

The Frequency-Watt Function

Simulation and Testing for the Hawaiian Electric Companies

July 2017

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Executive Summary

This report describes research related to frequency-watt control of solar photovoltaic (PV) inverters conducted under the U.S. Department of Energy's Grid Modernization Laboratory Consortium (GMLC) by a regional partnership for Hawaii. The purpose of this interim report is to inform an ongoing discussion around frequency-watt activation between the Hawaii Public Utilities Commission, the Hawaiian Electric Companies, and other Hawaii stakeholders. A future report will describe other outcomes of the GMLC Hawaii regional partnership.

This report contains the following:

- A description of the current state of the art of distributed PV-based frequency support
- Lab test results of the frequency-watt function in presently-available distributed-scale PV inverters
- Bulk power system simulation results of the Oahu power system in 2019 scenarios with frequency support from distributed PV inverters
- Power hardware-in-the-loop (PHIL) test results of PV inverters with frequency-watt control enabled
- Conclusions and recommendations related to activation of frequency-watt control in distributed PV inverters.

Brief summaries of each of these topics are presented in this section.

Frequency-watt control is an autonomous inverter function that does not require communications. Hence 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 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.¹

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 most certainly reached the point where distributed PV impacts must be accounted for by bulk power system operators; hence Hawaii 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-

¹ Abnormal frequency events are due to a mismatch in generation relative and load. Generators with droop response enabled autonomously change their power output in inverse proportion to the deviation in frequency, which re-balances generation and load (but does not restore frequency all the way back to the nominal value).

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, this report focuses on analyzing the currently-available frequency-watt function with downward response only.

While PV inverters available today can typically provide frequency-watt control for overfrequency events, this function is not always certified as part of the inverter's UL 1741 Supplement SA testing because UL 1741 SA designates frequency-watt control as optional (though Hawaiian Electric's interconnection tariff, Rule 14H, designates frequency-watt as mandatory). Some inverter manufacturers are in the process of obtaining this certification, and others have recently obtained it, but the exact form of the certified frequency-watt function varies and is not necessarily in compliance with Hawaiian Electric's Source Requirements Document Version 1.0 (SRD V1.0), which was recently published on March 10, 2017.

Lab tests conducted at the National Renewable Energy Laboratory (NREL) as part of this project have confirmed that presently-available PV inverters can perform the frequency-watt function but that the form of the function varies between inverters. They have 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 Hawaii because frequency events happen very quickly on island grids with no inerties to other electric power systems, so any response must occur very quickly to be effective in mitigating a frequency event. The inverters tested under this project include one type of microinverter and two types of residential-scale string inverter.

For frequency-watt control of distributed PV inverters to be effective on the major Hawaiian island power systems, many MW of PV systems must have the function enabled. Unless existing PV systems are re-programmed or retrofitted, it will likely take several years to accumulate sufficient frequency-watt capable PV. In addition, frequency-responsive PV generation does not replace downward reserve on a one-to-one basis because of the uncertainty in the amount of distributed PV generation online at any given time, and because PV generation is often operating below its rated capacity.

Bulk power system simulations of the projected 2019 Oahu 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 PSS/E model of Oahu, 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 the tested hardware inverters.

The PSS/E simulations found that frequency-watt control can improve the Oahu 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.

The PSS/E model was also converted into a real-time Simulink model and linked to a real-time SimPowerSystems model of an Oahu distribution feeder. This real-time hybrid model of the bulk power system and distribution system was used for PHIL simulations, in which hardware inverters were connected to selected locations on the simulated distribution system to validate their performance in an environment that emulates the dynamics of the Oahu power system. The hardware inverters rode through the various transients tested and provided frequency support as desired.

In the PHIL simulations, the bulk power system and the distribution system were both populated with aggregate models of PV inverters having dynamic responses designed to emulate the measured hardware inverter responses. This allowed the dynamic models of PV inverters to be validated against hardware PV inverter responses in the same PHIL tests. It also allowed the system frequency response to be observed in the presence of large aggregate ratings of frequency-watt enabled PV inverters. The PHIL test results confirmed the findings of the PSS/E simulations, adding confidence that real distribution-connected hardware inverters can successfully support the grid during frequency events.

This study has several limitations that are important to acknowledge. First of all, it focuses on the island of Oahu, so while it is expected that these results will apply in general terms to other islands (and to other power systems in general to a lesser degree), this has not been validated. It is important to note that the island of Oahu has the highest system inertia of the three major Hawaiian island systems, but this is expected to change as renewable resources displace traditional synchronous generators in the coming years. In addition, all models used here are approximations of the real systems they represent, so simulation and PHIL results should not be considered exact representations of specific real-world events. Certain effects are not modeled at all in this work; for example, the modeling tools used do not capture sub-synchronous interactions that can occur between power electronic sources and conventional generators, including sub-synchronous torsional interactions with turbine shafts.

Although the study focuses on 2019, Oahu's power system is expected experience significant change over the next five years. Oahu does not have the diversity of renewable energy resources that Maui and Hawaii islands, have so distributed PV is expected to provide much of the renewable energy resources needed to meet Oahu's renewable portfolio standard goals. As more synchronous generators are displaced, distributed PV will play a larger role in stabilizing grid frequency during system disturbances. Thus this report is just a first step down a path in which continued research and analysis will be needed to determine new and improved ways that distributed PV can support grid frequency.

With those limitations in mind, this report makes the following conclusions and recommendations:

1. The currently available frequency-watt control function of PV inverters helps mitigate overfrequency events and will help to support the downward reserve planning

requirements in Hawaiian Electric's system-level hosting capacity analysis. Assuming PV systems are not retrofitted, it will likely take several years to build up enough aggregate capacity of frequency-watt enabled PV systems to have a significant benefit. Thus it is recommended that new PV systems be required to activate frequency-watt upon commissioning in the near future. The impact of frequency-watt control on PV system owners' energy production is predicted to be negligible based on analysis included here, and the eventual benefit to system operations and reliability is expected to be significant. In addition, enabling frequency-watt control will support the continued growth in distributed PV capacity. Remaining technical questions surrounding frequency-watt control can continue to be investigated while a base of responsive inverters is being built.

2. The form of the frequency-watt function is recommended to align with the soon-to-be-published revision of IEEE 1547 (which is also largely aligned with Hawaiian Electric's SRD V1.0). This version of the frequency-watt function calls for the frequency-watt curve to be defined as starting from the pre-disturbance output power of the inverter (as opposed to starting from the rated power). The droop slope is a constant function of the inverter's rated power. This is the version of the function used in this work, and will provide the most effective and predictable response, improving the integration of PV into the power system.
3. The upcoming revision to IEEE 1547 defines the desired open-loop response time of the frequency-watt function for "small-signal" events (events resulting in a power change of less than 0.05 pu), but it does not clearly define a response time requirement for larger events. This is adequate for larger interconnected power systems such as those on the U.S. mainland, and it allows for certain types of DERs that cannot easily make large power adjustments quickly. However, on low-inertia power systems such as Hawaii's, worst-case frequency events are not small-signal events, and PV inverters are capable of fast large-signal power ramping, as demonstrated in tests described in this report. For frequency-watt control to be effective in Hawaii, 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. Specific response-time recommendations are included below.
4. The recommended droop slope of the frequency-watt function based on this work is between 5% and 3%. A droop slope equal to that of conventional generators will allow for proportional sharing of the burden of primary frequency response between synchronous generation and distributed resources. It may also be desirable for logistical reasons to have a uniform droop slope on all major islands. A droop slope of 4% would be a reasonable and conservative choice that would align with the steeper end of droop slopes currently used by synchronous generators on the major islands. A wider range of adjustability of droop slope in both directions is recommended to allow for future adjustments as the portion of energy coming from DERs continues to rise.
5. The deadband of the frequency-watt function is recommended to be large enough that typical frequency fluctuations do not activate the function onerously, to avoid unintended impacts. A deadband of 36 mHz (the maximum deadband recommended by the North American Electric Reliability Corporation) will achieve this on Oahu based on analysis presented in this report. The analysis indicated that deadbands as small as 17 mHz would have minimal impact on monthly PV energy generation.

6. It is recommended that the response time of the frequency-watt function, defined as the time required for an inverter to execute 90% of the power change resulting from a frequency event, should be less than two seconds. Faster response times are expected to be more beneficial. A response time of 0.5 seconds would be a reasonable requirement. However, the possibility of unintended interactions with synchronous generators should be investigated before the aggregate power rating of frequency-responsive PV rises to a level that significantly affects grid frequency.
7. Because Hawaii represents a relatively small PV inverter market, and no other U.S. region currently requires frequency-watt control, inverter manufacturers may resist providing a uniform, certified frequency-watt control function prior to the final approval of the ongoing revision to IEEE 1547 – which is expected to occur in the coming months. As an interim solution, it may make sense to allow manufacturers to provide inverters with whatever form of frequency-watt control they currently have available, with Hawaiian Electric's specified form of the function to be required shortly after the approval of the revision to IEEE 1547. Other versions of the frequency-watt function are likely to be somewhat less beneficial, but are not likely to be harmful if implemented in a relatively small number of inverters. Based on a Hawaiian Electric survey of inverter manufacturers, most manufacturers should have inverters certified to Hawaiian Electric's SRD V1.0 by the September 7, 2017 deadline in Rule 14H, or within the timeframe of the anticipated final approval of the ongoing revision to IEEE 1547.

In summary, it is recommended that Hawaiian Electric, in discussions with the members of the Advanced Inverter Functions Working Group, should agree to modify the Rule 14H interconnection tariff to activate the frequency-watt settings defined in Table 1. Figure 1 depicts a frequency-watt curve showing the droop slope and deadband. Equation C in SRD V1.0 and the surrounding text describes how to apply the variables in Table 1.

Table 1: Recommended frequency-watt control settings for overfrequency events

		Default value	Range of adjustability
Deadband (Hz)	db_{OF}	0.036	0.017 – 1.0
Droop slope (pu)	k_{OF}	0.04	0.02 – 0.07
Response time (s)	t_R	0.5 ^A	0.05 – 3.0 ^A

Note A: SRD V1.0 does not define a specific default response time. It specifies that the response time shall be between 50 ms and 3 s, with the intent that the inverter manufacturers select their response times for now. The intent of SRD V1.0 is not to require inverters to be certified for the full range, but to allow them to be certified with any response time between 50 ms and 3 s. To avoid causing manufacturers to have to recertify their products, it is recommended that any response time in the range between 50 ms and 3 s be allowed at this time. The purpose of the default response time of 0.5 s is to provide a suggested value. However, it is expected that in future SRDs and revisions of Rule 14H, requirements on default response time may be updated to achieve a more predictable frequency response.

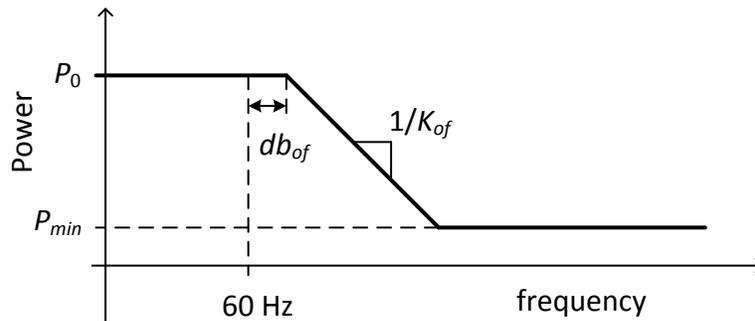


Figure 1: Frequency-watt droop curve settings

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Any flaws are the sole responsibility of the authors.

Acronyms and Abbreviations

AGC	automatic generation control
DER	distributed energy resource
DOE	Department of Energy
dq	direct-quadrature
GMLC	Grid Modernization Laboratory Consortium
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
MW	Megawatt
mHz	millihertz
MPPT	maximum power point tracking
NREL	National Renewable Energy Laboratory
PFR	primary frequency response
PHIL	power hardware-in-the-loop
PLL	phase-locked loop
pu	per unit
PV	photovoltaic
ROCOF	rate of change of frequency
s	seconds
SRD	Source Requirements Document
UDM	user-defined model
U.S.	United States

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1.0 Introduction

As increasing amounts of non-synchronous generation such as solar photovoltaic (PV) systems are interconnected with electric power systems, those generators displace some of the synchronous generators that typically stabilize grid frequency on the fastest time scales through their rotational inertia and primary frequency response (PFR), resulting in reduced frequency stability. The state of Hawaii leads the nation in the proportion of its energy that is provided by distributed PV. This, in combination with its small size and geographic isolation, is forcing Hawaii utilities to confront grid reliability issues associated with high PV penetrations sooner than their mainland U.S. utilities.

Hawaiian Electric has already required that new distributed PV systems continue operating during (or “ride through”) a wide range of frequency events to avoid exacerbating frequency disturbances. However, as levels of distributed PV have continued to rise, it has become desirable for distributed energy resources (DERs) such as PV to not just avoid exacerbating disturbances, but also to actively help restore frequency to its normal operating range.

This report examines the use of frequency-watt droop control by solar PV inverters as a partial solution to grid stability issues arising from very high levels of non-synchronous generation in electric power systems. The dynamics of this control are crucial – it must be fast enough to respond to the rapid frequency events that are characteristic of Hawaii’s relatively low-inertia systems, but it must not cause further instability.

Laboratory tests of presently available PV inverters’ frequency-watt functionality were conducted both to validate the functionality and to characterize the inverters’ dynamic responses. Simplified models of the inverters’ frequency-watt responses were developed and used to simulate the effect of large aggregations of such inverters during Oahu frequency events. In addition, a power hardware-in-the-loop (PHIL) test apparatus was developed to capture Oahu’s bulk system frequency dynamics as well as the electromagnetic dynamics of an Oahu distribution feeder. The PHIL model was populated with modeled PV systems, and two hardware PV inverters were connected to it, allowing them to be tested in an environment that emulates the voltage and frequency dynamics seen by distributed PV inverters on Oahu. This combination of conventional lab testing, simulations, and PHIL testing was used to investigate the effect of various frequency-watt control settings on Oahu frequency response.

This report is part of a larger project that examines the ability of distributed PV and energy storage to support grid frequency on the inertial and PFR time scales, and also investigates and develops new methods of DER frequency support. The frequency response control time scales are depicted in Figure 2, which is adapted from [1]. The focus of this interim report is on the presently-available frequency-watt control function of PV inverters, which reduces power in response to overfrequency events but does not increase power in response to underfrequency events. A subsequent publication will summarize other aspects of this ongoing project. The purpose of this interim report is to provide information and guidance on the basic PV frequency-watt function for use in stakeholder discussions around the activation of grid-support functions in distributed PV inverters in Hawaii.

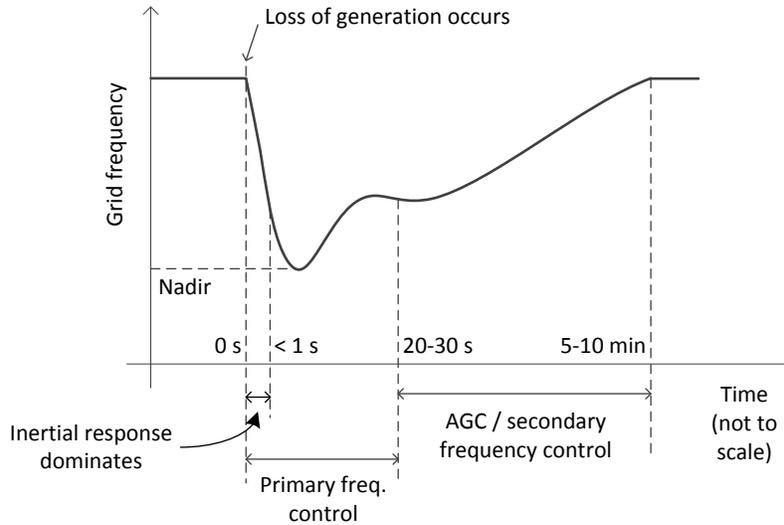


Figure 2: Qualitative depiction of a frequency event showing frequency response time scales. While this figure depicts an underfrequency event, the same time scales apply to overfrequency events as well.

1.1 State-of-the-Art of DER-based Frequency Support

PV and other DERs are not currently required to provide frequency support in the U.S., though they are in some other countries, notably Germany [2]. As of recently, most PV inverters available in the U.S. include the ability to reduce power output in response to overfrequency events following a frequency-watt droop curve. This function is similar to the governor droop control often enabled in synchronous generators, though inverters can typically respond much more quickly. Presently available PV inverters for residential- and commercial-scale applications typically do not include the ability to increase power in response to underfrequency events. Hence, while underfrequency events are more common and can be more severe than overfrequency events, the “low-hanging fruit” in terms of DER-based frequency support is simply to have PV systems reduce power in response to overfrequency via the frequency-watt function. This assumes the PV inverters are configured to remain online during (ride through) frequency events, as is the case in Hawaii but not yet in most of the U.S.

Frequency-watt control is an autonomous function that does not rely on communications for its operation. The inverter measures the AC grid frequency at its terminals and responds by modulating its output power to follow a droop curve such as the one shown in Figure 3.

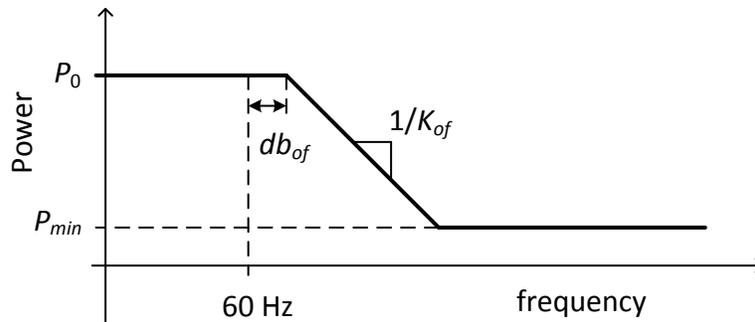


Figure 3: A frequency-watt droop curve

There are several possible forms the frequency-watt function can take. For example, the starting point of the droop curve, P_0 , can be the pre-disturbance operating power, or it can be the rated power. There is currently no standardized form for the frequency-watt function in the U.S. It is expected that in late 2017 a revision to IEEE 1547 will be approved that will contain a standardized frequency-watt specification, but it may take some time after that before most DERs manufacturers comply with the new IEEE 1547. The current draft of the revision to IEEE 1547 calls for P_0 to be the pre-disturbance operating power.

Underwriter's Laboratories (UL) Standard 1741 Supplement SA (UL 1741 SA) [3], published in September 7, 2016, provides a standardized test procedure for frequency-watt control. UL 1741 SA is largely agnostic to the form and parameters of the frequency-watt function; it relies on each utility to provide a Source Requirements Document that specifies the details of the desired grid support functions. In March 2017, Hawaiian Electric published its first SRD, which specifies frequency-watt control details that are closely aligned with those in the recently-balloted draft 6.7.2 of IEEE P1547. Hawaiian Electric's SRD Version 1.0 (SRD V1.0) [4] is the only SRD that calls for mandatory frequency-watt control; the California utilities officially consider frequency-watt control optional at this time.

According to a recent Hawaiian Electric survey of PV inverter manufacturers selling inverters in Hawaii, most manufacturers can already implement frequency-watt control in some form, and about half can implement frequency-watt in the form specified in Hawaiian Electric's SRD V1.0 [4]. However, most manufacturers stated that they would not have UL 1741 SA certified products available to meet Hawaiian Electric's SRD V1.0 by the deadline of September 7, 2017 as specified in Rule 14H. It appears that some manufacturers are obtaining UL 1741 SA certification using other forms of the frequency-watt function rather than the form specified in Hawaiian Electric's SRD V1.0.

While frequency-watt control does not rely on communications, a communication pathway could be used if desired to remotely change frequency-watt settings. At the time of this writing, most inverter manufacturers support some form of communications, but there is no single communications protocol that is supported by all manufacturers, and not all distribution-connected PV systems are connected to a communications network. Thus there would be no uniform way to remotely configure and activate the frequency-watt function (or any other function) for many PV systems from many different manufacturers. This project focuses on the power functionality with the assumption that if frequency-watt control is enabled in the near future, each PV system will be configured to provide it at the time of installation.

While frequency-watt control of inverters is similar to conventional generator governor droop response (typically used for primary frequency response, or PFR), it differs in several key ways:

1. Typically only downward response is available today, as most PV inverters are operating at their maximum available power most of the time.
2. An inverter's response can be much faster than a conventional generator's response if desired. While synchronous generators typically have power response time constants on the order of a few seconds, inverters can typically adjust power in less than one second if desired.
3. PV systems are coupled to the grid through power electronics and do not have rotational inertia, so they do not have an inherent physical mechanism for resisting frequency change.

While inverters do not have stabilizing inertia, their ability to respond quickly can allow them to support grid frequency on what are conventionally considered inertial time scales [5]. This ability to respond quickly can be beneficial in low-inertia power systems such as those in Hawaii because frequency events happen very quickly (i.e. with high rate of change of frequency, ROCOF), so resources providing PFR must do so very quickly. However, there may be increased risks of unintended consequences associated with fast responses [6]. Inverters can be controlled to emulate inertial response (imperfectly), though this is not addressed in the upcoming revision to IEEE 1547. Even when performing frequency-watt droop control, inverters can do so much faster than synchronous generators such that the response begins during the portion of the frequency event where inertia conventionally dominates, though the effect is not the same as physical inertia.

Theoretically, inverters can also respond to underfrequency by increasing output power [7], [8]. For PV inverters, which make up the vast majority of DERs in Hawaii, this would require operating with some reserve power (i.e. below maximum power), which entails a significant opportunity cost. Battery inverters can provide upward response, but most residential- and commercial-scale battery inverters do not currently offer this capability.

While synchronous generators providing PFR often also provide secondary frequency regulation (also known as automatic generation control, or AGC), AGC requires reliable continuous communication with the utility, which DERs typically do not have available. Therefore, while it is possible for PV and storage systems to provide AGC [7], [9], that is not considered in this project.

To summarize, the focus of this report is on evaluating the ability of distributed PV systems to provide PFR through frequency-watt droop control on time scales faster than conventional PFR. This response does not require communications. In addition, this interim report focuses specifically on overfrequency response and does not consider underfrequency response.

2.0 Open-loop Inverter Testing

Three PV inverters' frequency-watt control responses were evaluated in a laboratory. A controllable AC power supply was used to apply frequency transients to each inverter while it was programmed with various frequency-watt curves, and the inverter's response was recorded.

Quantifying the time-domain dynamics of an inverter's response to a frequency change is challenging. One common method of characterizing the time-domain response of a system to a

change in an input is to step the input signal from one value to another and record the output response over time. However, many inverters will trip if a step change in frequency is applied; inverters are not designed for this as step changes in frequency do not occur on power systems containing synchronous generation. Even if the inverter does not trip, its response to a step change in frequency may not be indicative of its response to a real frequency event, as the step change may cause its internal frequency measurement to become temporarily inaccurate. Therefore the inverters were tested using relatively fast frequency ramps rather than frequency steps. Frequency ramp rates were in the range one to three Hertz per second for most tests, faster ROCOFs were used in some tests in an attempt to better quantify the inverters' responses. Test waveforms were recorded at 50 kHz sample rates and post-processed to calculate power, frequency, and other quantities.

Figure 4 shows a plot of the time response of Inverter 1 to a fast frequency change. The inverter's active power response is fast and well-damped, completing within about 0.5 s of the end of the frequency ramp with no undershoot. The inverter's reactive power response does show some unexpected dynamics during and immediately after the frequency event. This may indicate that while the inverter's active power control loop handles high ROCOF events very well, the reactive power control loop's response to such events could be improved. While the slight fluctuation in reactive power may cause some brief local voltage variations, it is not of concern from a frequency stability perspective.

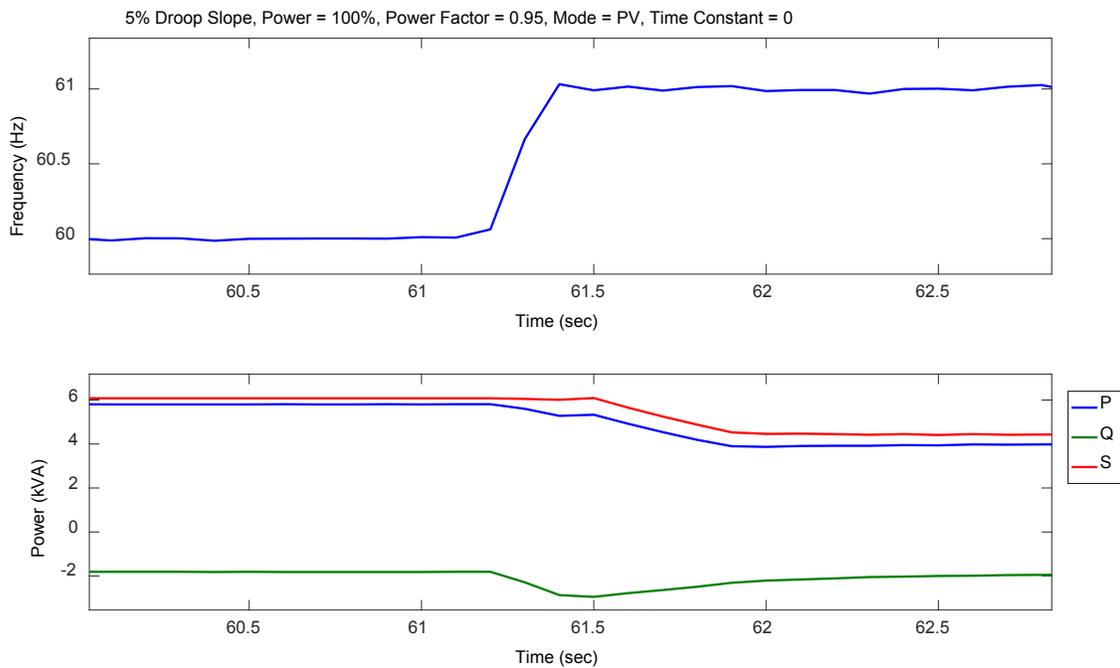


Figure 4: Example of Inverter 1 frequency-watt time response

The left portion of Figure 5 shows the measured frequency and power of Inverter 1 during a frequency-watt test similar to those prescribed in UL 1741 SA. The frequency is adjusted upwards and then back downwards in a series of “steps” The ROCOF from one step to the next is 1 Hz/s. At each step, the measured active power is plotted versus the frequency in the right-hand portion of Figure 5. The expected active power according to the programmed droop curve

is superimposed on the measurements. The measured droop curve matches the expected droop curve very well.

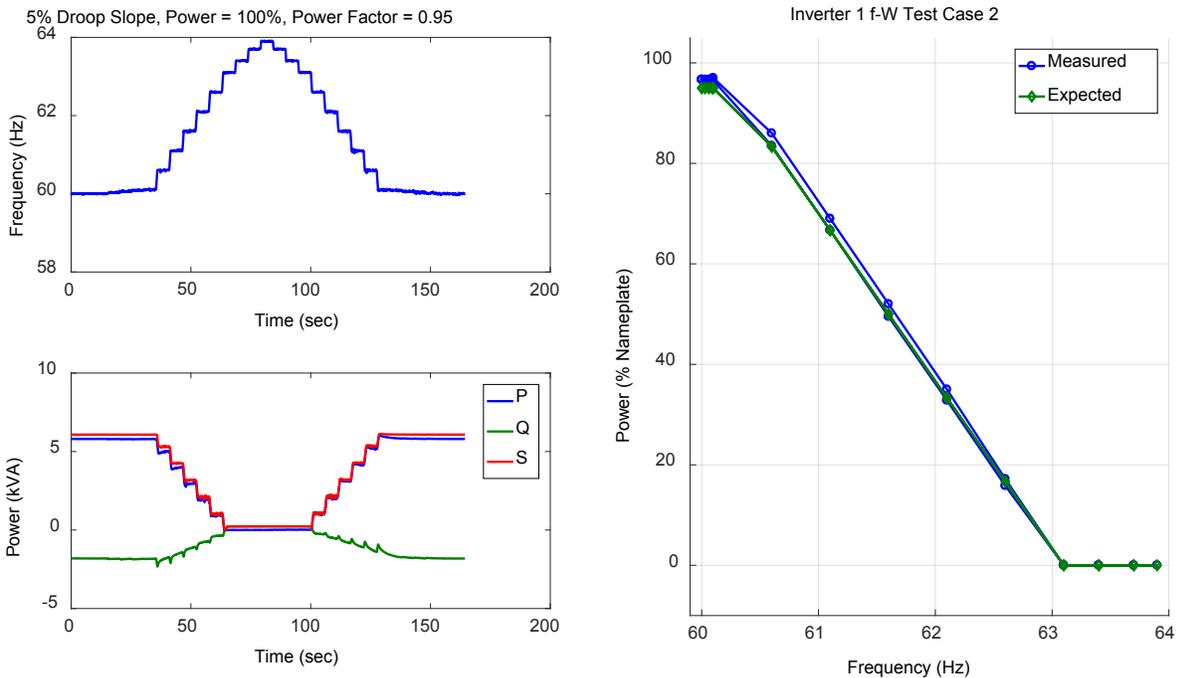


Figure 5: Example of Inverter 1 steady-state frequency-watt response test

Inverter 2 tended to undershoot slightly in its power response to fast frequency changes, as seen in Figure 6. Therefore it was modeled using a second-order transfer function. The simulated response is superimposed on the hardware test response in Figure 6. This inverter model represents roughly 2.4% of the distributed PV on Oahu, so the effect of its undershoot is expected to be small (and was found to be small in subsequent PHIL testing). The manufacturer of this inverter was informed of these test results and may make control modifications given simulations presented later in this report show that such undershoot in frequency-watt response can be detrimental to system stability in large quantities.

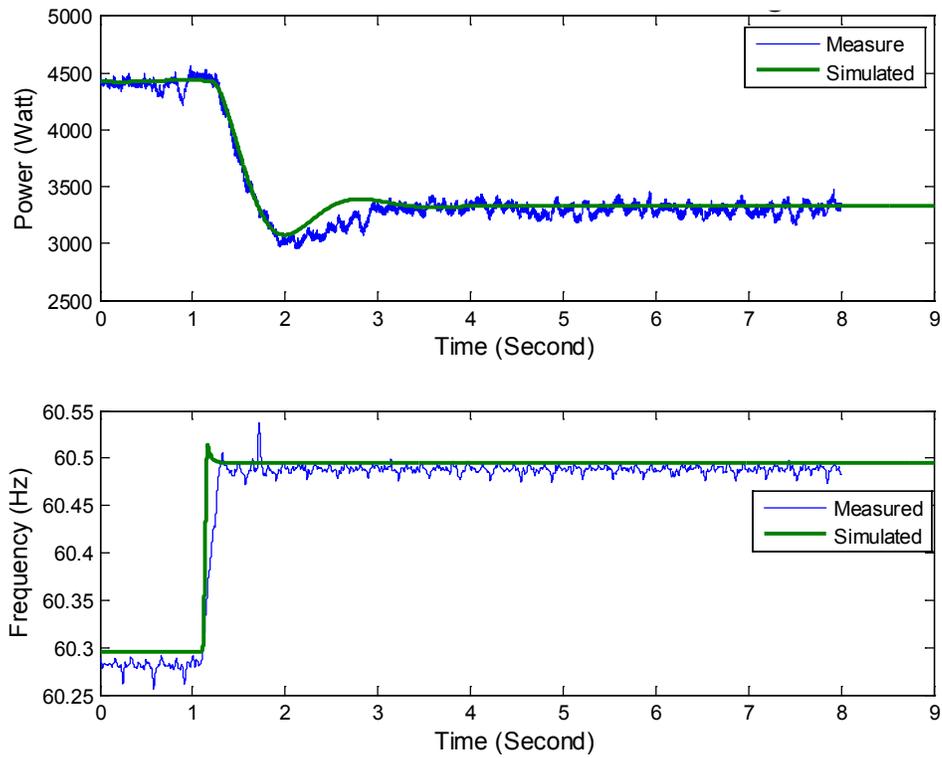


Figure 6: Example of Inverter 2 frequency-watt time response

An example of the response of Inverter 3 to a very fast frequency change (six Hz/s ROCOF) is shown in Figure 7. The inverter response is fast and well-damped, completing within about 250 ms of the end of the frequency ramp with no overshoot despite the very fast ROCOF.

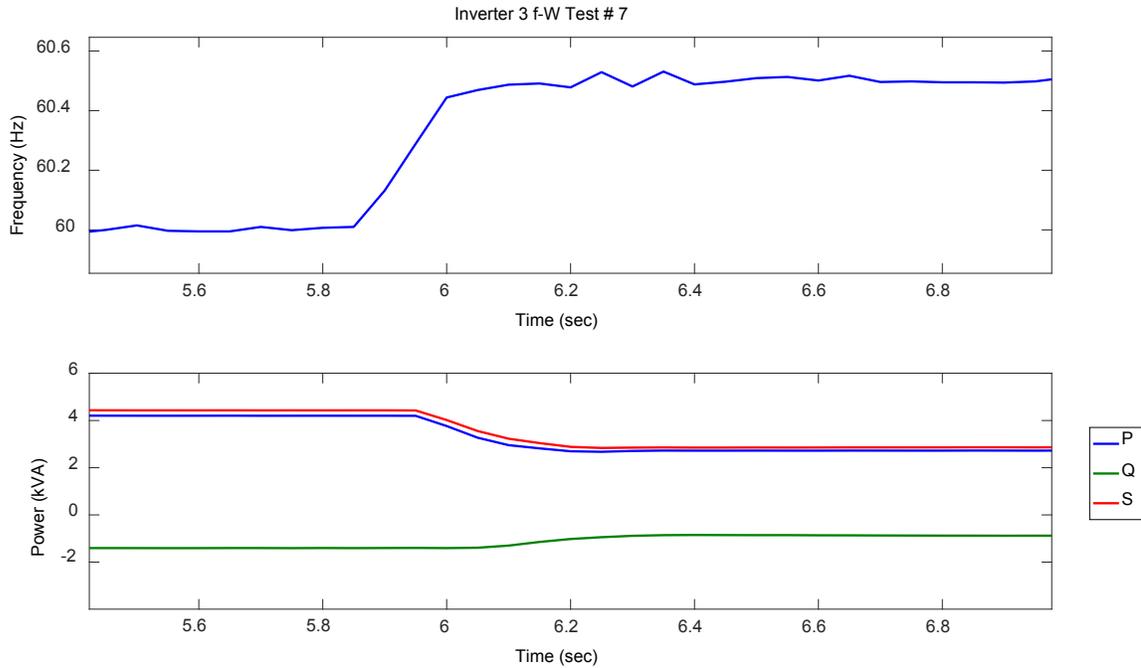


Figure 7: Example of Inverter 3 frequency-watt time response

Figure 8 shows a comparison of the measured steady-state power and expected power during a series of frequency changes designed to trace the frequency-watt curve, similar to a UL 1741 SA frequency-watt test. The measured curve matches well to the expected curve. Other tests of this inverter showed some discrepancies between the measured curve and the expected curve. The discrepancies are believed to be a result of the inverter not yet having been programmed by the manufacturer for the form of the frequency-watt function required by Hawaiian Electric's SRD V1.0, which was published March 10, 2017, after these tests were conducted. In addition, the inverter sometimes stopped reducing power before reaching zero. An example of a test with this larger discrepancy is shown in Figure 9. At the time of this test, this inverter was not yet certified to UL 1741 SA. It is expected that the failure to reach zero power when expected would be resolved before or during UL 1741 SA testing.

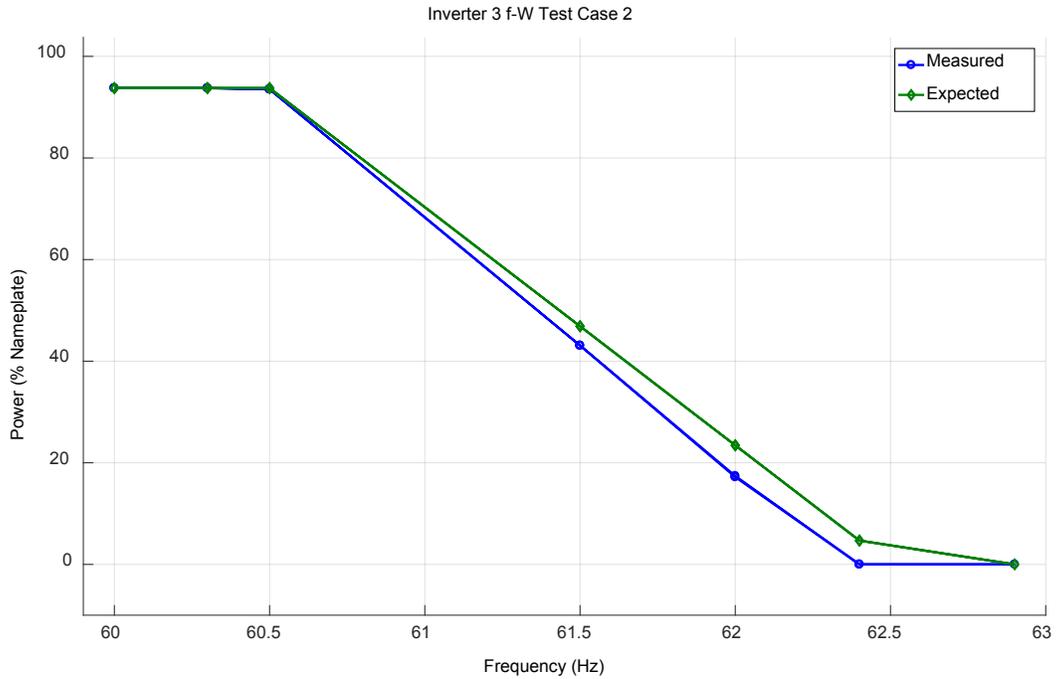


Figure 8: Example of Inverter 3 steady-state frequency-watt response

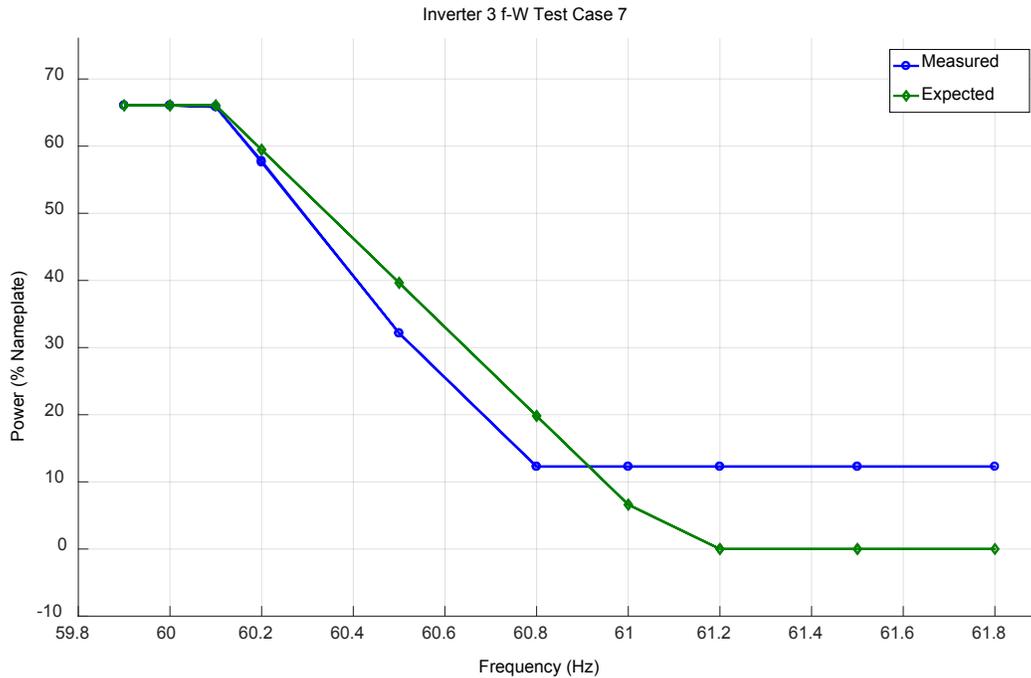


Figure 9: Example of Inverter 3 steady-state frequency-watt response with larger discrepancies between measured and expected power

Overall, all three inverters tested had satisfactory frequency-watt responses considering both response time and steady-state characteristic, especially considering that no U.S. utility has yet required frequency-watt control for distributed PV at the time of testing. These tests occurred

before the publication of Hawaiian Electric’s SRD V1.0, which defined the form of the frequency-watt function for Hawaii, and before the inverters were certified to UL 1741 SA. It is expected that remaining wrinkles in the inverters’ frequency-watt control will be ironed out as the inverters prepare for and go through UL 1741 SA certification testing.

3.0 Bulk Power System Simulations

This section describes simulations conducted to examine the effects of PV inverter frequency-watt control on the transient stability of the Oahu bulk power system. Hawaiian Electric’s dynamic model of Oahu’s projected bulk power system in the year 2019 was used for these simulations. The specific generation dispatch modeled was a lightly-loaded case with high non-synchronous generation (the “light Spring” mix), as this represents the highest stability risk for loss-of-load scenarios on Oahu. Siemens’ PSS/E software was used, and a user-defined model (UDM) of aggregate distributed PV generation was developed and tuned based on lab testing of residential-scale PV inverters. The 2019 light Spring PSS/E model and the PV UDM were used to simulate a variety of loss-of-load cases.

3.1 Distributed PV User-defined Model for PSS/E

Current-controlled PV inverters design has been extensively investigated in the literature – see [10] and the references therein. Typically, a dq -frame current-controlled inverter controller consists of an inner current control loop and an outer power control loop. The dq -frame is synchronized with the grid voltage using a phase locked loop (PLL). The current control loop is responsible for regulating the output current of the inverter, while the power control loop is responsible for adjusting the reference current for the current controller in order to control the output power of the inverter. Typically, the inverter is controlled to produce the maximum available power based on a maximum power point tracking (MPPT) controller.

Figure 10 shows the simple model used here to capture distributed PV inverter frequency-watt dynamics. For bulk power system transient stability analysis, the fast switching transients of inverters occur on a much faster time scale than the power system dynamics and can be neglected. Hence inverters are typically represented as controlled power sources. In this report, the inverter is modeled by a first order transfer function with a time constant which models the speed of response of the inverter’s power control. The frequency-watt function is modeled as a lookup table indexed by the measured frequency of the system. An optional first order block is used to model the frequency measurement dynamics, i.e. the PLL. In Figure 10, T_1 represents the time constant associated with frequency measurements, which accounts for PLL and other related dynamics; T_2 represents the inverter’s power regulation response time; P_{set} represents the power set point of the inverter in steady state; and P_{out} is the total output power of the inverter. The frequency-watt function is modeled using droop and deadband values as shown in Figure 11. Other equivalent parametrized representations could be used as well [11]. For typical PV inverter operation, the inverter is usually exporting its maximum available power, so P_{set} is equal to the maximum available PV power, P_{avail} . Thus the PV inverter only responds to overfrequency events and cannot increase power in response to underfrequency events. Once the output power of the inverter is determined by the model, a current source representation is connected to the PSS/E transmission network and used in the transient stability simulations.

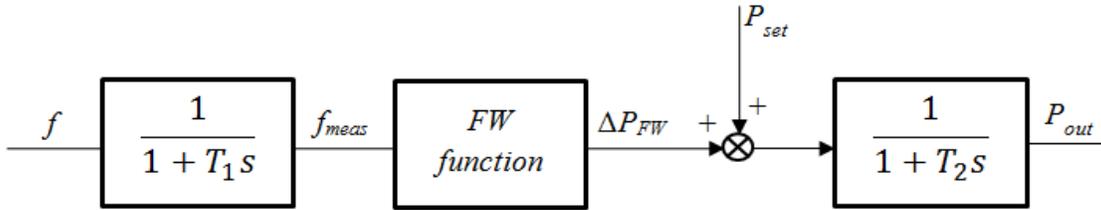


Figure 10: Distributed inverter PV model including frequency-watt function

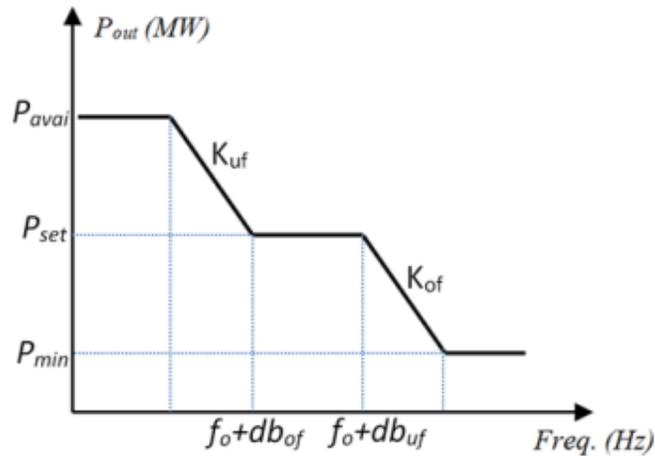


Figure 11: Frequency-watt function parameters

3.2 Sensitivity Analysis

A dynamic PSS/E model of the Hawaiian island of Oahu was obtained from Hawaiian Electric for the 2019 lightly-loaded Spring-season planning case. In this model the aggregate distributed PV power was 467 MW, which represents about 50% of the load. DERs were aggregated at their respective transmission buses and a PSS/E user-defined model was developed to model the aggregated DER based on the block diagram shown in Figure 10.

To study the performance of the system for overfrequency events, a light Spring case with total load of about 920 MW was used. The total system inertia (kinetic energy at 60 Hz) for this case is 3143 MW-seconds. The case has seven active synchronous generators with a total output of 262 MW, two active synchronous condensers, and transmission-connected renewable sources with a total output of 192 MW. The rest of the generation fleet is comprised of distributed PV with a total of 467 MW. Only 322 MW of the distributed PV inverters were equipped with the developed UDMs and thus enabled to participate in frequency response. The rest of the distributed PV inverters represent legacy PV and were assumed to inject constant power regardless of the frequency on the short time scales simulated here. For this simulation study, the initiating contingency is the loss of 62 MW of load due to a transmission failure, which causes an additional loss of 20 MW of distributed PV by configuration. This contingency was identified by Hawaiian Electric as a worst-case loss of load scenario.

Table 2: Oahu 2019 Light Spring Case Generation Mix

	Instantaneous Power (MW)	Instantaneous power proportion
Total Generation	920	
Synchronous Generation	262	28.5%
Wind	64	7.0%
Station PV	128	13.9%
Distributed PV*	467	50.8%
Energy Storage	0	0.0%
Renewables (Total)	659	71.6%
*322 MW of distributed PV was equipped with frequency-watt control.		

Sensitivity analysis is presented for the Oahu frequency response with respect to the following parameters:

- Inverter’s power control response time
- Frequency-watt function droop slope
- Penetration of frequency-watt-enabled inverters.

The base frequency-watt parameters are shown in Table 3. The value of the frequency measurement time constant, T_1 , was chosen conservatively; it is expected that modern frequency measurement methods can act more quickly. Frequency measurements methods vary between inverter models and are a crucial component of effective frequency response. In the sensitivity analyses described below, the appropriate parameters from Table 3 were varied to investigate their effects on the Oahu frequency response.

Table 3: Frequency-watt function base model parameters

Frequency measurement time constant	T_1	0.5 sec
Power response time constant	T_2	0.5 sec
Underfrequency deadband	db_{uf}	-36 mHz
Overfrequency deadband	db_{of}	+36 mHz
Underfrequency droop slope	K_{uf}	5%
Overfrequency droop slope	K_{of}	5%
Nominal frequency	f_0	60 Hz

The hardware inverters' time responses were found to be faster than the default values shown above. For example, in most PHIL tests the measurement response time was set to 0.15 s and the power response time was set to 0.125 s; these values were found to match reasonably well with the behavior of hardware Inverter 1. The manufacturer of Inverter 3 states a frequency-watt response time of 0.5 s, which includes both the measurement response time and the power response time. Inverter 3 is certified to UL 1741 SA with this frequency-watt time response. Inverter 2 was modeled as having a second-order time response with an open-loop response time on the order of 0.5 seconds. In summary, response times defined by the time constants shown in Table 3 are within the hardware inverters' capabilities.

3.2.1 Sensitivity to inverter's response time

In this series of simulations, the inverter response time constant, T_2 , was varied between 0.1 to 10 seconds. As shown in Figure 12 and Figure 13, slowing down inverters (i.e. increasing T_2) resulted in higher magnitude of oscillations and higher frequency apex values. However, as shown in Figure 13, as T_2 increases further, the frequency apex continues to increase, but the magnitude of subsequent oscillations tends to decrease again. The magnitude of oscillations peaks around $T_2 = 5$ to 7 seconds (corresponding to a 12.5-17.5 second response time), likely due to excitation of a natural mode of the Oahu power system related to synchronous generator governor-turbine dynamics.

It is important to note that the PSS/E model would not capture any sub-synchronous interactions between the frequency-responsive inverters and the synchronous generators. Therefore the sensitivity analysis shown here should not be taken to indicate that no sub-synchronous interactions will occur. For example, sub-synchronous torsional interactions between the power injection from the distributed PV inverters and the torsional modes of turbine shafts [12] would not be captured in these simulations. The investigation of sub-synchronous interactions is beyond the scope of this work.

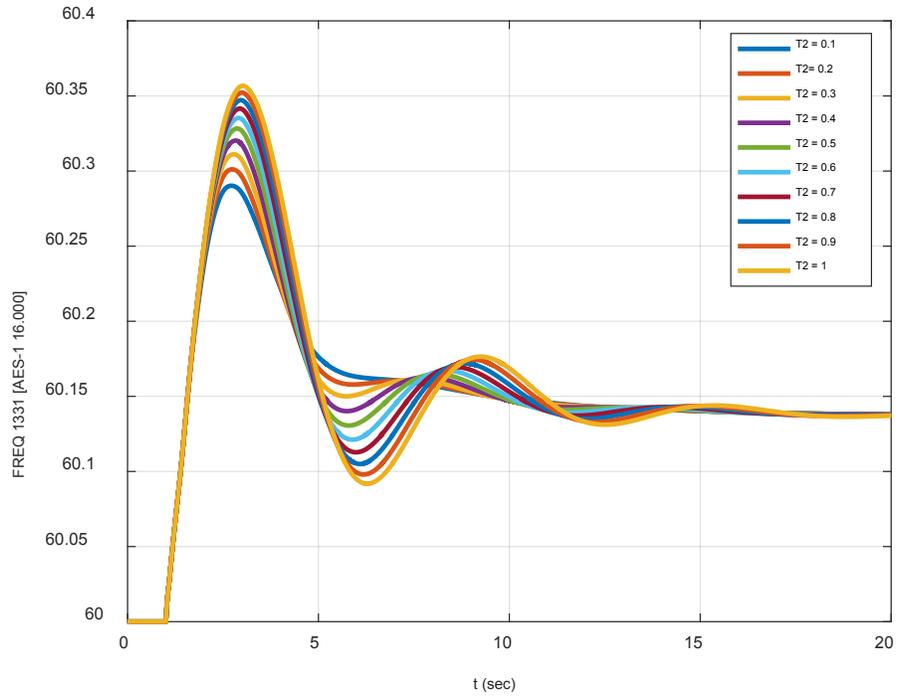


Figure 12: Sensitivity to inverter time constant T_2 with $K_{of}=5\%$ and $T_1=0.5$ s

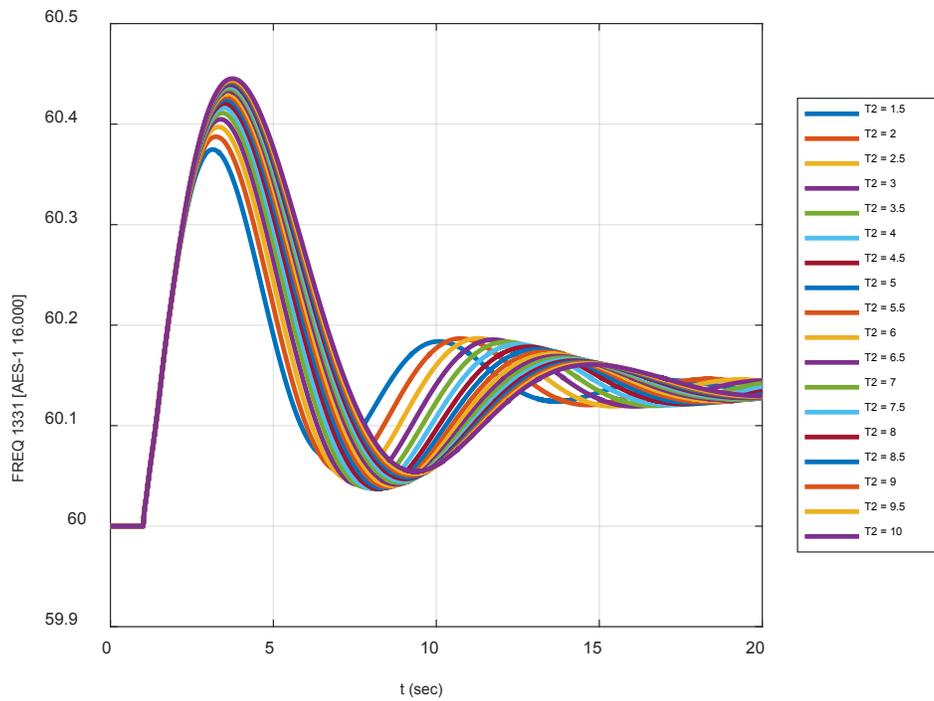


Figure 13: Sensitivity to inverter time constant T_2 with $K_{of}=5\%$ and $T_1=0.5$ s

3.2.2 Sensitivity to frequency-watt droop slope

In this series of simulations, the droop slope of the frequency-watt function was decreased from 5% to 1%, which *increases* the magnitude of the inverters' response to a given frequency change.¹ As a result, the frequency response was improved, as measured by the frequency apex, shown in Figure 14. However, steeper droop also resulted in higher magnitudes of oscillations in the frequency response, as shown in Figure 15. The oscillations become large and poorly-damped for the steepest droop slopes.

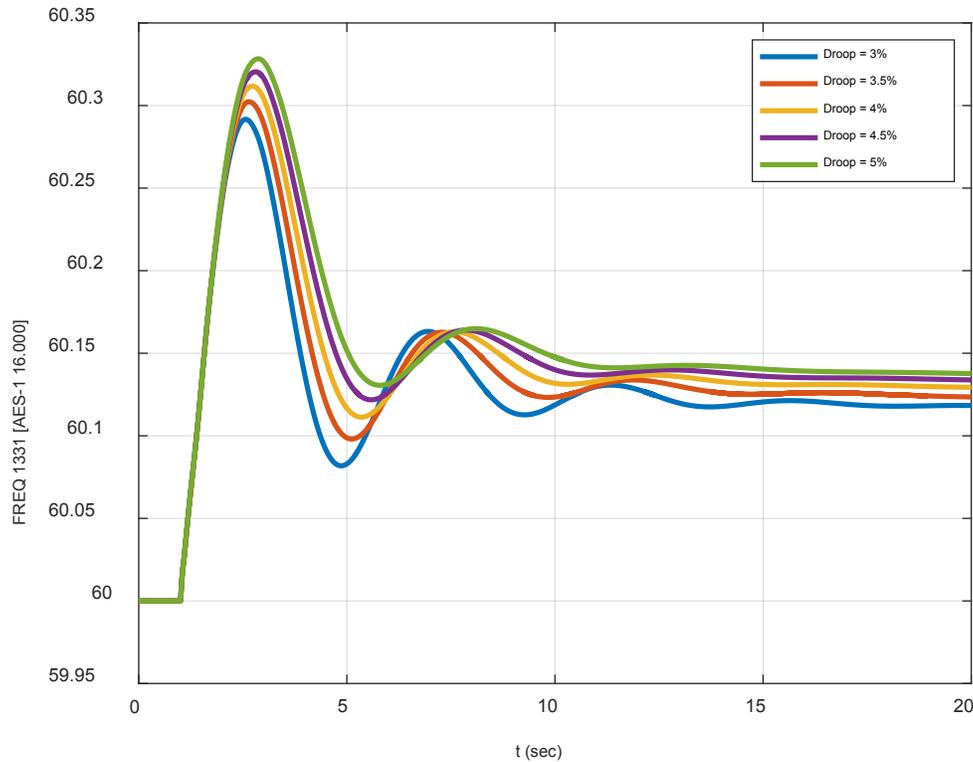


Figure 14: Sensitivity to variation in droop slope with $T_1 = 0.5$ sec $T_2 = 0.5$ sec

¹ A 5% droop slope indicates the inverter power changes by 100% of its power rating in response to a frequency change equal to 5% of the nominal frequency. For example, for a 5% droop, a 3 Hz change in frequency will result in the inverter dropping from its rated power to zero. Likewise, for a 1% droop, a 0.6 Hz change in frequency will result in the inverter dropping from full rated power to zero.

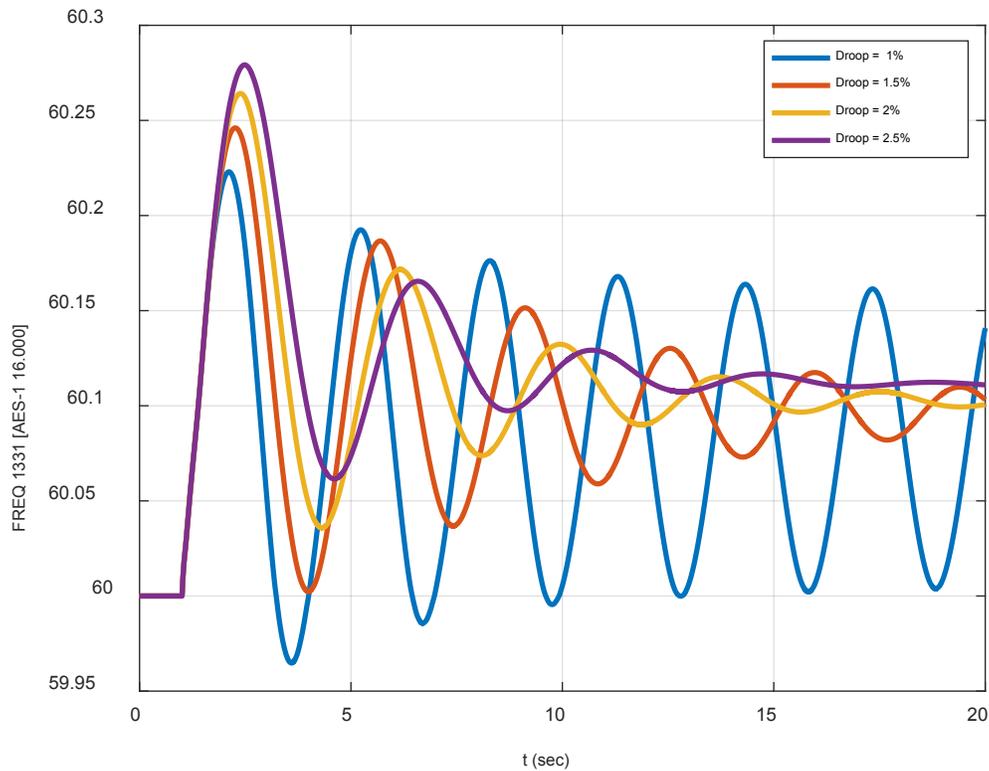


Figure 15: Sensitivity to variation in droop slope with $T_1 = 0.5$ sec $T_2 = 0.5$ sec

3.2.3 Sensitivity to frequency-watt deadband

In this series of simulations, the deadband of the frequency-watt function was varied between 36 mHz to 5 mHz, which makes the inverters more responsive to frequency changes. As shown in Figure 16, the frequency response was improved as measured by the frequency apex, however, the improvement is not significant.

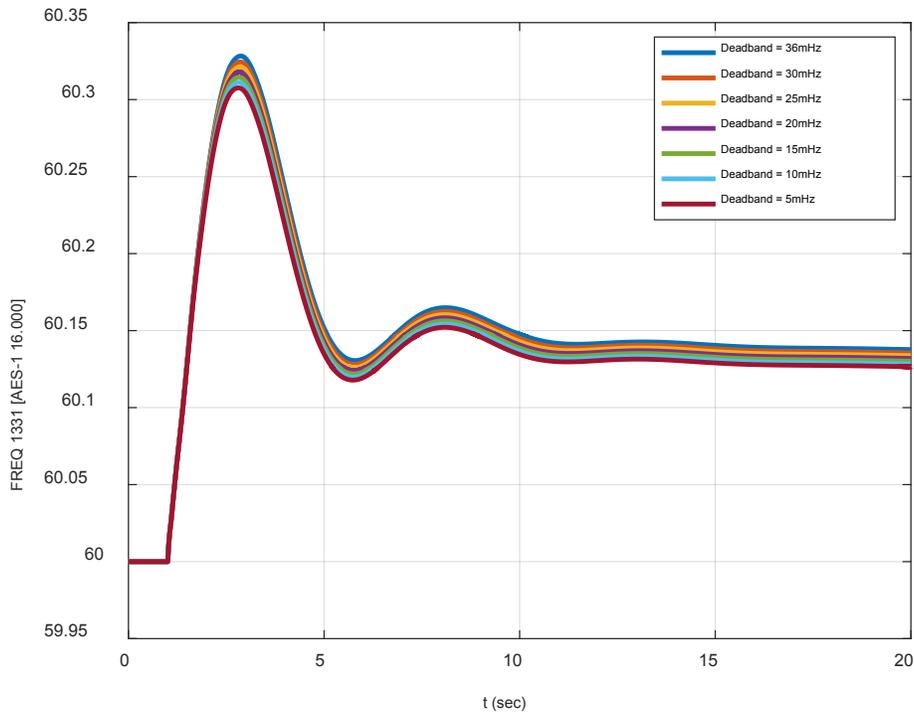


Figure 16: Sensitivity to variation in deadband with $T_1 = 0.5$ s $T_2 = 0.5$ s and $K_{of} = 5\%$

3.2.4 Sensitivity to penetration of frequency-watt enabled inverters

This series of simulations increased the penetration level of frequency-watt enabled inverters. Increasing the level of frequency-watt enabled inverters in the system resulted in better frequency response, as determined by the frequency apex and settling frequency, as shown in Figure 17. However, depending on model parameters, higher penetrations can make the system more susceptible to oscillations, especially if parameters are not chosen well. For example, Figure 18 shows that the frequency oscillations associated with steep droop slopes become more severe as the amount of PV responding to frequency increases.

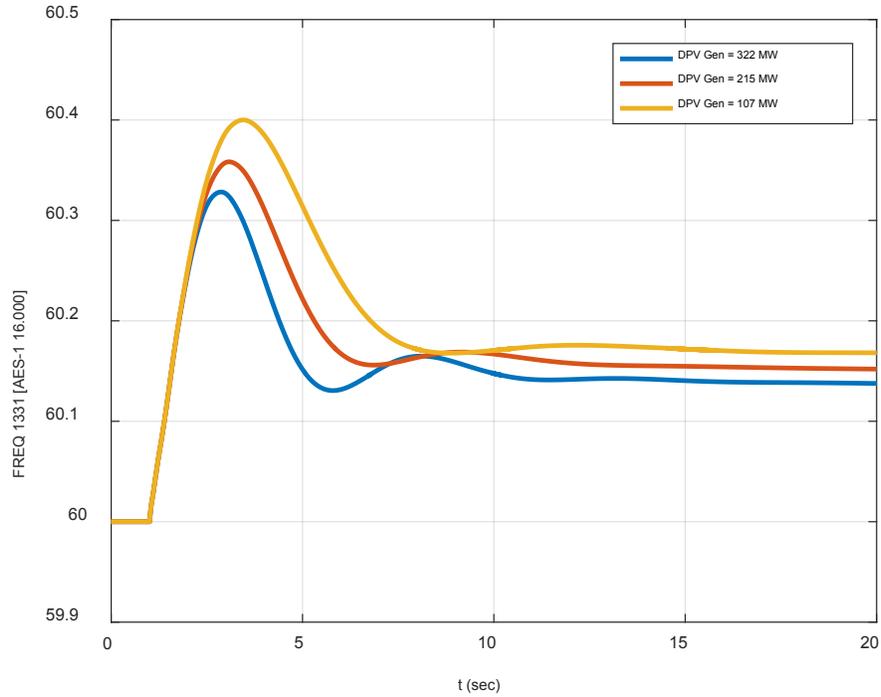


Figure 17: Sensitivity to variation in frequency-watt enabled PV penetration $T_1 = 0.5$ s, $T_2 = 0.5$ s, and $K_{of} = 5\%$

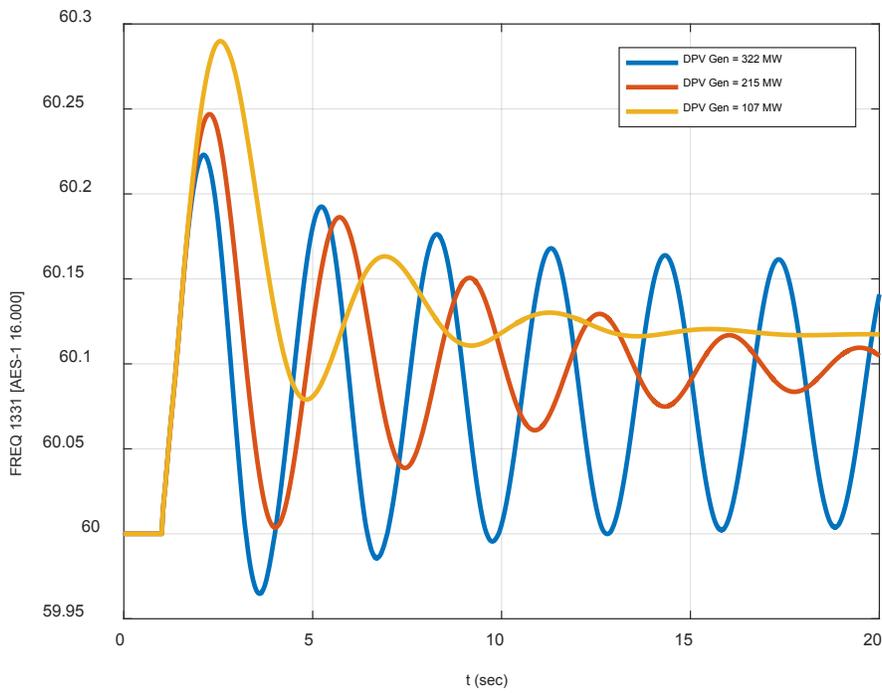


Figure 18: Sensitivity to variation in frequency-watt enabled PV penetration with $T_1 = 0.5$ s, $T_2 = 0.5$ s, and $K_{of} = 1\%$

3.3 Bulk power simulation with overfrequency PV trip

To investigate the effects of a slightly more severe overfrequency event, the load rejection event simulated above was modified so that the loss of load was not mitigated by a concurrent loss of PV. In addition, the aggregate power from legacy PV prior to the event was increased to 150 MW. As seen in the blue traces in Figure 19, this event reaches 60.5 Hz, which causes the legacy PV to trip offline. This in turn causes an underfrequency event which results in the activation of an underfrequency load shedding block (the large drop in load around four seconds into the event in Figure 19). The red trace in Figure 19 shows the same events with frequency-watt control enabled, which prevents the frequency from reaching 60.5 Hz and thus prevents the underfrequency event and associated load shedding.

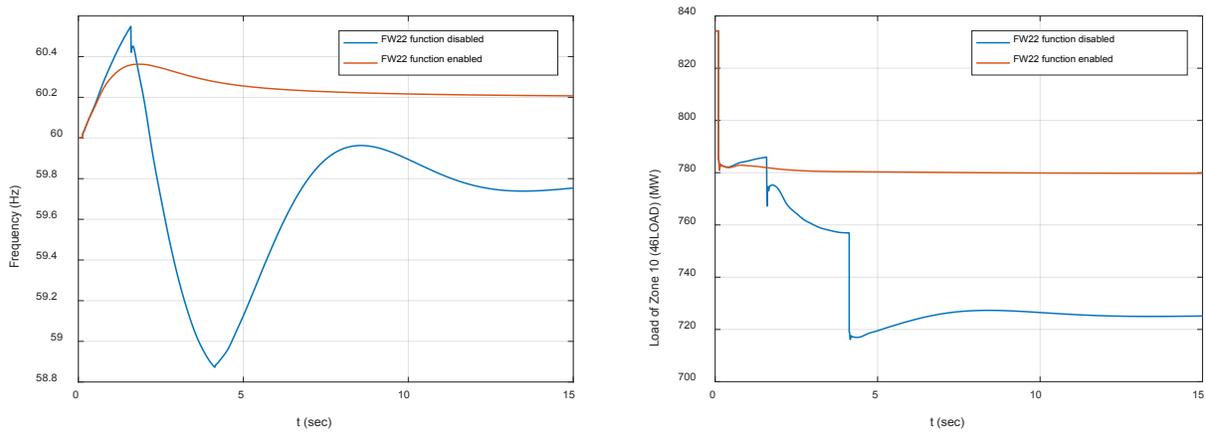


Figure 19: More severe overfrequency event showing trip of legacy PV system on overfrequency

Additional bulk system PSS/E simulations will be included in the full report.

3.4 Frequency-watt control during a fast irradiance ramp

Most of this report focuses on the ability of frequency-responsive PV inverters to mitigate overfrequency contingency events due to loss of load. While that is the primary purpose of frequency-watt control, it can also be useful in mitigating overfrequency events due to other causes. For example, over-generation due to fast irradiance ramps can also cause overfrequency. One such event occurred on Oahu on February 25, 2017, when the solar irradiance on a large area of Oahu ramped from 300-400 W/m² to over 750 W/m² over a period of a few minutes due to cloud movement. This resulted in an estimated increase in PV generation of 80 MW in about 10 minutes.

While it would likely not be feasible to simulate an event of many minutes duration in conventional transmission system transient software such as PSS/E, it is possible to dynamically simulate such an event using governor-only model of Oahu developed in this project by NREL. This model is shown conceptually in Figure 24 (in the next section) and will be described in detail in a subsequent publication. To simulate the February 25, 2017, event, the governor-only model was tuned to match the generation dispatch at the time of the event.

Estimated load was used for the simulation. The simulated frequency from the governor-only model is compared to the measured frequency in Figure 20. In this baseline simulation, as on Oahu during the event, there is no frequency-responsive PV.

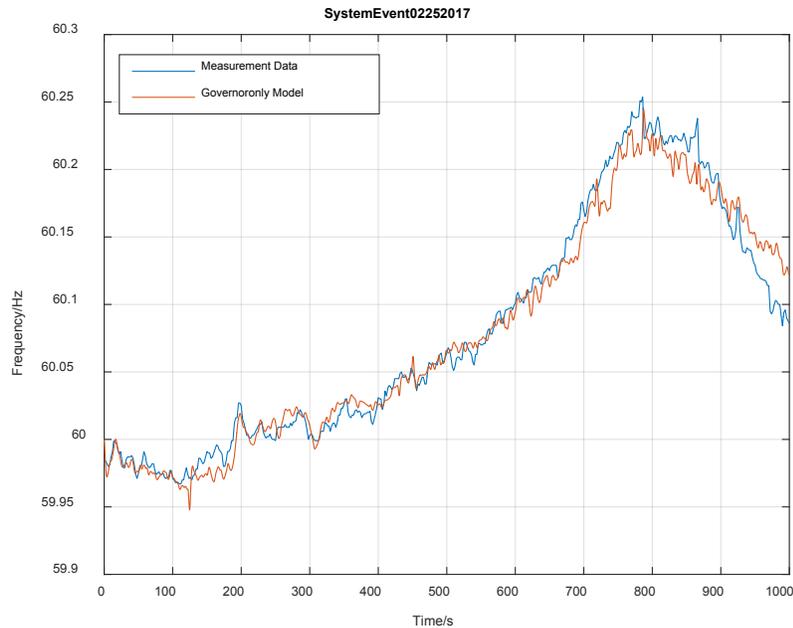


Figure 20: Measured and modeled frequency during a fast irradiance ramp event.

In the series of simulations Figure 21, half of the distributed PV had frequency-watt control enabled with varying droop slopes. The baseline case with no PV frequency-watt control is shown in light blue. As the droop slope increases, the PV generation decreases during the high-frequency period, and the peak frequency is reduced. However, for very steep droop slopes such as 1% and 2% (dark blue and orange, respectively), small variations in frequency due to load changes become amplified due to dynamic interactions with the frequency-responsive PV. The system does not become unstable for these steep droop slopes, but the fast and frequent variations in PV generation and frequency are not desirable. For low droop slopes (3% to 5%), the system frequency response shows a good balance between reduction in peak frequency and minimal amplification of small frequency variations, so the frequency-watt function is beneficial.

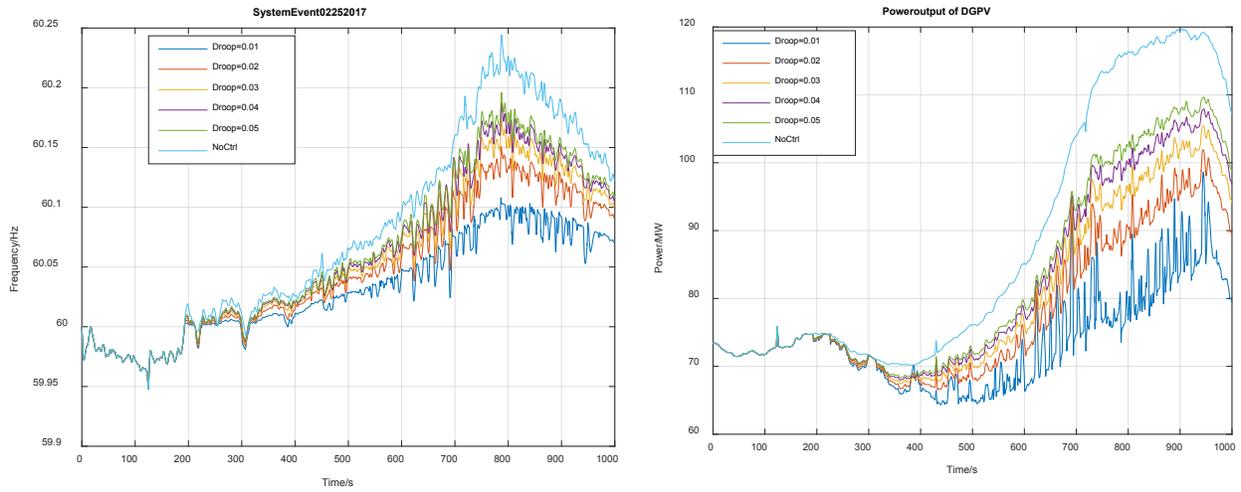


Figure 21: Simulations of an overfrequency event caused by a fast irradiance ramp with varying droop slopes

Figure 22 shows a comparison of different droop deadbands during the irradiance ramp event with the droop slope set to 5%. While smaller deadbands do reduce the peak frequency, the effect is fairly minimal.

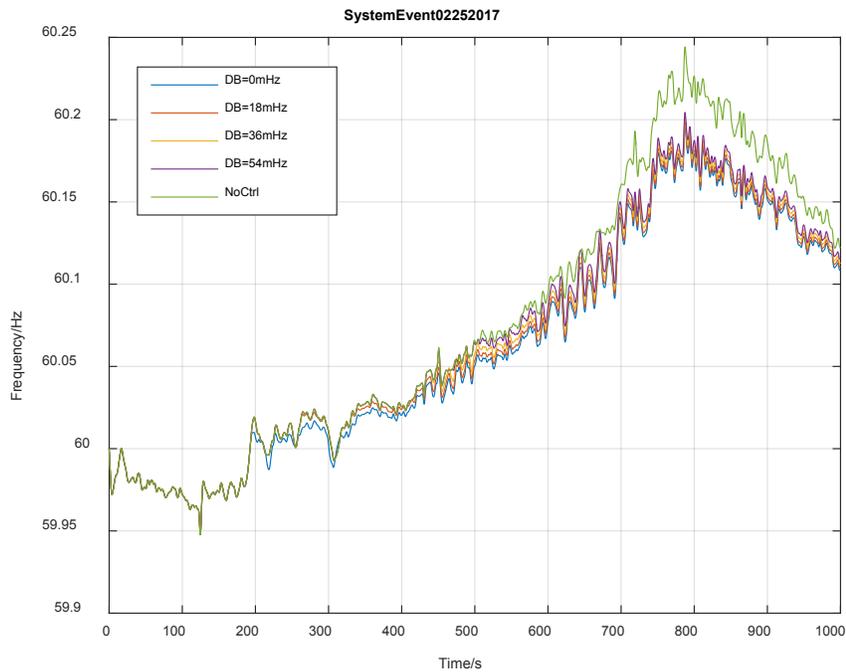


Figure 22: Comparison of frequency-watt deadbands during irradiance ramp event.

These simulations demonstrate that frequency-watt control can be effective in mitigating over-generation events due irradiance ramps as long as the parameters are selected well.

4.0 Power Hardware-in-the-Loop Testing

4.1 PHIL model overview

To evaluate the hardware inverters in an environment that emulates the dynamics that would be seen on a real Oahu distribution feeder during a frequency event, the real-time model of Oahu's bulk power system and a selected distribution feeder was developed, as seen in Figure 23. The real-time model was used to run PHIL tests in which two residential-scale PV inverters were connected to two nearby distribution secondary locations. Both the distribution model and the bulk system model were populated with modeled PV inverters representing a projection of the distributed PV that is expected to be present in 2019. The PV inverters' frequency-watt response was simulated using a model corresponding to the PSS/E user-defined PV model (Figure 10). Frequency events similar to those simulated in PSS/E were run using the PHIL setup, and the responses of the hardware inverters, the modeled inverters, the bulk system, and the distribution system were recorded. The operation of the real-time model is summarized here and will be described in detail in a forthcoming publication.

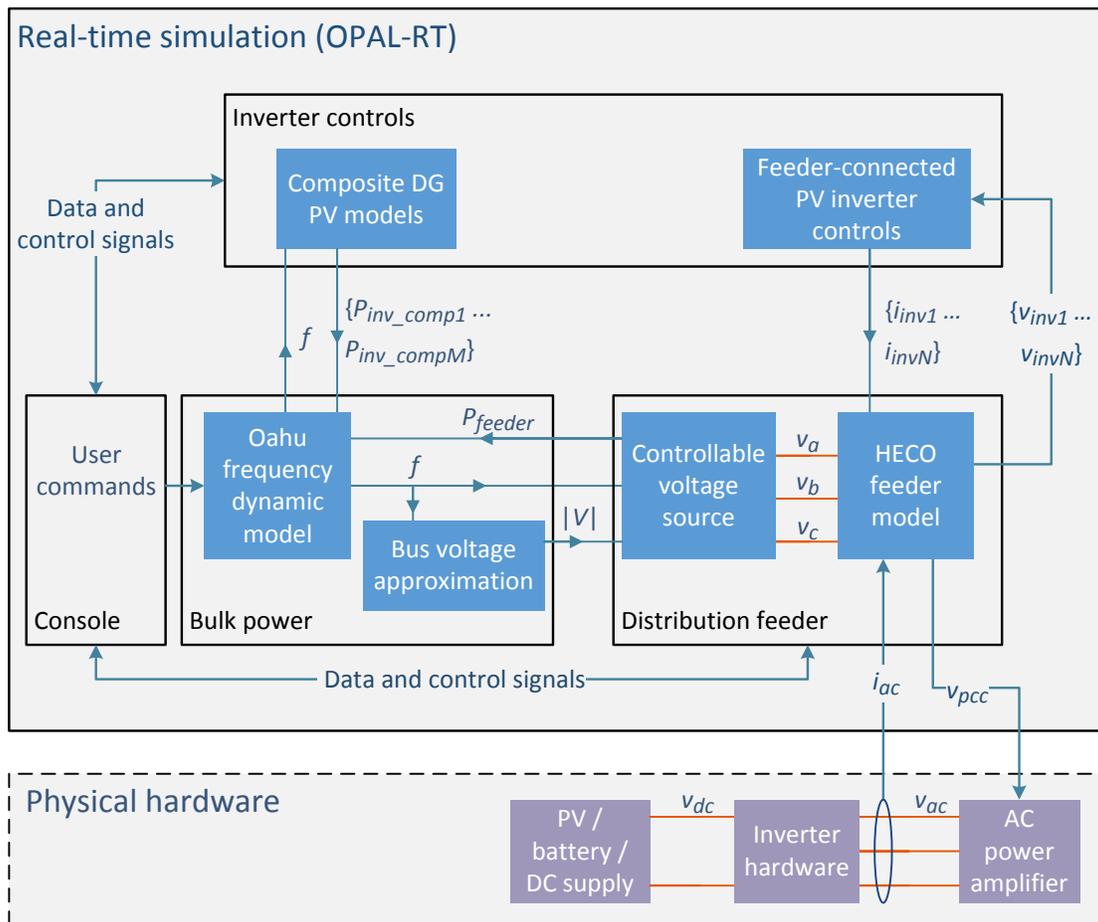


Figure 23: Real-time model of Oahu bulk system and distribution system for PHIL

The real-time bulk power system model was based on the one described in [13]. The model was modified to better capture the frequency dynamics of the Oahu power system. A schematic of the model is shown in Figure 24. The model solves for frequency directly without solving for electrical power flow. Synchronous generator governor and turbine dynamics are captured, as are the power-frequency dynamics of PV inverters. The inertia of the various generators is represented in aggregate, so the individual dynamics of the rotating generators are aggregated together, as in [14]. The aggregate bulk power system model was tuned to match the dynamics of Hawaiian Electric's PSS/E model with good but not perfect accuracy.

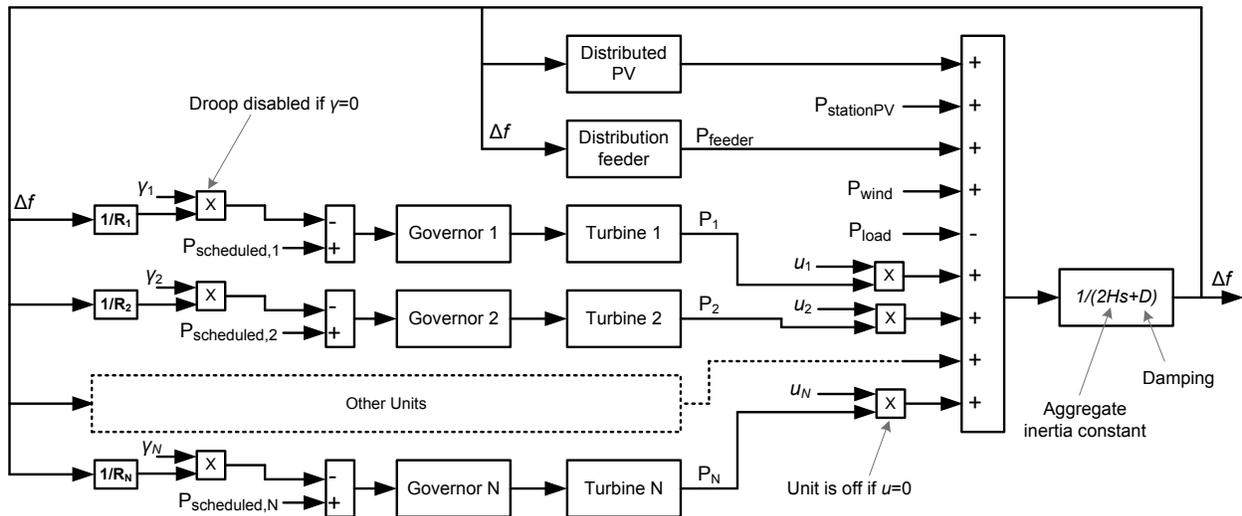


Figure 24: Oahu bulk power system frequency dynamic model

The frequency calculated in the bulk system model was used to drive the voltage at the head of a reduced order distribution model, as originally proposed in [15]. The reduced order distribution model was developed using the technique described in [16] from a Hawaiian Electric Synergi model of an Oahu distribution feeder with a high level of distributed PV. The overall approach is similar to that used in [13], but the following additional elements were added to better capture the realistic dynamics of a frequency event:

- Underfrequency load shedding dynamics were added to the bulk system model, including the effects of load shedding on distributed PV production.
- Aggregate models of the distributed PV inverters connected to the rest of the system were added to the model. Four types of distributed PV models were added:
 1. Legacy PV with no frequency ride-through and no frequency-watt control
 2. PV inverters with underfrequency ride-through but no overfrequency ride-through and no frequency-watt control
 3. Grid supportive PV inverters with full frequency ride-through and frequency-watt control with the power response modeled with a first-order transfer function
 4. Grid supportive PV inverters with full frequency ride-through and frequency-watt control with the power response modeled with a second-order transfer function

The frequency ride-through capabilities of these inverters represent the present and expected future PV on the Oahu power system, and the aggregate ratings of each type. Types 3 and 4 are intended to model the two types of frequency-watt response seen in laboratory testing. Because most inverters tested showed frequency-watt responses that can be well modeled with first order transfer functions, most frequency responsive PV was modeled using Type 3. Most tests were conducted assuming that all of the fully ride-through capable PV in 2019 was also capable of frequency-watt control. This assumption likely overestimates the amount of frequency-watt capable PV that will actually be present in 2019.

- The same four types of PV inverter models were also added to each node in the distribution system model with power rating that approximate the expected aggregate power rating of each type of inverter in 2019.
- Power changes in the modeled distribution system are now incorporated in the bulk power system model frequency dynamics.
- A method was developed for approximating the changes in voltage that occur on the selected distribution system due to bulk power system transients during load rejection events and generation loss events. This allows the model to expose the hardware inverters to realistic fast voltage transients that occur during frequency events, which better validates the inverters' ability to remain online and provide frequency support during such transients. The details of the method of approximating voltage transients associated with frequency events will be described in subsequent publications.

4.2 Selected PHIL test results

A series of PHIL tests were run using load rejection events similar to the PSS/E event shown in Figure 19 to initiate an overfrequency event. Selected results are described here, and a more complete set of results will be shown in the final report.

Figure 25 shows a series of four overfrequency events with the hardware inverters and modeled frequency-responsive inverters programmed with varying droop slopes. The solid lines in all PHIL tests represent measurements of hardware inverter responses, and the dotted lines represent modeled inverter responses. Several conclusions and observations can be made:

- With frequency-watt droop disabled (red traces), the frequency reaches 60.5 Hz, causing the legacy PV to trip and load shedding to occur, as in the PSS/E simulations.
- In the three cases with frequency-watt enabled (black, green and blue traces), the frequency-watt response prevents the frequency from reaching 60.5 Hz, so no subsequent underfrequency event occurs.
- For the cases with frequency-watt enabled, the hardware inverter responses match reasonably well with the corresponding modeled inverter responses. Some of the slight mismatch is due to slight differences in the pre-event power, and some is due to the fact that the inverter models are only an approximation of the hardware inverter dynamics.
- The steeper droop slopes (lower droop percentages) lead to more frequency oscillations, as in the PSS/E model.

- With frequency-watt control disabled, the hardware inverter shows some changes in power around its pre-event level. This is a characteristic of this particular inverter: its real and reactive power outputs diverge from their expected values during fast frequency transients. Because other inverters tested do not show this behavior, and because this inverter represents a small portion of the distributed PV on Oahu, the changes in reactive power when not in frequency-watt mode are not modeled. The downward spike in power for the red trace around 3 seconds is due to a voltage transient on the distribution system caused by the tripping of the legacy PV inverters. The two downward steps in the dotted red trace just before 5 seconds are due to the activation of two load shedding blocks, which trip the distributed PV systems in those regions, causing reductions the aggregate distributed PV power output.

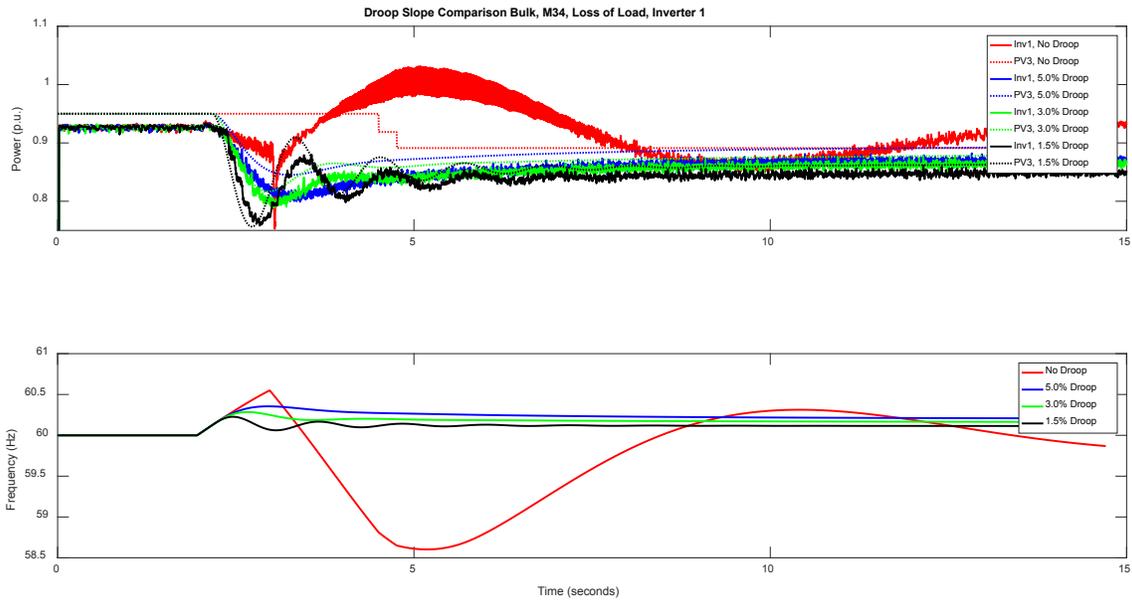


Figure 25: PHIL overfrequency events with varying droop slope – Inverter 1 response

Figure 26 shows the response of Inverter 2 to the same events. Most of the observations made above also apply to here. The four tests shown in Figure 26 are the same four tests shown in Figure 25; the two figures simply show different measurements extracted from the same tests. The frequency traces are identical, but are repeated for visual reference. The small spikes in power output at regular intervals several times per second are a characteristic of this inverter’s anti-islanding mechanism [17]. As with Inverter 1, the hardware inverter responses match the modeled inverter responses well but not perfectly.

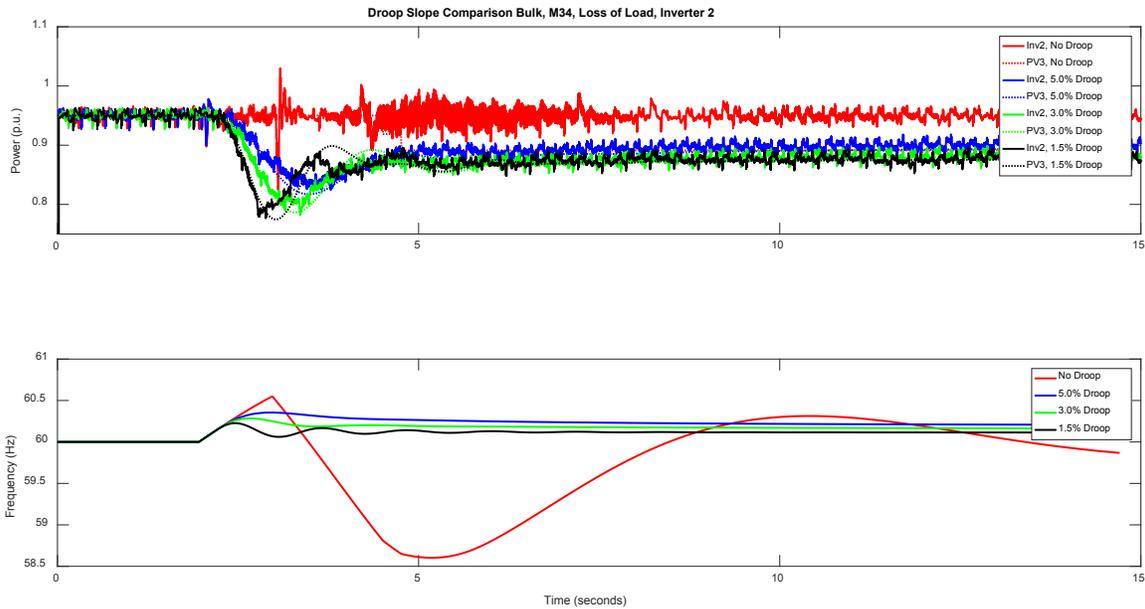


Figure 26: PHIL overfrequency events with varying droop slope – Inverter 2 response

Because it is possible (though not expected) that other inverters may react similarly, simulations were conducted with larger proportions of inverters modeled with second-order frequency-watt responses, up to 54.5%, which represents a scenario in which all of the distributed PV inverters currently on Oahu that are not made by the manufacturer of Inverter 3 are modeled as second order. Figure 27 compares the Oahu frequency response with varying proportions of inverters modeled as second-order, like Inverter 2. In the baseline test (red trace), the proportion of this inverter type is equal to the current (2016) penetration of this inverter type in Oahu, which is 2.4%. As the proportion of second order inverters increases, oscillations in frequency increase. Therefore it is recommended that as frequency-watt control becomes more common, inverter manufacturers should design their inverters so that the frequency-watt response is well-damped.

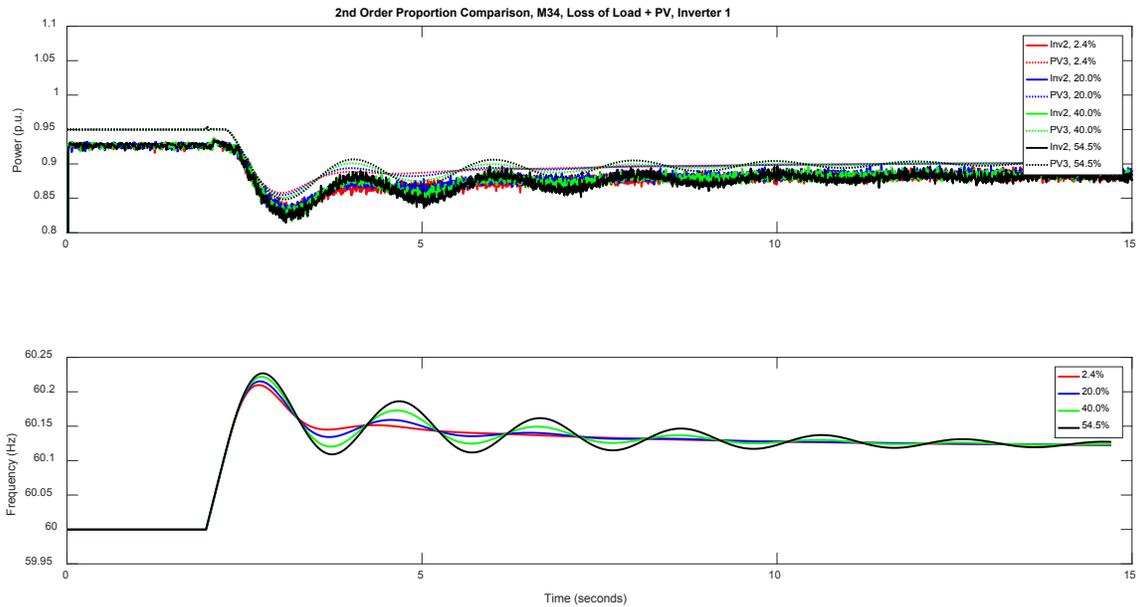


Figure 27: PHIL overfrequency events with varying droop slope – Inverter 2 response

Additional PHIL tests will be included in the full project report.

5.0 Impact of Frequency-Watt Control on PV Energy Production

Historical frequency data was analyzed to estimate how often frequency-watt control would reduce PV power production and what impact that reduction would have on monthly PV power production. Because frequency is essentially uniform throughout an interconnected power system, this analysis is much simpler than for voltage-related functions.

Oahu frequency data recorded every two seconds during the entire month of May 2017 was used for this analysis. May 2017 was a fairly typical month in terms of overfrequency events compared to other months in 2016 and 2017. Figure 28 shows a histogram of the Oahu frequency in May, with the vertical scale displaying the number of seconds frequency was within each histogram bin. Frequencies above 60.017 Hz are not uncommon. The maximum frequency for the month was 60.32 Hz, but the amount of time above 60.067 Hz was very small. This is consistent with what is generally known about overfrequency events: they tend to be brief and fairly uncommon.

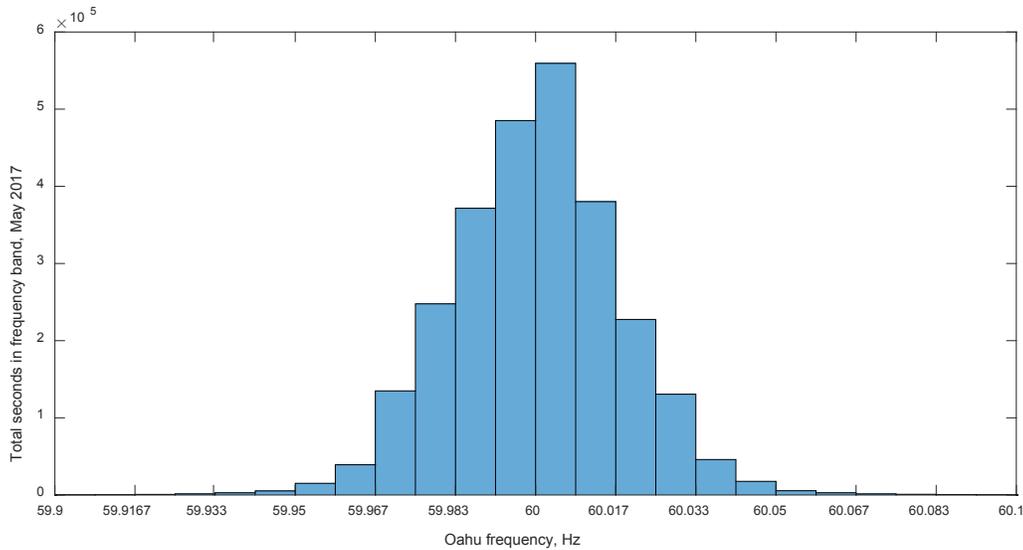


Figure 28: Oahu frequency histogram, May 2017

It may at first appear concerning that PV systems would experience substantial reductions in energy production due to frequency-watt control since frequencies above typical droop deadbands (e.g. 60.017 to 60.033 Hz) are not particularly uncommon. However, it is important to take into account not just how often the frequency exceeds the deadband, but also by how far. Frequencies well in excess of typical deadbands are quite uncommon. From the data used to produce the above histogram, it is possible to estimate the reduction in energy production that a PV system with a given deadband and droop slope would experience. Table 4 shows the estimated PV energy reduction as a percentage of expected monthly energy production for droop slopes of 4% and 5% and deadbands between 8.3 mHz and 50 mHz. In all cases the energy reduction is below 0.25%.

Table 4: Estimated impact of frequency-watt control on PV energy production

Deadband (mHz)	Droop (%)	PV energy reduction (%)
50	4	0.006%
33.3	4	0.023%
16.6	4	0.130%
8.3	4	0.290%
50	5	0.005%
33.3	5	0.019%
16.6	5	0.110%
8.3	5	0.230%

Based on this analysis, the impact of frequency-watt control on PV energy production is expected to be extremely small.

It is possible that as more PV is added to the Oahu power system, overfrequency events will become more common due to lower system inertia, causing the impact of frequency-watt control on PV energy production will increase slightly. However, as shown in this report, when a substantial number of PV systems are performing frequency-watt control, the severity of overfrequency events will be reduced. This will tend to mitigate any increasing impact on PV energy production. Overall the impact of frequency-watt control on PV energy production is expected to remain very small.

6.0 Conclusions and Recommendations

6.1 Summary of findings

As confirmed by the hardware tests shown in this report, most currently-available residential-scale PV inverters can perform frequency-watt control, and can do so reliably. This result is consistent with other recent test publications [13], [18], [19]. However, the exact form and time-domain response of the frequency-watt function varies between inverters models.

The tests and simulations in this interim report have shown that the basic PV inverter frequency-watt function can be beneficial for stabilizing overfrequency events. The simulations and tests focused on the Oahu power system.

Very steep droop slopes, i.e. steeper than 3%, were found to cause increased frequency oscillations, while droops slopes in the 3% to 5% range were found to lead to more stable frequency responses. Frequency-watt responses where the power undershoots before settling to the target value were also found to result in increased frequency oscillations if deployed widely. Faster frequency-watt responses were found to be more stable than slower responses over the range simulated, though investigation of possible sub-synchronous interactions was not in the scope of this research.

The effect of frequency-watt control (with downward response only) on the annual energy production of any given PV system is expected to be negligible (less than 0.02% for the recommended settings) due to the relative rarity and brief duration of overfrequency events. This assumes the deadband chosen lies above the normal range of frequency variation. In addition, because frequency is largely uniform across an interconnected power system, there should be no outlier customers who experience a larger impact. Therefore the downside to PV system owners is minimal; in fact if frequency-watt control results in reduced load shedding in future years, it may actually increase PV energy production for affected customers.

PV inverter frequency-watt control was found to be effective in mitigating overfrequency events due to both load-loss events and irradiance ramp events.

Several challenges associated with frequency-watt control of distributed PV are summarized in the next section followed by recommendations for frequency-watt deployment.

6.2 Challenges of DER-Based Frequency Support

While enabling frequency-watt control of distributed resources is expected to be beneficial for bulk system stability, several challenges must be overcome to best take advantage of the full capabilities of DER-based frequency support. Those challenges are briefly summarized here.

Grid operators today typically have no communications with distributed PV systems, so it is currently difficult to make changes to frequency-watt settings once inverters are placed in service. This could be mitigated by making provisions (both technical and contractual) to remotely modify settings of distributed PV systems and similar resources in the future.

Grid operators also typically have no way to directly measure the individual or aggregate output of distributed PV systems, and must rely on estimates. Thus, as weather conditions cause variations in PV generation, the amount of downward response available from distributed PV at any given moment is not known with a high degree of confidence. This could be mitigated by making provisions to monitor distribution-connected, customer-owned resources such as distributed PV in the future, or by improving tools for estimating the online capacity of distributed PV. Ideally these tools should estimate not just the total capacity, but also the aggregate capacities of legacy PV, PV with partial ride-through, PV with full ride-through, and PV with frequency-watt control enabled.

Acute overfrequency events are typically initiated by the loss of a section of load. Because distributed PV is embedded with load, some amount of PV is typically lost during daytime load rejection events. This loss of PV generation mitigates the overfrequency event to some degree, but it also reduces the amount of downward response available from distributed PV by an unknown amount. This increases the uncertainty and variability in the system frequency response.

Bulk power systems are designed to be powered using three-phase generation resources. Distributed PV inverters, especially those on Oahu, are typically single-phase connected, and like single-phase loads, single-phase PV systems are typically not perfectly balanced between phases. Relying on unbalanced resources for essential bulk system services such as frequency response may introduce new challenges.

Frequency events sometimes occur in association with voltage events, and the uncertain response of distributed PV to low voltage events contributes to the uncertainty in distributed PV frequency response, and to bulk system challenges in general. For example, fault-induced delayed voltage recovery on the distribution system may cause voltages to remain below 0.5 pu for over 0.6 seconds. This will cause distributed PV to either trip offline or momentarily cease to export current. In the case of momentary cessation, the time for the inverter to return to service following voltage recovery introduces additional uncertainty. Preliminary modeling of these issues performed in this project found that PV responses to voltage faults can have profound consequences for Oahu bulk system operations and stability. Further details will be included in a subsequent report.

Most of the above challenges are exacerbated by the inability of current models and modeling tools to adequately capture both transmission systems and distribution systems in the same simulation. For example, PSS/E and other bulk system transient modeling tools use positive-sequence models, so they assume balance between phases. While this project and some other ongoing work are beginning to develop modeling tools that can capture both transmission and distribution dynamics, those modeling tools have many limitations. In addition, even given

perfect modeling tools, some aggregation of distributed resources and loads is necessary to achieve a tractable model. Accurate models of the frequency and voltage responses of loads and DERs are often not available.

6.3 Recommendations for Activation of Frequency-Watt: Default Settings and Ranges of Adjustability

A large aggregate power rating of frequency-responsive PV is needed to have a measureable effect on grid frequency stability, even in a relatively small power system such as Oahu's. Because it takes time to build up a base of frequency-responsive PV systems, it is recommended that frequency-watt control requirements be implemented expeditiously.

While it is possible to increase the magnitude of the frequency-watt response from distributed PV by increasing the droop slope (i.e. reducing the droop percentage), steeper slopes have been shown to lead to greater oscillations in frequency, which is undesirable. Thus a moderate droop slope between 5% and 3% (inclusive) is recommended. A droop slope equal to that of synchronous generators' governor responses will lead to proportional sharing of the primary frequency response burden, but it may also be desirable to have fast-responding inverter-based resources shoulder more of the PFR burden, especially because they do not provide stabilizing inertial response. The recommended range of adjustability of droop slope allows for a somewhat wider range of droop slopes in both directions to facilitate future adjustments as even larger amounts of DERs are deployed. While the high end of the frequency-watt range of adjustability is above the range specified in the ballot draft of IEEE P1547, the ballot draft states that "the range of adjustability may be extended" on the high end. Thus the range of adjustability recommended here is allowable per the ballot draft.

Faster time responses of frequency-watt control can increase the ability of the function to reduce overfrequency event apexes. Faster time responses have also been shown to lead to fewer frequency oscillations on the Oahu system, as compared to slower time responses. However, this report has not examined possible interactions between fast inverter responses and conventional generator dynamics, such as sub-synchronous torsional interactions. Before the aggregate rating of frequency-responsive PV inverters becomes large enough to significantly affect the frequency (likely several years in the future), the potential for such interactions should be investigated.

It was found that frequency-watt deadbands ranging from 17 mHz to 50 mHz should have little impact on monthly PV energy production and should provide effective mitigation of overfrequency events. Hawaiian Electric's SRD V1.0 calls for a deadband of 36 mHz, in alignment with the recommendation of the North America Electric Reliability Corporation that deadbands not exceed 36 mHz [20]. The recommendation of this report is to use a 36 mHz deadband in alignment with the SRD V1.0, though other deadbands could certainly be considered in the future.

Table 5 shows the recommended frequency-watt control parameters from this work. These parameters correspond to those listed in Hawaiian Electric's SRD V1.0.

Table 5: Recommended frequency-watt control settings for overfrequency events

		Default value	Range of adjustability
Deadband (Hz)	db _{OF}	0.036	0.017 – 1.0
Droop slope (pu)	k _{OF}	0.04	0.02 – 0.07
Response time (s)	t _R	0.5 ^A	0.05 – 3.0 ^A
<p>Note A: SRD V1.0 does not define a specific default response time. It specifies that the response time shall be between 50 ms and 3 s, with the intent that the inverter manufacturers select their response times for now. The intent of SRD V1.0 is not to require inverters to be certified for the full range, but to allow them to be certified with any response time between 50 ms and 3 s. To avoid causing manufacturers to have to recertify their products, it is recommended that any response time in the range between 50 ms and 3 s be allowed at this time. The purpose of the default response time of 0.5 s is to provide a suggested value. However, it is expected that in future SRDs and revisions of Rule 14H, requirements on default response time may be updated to achieve a more predictable frequency response.</p>			

This report has focused on the Oahu island power system. While many aspects of this work may apply to some extent in other Hawaii power systems (and other power systems in general), other Hawaiian islands have not been studied as part of this project. Because it will take some time to build up a base of frequency responsive inverters, grid operators may want to consider calling for frequency-watt activation in the near future while simultaneously taking the necessary steps to ensure it will have the desired effect (and no unmanageable side effects) on other power systems.

Oahu will rely heavily on distributed PV to meet its renewable portfolio standard goals so the island's power system is expected to change dramatically over the next five years. As synchronous generators are displaced, distributed PV must play a bigger role in providing frequency stability to Oahu's power system so new settings and/or functionality may be required.

One project partner commented that it may be possible to remotely enable frequency-watt (as-is) in a large number of existing distributed PV systems. It may also be possible to enable frequency-watt control in existing multi-megawatt PV systems. These steps would likely be beneficial, but should be considered carefully, as they may lead the Oahu system to more quickly reach a level of frequency-watt enabled PV where unintended dynamics are possible.

Appendix A

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