Integrating More Solar with Smart Inverters

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Integrating More Solar with Smart Inverters

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SUMMARY: In Hawai‘i, the relatively high cost of electricity costs coupled with various incentives have made it cost-effective to install solar photovoltaics (PV) on residential homes and larger central-station PV plants. On some of the islands, PV has reached over 50% of the installed generation capacity base. To make sure these inverter-based PV plants can maintain stable and safe operations, new smart inverter functionality is being evaluated and demonstrated at significant scale across the islands. This paper describes research conducted to validate high PV penetration scenarios with smart inverters and recent progress on the use of these advanced inverter grid support functions in actual power grids in Hawai‘i.

Keywords: photovoltaic, smart inverter, grid integration, grid support functions

1.0 INTRODUCTION

In Hawai‘i, the relatively high cost of electricity coupled with various incentives have made it cost-effective to install solar photovoltaics (PV) on residential homes and larger central-station PV plants. On the most populous Hawaiian island of O‘ahu, the PV generating capacity is 502 MW. This is nearly half of the annual peak load for the entire island of 1.1 GW. Of the total PV installed, 54% is on private rooftops—nearly 50,000 residences, or about one out of every three single-family homes. Hawaiian Electric, the local utility, does not own or control the residential PV systems. The output from these PV systems can be a significant portion of the generation of the island on sunny days, creating both daily operational and longer-term planning challenges. Back-feed of power into the utility substations is not necessarily a problem, but it does require some changes to maintain grid reliability and safety, especially in regards to voltage regulation on the distribution circuits. When PV systems inject active power back to the grid, this causes the utility voltage to rise. In addition to voltage regulation issues, PV systems displace synchronous generators that provide rotational inertia and short circuit current that stabilize the grid during abnormal operating conditions.

To address these concerns, smart inverters are increasingly being used with functionality that can help support stable and safe operation at high PV penetrations. The functionality of these inverters is critical to maintaining grid stability and has been added to the inverters such that they can respond to grid abnormalities in an autonomous fashion.

Although using autonomous grid support functions bypasses the need for a vast communications network and a control system capable of coordinating tens of thousands of devices, it raises several questions regarding how PV inverters will interact with the rest of devices on the grid. To answer these questions, Hawaiian Electric began working with the National Renewable Energy Laboratory (NREL) on several research projects to recommend and justify advanced inverter functionality that would be beneficial not only to the utility but also to other stakeholders. This research discusses voltage regulation and frequency response grid support functions that have been validated and deployed. This paper summarizes the results of several of these studies that examine how smart inverters can increase the amount of deployed PV systems in electric power grids.

2.0 INVERTER-BASED GRID SUPPORT FUNCTIONS

2.1 Voltage Regulation

Active power production from PV inverters tends to increase steady-state grid voltage. Inverters have two output parameters available to mitigate this: reactive power and active power. Absorbing reactive power can bring down voltage with minimal (sometimes zero) impact on real power production, and hence it is generally preferred. Reducing active power can also mitigate overvoltage, but this directly reduces PV energy production and is therefore typically considered an option only when voltage is very high and reactive power is not solving the problem. Being able to set real and reactive power levels based on local voltage is critical to controlling voltage levels on distribution circuits with large amounts of PV.

2.2 Frequency Response

Grid frequency is an indicator of the balance between load and generation. Nominal AC grid frequency in the United States and in Hawai‘i is 60 Hz. When frequency is low, more generation (or less load) is needed; and when frequency is high, less generation (or more load) is needed. Advanced inverters can reduce power in response to overfrequency events. This function is called frequency-watt control. It follows a frequency-watt curve to reduce/curtail real power so that the system frequency would be reduced. Responding to underfrequency events requires the ability to increase power output and this may not be possible unless the inverter is already running in a curtailed mode. The over/under frequency response can be programmed into the inverters based on desired response to abnormal grid conditions.

The challenges of operating a grid that has high levels of PV include technical and nontechnical challenges. Because the PV systems are not owned by the utility, their operation is governed by contracts and interconnection agreements that currently do not typically allow for changing how a PV system is operated after it is commissioned. Interconnection rules must allow smart inverter functionality that can maximize customer solar production while minimizing any adverse impact on grid operations. As Hawaiian Electric and other Hawaiʻi stakeholders work to meet the state's legislated renewable portfolio standard of 100% by 2045, these issues are important to solve to create a stable and safe grid.

3.0 VALIDATING INVERTER CONTROLS IN A SYSTEMS CONTEXT

To gain confidence that advanced inverters being deployed in Hawaiʻi were performing as expected, Hawaiian Electric, NREL, and Hawaiian Electric's Smart Inverter Technical Working Group evaluated representative inverters from different manufacturers in NREL's Energy Systems Integration Facility. The evaluations sought to characterize the inverter's behavior and determine how they would interact with real distribution feeders in Hawaiʻi. This was achieved by designing a power hardware-in-the-loop (PHIL) platform to simulate Hawaiian Electric feeders in real-time with hardware inverters dynamically connected to the simulation [1].

The inverters of interest were selected from products commonly used on the Hawaiʻi's island grids and from manufacturers who were willing to participate in this study. For the evaluations, a selection of five grid supportive inverters representing a broad spectrum of technologies including one split-phase residential-scale string inverter, assemblies of three types of microinverters, and one three-phase 480 V small commercial string inverter were used to conduct functionality evaluations. The seven grid support functions that were evaluated included:

- Fixed power factor operation
- Volt-watt control
- Volt-var control (baseline only)
- Voltage ride-through
- Frequency ride-through
- Ramp rate control
- Soft start reconnection

Some combinations of these functions were also evaluated simultaneously to the extent the specific inverter model was able to support the combined activation of functions.

Two types of evaluations were conducted. The first category, referred to as "baseline", consisted of conventional lab evaluations, in which the input and output terminals of the inverter were connected to DC and AC power supplies, the AC voltage or frequency was varied systematically, or the available DC input power was varied, and the inverter's response was recorded. For the baseline, the procedures were based on a draft version of the recently-published UL 1741 Supplement SA [2]. The goal was to characterize their responses for the grid support functionality. A total of over 238 baseline experiments were performed across the five inverters. In the baseline, all grid supportive PV inverters evaluated were able to perform all of the functions satisfactorily.

The second category consisted of PHIL experiments, which coupled computer simulation with hardware. In the PHIL experiments, real-time models of two of Hawaiian Electric's electrical distribution feeders were run, and the simulated voltage at a distribution secondary location was used to drive the voltage waveforms of an AC power supply connected to a PV inverter. The measured AC current from the inverter was fed back into the feeder model, such that the inverter and the simulated distribution system were dynamically connected. Thus, the PHIL experiments simulated placing the inverter on a real feeder. A total of over 250 PHIL experiments were performed across four inverter models; the legacy inverters were not evaluated in PHIL.

The PHIL experiments simulated two distribution circuits on the Hawaiian island of Oʻahu with high levels of legacy distributed rooftop PV (penetration levels of 88% and 140% of gross daytime minimum load as of the end of 2015). Scenarios reflecting Hawaiian Electric's forecast of PV penetration by 2021 were also evaluated in PHIL. Each PHIL experiment examined a scenario covering a time window of several minutes. In addition, each feeder model contained only one secondary circuit.

An example of an inverter responding to a grid voltage change is shown in Figure 1. The top graph shows the grid voltage going from 257.4 volts to 259.4 volts. The bottom graph shows the power output from the inverter decay from 4.1 kW to 3 kW over a period of 150 seconds.

PHIL experiments showed both volt-watt control and absorbing power factor operation to be effective tools to manage high voltage in many scenarios. Based on this initial work, it was recommended that Hawaiian Electric continue to require 0.95 power factor (absorbing) operation at least until other reactive power functions (e.g. volt-var control) were certified. However, it was noted that adding grid supportive inverters will not necessarily fix voltage issues in all cases.

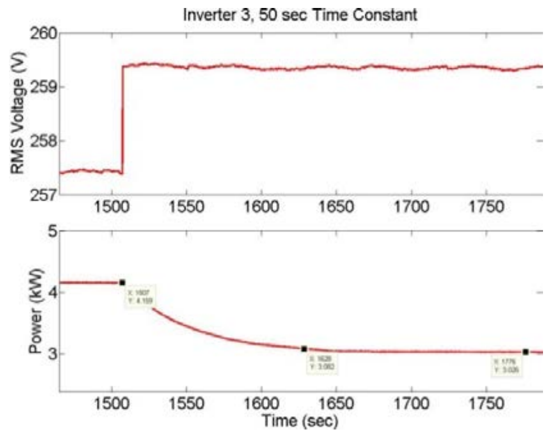

Figure 1. Inverter volt-watt time response.

The effects of volt-watt control and fixed power factor depended strongly on the total rating of inverters performing the grid supportive functions, the ratio of grid supportive inverters to legacy inverters, and the circuit being evaluated. In scenarios with a large number of grid support capable inverters relative to the total rating of legacy inverters, operating at a power factor of 0.95 (absorbing) tended to reduce the voltage such that the volt-watt function was not very active. However, in scenarios with smaller numbers of inverters performing grid support, circuit voltages were higher and the volt-watt function became more active. In other words, a "critical mass" of grid supportive inverters is needed to effectively mitigate high voltages, and that critical mass depends on factors including load, legacy PV penetration, circuit impedance and topology, and the specific grid support functions and parameters in use.

Only limited information can be obtained from these experiments about other locations on the circuit or other points in time. Therefore, only limited conclusions were drawn about the effects of the functions on annual voltage profiles, and still fewer conclusions were made about the effects of these functions on annual PV energy production. These important considerations are the reasons that NREL and Hawaiian Electric proactively conducted a follow-up Voltage Regulation Operational Strategies (VROS) project to examine these effects, as discussed in the next section.

4.0 VOLTAGE REGULATION OPERATIONAL STRATEGIES

To provide the technical basis and recommendations for the activation of voltage-regulation functions that would allow Hawai‘i grid planners to interconnect more customer-sited rooftop solar PV systems, researchers conducted the Voltage Regulation Operational Strategies (VROS) Project [3]. This study used quasi-static time-series simulation analysis to address the higher level technical voltage management operation strategies and impacts of activating advanced inverter voltage regulation grid support functions (GSF).

The VROS project was designed to address the following research questions.

- Which advanced inverter function is more effective in regulating voltage?
- What is the relative impact of the advanced inverter voltage-regulation functions on customer-sited PV system kilowatt-hour (kWh) production?
- What is the relative impact of advanced inverter voltage-regulation functions on overall feeder reactive power demand?
- Is active or reactive power priority the right implementation for Hawai‘i?

To answer these questions, NREL conducted quasi-static time-series simulations and PV growth scenario analyses on two representative O‘ahu island feeders with current high penetration of legacy rooftop net energy metering and feed-in tariff solar PV systems (penetration levels of 64% and 150% of gross daytime minimum load) to understand the effectiveness of the voltage-regulation GSF.

Different PV penetration cases described in this study were simulated with the following operational modes: (1) Constant power factor (CPF) of 0.95 absorbing, (2) volt-var with reactive power priority, (3) CPF 0.95 absorbing in combination with volt-watt, and (4) volt-var in combination with volt-watt.

The VROS Project successfully identified technical recommendations for the activation of the replacement volt-VAR voltage regulation GSF that addresses Hawai‘i's unique feeder characteristics and high penetration of rooftop PV, as well as the energy curtailment impacts to PV customers. The key findings from the VROS project were:

- Additional PV systems with GSF interconnected to a distribution circuit increase the impact on improving overall voltage profiles.
- Activating GSF in new PV systems had no adverse impact to the utility's voltage regulation equipment (substation load tap changers) in terms of increasing total number of operations.
- For the scenarios studied, volt-var was always as effective or more effective than CPF of 0.95 absorbing at regulating voltages during PV system production hours. This was quantified by looking at the DeltaV metric—a measure of how much "flatter" voltages are with a given activated GSF as compared to the no advanced inverters scenario during high PV-system productions hours (10 a.m. to 2 p.m.).
- Because volt-var is a voltage-based control and voltages present on the circuits are often within the proportional band of the volt-var curve, it provides proportional reactive power support, in contrast to CPF 0.95, which absorbs reactive power regardless of voltage. Consequently volt-var in this study always resulted in less energy

curtailment to the customers with advanced inverter GSF activated, and less reactive power demand at the feeder-head.

- Activating GSF with reactive power priority, as opposed to active power priority, is recommended to avoid momentary overvoltages. When implementing the GSF with active power priority, momentary overvoltages are observed at peak PV system production hours because reactive power support drops to zero during very high irradiance values to accommodate for real power production.
- Enabling volt-var in combination with volt-watt could cause small reductions in PV energy production for some customers (less than 1% annual energy curtailment for over 90% of the customers evaluated at very high PV penetration levels), but it will result in more total customers being able to interconnect PV systems, so the net effect will allow for more cumulative renewable energy production.
- By providing a backstop against voltages above ANSI C84.1 levels, enabling volt-watt and volt-var sooner will result in removing high voltage as a barrier for interconnecting higher levels of distributed PV.

5.0 FREQUENCY STRATEGIES TO SUPPORT GRID STABILTY

An additional part of this research focused on very short-term responses on the timescales of primary frequency response and faster (i.e., milliseconds to tens of seconds) [4]. Frequency-watt control is an autonomous inverter function that does not require communications. Using autonomous functions, it is feasible for large numbers of distribution-connected inverters to perform such a function without a communications network or standardized communication protocols by pre-programming the inverters. The frequency response function itself is similar to governor droop control of synchronous generators in that the inverter measures the AC grid frequency present at its terminals and responds by modulating its power following a droop curve designed to help move the frequency back towards its normal range.

Frequency-watt control of distributed PV inverters is of interest because as the cumulative installed capacity of distributed PV becomes large enough that it can affect the AC grid frequency, it would be beneficial for distributed PV systems to be operated in a way that minimizes negative impacts on frequency stability, and if possible has a beneficial impact. The Hawaiian island power systems have reached the point where distributed PV impacts must be accounted for by bulk power system operators; hence Hawaiʻi was the first location in the U.S. to require distributed PV to continue operating during (or “ride through”) a wide range of frequency conditions.

Inverters with frequency-watt control enabled go beyond simply riding through frequency disturbances by actively adjusting their power output to stabilize system frequency, similar to the droop response of synchronous generators. Most residential- and commercial-scale PV inverters sold today are capable of frequency-watt control for overfrequency events, which require a reduction in output power to mitigate excess generation. PV inverters sold today are not generally designed to be capable of responding to underfrequency events by increasing their output power; this is certainly possible, but it would require the inverter to operate below the maximum available power from the PV array, a major change from current operating scenarios. Because responding to underfrequency events would require development of new inverter functionality that is not available today in off-the-shelf residential and small commercial PV inverters, much of this research focused on analyzing the currently-available frequency-watt function with downward response only.

Experiments conducted at NREL in this project confirmed that presently-available PV inverters can perform the frequency-watt function but that the form of the function varies between inverters. They also confirmed that PV inverters can respond very quickly to frequency changes, modifying their output power on a sub-second time scale. This is an important finding for low-inertia grids such as those in Hawaiʻi because frequency events happen very quickly on island grids, so any response must occur very quickly to be effective in mitigating a frequency event.

In this study, bulk power system simulations of the projected 2019 Oʻahu power system were used to evaluate the effects of frequency-watt droop control by distributed PV inverters. The simulations were performed using Hawaiian Electric’s model of Oʻahu, in which distributed PV inverters are aggregated at the nearest 46 kV bus. The aggregations of distributed PV inverters in the model were modified so that a portion of them could perform frequency-watt control with dynamics corresponding to the dynamics of actual inverters as measured at the laboratory.

The simulations found that frequency-watt control can improve the Oʻahu frequency response, as expected. Various frequency-watt droop curve parameters were simulated. It was found that steeper droop curves reduce the peak frequency of the event, but are more prone to cause oscillations in system frequency, especially when the aggregate power of inverters responding is large. It was also found that the time dynamics of the PV system response have an important impact. Specifically, if the inverters respond with a first-order time constant in the range of five to seven seconds, the system frequency is more prone to oscillations than at higher or lower frequencies. Faster responses or slower responses tend to reduce the oscillations. However, slower responses are less effective at mitigating frequency events, as judged by the maximum frequency reached during the event; slower responses can allow the frequency to approach or reach 60.5 Hz, at which point a large quantity of legacy and re-programmed PV trips due to overfrequency, causing an underfrequency event and possibly load shedding. Within the simulated range of frequency-watt deadbands, narrower deadbands led to a slightly improved frequency response.

Secondary frequency regulation and other slower-acting services were not examined in this study, partly because these services tend to require communications. It was found that relatively fast frequency responses (i.e., subsecond time constants) are needed to effectively mitigate frequency events due to the high rates of change of frequency in Hawai‘i’s relatively low inertia grids. Current PV inverters are able to respond quickly enough to mitigate realistic frequency events. Aggressive frequency-watt droop slopes can improve the steady-state system frequency response but can cause unstable dynamic system response, especially when the aggregate power of frequency-responsive inverters is high. This study drew the following conclusions and recommendations:

- The currently available frequency-watt control function of PV inverters can help mitigate overfrequency events and will help to support the downward reserve planning requirements in Hawaiian Electric's system-level hosting capacity analysis.
- The form of the frequency-watt function is recommended to be a curve that starts from the pre-disturbance output power of the inverter (as opposed to starting from the rated power) and the droop slope is a constant function of the inverter’s rated power, as in IEEE 1547-2018.
- For frequency-watt control to be effective in Hawai‘i, the time response of the frequency-watt function must be fast regardless of the magnitude of the power change. This will improve frequency stability and also improve the testability of the frequency-watt function.

6.0 DEPLOYING MORE SOLAR

The results from this research demonstrated that it is possible to deploy significant amounts of PV without impacting grid reliability or customer production if smart inverter functions are properly used. The impact on customers’ solar energy production due to voltage regulation was quantified for the first time. Impacts on energy production were negligible for the vast majority of customers, even in future PV penetrations cases beyond the already-high present-day scenario. This was true even though all PV systems were modeled as exporting power without restriction, which will not be the case in Hawai‘i due to new DER programs that are designed to avoid export during high irradiance periods and provide operator controls over DER systems. Reaching 100% renewables will likely require fundamentally rethinking how the inverters themselves operate to ensure overall grid stability [5]. Significant additional work is needed to address remaining issues including the impacts of inverter fault response on bulk system stability.

7. 0 ACKNOWLEDGEMENT

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