FINAL TECHNICAL REPORT

Development and Demonstration of Smart Grid Inverters for High-Penetration PV Applications

Prepared for the

U.S. Department of Energy

Under Award No. DE-EE0005338
Project Duration: September 1, 2011 to June 30, 2014

By the

Hawaii Natural Energy Institute
School of Ocean and Earth Science and Technology
University of Hawaii
Principal Investigator: Leon R. Roose

October 31, 2014

Acknowledgement: This material is based upon work supported by the United States Department of Energy under Cooperative Agreement Number DE-EE0005338.

Final Technical Report

Project Title:	Development and Demonstration of Smart grid inverters for High-Penetration PV Applications
Project Period:	09/01/2011 – 06/30/14
Submission Date:	10/31/2014
Recipient:	University of Hawai'i, Hawai'i Natural Energy Institute
Address:	1680 East-West Road, POST 109 Honolulu, HI 96822
Award Number:	DE-EE0005338
Project Team:	Silver Spring Networks, Inc. Fronius USA LLC Hitachi Ltd. Maui Electric Company, Ltd. Hawaiian Electric Company, Inc. PEPCO Holdings, Inc. New Energy and Industrial Technology Development Organization (NEDO) Rising Sun Solar Electric LLC. Standard Solar, Inc. Oklahoma Gas and Electric Energy Corporation
Principal Investigator:	Leon R. Roose Phone: 808-956-2331 Email: lroose@hawaii.edu
Business Contact:	Yaa-Yinn Fong Phone: 808-956-8259 Email: yaayin@hawaii.edu
HQ Tech Manager:	Guohui Yuan
HQ Project Officer:	Thomas Rueckert
GO Grant Specialist:	Fania Gordon
GO Contracting Officer:	Diana Bobo

Executive Summary:

The focus of this project is to implement, on operating utility distribution feeders with "very high" penetration of rooftop PV, enhanced capability smart inverters to achieve improved operational performance, control and visibility via standards based communications technology. This will be accomplished by creating, deploying, and evaluating new smart inverters using integrated inverter management control software (IMCS) and standards-based communications systems. In addition, detailed distribution modeling (modeled to the home meter) will be employed to aid in development of inverter control algorithms/settings and the model will be validated using high resolution field data monitoring to capture inverter field performance. The project will test these different inverter control strategies in two project deployment locations – Maui, Hawai'i and Maryland/Washington D.C.

Focus areas of demonstration will include:

- Standards based cost effective communications and control architecture extending from utility head-end to field deployed "smart " inverters for rooftop PV
- Coordinated control algorithms for multiple inverters on same feeder
- Interoperability of smart inverters supplied by multiple manufacturers operating under a common control platform
- Collection of high resolution (1 second time step), time synchronized field performance data across entire feeder
- Develop high fidelity distribution feeder model; validate model, test inverter control algorithms, and iterate with operational performance data
- Enhanced distribution feeder level control interface for utility grid operators
- Through improved control and visibility, improve feeder operational performance and reduce the scope, time and cost of interconnection requirement studies
- Enhanced visibility of energy use and on-site production for utility customers

To date the research that has been done on advanced inverter functions has focused on large utility scale PV systems, theoretical model based analysis or lab tests on a single residential PV inverter operating in isolation. In contrast, this project will not only consider advanced residential inverters in a modeling environment, but it will also deploy multiple advanced inverters operating in a coordinated manner on an actual residential feeder with high penetration of PV systems to test their actual response and impact on improved grid performance.

The UH-HNEI led consortium, which includes Silver Spring Networks (SSN), Fronius, Hitachi, Maui Electric Company (MECO), Hawaiian Electric Company (HECO), Pepco Holdings, Inc. (PHI), Oklahoma Gas and Electric (OG&E), Standard Solar, and Rising Sun Solar & Electric (Rising Sun), will demonstrate smart grid inverters from three industry leading manufacturers, Fronius, Hitachi and SMA, at two different utility sites. The inverters and communications protocols were initially tested in a newly constructed inverter laboratory at OG&E to test smart inverter control capabilities in various programmed scenarios. The project has also completed end-to-end testing of the control

system, field communications systems, and inverters using a pre-deployment installation at Maui Electric.

The team will install new and retrofit PV inverters to test the feasibility of using inverters to mitigate voltage fluctuations caused by the intermittency of PV systems, and control PV system output with the curtailment capability. At a second site on the PHI grid, the project team will install new residential PV systems in two locations. The first deployment area at PHI will use the curtailment function of the inverters to study their ability to prevent back feeding in an underground secondary network grid. In the second location, a single inverter has been deployed in Maryland at the Watershed demonstration center to provide an opportunity for public demonstration and outreach showcasing this new technology. The project will leverage smart grid infrastructure previously installed at each site and knowledge and experience gained. PHI has deployed a SSN Smart Grid network and MECO/UH-HNEI has deployed a SSN demonstration network as part of their DOE RDSI Smart Grid Project (Maui Smart Grid). This project will further leverage the Japan New Energy and Industrial Technology Development Organization (NEDO) demonstration project on Maui by utilizing a smart inverter developed for that project by Hitachi, thereby demonstrating in this project the interoperability of multiple inverters from multiple manufacturers.

The project has developed a detailed model of the Maui Meadows deployment area using EDD's DEW power system modeling application. The project team has also deployed high resolution (1 second interval) power monitors in the Maui and PHI project sites to monitor the output of the smart grid inverters and the distribution system to understand their effect on the power system. The project team will use the DEW model to simulate the smart inverters and their impact on the grid to develop control strategies for the inverters. These strategies will then be implemented in the field and their actual impact to the grid measured by the power system monitors. This measured data will then be used to validate and update the results from the model. This iterative process will be used to fine tune the inverter control strategies.

The development and demonstration of the technology aims to reduce the integration and interconnection costs of future distributed PV systems. By assembling a world class team with significant expertise, experience, sizable share of the PV inverter market, PV sales and installation experience, and smart grid solutions expertise, the team is well positioned to commercialize the proposed solution.

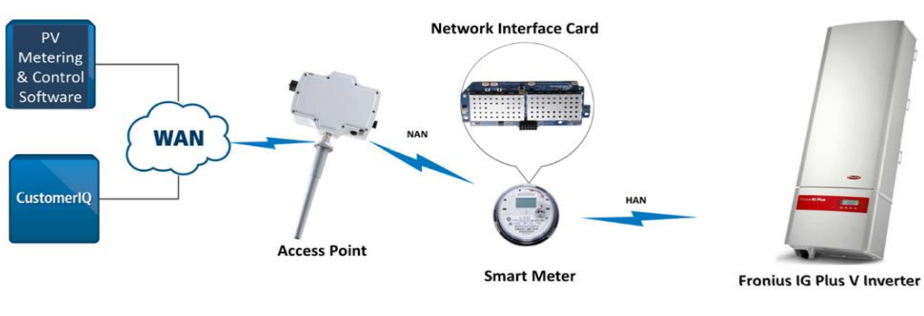

Figure 1: Smart Grid Inverter solution primary components.

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Background:

The concept of utilizing advanced inverter technologies to support the integration of distributed rooftop PV systems has been discussed and studied for several years. However, until this project, the concept has not been implemented on systems like those in the U.S., particularly on high penetration residential rooftop PV systems. The analysis and assessments have been theoretical and model based. A summary of examples of such research are provided below.

OPTIMAL REACTIVE POWER SUPPLY IN DISTRIBUTION NETWORKS
- TECHNOLOGICAL AND ECONOMIC ASSESSMENT FOR PV-SYSTEMS
M. Braun, T. Stetz, T. Reimann, B. Valov, G. Arnold
24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany

Abstract:
As a reaction to the steadily increasing share of photovoltaic (PV) power, German utilities are working on a new standard for the connection and parallel operation of generators in low voltage networks. The new grid code could be a big step towards active participation of PV-Systems in low voltage network operation. Reactive power provision by PV systems is expected to be interesting in the future. This paper starts with a theoretical introduction on how reactive power can be used to influence PV power feed-in on the voltage at its point of common coupling. For a technical and economical optimization of the most common reactive power provision methods, two typical German low voltage distribution test feeders (rural and suburban network structure) with high level PV penetration have been modelled and analyzed. Here, the economic evaluation considers the perspective of the PV plant operators as well as of the distribution system operator. The results show that the highest share of the total additional operational costs arises for the PV plant operators and that there exists a big difference in the costs of the different reactive power supply approaches. Also an overview is given about the actual situation on grid codes and the certification procedures in Germany.

Discussion:
This paper considers four different reactive power algorithms (Q-methods) in distributed PV inverters and their technical effectiveness and associated cost-benefit analysis. The Q-methods considered were:

- cosφ(P) characteristic (Watt-PF curve)
- fixed cosφ method (Fixed PF)
- fixed Q method (Fixed VAr)
- Q(U) droop function (Volt-VAr curve)

The SGI project will test the effectiveness of these measures as well.

The authors used a model based approach to assess the technical ability to stabilize voltages on two types of feeders (suburban and rural) using their four Q-methods limited to inductive reactive power consumption.

The results in the paper primarily focus on the economic aspects of the different Q-methods. However, Figure 2 shown below indicates that for the suburban system model that assumes 18 PV systems (PCC 1 at the start of the circuit and PCC18 at the end of the circuit) on a 3-phase secondary network in Germany:

1. PV systems do cause a greater fluctuation in voltage (without PV vs. CosPhi=1); and
2. Version 1 of the Fixed Q method seems to lower the voltage more than Version 4 of the Watt-PF method, however the Fixed Q method has a wider voltage range.

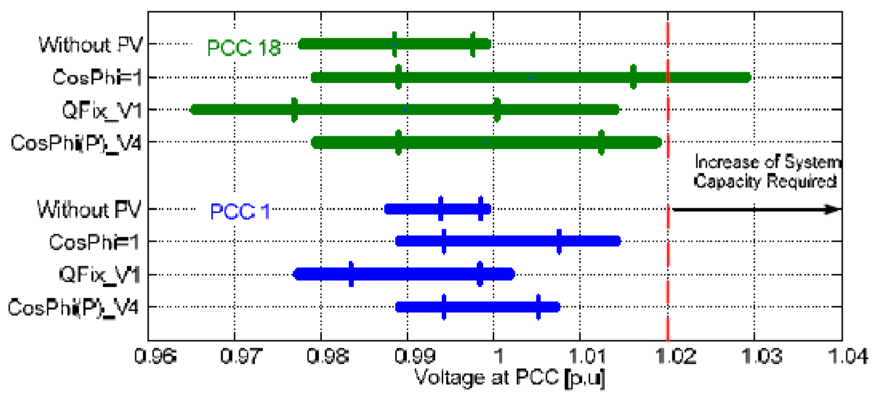


Figure 2: Voltage range occurring at PCC 1 and PCC18

Figure 3 below shows the impact on transformer loading of the different Q-methods and indicates that:

1. All VAr control methods increase the loading on the transformer. The Volt-VAr method has a lower impact on the maximum loading in green. However, this is assuming that all the inverters are doing the same control scheme, i.e. all absorbing VArs.

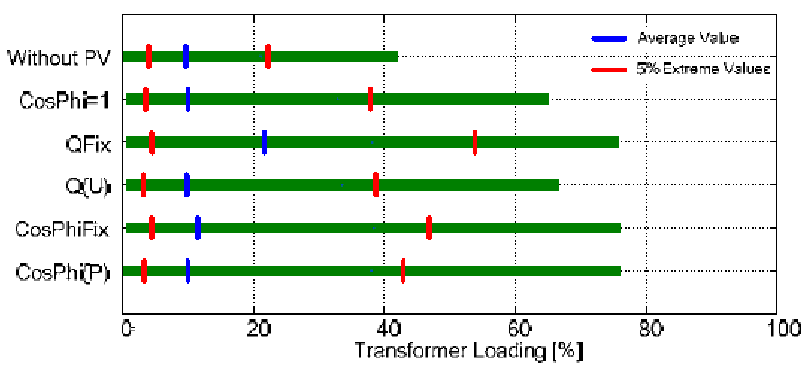


Figure 3: Transformer loading over one year.

This paper is similar to the SGI project in that it focuses on using distributed PV inverter functions to attempt to stabilize the voltage on a distribution feeder.

There are, however, some key differences:

1. This paper uses solely a modeled based approach, whereas the SGI project will implement inverter control functions on an actual feeder using actual customer owned PV systems.

2. German low voltage distribution systems are significantly different from systems in the U.S. in their voltage (220 vs. 120), configuration (3-phase vs. 1-phase), and length (300m vs. 100m or less).

3. The inverters used in the SGI project will not be limited to absorbing VArs. It may be advantageous to produce VArs from inverters at the beginning of the circuit and absorb VArs from the inverters at the end of the circuit, thereby reducing or eliminating the increased loading on the transformer.

That said, the SGI project can consider the results of this paper as the control strategies for the inverters are developed to compare our field results with the modeling result from this paper and, although not currently in the scope of the SGI project, consider the economic impact on the grid of the voltage control strategies used, such as their impact on losses.

IMPLEMENTATION OF ADVANCED INVERTER INTEROPERABILITY AND FUNCTIONALITY
Sigifredo Gonzalez, Frank Hoffmann, Michael Mills-Price, Mark Ralph, Abraham Ellis
Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE, vol., no., pp. 001362, 001367, 3-8 June 2012.

Abstract:
The high penetration of utility-interconnected Photovoltaic (PV) systems requires nontraditional and seemingly noncompliant modes of operation at the distribution level as a method to accommodate the high level of distributed generation. The normal operation of utility interconnected PV systems is governed by IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems and provides relevant requirements for performance, modes of operation, safety, and maintenance considerations. A recommended practice that provides flexibility of the existing interconnection standard by expanding the implementation requirements for utility interconnection is currently being addressed in IEEE 1547.8. The proposed recommended practice establishes methods and procedures for the expanded use of the governing utility-interconnected standard and is intended to address the increasing implementation of a varying resource. This recommended practice is designed for the implementation of advanced smart-grid functionality and allows the continued operation of Distributed Energy Resources (DER) during abnormal voltage and frequency conditions. The distributed resource smart-grid functionality is described in IEC61850-7-

420, Advanced Functions for DER Inverters Modeled in IEC 61850-90-7. This report describes the implementation of advanced functionality and successful criteria to assess proper operations of the "smart inverter" under communication driven control.

Discussion:
This study tested advanced inverters in a laboratory environment using the test setup shown in Figure 4 below. These tests used the IEC61850-7-420 DER functionality mapped to the DNP3 protocol. The study focused on the functions in Table 1 below.

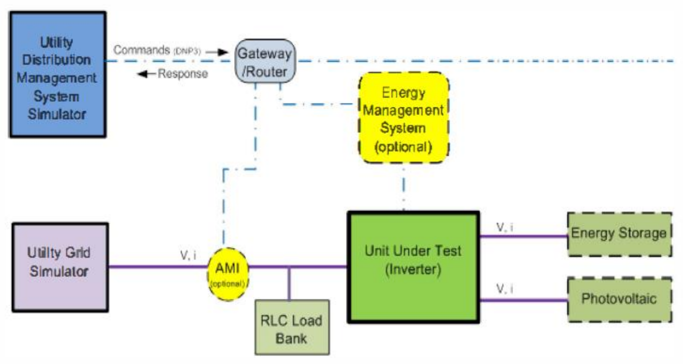


Figure 4: Communication to smart inverter interoperability structure

Control Function	Description
Connect/Disconnect	Physically connect or disconnect from grid
Adjust Max Generation Level	Set max generation level at Electrical Coupling Point (ECP)
Adjust Power Factor	Issues a power factor angle value
PV/Storage Functions	Change PV/storage parameters
Event/History Logging	Request event logs
Status Reporting	Request inverter status
Time Synchronization	Set inverter time

Table 1: DNP3 commands

The study described in the paper was able to successfully control advanced inverters in a laboratory environment using a subset of IEC61850-7-420 commands mapped to the DNP3 protocol and using hardwired TCP/IP communications.

The future work section of the report states:

> *At this time, the implementation of four advanced functions have been achieved and documented as part of this paper. To achieve high penetration, more advanced functions need to be adopted in the near future. Of the remaining functions, the following three are essential to achieving the objective of distributed advanced function control: 1) volt/VAr, 2) freq/Watt, 3) LVRT/HVRT.*

The SGI project takes the next step in implementing Volt/Var, fixed power factor, Watt/ power factor, Volt/Watt and freq/Watt curves in advanced inverters, but it also goes beyond the laboratory testing by implementing these functions in the field on an operating utility grid and using customer owned inverter systems. The SGI project will also use standards based protocols (IPV6, SEP 2.0, Modbus) over a wireless AMI mesh and Zigbee network thereby testing a real world implementation of these functions using commercial products from end to end.

JUMPSMART MAUI PROJECT

The JUMPSmart Maui Project ("JMP") is taking place in parallel with and near the same location as the SGI project. The JMP is a collaboration between NEDO and Hitachi of Japan and Maui Electric Company, County of Maui, State of Hawaii, the Maui Economic Development Board and UH-HNEI.

The JMP will demonstrate a distributed and hierarchical control architecture that utilizes DER to address both local and system level issues related to the integration of intermittent renewable energy and electric vehicles. As part of this project, Hitachi developed an advanced inverter that will be installed as one of the DER to be controlled by the new control system. The JMP will utilize cellular M2M communications to communicate with the inverter and will send commands from a Distribution Management System to be installed by Hitachi for the project. The SGI project will utilize the same Hitachi inverters as the JMP; however, the communications card in the inverter will be changed to utilize the SSN mesh network to receive commands from SSN's Inverter Management Control Software (IMCS). This will enable the project to test the interoperability of the Hitachi Inverters using the SunSpec controls via the SEP 2.0 and Modbus protocols used in the SGI project.

Introduction:

The goal of this project is to develop, deploy, and evaluate new smart grid inverters utilizing integrated inverter management software and standards-based communications systems. Detailed distribution models (modeled down to the meter) will be used to determine control settings and high resolution data monitoring will be used to validate the modeling results.

As discussed in the Background section above, there have been limited modeling studies done to assess the effectiveness of advanced inverters using different control schemes and feeder types. There have also been laboratory tests done to assess the ability to send limited commands to the inverter using standards protocols and show that the inverter responds to the command that was sent. However, advanced residential PV inverters have not been implemented and tested in the field on customer owned systems using commercially available AMI mesh networks. The effectiveness and optimization of the available control functions at different locations on the feeder (volt/var, volt/watt, feeder head vs. end of feeder, etc.) have not been tested and evaluated in the field to date. This project will test different control strategies in two different locations (Maui and

Washington DC) utilizing two different types of distribution service (radial distribution feeder and secondary network).

Maui and Washington DC are ideal locations to test advanced functions in the smart grid inverters. High penetration levels of PV on distribution circuits are the norm rather than the exception on Maui. Figure 5 below shows that many of the circuits on Maui are near, at, or exceeding 100% of the Daytime Minimum Load (DML) of the circuit. The utility will allow up to 120% of DML without an interconnection requirement study. Given the rapid rise in PV penetration, this project conducted a utility mandated Interconnection Requirements Study (IRS) to assess the circuit impacts of the existing PV on the circuit as well as adding in the project's inverters on the circuit. At these high penetration levels, steady state and transient over voltage levels are a concern. The inverters deployed as part of this project will be able to adjust their real and reactive power output based on the voltage measured at the inverter terminals. They can also be commanded to reduce their output by the system operator using the Inverter Management Control Software (IMCS) that was developed as part of this project. The transient overvoltage concern is mitigated by using inverters that are certified to be capable of shutting down within one cycle if the voltage at the inverter terminals exceeds 1.2 per unit (p.u.).

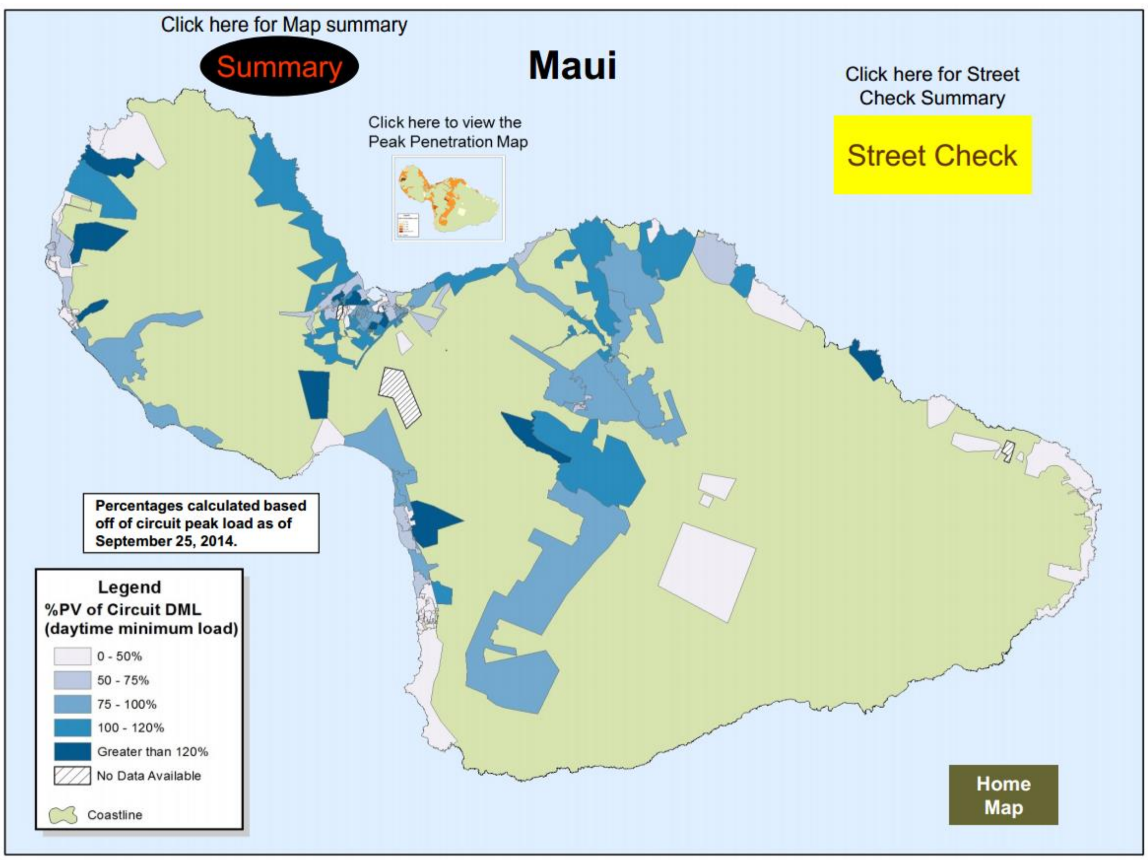


Figure 5: Percentage of nameplate PV to daytime minimum load by circuit.

With regard to more steady state voltage issues, large penetration levels of distributed PV systems can cause voltages to exceed their allowable limits, and also cause voltage variations that can make voltage optimization techniques such as Conservation Voltage Reduction (CVR) difficult or impossible if the voltage fluctuations are large enough. Voltage regulation using distributed PV inverters may be able to not only help address voltage violations, but also help to flatten the voltage profile along the circuit such that the benefits of CVR can be realized and increased.

The secondary networks in Washington DC are somewhat different in that the issue is not so related to high PV penetration levels as much as the relatively low penetration levels that are allowed on secondary networks given their inability to "back feed" power through network protective devices. PV generation can never be allowed to exceed the load on the network or the network protectors will open due a reverse power flow and the customers will experience an outage. In this case there could also be a cycle of outages, if the protectors close again until the PV systems restart and then cycle open again. In this case the impact of the PV generation on voltage is less a concern, but control of the real power production is needed.

In short, these smart grid inverters will not only help to manage the integration of higher levels of PV onto the grid, but it can also help the system to ensure its power quality and improve efficiency through the use of Volt/VAr optimization techniques, and this can all be done using commercially available equipment with a small incremental cost for the inverter and leveraging investments already made in AMI communications systems around the country.

In order to achieve the goals and objectives described above, the implementation of the project pursuant to the Statement of Project Objectives (SOPO) was to be executed as a two Phase project with a period of performance of three years. The first year (Phase 1) was to be the development and testing phase with the second and third years (Phase 2) were to be the deployment and assessment of the smart grid inverter on the grid and its performance impact.

Project Results and Discussion:

The following section focuses on the results of the work accomplished under each SOPO task.

Phase 1: Development and Testing of Smart Grid-Enabled Inverters

Task 1.0 – <u>Develop Internal and External Communications and Control Software</u>

- *Subtask 1.1 – Design, Code, and Test Software for PV Control*
- *Subtask 1.2 – Design, Code, and Test Communications Protocols and Interface*
- *Subtask 1.3 – Design, Code, and Test SW for the PV Metering System*
- *Subtask 1.4 – Design, Code, and Test SW for the PV Customer Web Interface*
- *Subtask 1.5 – Integrate and Test Communications for New Inverter Systems*

The project team designed and prototyped the communications to and from the Fronius smart grid inverter. The virtual environment was the first phase of development for rapid prototype development of the three system components, the Head End System, the Energy System Interface, and the Inverter. This virtual environment was used to establish a proof-of-concept of the system's architecture and design. Phase 1 system design, development, and testing was completed in the virtual environment before moving to the next phase of system development - the integrated environment. Representation of the Integrated Environment follows (see Figure 6):

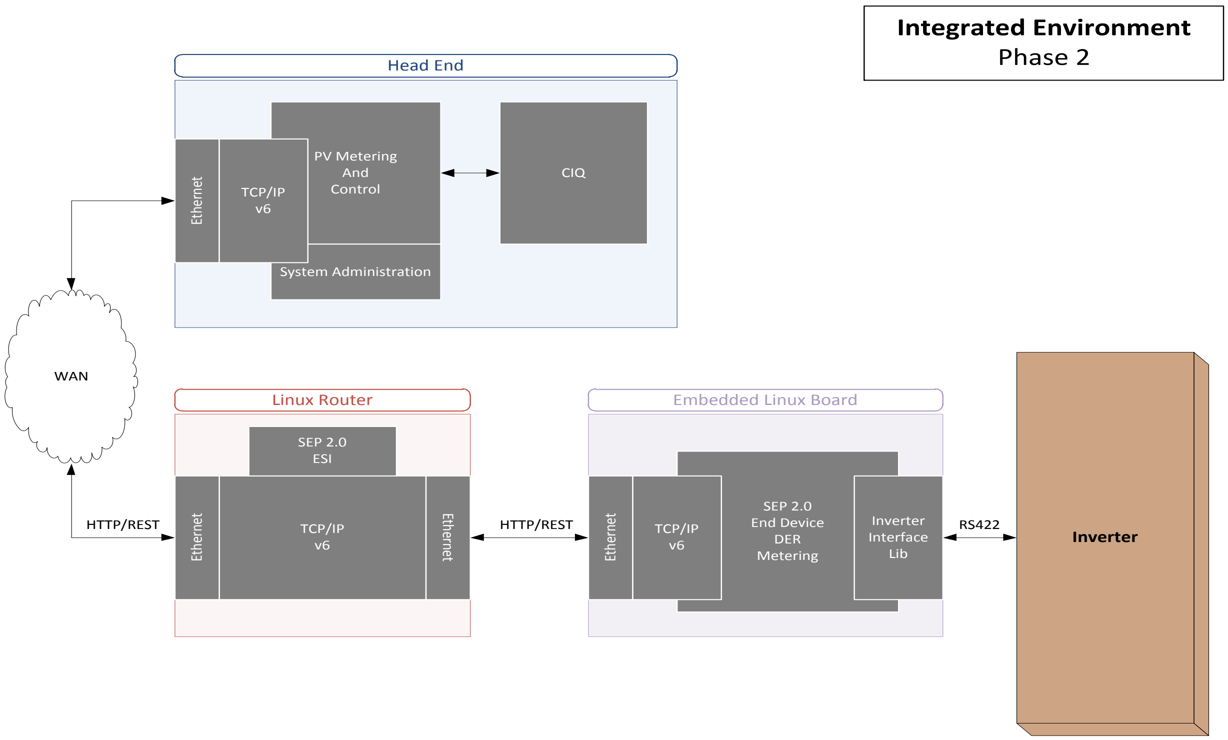


Figure 6: Integrated Environment - Inverter deployment to the Integrated Environment

In the integrated environment, the three system components were run on independent hardware with a direct physical communication connection. The third and final phase of development, the embedded environment, involved porting the integrated environment system component solutions to embedded firmware on their respective Network Interface Card (NIC) hosts. Representation of the Embedded Environment follows (see Figure 7):

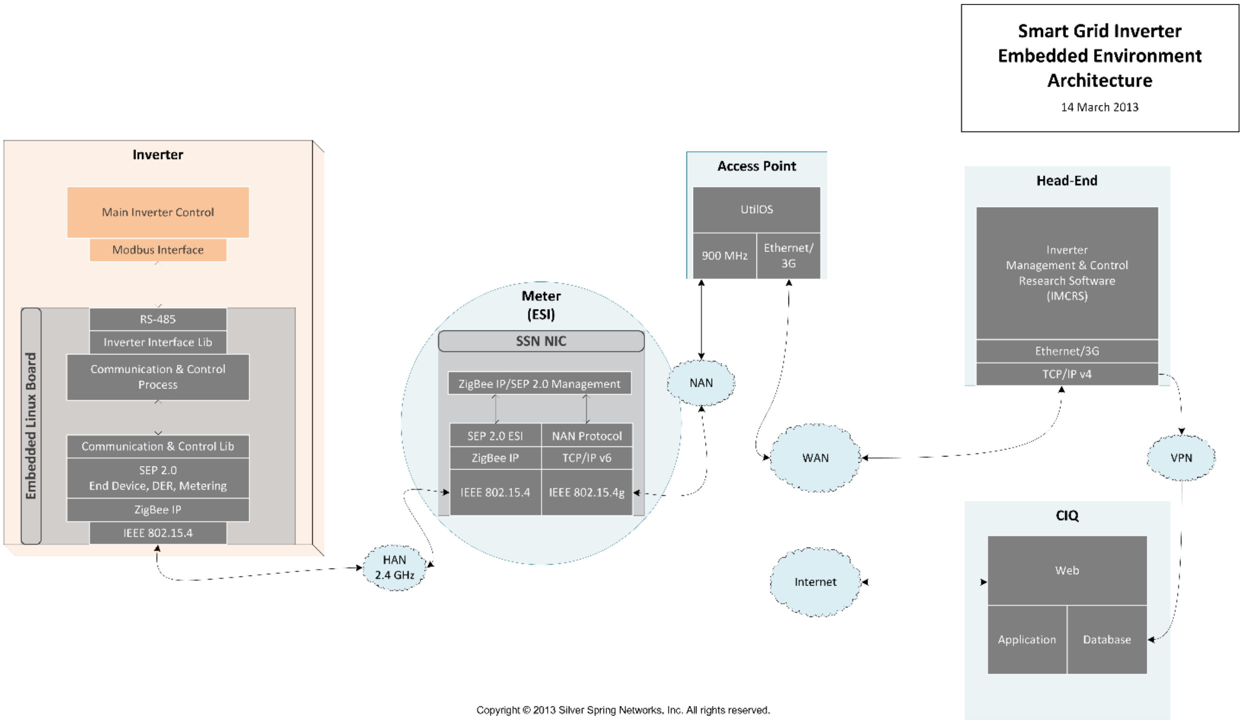


Figure 7: Embedded Environment - Inverter deployment to the Embedded Environment.

In addition to validating the end-to-end communications architecture, the Task also included the development of a new module in the CustomerIQ (CIQ) software: CustomerIQ-PV (CIQ-PV). The CIQ-PV software module includes data received from the smart grid inverter system, allowing customers to view PV production and total home consumption, enabling them to understand the net impact of PV on their home as shown in Figure 8 A and B below.

Figure 8 A: Home energy use and PV production overlay in CIQ-PV. 8 B: Home energy use data presented in CIQ-PV.

The project team finalized the inverter-agnostic functional requirements for the smart grid inverter system. The team took the standard functional requirements for the smart grid inverter system and generalized them to apply to any inverter built to SunSpec specifications. The requirements include specific references for data elements coming from the inverter to ease an inverter manufacturer in integrating with the smart grid inverter system. In addition to the contracted functional requirements, the team has prepared a working document of inverter control issues that arose during inverter integration with the smart grid inverter system. Finally, the team has included the SunSpec Inverter Control Draft from November 2012, which an inverter manufacturer should use to understand the problems that the SunSpec Alliance is hoping to address and solve with inverter controls. This document should be viewed in conjunction with the SunSpec PICS document, a detailed reference document containing information relevant to inverter manufacturers in tabs IC100 – IC134 (IC = Inverter Control). Each of these tabs is related directly to a concept outlined in the SunSpec Inverter Control Draft from November 2012.

Task 1.0 Deliverables:

- Communications and Control SW System design document outlining functional requirements and specifications
- Acceptance test plan and report
- Communications system integration and testing plan

Functional Requirements

The UH-HNEI Smart grid inverter System Functional Requirements recommendations are for use in the development and testing of smart inverter communication specifications for integration of high-penetration residential photovoltaic (PV) systems into existing electrical distribution networks. These functional requirements capture the intended behavior of the UH-HNEI smart grid inverter system, and can drive architectural decisions. They are grouped into high-level categories as follows:

- PV Metering and Control Software
- Meter Communications (Home Primary Meter)
- Inverter Communications
- Customer Engagement PV Software

Communication Sequence Diagrams

The UH-HNEI smart grid inverter System Control Sequence Flow Diagram emphasizes the flow of control and data among the Head End, Energy Services Interface (ESI) and the Inverter in the system being modeled. The diagram represents a communication sequence flow where Head End back office software is used by utilities to monitor PV output. The Head End back office software is also used to monitor and control the smart grid inverter.

SEP 2.0 – AGF Mapping

The UH-HNEI smart grid inverter system smart inverter commands mapping schema is based on the SunSpec Smart Energy Profile 2.0 Application Protocol Specification (SEP 2.0 App Spec). The goal is to create standards necessary for smooth integration of smart inverters into distribution utility network systems. The aim is to identify capabilities and limitations of the command mapping the Fronius Advanced Grid Functionality (AGF) Modbus Register Map v1.2 to the SEP 2.0 App Spec for Distributed Energy Resources (DERs).

Acceptance Test Plan & Test Results

The Acceptance Test Plan verifies the system works as required and validates that the correct functionality has been delivered. The details of the test phases were developed according to the specifications set out in the UH-HNEI SGI Functional Requirements and Use Cases documents, the primary drivers for identifying these tasks. The project team first created the Acceptance Test Plan and Test Results for the Virtual Environment implementation. The project team then created the Acceptance Test Plan and Test Results for both the Integrated and Embedded Environment implementations. Also included in the Acceptance Test Plan & Results document are the Solution Architecture diagrams and Functional Requirements for CIQ-PV. Cover pages and a description of one acceptance test from the Acceptance Test Plan & Results documentation are shown in Figure 9 below:

UH-HNEI Smart Grid Inverter Project
Acceptance Test Plan & Results
Integrated Environment Acceptance Testing

UH-HNEI Smart Grid Inverter Project
Task 1.3 Acceptance Test Plan & Results
Wireless Embedded Environment Acceptance Testing

4.4.1.1. TC_0001 Acceptance Test

Test Case Identifier	TC_0001
Purpose	Retrieve inverter metering data
Description	Utilizing metering functions, capture and store output data from the inverter.
References	4.2.5 "Performing metering functions" Functional Requirement 4.2.5.1. "Receive real-time PV output communications from home meter (via NAN)" Functional Requirement 4.2.5.4 "Capture PV output data from inverter (via NAN)"
Steps	The process of retrieving metering data is automatic once the Wireless Embedded Environment has been set up. There is no "trigger" for this test, other than enabling the system. The following events occur simultaneously. These steps show the logical progression of what happens in each system component during this test. **HEAD END** 1. The Head End application runs the Python script and updates the creation time. 2. DERProgram is sent to the ESI. **ESI** 3. Loads DERCapability from Inverter. 4. Waits for the Inverter to start up to download the inverter DERCapability. 5. Retries every 5 seconds to connect with the inverter. 6. Once the Inverter starts, DERCapability is downloaded by the ESI. **INVERTER** 7. Calls *inv_get_der_capability()* API to get Fronius nameplate data. 8. Receives GET /dercap from ESI and downloads DERCapability.
Test Result	Passed

Figure 9: Cover pages and description of one acceptance test.

Communications system integration and testing plan

The Acceptance Test and Results for the prototype system confirm the end to end communications testing of the prototype system in the Development Laboratory at Silver Spring Networks headquarters. This Development Laboratory includes all of the prototype system components which shall be seen in the field during Phase 2. The prototype system Acceptance Test Plan & Results confirms that the back office software, communications, and smart inverter functionality developed for Phase 1 of the project perform as expected.

Task 2.0 – <u>Smart Inverter Internal Communications and HW/SW Control</u>

- *Subtask 2.1 – Design, Code, and Test Embedded Firmware*
- *Subtask 2.2 – Design, Code, and Test Script Manager and Control Software*
- *Subtask 2.3 – Integrate and Test Control Software*

The project team finalized the functional requirements and the communications to and from the Fronius and Hitachi inverters in embedded firmware. The embedded environment was the third and final phase of development of the three communication system components, the Head End System, the Energy System Interface, and the Inverter. The third and final phase of development, the embedded environment, involved porting the integrated environment system component solutions to embedded firmware on the respective NIC hosts.

Task 2.0 Deliverables:

- Inverter system design document outlining functional requirements and design specifications
- Inverter acceptance test plan and report

Functional Requirements

The project team developed and documented the functional requirements for the inverter internal communications and HW/SW control in the report – cover page shown in Figure 10 below.

Figure 10: Functional Requirements cover page

Acceptance Test Plan & Test Results

The Prototype System Acceptance Test Plan and Results includes 14 Test Cases which were constructed to validate the back office software, communications, and smart inverter functionality developed for the prototype system, with consideration to the Functional Requirements and Use Cases set forth by the project. Test cases were tailored to reflect the fulfillment of functionality that the project partners require of the prototype system, as described in the Functional Requirements and Use Cases which can be found in this document's Appendix. Unlike the Wireless Embedded Environment Acceptance Test Plan and Results deliverable (SOPO Task 1.0), the document below (Figure 12) details the fulfillment of the back office software and smart inverter functionality in addition to the communications.

UH-HNEI Smart Grid Inverter Project

Task 2.1b Acceptance Test Plan & Results

Prototype System Acceptance Testing

Figure 11: Prototype System Acceptance Test Plan & Results cover page

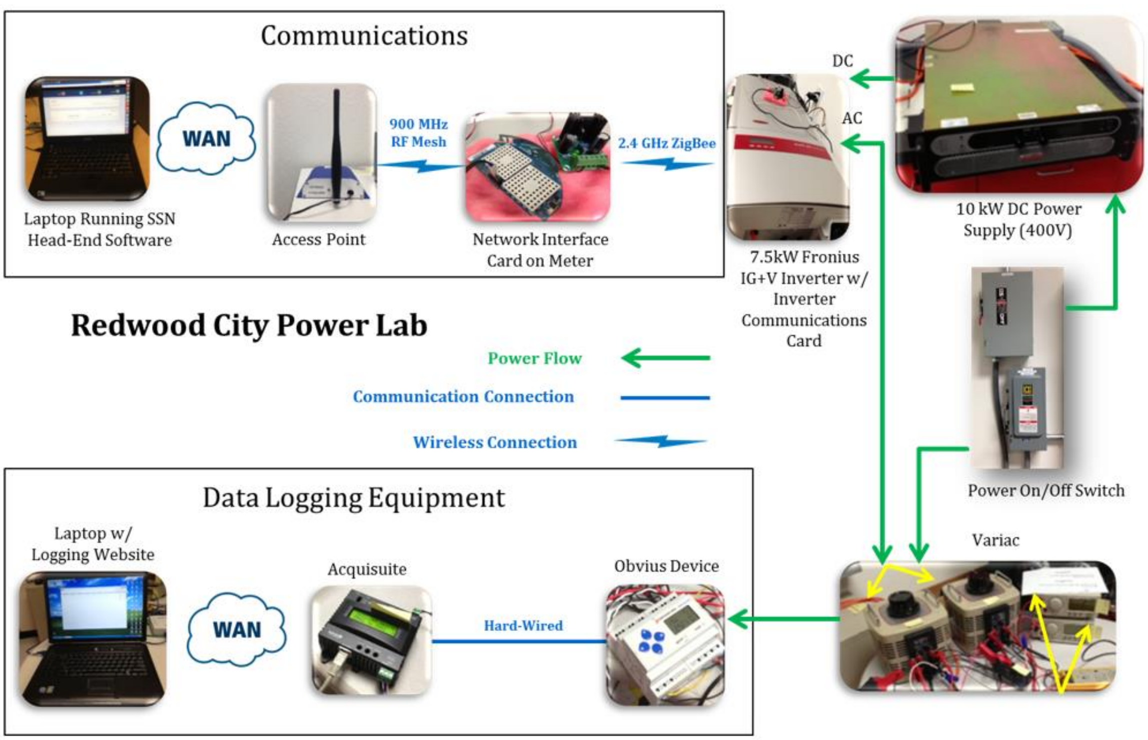


Figure 12: The test setup at the Development Laboratory at Silver Spring Networks headquarters.

Task 3.0 – <u>Preliminary Acceptance Testing of Smart Inverters at the Inverter Laboratory</u>

- *Subtask 3.1 – Define Requirements and Develop Test Plan*
- *Subtask 3.2 – Conduct Pre-deployment Testing*
- *Subtask 3.3 – Develop Smart Inverter Business Case*

The Acceptance Test Plan (ATP) and Results report captures the results of the end to end testing of the prototype system in the Maui Electric Warehouse Test Laboratory (MEWTL). The MEWTL used the components of the prototype system which will be deployed in the field during Phase 2.

In the ATP, the grid and inverter impact of various forms of inverter control are presented in the form of test results from running various immediate controls and dynamic curves through the prototype software. The ATP focused on the application of remote kW curtailment immediate controls, Volt-VAR and Volt-Watt dynamic curves, which can be described as follows:

1. Remote kW Curtailment - reducing kW output of inverter
2. Remote Volt-VAR Curve - managing inverter VAR output in response to the local service voltage
3. Remote Volt-Watt Curve - managing inverter Watt output in response to the local service voltage

In essence, the Prototype System Power Lab ATP provided data to analyze the expected command and response of remotely controlled inverters. In doing so, the Prototype System Power Lab ATP simultaneously validated the prototype system's ability to communicate wirelessly between the utility's back office and the inverter, effectively sending those commands remotely and validating functional execution of the tests.

Task 3.0 Deliverables:
- Validation and acceptance testing requirements and test plan
- Validation and acceptance testing report

The Prototype System Power Lab ATP and the test cases performed are shown in Figures 13 & 14 below:

Figure 13: Prototype System Power Lab Acceptance Test Plan & Results cover page

Test Cases:

Test Number	Test Case
TC_0001 Acceptance Test	Pre-Test #1
TC_0002 Acceptance Test	Pre-Test #2
TC_0003 Acceptance Test	Volt-VAR Moderate Curve
TC_0004 Acceptance Test	Volt-Watt 4-Point Curve
TC_0005 Acceptance Test	Volt-VAR Aggressive Curve
TC_0006 Acceptance Test	Volt-VAR Low Voltage Area Curve
TC_0007 Acceptance Test	kW Curtailment 80%
TC_0008 Acceptance Test	Volt-Watt 5-Point Curve
TC_0009 Acceptance Test	Volt-Watt 3 Point Curve
TC_0010 Acceptance Test	kW Curtailment 40%
TC_0011 Acceptance Test	kW Curtailment 8%

Figure 14: Test cases performed during acceptance testing for the prototype system power lab.

Task 4.0 - __Define Field Demonstrations__

- *Subtask 4.1 – Final Site Selection*
- *Subtask 4.2 – Define Requirements and Draft Preliminary Demonstration Plan*

The project team objective is to deploy up to thirty (30) smart grid inverter systems in Maui Electric Company's (MECO) service territory, specifically the Maui Meadows subdivision. The project team also deployed and operated the IMCS developed in Phase 1, and performed any upgrades or maintenance to be done to the smart grid network at MECO.

The project team objective in Pepco Holding, Inc.'s (PHI) service territory is to deploy up to ten (10) smart grid inverter systems. The deployment locations will include the District of Columbia (up to 9 systems), and Maryland (1 system), with each location respectively focusing on back feed in underground networks and public demonstration as research concentrations. The PHI demonstration will include deployment and maintenance of smart meters, access points (AP), and other devices to build the smart grid network required for the project. This demonstration includes Software as a Service (SaaS) licenses for key back office applications to be deployed at PHI to aid in the research and data collection required by the project.

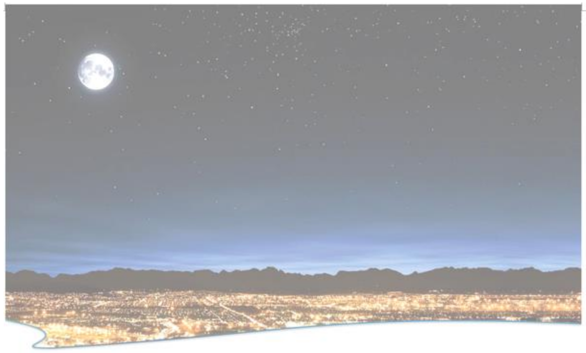
Concurrently, PHI will contribute to the project's deployment and trial phases by continuing to support existing back office software (Utility IQ AMM in DEVL03 environment), project management activities, field engineering services, and meter installation practices

Task 4.0 Deliverables:

- Field Demonstration and Test Plans

The document below entitled Field Demonstration, Planning and Staging, defines requirements and outlines the preliminary plan for the demonstration. This document includes details for the following four arrangements involved with Phase 2:

1. Field & Engineering Support (SSN – HNEI)
2. MECO Deployment (SSN – MECO)
3. PHI Deployment (SSN – PHI)
4. Research & Analysis Support (SSN – HNEI)



UH-HNEI Smart Grid Inverter Project

Task 4.1: Field Demonstration, Planning and Staging

Figure 15: Field Demonstration, Planning and Staging document cover page

Task 5.0 – __Project Management and Reporting__

- *Subtask 5.1 – Project Monitoring and Meetings*
- *Subtask 5.2 – Author and present technical papers at one or more of the following conferences: InterSolar USA; Solar power International; IEEE PVSC; IEEE PES T&D Conference; IEEE PES General meeting; Distribu Tech; and EPRI webinar and workshop for SEGIS*
- *Subtask 5.3 – Active participation by appropriate team participants at working group level to help define and adopt the IEEE 1547.8 standard*
- *Subtask 5.4 – Active participation by appropriate team participants at working group level in the EPRI Smart inverter Communication Initiative*
- *Subtask 5.5 – Quarterly Reports covering all tasks and subtasks for Phase 1*
- *Subtask 5.6 – Final report covering Year 1 (Phase 1)*

Task 5.0 Deliverables:

- Project Management Plan
- Quarterly Reports Documenting Phase 1 technical and financial status
- Final Report Documenting Phase 1

The discussion of project management and reporting under Task 5.0 is consolidated in the discussion below under Task 9.0.

Task 6.0 - __Distribution Level Modeling and Analysis__

Task 6.0 Deliverable:
- Report on model selection criteria

Through distribution circuit modeling and field testing at two utility sites, the Smart grid inverter project will assess to what degree smart inverters can resolve utility interconnection issues and maintain the reliability of the electric grid at high PV penetrations.

The project has developed a detailed model of the Maui Meadows deployment area using EDD's DEW/ISM power system modeling application. The project team has also deployed high resolution (1 second interval) power monitors in the Maui and PHI project sites to monitor the output of the smart grid inverters and the distribution system to understand their effect on the power system. The project team will use the DEW model to simulate the smart inverters and their impact on the grid to develop control strategies for the inverters. These strategies will then be implemented in the field and their actual impact to the grid measured by the power system monitors. This measured data will then be used to validate and update the results from the model. This iterative process will be used to fine tune the inverter control strategies.

To this end, the project team collaborated and reviewed the following distribution system modeling tools (see Table 2 below) for consideration before ultimately settling upon its selection of its tool of choice:

Distribution Modeling Tool Name	Vendor	Website
CYME / CYMEDIST	Cooper	http://www.cyme.com/software/cymdist/
GridLAB-D	National Renewable Energy Laboratory (NREL)	http://www.gridlabd.org/
ETAP	ETAP	http://etap.com/smart-grid/smart-grid.htm
OPENDSS	Edison Power Research Institute (EPRI)	http://www.smartgrid.gov/sites/default/files/doc/files/1529_doc_1.pdf
SynerGEE	Germanischer Lloyd (GL)	http://www.gl-group.com/en/powergeneration/SynerGEE_Electric.php
DEW	Electrical Distribution Design (EDD)	http://www.edd-us.com/ISM_Overview.html

Table 2: Distribution system modeling tools

A summary description and review of each tool is included below.

CYME / CYMEDIST
CYME enables utilities to model the low-voltage distribution system. The low-voltage network can be built and shown in a distinct view, distinguished from the primary network, but with the ability to see where they overlap. The user can select certain devices to be shown in the tool, but regardless of what is loaded into the tool, the network equivalent of the unloaded network is calculated accurately and taken into consideration for simulation. The tool was built to analyze network losses, equipment loading, and contingency scenarios.

GridLAB-D
GridLAB-D is a flexible simulation environment that can be integrated with 3rd party data management tools. Its algorithm-based modeling coordinates independent devices, allowing users to handle unusual situations more accurately, recognize disparate time scales (from seconds to years), and integrate with 3rd party systems. The system examines the interplay between all elements of a distribution system, from the substation to end-use load.

ETAP
ETAP integrates into existing SCADA system and "mines" the data layer, so information can be calculated and summarized. The software allows the user to manage, control, visualize, optimize, summarize, and automate power distribution networks. Economic dispatch allows generation changes of a power system among generation units, and uses advanced optimal power flow algorithms to determine the optimal generation pattern while maintaining reserve margins. Generation levels of individual units are calculated and dispatched to meet load demand at minimal costs.

OPENDSS
Distribution System Simulator (DSS) is designed to simulate utility distribution systems in arbitrary detail, for most types of analysis related to distribution planning. It performs power flow, harmonics, and dynamics analysis in the frequency domain. It is used in the development of distributed generation models for IEEE radial test feeders, and other applications. It shows DG impact (of wind generation) on switched capacitors and voltage regulators. Many of the features found in the program were originally intended to support the analysis of distributed generation interconnected to utility distribution systems.

SynerGEE
SynerGEE can perform detailed load modeling and other analyses on radial, looped, and mesh network systems comprised on multiple voltages and configurations. All analyses rest on the solid load-flow foundation, including circuit analyses. The product is used for anything from multi-year work plans, to assisting operators with switch plans for maintenance or emergency.

DEW/ISM
DEW's Integrated System Model allows users to build large, complex distribution models. Base applications include the ability to measure power flow, calculate network faults, and estimate loads. For distributed resources specifically, users can analyze the impact of new and existing distributed energy resources by customer class, evaluating the impacts of PV on primary and secondary systems. It also enables the user to perform interconnection studies, and retrieve local measurement data for solar incidence from the NREL database.

Each tool was analyzed by the team, drawing upon product experience and other information gathering activities.

Tool Selection Criteria
Given the nascence of distribution planning at the customer premise level, distribution planning models today generally do not go to the level of granularity that is desired for application in this project. However, the project team assessed the products currently available to select one that most adequately suits the research needs of the project.

The project team defined selection criteria based upon the needs of utility users (Distribution Planning staff from Maui Electric Company and Pepco Holdings, Inc.) and the project. These criteria include:

- Detailed support for PV modeling, including solar irradiance and distributed PV generation, individual inverter modeling, and advanced inverter functions capability (e.g., power factor, reactive power, volt-var function, etc.);
- Incorporation of high resolution real-time sensor (e.g., Obvius monitoring devices, AMI, and SCADA) data into the model;
- Ease of use – Drag and drop GUI (e.g., some of the modeling tools such as GridLAB D are notoriously difficult to use and time consuming because the models must be built by editing raw XML structures. It is also difficult to share/collaborate without an easy to use GUI);
- Detailed support for distribution feeder and secondary-level modeling of individual homes (e.g., many modeling tools do not model secondary circuits well, if at all, and thus are not capable of modeling to the level of detail required for this project);

Project utility partner experience:
DEW/ISM is the DER study tool that is currently used by the DERPA (Distributed Energy Resource Planning and Analytic) team at PHI. DEW is capable of performing high resolution time series studies based on historical, SCADA, solar, and customer use data. The program is also capable of modeling the complete transmission, substation and distribution system by components, and tied to GPS coordinates and secondary networks. The DEW program model is being populated for the ACE region right now, but eventually will be populated for the whole PHI companies.

Based on the criteria and capabilities, the DEW/ISM tool was selected for this project.

Distribution Modeling Tool Analysis

Tool	Manufacturer	Detailed support for PV Modeling - irradiance, power factor, individual inverter modeling?	Incorporates real time sensor data into the model	Ease of Use	Detailed support for distribution feeder and secondary modeling of individual homes / businesses	Overall Review
CYME/CYMEDIST	Cooper	- Individual inverter modeling is not possible (can enter new devices to be shown, like diesel generator) - No visibility of PV system irradiance or power factor	- Not possible	- Drag and drop GUI	- Can view low voltage network as part of detailed distribution system, or alone	
GridLAB-D	NREL	- Individual inverter modeling is possible (mention of ability to analyze DER resources for increased wholesale purchasing elasticity, improved reliability metrics, ability to sell ancillary services in wholesale markets) - No visibility of PV system irradiance or power factor	- Advanced API for interfacing with 3rd party tools	- Manually created XML scripts	- Can view end-use load behavior of homes and appliances, in addition to 3 phase (meshed or radial) power systems	
ETAP	ETAP	- Individual inverter modeling is not possible - No visibility of PV system irradiance or power factor	- Mines SCADA system for data	- Somewhat drag and drop GUI (from tutorial)	- Can create distribution feeder and secondary level models of individual homes / businesses	
OPENDSS	EPRI	- Individual inverter modeling is not possible - No visibility of PV system irradiance or power factor	- Not possible	- Manually created XML scripts (object-oriented structure)	- Can create distribution feeder (n-phase lines, of arbitrary configuration) models	
SynerGEE	GL	- Individual inverter modeling is not possible - No visibility of PV system irradiance or power factor	- Data can be input from SCADA using MiddleLink, a tool that reads .csv files	- Drag and drop GUI	- Can create distribution feeder level modeling	
DEW	EDD	- Individual inverter modeling is possible - Can see power factor, primary, secondary voltage, and many other key indicators	- Advanced API for interfacing with 3rd party tools	- Drag and drop GUI	- Can create distribution feeder level and secondary modeling	

Table 3: Analysis of distribution system modeling tools

Phase 2 – Field Demonstration of Smart Grid-Enabled Inverters at Test Sites

Task 7.0 – PV System Deployment; New Installation and Inverters

- *Subtask 7.1 – Site Preparation, Selection and Permitting*

Before project volunteers could be recruited, the project team, in collaboration with UH legal counsel completed a Volunteer Agreement form as shown below in Figure 16

Voluntary Addendum to Installation Agreement

If the home owner or resident of the home wish to participate in a University of Hawai'i energy sustainability research project, they must sign this Participation Agreement. Participation is voluntary. This agreement supplements and modifies the installation agreement between the PV Installer and the home owner and sets forth the responsibilities of the parties to facilitate a successful completion of the research Project.

MAUI ADVANCED SOLAR INITIATIVE
Participation Agreement (Phase II)

This Participation Agreement ("Agreement") is made between (1) the **University of Hawai`i on behalf of the Hawai`i Natural Energy Institute, University of Hawai`i at Manoa** ("University"), whose business address is 1680 East West Rd, Honolulu, Hawai`i 96822; (2) the **legal owner** of the Participating Home ("Owner"); and if applicable (3) the **resident of dwelling unit** participating in the Project ("Participant") if resident and Owner differ. This Agreement must be read in conjunction with the installation agreement between Rising Sun Solar and the Owner.

Description of Research Project

The objective of the research Project is to evaluate the effectiveness of Smart Inverter Technologies in reducing overall home energy consumption, lowering electricity demand during periods of high usage, integrating more renewable energy sources, and improving the quality of electricity service to customers.

Definitions

"Project": The Maui Advanced Solar Initiative is a research and demonstration project that is evaluating the effectiveness of smart grid technologies. This Project is funded by the United States ("U.S.") Department of Energy and is conducted with the collaboration of The Maui Electric Company ("MECO"). This phase of the Project is designed to test smart inverter technologies with volunteer participants from the Maui Meadows neighborhood in Maui, Hawai`i.

"Participating Home": Participating Home refers to the dwelling unit on which the PV system, including certain smart grid equipment, is installed and which will be monitored for electricity use and equipment operating efficiencies during the term of the Project.

"Owner": The "Owner" is the person or entity that legally owns the Participating Home. If the Owner lives in the Participating Home, the Owner may also be referred to as the Participant or the Resident.

Page 1 of 7

Figure 16: Volunteer Agreement.

The volunteer recruitment strategy and marketing materials development (see Figure 17) was completed on schedule by February close.

Figure 17: Marketing material.

- *Subtask 7.2 – System Installations and Testing at Selected Sites*

HNEI and Rising Sun Solar Electric recruited the first volunteer, an existing PV customer on the Maui Meadows distribution circuit, for rapid deployment of the first smart inverter via inverter swap-out. The Volunteer Agreement was executed with the customer. The existing Fronius inverter was swapped with a new Fronius advanced function inverter (see Figures 18 and 19). This initial installation enabled the project team an opportunity to continue to work out undiscovered "bugs" through testing prior to mass deployment.

Figure 18: Original inverter.

Figure 19: New advanced Fronius inverter

Seventeen volunteers have been recruited to date on the Maui Meadows distribution circuit.

One advanced function inverter (a Hitachi unit) has been installed at the Watershed Demonstration Center at PHI (see Figure 20) and recruitment of nine (9) volunteers on the PHI network distribution feeder is ongoing.

Figure 20: Hitachi inverter at Watershed Demonstration Center.

- *Subtask 7.3 – Engineering Field Support, and Training*

SSN developed field support and training documentation which is being used to provide training to installers from Rising Sun Solar (MECO service territory) and Standard Solar (PHI service territory) to enable them to provision smart inverters onto the smart grid network and connect them to SSN's back office systems. SSN engineers have supported the solar installers in resolving issues that may arise during system deployment and field testing. Field support will continue throughout the remainder of inverter field deployment and operations. A Phase 2 deliverable consisting of field support and training documentation has been completed by the project team as shown in Figure 21.

Figure 21: Solar Installation Training Materials.

Task 8.0 – __Test Plan, Data Collection, and Demonstration__

- *Subtask 8.1 – Define Test Objectives and Develop Test*

A primary objective of the smart grid inverter project is to study the use of a multitude of smart inverters and their advanced functionality exercised via a smart grid network to manage the impact of high penetration distributed residential rooftop PV systems on the electric grid. The primary hypothesis to test is that the advanced functionality of the inverters can enable penetrations of rooftop residential PV that is higher than currently in operation by effectively managing voltage variability on a radial distribution feeder, and thus potentially reducing the number of new PV system applications requiring a detailed interconnection study. The project will also test the ability to curtail PV system production under circumstances that may result in back-feeding network protectors in a secondary distribution network, again enabling higher numbers of grid-tied PV systems to be installed in those areas than are currently allowed. Through distribution circuit modeling as well as field testing at two utility sites, the SGI project will develop and assess different types of inverter control algorithms (Volt/VAr, fixed PF, etc.) and coordinated control methodologies (using different algorithms for different inverter groups) to determine to what degree the coordinated operation of multiple smart inverters can resolve utility interconnection issues and maintain the reliability of the electric grid at high PV penetrations.

In order to understand the impacts PV is currently having on the system and to validate the impacts of smart inverter control within a detailed model, high resolution and time synchronized field data measurements will need to be collected from sensors in the field and analyzed in both spatial and time domains. Smart inverter monitoring and control will also be initiated and tested in the field to analyze the impacts on the grid. The research and testing plan will evolve over time as first baseline data is collected, smart inverters are installed, and new insights are acquired through continuing analyses.

- *Subtask 8.2 - Data Collection and Reporting*

In addition to leveraging smart meter data being captured by the Silver Spring UIQ system that has been deployed in another earlier DOE funded project, additional monitoring devices have been deployed on the Maui Meadows circuit. These monitoring devices have been installed at strategic locations along the feeder length such as the secondary side of pole mounted service transformers, customer service entrances, and PV inverters. The intent is to collect the necessary data at various locations to capture the smart grid inverter and feeder performance. In order to validate the smart inverter performance, it is necessary to capture operational performance data in the seconds time domain, much faster than the rate of data capture of smart meters alone (typically in the 15 minute time range). Data granularity at a one second interval over a desired research period of twelve months is important to perform the associated research and development of control algorithms utilizing the smart inverter functionality in a coordinated manner.

Furthermore, each individual data will be time synchronized (i.e. UTC time-stamped). Data to be captured may include, but is not limited to voltage, current, watt, watt-hour, var, var-hour, power factor, irradiance, and temperature data.

Presently, a total of twenty (20) data monitoring and collection device have been installed on the Maui Meadows distribution feeder. Seventeen (17) of these devices are deployed on the secondary side of select utility service transformers. An additional three (3) devices are deployed at the homes of several volunteer customers with rooftop PV systems in Maui. Figure 22 is a map detailing the different electrical phases of the feeder throughout the entire subdivision and the high resolution data monitoring and collection device (Obvius Box) locations.

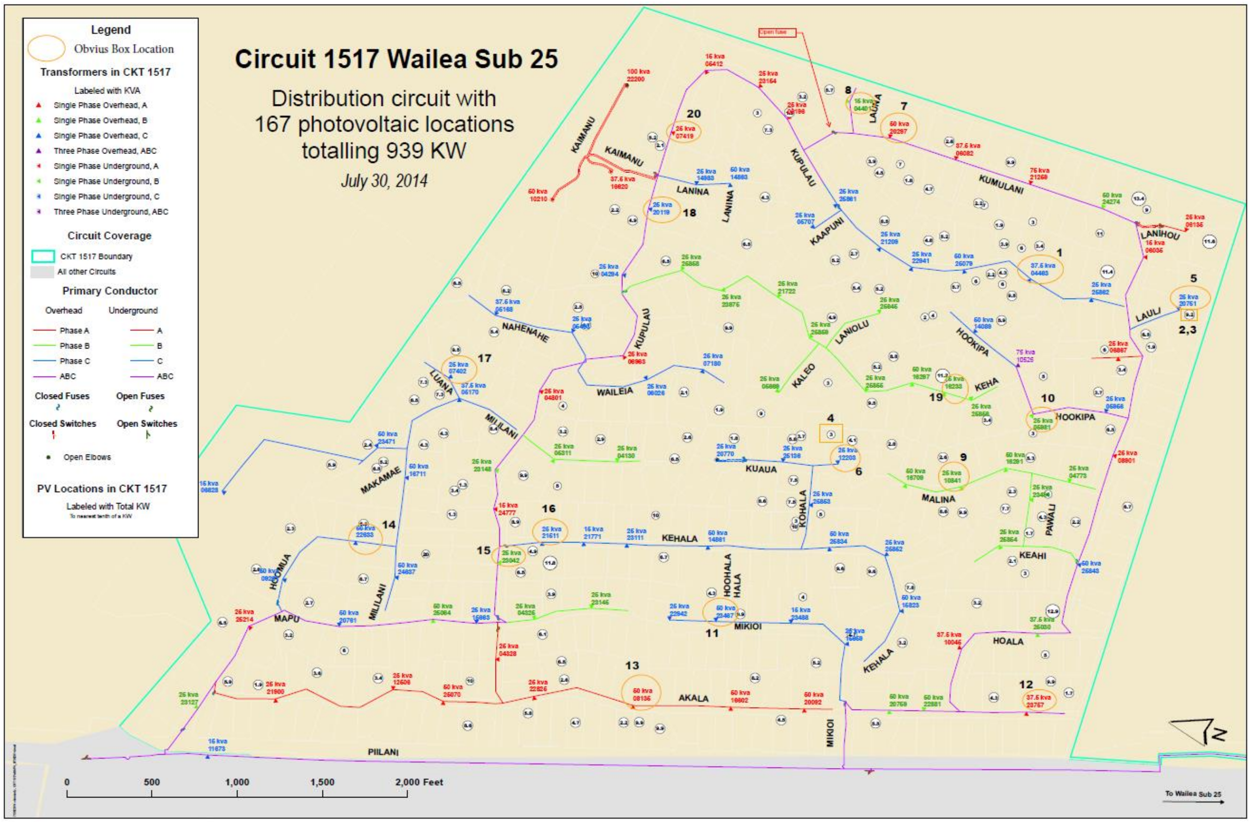


Figure 22: Existing locations of monitoring devices.

The monitoring devices need to be deployed on all three phases of the Maui Meadows circuit. It is expected that the circuit loading will be unbalanced due to the fact that nearly all the loads are single phase residential customers. Therefore, the voltage will be somewhat different between the phases. The phase which is lightly loaded and with high PV penetration may experience high voltage problems during periods of high PV generation. Conversely, the phase with high levels of customer load, yet with a lesser amount of total PV penetration may experience a relatively lower voltage. Thus, it is essential to install the monitoring devices at various locations of the circuit that are well thought out.

The data collected is be archived in a database server at the University of Hawaii at Manoa for analytical purposes and is also to be made available for extended research activities.

All data exports will continue to run through the entire project duration (from device activation to project close) in order to maximize the data sets available for analyses.

Maui Meadows Circuit Data Analyses

For this report, the C-phase of the circuit is selected for data analyses. The analytic is centered on the effect of PV generation to the voltage along the entire feeder using the data collected from the high resolution data monitoring and collection devices.

There are two locations within the subdivision where the high resolution data collection devices were installed at both the service transformer and at a PV system connecting to that service transformer. Expanded setup information for these locations follows.

Location 1 is where Obvius Box 5 is collecting data from a 25 kVA C-phase to neutral distribution transformer about 1.7 miles from the beginning of the feeder (see Figure 23). This service transformer serves eight customers and three of the eight have PV systems totaling to 17.6 kW of distributed generation. The largest PV system is 9.2 kW and its data is currently being collected by Obvius Box 3. The customer's net electrical service data is also being collected by Obvius Box 2, in addition to the 15 minute smart meter data.

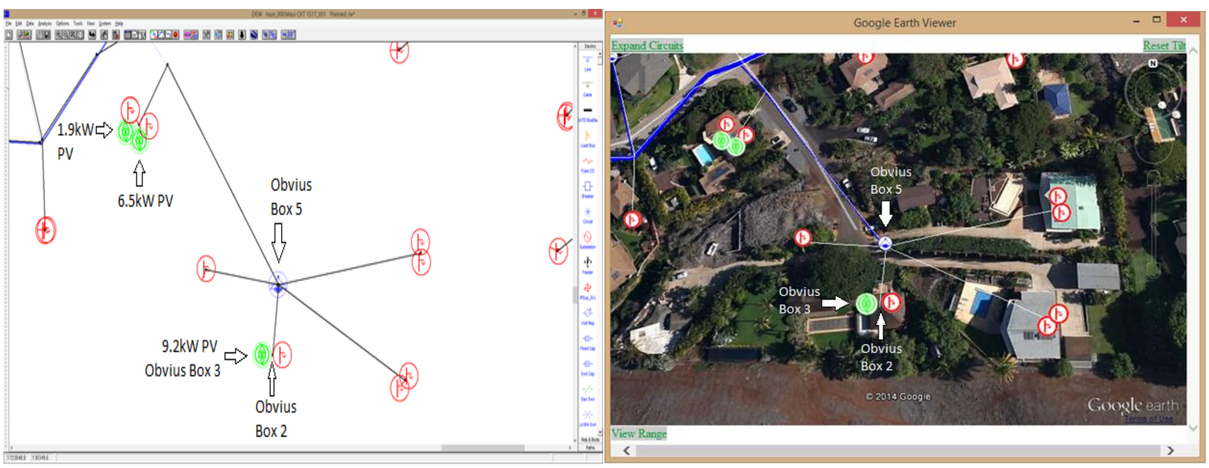


Figure 23: Obvius Box 5 location.

Location 2 is where Obvius Box 6 is collecting data from a 25 kVA C-phase to neutral distribution transformer about 2.65 miles from the beginning of the feeder (see Figure 24). This service transformer serves seven customers and two of the seven have PV systems totaling 7.1 kW of distributed generation. Obvius box 4 is collecting the 3 kW PV system data.

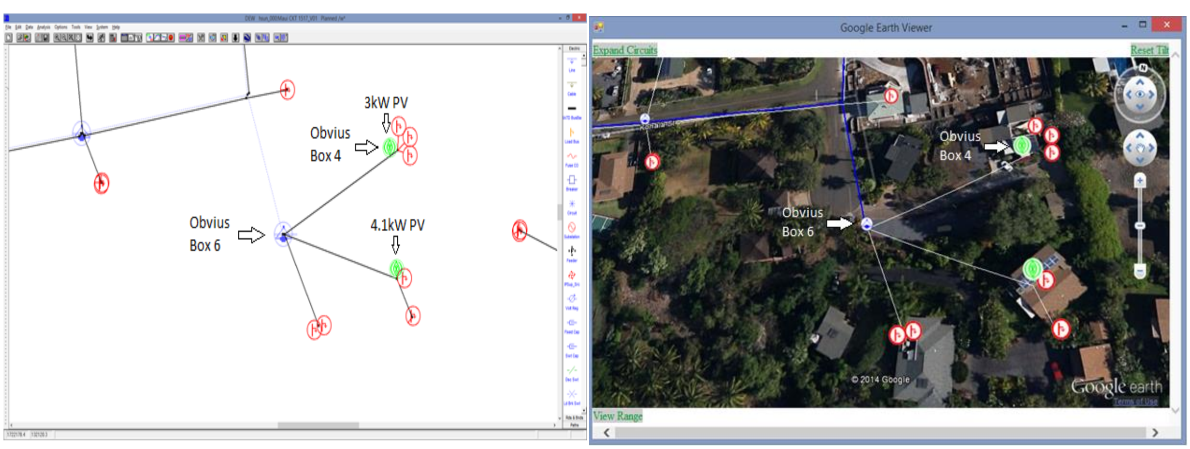


Figure 24: Obvius Box 6 location.

Identifying an interesting time frame

To get a better understanding of the relationship between PV generation and grid voltage, a time frame that has both high variation in PV generation and low net load during peak production time of 10AM-2PM were identified. The data from the two Obvius devices (boxes 3 and 4) that are measuring the output of PV the systems were used identify periods of highly variable PV production. The transformers that serve these two systems are associated with Box 5 and 6 as noted in the figures above.

To see how short term variations of PV generation affect voltage, a time frame of 5 minutes was chosen similar to a previous Solar Integration Study for Oahu by GE. To identify this time frame, first the 30 second moving average for PV generation at Box 3 and 4 and the 30 second moving average for net load at Box 5 and 6 were calculated. Then the RMS value for 5 minute time frame was calculated from the 30 second moving average for Box 5 and 6 using the formula:

$$L_{rms} = \sqrt{1/300 \sum L_{ma}^2}$$

Where L_{ma} is the 30 second moving average of the load measured at Box 5 and 6.

This RMS value reflect the average value of the 30 second moving average for a 5 minute time frame. Using this RMS value, we can identify the 5 minutes time frame that has the lowest amount of net load.

Similarly, the RMS value for Box 3 and 4 was calculated. However, since the interest at box 3 and 4 is the variation, first the deviation at each time step is calculated then the RMS value according to:

$$P_{dev\,rms} = \sqrt{1/300 \sum P_{dev}^2}$$

Where P_{dev} is the deviation of power calculated by:

$$P_{dev} = P - P_{ma}$$

P is the power at a given time and P_{ma} is the 30 second moving average.

After the RMS values were calculated, we observed that a time period of high variability in general has a direct relationship to the 5 minute average net load, i.e. the time with the lowest net load has very low variability and the time with highest variability has relatively normal load. This makes intuitive sense, since high variability means that PV generation during that time period has a lot of fluctuation and thus on average produces a lower average power output.

Because the main interest is the short term variation of PV generation, the 5 minutes time frame from 13:22 to 13:27 on August 22nd 2014; the period with the highest variability in PV production for box 3 and 4 was chosen.

Characterization of voltage behavior at the two PV locations

Using the 5-minute time frame identified in the previous section, data from Obvius boxes 2-6 were plotted in a number of different configurations to get a better understanding of the effects of PV generation on the service transformer's voltage.

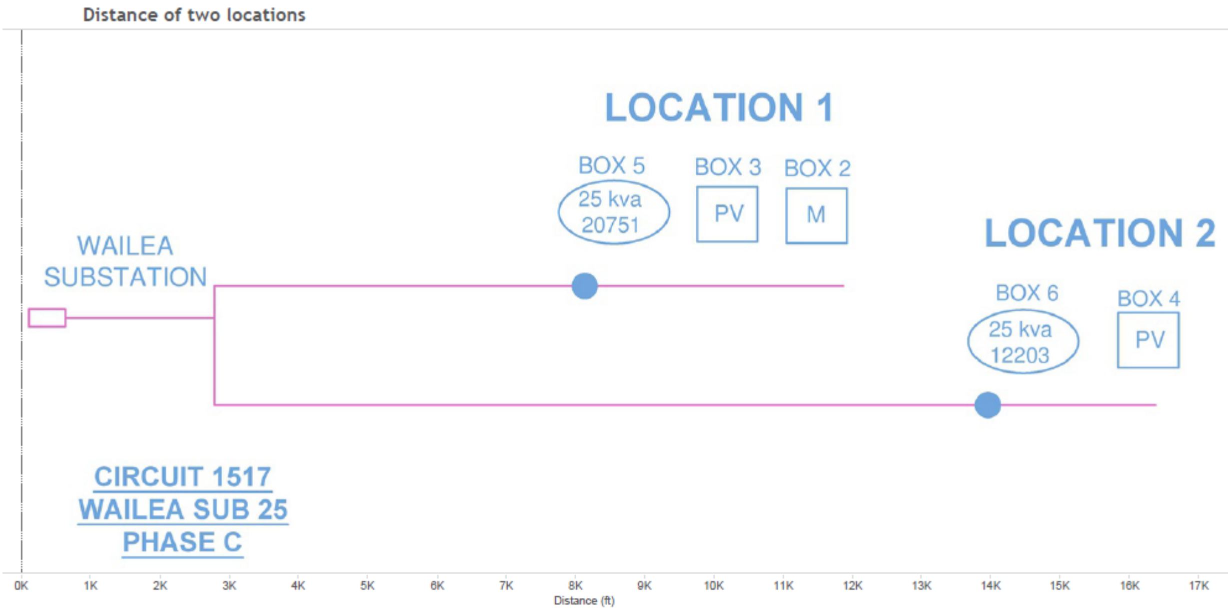


Figure 25: Distance view.

Figure 25 shows the relative distances between two locations (Box 2 – first customer's net meter, Box 3 – first customer's PV, Box 5 – first customer's transformer are located at location 1 and Box 4 – second customer's PV, Box 6 – second customer's transformer are located at location 2) and the Wailea substation of Maui Meadow Circuit.

Figure 26: Average voltage.

Figure 26 shows the average voltage for the 5-minute time frame at each Obvius box. Comparing the transformer voltages, the voltage at first customer's transformer (as shown in green bar) is slightly higher than the voltage at second customer's transformer (as shown in red bar). This voltage drop is plausible since first customer's transformer is closer to the substation than second customer's transformer and the voltage along the feeder generally tends to drop towards the end of the distribution line. Note that this may not be always the case as the voltage at any given point along a circuit is a function of line impedance, customer's load, and PV output.

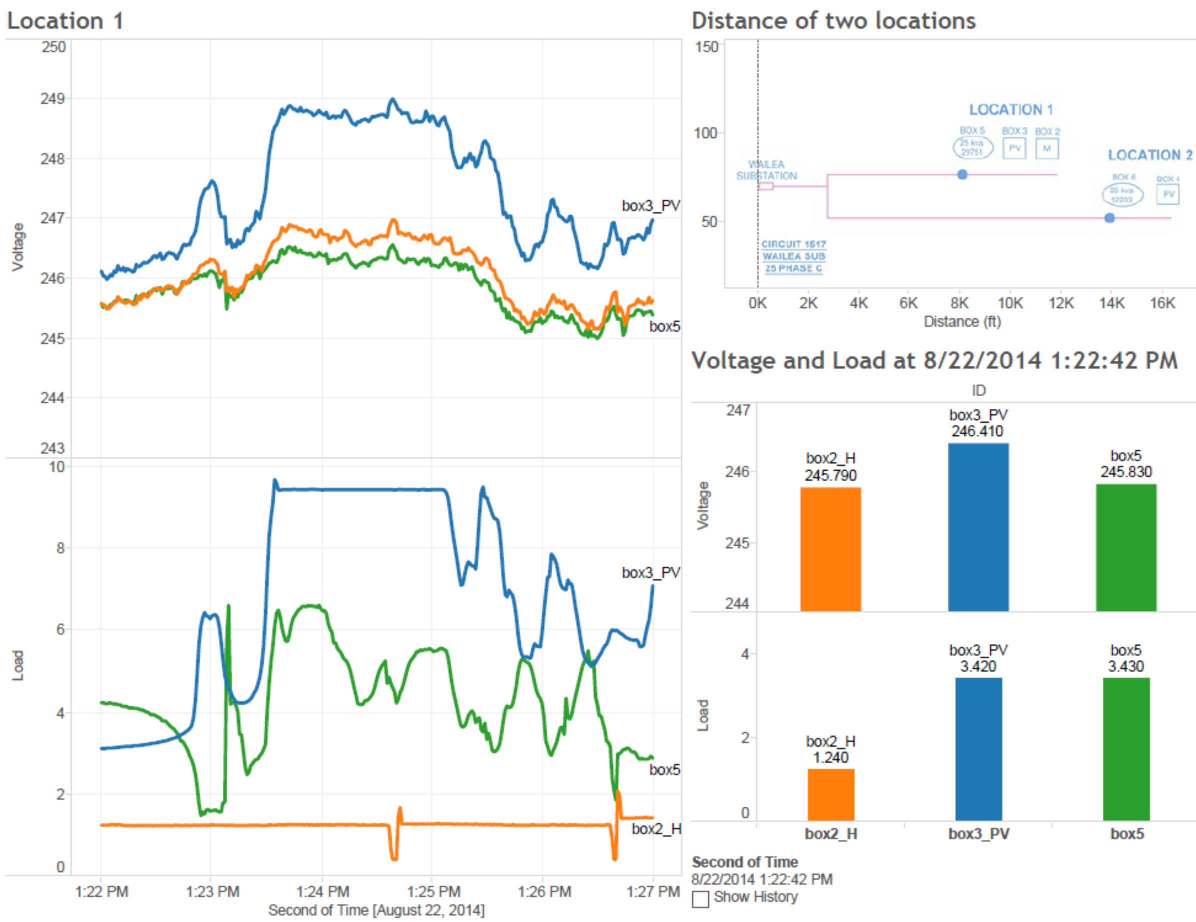


Figure 27: System characterization at location 1.

The left side of Figure 27 shows the voltages and power usage flow for location 1. As a reference, the distance map and voltage magnitude bars are also provided on the right side for a particular measurement at 1:22:42 PM.

Looking at the left half of Figure 27, the voltage at the first customer's PV (box3_PV) is higher than the voltage at the first customer's net meter (box2_H) and the first customer's transformer (box5) and the voltage plots for all three boxes follow the same trend. For this particular location, the voltage behavior of PV generation dominates the voltage behavior of the house and the service transformer.

The load at the first customer's transformer (box5) versus the first customer's PV generation (box3_ PV) shows an inverse relationship for most of the peaks. It is clear that the increased in generation from PV decreased the overall net load at the transformer. The flat line behavior of the PV output between 13:23 and 13:25 is due to the PV generation being clipped as the customer's PV panel ratings are larger than the inverter ratings.

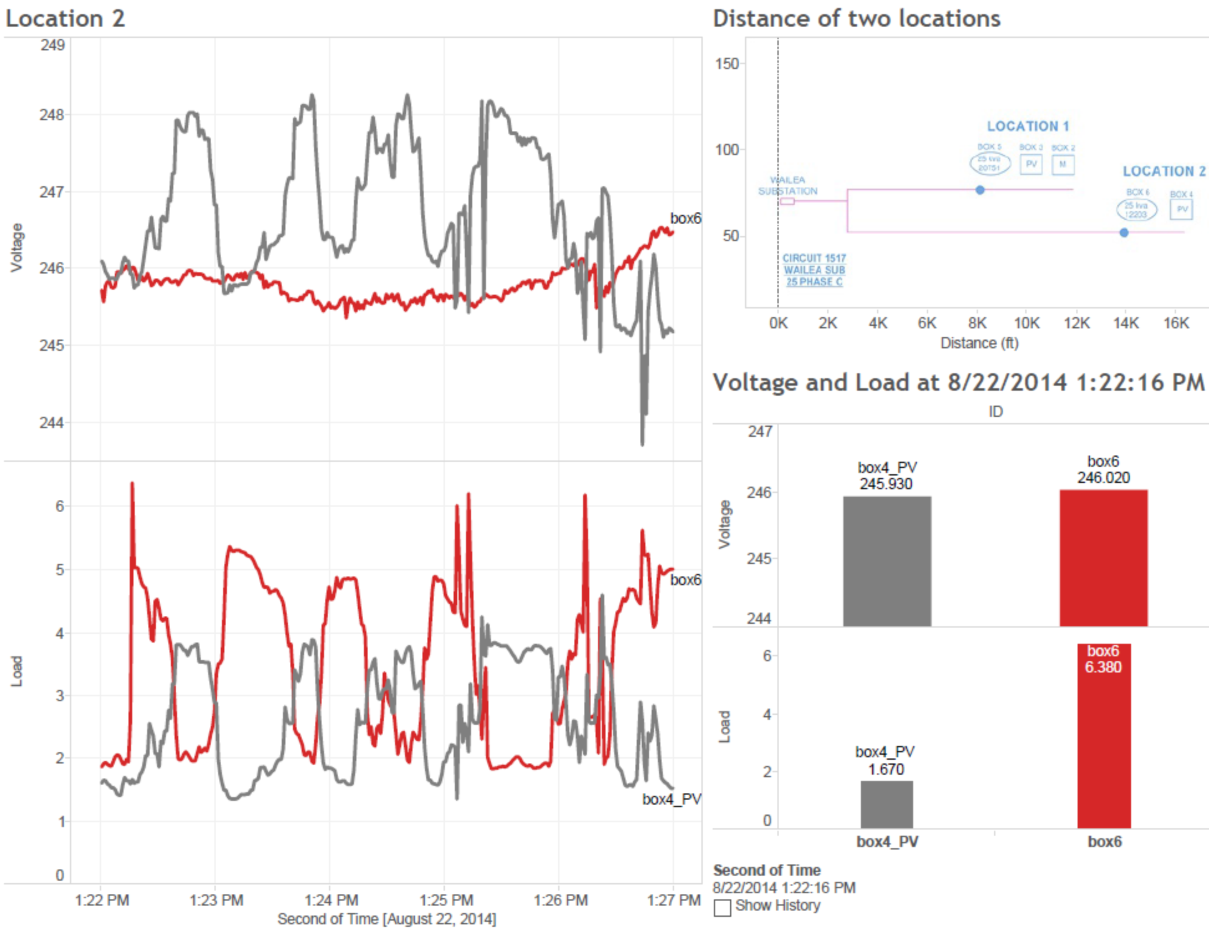


Figure 28: System characterizaton at location 2.

The left side of Figure 28 shows the voltages and power usage for location 2. In contrast to location 1, the voltage at second customer's PV (box4_PV) does not follow the same trend as the voltage at the second customer's transformer (box6). Big swing in voltage at the PV panel has little effect on the transformer's voltage. This is mainly due to the fact that location 1 has a much higher penetration of PV compared to location 2 (17.6 kW on a 25 kVA transformer with 8 customers vs 7.1 kW on a 25 kVA transformer with 7 customers). The difference in voltage behavior at the two locations shows that neighborhood with higher penetration of PV will see more effect of PV generation on the transformer voltage.

The load at the second customer's transformer (box6) versus the second customer's PV generation (box4) agrees with the observations at location 1. Net load and PV generation have an inverse relationship, higher PV generation means lower net load at the transformer and vice versa.

- *Subtask 8.3 – Perform Testing and Monitoring*

The project team installed the first smart inverter at a volunteer customer's home on Maui to gain field experience and troubleshoot any potential issues which may surface prior to mass smart inverter deployment.

The following are initial objectives to be achieved in the testing and monitoring of the smart grid inverters deployed in Maui Meadows:

- Determine to what degree voltage can be effectively controlled using reactive power (Var) capability as opposed to control of real power production (Watts)
- Maintain a level voltage profile from source to the end of the feeder
- Provide a localized supply of reactive power for the feeder while maintaining a level voltage profile across the feeder length (i.e., reducing feeder VAr being supplied through the substation transformer from the transmission system).
- If feeder voltage is still too high after utilizing smart inverter VAr capabilities, use the Volt/Watt capability to avoid exceeding utility voltage limits.
- Curtailment capabilities need to be considered in the context of where distributed PV fits within the curtailment priority of all renewable resources interconnected to the power grid.
    - While this project will develop the technical and operational capability to curtail power output of rooftop residential PV system, policies will need to be developed beyond the scope of this project to determine how and when such capabilities will be used.

Task 9.0 – <u>Project Management and Reporting</u>

UH-HNEI used rigorous project management processes to manage the project to meet deliverables and maintain budgetary compliance of the project.

- *Subtask 9.1 – Project Monitoring and Meetings*
    - Weekly meetings are held with project team members to review tasks and update status on action items.
    - Contracts for project partners in Budget Period 2 were executed.
    - Equipment for AMI infrastructure in the PHI service area was procured.
    - Rising Sun Solar Electric active volunteer recruiting continues.
    - All Fronius, SMA, and Hitachi smart inverters were procured in Budget Period 2.
        - Inverters purchased for Maui are two (2) Hitachi inverters, seventeen (17) Fronius inverters, and nine (9) SMA inverters (28 total inverters)

- Inverters purchased for PHI are one (1) Hitachi inverter, eight (8) Fronius inverters, and one (1) SMA inverter (10 total inverters)

- *Subtask 9.2 – Author and present technical papers by appropriate team participants at one or more conferences.*

Periodical Publications Authored

- Roose, L., 2013. "Securing Paradise in Hawai'i: A Japan-Hawai'i Partnership to Develop Smart Technologies and Unlock a Renewable Energy Future," Hitachi Hyoron, Vol. 95, No. 4, 2013.

Conference Presentations (without full publication)

- Roose, L., Matsuura, M., 2014. "Solar and Wind Energy Integration on Island Power Grids - The Hawai'i Experience," Presented at Overseas Specialist PV Integration Seminar for Okinawa Electric Power Corporation, Okinawa, Japan, September 29 – October 1, 2014.
- Roose, L., 2014. "Achieving Hawaii's Clean Energy Future - Business Opportunities in Smart Energy Innovation & Collaboration," Presented at Hawaii Clean Energy Seminars, Honolulu Japanese Chamber of Commerce Trade Mission to Japan, Hiroshima & Shizuoka, Japan, May 30 – June 2, 2014.
- Roose, L., 2014. "Development and Demonstration of Smart Grid Inverters for High-Penetration PV Applications poster presentation and project peer review," Presented at SunShot Grand Challenge Summit and Peer Review 2014, Anaheim, California, May 19-22, 2014.
- Matsuura, M., Roose, L., 2014. "Unlocking a Solar Energy Future in Hawai'i," Presented in February 19th Recent Progress in Solar Energy Grid Integration Systems Panel Session, Innovative Smart Grid Technologies 2014, Washington DC, February 19-21, 2014.
- Roose, L., 2014. "Hawai'i's Renewable Energy Future," Presented in January 11th Session, 2014 Joint JST-NSF-DFG Workshop – Distributed Energy Management Systems, Honolulu, Hawai'i, January 11-13, 2014.
- Roose, L., 2013. "Unlocking a Renewable Energy Future - Evolution of the Maui Grid," Presented in 3rd Annual Hawai'i Renewable Energy Development Interconnection & Integration Potential Workshop, Honolulu, Hawai'i, September 26, 2013.
- Roose, L., 2013. "Securing Paradise in Hawai'i; Hawai'i Efforts to Unlock a Renewable Energy Future," Presented in Hawai'i Renewable Grid Integration Lessons Learned Concurrent Session, Asia Pacific Clean Energy Summit and Expo., Honolulu, Hawai'i. September 11, 2013.
- Roose, L., 2013. "Building Island Economies, Hawai'i Research Opportunities in Renewable Energy and Smart Grid Technologies," Presented in Association of Pacific Island Legislatures Workshop, 2013, Honolulu, Hawai'i, June, 25, 2013.
- Roose, L., 2013. "Securing Paradise in Hawai'i; A Japan – Hawai'i Partnership to Develop Smart Technologies and Unlock a Renewable Energy Future," Presented in Joint NEDO and JSCA sponsored Smart Community Summit 2013, Tokyo, Japan, May 29, 2013.
- Rawson, J., 2013. "Securing Paradise in Hawai'i," Presented in CEOs' Conference with Communications Symposium 2013, Kingston, Jamaica, May 28, 2013.
- Roose, L., 2013. "Building Island Economies, Hawai'i Research Opportunities in Renewable Energy and Smart Grid Technologies," Presented in GESL International Symposium 2013, Keio University, Tokyo, Japan, February 26, 2013.

- Roose, L., 2013. "Development and Demonstration of Smart grid inverters for High-Penetration PV Applications," Presented in High Penetration Solar Forum 2013, U.S. Department of Energy, San Diego, California, February 14, 2013.
- Roose, L., 2013. "Building Island Economies Through Clean Energy," Presented in Hawai'i – Okinawa Clean Energy Workshop, Naha, Okinawa, Japan, January 28, 2013.
- Roose, L., 2012. "Building the Maui Smart Grid, Presented in Power Generation & Efficiency Concurrent Session, Asia Pacific Clean Energy Summit and Expo., Honolulu, Hawai'i, August 13, 2012.
- Roose, L., 2012. "Making of the Maui Smart Grid," Presented in Concurrent Session 4, 20th Annual Hawai'i Conservation Conference, Honolulu, Hawai'i, August 1, 2012.
- Roose, L., 2012. "Development and Demonstration of Smart grid inverters for High-Penetration PV Applications," Presented in Grand Challenge Panel Discussion – Grid Integration, U.S. Department of Energy SunShot Initiative Summit and Technology Forum, Denver, Colorado, June 13-14, 2012.
- Roose, L., 2012. "Renewable Energy Integration on Island Systems - The Hawai'i Experience," Presented in Accelerating Renewable Energy Deployment in the Pacific Region, Japan-IRENA Joint Workshop, Okinawa, Japan, May 26, 2012.

Invited Academic Seminars and Lectures (University of Hawai'i)

- Roose, L., 2014. "Smart Grid Developments in Hawaii," 3-hour presentation series. Invited lecturer, Asian Productivity Organization Study Mission to a Nonmember Country on Smart Grids for Communities, co-sponsored by University of Hawaii, Hawaii Natural Energy Institute. Honolulu, Hawai'i. October 13, 2014.
- Roose, L., 2014. "Smart Grids and Renewable Energy Integration," Invited lecturer, University of Hawai'i College of Engineering, EE 693K. Honolulu, Hawai'i. April 28, 2014.
- Roose, L., 2014. "Island Systems - The opportunities and challenges of an island electric grid," Invited lecturer, University of Hawaii School of Ocean & Earth Science & Technology sponsored conference, Ascent: Building a Secure and Sustainable Water and Energy Future for Hawai'i, Energy Policy Panel. Honolulu, Hawai'i. April 15, 2014.
- Roose, L., 2014. "Research in Advanced Grid Technologies and Renewable Energy Integration in Hawai'i," Presented at US-Taiwan Bi-lateral Energy Forum, co-sponsored by the Office of Naval Research and University of Hawaii, Hawaii Natural Energy Institute. Honolulu, Hawai'i. March 12, 2014.
- Roose, L., 2013. "Securing Paradise in Hawai'i, The Maui Smart Grid – Smart Energy Technologies to Unlock a Renewable Energy Future," Presented at Tropical Plant and Soil Sciences 336 course, University of Hawai'i College of Tropical Agriculture and Human Resources, Honolulu, Hawai'i, November 28, 2013.
- Smart Energy Technologies to Unlock a Renewable Energy Future," Presented at Mechanical Engineering 610 course, University of Hawaii College of Engineering, Honolulu, Hawai'i, and September 3, 2013.
- Roose, L., 2012. "Making of the Maui Smart Grid," Presented at the University of Hawai'i College of Engineering Seminar in Renewable Energy and Island Sustainability (REIS), Honolulu, Hawai'i, and October 4, 2012.

- *Subtask 9.3 – Active participation by appropriate team participants at working group level to help define and adopt the IEEE 1547.8 standard*
    - Project team members are active in the IEEE 1547.8 working group.

- *Subtask 9.4 – Active participation by appropriate team participants at working group level in the EPRI Smart inverter Communication Initiative*

    - Project team members have been active in the EPRI Smart Inverter Communication Initiative. HNEI is supporting EPRI's Smart Grid demonstration project and EPRI has provided briefings to project teams members on their smart inverter standards work in the past.

- *Subtask 9.5 – Quarterly Reports covering all tasks and subtasks for Phase 2*

    - All project Quarterly Reports have been timely submitted.

- *Subtask 9.6 – Final report covering years 2 and 3 at the end of year 3 (Phase 2)*

    - This deliverable is pending the completion of year 3 of the project.

Task 10.0 - <u>Distribution Level Modeling and Analysis</u>

The Maui Meadows residential subdivision is served by Maui Meadows Circuit 1517 originating from Wailea Substation. This subdivision consists of single phase residential loads along with only one three phase load feeding the water supply pumps for the community. There are approximately 1,000 homes on Circuit 1517 which presently has a large amount of rooftop distributed PV systems, over 160 sites totaling over 930 kW of nameplate distributed generation (approximately 240 kW on A-phase, 260 kW on B-phase, and 430 kW on C-phase). The circuit's day time minimum load (gross) is roughly 930 kW. The high amount of PV generation on the feeder can more than serve this load level and, at certain times of the day, back-feed from the feeder to the substation can occur.

For this particular analysis, the electrical circuit components and individual residential customer loads and rooftop PV systems are modeled in detail using available information from MECO. The Maui Meadows electrical circuit components were modeled using GIS and construction data provided by MECO in the DEW modelling software. Each individual home is modeled an estimated service line impedance and with the load and PV generation disaggregated. Any missing information from MECO records and data regarding the secondary services to the home were gathered via arduous field inspections. Customer billing data, load research statistics, and SCADA measurements were used to build the customer and aggregate circuit loads and ultimately to calibrate the model. Actual PV generation profiles from the existing PV systems in Maui Meadows were used to develop PV production data for the model. Once the system model was built and calibrated the DER Assessment tool within DEW was used to determine any adverse impacts which maybe encountered with increased deployments of PV generation at the residential customer level.

Figure 29 shown below is a detailed DEW electrical model of Maui Meadows Circuit 1517. There are about 1,000 load buses (red circles) each representing a customer home and approximately 160 inverter distributed resources (green circles) each representing a distributed rooftop PV systems.

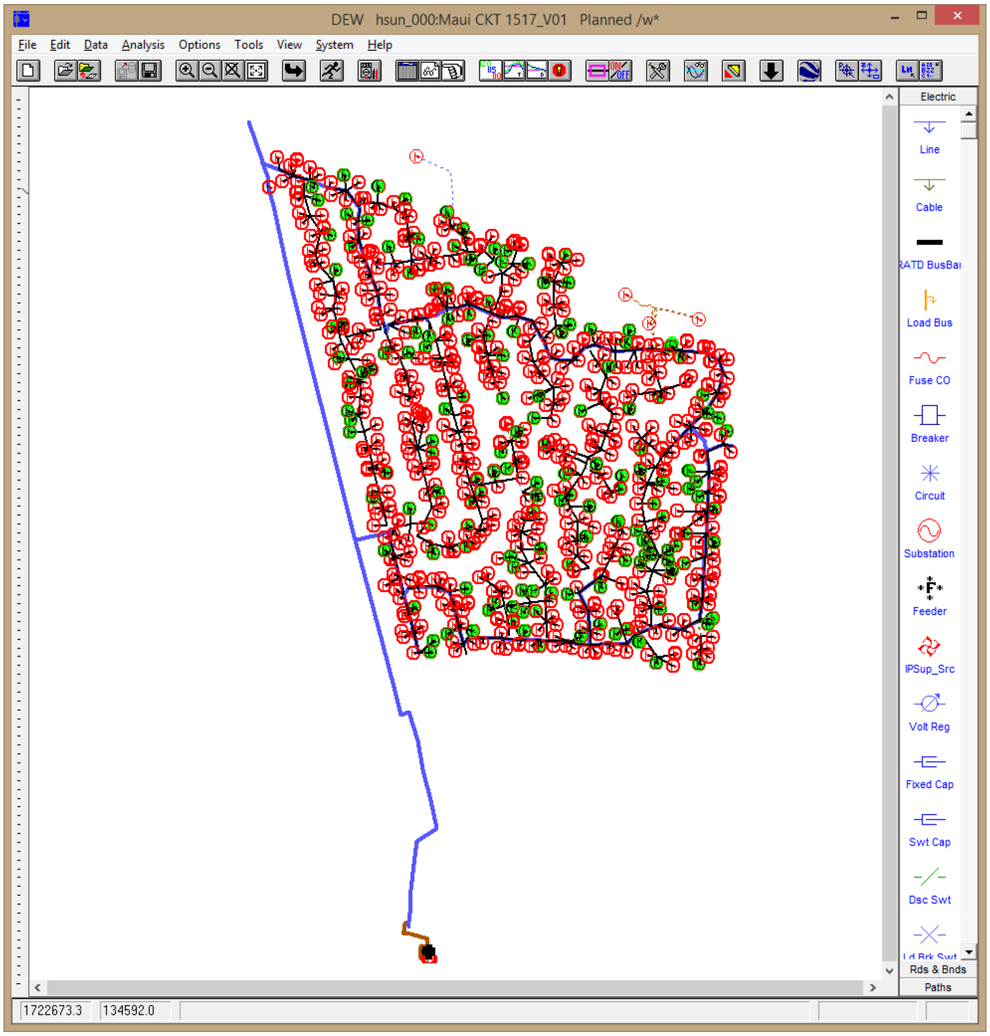
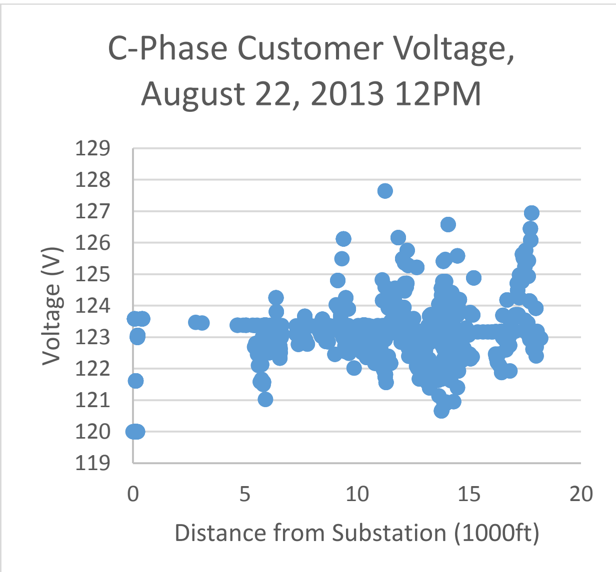


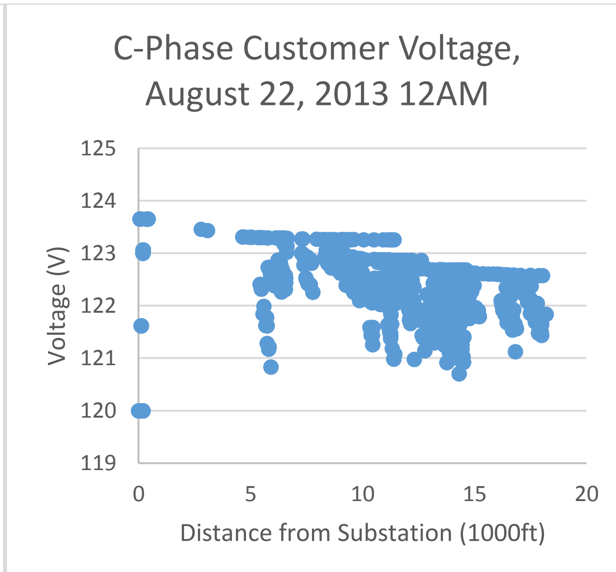
Figure 29: Model of Maui Meadows Circuit 1517.

With the high resolution monitoring data coming in from the field, including performance of smart inverter functionality, the distribution planning model can be updated to reflect the actual dynamics of high penetration PV on the electric grid. Subsequently, the analysis of the smart inverter advanced features can be performed and validated. It is anticipated that there will be iterations of fine tuning the smart inverter settings in the model and comparing them with actual inverter operational impacts in the field.

Maui Meadows Circuit Simulation Results

The two graphs in Figures 30 & 31 (provide results from the detailed DEW model simulations and illustrate the C-phase voltage magnitude along Circuit 1517 from the substation to the end of the feeder. The first graph uses the noon data while the second graph utilizes the midnight data. By comparing the two graphs it is apparent that the voltage profile along the circuit is quite different between day and night due to the presence of the distributed PV systems. For the day time (12:00 p.m.) graph, with all the PV generating near its nameplate rating, the voltage trend is almost flat and maintained between 123 to 124 volts with varying high/low voltage spots along the line depending on the amount of PV generation and load at a particular locations. The night time (12 a.m.) graph, with no generation from the PV systems, the circuit voltage along the line decreases as the distance increases due to the impedance in the conductor and the loading.





Figures 30 & 31: C-phase voltage magnitude along Circuit 1517

The detailed DEW simulation model is a very useful tool to perform various simulations and testing before applying it to the real world. The following graphs are generated from the simulation results on a day with max load on Circuit 1517. The graph titled "A-Phase Load Bus Voltage" (Figure 32) is a plot of the all the voltages seen at the load buses on the circuit to their distance from the substation. The lowest voltage is about 119.4V; this low voltage along with other low spots are the limiting factor to shifting the entire feeder's voltage down to perform conservation voltage reduction (CVR). The triangles on the graph are various size inverters simulated at different locations to export reactive power. The next graph titled "A-Phase Customer Voltages w/ Simulated Inverters" (Figure 33) is a plot of the resulting load bus voltages with the various simulated inverters exporting reactive power. As you can see the lowest voltage is now about 122.3V and the majority of voltages along the feeder have become more compressed into a narrower band. After all the low voltages have been addressed and the voltage magnitude has become fairly level along the feeder, lowering the load tap changer (LTC) on the substation transformer will shift the entire feeder voltage down as seen in the third graph titled "A-Phase Customer Voltage w/ Simulated Inverters & Lowering LTC" (Figure 34).

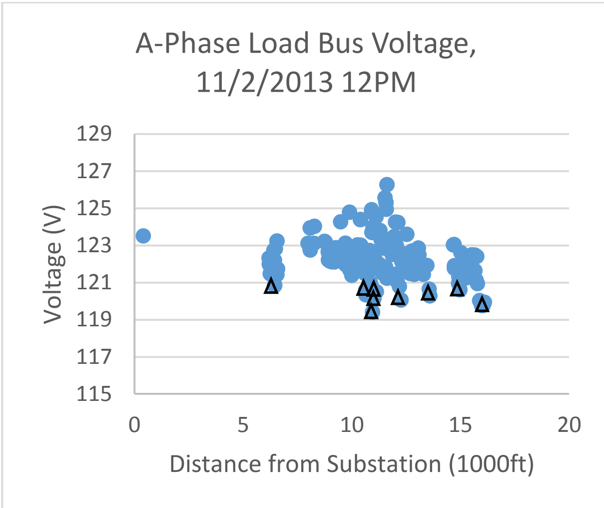


Figure 32: A-phase voltages

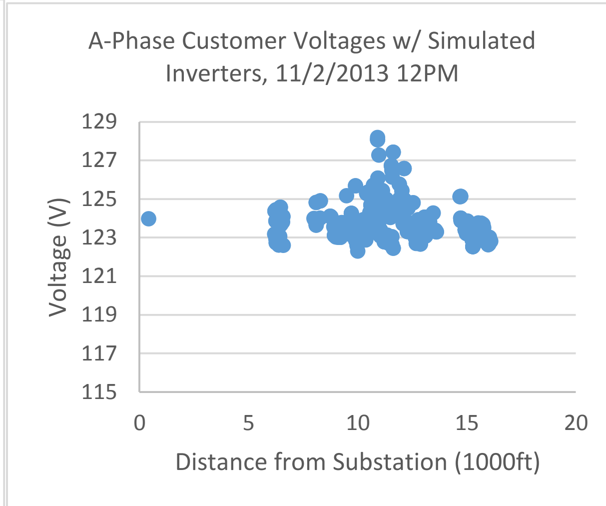


Figure 33: A-phase voltages w/ simulated inverters

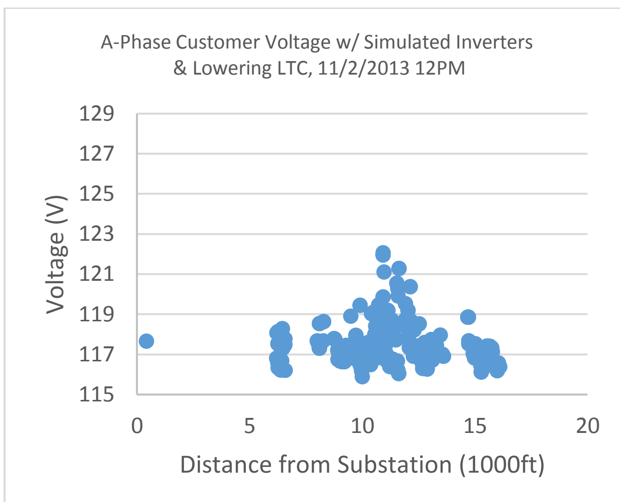


Figure 34: A-phase voltages w/ simulated inverters & lowering LTC

In conclusion, the results of the analyses in the above sections will aid in the development of the algorithm of the advanced function inverter's reactive power to manage the voltage along the feeder. The ability to narrow the voltage band across all the phases of the entire feeder will enhance the success of the implementation of the conservation voltage reduction (CVR). The next chapter to this project will aim at performing CVR on the Maui Meadows circuit. The benefits to the utilities will be greatly realized once the CVR is achieved.

Conclusion:

The project at the end of Budget Period 2 produced the following key results:

- Completed successful field test at Maui Electric Company of advanced inverter functionality (e.g., volt/var, volt/watt, watt curtailment, watt/frequency) for Fronius, Hitachi and SMA manufactured inverters via remote control through the back-office IMCS and end-to-end 900 MHz mesh utility network and SEP 2.0 over 2.4 GHz ZigBee HAN to the inverter.

- Twenty high-resolution data monitoring/communications devices were field deployed throughout the Maui distribution feeder targeted for smart grid inverter installations, allowing for time synchronized one second time-step feeder operational performance data to be captured and analyzed. A detailed distribution circuit model has been constructed in the DEW/ISD environment and the utility mandated Interconnection Requirements Study (IRS) for installation of additional PV systems under this project on the selected high-penetration PV distribution feeder on Maui was completed.

- Project volunteer recruitment activities continue (including execution of form volunteer agreements, use of marketing and recruitment materials, and prioritization and targeting of volunteer recruits). Volunteer recruitment to date is nearing 20 volunteers. In addition, a smart grid inverter was deployed at the Watershed Demonstration Center in Maryland, PHI's service territory.

- Preliminary analyses of distribution circuit field performance data and distribution system modeling has been conducted.

The US DOE has opted not to continue funding this project beyond the close of Budget Period 2, ending on June 30, 2014.

Budget and Schedule:

Table 4 below represents PRELIMINARY financial information, provided by the technical project team. Official information will be provided by the University of Hawaii's Office of Research Services using Form SF-425.

Object Class Categories	APPROVED BUDGET per SF424			ACTUALS Cumulative to 6/30/2014	
Per SF 424a	**Budget Period 1**	**Budget Period 2**	**Budget Period 3**	**DOE Share**	**Cost Share**
a. Personnel	$48,125	$236,127	$466,127	$143,144.59	
b. Fringe Benefits	$17,999	$88,311	$174,331	$34,167.69	
c. Travel	$21,000	$53,000	$7,500	$51,419.24	
d. Equipment	$51,500	$0	$10,000	$10,000.00	
e. Supplies	$4,291	$243,391	$12,000	$338,507.31	
f. Contractual	$1,904,145	$5,098,496	$1,784,980	$2,320,833.56	
g. Construction	$0	$0	$0	$0.00	
h. Other	$3,289	$6,218	$16,000	$17,525.20	
i. Total Direct Charges (sum a to h)	$2,050,349	$5,725,543	$2,470,938	$2,915,597.59	
j. Indirect Charges	$63,068	$176,556	$148,489	$192,992.44	
k. Totals (sum i & j)	**$2,113,417**	**$5,902,099**	**$2,619,427**		
DOE Share	$1,492,155	$1,780,890	$1,839,888	**$3,108,590.03**	
Cost Share	$621,262	$4,121,209	$779,539		**$3,709,217.00**
Calculated Cost Share Percentage by Budget Period	29.4%	69.8%	29.8%		
By Project Phase	**Phase 1**	**Phase 2**			
Calculated Cost Share Percentage by Project Phase	29.4%	57.5%			
Total Project				**Actual Cost Share Percentage to 6/30/2014**	
Calculated Cost Share Percentage for Total Project	51.9%			54.4%	

Table 4: PRELIMINARY Financial Information

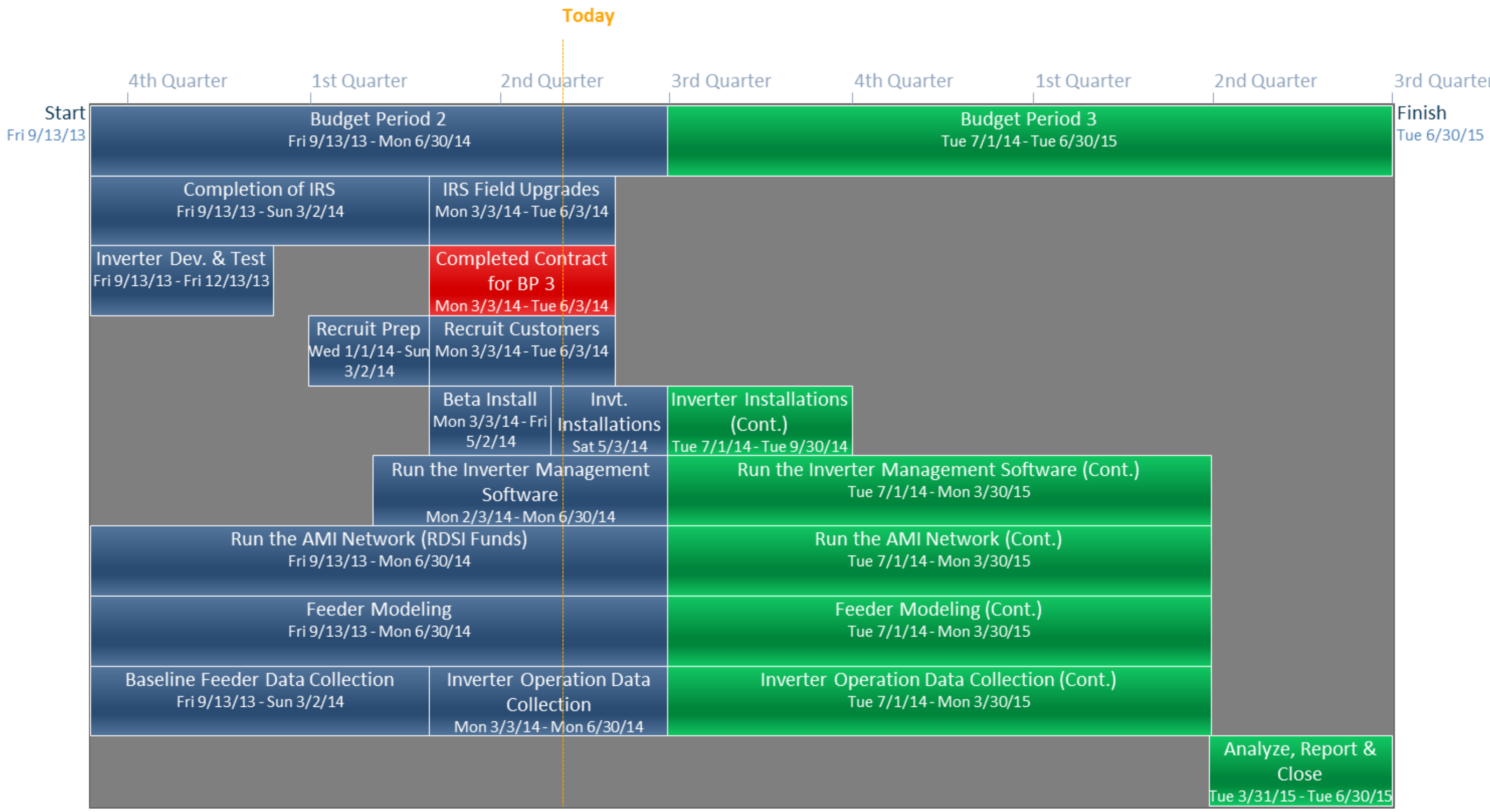


Figure 35: Project Schedule

The project schedule above was provided in previous report submitted at the end of Budget Period 2 (BP2). At that time the development of the Fronius and Hitachi Inverters were completed and the SSN Inverter Management Control Systems was completed and inverter deployments to project volunteers were underway. Also, base line data had been collected and the feeder model was being validated and feeder analytics were underway. It was anticipated that the contract for Budget Period 3 (BP3) would be completed near the middle of the second quarter and the algorithm development and demonstration could then get underway. Unfortunately an agreement for BP3 was not reached and DOE funding to complete the work in BP3 was denied and the DOE's involvement in this project ended at the end of BP2.

Path Forward:

The major tasks going forward for the project includes the following:

- Complete volunteer recruitment
- Complete installs of new PV/inverter systems and retrofit existing PV systems with smart grid inverters
- Complete baseline data gathering and analytics
- Develop and test inverter algorithms
- Assess inverter field performance and fine tune the model and algorithms

This project has delivered many useful learnings in terms of managing DER devices in the field using a moderate bandwidth, moderate cost Field Area Network. These learnings are guides as SSN considers its plans for making production products to assist in scaling DER penetration.

One issue has been that the Home Area Network interface has been more challenging than expected. SSN's planned products will be "Direct to Grid"(trademark), meaning directly on the Field Area network, not on the Home Area Network. SSN's intent is to focus on delivering CEA-2045 modules that can be plugged directly into inverters or other DER devices, implementing SunSpec to the device, but with commonly defined form factors, mounting, power supplies, antenna locations and other items that were custom developed for this product. SSN will solicit many inverter vendors to support this ANSI standard to minimize the time required for individual product integration. SSN will utilize SunSPEC and the USNAP alliance to assure conformance and interoperability, rather than bilaterally working directly with the specific inverter manufacturer on a product by product basis. This is necessary to scale production level deployment across a range of products from different suppliers.

SSN is considering integration of the CEA-2045 modules into a variety of devices beyond solar inverters, especially small scale or community scale storage. Any remote device which can contribute to feeder voltage or power factor stability is a candidate for such a device.

This project was very useful in developing standards – it was the first implementation of the SunSPEC Controls specification and several minor issues in the specification were discovered and resolved though the feedback the project team provided.

References:

M. Braun, T. Stetz, T. Reimann, B. Valov, G. Arnold, "OPTIMAL REACTIVE POWER SUPPLY IN DISTRIBUTION NETWORKS - TECHNOLOGICAL AND ECONOMIC ASSESSMENT FOR PV-SYSTEMS –," in Topic: PV Systems, Subtopic: PV Power Plants, 24th European Photovoltaic Solar Energy Conference, Hamburg, Germany, 21-25 September 2009, pp. 3872 – 3881,ISBN: 3-936338-25-6.

Sigifredo Gonzalez, Frank Hoffmann, Michael Mills-Price, Mark Ralph, Abraham Ellis, "IMPLEMENTATION OF ADVANCED INVERTER INTEROPERABILITY AND FUNCTIONALITY," in Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE, Austin, Texas, 3-8 June 2012, pp. 001362 - 001367, ISBN: 0160-8371.