Impacts of Voltage-Based Grid-Support Functions on Energy Production of PV Customers

Preprint

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Impacts of Voltage-based Grid Support Functions on Energy Production of PV Customers

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***Abstract*—This paper presents the impact of inverter grid-support functions (GSFs) on photovoltaic (PV) customer energy production on a real distribution feeder in Oahu, HI. These autonomous GSFs based on local voltage measurements are good alternatives to increase PV hosting capacity. However, these functions can result in PV energy curtailment to the customer, and this study addresses the concerns about the impact of inverter GSFs through detailed quasi-static time series (QSTS) simulations. It proposes four metrics: maximum and average GSF curtailment, average increased generation and average net generation change, to assess the impact of a given control on PV systems located on customer sites. It was found that curtailment of PV production is negligible for customers where peak voltage is within ANSI C84.1 range. A reliable relationship between curtailment and peak customer voltage is demonstrated, suggesting that peak voltage could be used as an indicator of customer curtailment.**

***Keywords*—Photovoltaic, voltage control, reactive power control, active power control, advanced inverter control.**

I. Introduction

Increasing levels of distributed energy resources (DERs) located at or close to the customer site is changing the way the power system, and in particular the distribution system, is planned and operated. Not only are power flows in the distribution systems now bidirectional, but DERs are able to provide grid support functions (GSFs) such as voltage and frequency support [1]. Utilities are increasing their efforts to include DERs in planning and operation. At the distribution level, utilities are looking at the impact of autonomous voltage-based GSFs such as Volt/Var and Volt/Watt in voltage regulating strategies, as well as impacts on energy production for customers that are activating such functions [2].

The newly revised IEEE 1547-2018 includes advanced specifications for DERs, particularly related to reactive power capability and autonomous voltage/power control requirements impacting the local distribution system to which they are interconnected. Curtailment of active power is required if necessary to meet the apparent power constraints while injecting or absorbing reactive power at up to 44% of the nameplate kVA rating [3]. Reference [4] describes the topology, characteristics, and simulation-based results of an advanced inverter designed to look beyond the recommendations of the previous version of the IEEE Standard 1547 (2003) by including reactive support function.

Inverter voltage support GSFs are activated to mitigate possible off-nominal voltage conditions including over-voltage violations outside of the allowable ANSI C84.1 Range [5], including those contributed to by DER integration. However, these GSFs can cause energy curtailment to photovoltaic (PV) customers. For instance, advanced inverter controls allow PV - inverter systems to support reactive power priority by curtailing active power output when required to keep the grid within its operational constraints [6].

In [7], techniques to create distribution models for determining the effectiveness and impacts of various GSFs were presented. There we leverage such distribution models to present the results of running time-series distribution models with different penetration levels of DERs.

The authors in [8] argue that there is no obvious nexus between increased Var output and decreased PV kWh generated. In [6], the authors show that the application of Volt/Var control could mitigate voltage violations without causing PV active power curtailment. Reference [9] investigated the impacts of various penetration levels of advanced inverters on a typical distribution network showing that smart inverters have the capability to improve tap operations, voltage variability, and minimum and maximum voltages. Reference [10] presented a methodology for the optimal settings of a group of advanced inverters using autonomous inverter control (i.e., an inverter output is a function of its primary node at the point of connection). The study revealed that optimal settings depend on inverter kVA rating, feeder layout, load and solar characteristics. A method to design a smart inverter Volt/Watt control to mitigate possible voltage violation for a high PV penetration case while curtailing energy evenly among all integrated PV systems is presneted in [11]. Other related studies in [12], [13] present the use of advanced inverter settings to enhance grid performance.

However, to the knowledge of the authors, the extended literature has not characterized and quantified or estimated the expected level of energy curtailment as a result of the activation of Volt/Var in combination with Volt/Watt. Our study proposes four metrics—maximum GSF and average GSF curtailment, average increased generation and average net genera-

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tion change—to assess the full impact of a given GSF control on customer-sited PV systems. We then apply those metrics to several detailed quasi-static time-series (QSTS) simulations of a distribution feeder with various levels of PV generation. Finally, we plot curtailment of customer PV generation as a function of peak customer voltage and demonstrate a tight and predictable relationship between the two. This relationship is leveraged to make recommendations for how utilties may take advantage of the benefits of Volt/Var and Volt/Watt control without significantly impacting customer PV generation and without investing in irradiance sensor deployment or advanced analytics to estimate curtailment. These findings align with field measurements of PV systems performing Volt/Var and Volt/Watt control on several distribution circuits with high levels of distributed PV on Oahu, Hawaii, as described in [14].

The rest of this paper is organized as follows: section II describes some voltage-based GSFs, metrics, and impacts; case studies are presented in section III and the results are discussed in section IV; and section V concludes.

II. Voltage Based Grid Support Functions, Metrics and Impacts

Active-power production from DERs tends to increase steady-state grid voltage, specially in secondary distribution circuits. Inverters, which are the most prevalent power electronics technology due to the popularity of PV systems in customer rooftops, have two output parameters available to mitigate this: reactive power and active power. Absorbing reactive power can bring down voltage with minimal (sometimes zero) impact on real power production and, hence, is generally preferred. Reducing active power can also mitigate overvoltage, but this directly reduces PV energy production and is, therefore, typically considered an option only when voltage is very high and reactive-power management does not solve the problem.

A. *Two voltage grid support functions*

In the Volt/Var control mode, reactive power is modulated in proportion to voltage deviation, absorbing and injecting reactive power (Vars) for high and low voltage scenarios, respectively. This is done by following a Volt/Var curve, which often has a deadband where reactive-power production is zero as shown in the top of (Fig. 1). The Volt/Var curve studied in this paper corresponds to a moderate curve with a deadband of ±0.03 p.u., and a droop curve above 1.03 and below 0.97 p.u.. The droop slope reaches full Var injection and absorption at 1.06 p.u. and 0.94 p.u., respectively. Full Vars are defined as 44% of the inverter apparent power rating which corresponds to power factor of 0.9 at full apparent power. The full Var capability, however, only is used when the voltage is far from nominal.

Under Volt/Watt control, active power is reduced for high voltages to remain on or below a Volt/Watt curve as shown in the bottom portion of (Fig. 1). The Volt/Watt function initiates reduction in real power when the voltage at the point of common coupling (PCC)—not necessarily the inverter terminals—breaches 1.06 p.u.. ANSI C84.1 Standard provides that voltage delivered at the PCC should generally be within ±0.05 p.u. of the nominal value. So Volt/Watt provides means to protect utility voltages from greatly violating ANSI C84.1 service voltage ranges.

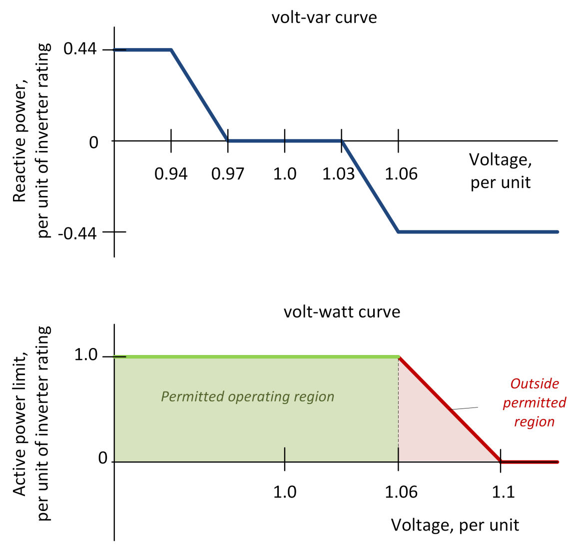

Fig. 1. The two voltage grid support functions and the settings used in this study

B. *Volt/Var in reactive and active power priority modes*

Reactive power-based functions such as Volt/Var control can be configured to prioritize either active or reactive power when the inverter's current limit does not allow it to produce the desired amount of both P and Q simultaneously. This is illustrated in Fig. 2. Active power priority (Watt priority) can be used to ensure zero impact on energy production when providing reactive-power support to the grid. This was briefly called for in California Rule 21; however, active power priority causes grid support to be unavailable during times of high PV production, when voltage control is most needed. For this reason, the IEEE Standard 1547-2018 revision requires reactive power priority.

Reactive power priority (Var priority) mode is required to allow DERs to supply or absorb reactive power when available up to 44% of the nameplate KVA rating for maximum Var injection and absorption at rated DER voltage [3]. However, enabling the Var priority mode can lead to active power curtailment as shown in 1-3: For a given PV system, the available active power with Volt/Var in Var priority mode, $P_{VVar,Var}$, is

$$P_{VVar,Var} = \sqrt{(S_{inv})^2 - (Q_{VVar,Var})^2} \quad (1)$$

where S_{inv} and $Q_{VVar,Var}$ are the inverter capacity (kVA) and reactive power, respectively. The Var priority mode will result in P_{curt} curtailment if the inverter capacity is not large enough to provide reactive power support based on the droop curve [8], [13].

The reactive power priority illustrated in Fig. 2 shows that the possible curtailment of available active power to meet the required reactive power as specified by the Var priority mode. The active power curtailed P_{curt} shown in Fig. 2 is given as:

$$P_{curt} = P_{VVar,Watt} - P_{VVar,Var} \quad (2)$$

where $P_{VVar,Watt}$ and $P_{VVar,Var}$ are the available active power in active and reactive power priority modes respectively.

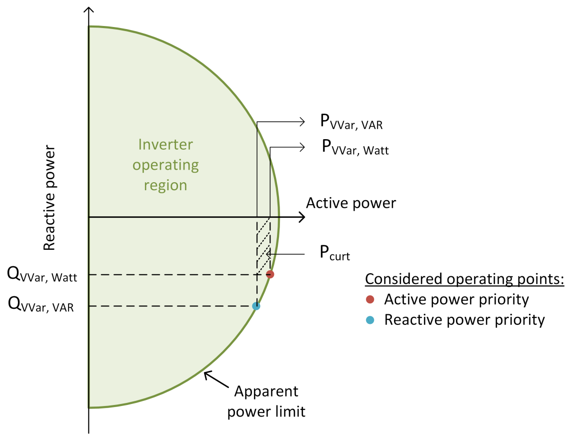

Fig. 2. Volt/Var reactive power and active power priority modes

C. Impacts of grid support functions

From the perspective of the distribution utility, any voltage-based GSF initiated by the DER will impact distribution system voltages. Reference [15] shows that most of the local reactive power based voltage control effectuated by DERs affects voltage magnitudes across the secondary of the service distribution transformer since it is the portion of the secondary circuit with higher reactance values (when compared to secondary conductors which tend to be dominated by the restive component of the impedance), and as such is affected by the production of reactive power by DERs. Primary feeder voltages are not highly affected by local voltage support by smaller customer-sited DERs, and the utility voltage-regulating equipment is not typically affected by these local voltage support functions.

From the perspective of the customer, voltage-based GSFs from the DERs can impact the energy production since the active power output of the inverter may be reduced during GSF actions. We focus on quantifying impacts of GSFs on energy production from customer-sited PV installations.

D. Metrics

The metrics proposed in this paper are related to the impact of a given GSF control on residential customers:

- *Max GSF curtailment* is the maximum customer energy curtailed over a given time period.
- *Average GSF curtailment* is the average customer energy curtailed over a given time period.
- *Average increased generation* is the average customer increased energy generation at the customer site for a given time period because resulting from reduced PV inverter disconnections for voltages above 1.1 p.u. With Volt/Watt activated, some PV systems continue to produce when they otherwise would have been disconnected at 1.1 p.u..
- *Average net generation change* is the average customer increased generation minus the average grid-support function curtailment for a given time period. A positive value represents a net increase in PV generation.

To calculate the energy curtailed due to voltage-based GSFs in DERs, the baseline scenario with no GSF must be establisged first. Similarly, to calculate the increased generation metric, the scenario with no disconnection fro voltages above 1.1 p.u. must be studied first.

III. Test Feeders, PV Penetration Cases and Grid Support Function Scenarios

Here we present the distribution feeder, the PV penetration cases, and the GSF scenarios studied to quantify the impacts of voltage-based GSFs on the energy production at PV installations located at customer sites.

Substation M34 located in Oahu, HI, has two 12 kV distribution circuits. This test system was selected for its diversity of the different types of PV installations already existing on a circuit (e.g., residential, commercial, and large feed-in-tariff (FIT) projects) that are rated at approximately 500 kW each. For more information on the feeder model preparation for QSTS simulation of tgis test system with detailed secondary circuit approximation, see [7].

Fig. 3. Geographical view of M34 distribution feeder

To create various levels of penetration of PV in the test system, calculated with respect to the gross daytime minimum load (GDML), blocks of approximately 1.6 MW of residential PV projects are added to the baseline feeder. Note that the baseline feeder already has 5.2 MW of large primary connected PV systems and 3.4 MW of residential PV, all connected at unity power factor. The scenarios shown in Table 1 were run for a week in June with incidences of high voltages.

Scenarios 1a and 1b are not expected to occur in the future since Volt/Var is a requirement for DER interconnection in Hawaii Rule 14H, but they are run to establish a baseline for PV production without advanced inverter functions, and obtain the baseline production of PV systems without GSFs. Scenarios 2a and 2b are studies to show the effectiveness and impact to energy production of enabling Volt/Var in all new residential PV systems added. These can be compared to scenarios 3a and 3b, which model blanket activation of

TABLE I. SCENARIO DESCRIPTION FOR M34 FEEDER AT VARIOUS GDML PV PENETRATION CASES

S/N	Scenario	PV Penetration with GSFs		
		175% "Low"	370% "Medium"	600% "High"
1a	PV-No GSFs-n/D	1.86MW	3.5MW	5.3MW
1b	PV-No GSFs-w/D	at PF = 1	at PF = 1	at PF = 1
2a	Volt/Var-n/D	1.86MW	3.5MW	5.3MW
2b	Volt/Var-w/D	in Volt/Var	in Volt/Var	in Volt/Var
3a	Volt/Watt-n/D	1.86MW	3.5MW	5.3MW
3b	Volt/Watt-w/D	in Volt/Watt	in Volt/Watt	in Volt/Watt
n/D = no disconnect; w/D = with disconnect (inverters disconnect if V >1.1 p.u.)				
There are 3.4 MW of rooftop and 5.2 MW FITs legacy PV systems connected at unity power factor.				

Volt/Var in combination with Volt/Watt (Volt/Var-Volt/Watt) in all new residential PV systems added to the 2016 baseline. Comparing scenarios 2a and 2b with 3a and 3b will provide insight into how much the Volt/Watt function is activated when implemented in combination with Volt/Var.

Note that the difference between scenarios "a" and "b" is that in the former PV systems do not disconnect when they sense voltages above 1.1 p.u., and in the latter they do, per IEEE 1547. Studying scenarios without disconnection above 1.1 p.u. enables the calculation of the increased generation metric that quantifies the PV systems that are able to produce more energy because they are no longer tripping at 1.1 p.u. voltage magnitude.

IV. RESULTS OF HIGH-PENETRATION PV CASES WITH RESIDENTIAL VOLT/VAR (VV) AND VOLT/VAR-VOLT/WATT (VV-VW) GSFS

A. *Customer Energy Production Metrics*

Table II shows the proposed calculated metrics for a high voltage week in June for three increasing PV penetration levels. The maximum customer curtailment in Volt/Var mode remains at 1.8% and is independent of the PV penetration level. However, for the Volt/Var-Volt/Watt mode, the maximum customer curtailment increases rapidly from 2.3% in the low PV penetration case to 5.7% in the high PV penetration. Yet, the average customer energy curtailment values are the same or slightly lower in the Volt/Var-Volt/Watt case, than in the Volt/Var alone scenario. This suggests that very few customers experience non-negligible Volt/Watt GSF activation, and that the effectiveness of Volt/Watt in lowering voltages for a few outlier customers slightly lowers the curtailment for the remaining of the customers that experience only Volt/Var activation.

The other metric proposed in this paper is the increased energy generation that is no longer lost due to disconnecting above 1.1 p.u. per IEEE 1547. The increased generation increases the higher the PV penetration is. This is expected since the more rooftop PV, the higher the voltages are, and as such more PV customers are p.u.shed above 1.1 p.u., and so with grid support functions reducing voltages, more generation is lowered below 1.1 p.u. and is able to generate.

TABLE II. IMPACT OF ACTIVATING GSF CONTROL ON PV SYSTEMS AND ENERGY CURTAILMENT AT DIFFERENT PENETRATION LEVELS

Metrics	GDML penetration levels					
	175%		370%		600%	
	VV	VV-VW	VV	VV-VW	VV	VV-VW
Max GSF Curt.	1.8%	2.3%	1.8%	3.7%	1.8%	5.7%
Ave. GSF Curt.	0.10%	0.07%	0.15%	0.13%	0.24%	0.23%
Ave. Incr. Gen.	2.1%	2%	2.7%	2.6%	2.7%	3%
Ave. Net Gen.	2%	1.9%	2.5%	2.4%	2.4%	2.8%

The net generation change—which is positive if there are more PV customers enabled to generate than curtailed for the GSFs—is positive for all the scenarios studied. The net generation change increases considerably between the low and medium PV penetration levels. However, as the PV generation increases between the medium and the high PV penetration case, the net generation change stalls since as there is more energy curtailed too.

B. *Customer Energy Curtailment versus Maximum Customer Voltage*

These findings are illustrated by plotting the customer energy curtailment values against the maximum voltage experienced by the customer. Each dot in Figs. 4 – 6 represents a customer, with blue and pink dots representing VV and VV-VW. In the low PV penetration case, very few customers experience the activation of Volt/Watt when combined with Volt/Var. As PV penetration increases, more customers have Volt/Watt activation, but still less than 10 customers out of 531 PV systems are affected by this activation in the very high PV penetration case.

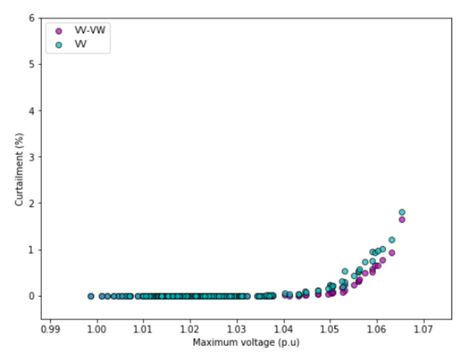

Fig. 4. Weekly customer energy curtailment versus maximum voltage for the low PV penetration case

These plots also show that the energy curtailment is negligible even for the very high penetration case provided peak voltages are within the ANSI C84.1 range. The utility can leverage this because voltage violation problems may point to possible curtailment issues, which require appropriate mitigation measures. Consequently, the concerned service provider may want to provide mitigation alternatives based on voltage thresholds rather than deploying sensing or advanced analytics to characterize and quantify possible curtailment. Voltage violation mitigations would address both curtailment and voltage issues.

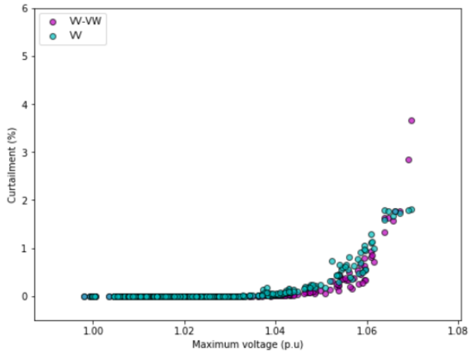

Fig. 5. Weekly customer energy curtailment versus maximum voltage for the medium PV penetration case

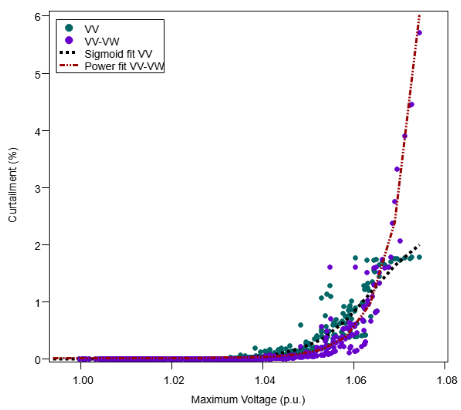

Fig. 6. Weekly customer energy curtailment versus maximum voltage for the high PV penetration case

In addition, we have added curve fitting functions to Fig. 6 for the high penetration PV case for the VV and VV-VW scenarios. The VV curtailment versus maximum customer voltage curve follows a sigmoid function with a plateau that accounts for the reactive power limit (0.44 p.u) of the VV curve; while a power fit function converged properly for the VV-VW scenario. The utility could use these curve fitting functions to estimate customer curtailment based on peak voltage. This will be further explored in future work.

V. Conclusion

We propose four new metrics for quantifying the impact of voltage-based GSFs to customer energy production, and provide results for three PV penetration cases for a high voltage week-long simulation on a 12 kV feeder in Oahu, HI. The metrics show that the activation of voltage-based GSFs, such as Volt/Var and Volt/Watt, results in a positive average net generation change, since there is less energy curtailed due to the activation of the GSFs than there is generation prevented from tripping above 1.1 p.u. per IEEE 1547. We also propose a new curve for plotting the customer energy curtailment versus customer maximum voltage, which shows that when customer peak voltages are maintained close to the ANSI C84.1 recommendations, customer energy curtailment from GSFs such as Volt/Var and Volt/Watt will be negligible or very low. These findings align with the limited field measurements available in [14].

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References

[1] M. Bello, D. Montenegro-Martinez, B. York and J. Smith, "Optimal Settings for Multiple Groups of Smart Inverters on Secondary Systems Using Autonomous Control," in IEEE Transactions on Industry Applications, vol. 54, no. 2, pp. 1218-1223, March-April 2018.

[2] A. Hoke et al., "Setting the Smart Solar Standard: Collaborations Between Hawaiian Electric and the National Renewable Energy Laboratory," in IEEE Power and Energy Magazine, vol. 16, no. 6, pp. 18-29, Nov.-Dec. 2018.

[3] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std 1547-2018.

[4] R. Carnieletto, D. I. Brandao, S. Suryanarayanan, F. A. Farret, and M. G. Simoes, "Smart Grid Initiative–A multifunctional single-phase voltage-source inverter," in IEEE Industry Applications Magazine, vol. 17, no. 5, pp. 27–35, Sep.–Oct. 2011.

[5] "ANSI C84.1", Voltage Ratings for Electric Power Systems and Equipment (60 Hz), 1977.

[6] J. Seuss, M. J. Reno, M. Lave, R. J. Broderick and S. Grijalva, "Advanced inverter controls to dispatch distributed PV systems," 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, 2016, pp. 1387-1392.

[7] J. Giraldez, P. Gotseff, A. Nagarajan, R. Ueda, J. Shindo and S. Suryanarayanan, "Distribution Feeder Modeling for Time-Series Simulation of Voltage Management Strategies," 2018 IEEE/PES Transmission and Distribution Conference and Exposition (TD), Denver, CO, 2018, pp. 1-5.

[8] J. Seuss, M. J. Reno, R. J. Broderick and S. Grijalva, "Analysis of PV advanced inverter functions and setpoints under time series simulation," Sandia National Laboratories SAND2016-4856 (2016).

[9] Z. K. Pecenak, J. Kleissl and V. R. Disfani, "Smart inverter impacts on california distribution feeders with increasing pv penetration: A case study," 2017 IEEE Power Energy Society General Meeting, Chicago, IL, 2017, pp. 1-5.

[10] M. Bello, D. Montenegro-Martinez, B. York and J. Smith, "Optimal Settings for Multiple Groups of Smart Inverters on Secondary Systems Using Autonomous Control," in IEEE Transactions on Industry Applications, vol. 54, no. 2, pp. 1218-1223, March-April 2018.

[11] M. Ghapandar Kashani, M. Mobarrez and S. Bhattacharya, "Smart Inverter Volt-Watt Control Design in High PV Penetrated Distribution Systems," in IEEE Transactions on Industry Applications, doi: 10.1109/TIA.2018.2878844.

[12] M. Rylander et al., "Methods to determine recommended feeder-wide advanced inverter settings for improving distribution system performance," 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, 2016, pp. 1393-1398.

[13] S. R. Abate, T. E. McDermott, M. Rylander and J. Smith, "Smart inverter settings for improving distribution feeder performance," 2015 IEEE Power Energy Society General Meeting, Denver, CO, 2015, pp. 1-5.

[14] P. Gotseff, N. Wunder, A. Hoke, E. Ifuku, "Residential Advanced Photovoltaic Inverter Pilot Study Results for Select Distribution Secondaries in Hawaii," IEEE Photovoltaics Specialists Conference (PVSC/WCPEC), Waikoloa, HI, 2018, pp. 1-5.

[15] J. Giraldez, A. Nagarajan, P. Gotseff, V. K. Krishnan, A. F. Hoke, R. Ueda, J. Shindo, M. Asano, and E. Ifuku, "Simulation of Hawaiian Electric Companies Feeder Operations with Advanced Inverters and Analysis of Annual Photovoltaic Energy Curtailment", No. NREL/TP-5D00-68681. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017.