Hawaiian Electric Advanced Inverter
Test Plan – Result Summary

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Honolulu, Hawaii
October 14, 2016
NREL/PR-5D00-67267
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
   • 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:
  o Apparent
  o Enphase Energy
  o SMA
  o SolarEdge
• Smart Inverter Technical Working Group
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 $P_{\text{max}}$ 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
Volt-Watt example

Moderate curve

Inverter 2 # 43: Time Const = 50 sec, Curve 1, Power = 100, Mode = 1

RMS Voltage (V)

Power (kVA)

Time (sec)
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-Watt Curve Tested with Volt-Var**

**Volt-Var Curves Tested with Volt-Watt**

*Volt-var curves depend on inverter’s maximum VArS. This plot assumes $Q_{max} = 0.5$ pu.*

Proprietary data and preliminary results
Please do not distribute
Volt-var with volt-watt example

Inverter 4 \(^{\text{fAr with V-W Test Case 1}}\)

- Reactive Power (% Nameplate)
- Real Power (% Nameplate)

Proprietary data and preliminary results
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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

Inverter 4  

SolarEdge Test # 26:

Inverter 4  

SolarEdge Test # 31:

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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:
  o Ramp-rate control
  o 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:
  o Volt-var requirements need to be defined in detail
    – Pay attention to var capability (rectangular vs triangular; vars at max P)
  o Volt-watt requirements need to be defined in detail
  o Clarify how response times are defined
  o Where possible, align with Rule 21 and/or IEEE P1547 (draft, near-final)
    – Some variation in settings from other codes should be okay
  o 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
  o Recommend continued discussions with stakeholders on the near-term, high-priority voltage regulation functions

Proprietary data and preliminary results
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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)

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Feeder reduction process

Reduction

- Original feeder
- Reduced feeder

Validation

- Independent variables: Line lengths
- Verification: Voltages at retained node
- Up to 50,000 Monte-Carlo simulations

Proprietary data and preliminary results. Please do not distribute.
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)

Reduced-order feeder primary

MV:LV transformer

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

Selected secondary circuit (detailed model)

Secondary nodes (e.g. houses)

Simulated PV inverter

Hardware inverter PCC

Feeder head

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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

Real-time simulation (OPAL-RT)

Slave subsystem: Inverter controls & data processing

Simulated inverter controls

$\text{HECO feeder model}$

Controllable voltage source

$\text{Master subsystem: Distribution system}$

$\text{Slave subsystem: Bulk power system}$

Oahu frequency dynamic model

$\text{Slave subsystem: Inverter controls & data processing}$

Data and control signals

Trip signal and event parameters

Console subsystem

Physical hardware

PV / DC supply
Inverter hardware
AC power amplifier
PV / DC supply
Inverter hardware
AC power amplifier

Proprietary data and preliminary results
Please do not distribute
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/m² → 1000 W/m²)
  - 18 soft-start tests:
    - Inverter comes online following voltage event and ramps to full power

Proprietary data and preliminary results
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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/m² → 1000 W/m² 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, $P_{\text{max}}$
  - 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

Proprietary data and preliminary results
Please do not distribute
Simulated inverters – volt-watt test scenarios

Total PV inverter ratings

• M34 circuit:

<table>
<thead>
<tr>
<th>Year</th>
<th>Portion of PV inverters retrofitted</th>
<th>Legacy PV (MW)</th>
<th>Advanced PV (MW)</th>
<th>Total PV (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>None</td>
<td>3.9</td>
<td>0</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>2.9</td>
<td>1.0</td>
<td>3.9</td>
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<td></td>
<td>50%</td>
<td>1.9</td>
<td>1.9</td>
<td>3.9</td>
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<tr>
<td>2019</td>
<td>None</td>
<td>3.9</td>
<td>11.2</td>
<td>15.1</td>
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<td></td>
<td>25%</td>
<td>2.9</td>
<td>12.1</td>
<td>15.1</td>
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<tr>
<td></td>
<td>50%</td>
<td>1.9</td>
<td>13.1</td>
<td>15.1</td>
</tr>
</tbody>
</table>

• K3L circuit:

<table>
<thead>
<tr>
<th>Year</th>
<th>Portion of PV inverters retrofitted</th>
<th>Legacy PV (MW)</th>
<th>Advanced PV (MW)</th>
<th>Total PV (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>None</td>
<td>3.0</td>
<td>0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>2.3</td>
<td>0.8</td>
<td>3.0</td>
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<td>50%</td>
<td>1.5</td>
<td>1.5</td>
<td>3.0</td>
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<tr>
<td>2019</td>
<td>None</td>
<td>3.0</td>
<td>1.8</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>2.3</td>
<td>2.5</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>1.5</td>
<td>3.3</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Volt-watt PHIL test example

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

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Volt-watt PHIL test example

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

**Proprietary data and preliminary results. Please do not distribute**
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)
Summary of Inverter 1 volt-watt tests, K3L circuit

• In this case, both V-W and FPF have significant impacts on voltage
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)
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 (Pmax mode), 0.95 PF

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

Final PCC Voltages, Inverter 3 V-W Tests, M34

 Voltage (p.u.)

- PF = 1.00, Curve = OFF
- PF = 0.95, Curve = OFF
- PF = 0.90, Curve = OFF
- PF = 1.00, Curve = MODERATE
- PF = 0.95, Curve = MODERATE
- PF = 0.90, Curve = MODERATE
- PF = 1.00, Curve = MILD
- PF = 0.95, Curve = MILD
- PF = 0.90, Curve = MILD

PV Ratings

- Ratings 1 = 2016, NO RETROFIT
- Ratings 2 = 2016, 25% RETROFIT
- Ratings 3 = 2016, 50% RETROFIT
- Ratings 4 = 2021, NO RETROFIT
- Ratings 5 = 2021, 25% RETROFIT
- Ratings 6 = 2021, 50% RETROFIT

2016

Fixed PF has the dominant impact for this circuit.

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

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

<table>
<thead>
<tr>
<th>PV Ratings</th>
<th>1 2 3 4 5 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (p.u.)</td>
<td>1.065 1.07 1.075 1.08 1.085</td>
</tr>
</tbody>
</table>

Ratings 1 = 2016, NO RETROFIT
Ratings 2 = 2016, 25% RETROFIT
Ratings 3 = 2016, 50% RETROFIT
Ratings 4 = 2021, NO RETROFIT
Ratings 5 = 2021, 25% RETROFIT
Ratings 6 = 2021, 50% RETROFIT

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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*.
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

Proprietary data and preliminary results
Please do not distribute
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)
Next steps

• Advanced inverter test plan:
  o NREL deliver final report to HECO
  o HECO deliver to PUC by Dec 15

• Voltage regulation operational strategies (VROS) study
  o Design simulation scenarios and collect data
  o Conduct simulations to select combinations of volt-watt, volt-var, and fixed PF
  o Quantify impacts of selected combinations on annual PV kWh production and feeder voltage profiles
  o Complete in Spring 2017

• DOE GMLC work
  o Simulation and testing of frequency-watt (both presently available function and possible future advancements)
  o Complete in Fall 2017
Thank you!

Questions welcome
Extra Slides
Baseline testing: Volt-var

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

  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

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Volt-var example

Inverter 3 Test # 74:

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

Inverter 3 -VAr Test Case 1

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Voltage ride-through examples

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

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

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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

Inverter 3 Power Factor Test # 72:

Apparent Power
Real Power
Reactive Power

Power Factor

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