California Solar Initiative

RD&D: Research, Development, Demonstration and Deployment Program

Final Project Report:

Quantification of Risk of Unintended Islanding and Re-Assessment of Interconnection Requirements in High Penetration of Customer Sited PV Generation

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Preface

The goal of the California Solar Initiative (CSI) Research, Development, Demonstration, and Deployment (RD&D) Program is to foster a sustainable and self-supporting customer-sited solar market. To achieve this, the California Legislature authorized the California Public Utilities Commission (CPUC) to allocate **$50 million** of the CSI budget to an RD&D program. Strategically, the RD&D program seeks to leverage cost-sharing funds from other state, federal and private research entities, and targets activities across these four stages:

- Grid integration, storage, and metering: 50-65%
- Production technologies: 10-25%
- Business development and deployment: 10-20%
- Integration of energy efficiency, demand response, and storage with photovoltaics (PV)

There are seven key principles that guide the CSI RD&D Program:

1. **Improve the economics of solar technologies** by reducing technology costs and increasing system performance;
2. **Focus on issues that directly benefit California**, and that may not be funded by others;
3. **Fill knowledge gaps** to enable successful, wide-scale deployment of solar distributed generation technologies;
4. **Overcome significant barriers** to technology adoption;
5. **Take advantage of California's wealth of data** from past, current, and future installations to fulfill the above;
6. **Provide bridge funding** to help promising solar technologies transition from a pre-commercial state to full commercial viability; and
7. **Support efforts to address the integration of distributed solar power into the grid** in order to maximize its value to California ratepayers.

For more information about the CSI RD&D Program, please visit the program web site at www.calsolarresearch.ca.gov.

Executive Summary

Unintended islanding happens when a part of a utility distribution circuit that has some level of distributed generation becomes disconnected from the utility system and the distributed generation remains connected to the utility load. In this project we are primarily interested in distributed generation sources based on solar PV and interfaced to the utility system using power electronic inverters. The exclusive focus of the work are inverters that are not designed to island, and are certified to UL 1741 requirements, set to operate at unity power factor and designed to maximize the renewable energy output, which is the vast majority of PV inverters being interconnected currently. While the power supplied by the PV panels and delivered via the inverters offsets the power consumed by nearby loads, both the inverters and the load depend on the utility voltage and frequency to operate correctly. If the utility voltage is removed, as is the case during islanding conditions, the inverters were not designed for voltage and frequency regulation and are inherently unstable on an island. But the combined short term behavior of inverters and connected loads is not easily predicable and it depends on a large number of factors. The most dominant of the factors is the generation to load ratio, also referred to as the level of penetration.

While it is universally accepted that islanding poses low risk at low levels of penetration, there is little information about what is the safe level of penetration that can be allowed. To make an informed decision whether a given level of penetration can be allowed, it is necessary to consider the second most important factor determining the circuit behavior during islanding: the *load composition*. In the context of this project the load composition is defined in accordance to load modeling guidelines of Western Electric Coordinating Council (WECC). The WECC guidelines recommend representing utility loads using a *composite load model*, which is based on seven equipment varieties including: four types of motor loads, power electronic loads such as various power supplies used in consumer electronics, resistive loads such as those in electric water heaters, and constant current loads representative of electronically controlled fluorescent lighting. For any given level of penetration, it is the load composition that dominantly determines the electrical behavior of the island.

The main goal of this project is to improve the understanding of the combined behavior of PV inverters and connected loads in the interval of time from occurrence of islanding to its eventual cessation. The desired behavior of inverters during islanding is fast detection and disconnection, leading to an orderly outage of the connected load. The need to prevent sustained islanding is well recognized in the industry and the UL 1741 standard includes a set of tests to evaluate the ability of inverters to detect islanding conditions and subsequently disconnect from the system. To be practical, these tests are performed as type-tests using a synthetic RLC circuit and, as a result, are unable to predict possible interactions of multiple inverters on the same circuit. Furthermore, the active anti islanding algorithms employed by the various inverter vendors are held proprietary, which prevents meaningful studies of islanding behavior using dynamic or transient simulations.

To overcome this challenge, we performed islanding tests in the laboratory using diverse groups of physical PV inverters. This made it necessary to also create a matching physical load, able to represent the behavior of composite loads. To achieve this without the impracticality of connecting a network of motors, lights, TV's, etc. in the lab, the load was implemented as a combination of a transient load model, executing in software, calculating currents in real-time in response to measured voltages, and a separate power-electronic amplifier extracting those currents from the power circuit. This approach enabled highly-streamlined experimental work and capture of a vast library of islanding experiments with consistently-recorded results in high-resolution. These recordings and the analysis code used to distill them into insights are placed in public domain to accelerate and inspire future work.

The technical work was organized into four main areas shown in Figure I. Quantification of field conditions is documented in the separately published Task 2 Report, details of the experimental setup in Task 3 Report, and testing, data analysis and evaluation of impact on interconnection in Task 4 Report. The findings from the project were shared with the utility industry at Distributech 2016 and PG&E has already modified some of its interconnection guidelines to make use of the insights from the project. PG&E relaxed its protection requirements related to the application of direct transfer trip and eliminated recloser blocking on sections with high penetration of PV, thereby reducing the associated interconnection cost.

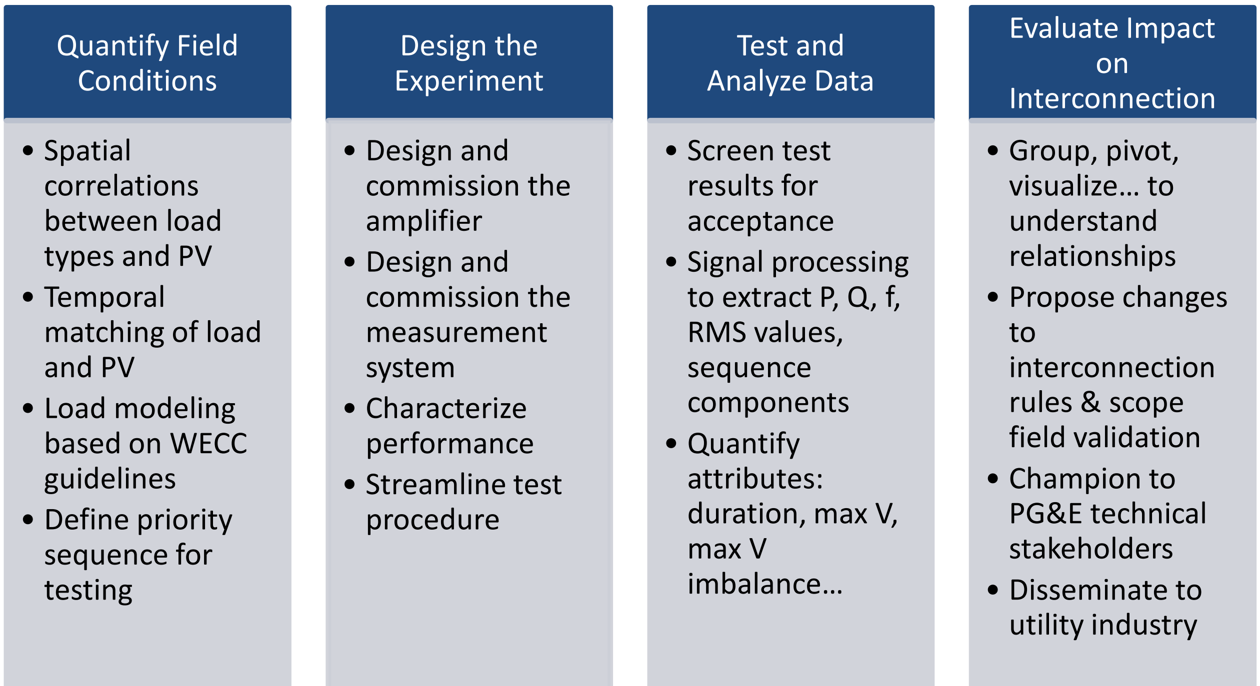


Figure I Main areas of the project

This Final Report provides an abbreviated overview of the work, highlights the main accomplishments and findings, and outlines a few ideas for future work. Extensive details are available in the task reports and in the corresponding data files and computer code accompanying those reports.

While we did find interesting and diverse voltage behaviors during islanded conditions, the severity of abnormal voltages was less than that of typical abnormal voltages experienced during unbalanced faults on a utility system, and the island duration in all performed experiments did not exceed 0.5 seconds for composite loads and 1 second for pure, high-inertia motor load. But this may be due to a large part on the tight voltage and frequency trip settings specified in IEEE 1547 and UL 1741. As a result of the tests, we found the pre-islanding power factor of the circuit section to be highly correlated with island duration and quantified this relationship over a wide range of conditions. This may be due to the fact that the tested inverters were set at unity power factor. The test results validate the fact that a stable island requires both real and reactive power to be dynamically balanced. This also pointed out that even though the real power is balanced, but if the reactive power is not balanced, the island still will collapse quickly. So, these test results implied that the allowable PV penetration on a circuit section may be increased without increasing the island duration by detuning the section to a power factor value between 0.95 and 0.98 inductive. Typically, the utility does not control the load. But it does have control over the operation of the capacitors and hence can control the power factor of a feeder.

Contents

List of Figures

List of Acronyms

ATS	Applied Technology Services
CPUC	California Public Utilities Commission
HVAC	High Volume Air Conditioning
MGTF	Modular Generation Test Facility
PG&E	Pacific Gas and Electric
PV	Photovoltaic
RTDS	Real Time Digital Simulator – the hardware product of RTDS Technologies Inc.
RSCAD	Software for RTDS – proprietary software used to run RTDS
WECC	Western Electricity Coordinating Council

Chapter 1

Introduction

Unintended islanding happens when a part of a utility distribution circuit that has some level of distributed generation becomes disconnected from the utility system and the distributed generation remains connected to the utility load. The need to prevent unintended islanding is well recognized in the industry and most customer-sited photovoltaic (PV) inverters deployed in California include features to detect an island and subsequently “cease to energize” the islanded portion of a utility feeder. The governing testing standard is UL 1741 and most utilities cite inverter compliance to anti-islanding test in UL 1741 as one of the criteria for evaluation of interconnection requests. For example, our partner Pacific Gas and Electric (PG&E), uses *Electric Rule 21 Generating Facility Interconnections* [1] to describe the interconnection requirements for generating facilities and, within it, specifies inverters qualifying for “Certified Non-Islanding Designation” as “Devices that pass the Anti-Islanding test procedure described in UL 1741”. However, despite its widespread use and enormous value to the industry, UL 1741 has several important limitations.

To be practical, UL 1741 tests islanding detection in a synthetic condition that does not capture all possible field conditions at the actual installed location and load variations. Furthermore, it is a *type test*, so it offers no insight into possible interaction of anti-islanding schemes from different inverter manufacturers. And finally, it limits the anti-islanding assessment to a pass/fail criteria, which does not address risks of damage to utility equipment or customer connected load due to transient conditions in the time interval between occurrence of the island and inverter's ultimate disconnection from the line. Utilities manage these risks by applying additional requirements to interconnection of certified inverters that in case of PG&E include the implementation of initial review and supplemental review screens and protection requirements sensitive to minimum load and to the presence of other, machine-based, distributed generation [2].

With limited experience in operating the distribution system with high penetration of PV inverters and absent design data on proprietary active anti-islanding algorithms from inverter vendors, these additional requirements are based on engineering judgment, which inevitably makes them subjective. As such, they are often a source of frustration for other stakeholders who see the additional requirements as an arbitrarily imposed impediment to greater adoption of distributed PV. In their defense, utilities are the only stakeholder with the responsibility to serve the loads with voltage and frequency within specified tolerances, yet, during islanding, they have no control over voltage and frequency because the island is disconnected from the utility system. To understand the scale of the conundrum faced by the utilities, it helps to list the variables affecting the electrical behavior of the island. In order of perceived importance, these variables are:

1) The level of penetration of PV relative to load. Note that both the PV and load depend on the time of day and the season of the year.
2) The makeup of load, where makeup means: lighting (incandescent, fluorescent, CFL, LED, halogen, mercury vapor, high pressure sodium, metal halide, …), refrigeration, air-conditioning, high-volume air handling, resistive heating, fans, pumps, compressors, electronics, household appliances, vehicle chargers, and many more. Like the penetration, the load makeup too depends on the time of day and season of the year, but also on the climatic conditions of the region.
3) The degree of utility-deployed reactive compensation on the distribution circuits and its time-varying operating state, because it determines the balance of reactive power at the initiation of islanding.
4) The variety of deployed PV inverters including: the number of phases, kW ratings, make, model, and vintage, all affecting the inverters' power circuit design and control design, where the control design includes the proprietary active anti-islanding scheme.

These many variables put two major barriers in the way of developing better understanding of circuit performance during islanding: First, the absence of information on active anti-islanding schemes makes it impossible to study islanding performance using large-scale computer simulations. While this could be overcome by performing experiments with physical PV inverters, the second challenge would still remain: Running laboratory tests with a network of motors, lights, TV's, to cover realistic varieties of load compositions would be both completely impractical and prohibitively expensive.

We were fortunate that our partner PG&E already has a laboratory facility with the representative variety of PV inverters used on their system. This left a second challenge: to create a matching physical load able to demonstrate the behavior of typical load varieties, and design the experimental setup to facilitate streamlined execution of a large number of tests to cover a representative set of scenarios. To achieve this, the load was implemented as a combination of a load model, executing in software, calculating currents in real-time in response to measured voltages, and a separate power-electronic amplifier extracting those currents from the power circuit.

To control the number of necessary experiments the team was interested in exploring only the realistic conditions -- those that can occur on distribution circuits with realistic load varieties, and with interconnected distributed generation (DG) that was screened and approved by an experienced utility company. Our partner, PG&E, is a role-model company in this context: They have a well-established interconnection process, they keep detailed electronic records of their vast and diverse distribution system, and they collect and archive operating data from more than one half of their distribution substations. The team was given access to PG&E system data of unprecedented scale and fidelity, analyzed it to fully understand the range of possible islanding conditions and, based on it, defined the test plan for the full-scale laboratory testing. This work is reviewed in Chapter 2 and covered in full detail in the, separately published, Task 2 Report [3].

In parallel, the research team designed, built, and commissioned the electronic load, implemented as a combination of a transient load model, executing in software, calculating currents in real-time in response to measured voltages, and a separate power-electronic amplifier extracting those currents from the power circuit. In the interest of standardization and flexibility, the load models were strictly aligned with the guidelines of Western Electric Coordinating Council (WECC) [4] and implemented on an industry-proven Real Time Digital Simulator (RTDS). The RTDS measures circuit voltages in real time and supplies it to the load model implemented in software. The load model calculates the would-be load currents and supplies these values as analog signals to the power amplifier that extracts the currents in real-time from a physical circuit. The physical PV inverters supplying the power island respond to currents by modifying their output voltage and the cycle repeats enabling study of transient behavior of realistic utility loads during islanding conditions. This work is reviewed in Chapter 3 and covered in full detail in the, separately published, Task 3 Report [5].

Next, the team performed over a thousand laboratory experiments, and processed and analyzed the data to gain insights about the risk to the load due to electrical conditions during islanding. This work is reviewed in Chapter 4 and covered in full detail in the, separately published, Task 4 Report [6].

Finally, based on the gained insights, recommendations were made for changes in PG&E's interconnection process and a few directions offered for future work. This is presented in Chapter 5.

Chapter 2

Quantifying the Field Conditions

As was discussed in the introduction, the project sets out to credibly predict electrical behavior of islanded portions of utility circuits containing representative mixes of loads and PV inverters. The chosen approach is to perform this evaluation experimentally by running physical inverters with an electronically-configurable physical load, disconnecting from the utility supply to force the island and observing the behavior. In layman's terms, the number of experiments that has to be executed is dependent on the number of independent variables expected to affect the electrical performance of the island, the number of levels of interest in each variable, and their relevant combinations. Allowing for: seven varieties of load stipulated by WECC guidelines arranged into different load compositions, different possible mixes of PV inverter varieties, different assumed levels of PV penetration, and different levels of reactive compensation, it is not possible to use a brute-force approach and run an experiment for every possible combination of factors. Fortunately, it is neither prudent nor necessary to cover every possible combination, only those that actually occur in the field. The purpose of Task 2 of the project was to perform a comprehensive study of realistic conditions in the field to understand the range of possible islanding conditions and, based on it, define the test plan for the full-scale laboratory testing. The outcome of Task 2 is essentially a priority sequence that defines the relative importance of tests. The combinations that are encountered more frequently on physical circuits are more important to evaluate and understand than those occurring less frequently, while those combinations not encountered at all, in a representative sample of field conditions, are of no interest and need not be evaluated.

The overall technical approach used to quantify the field condition is shown in Figure 1. The individual steps are reviewed in the following sections.

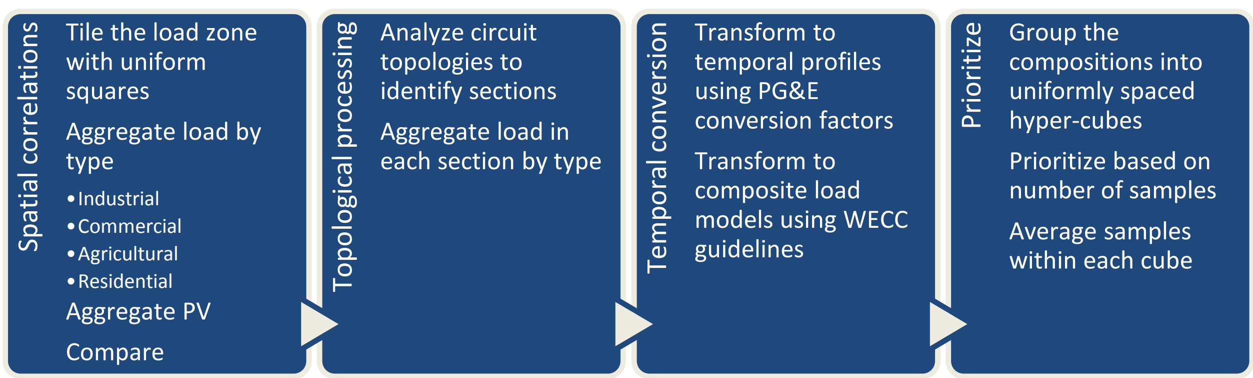


Figure 1 Technical approach to quantifying the field conditions

Spatial correlation between load and PV

PG&E has their distribution system organized into load zones that are contiguous geographic areas with similar climatic conditions. The team considered three load zones representing different climates, shown on the stylized map of California in Figure 2.

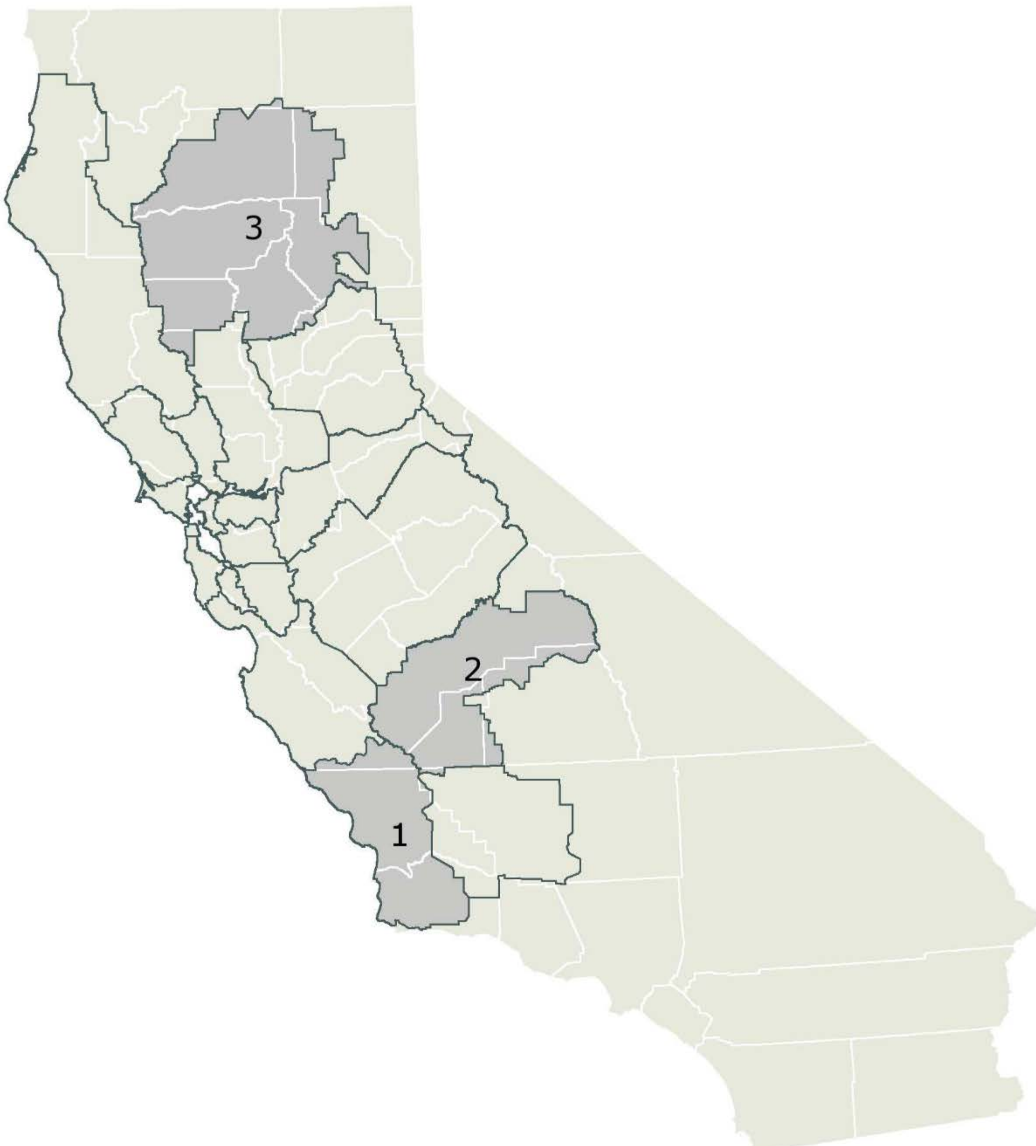


Figure 2 Studied load zones within PG&E service territory, map reprinted with permission from PG&E

Table 1 captures summary information about the studied load zones. Most of the data in this table is obtained by direct summation of available records within PG&E's databases.

The first section of the table documents the total number of substations and distribution feeders, and provides the calculated circuit miles and land area served. The total circuit miles were calculated by summing the distances spanned by the individual line segments. The calculations of total land area served is more complex, and it was review to introduce the concept of *tiling* later used in calculating load densities by type. The first step in calculating the land area served is to process all line segments within the load zone to determine the most south-west and the most north-east coordinate of the zone and thus establish the rectangular reach of the zone. Next, this rectangle is tiled with squares of an arbitrary area, we chose 0.25 square mile (0.5-mile square side) as a good compromise between precision and speed of calculations. Finally, the line segments are processed again to determine if the tiles include a line segment or not. In other words, existence of any line segment within a tile "flags" the tile as a part of the land area served. The total land area served is calculated as the sum of areas of all flagged tiles.

Table 1 Summary information about studied load zones

Attribute/Metric	Zone 1	Zone 2	Zone 3
Number of substations	27	66	64
Number of distribution feeders	84	325	148
Total circuit miles [mi]	1774	4101	3238
Total land area served [sq. mi]	92.3	190.7	174.2
Number of load points (1000s)	114.2	235.3	189.3
Total load [connected MVA]	2647.3	7123.6	3085.1
Total load [MWh/day]	7253.7	29359.8	8372.8
Residential [%]	36.5	42.2	55.9
Commercial [%]	12.6	6.1	6.0
Industrial [%]	37.4	29.9	27.4
Agricultural [%]	13.4	21.4	10.5
Other [%]	0.1	0.4	0.2
Number of power-factor correction capacitors (including fixed and switched)	394	1465	702
Total reactive compensation [MVAr]	308.5	1457.4	491.1
Fixed [as a % of total] (by MVAr)	24	16	15
Number of reclosers	258	593	545
Number of voltage regulators	124	356	254
Number of PV installations	3352	7948	3521
Total PV capacity [MW] (nameplate AC)	24.8	83.8	39.2
PV/Connected MVA load [%][1]	0.94	1.18	1.27

[1] Note that the system-wide DG penetration is ~13% at the time of this writing. See text for details.

The second section of Table 1 captures information about the loads. PG&E tracks "point loads"[2], where each point has an association with a customer, or a group of customers, served from that point on the distribution circuit. The load points are essentially service transformers and secondary connections to the individual customers' meters are not represented in this model, leading to expressing those connections as associations between meters and service transformers.

The number of (individually recorded) load points gives the sense of scale of the underlying dataset; the smallest studied load zone, Zone 1, contains 114,000 individual load points, while the largest, Zone 2, has 235,000 load points. Each load point further includes the information of the total connected load (in MVA) and the energy consumption (in MWh/day,) segregated by load type: Agricultural, Commercial, Industrial, Residential, and Other. The connected MVA gives a sense of the maximum possible load demand at the load point, while the energy consumption is a measure of actual energy usage that PG&E calculates based on the metering data for the customers associated with a load point.

The third section of Table 1 summarizes the installed utility equipment: the number of individual power-factor correction capacitors, the total rating of those capacitors (in MVAr), and the percentage of fixed (non-switched) capacitors determined by total MVAr, not the count. This is followed by the number of reclosers (circuit elements that can separate parts of the feeder from the upstream utility system and isolate faulted sections and possibly create electrical islands downstream with the presence of DG), and by the total number of voltage

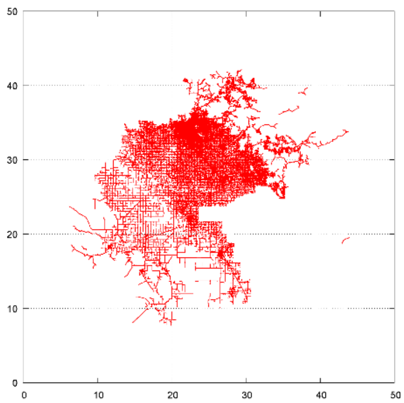
[2] This is a more accurate representation relative to alternative practice of distributing loads over line segments---used by utilities that do not have accurate spatial records of their distribution loads.

regulators. (Voltage regulators have no direct impact on risk-of-islanding, but were included for completeness, as they are sometimes affected by PV variability associated with cloud shading.)

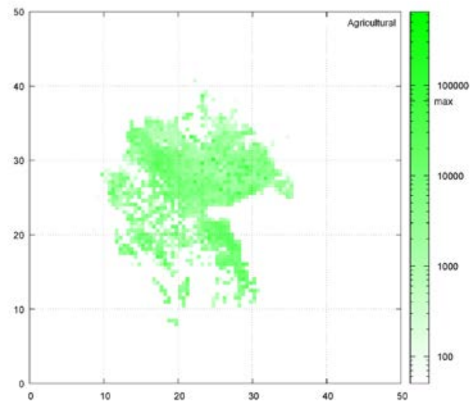
The fourth section summarizes the available information about installed PV: the total number, the total MWs based on the nameplate AC ratings, and the PV penetration expressed as a percentage relative to connected load MVA. Note that since this information was aggregated during Task 2 execution, the system-wide DG penetration has grown to ~13%. This trend explains the motivation and urgency of PG&E to fully understand all factors relevant to interconnecting additional DG, and illustrates how timely this project was.

The spatial densities of various load types can be depicted as shown in Figure 3. The load densities were calculated using the same square grid used to calculate the land area served. Every square of the grid was assigned an array element for summation of load by type and sums were calculated based on location of individual load types on the grid. The resulting load densities were then transcoded into colors for the individual heatmaps. Large variations in values of spatial densities made it necessary to use logarithmic scales.

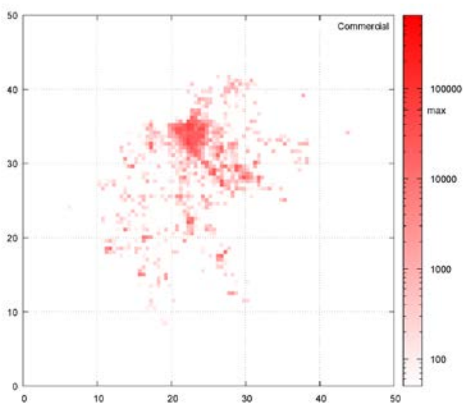
The heatmaps show the relative spatial spreads of loads, indicating that the agricultural loads are the load type most evenly spread throughout the load zones, and that the other three types: industrial, commercial, and residential, have less uniform, but mutually correlated spatial patterns. The spatial distribution of PV installations correlates well with the latter three load types.



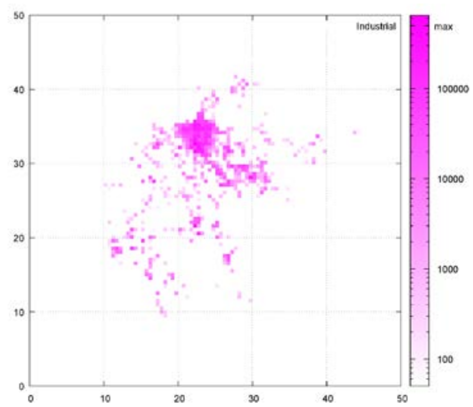
(a) Zone 2 spatial reach



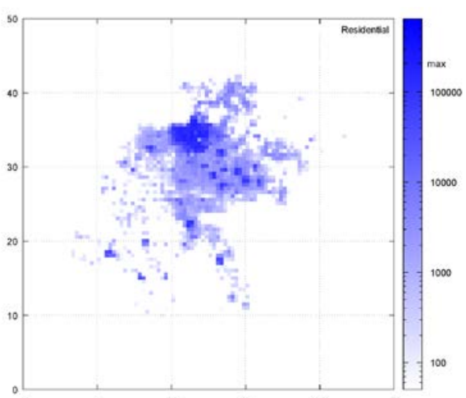
(b) Agricultural loads



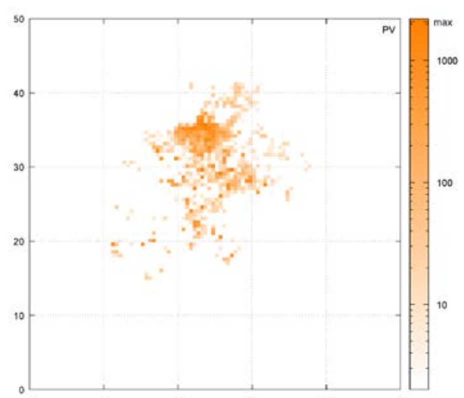
(c) Commercial loads



(d) Industrial loads



(e) Residential loads



(f) PV installations

Figure 3 Zone 2 spatial densities of four load types (MWh/0.25sqmi) alongside spatial density of PV (kW/0.25sqmi)

The spatial correlation of PV with load types gives rise to the notion of using statistics to determine load mixes by type which correspond to the areas with high penetration of PV, and to perhaps prioritize laboratory evaluation to cover the load mixes with highest probability of co-occurrence with the high penetration of PV. This was discussed at length with PG&E distribution planning and it was decided that it is more useful to uniformly sample all possibilities, than to down-select only the mixes that currently have high penetration. The reason for this decision is twofold:

1) The PV penetration is a localized phenomenon and one large installation can drastically change the penetration level of the associated line section.
2) It is easier to procure land at the fringes of load zones, where the load densities are not as high, so it is possible (and perhaps likely) that the future PV projects will be spreading throughout the load zones and begin to mix with dominantly agricultural loads, not continue to be correlated with the industrial-commercial-residential load types.

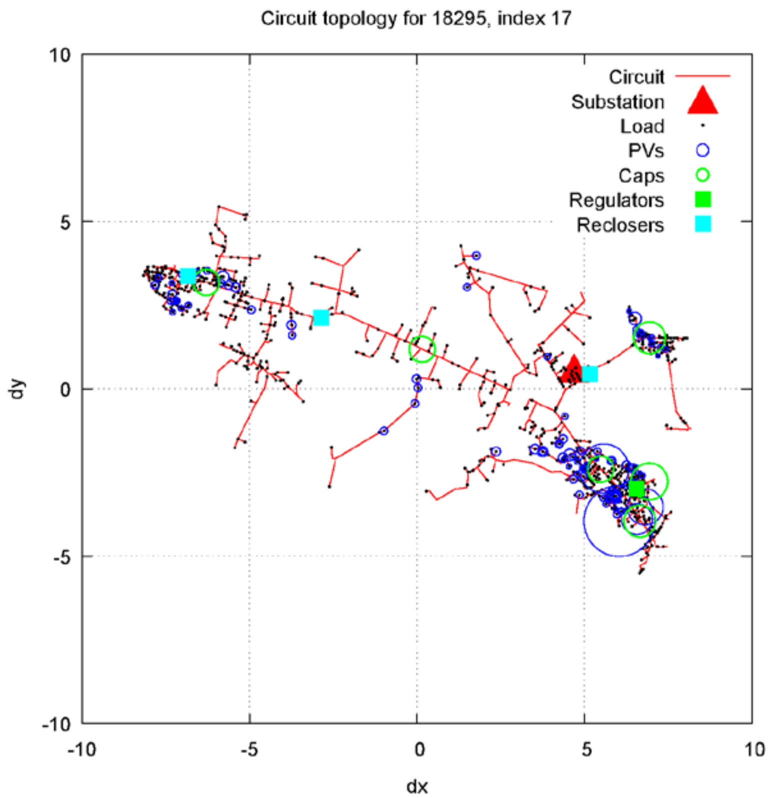
Essentially, it was decided that it is better to run laboratory experiments to be prepared for all options in the future than to prioritize based on the situation at present and possibly miss a future scenario.

Referring again to summary information in Table 1 the load zones are similar with respect to distribution system design practices. The average number of circuit miles per recloser is consistent (between 5.9 and 6.9), the average number of circuit miles per voltage regulator is consistent (between 11.5 and 14.3) the ratio of reactive power compensation to load energy is consistent (between 0.0425 and 0.0587), the ratio of fixed to total reactive compensation is consistent (between 15 and 24%), and so on. The average penetration of PV is small (between 0.94 to 1.27%), but, as will be discussed later, this number varies greatly by individual circuits and sections of circuits.

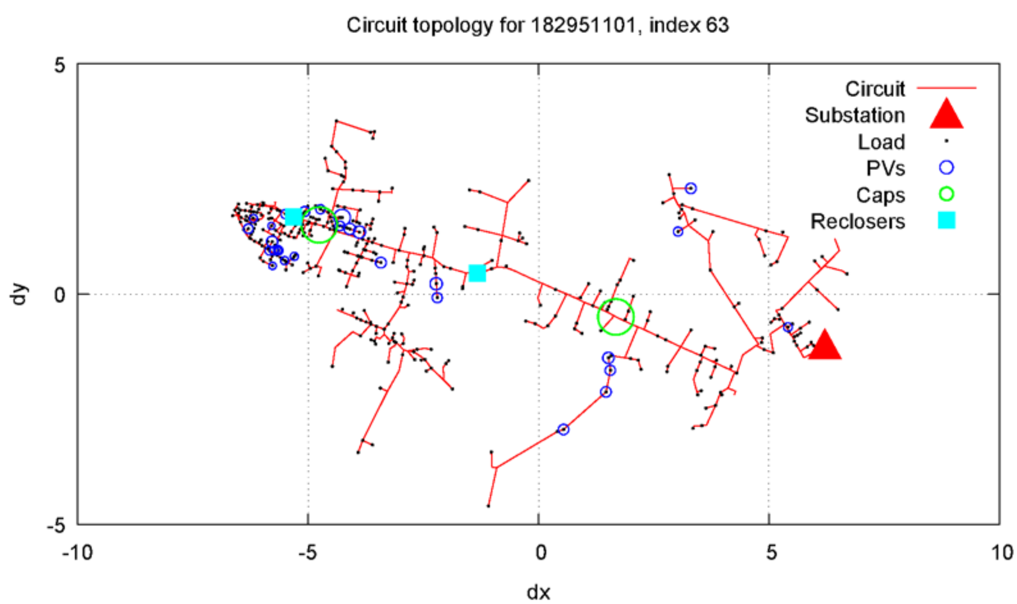
In terms of the inherent properties, Zone 2 has the highest average load density and the highest percentage of agricultural load (the two are not necessarily correlated.) Zones 1 and 3 have comparable load densities, but Zone 3 has a higher content of residential loads. The load types (residential, commercial, industrial, agricultural) are relevant as they are the proxy that determines the load mix, which affects the combined behavior of PV and load during islanding. For a complete coverage, the load mix must be assessed at any level of circuit aggregation that can become islanded. Consistent with PG&E screening practices, this means any circuit section downstream from any recloser.

Topological processing

For illustration, Figure 4 (a) shows a map-view of the feeders for substation 295 in Zone 1, and Figure 4 (b) a map-view of one of those feeders. As before, the circuit sections are shown using red lines, but we now introduced additional elements: point loads are shown as black dots, PV installations as blue circles with areas proportional to the installed AC ratings, power factor correction capacitors are shown as green circles, and reclosers as cyan squares.



(a)



(b)

Figure 4 Levels of circuit hierarchy supported by raw data: (a) substation, (b) feeder

PG&E maintains relational hierarchy of circuit data that allows for identifier-based aggregation of circuit loads to a level of a feeder, but stops short of supporting aggregation at a section level. Referring back to Figure 4 (b), two reclosers can be seen within the feeder, creating three possible island topologies:

1) the whole circuit, precipitated by the fault between the substation and the first recloser and cleared by the action of protection devices at the substation (feeder-head),
2) the part of the circuit downstream from the first recloser, precipitated by the fault between the first and second recloser and cleared by the action of the first recloser, and
3) the part of the circuit downstream from the second recloser, precipitated by the fault downstream from the second recloser and cleared by action of the second recloser.

It is evident from the figure that the relative density of installed PV is the highest downstream from the second recloser, illustrating the earlier observation that PV penetration is a local phenomenon that can vary significantly in different possibly-islanded regions of the same feeder. It is also evident that the location of power factor capacitors relative to location of reclosers is a matter of some chance, resulting in the similarly variable ratio of reactive compensation relative to load and PV within different feeder regions.

This makes it necessary to study the possible mixes of PV, load, and reactive power compensation at levels of circuit hierarchy corresponding to all feasible electrical islands. To enable this, a technique developed in earlier work was used that parses the graph comprised of nodes and sections and establishes the downstream and upstream associations between nodes relative to the root node (the substation.) The description of the technique and its illustrative outputs are given in [3].

Temporal conversion of load

Next, the load aggregates collected by circuit and by circuit section need to be transformed into temporal profiles of load compositions in accordance with WECC load modeling guidelines. This transformation was performed using PG&E-provided *conversion factors*, which are charts of kW/kWh and the corresponding power factor as a function of time, given at two-hour time intervals. PG&E defines these chart pairs for summer and winter, with additional subdivision for summer into coastal and inland.

Given a season (summer, winter), a location (inland, coastal), and a circuit or circuit-section of interest (described by aggregated energy by load type), the temporal active power profile (P(t)) of the circuit-section aggregate load is determined as a product of energy by load type and its corresponding time-varying conversion factor, summed over all load types. The temporal reactive power profile (Q(t)) of the circuit section aggregate load is determined by converting samples of P(t) for each load type using the corresponding temporal profiles of power factor and then summing over all load types.

The remaining step is to transform the temporal profiles based on load types into load compositions according to WECC guidelines. The temporal load profiles were determined by application of PG&E conversion factors, and transformed each hour into relevant compositions using hour-specific distributions from WECC "light" process. The team then sampled the temporal profiles of load compositions at noon to create a representative set of load compositions likely to become islanded at the time of highest output from PV. For detailed description of the entire procedure please refer to [3].

The final result is a sample of load composition for each circuit section analyzed. There are 3440 samples representing the full set of possible load compositions. Each of the 3440 samples corresponds to a unique circuit section within three studied load zones and its load has been converted into load composition using this procedure. In the next section we discuss how are these samples grouped to cover their highly-dimensional space of values with a feasible number of laboratory experiments.

Prioritization of load compositions

Starting from the table of samples described in the previous section, the first step is to normalize load compositions to reduce all variables to the same scale. The normalization was done by dividing values of all attributes with total P. This makes perfect sense for load components as it establishes percentage content of each. It also makes sense for PV, as it describes the level of penetration at noon-time, i.e. the time period with the most significant PV output.

The normalized compositions were then studied for correlations. This is a substantial undertaking in the seven-dimensional variable space and several methods were tried to gain insights into the groupings of samples. Using a matrix of scatter plots of variable pairs proved existence of significant correlations between the variables and the parallel coordinate plots provided the sense of range for each variable and uncovered the notable differences between summer and winter load compositions. These insights provided the inspiration to group the samples of load compositions into hypercubes of the seven-dimensional space.

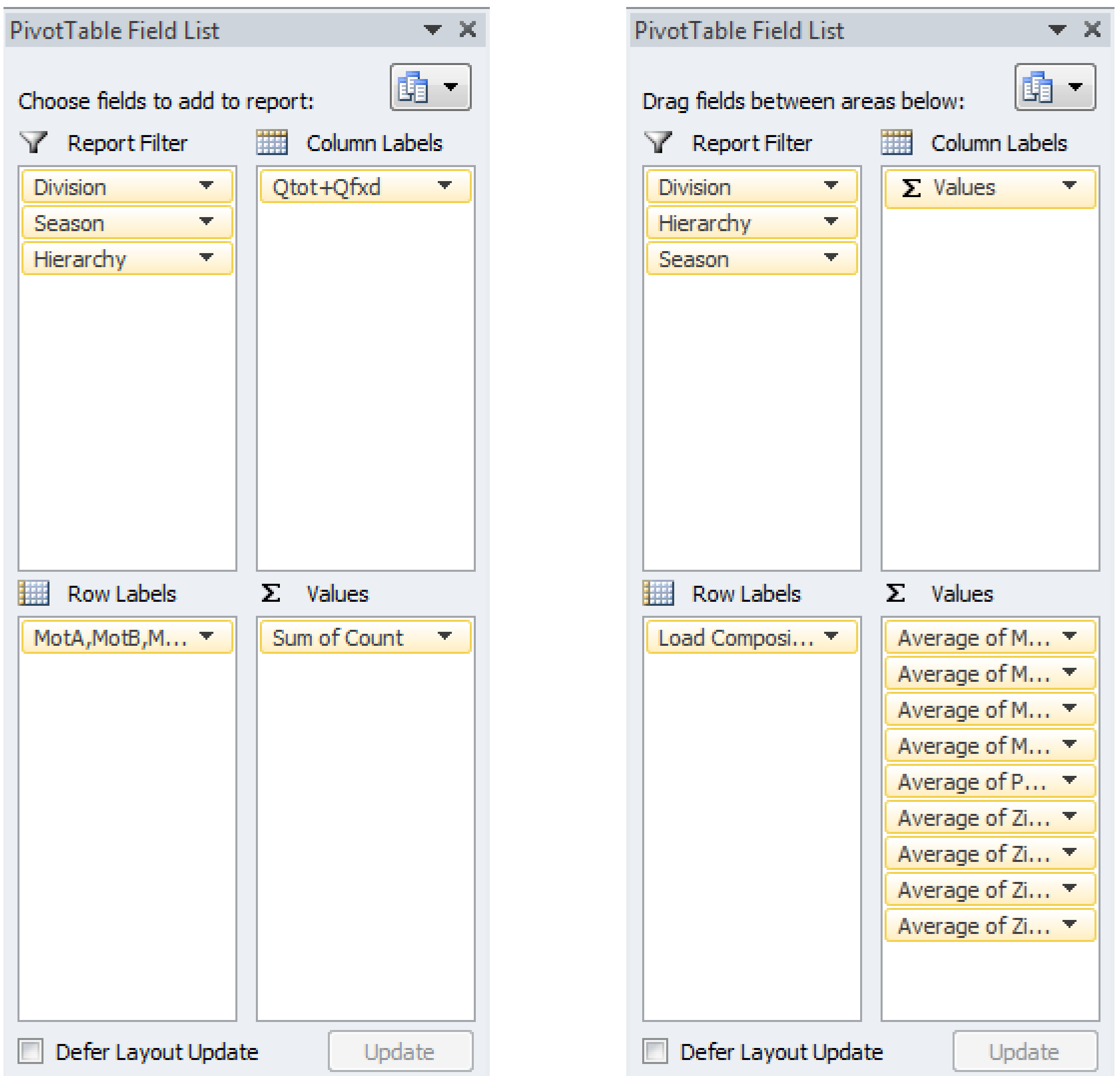
To do this, we assumed ten bins per axis (a dimension of the hypercube edge equal to 0.1) and processed all samples to associate them with the hypercubes. This is not difficult – given a vector representing the sample, each variable within the vector is associated with the bin of the corresponding hypercube-axis by integer rounding of a ratio of the variable value and the edge size. For example, applying this formula associates the vector of normalized load compositions: `(0.2112, 0.1021, 0.2235, 0.1325, 0.0971, 0.1791, 0.0545)` with the hypercube

`(0.2,    0.1,    0.2,    0.1,    0.0,    0.1,    0.0)`

This enables further analysis of the population using *Pivot Tables* in Microsoft Excel. The hypercube designations are transformed into labels and used as pivot rows. The load division, the season, and the circuit hierarchy are used as filters. There are two pivot tables:

The first one is used to count the number of load composition samples per hypercube. Subsequently, the counted samples are sorted in descending order to provide the priority order for laboratory evaluation of load compositions. As an added convenience, this pivot table also includes a binned value for Qtot+Qfxd as a pivot column to count the subdivision of samples within a load composition hypercube into bins of total reactive power on those circuit sections. Because the total reactive power is of interest, we use the sum of Qtot (reactive power of the load) and Qfixed (total reactive power on non-switched power-factor correction capacitance.) The definition of this pivot table is shown in Figure 5 (a).

The second pivot table provides the averages of the variable values within the hypercube. This is important as the association of samples with hypercubes lost information of actual variable values, so to have the representative value of samples within a hypercube, it is appropriate to use the vector average of the samples located in the hypercube. The definition of this pivot table is shown in Figure 5 (b).



(a) Counts within hypercubes

(b) Averages within hypercubes

Figure 5 Ranking of load-composition hypercubes using excel pivot tables

The analysis of the load compositions datasets revealed that the samples are concentrated in a relatively small number of hypercubes. The results are summarized in Table 2. Note that the row totals are not algebraic sums of column values because many hypercubes are shared between the load zones. The column totals are algebraic sums of row values because of the differences between summer and winter data sets. These numbers are a significant reduction from the total number of hypercubes of one million[3].

Table 2 Number of hypercubes containing load composition samples

Season	Zone 1	Zone 2	Zone 3	Total
Summer	38	63	67	80
Winter	47	67	66	85
Total	**85**	**130**	**133**	**165**

The hypercubes of load compositions were then ranked in descending order by frequency of occurrence. The number of samples per hypercube is proportional to the covered part of the total space of options and, consequently, this ranking provides a relationship between the number of compositions tested and the percentage of total space covered. This relationship is shown in Figure 6 for summer and winter family of load compositions.

[3] There are 10 choices per variable, and 7 variables constrained by their sum being equal to 1. This provides six independent choices with a total number of choices equal to 10^6.

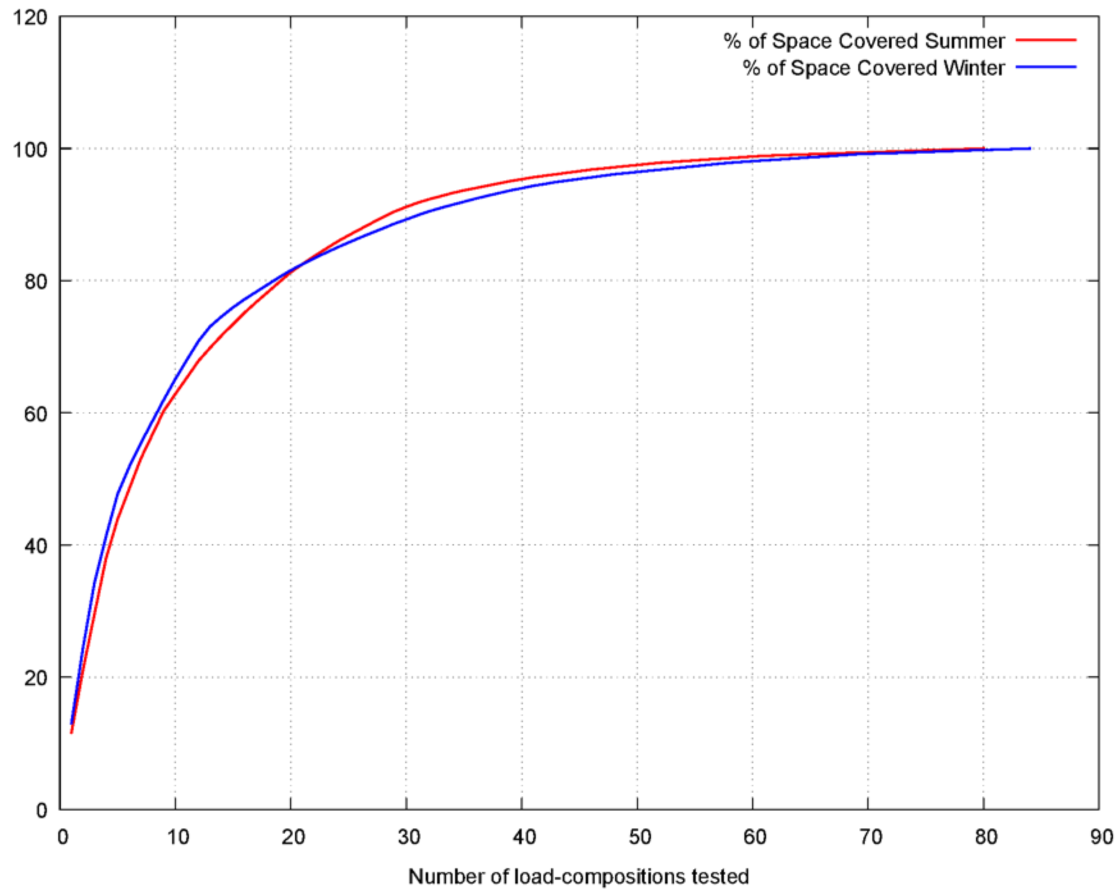


Figure 6 Coverage of load compositions space by number of compositions tested

Furthermore, the analysis of total reactive power on circuit sections revealed that over 95% of samples have normalized Qtot+Qfxd in the range between -0.7 and +0.3. This led us to the following formulation for laboratory testing:

1) Generate the combined priority list and the corresponding table of averages
2) Chose the hypercube of load composition from the priority list
3) Set normalized Q of the experiment to the minimum desired end of Q range
4) Set PV penetration to the maximum desired value
5) Run the islanding experiment and capture data
6) Repeat 4 to 5 for all desired levels of PV penetration

7) Repeat 3 to 6 over the desired range of Q

8) Repeat 1 to 7 for additional hypercubes following the priority sequence.

Note that the number of points in the desired range of PV penetration and the number of points in the desired range of Q, multiply the number of tests required for each load composition. Assuming that the total number of tests is inevitably limited, there is a tradeoff between the precision in covering the “PV x Q matrix” and the attainable coverage of load space. The next chapter revisits this in the context of available equipment and reviews the final test plan.

Chapter 3

Experiment Setup

Facility overview

All experimental work in this project was performed in the Modular Generation Test Facility (MGTF) at PG&E's San Ramon Applied Technology Services (ATS) Center. This facility has the capability for testing and evaluating distributed generation and storage equipment and their interactions with a utility grid. Overall capabilities of MGTF include:

- 500 kVA facility rating and equally rated switchgear for independent power production
- 3-phase, 480 Volt wye service
- Multiple bus configurations for islanding capability
- Protection for utility under/over frequency, under/over voltage, and ground fault current
- 400 kW variable resistive load controllable in 5kW increments
- 300 kVAR variable inductive load controllable in 3.75 kVAR increments
- 150 kVAR variable capacitive load controllable in 50 kVAR increments

- Natural gas supply
- 70-foot by 40-foot building designed for distributed resource testing

PV Inverters

The facility also includes the fleet of PV inverters powered by controllable DC power supplies. The available inverters are a sample of popular makes and models deployed on PG&E's distribution system. Figure 7 is the photograph of the so-called "wall of inverters" with the multi-vendor, multi-model variety of residential PV inverters.

Figure 7 Residential PV inverters installed at PG&E Applied Technology Services Center in San Ramon CA

The overview of ratings of all available units is provided in Table 3. Vendor names and model numbers are obscured by unit codes for privacy.

Table 3 List of PV inverters available at PG&E's Applied Technolgy Services Center in San Ramon CA

Unit Code	Number of Phases	Number Available	Maximum AC Output (kW)
x100	3	1	75
x45	3	1	42
r4kW 120Vac	1	4	4
r4kW 240Vac	1	10	3.8-4
r3.3kW 240Vac	1	6	3-3.3
r2.5kW 240Vac	1	10	1.5-2.5

The maximum concurrent output of the installed inverter fleet is 140kW; limited by the capabilities of their DC power supplies and the need to balance the total generation over three phases to match the 3-phase electronic load.

Islanding Test Circuit

The simplified circuit diagram of the test circuit is shown in **Error! Reference source not found.**. Starting from the left, there is a connection to PG&E 480V service which powers the DC power supplies of the PV inverters. Another connection to the same 480V service is made on the other side of the diagram via the islanding circuit breaker (CB.) From top to bottom, the equipment shown between the two 480V rails includes:

1) A three-phase DC power supply powering two three-phase PV inverters. Each is interfaced via a dedicated step-up transformer to the 480V bus on the right-hand side.

2) Below it, there are three groups of residential PV inverters. Each group consists of multiple power-supply/inverter pairs connected together on the AC side and interfaced to the 480V bus using a single phase transformer dedicated to the group.
3) Shown near the bottom is the electronically controlled load. From left to right there is an isolation transformer, the three phase power supply, and the three phase power-electronic amplifier controlled by the signals from RTDS.

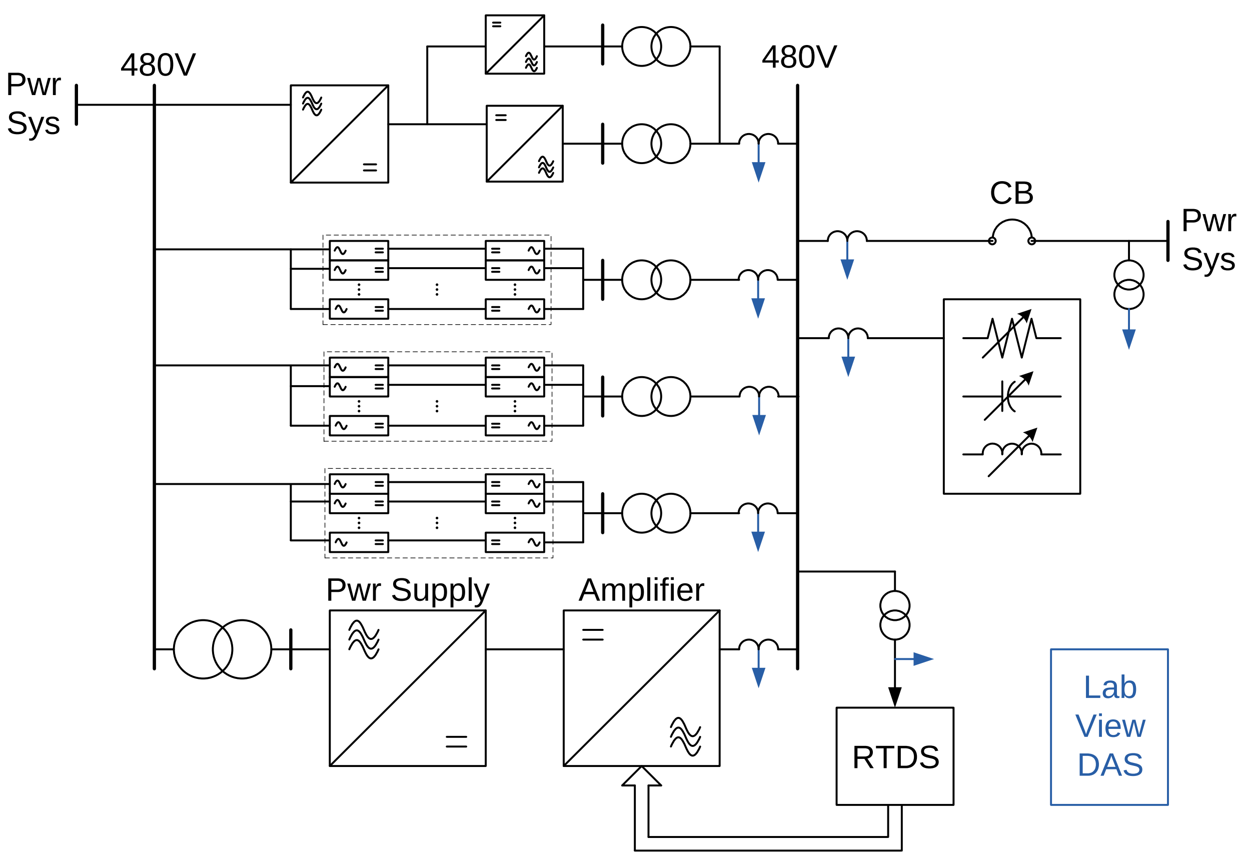


Figure 8 Test Facility Overview Diagram

The islanding tests are performed by bringing up the equipment to the desired operating point and then opening the circuit breaker CB to create the electrical island. This forces the output of the PV inverters to flow into the electronic load and enables observation of transient values of voltages and currents from the initiation of islanding up to its cessation. The tests are orchestrated and recorded using the custom-built data acquisition system (DAS) based on National Instruments' PXIe-1062Q Express Chassis and programmed in LabView. This system is symbolically shown as the blue rectangle labeled LabView. The signals from current and voltage transformers recorded by the DAS are designated by blue arrows in the diagram. Note that the voltage signals from the island are also supplied to RTDS to allow execution of the load model in response to actual circuit voltage.

The passive adjustable load, shown below CB, was used in characterization of the amplifier during commissioning of the test and to reduce capacitive current of the amplifier during testing.

Implementation of Controllable Load

As was already discussed, the electronically controllable load is the key enabler of comprehensive study of behavior of utility loads supplied by PV inverters during islanding conditions. Load modeling was generalized by dividing it into two parts:

1) the model of arbitrary load implemented in Real Time Digital Simulators (RTDS) responsible for calculating would-be load currents in response to system voltage, and
2) the power amplifier receiving calculated load currents and extracting them from the power circuit.

These two functional blocks are described in detail in [5]. The discussion is limited to the review of equipment. The photograph of the RTDS rack (located inside MGTF) is shown in Figure 9 (a) and the integration of RTDS analog output card within the control cabinet of the Amplifier (located outside MGTF) is shown in Figure 9 (b). Locating the RTDS analog output card within the amplifier control cabinet minimizes the noise pickup on the signals. The card is referenced to the same analog ground as other control cards within the amplifier and connected to RTDS via a fiber optic cable.

(a) (b)

Figure 9 Photographs of hardware: (a) RTDS rack and (b) Amplifier control cabinet with RTDS analog output card installed atop standard controls (right)

The amplifier part of the electronic load was built using two utility scale solar inverters connected back to back to exchange power via a DC circuit (normally used to connect PV panels). The photograph of the two units as installed in PG&E ATS facility is shown in Figure 10. One inverter, acting as a power supply, has its AC terminals continuously connected to the utility voltage via an isolation transformer. It is operated to control the voltage on the DC connection between the two units. The other one, acting as a current amplifier, has its AC terminals connected to the bus that gets islanded. The nameplate ratings of the two units are 750kW for the power supply and 1MW for the amplifier. However, since the total simultaneous capability of PV inverters used in the test amounts to 140kW, the internal measurement system on the amplifier was modified to correspond to 250kW, one quarter of its design ratings.

Figure 10 MW-scale electronic load at PG&E Applied Technology Services in San Ramon CA

Measurement and Control System

The measurement system used in the experiments is based on National Instruments' "PXIe-1062Q Express Chassis" and programmed in LabView. The same hardware orchestrates the tests – it operates the islanding contactor and several other switches that can be used to isolate groups of equipment and triggers the data acquisition and recording of test results into files.

The three-phase line to neutral voltages of the island bus and the utility bus and the phase currents supplied or consumed by different equipment groups are monitored by voltage and current transformers and their instantaneous values tracked by the measurement system. A photograph of the breaker panel with side panels removed to expose current transformers is shown in Figure 11.

Figure 11 Measurement system: Breaker panel and current transformers

The execution of the islanding test sequence is programmed into the custom-designed LabView tool – after a user-issued command to start the test, the system begins recording of all analog channels into a file, opens the islanding contactor and continues to record until either a specified recording time is reached, or until voltage falls under a specified threshold. The recordings are saved as binary files in the native LabView format, which includes data describing the configuration of input channels (e.g. scale, offset, sampling frequency) and the raw recordings.

Test Plan

As was already discussed, the main objective of this project is to improve the understanding of the combined behavior of PV inverters and connected loads in the interval of time from occurrence of islanding to its eventual cessation. The research team is seeking to find and evaluate conditions that make islanding detection difficult and to capture the resulting voltage and frequency during these conditions in laboratory measurements. The team is only interested in realistic conditions – those that are likely to occur on real distribution circuits with realistic load varieties.

The work reviewed in Chapter 2 assessed the diversity of load compositions on a statistically representative sample of PG&E circuits. The seven-dimensional space of load compositions was then prioritized based on frequency of occurrence to prioritize laboratory evaluation. Next, the controllable load was built as described in the earlier sections, to enable efficient evaluation of different load compositions. The load composition is adjusted via a user interface to the RTDS model instead of making changes to the power circuit, providing critically important efficiency of the testing process.

The remaining variables of interest are the level of reactive compensation on the circuit section, and the level of PV penetration. These selections are orthogonal to one another and to load compositions, meaning that any number of choices for reactive power factor will multiply the number of choices for PV penetration then multiply the number of choices of load compositions, resulting in combinatorial expansion in number of experiments. This was given careful consideration by the project team, and it was ultimately decided to consider four choices of reactive compensation and five levels of PV penetration. The rationale is provided in the following paragraphs.

For reactive compensation we chose power factors of: 0.95 inductive, 0.98 inductive, 1.0, and 0.98 capacitive. These choices are prudent because PG&E is quite vigilant about reactive compensation of its distribution circuits – in the three load zones we studied the average number of reactive compensation capacitors per feeder is ~4.6. It is therefore likely that an islanded section of a distribution circuit will operate at a power factor close to unity and exploring the range between 0.95 inductive and 0.98 capacitive covers all likely options.

To achieve different penetration levels of PV, the choice was made to vary PV on a fixed load by running the PV inverters at their maximum attainable output and varying the number of inverters in service. The residential units were grouped into four configurations resulting in different levels of power output. Table 4 documents these configurations in order of descending power output, and introduces letter codes: “d” through “a” used to designate them. The equipment used for each configuration is listed in table columns under each letter code. Each row of the table corresponds to one type of available PV inverters and the table cells document the power output from the corresponding types of units and the number of units used in the test. For example, configuration “d” gets 24kW of PV generation from 6 PV inverters of “r4kW 240Vac” type; designated by 24 (6) in the corresponding table cell.

Table 4 Groupings of residential inverters in different test configurations

Configuration Code	d	c	b	a
r4kW 120Vac	16 (4)	16 (4)	16 (4)	12 (3)
r4kW 240Vac	24 (6)	20 (5)	16 (4)	12 (3)
r3.3kW 240Vac	16 (5)	13 (4)	10 (3)	7 (2)
r2.5kW 240Vac	10 (4)	5 (3)	5 (3)	5 (3)
Total Power (kW)	**66**	**54**	**47**	**36**

Using these configurations individually or combining them with either of the three-phase units (x45 and x100) allows for twelve possible values of PV power output and, consequently, twelve possible values for % penetration assuming that the load is held constant. The team has ultimately chosen five levels of penetration designated by: “`xoff b`”, “`x45 a`”, “`x45 c`”, “`x100 b`”, “`x100 c`”. To explain the nomenclature: the label “`xoff b`” means that both available three-phase inverters are kept off and only the group “`b`” of the roof-top inverters is in service, while the label “`x45 c`” means that the 45kW three-phase inverter is operated with the group “`c`” of the roof-top inverters. Holding the load constant at 120kW these combinations of PV inverters results in levels of penetration of: 36%, 61%, 80%, 100%, and 108%, respectively.

The complete set of steps of the test procedure is shown in Figure 12. More detailed description of this procedure including the steps for quality assurance and the design of test log files can be found in [5].

1) Select a load composition from the priority list
   - Configure load model in RSCAD runtime
   - Record baseline P, Q seen by the RTDS, Amplifier, and LabView

3) Set PF to 0.95ind (by dialing the capacitive correction on the amplifier)

4) Set PV penetration to 108% (by starting the pre-determined group of PV inverters)

5) Run the experiment and capture data

6) Repeat for PV penetrations of: 100, 80, 61, 36% (restart tripped inverters, repeat from 4)

7) Screen for acceptance, repeat tests if required

8) Repeat for other PF choices: 0.98ind, 1.0, 0.98cap

9) Upload data to cloud storage

10) Repeat for other load compositions from the priority list

Figure 12 Test Procedure

Chapter 4

Analysis of Test Results

This chapter documents the data-analysis used to characterize relevant electrical conditions expected to be seen by the PG&E distribution system loads when supplied by solar PV inverters and islanded (disconnected) from utility supply. These data are used to assess the risk of damage to the load. The risk assessment is based on comparing electrical conditions during islanded operation with known electrical conditions during unbalanced operation of power systems, such as unbalanced faults or phase openings. Utility loads are generally able to tolerate time-limited exposure to distorted system voltages, so it was key in this evaluation to quantify both the severity and duration of abnormal voltage conditions during islanded operation.

In this chapter provides an overview of the analysis of test results used to quantify the indicators of abnormal voltage conditions and to deduce relationships between these indicators and the variables affecting them.

Extracting Risk Indicators from Waveform Data

The laboratory experiments carried out in Phase 3 of the project captured the rich library of high-speed waveform data covering combined behavior of PV inverters and loads for different load compositions, different levels of reactive power compensation, and different levels of PV penetration. While these waveforms contain all relevant information about the combined behavior of PV inverters and utility loads, they are not immediately useful in their raw form and need to be post-processed to enable the comparison of electrical conditions during islanding to, known electrical conditions occurring during unbalanced operation of power systems, such as unbalanced faults or phase openings.

All the calculations are implemented as a library of Python functions which are described in detail in the separately published Task 4 Report [6] and the published source code. In short, the captured results include 21 signals recorded at 20kHz sampling rate and the post-processing calculates and saves the additional 46 signals. The most important calculated variables are:

1) instantaneous magnitude of island voltage,
2) frequency of island voltage
3) sequence components of island voltage
4) power and reactive power supplied by PV inverter groups and consumed by the load
5) RMS values of voltages and currents

In addition, the analysis code also detects the onset and cessation of islanding, which enables it to down-select only the time period of importance and exclude inherently unstable behavior of the amplifier and RTDS after the PV inverters have tripped. The origin of this instability and the approach used to mitigate it are described in detail in [5].

Overview of the processing tools

As was already mentioned, all post-processing calculations are implemented in Python programming language. The post-processing functions are organized into four python packages:

`ProcessResultsATS.py`,
`MeasurementCampaignTools.py`,
`MeasurementGroupTools.py`, and
`PlotTestLogs.py`.

Table 5 to Table 9 describe the five main functions of these modules. The source code and the complete library of test results are placed in public domain to accelerate and inspire future work.

Table 5 MergeSavePlotTDMS – Function for screening results during testing

Function name	MergeSavePlotTDMS
Module name	ProcessResultsATS
Primary use case	Periodic, during-the-testing, screening of interim test results to catch any non-obvious equipment malfunction by reviewing the plots of test data
Dependencies	None
Input arguments	Directory path to raw results files Optional parameters defining various detection thresholds and the base value for L-N voltage
Functionality	Concatenation of Labview files, and plotting of test results into a multipage Results.pdf file placed in the directory alongside the data files. The function assists the test engineer in populating the TestLog file and therefore does not depend on the TestLog file. Instead, it searches for all LabView files within the specified directory, sorts them alphabetically, and concatenates the adjacent files based on time stamps of recorded signals. The file naming system employed by the LabView control system ensures that the adjacent result files are also adjacent alphabetically. Optionally, the function can also save the Excel spreadsheets with the concatenated results. Saving Excel spreadsheets may be useful for troubleshooting of file concatenation, but the saved files are too large and the file write too slow for this operation to have practical value.
Output	Results.pdf – A portable document format file containing the multi-page plots of test results. MergeSummary.xlsx – A spreadsheet listing rudimentary meta-data found in merged data files. The output files are saved on the directory path provided as the input argument (alongside the processed data files)

Table 6 PopulateMasterTestLogTable – Function for post-processing of all the results in measurement campaign

Function name	**PopulateMasterTestLogTable**
Module name	MeasurementCampaignTools
Primary use case	Processing a set of result files corresponding to a measurement campaign. Builds and saves a master spreadsheet correlating test conditions to the extracted scalar signal properties of islanding tests. The master spreadsheet is a major output of the analysis that can be used to study correlations between test conditions and electrical performance of the island.
Dependencies	MergeTestLogs in the same module, and MeasurementGroupTools.ProcessResults
Input arguments	Directory path to the measurement campaign. This directory contains subdirectories with the result file groups, each containing the coordinated LabView result files and the TestLog spreadsheet.
Functionality	The subdirectories of the input directory are searched for TestLog spreadsheets and the content of each is loaded into the master table. In the same pass, placeholders for scalar indicators are initialized The subdirectories are then traversed again using calls to ProcessResults function in MeasurementGroupTools module, which concatenates the LabView result files, processes the waveform data to calculate additional signals and scalar risk indicators, and places the calculated scalar values back into the master table.
Output	TestLogsAll.xlsx – The master spreadsheet containing correlated test conditions and scalar test results TestLogsAll.h5 – The underlying dataframe saved into the hdf5 data format The output files are saved on the directory path provided as the input argument (the directory path of the measurement campaign)

Table 7 ProcessResults Function for analysis of a measurement group, e.g. multiple penetration levels and power factors corresponding to a load composition

<table>
<tr><th>Function name</th><th>ProcessResults</th></tr>
<tr><td>Module name</td><td>MeasurementGroupTools</td></tr>
<tr><td>Primary use case</td><td>Processing groups of test results to concatenate the LabView result files, processing of the waveform data to calculate additional signals and extract scalar values of risk indicators. Coordinating and storing scalar risk indicators with TestLog records in the master table pointed to by the input argument.</td></tr>
<tr><td>Dependencies</td><td>Functions within the same module for formatting the plot pages</td></tr>
<tr><td>Input arguments</td><td>Directory path to raw results files and the pointer to master table containing complete TestLog records for the measurement campaign</td></tr>
<tr><td>Functionality</td><td>Concatenation of Labview files, processing the waveform data to calculate additional signals and extract scalar values of risk indicators.

Saving scalar indicators into the master table

Plotting groups of results in multipage Results.pdf files placed alongside raw test results.

Saving of groups of temporal test results into a single HDF5 file placed alongside raw test results.

As the MergeSavePlotTDMS function, this function also searches for all LabView files within the specified directory, sorts them alphabetically, and concatenates the adjacent files based on time stamps of recorded signals. The supplied master table is then searched for the file number corresponding to the concatenated test results to ensure there is a placeholder for scalar risk indicators. The processing of the test results is skipped if its file number is not accounted-for in the master table. (This allows for capturing results of corresponding to a load composition over two different days and using the same TestLog file to document test conditions)</td></tr>
<tr><td>Output</td><td>Results.pdf – A portable document format file containing the multi-page plots of test results.

Results.h5 – Groups of processed temporal results

The output files are saved on the directory path provided as the input argument (alongside the raw data files)</td></tr>
</table>

Table 8 AddSeqComp Template function to generate additional post-processed signals and compare with signals created by ProcessResults, without contaminating the Results.h5 files

Function name	AddSeqComp
Module name	MeasurementGroupTools
Primary use case	Processing groups of test results to calculate additional or alternative signals and scalar indicators using test data stored in Results.h5 files. Used to troubleshoot code without contaminating the data in Results.h5 files. Storing additional scalar risk indicators in the master table.
Dependencies	Functions within the same module for formatting the plot pages
Input arguments	Directory path to raw results files and the pointer to master table containing complete TestLog records for the measurement campaign
Functionality	Accessing waveform data in Results.h5 files, processing to calculate additional signals and scalar values. Cross-plotting new and old results and saving a separate multipage PDF file. Saving additional temporal results into a separate HDF5 file Saving scalar indicators into the master table. The master table needs to be pre-configured to receive the additional indicators within the PopulateMasterTestLoogTable function
Output	Results1.pdf – A multi-page file with cross plots. Results1.h5 – Groups of newly calculated temporal results The output files are saved on the directory path provided as the input argument (alongside the data files)

Table 9 PlotTestLogsAll – Function for plotting trends from the master table

Function name	PlotTestLogsAll
Module name	PlotTestLogs
Primary use case	Processing and plotting of scalar indicators corresponding to a measurement campaign. Used to visualize correlations between test conditions and electrical performance of the island.
Dependencies	None
Input arguments	Full path to the HDF5 file containing the master table correlating test conditions to the extracted scalar signal properties of islanding tests
Functionality	Filters and pivots data and plots the trends and relationships between islanding test results and scalar risk indicators.
Output	The multipage plot file named the same as the input file, but with the file extension changed from “h5” to “pdf”. This enables the flexibility to rename master table files from the generic TestLogsAll.h5 to add information about the processing date or version of the processing code, etc. The pdf output file is saved alongside the input h5 file.

Chapter 5

Key Observations Recommendations and Public Benefit

The scalar results from the composite load islanding tests were studied for correlations between circuit conditions and island performance. Figure 13 shows the correlation of island duration to PV penetration as a function of power factor for all experiments with composite loads. Figure 14 to Figure 17 show the same correlation for fixed values of power factor and further discriminate the results by season, showing winter and summer composite loads in different colors. Finally, Figure 18 compares the island duration for all composite loads and pure `MotorB` load, which is the high-inertia motor load component of composite load.

Key observations

The islanding duration is correlated to PV penetration and, importantly, this correlation is dependent on the load power factor. The observations are enumerated for referencing convenience:

1) Power factor of the circuit has significant impact on island duration
2) Inductive load power factor is more significant in limiting island duration than capacitive load power factor
3) Unity power factor and 0.98 capacitive power factor have similar spreads of island duration at PV penetrations of 100% and 108%.
4) Summer and winter loads have similar spreads of island duration at all values of penetration and all values of power factor.
5) Pure `MotorB` loads have island durations significantly higher than composite loads.

The numerical results also show, though this is not shown in the charts, that the power quality during islanding does not present significant risk to the load – the highest observed negative sequence voltage reached 8%, and the highest observed voltage magnitude 1.2pu. Please note that the certified inverters will trip at 110% voltage in 1 sec and 120% voltage in 10 cycles. The results ultimately confirm two common expectations of the utility industry: a) circuits close to electrical balance in active and reactive power sustain the islanding longer, and b) circuits with heavy motor load content sustain islanding longer than the circuits with mixed loads. The real value of the work is that it quantified these relationships in a large number of experiments and thus enabled drawing practical guidelines for interconnection studies.

The recommendations for interconnection based on these findings are given in the next section.

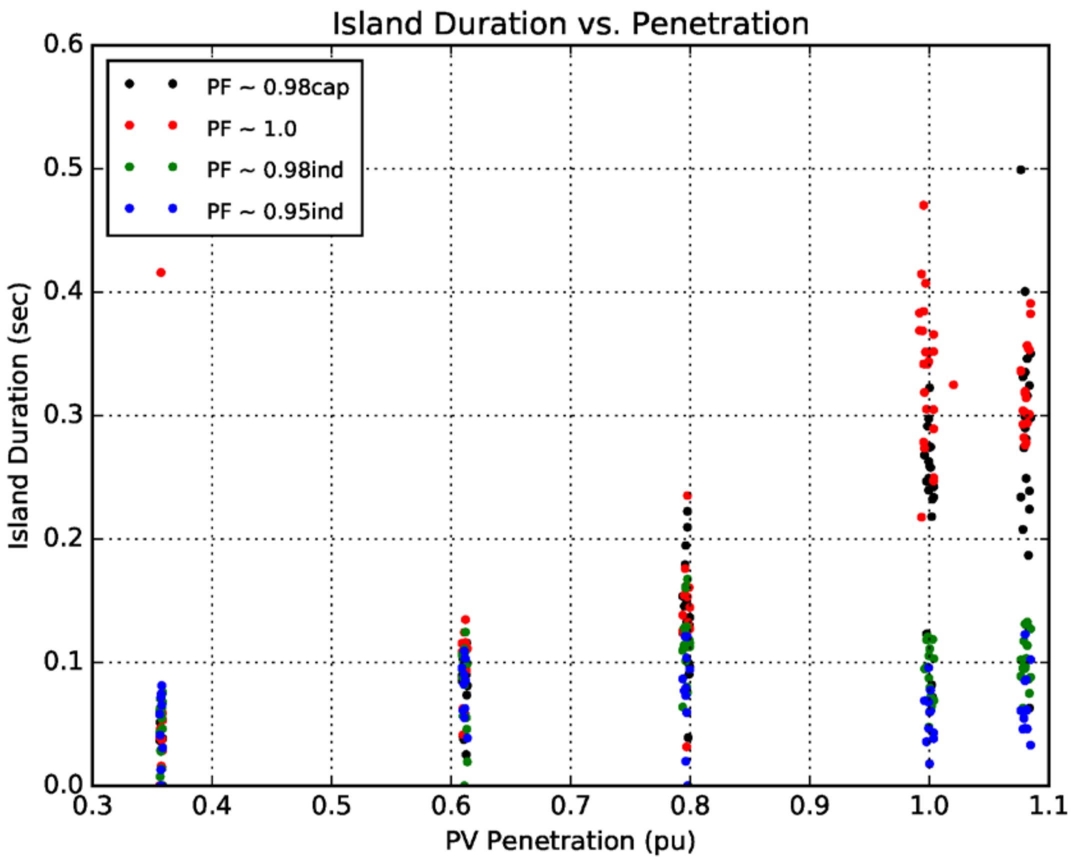


Figure 13 Island duration versus PV penetration – separated by power factor

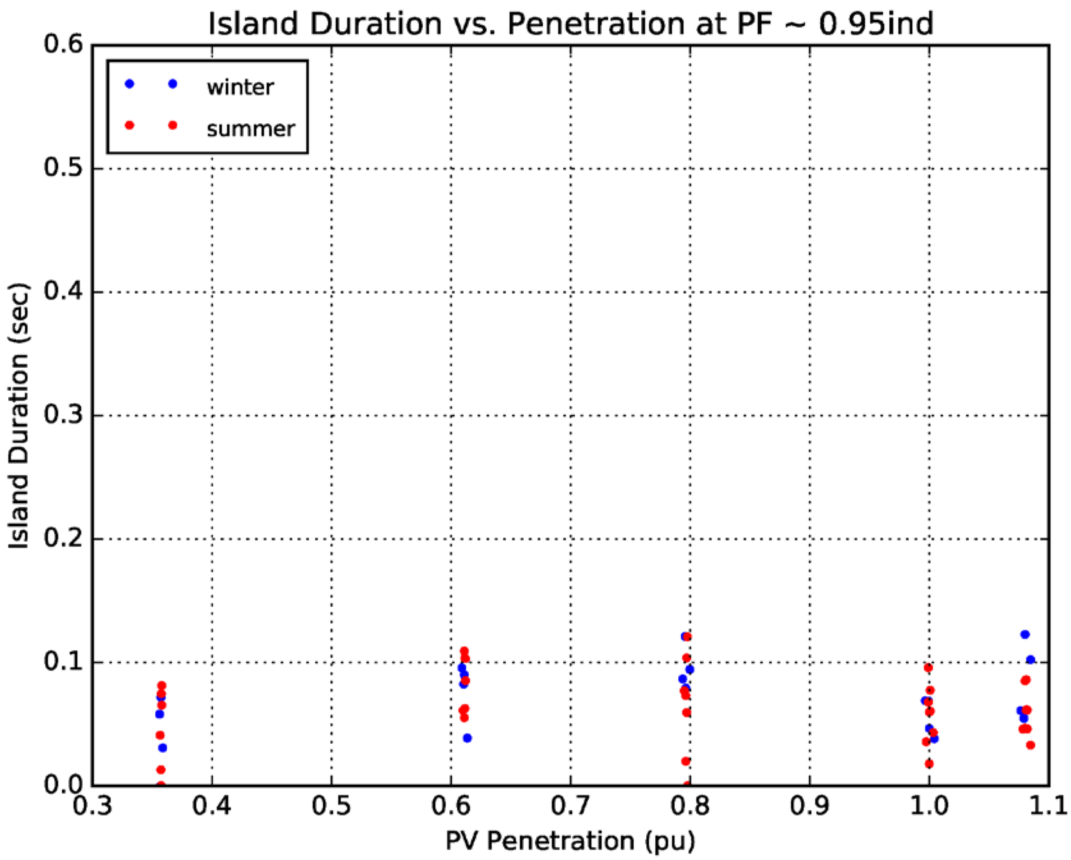


Figure 14 Island duration versus PV penetration at power factor of 0.95ind – separated by season

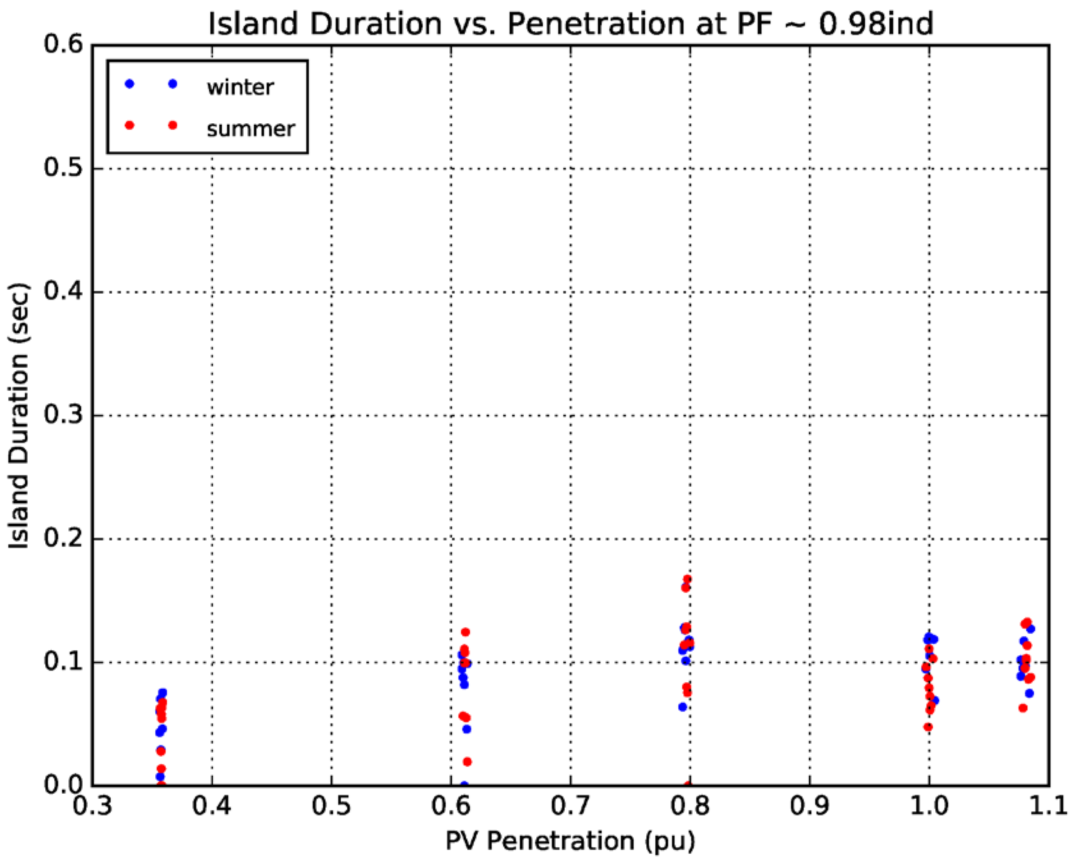


Figure 15 Island duration versus PV penetration at power factor of 0.98ind – separated by season

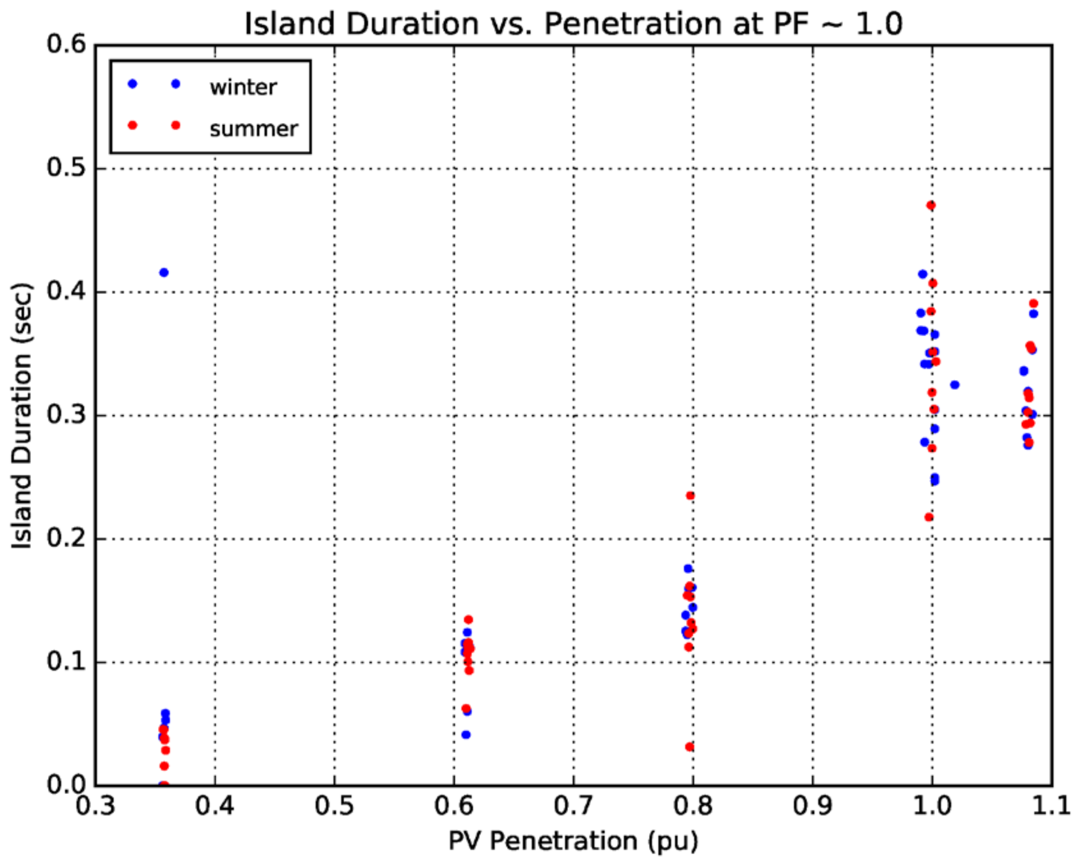


Figure 16 Island duration versus PV penetration at power factor of 1.0 – separated by season

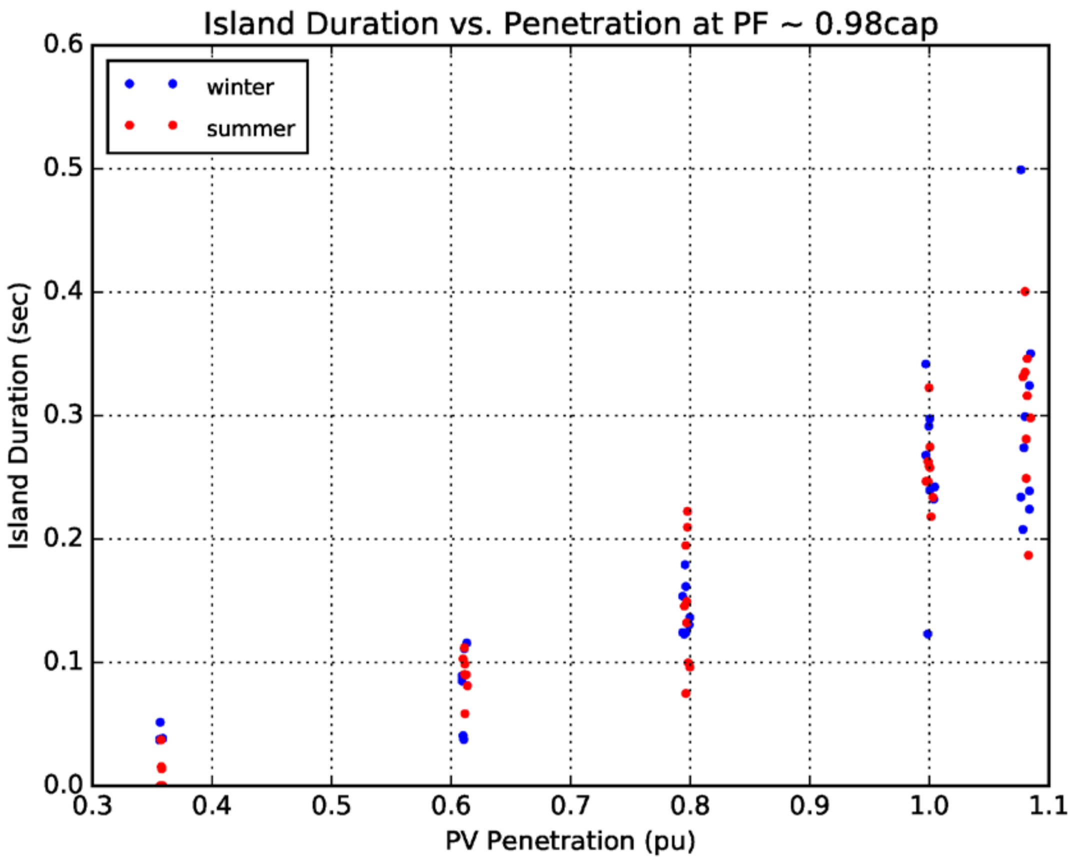


Figure 17 Island duration versus PV penetration at power factor of 0.98 capacitive – separated by season

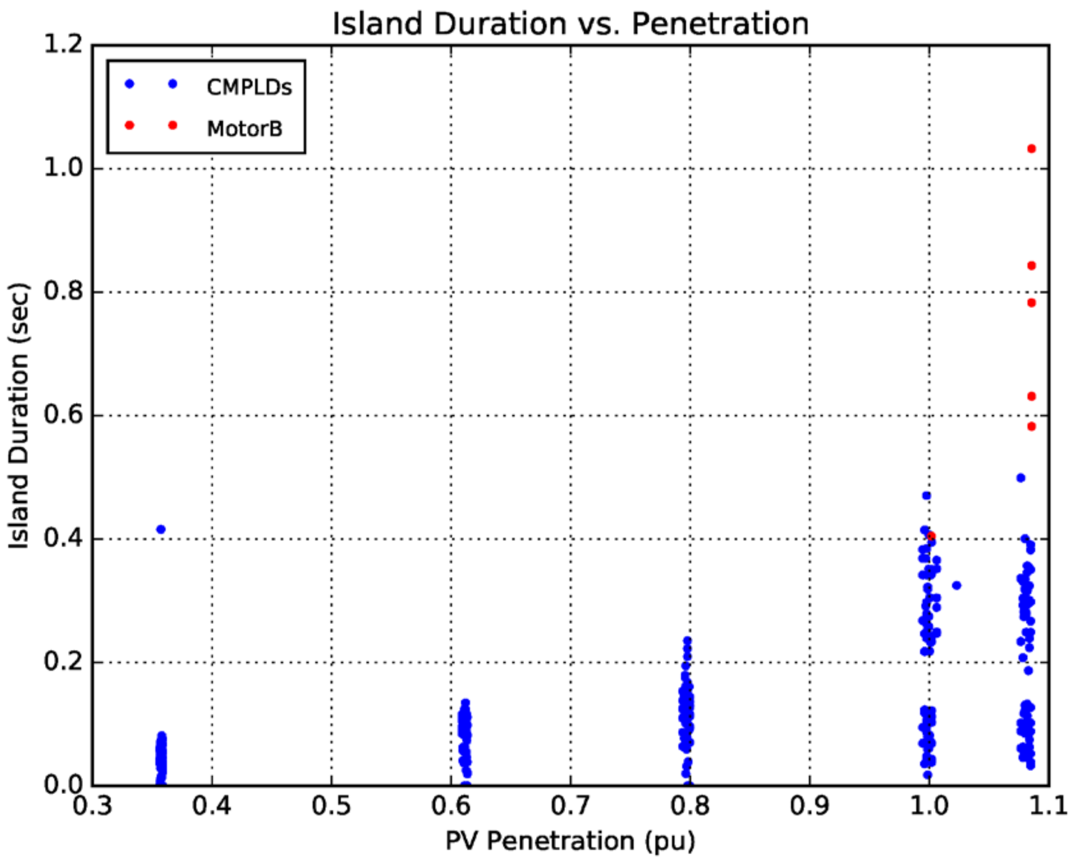


Figure 18 Island duration versus PV penetration – comparison of composite with pure MotorB load

Recommendations for interconnection process

Based on the finding in the project, the following recommendations were made for updating the PG&E interconnection process:

1) **In initial review**: raise the screening limit from 15% peak load to 60% of estimated simultaneous load; the estimated simultaneous load will be based on conversion factors as was defined and implemented in [3].
2) **In supplemental review**: Keep the existing minimum day-time load screen when SCADA data is available, and allow 80% of estimated simultaneous load by maintaining the power factor of the section below 0.98 inductive.
3) **In detailed review**: Allow up to 105% of simultaneous load by de-tuning circuits to maintain the power factor between 0.95 and 0.98 inductive, to address islanding concern if needed.
4) **In protection requirements**: Modify the Direct Transfer Trip exemption bulletin to enable the quick interconnection of certified inverters rated less than 1MW if there is no significant machine based generators on the island.
5) **In protection requirements**: Eliminate reclose blocking for all certified inverters by lengthening reclose time on high penetration feeders to 10 seconds.

We are pleased to report that recommendations 4 & 5 were implemented by PG&E. Others are under consideration.

Summary and future work

To summarize, the major technical achievements of this project are:

1) Applied a novel analysis process to the comprehensive set of utility data to rank the seven-dimensional data space based on frequency of occurrence
2) Built the most sophisticated MW-scale load model in the utility industry
3) Developed a highly-streamlined testing procedure that enabled capture of a large number of islanding experiments.
4) Captured and published an exhaustive library of islanding experiments with consistently-recorded results in high-resolution.
5) Developed a set of computationally efficient analysis tools and placed them in public domain.

A few suggested directions for future work are:

1) Revisit the variety of PV inverters deployed in PG&E's distribution system and perform incremental characterization of inverter mixes expected to be common in the future. In particular, consider the new inverter characteristics recommended by the Smart Inverter Working Group convened by the CPUC, especially with the ride through features. The run-on time is expected to be longer with the new settings.
2) Refresh the load conversion factors to align them with the emerging loads
3) Confirm the accuracy of laboratory tests by instrumenting circuits with high penetration of customer-sited PV and capturing voltage transients during scheduled circuit

switching. Run more capacitive load studies to identify whether the transient voltage will be higher, especially with voltage ride through settings.

4) Consider integrating the database of test results into the distribution management system to enable efficient circuit-specific interconnection studies.

Public benefit

As solar deployment advances in California, a level of penetration will be achieved where unintentional islanding could become a serious risk to the safe and reliable performance of the power system. When this risk becomes substantial, it will create a barrier in the market to further deployment of solar installations across the State.

The most important step in removing this barrier is to develop a comprehensive understanding of the conditions necessary for unintentional islanding to occur, along with the associated risk and magnitude of the problem. To date, this has not been done.

This project delivers what we believe is the most credible approach for understanding the necessary conditions for, risks and magnitude of the unintentional islanding problem. The results aid all three phases of interconnection review process and enable more informed, circuit specific, interconnection review and study work with minimal additions to the timeline.

As a result, utilities in California can integrate higher levels of behind-the-meter PV resulting in lower electricity energy demand from conventional generation sources across the system and dramatically reduce GHG emissions.

Bibliography

[1] Pacific Gas and Electric Company, "Electric Rule No. 21 Generating Facility Interconnections", *Advice Letter No: 4110-E, Decision No. 12-09-018*, Sep. 2012

[2] Sun C, Mulkey D, Tran P, Jensen M, and Jantz D, "Distributed generation protection requirements", *Utility Bulletin TD-2306B-002*, Jul. 2013

[3] Bebic J. Z. et al. "Task 2 Report: Statistical Analysis of PV Generation and Load Balance", http://calsolarresearch.ca.gov/funded-projects/86-quantification-of-risk-of-unintended-islanding-re-assessment-of-interconnection-reqs-in-high-penetration-of-customer-sited-distributed-pv-generation, accessed 2015-09-30.

[4] WECC Modeling and Validation Work Group, "Composite Load Model for Dynamic Simulations", https://www.wecc.biz/Reliability/WECC%20MVWG%20Load%20Model%20Report%20ver%201%200.pdf, accessed: 2015-09-30.

[5] Bebic J. Z. et al. "Task 3 Report: Aggregate PV Inverter Islanding Performance Testing" http://calsolarresearch.ca.gov/funded-projects/86-quantification-of-risk-of-unintended-islanding-re-assessment-of-interconnection-reqs-in-high-penetration-of-customer-sited-distributed-pv-generation, accessed 2015-11-30.

[6] Bebic J. Z. et al. "Task 4 Report: Key Findings from Laboratory Experiments Including Evaluation of Probability of Islanding and Associated Risk to Utility and Connected Load" http://calsolarresearch.ca.gov/funded-projects/86-quantification-of-risk-of-unintended-

islanding-re-assessment-of-interconnection-reqs-in-high-penetration-of-customer-sited-distributed-pv-generation, accessed 2016-08-17.