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# Photovoltaic Frequency-Watt Curve Design for Frequency Regulation and Fast Contingency Reserves

Jay Johnson, Jason Neely, Jarod Delhotal, Matthew Lave

**Sandia National Laboratories**

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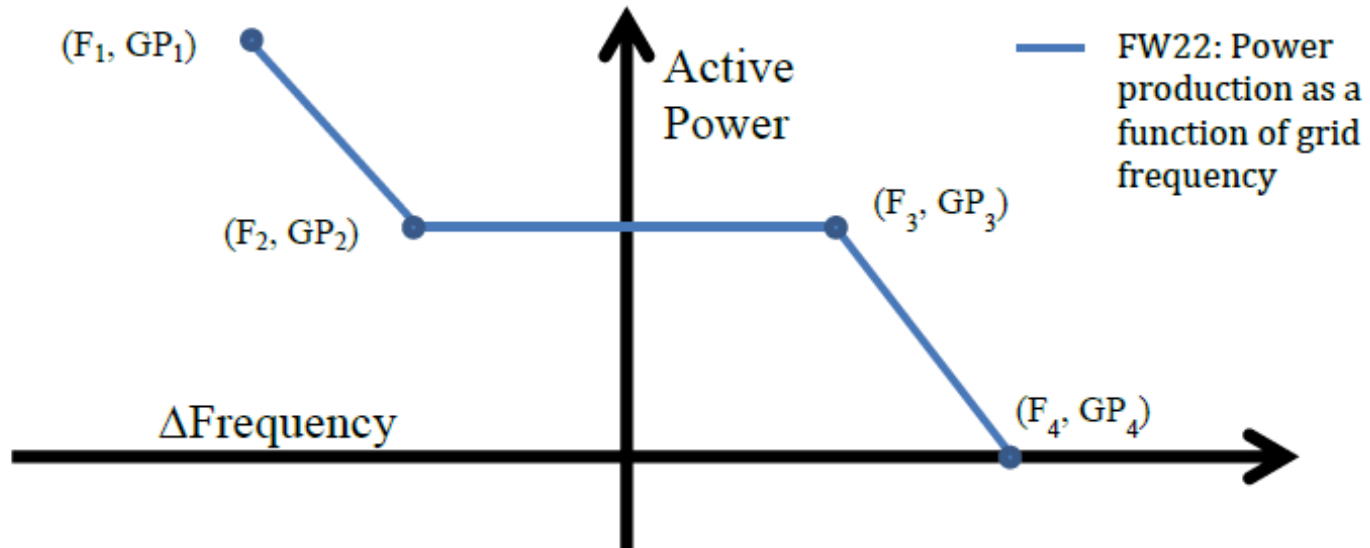


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# Autonomous Grid Support Functions Can Improve PV Penetration

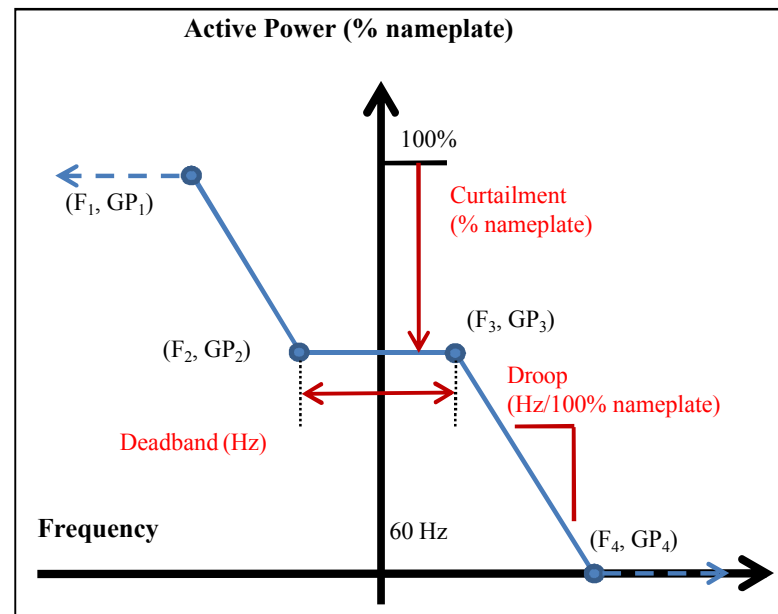
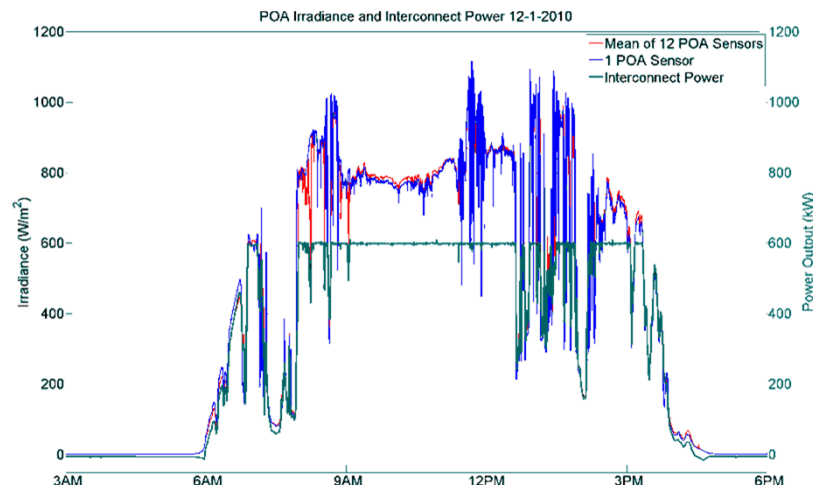
- Non-dispatchable, renewable sources are displacing conventional controllable synchronous generators, thus affecting grid frequency
- By deploying autonomous grid-support functions into distributed PV inverters, these resources can collectively improve grid response
- In this work, use of the existing IEC 61850-90-7 frequency-watt function was investigated



# PV Curtailment Provides Headroom for Under-Frequency Response (without Energy Storage)

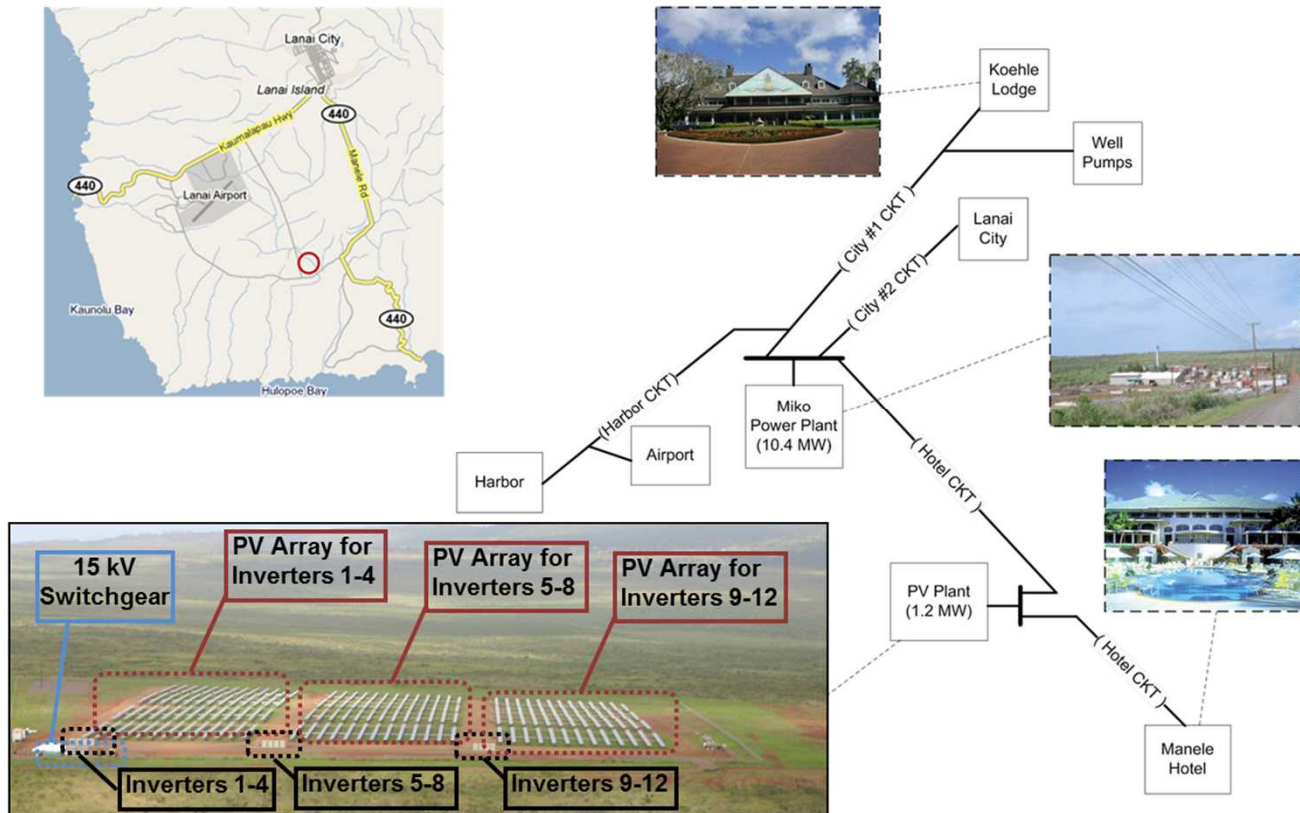
- Previously, the 1.2 MW PV system on Lana'i, HI was curtailed to manage power ramp rates that affect grid frequency and voltage [1]
- In this study, simulated Lana'i PV power was curtailed to provide “head room”, allowing frequency-watt functions to respond to over and under frequency events without energy storage

[1] J. Johnson, B. Schenkman, J. Quiroz, and A. Ellis, “Initial operating experience of the La Ola 1.2 MW photovoltaic system,” Sandia National Laboratories Technical Report SAND2011-8848, 2011.



# Study Focused on the Lana'i Power System

- Island is 140.5 square miles
- 3,200 residents in 1,150 households
- 6 MW peak load
- 10.4 MW diesel power plant, 1.2 MW La Ola PV Power plant
- Characterized by high solar variability



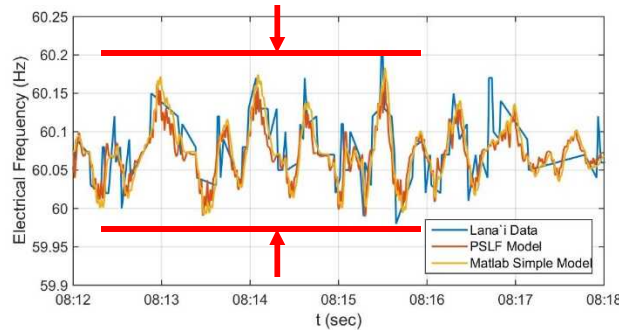
# High PV Penetration Scenarios were Evaluated on Two Simulation Platforms

- The Lana’i Power System was Modeled in Matlab and PSLF
  - *Matlab - simplified model for day-long simulations*
  - *PSLF - high fidelity model for “event” simulations*
- Solar Irradiance data was collected at Lana’i and used to compute PV power delivery [2]
  - *Sandia Wavelet Variability Model*
  - *Sandia Array Performance Model*
- The Lana’i Power System Models were modified to include greater PV penetration levels, defined by installed PV and peak load
  - *20 %, 70 %, and 120 %*
- Both models were validated at 20% PV penetration using data from Lana’i [2]
- Laboratory experiments were done to validate the approach [2]

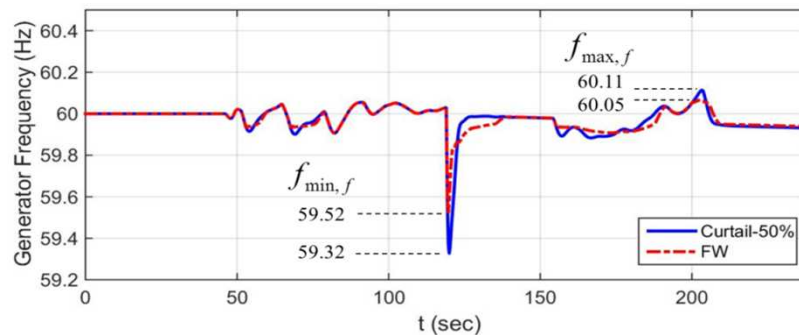
# How do the FW parameters effect grid-operations and energy costs?

## Simulation parameters of interest:

1. Provide frequency regulation: adjust PV output power to return grid frequency to 60 Hz.



2. Provide primary frequency reserves: quickly respond to fault conditions with rapid changes in PV power.



3. Minimize energy lost from curtailment.

# Latin Hypercube Sampling (LHS)

- LHS used to understand the effect of each control variable on the Figures of Merit.

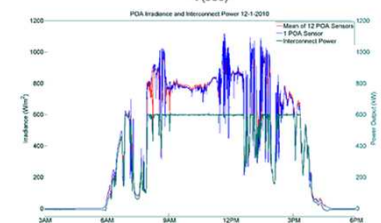
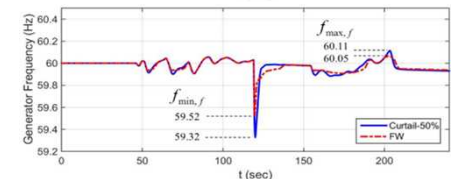
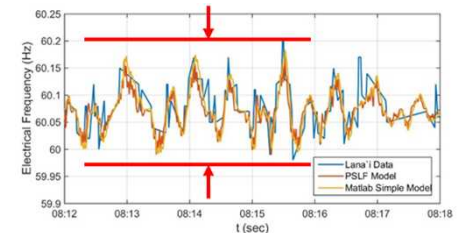
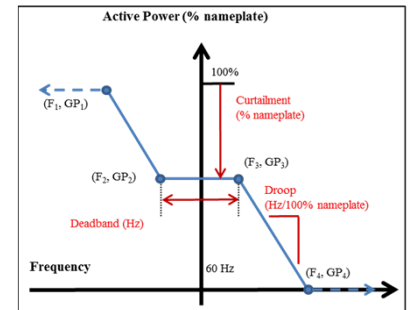
- Similar to random sampling, but ensures even sampling across the design space.

- LHS Parameters:

- curtailment, with range 0-100% of nameplate
- deadband, with range 0-2 Hz
- droop, with range 0.001-2.0 Hz/100% of nameplate

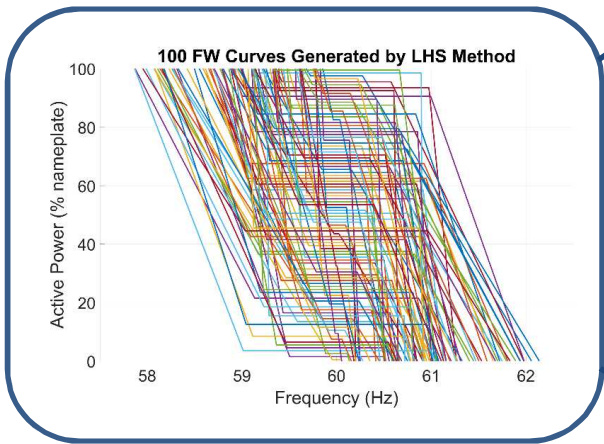
- Figures of Merit

- The absolute minimum ( $f_{min}$ ), absolute maximum ( $f_{max}$ ), and average standard deviation ( $\sigma$ ) of the Lanai grid frequency for the three simulation days.
- The maximum ( $f_{max\_f}$ ) and minimum ( $f_{min\_f}$ ) grid frequency measured at the power plant for the six different PSLF scenarios (two fault types and three times during the day).
- The average PV energy loss,  $E_{loss}$ , for the three days with different irradiance values (low, 'average', and high solar variability)



# Frequency-Watt Curves

100 FW curves were generated by LHS tool and sent to PSLF simulations and to the simplified Matlab model for fault and day-long simulations.



The LHS analysis was repeated for 3 different penetration scenarios: 20%, 70%, and 120% of peak Lana'i load.

**PSLF Fault Simulations**

2 fault types at 3 different times during the day

## Figures of Merit

6 fault simulations were run to find the:

- maximum grid frequency during the faults ( $f_{max\_f}$ )
- minimum grid frequency during the faults ( $f_{min\_f}$ )

**Simplified Lana'i power system model**

3 irradiance profiles

Power Plant Simplified Model

3 simulation days were run to find the:

- minimum grid frequency ( $f_{min}$ )
- maximum grid frequency ( $f_{max}$ )
- grid frequency standard deviation ( $\sigma$ ) of the Lana'i grid frequency
- The average PV energy loss,  $E_{loss}$ , for the three days

4<sup>th</sup>-order Adams-Bashforth integration method with a 0.001 second timestep.

# LHS Results

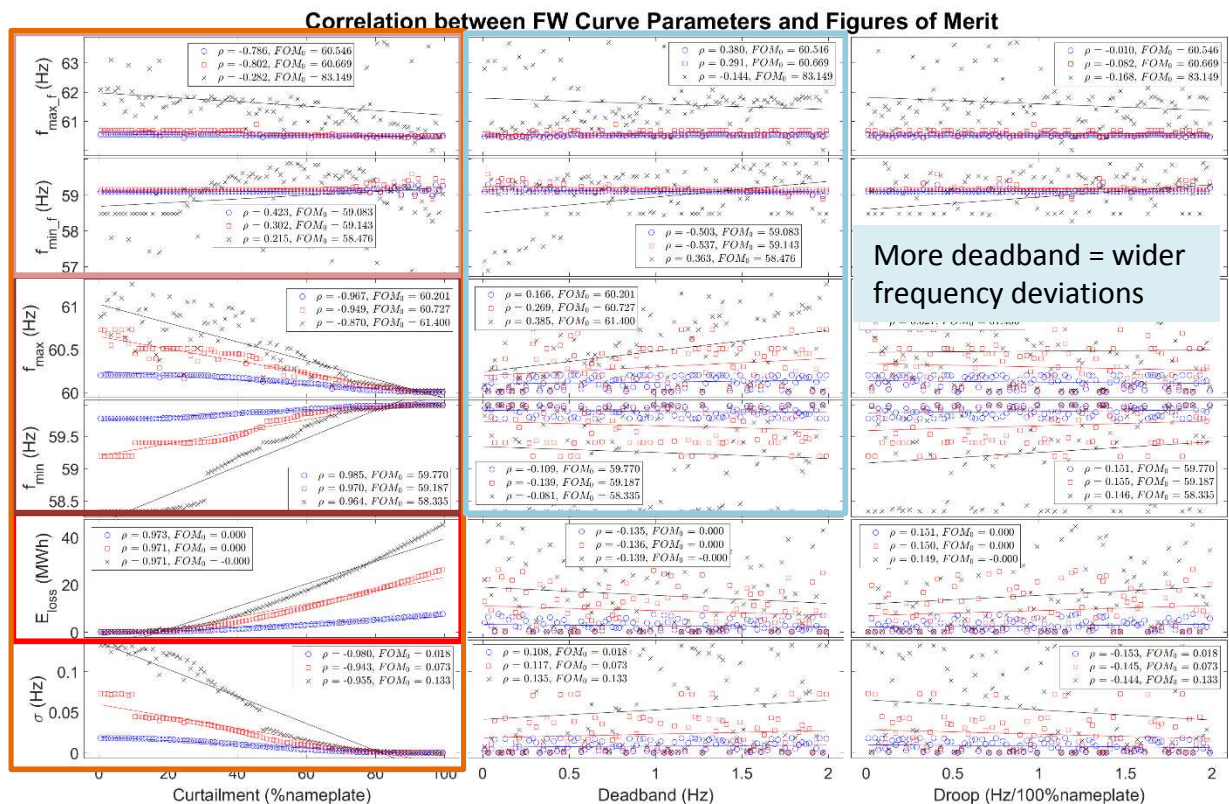
- Influence of the FW parameters (x-axes) and performance metrics (y-axes) are shown.

More curtailment = greater headroom for the PV to respond to the loss of generation event (correlation less clear because of PSLF transient dynamics [2])

More curtailment = less 24-hour simulation deviation (no load in model)

More curtailment = more  $E_{loss}$

Higher penetrations mean larger frequency deviations and Energy Losses

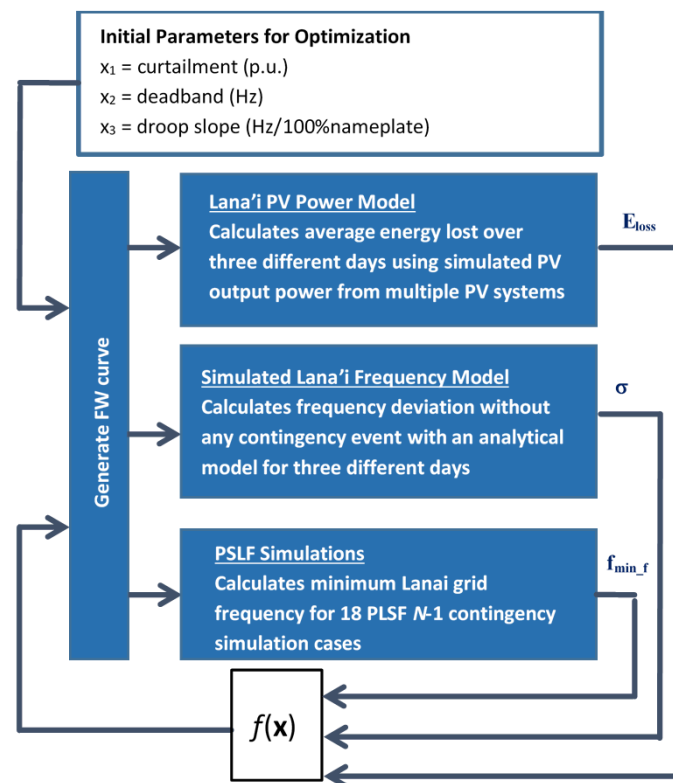


Curtailment has strongest influence on the FOMs

Deadband and droop have less effect on the FOMs.

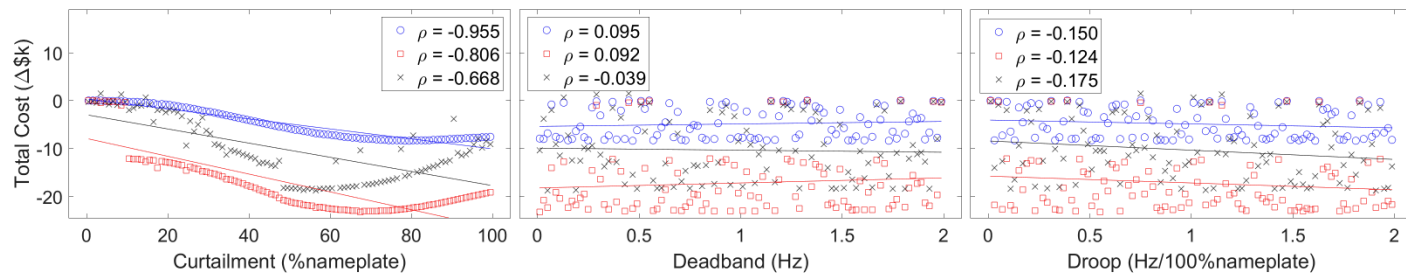
# Optimization of FW Function for Frequency Support but Minimizing Total Cost.

- **Optimization function accounts for 3 costs:**
  - The average revenue lost from FW curtailment for three days,  $f(E_{\text{loss}})$ .
  - The cost of blackouts, the consumer interruption costs,  $f(f_{\text{min}_f})$ .
  - The operations and maintenance (O&M) costs for the synchronous generators,  $f(\sigma)$ .
- **Only considered the cost differences between no FW function and the FW implementation.**
  - Positive cost = FW will cost more money to the utility
  - Negative cost = FW implementation saves money over not implementing the function
  - Note: costs assume the utility pays for blackout costs and pays for curtailed power.



# Optimization Results

- Results highly dependent on assumptions used to create the cost function.
  - These results are purely exemplary.
- LHS results for total cost FOM



- Optimization problem was solved for different penetrations with sequential quadratic programming (SQP) and interior point.

Penetration	Technique	Curtailment (%)	Deadband (Hz)	Droop (Hz/100%nameplate)	Cost (Δ\$k/day)
20%	LHS	78.50	1.730	1.610	-8.35
	SQP (76 Steps)	78.89	1.681	1.566	-8.35
	Interior Point (203 Steps)	78.91	1.733	1.622	-8.35
70%	LHS	67.50	0.010	0.551	-23.22
	SQP (147 steps)	67.50	0.010	0.551	-23.22
	Interior Point (77 Steps)	67.11	0.002	0.416	-23.30
120%	LHS	56.50	0.050	1.910	-18.78
	SQP (78 steps)	56.50	0.050	1.910	-18.78
	Interior Point (128 Steps)	47.70	0.042	0.004	-20.43

FW functions could save money in HI today if energy losses offset blackout costs and thermal generator O&M costs!

# Concluding Remarks

- Frequency-watt function can mitigate frequency deviations in a power system with high-pen PV.
- Pointwise FW functions can be used to provide frequency stabilization in + and - directions.
- Models of the Lana'i island grid were created to determine energy loss and frequency response of FW functions.
- Simulations show tuning FW parameters can achieve greater grid performance than operating PV at full output or using “pure” curtailment.
- Financial optimization was conducted to show aggregate costs are reduced with proper FW function design.

## Photovoltaic Frequency-Watt Curve Design for Frequency Regulation and Fast Contingency Reserves

Jay Johnson, Member, IEEE, Jason Neely, Member, IEEE, Jarod Delhotal, and Matthew Lave, Member, IEEE  
Sandia National Laboratories  
Albuquerque, NM  
john2@sandia.gov

**Abstract**—When renewable energy resources are installed in electricity grids, they typically increase generation variability and displace thermal generator control action and inertia. Grid operators combat these emerging challenges with advanced distributed energy resource (DER) functions to support frequency, and provide voltage regulation and protection mechanisms. This paper focuses on providing frequency reserves using autonomous IEC TR 61850-90-7 pointwise frequency-watt (FW) functions that adjust DER active power as a function of measured grid frequency. The importance of incorporating FW functions into a fleet of photovoltaic (PV) systems is demonstrated in simulation. Effects of FW curve design, including curtailment, deadband, and droop, were analyzed against performance metrics using Latin Hypercube Sampling (LHS) for 20%-, 70%-, and 100% PV penetration scenarios on the Hawaiian island of Lana'i. Finally, to understand the financial implications of FW functions to utilities, a performance function was defined based on monetary costs attributable to curtailed photovoltaic production, load shedding, and generator wear. An optimization wrapper was then created to find the best FW function curve for each penetration level. It was found that in all cases, the utility would save money by implementing appropriate FW functions.

**Index Terms** – advanced inverter functions, grid-support functions, advanced inverters, smart DER, frequency regulation.

### I. INTRODUCTION

In June 2015, Hawaii passed a renewable portfolio standard (RPS) bill that required Hawaiian utilities to generate 100% of their energy from renewable sources by 2045 [1]. In order for the Hawaiian Electric Industries to meet this requirement, an assortment of energy technologies must be implemented, including installation of energy storage systems and activation of advanced grid-support functions in PV and other DER inverters.

Advanced DER functions have been gaining acceptance in Europe and the United States as a cost-effective tool for improving grid stability. Grid codes around the world have been adding grid-support requirements for PV and Energy Storage Systems (ESS) [2]–[6], major activities are creating interoperability standards to communicate with the devices [7]–[9], and international research programs are creating

This work was supported by the U.S. Department of Energy SunShot program under Award Number 29092. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

advanced DER testing protocols [10]–[13].

Frequency-watt (FW) implementation is required in distributed energy resources in many European countries [2] and is included as an optional function in California Electric Rule 21 [3]. Deployment of distributed active power controls to provide ancillary services including regulation and primary contingency reserves is well studied in the literature [14]–[18]. The active power headroom for PV inverters is derived from operating off the maximum power point (MPP) in the grid codes; this curtailment is defined as a percentage of the nameplate power of the DER, thus, the curtailment is only active for the part of the day for which available solar power exceeds the curtailment level. In laboratory experiments of the response time of advanced grid-support functions, the inverters were found to rapidly respond in approximately 0.25 seconds when decreasing power—though the inverter response can be multiple seconds when increasing output to near maximum power [19].

This work explores the influence of FW function parameters on multiple performance and economic figures of merit (FOMs) for the small island grid on Lana'i, Hawaii. This evaluation is done at current and future (speculative) penetration levels. Given the large number of parameter permutations, Latin Hypercube Sampling (LHS) [20] was used to design simulation experiments to investigate the relationship between FW parameters and FOMs using (a) General Electric's Positive Sequence Load Flow (PSLF) software and (b) a simplified dynamic model in MATLAB with full day (sunrise to sunset) irradiance profiles. The former was used to simulate transient events during N-1 contingencies while the latter provided aggregate performance data over a diurnal solar cycle. Finally, an economic study was performed on selection of FW parameters to minimize total cost attributed to energy loss due to curtailment, generator wear, and risk of blackout.

### II. LANAI GRID MODELS

Lana'i is a 140.5 square mile Hawaiian island with approximately 3,200 residents in 1,150 households, living mostly in Lana'i city. The power system includes a 10.4 MW diesel power plant with ten generators, three 12.47 kV distribution circuits, and the 1.2 MW 'Le Oia PV power plant [21]–[22]. The peak load of the island is approximately 6 MW. It is noted that the diesel power plant does not energize all generators; in this study two, three or four generators were

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