Smart Inverter Utility Experience in Hawaii

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(Testing and Validation of IEEE 1547 DER Interconnection Requirements)

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Outline

1. Background – why Hawaii?
2. Selected technical challenges
3. Case study – volt-var and volt-watt
4. Case study – frequency-watt

Why Hawaii?

- Highest distributed PV capacity of any state (as percentage of load)
  - ~50% of peak load
  - High electricity costs for geographic reasons
  - Historical PV incentives
- First state to mandate a 100% renewables goal (100% by 2045)
  - Distributed PV will play a major role due to land constraints
- Peak island-wide inverter penetrations of 50%-80% in 2018 (depending on island)

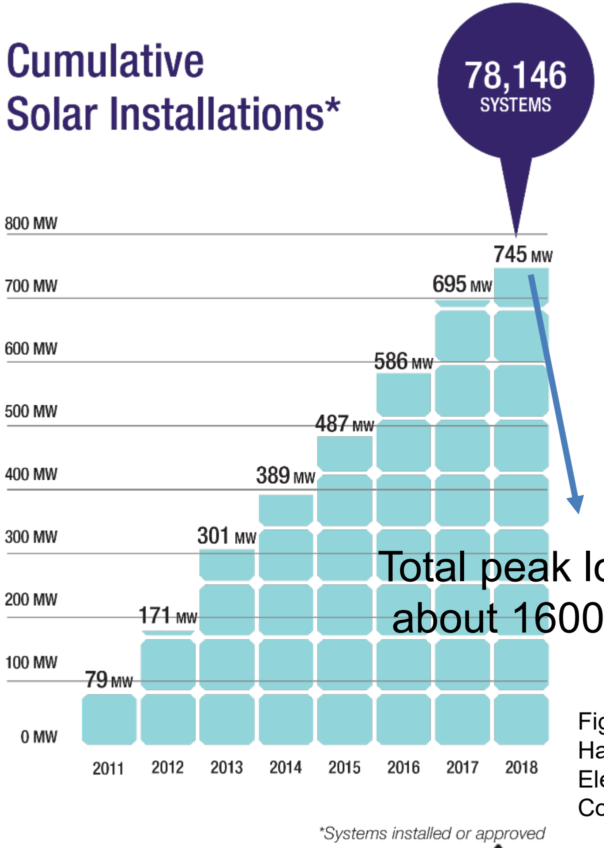
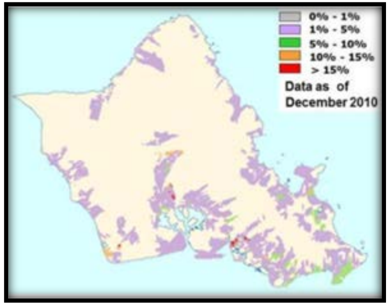


Figure Credit: Hawaiian Electric Companies

Why Hawaii?

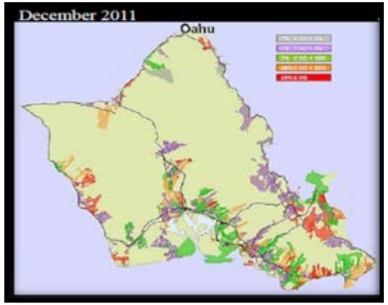
- Hawaii's Rule 14H (DER interconnection) has led the way in smart inverter functionality adoption in the U.S. (along with California's Rule 21)
- Hawaii required some advanced functionality even before it could be tested and certified under UL 1471 SA
- Advanced inverter functions currently required in Hawaii:
  - Voltage and frequency ride-through
  - Transient overvoltage mitigation (self-certification)
  - Volt-var control
  - Frequency-watt control
  - Soft-start
  - Ramp-rate control
  - Volt-watt (currently optional; under discussion for blanket activation)
  - Remote upgrade capability
- So far, no requirement for communications between utility and inverter

Distribution PV Penetration (Oahu Example)



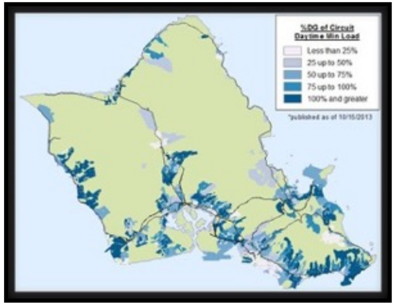
<u>2010</u>

Many feeders
> **1%**
Gross
daytime
minimum
load (GDML*)



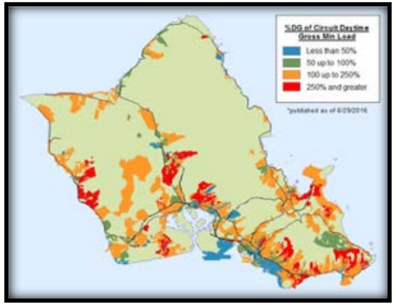
<u>2011</u>

Many feeders
> **15%**
GDML



<u>2013</u>

Many feeders
> **100%**
GDML



<u>2016</u>

Many feeders
> **250%**
GDML

*GDML = The minimum feeder load the utility would see during daylight hours if PV were not present

Slide courtesy of Adam Warren, NREL. (Modified)

System-Wide PV Penetration (Oahu Example)

Generating Facilities

These maps show existing and planned generating facilities and the maximum potential power in megawatts (MW) they can produce.

F **FIRM GENERATION:** Energy available on demand, which can be adjusted as needed.

V **VARIABLE GENERATION:** Energy that may not always be available or controllable.

BESS: Battery Energy Storage System

- BIOFUELS
- BIOMASS
- GEOTHERMAL
- HYDRO
- CUSTOMER-SITED SOLAR
- GRID-SCALE SOLAR
- STORAGE
- WASTE TO ENERGY
- WIND
- COAL
- OIL
- OIL (DEACTIVATED)

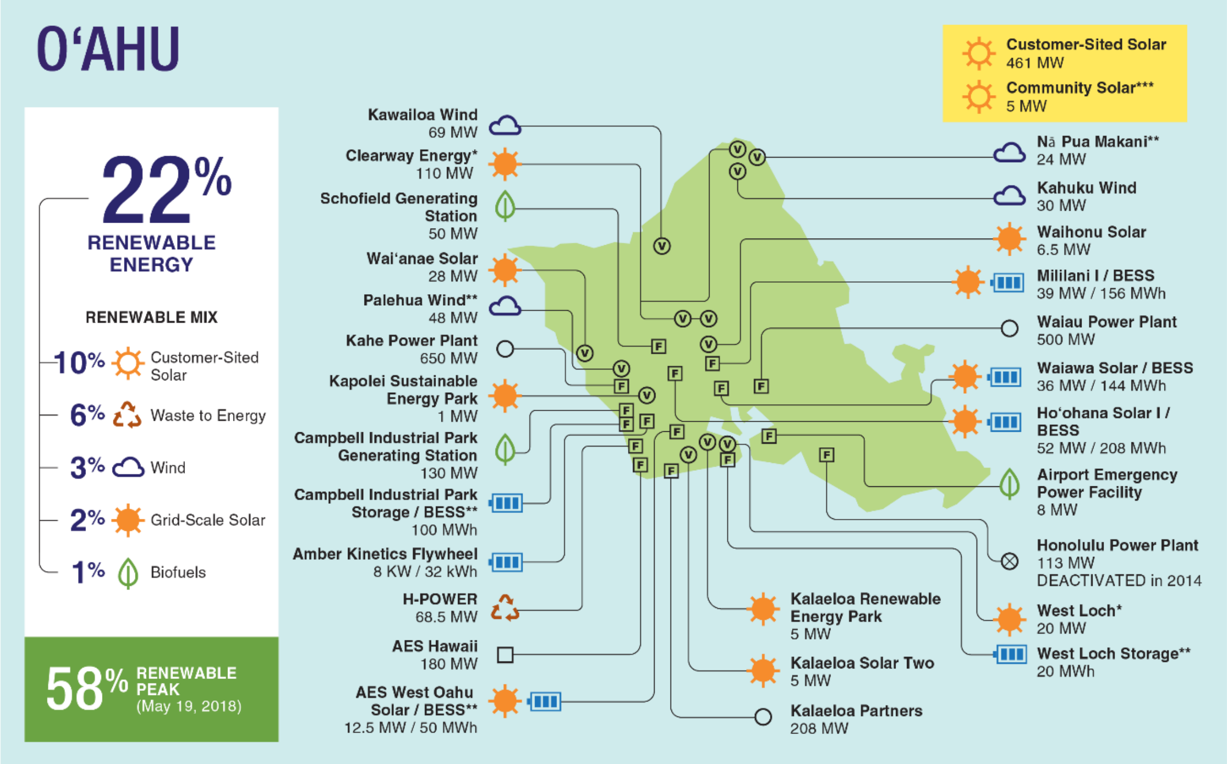


Figure Credit:
Hawaiian Electric Companies

System-Wide PV Penetration (Maui Example)

Generating Facilities

These maps show existing and planned generating facilities and the maximum potential power in megawatts (MW) they can produce.

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STORAGE
WASTE TO ENERGY
WIND
COAL
OIL
OIL (DEACTIVATED)

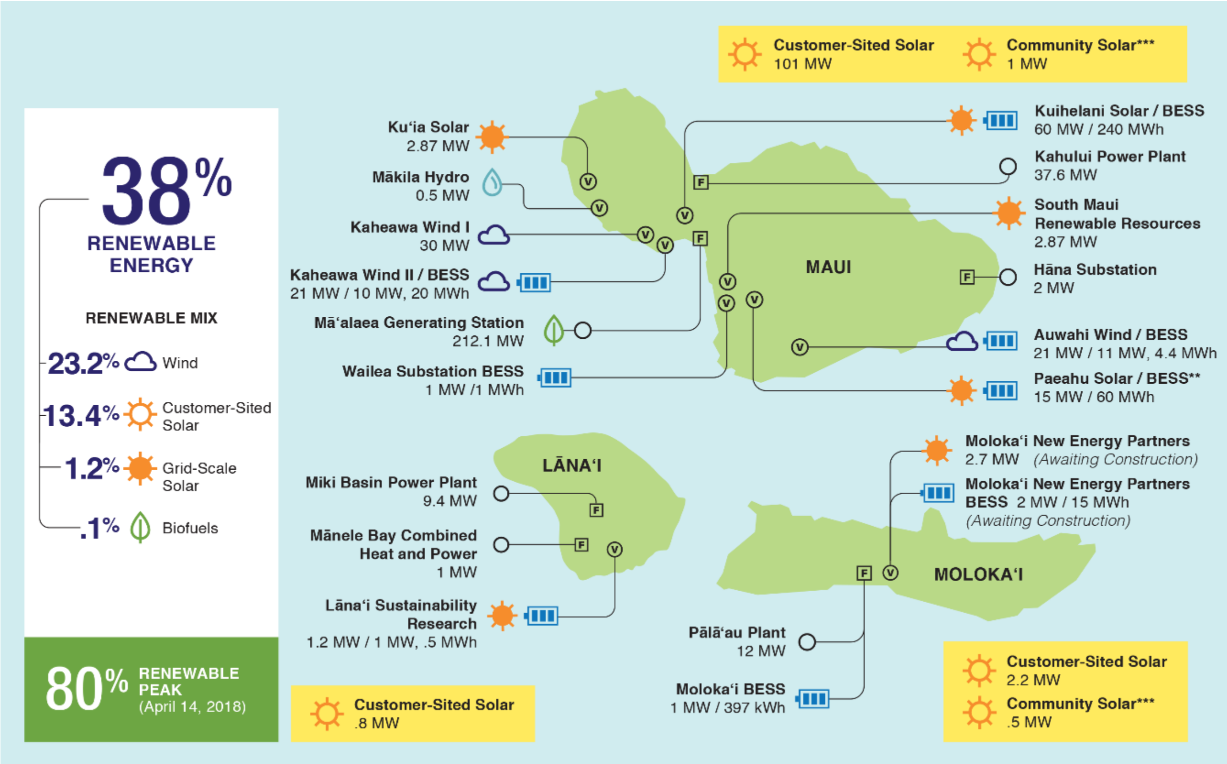

Figure Credit:
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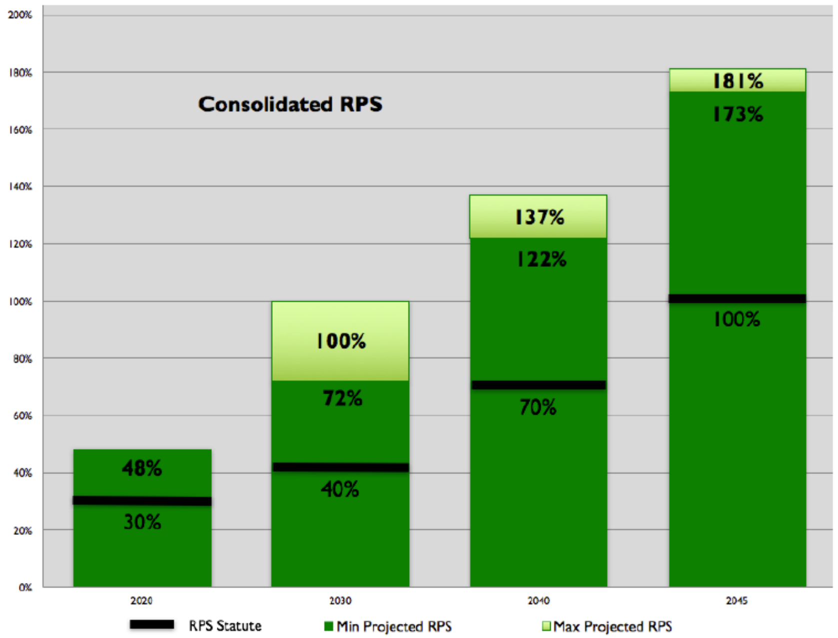
Future Expected Renewables and PV

Total renewable penetration:

$$\equiv \frac{renewable\ kWh\ generated}{utility\ kWh\ sold}$$



Total distributed PV

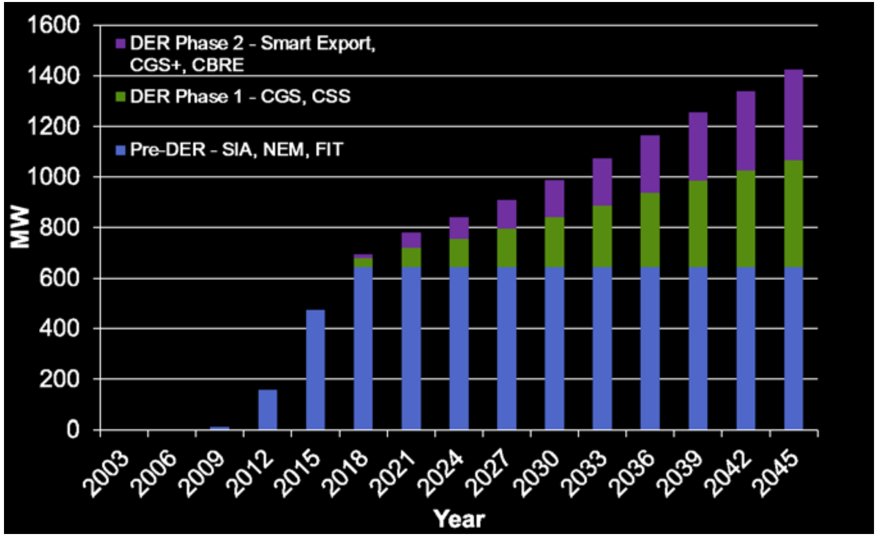


Figure Credits:
Hawaiian Electric Companies

Outline

1. Background – why Hawaii?
2. **Selected technical challenges**
3. Case study – volt-var and volt-watt
4. Case study – frequency-watt

Selected Technical Challenges

Existing and past challenges

- Steady-state voltage issues
- Islanding and transient voltage issues (GFOV/TOV, LROV/TrOV)
- Deterioration of frequency response (reduction of inertia, PFR, regulation)
- Lack of visibility and controllability of DER and grid-edge conditions
- Extremely difficult to change settings of legacy inverter fleet (due to logistical, cost, and policy challenges)
- …

Emerging and future challenges

- Operation of very low inertia grids with 80-100% inverter-based generation at times
- Balancing load and variable generation across multiple timescales
- Control of thousands of individual customer-owned DERs
- Cybersecurity of DERs (manufacturer communications; possible future utility/aggregator comms)
- …

Solutions: Voltage and Frequency Ride-through

- Activating relatively wide voltage and frequency ride-through capabilities was step #1 towards successfully operating a grid with high levels of PV

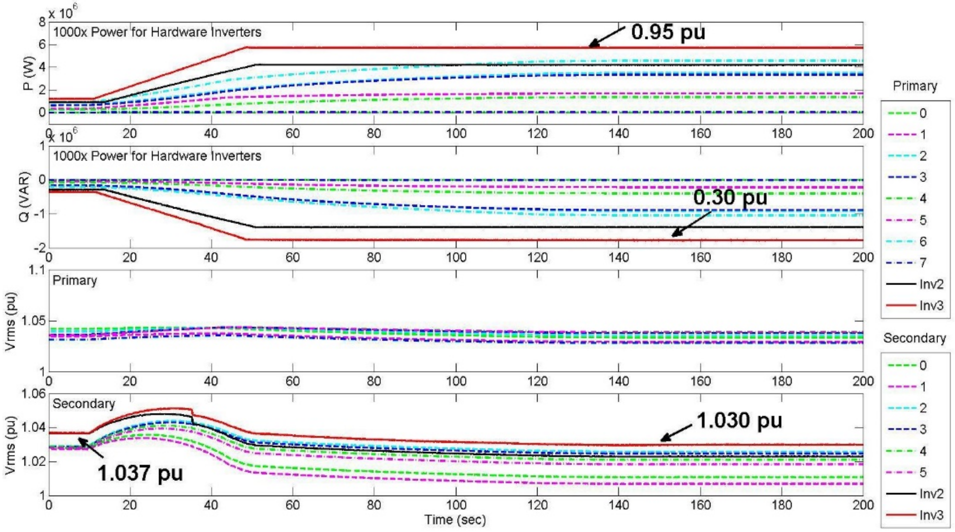
- "Legacy" inverters that don't have ride-through capability (or can't easily have ride-through enabled) are an ongoing system stability problem
  - *Lesson learned: require voltage and frequency ride-through capability and relatively wide trip settings early to avoid future problems when more DERs come online*
  - *This required compromises between transmission and distribution planners*

- By working with Enphase, Hawaiian Electric was able to retroactively widen voltage and frequency trip settings for many legacy DERs
  - This was a major effort and would be even harder in a market not dominated by one manufacturer
  - Would not have been possible without Enphase's communication solution, which many other inverter manufacturers may not have

Solutions: Establishing Trust in Smart Inverters

- In 2015 and 2016, HECO and NREL tested advanced functionality of several inverters:
  - V and F ride-through
  - Ramp rate control and soft start
  - Fixed power factor
  - Volt-var and volt-watt
- Tests conducted at NREL's ESIF*:
  - Baseline tests to characterize inverter responses (*pre UL1741 SA*)
  - Power HIL tests to validate inverter behavior while connected to a real-time simulation of HECO's system
- Conclusions:
  - Inverters largely performed as expected
  - Anomalous behavior was reported to manufacturers and fixed (firmware upgrade)
  - Smart inverter functions generally benefit grid operations

Example power HIL test of two inverters at fixed PF of 0.95 (absorbing) in volt-watt control mode



https://www.nrel.gov/docs/fy17osti/67485.pdf

*ESIF = Energy Systems Integration Facility, DOE's flagship lab for smart grid and related testing.
**HIL = Hardware-in-the-loop: A computer simulation running in real-time linked to actual hardware.

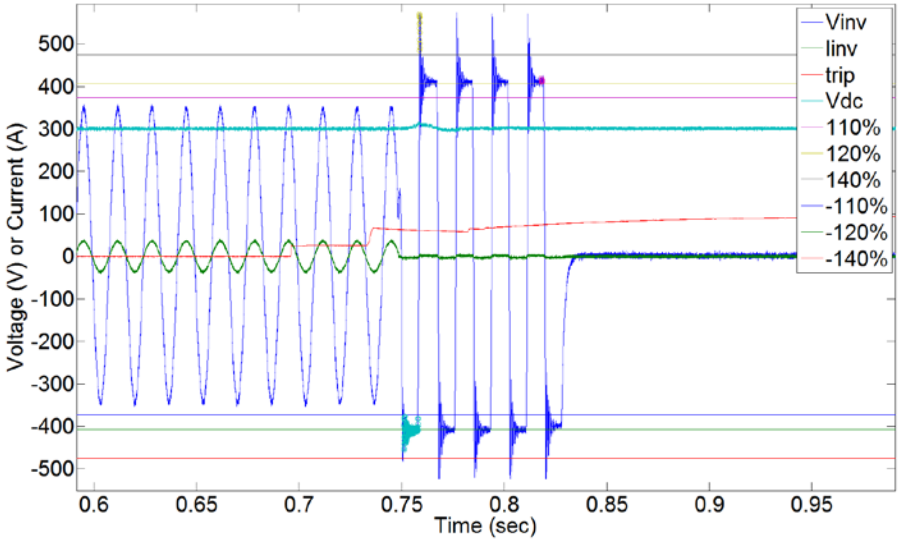
Solutions: LROV

- As feeders began backfeeding substations, *load rejection overvoltage* became a concern
- SolarCity, HECO, and NREL collaborated to test several inverters' load rejection responses
- FIGII* developed consensus test procedure to quantify LROV response
- NREL evaluated load rejection response of five inverters in ESIF lab
- Typically, inverters disconnected very quickly, avoiding potentially damaging overvoltage

Outcomes:

- HECO required all inverters be tested for LROV prior to interconnection, and increased feeder PV limit from 120% of GDML to 250% of GDML
- LROV test now incorporated into draft IEEE 1547.1 (and so will become part UL 1741 in 2020)

Example LROV test waveform at 10:1 generation:load ratio



http://www.nrel.gov/docs/fy15osti/63510.pdf

*Forum on Inverter Grid Integration Issues, an industry group (formerly ITFEG)

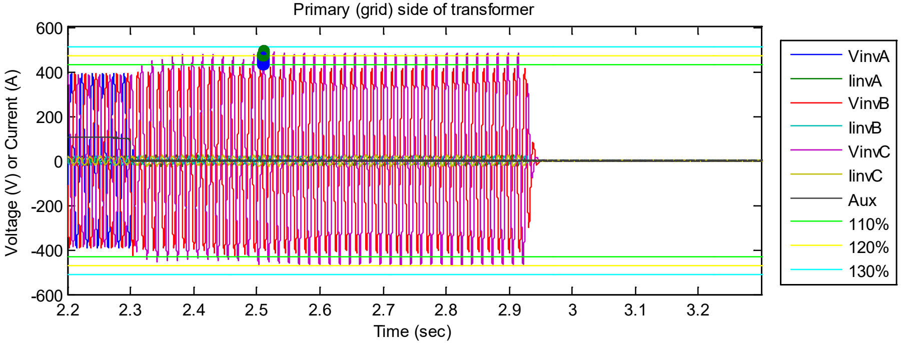
Solutions: GFOV

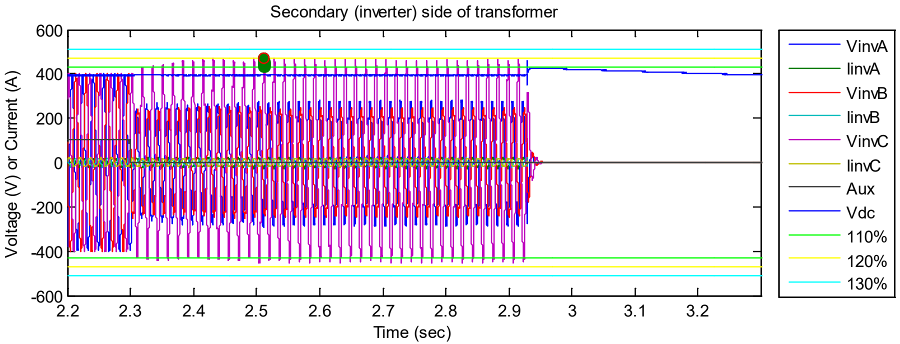
- As high-PV feeders began backfeeding substations, *ground fault overvoltage* became a concern
- SolarCity, HECO, and NREL collaborated to test several inverters' ground fault responses
- FIGII developed consensus test procedure to quantify GFOV response
- NREL evaluated three inverters in ESIF lab

Findings:

- Inverters do not maintain line-line voltages and typically disconnect quickly, avoiding potentially damaging overvoltage, but may remain connected briefly when fault is masked by transformer
- Where a GFOV may occur in a location that could be islanded with balanced real and reactive power, minimal wye-connected load, and no zero-sequence continuity to the DER location, an analysis may be needed to evaluate the possibility of damage to surge arrestors

Example GFOV test waveforms with fault masked by D:Y transformer





See IEEE C62.92.6 for GFOV with inverters

http://www.nrel.gov/docs/fy15osti/64173.pdf

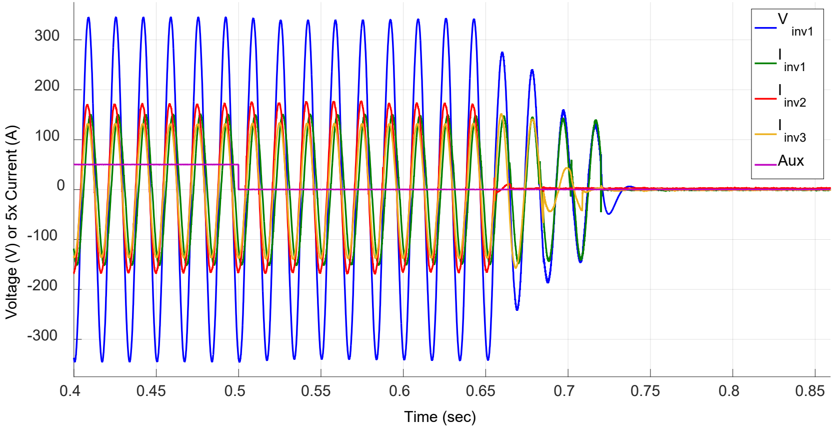
Solutions: Unintentional Islanding

- With rollout of ride-through (V and f) and other smart inverter functions, possible conflicts with inverter anti-islanding controls became a concern
- HECO, NREL and SolarCity tested the effects of ride-through, volt-var, and frequency-watt on three inverters' anti-islanding performance
- Tests included cases with multiple inverters connected at multiple neighboring locations on the same feeder

Outcomes

- No islands were found to extend beyond 0.7 seconds
- Volt-var and frequency-watt control had no statistically significant impact on island duration
- Ride-through tended to extend island duration by ~75 ms
- HECO relies on inverter anti-islanding in almost all cases. HECO recloser time settings are long enough to minimize the chance of out-of-phase reclosure

Example multi-inverter island test waveforms



https://www.nrel.gov/docs/fy16osti/66732.pdf

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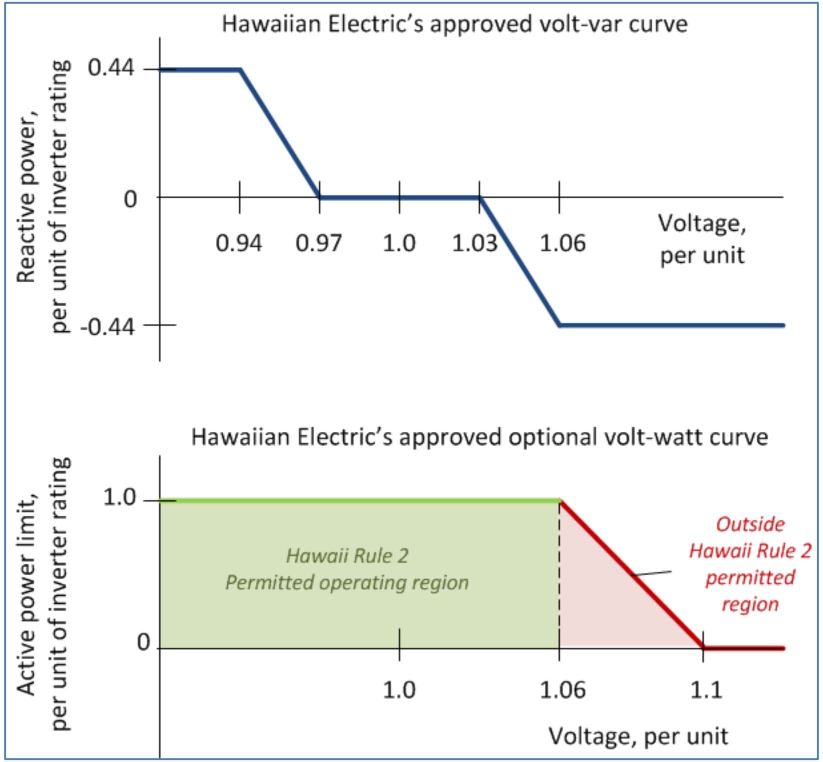
Case Study: Volt-Var and Volt-Watt Control

- PV at unity PF causes steady-state overvoltage issues in some locations
- Currently impractical to actively control thousands of individual PV systems
- Near-term solution: autonomous inverter responses
  - Fixed power factor operation
  - Volt-var control
  - Volt-watt control
- HECO initially required PV systems operate at 0.95 PF (absorbing vars)
- NREL, HECO, and industry collaborators expected volt-var control be more beneficial (to all) than fixed PF
- NREL and HECO conducted several studies
  - Detailed time-series simulation
  - Field pilot study
  - Lab testing at ESIF
  - Objective: Quantify impacts on utility and on customers (i.e. curtailment?)

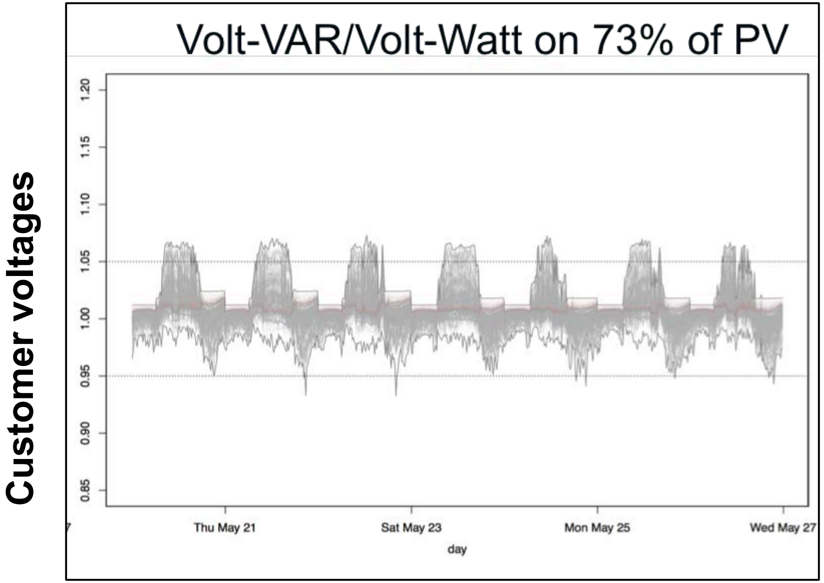


Case Study: Volt-Var and Volt-Watt Control

Detailed feeder simulations:

- NREL and HECO performed detailed quasi-static time-series analysis of two HECO feeders to evaluate 0.95 PF, volt-var control, and volt-watt control
    - *Accurate analysis of volt-var and volt-watt requires modeling of secondary circuits*
- Volt-var was found to result in fewer voltage violations, fewer tap-changer operations, reduced losses, and less PV curtailment than fixed PF of 0.95
- PV energy curtailment due to volt-var and volt-watt was near zero in almost all cases, with a few outliers
- Also simulated cases with self-supply PV-battery systems.
    - Lower voltages
- HECO now requires volt-var for all new DERs

Example weekly simulation of feeder with 6.8 MW of distributed PV



https://www.nrel.gov/docs/fy17osti/68681.pdf
https://www.nrel.gov/docs/fy19osti/72298.pdf

Case Study: Volt-Var and Volt-Watt Control

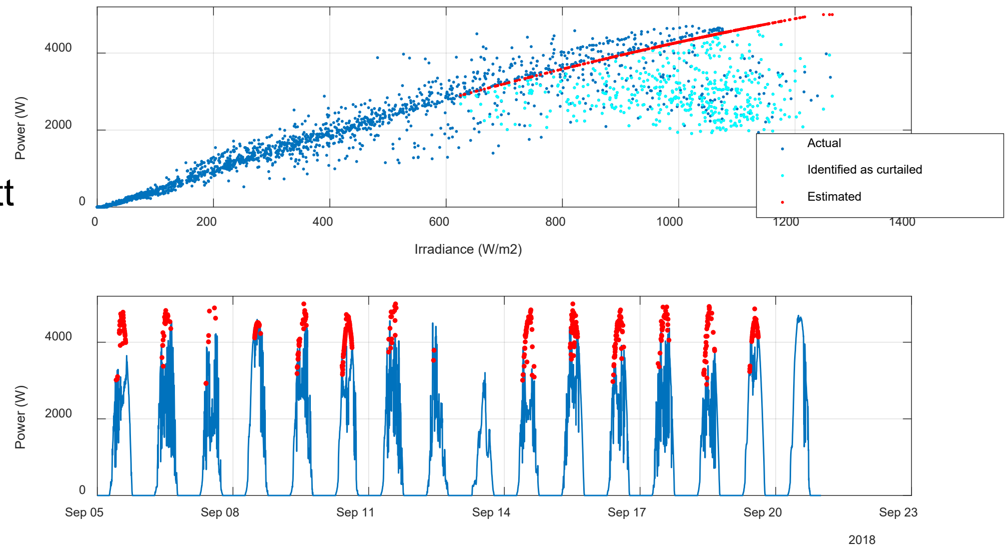
Pilot study:

- NREL and HECO installed monitoring, sensors, and communications to about 30 PV locations expected to have high voltage

Findings

- Voltages were typically lower than expected
  - Limited information available in planning studies leads to conservative assumptions
- PV energy curtailment due to volt-var and volt-watt was typically zero or near-zero
  - Curtailment of >1% identified in two cases
    - One location mitigated through conventional (wires) solution
    - Other location has ~1.1% curtailment. Mitigation needed?
- Large-scale deployment of sensing for accurate curtailment estimates is cost-prohibitive for residential-scale PV

Estimating PV curtailment due to volt-var and volt-watt using plane-of-array irradiance data during an unusual high-voltage period



https://www.osti.gov/servlets/purl/1464444

Case Study: Volt-Var and Volt-Watt Control

Conclusions:

- Volt-var and volt-watt control are useful tools for mitigating high customer voltages due to behind-the-meter PV
  - Volt-var curtailment impacts on PV production are typically near-zero (at least for the volt-var curve used in Hawaii)
  - If the sloping region of the volt-watt curve is outside ANSI Range B (1.06 pu), volt-watt provides a backstop against occasional high voltages while maintaining near-zero curtailment
- It is difficult to predict in advance exactly which locations will have high voltages, and periods of high voltage sometimes occur for a few days at a time due to feeder reconfigurations (utility switching)
- Volt-var and volt-watt are most beneficial if deployed system-wide

Ongoing work and next steps:

- HECO deploying AMI with all new PV systems
  - NREL receiving and analyzing AMI data in ESIF High Performance Computing (HPC) Center
  - NREL and HECO developing "non-wires alternatives toolbox" for mitigation of high voltages
- Most new PV systems in Hawaii now have integrated battery storage – daytime export is no longer economical in most cases
  - This helps maintain voltages within ANSI Range A
  - Leverage storage for other purposes?

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4. **Case study – frequency-watt**

Solutions: Frequency-Watt Control

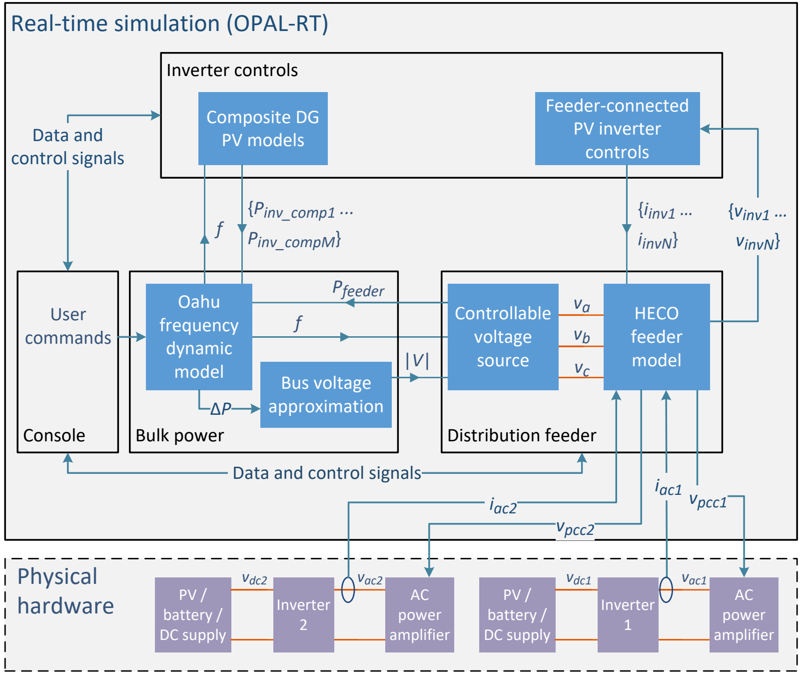
- As PV displaces conventional generation, system frequency stability is degraded
- DERs can help mitigate this by providing rapid frequency response (e.g. frequency-watt droop)

DOE GMLC project (HECO-NREL-SNL) examined ability of real hardware inverters to provide fast droop response

Approaches:

- Inverter hardware response characterization
- PSSE simulations
- Stability analysis
- Inverter controls development
- PHIL tests (at NREL ESIF)

PHIL Test Setup Including Real-time Model of Oahu Power System



https://www.nrel.gov/docs/fy17osti/68884.pdf

Solutions: Frequency-Watt Control

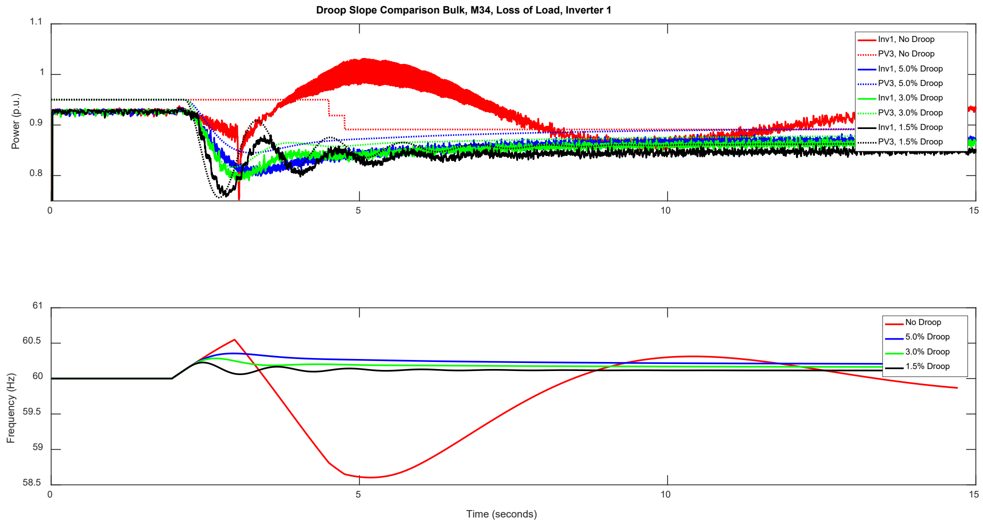
Findings:

- Many (but not all) off-the-shelf inverters can respond very quickly (sub-second) to frequency events
- At the time of testing (2017), most inverters only provided overfrequency response (even if headroom for underfrequency response available)
- *Fast response is needed to mitigate frequency events in low inertia systems*
- Under-frequency load-shedding (UFLS) can make DER frequency response less effective

Outcomes:

- IEEE 1547-2018 allows for very fast frequency droop if needed
  - Very fast response may not be needed/desired in all cases
- HECO now requires freq-watt for all new DERs

Example PHIL test of overfrequency event demonstrating DER inverters mitigating cascading event



https://www.nrel.gov/docs/fy17osti/68884.pdf

Conclusions

- Activating relatively wide voltage and frequency ride-through *early* is step #1 towards successfully operating a grid with high levels of PV
- Inverter anti-islanding controls were found reliable even with grid support active, and even in the multi-inverter, multi-PCC scenarios tested
- LROV concerns are easily mitigated through type-testing; GFOV is more complicated (but is not a problem if zero-sequence continuity is maintained)
- Power HIL tests validate the benefits of advanced inverter functions
- For feeders with very large numbers of distributed inverters, volt-var control is more beneficial to the utility and the customers than fixed PF
- Volt-watt control is beneficial as a backstop against high customer voltages, especially given limited grid-edge visibility
- Ensuring the correct inverter settings are deployed in field requires verification
- Smart inverters won't solve all your problems, but they can help!

Questions and possible next steps

- How to transition older "legacy" PV systems to advanced inverters?
- DER inverter fault response? Is "momentary cessation" okay if 100+ MW of distributed inverters do it?
- Grid services from DERs?
  - Bulk grid services? Local services? Aggregators? DERMS? … Cybersecurity?
- Inverter data integration into utility systems?
  - Planning? Operations?
- Coordinated control of DERs?
- What other utility devices are needed in ultra-high DER world? D-STATCOMs? Synchronous condensers?
- What is the role of grid-forming inverters?
- Which of the above are appropriate for DERs vs larger utility-scale PV-battery plants?

Thank you!

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- Frequency-watt testing and simulation including power HIL: https://www.nrel.gov/docs/fy17osti/68884.pdf
- Experimental Evaluation of PV Inverter Anti-Islanding with Grid Support Functions in Multi-Inverter Island Scenarios: https://www.nrel.gov/docs/fy16osti/66732.pdf
- Advanced Inverter Voltage Controls: Simulation and Field Pilot Findings: https://www.nrel.gov/docs/fy19osti/72298.pdf
- Energy System Integration, High Penetration PV: How High Can We Go? http://www.nrel.gov/docs/fy16osti/65591.pdf
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