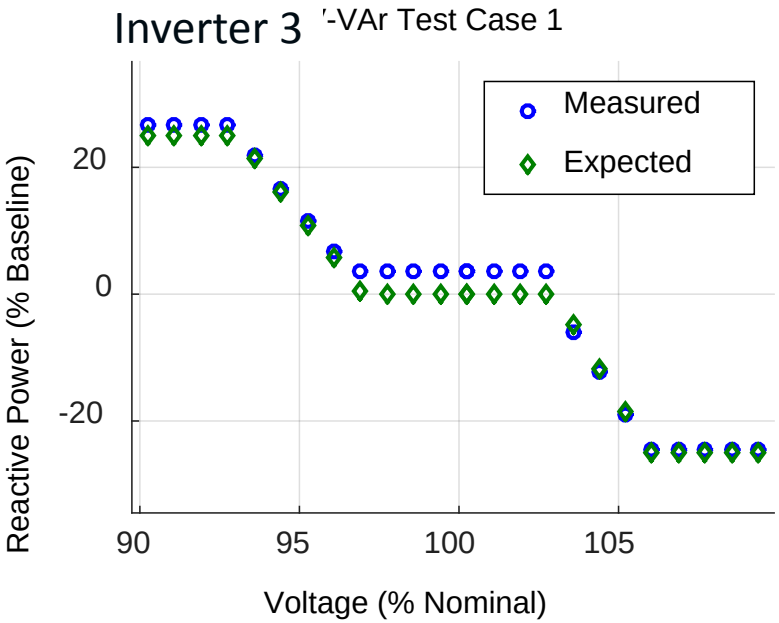
- Tested at various power levels
- Varying time responses tested
- 29 test series, 950 total points tested

Proprietary data and preliminary results
Please do not distribute

Volt-var example



- Moderate curve
- 1-second response time
- Full power



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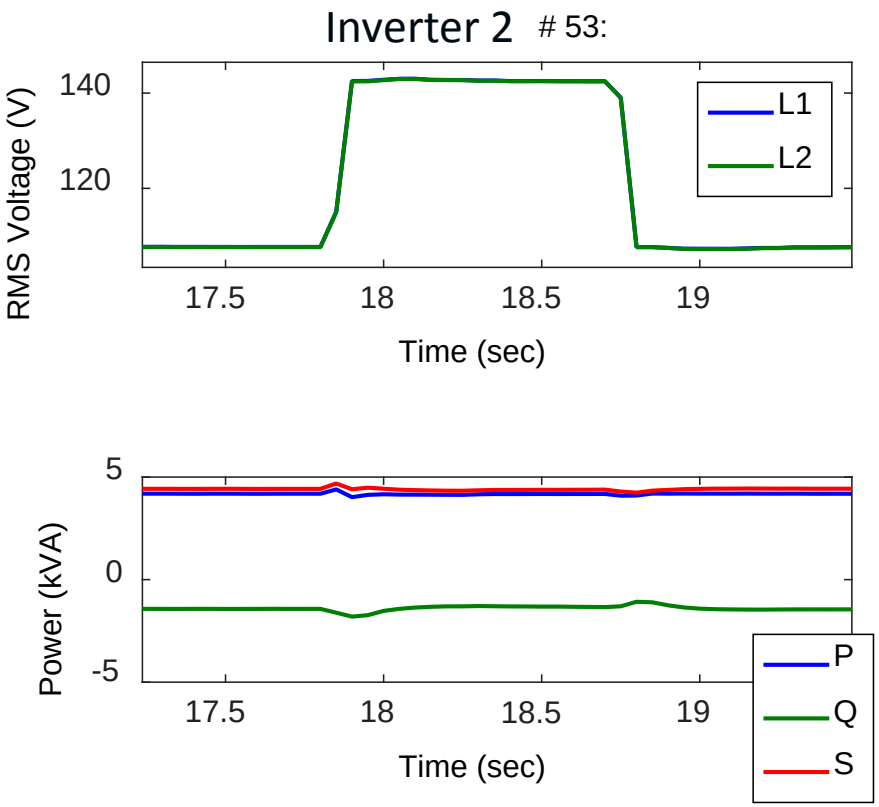
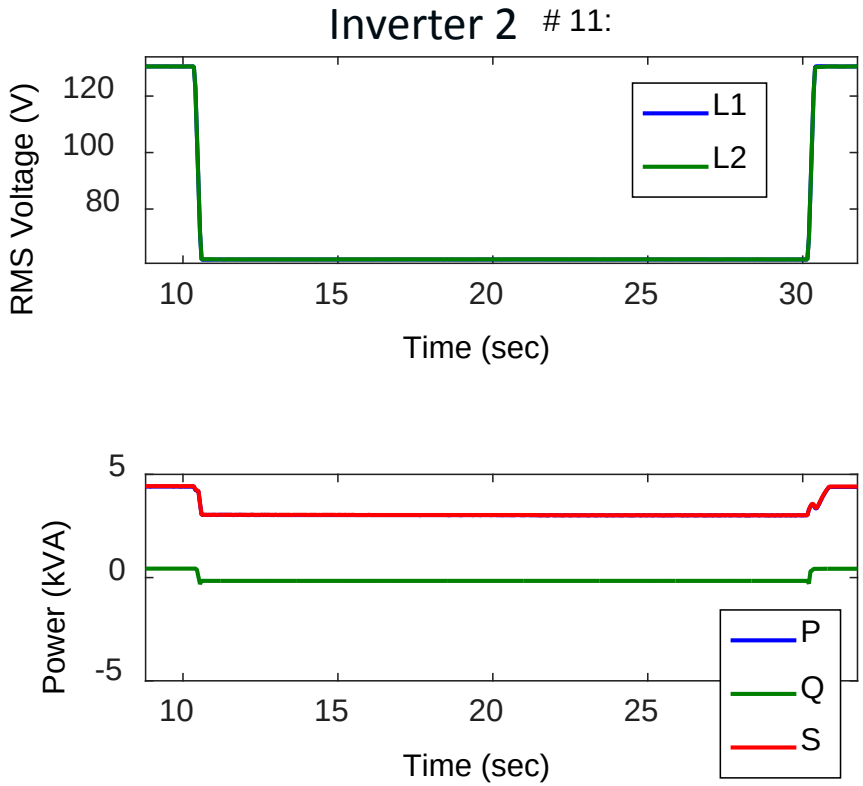
Voltage ride-through examples

OVR1: 110% < V < 120% for 1 s



UVR1: 70% < V < 88% for 20 s



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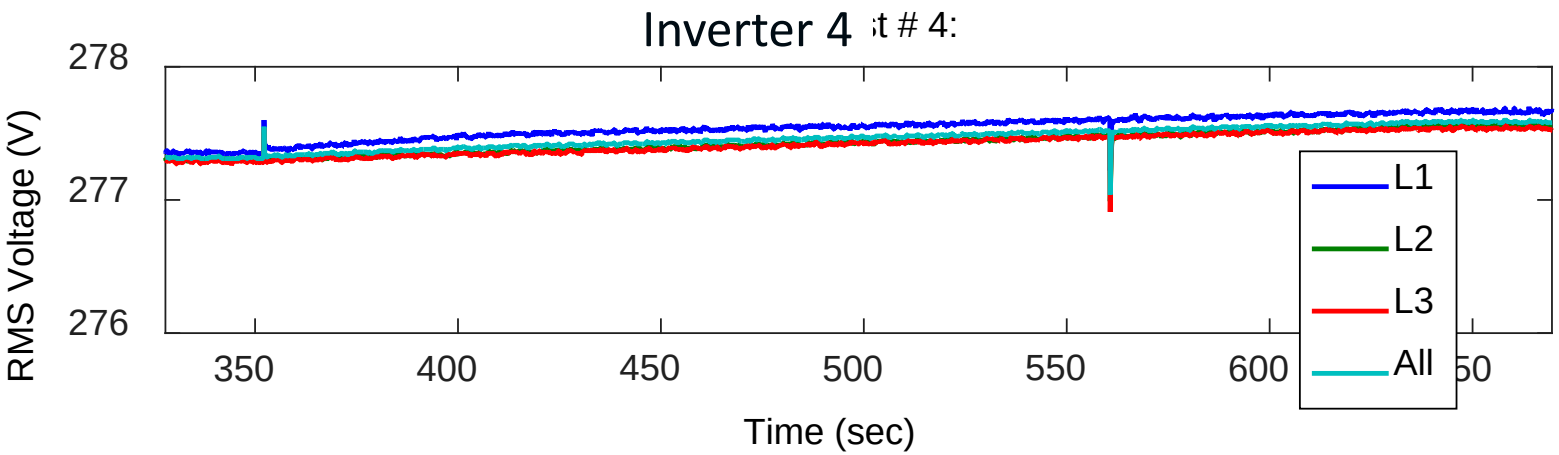
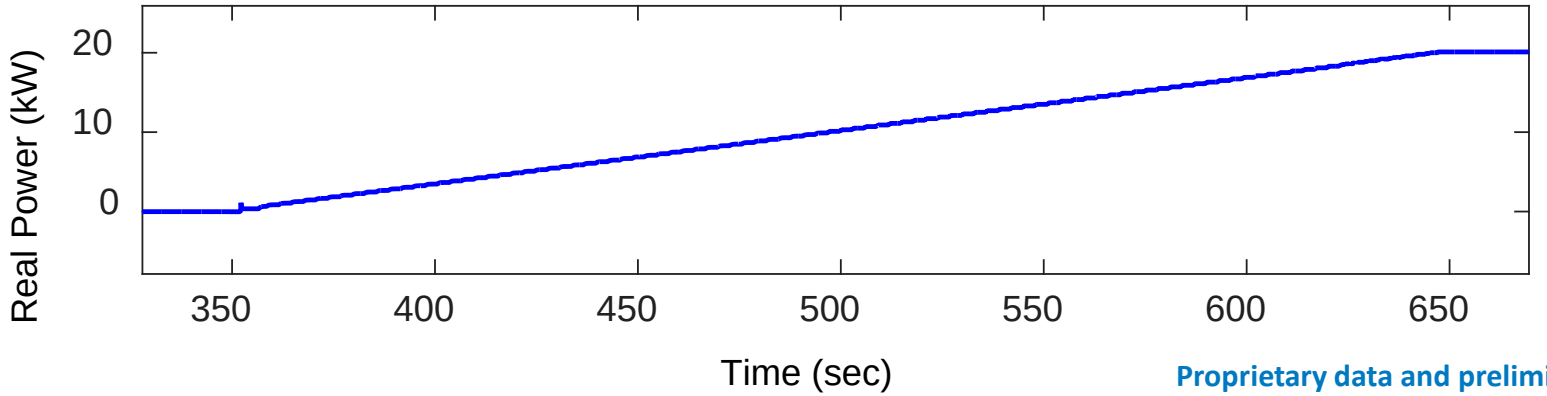
Baseline testing: Soft-start and ramp rate control

- Based on UL 1741 SA tests
- Soft-start tested at three rates:
  - Fastest available
  - 0.33% per second
  - Slower ramp rate (typically slowest available)
- Ramp rate control (normal operation) tested at three rates:
  - Fastest available
  - 0.33% per second
  - Slower ramp rate (typically slowest available)
- Legacy Enphase inverters also tested (default values only)
- Ramp rate control was a new function for some inverters

Soft-start example

Soft-start ramp-rate: 0.33% per second:





Proprietary data and preliminary results
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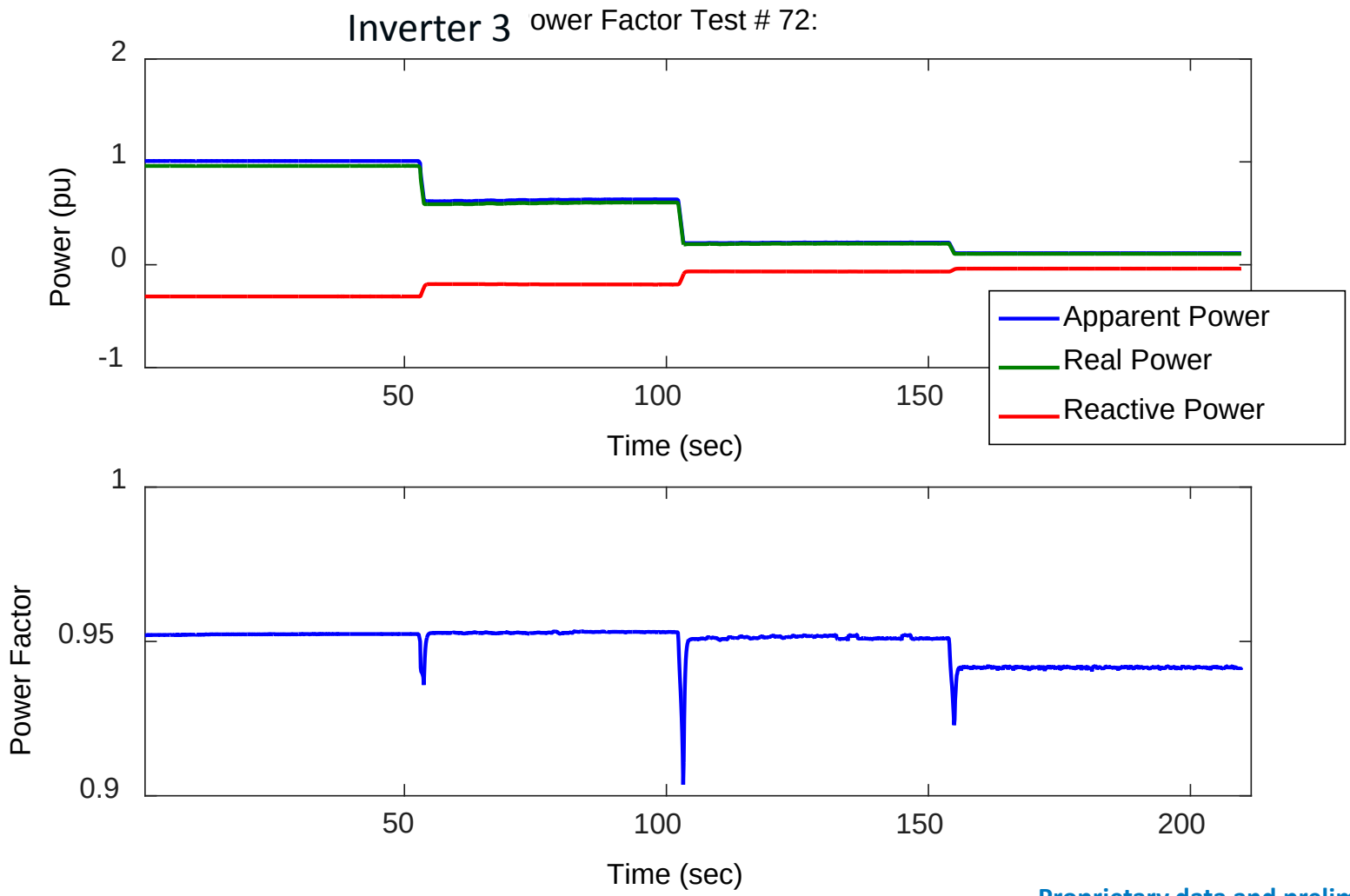
Baseline testing: Fixed power factor

- Based on UL 1741 SA tests
- Not in original test plan – added to allow for PHIL testing of volt-watt with fixed PF.
- Tested 0.9 and 0.95 PF
- 0.95 PF tested using Oahu profile
- Tested at 100%, 60% and 20% power
- Power factor accuracy typically only guaranteed down to 20% of rated real power. Tested at 10% power as well to characterize behavior.
  - Commanded power factors still maintained at 10% power, but accuracy slightly reduced (e.g. 0.94 instead of 0.95)

Fixed power factor example



Proprietary data and preliminary results
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