California Solar Initiative

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

GO solar CALIFORNIA

Final Project Report:

Standard Communication Interface and Certification Test Program for Smart Inverters

Grantee:

Electric Power Research Institute (EPRI)

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http://www.calsolarresearch.ca.gov/Funded-Projects/

Preface

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

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

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

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

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

Abstract

This document is the final report of a two-year development and demonstration program under the California Solar Initiative (CSI) RD&D Solicitation #4, entitled “Standard Communication Interface and Certification Test Program for Smart Inverters”. The project was carried out between June 2014 and June 2016 by a diverse project team including key stakeholders in the area of grid-supportive smart solar inverters. The motivation for the project, and its functional scope, were driven by the revision of California Rule 21 which was ongoing during the project. Rule 21 establishes the requirements for distributed energy resource (DER) interconnection in California.

On a broader stage, the Institute of Electrical and Electronic Engineers (IEEE) was actively revising the P1547 standard which has served as the basis for grid codes throughout North America. This revision is similar to those in California and in this sense this project relates-to and accelerates industry activities beyond California.

The central focus of the project was communication interoperability based on open standards. Specifically, the project sought to assess the potential for solar inverter manufacturers to mass-produce and certify products that could work in any communication system by way of a standard modular communication interface. Likewise, the project sought to assess the potential for communication system providers to develop standard modems/modules that connect seamlessly to any solar inverter without customization or modification.

The value of achieving such interoperability cannot be overstated. Studies by EPRI and others have shown that smart inverter functions can double the amount of solar PV that can be hosted on a typical distribution system. Further studies have shown that it is difficult to identify particular settings that can be used universally and have positive benefit at all times and all locations. In fact, smart functions can work against the grid, making conditions worse in many cases. To achieve maximum potential to deploy distributed energy resources (DER), communication systems will be needed. And in order for such communication system to be feasible, standard communication interfaces will be needed. This is the specific issue that this project aimed to address.

To enable the interoperability assessments, members of the project team independently developed two types/brands of residential smart inverters and two types/brands of communication systems. This resulted in four combinations (2x2) that could be tested.

Testing was first performed in a certification and compliance environment, involving just the smart inverters. This was followed by end-to-end integration testing of the communication systems and inverters in laboratory environments and then finally with field testing of the same equipment so that exposure to real world conditions is gained.

This project resulted in a number of detailed reports that preceded this final report. These are available on the CSI website at: http://www.calsolarresearch.ca.gov/funded-projects/107-sol-4-standard-communication-interface. This report summarizes those detailed accounts to provide a more concise summary of the work performed and conclusions of the project.

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1 INTRODUCTION

This project created next-generation solar inverters, tested their functionality, assessed interoperability, and developed a certification and compliance framework. The value of this activity is based on the proposition that the grid can accommodate more distributed renewable energy if the devices can be successfully connected in communication networks. The approach taken applied open standards, recognizing that to practically achieve connectivity in an environment of diverse brands and types of equipment, standard communication interfaces will be required.

The primary steps involved in the project are identified in flowchart of Figure 1-1, and described throughout this report. The project was carried out concurrently with the California Rule 21 revision process and development of the UL 1741 SA and sought to support and accelerate those developments. California Rule 21 establishes the requirements for distributed energy resource (DER) interconnection in California and UL1741 is a compliance test specification for DER that is used for certification.

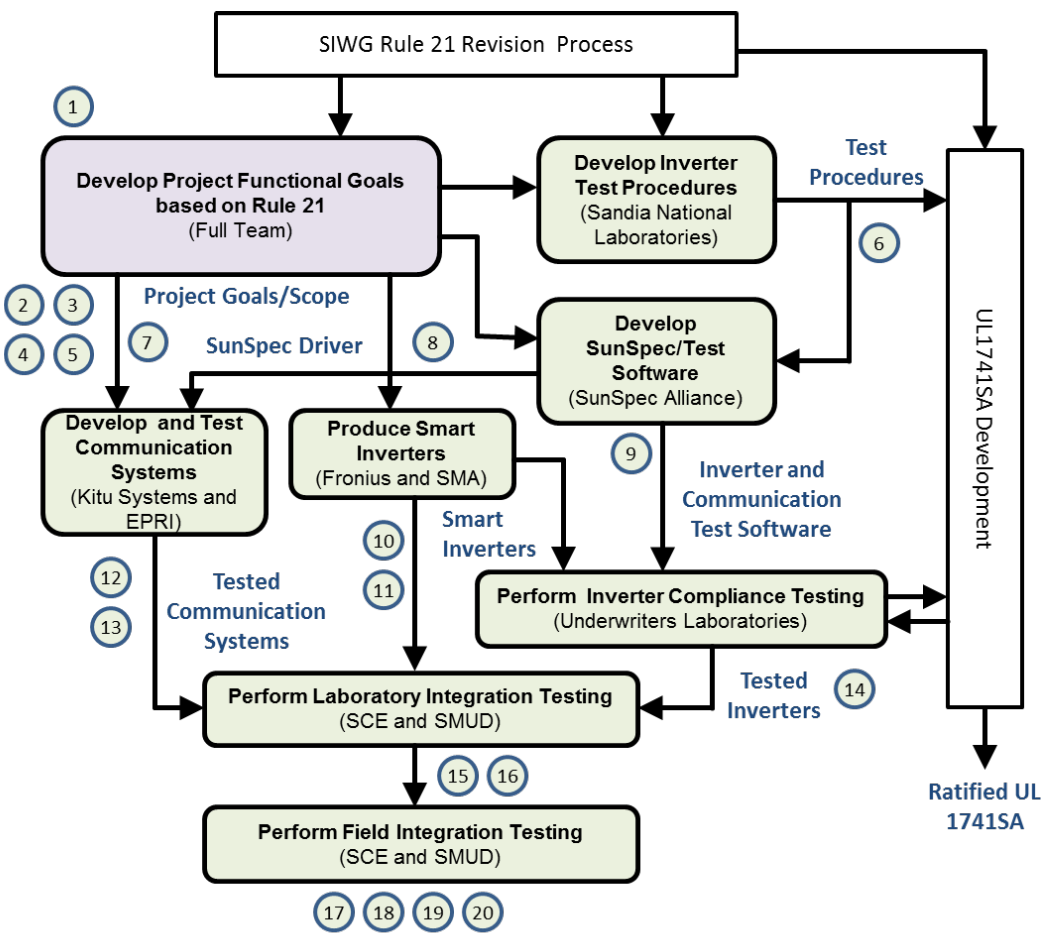


Figure 1-1, Overall Project Process and Deliverables

The numbered circles in Figure 1-1 indicate resulting materials and artifacts of the project, as listed in Table 1-1.

Table 1-1, Project Deliverables

Deliverable Number	Title	Description
1	Standard Communication Interface and Certification Test Program for Smart Inverters	One-page summary
2	Applying SunSpec Modbus to Meet California Rule 21 Requirements	Technical/Protocol Document
3	OpenADR Mapping for Grid Control Enabled Inverters	Technical/Protocol Document
4	SEP 2.0 Mapping for Grid Control Enabled Inverters	Technical/Protocol Document
5	Suggested Additions to the CTA-2045 Standard	Technical/Protocol Document
6	Provisional Electric Rule 21 Test Protocols for Advanced Inverter Functions	Test procedure for inverter functional evaluation
7	Cyber Security Requirements and Recommendations	Recommendations/Guide for future systems
8	Open Source SunSpec Driver Code	Software
9	SunSpec Test Software	Software
10	Fronius Advanced Inverter	Product – Hardware and Firmware
11	SMA Advanced Inverter	Product – Hardware and Firmware
12	Kitu Systems IEEE 2030.5 Communication System and Modules	Product – Hardware and Firmware
13	EPRI OpenADR Communication System and Modules	Product – Hardware and Firmware
14	Compliance Test Report for Two Inverters	Compliance Test Results
15	Laboratory Integration Test Plan	Test Plan
16	Laboratory Test Results	Test Results
17	Filed Test Plan	Test Plan
18	Field Test Results	Test Results
19	Final Report	This Document
20	Final Webcast Slides	PowerPoint Slides

1.1 Assessing Interoperability

The primary purpose this project was to assess the ability for residential solar inverters to be designed with an open standard communication interface enabling them to connect and work in any communication system. Such capability is needed in order to maximize the amount of renewable energy that can be connected to the grid. The wide range of types, brands, and scales of solar photovoltaic systems make it impractical to create cohesive grid-supporting systems without a common communication interface to the devices.

The approach used for this project utilized the SunSpec Modbus protocol and the Consumer Electronics Association's CTA-2045 modular port interface. This approach was interesting, particularly for small-scale residential inverters, for four primary reasons:

1. It has the potential to reduce product cost upfront, avoiding the integration of communication technologies that might not be needed into an increasingly cost-sensitive class of product.
2. It could enable mass production and communication diversity – allowing a single inverter design to be mass produced and widely distributed because it is compatible with all kinds of communication systems.
3. It could avoid communication obsolescence, enabling communication systems to evolve over the long service life of the inverter through easily replaceable modem/modules.
4. It could enable certification and compliance testing to be streamlined and better automated by making a common test harness possible.

In order to perform the assessment, the project developed a two-by-two test environment as illustrated in Figure 1-2. Two residential inverter companies, project partners Fronius and SMA, independently developed inverters with grid-supportive functionality and the SunSpec-based port interface. Two communication systems were also developed, one by Kitu Systems based on the IEEE 2030.5 protocol and one by EPRI based on the OpenADR 2.0b protocol. Both systems included head-end software and local modem/modules that could be plugged into the inverters. In both cases, the local connection to the inverter was the same, based on the SunSpec protocol, with the modem/modules providing translation to/from their native system protocols and cyber security as needed.

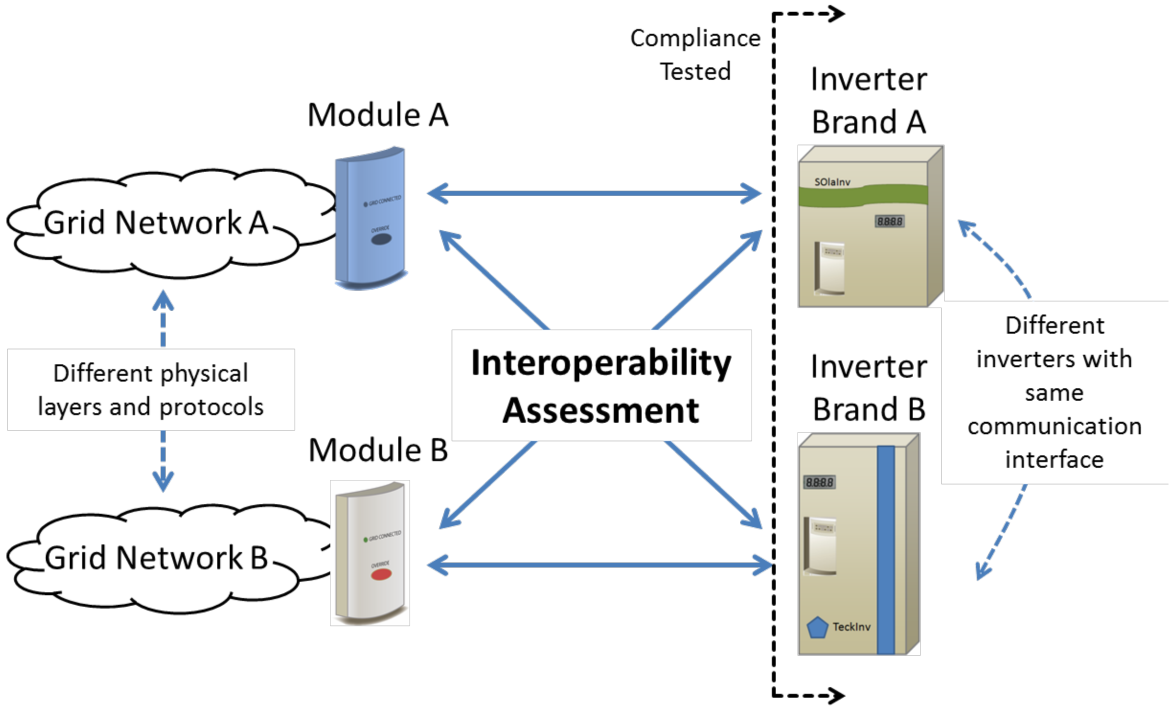


Figure 1-2, Interoperability Assessment in a Two-by-Two Fashion

1.2 Certification and Compliance Framework for Smart Inverters

The project also focused on developing a ready certification and compliance test framework that includes the functional and communication aspects of smart inverters. Regardless of how well they are written, paper standards alone are not sufficient to achieve product interoperability because even small differences in implementation can result in failure of information and communication systems to work together.

The end-goal of establishing a comprehensive certification framework is to ensure that devices that are fielded today can be practically and economically integrated into smart-home, aggregator, and advanced distribution management systems in the future. Inverters and solar installations are long-life systems and as levels continue to rise, the need to intelligently connect will be heightened.

To address this goal, project partner Sandia National Laboratories developed a comprehensive test procedure for smart inverters. These procedures sought to balance the completeness of testing with the time and cost of test execution. Many smart inverter functions are continuously adjustable, so the question of how many levels/values to configure and test is difficult. For example, if a smart inverter supports volt-var control using a curve configuration, how many curves, of how many points, and of what curve shapes must be tested to become confident that the product works properly? In addition, many smart inverter functions can be simultaneously active, resulting in an essentially infinite number of combinations of inverter settings.

The test procedure developed by Sandia National Laboratories, entitled “Provisional Electric Rule 21 Test Protocols for Advanced Inverter Functions” has been published[1] and is publicly available. This procedure was provided to project partner Underwriters Laboratories and used to accelerate the development of the UL1741 SA – a certification procedure aligned with the California Rule 21 revisions.

It is important to note that the official UL1741 SA certification process does not require a particular or standard communication protocol because the approved Phase 1 CA Rule 21 revisions did not require communications. In this regard, the compliance testing performed in this project is different than the UL1741 SA. The functional scopes are aligned, but the certification framework in this project also required strict adherence to the SunSpec/CTA-2045 communication interface specifications. If a function existed in an inverter, but could not be accessed (monitored and managed) via the standard communication protocol, then it was considered to be non-compliant because it would not be accessible/useable in the field.

As indicated by the dashed lines in Figure 1-2, UL testing was performed using the local ports at the inverters. The SunSpec Alliance developed and provided to UL a test software and protocol to support this testing.

[1] http://www.calsolarresearch.ca.gov/funded-projects/107-sol-4-standard-communication-interface

2 PROJECT CONTEXT AND FUNCTIONAL SCOPE

This project was carried out during a time of high industry activity in the area of smart inverter integration. The annotated timeline in Figure 2-1 identifies key activities to which this project related.

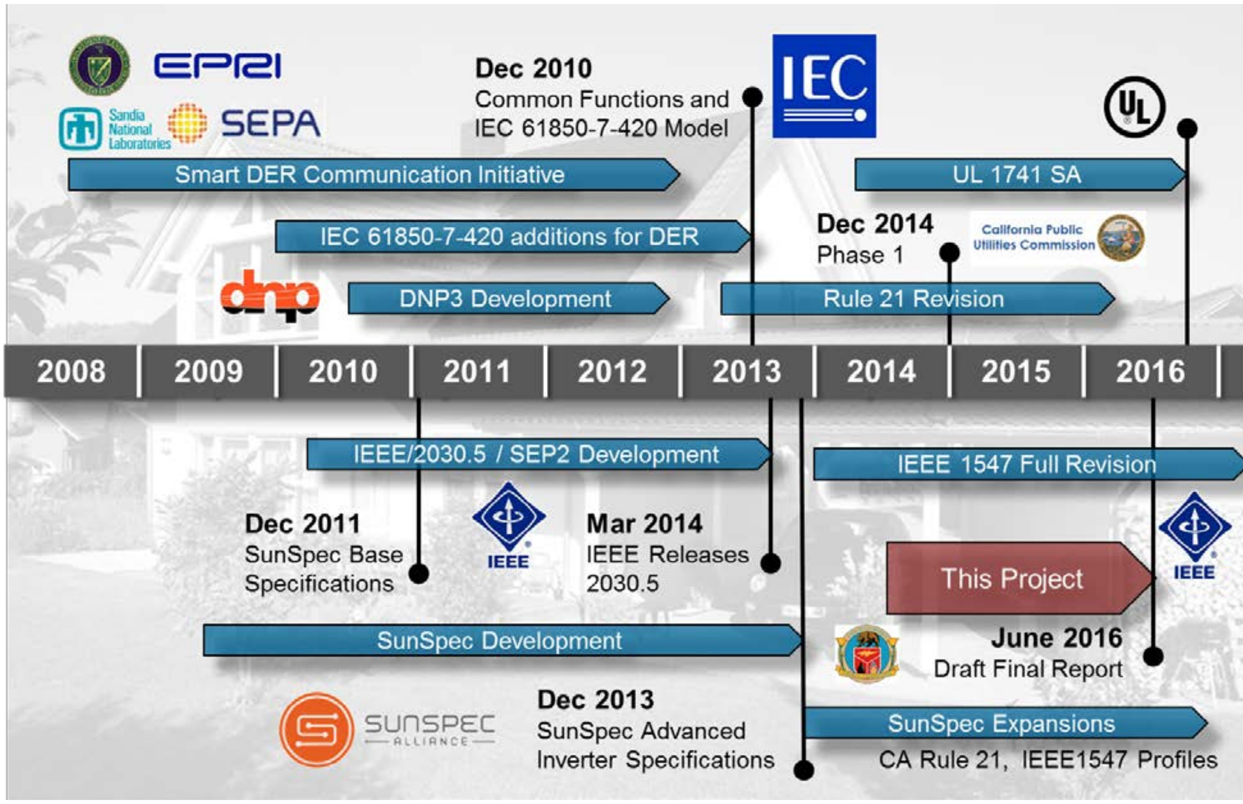


Figure 2-1, This Project in the Context of Related Industry Activities

Global efforts to define common smart inverter functions began in 2008 and resulted in the IEC 61850-7-420 and IEC 61850-7-520 standards. These provide text descriptions of common grid-supportive functions and a reference information model that can be mapped into other communication protocols. EPRI also published a description of these common functions that is publicly available[2]. These common grid-supportive functions have been mapped SunSpec Modbus, IEEE 2030.5 and OpenADR 2.0b as used in this project.

Grid codes are being developed that require DER to have certain grid-supportive functionality in order to be deployed and grid-tied. In the state of California, the grid-codes are based on Rule 21, which has been undergoing revision as indicated in Figure 2-1. This revision process was supported by an open focus group called the Smart Inverter Working Group (SIWG) led by project partner Xanthus Consulting. The SIWG's work was performed in phases, the first of which was approved by the state of California during this project.

[2] Common Functions for Smart Inverters, Version 3. EPRI, Palo Alto, CA: 2013. 3002002233

A primary focus of the SIWG was selecting the functionalities that DER must support in order to be deployed in California. This selection was done through a stakeholder engagement process and built upon the IEC 61850-7-420 common functions. As a result of the SIWG process, a set of requests was submitted to the International Electrotechnical Commission (IEC) to improve the IEC 61850-7-420 and IEC 61850-7-520 specifications. This request was accepted and, as a result, revision of these specifications is presently underway.

2.1 Functional Scope

The present project aimed to use the California Rule 21 revisions to establish the functional scope. Although the SIWG process remained in process during the project, the team did what was possible to track the work in process and to adhere as closely as possible to the latest definition. This included awareness of the advanced functionalities considered during Phase 3.

Table 2-1 provides a summary of the functional scope for the project. The left-hand column identifies the most significant functions and features of smart inverters relative to the CA Rule 21 process as of the beginning of the project. The headings in the top row identify the key steps of the project, and the marks in the matrix indicate whether or not each function was covered in that step:

- To be Included in Sandia Test Procedures
- To be Included in the Communication Interface Specification Document
- To be Supported by the SunSpec Modbus Reference Code
- To be Supported by SMA Sunny Boy
- To be Supported by Fronius IG Plus
- To be Tested in the UL Test System
- To be Operational, but in a fixed fashion, During Utility Testing
- To be Managed/Exercised by the Utility Communication Systems

This matrix was developed early in the project, a reflection of the team's estimates of what would be possible. The scope was then constrained as the project progressed as standards developments evolved and manufacturer limitations were identified in R&D.

Table 2-1, Functional Scope Matrix

Function or Communication Verification	Definition of this Function within the context of this project.	To be Included in Sandia Test Procedures	To be Included in the Comm Interface Specification Document	To be Supported by the SunSpec Modbus Reference Code	To be Supported by SMA Sunny Boy	To be Supported by Fronius IG Plus	To be Tested in the UL Test System	SMUD: To be Active in the Inverter During SMUD Field Testing (fixed)	SMUD: To be Exercised by the SMUD Communication Systems (lab and field	SCE: To be Active in the Inverter During SCE Field Testing (fixed)	SCE: To be Exercised by the SCE Communication Systems (lab and field
Anti-Islanding Protection	Non-configurable. A built-in function of the inverter.	✓	N/A	N/A	✓	✓	✓	✓	N/A	✓	N/A
Low/High Voltage Ride-Through	Non-configurable. A built-in function of the inverter. Set to the levels identified in the CA Rule 21 recommndations. Able to pass the test as described in the Sandia test procedure.	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗
Low/High Frequency Ride-Through	Non-configurable. A built-in function of the inverter. Set to the levels identified in the CA Rule 21 recommndations. Able to pass the test as described in the Sandia test procedure.	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
Volt-Var Function with Watt-Priority	Implemented as a variably-adjustable function. Able to accept and act on an array of X-Y points sent per the Sunspec standard. Able to handle curves with up to 6 points. It is acceptable for this project to NOT support hysteresis curves. The "Time Window" and "Ramp Time" variables that are part of these functions must be supported.	✓	✓	✓	✓	✓	✓	N/A	✓	N/A	✓
Ramp Rates and Soft Start	This refers to the ramp limit that is called out in CA Rule 21 and separate from those associated with control actions (see description of the volt-var function for example). Specifically, this refers to a ramp-time limit in response to rising PV output (positive limit)	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗
Power Factor Function	To be continuously adjustable from unity to .9[PF]	✓	✓	✓	✓	✓	✓	N/A	✓	N/A	✓
Monitor DER Status		✓	✓	✓	✓	✓	✓	N/A	✓	N/A	✓
Limit Maximum Real Power Function	To be continuously adjustable from full power (100%) to the shutdowwn level (e.g. 10%) of the inverter.	✓	✓	✓	✓	✓	✓	N/A	✓	N/A	✓
Connect/Disconnect Function	A simple boolean function. Cease to energize at the ECP.	✗	✓	✓	✓	✓	✓	N/A	Lab	N/A	Lab
Frequency-Watt Function	Same expectations as for Volt-Var function.	✗	✓	✓	✓	✗	✓	TBD	TBD	TBD	TBD
Voltage-Watt Function	Same expectations as for Volt-Var function.	✗	✓	✓	✓	✓	✓	N/A	TBD	N/A	✗
Dynamic Reactive Current Support		✗	✗	✗	✗	✗	✗	N/A	✗	N/A	✗

2.2 Cyber Security Guidelines and Recommendations

The scoping and planning part of this project included a cyber-security assessment and development of guidelines. The detailed results of this assessment were published separately and are summarized here.

The cyber security assessment focused on residential inverter-based DER that used a modular approach to communication connectivity such as the SunSpec/CTA-2045 example used in this project. The project recognized that communication interfaces are often modular in practice in order to provide flexibility (one DER design compatible with many system types). With this in mind, products are designed with various communication options that may be selected by the buyer and replaced if desired. The improvement in this project is that the modular interface was standardized so that common communication modules could be used across multiple brands of DER.

Whether standardized or not, a modular approach results in two interfaces as illustrated in Figure 2-2. Each of these must be considered from a cyber-security perspective. As depicted in the figure, the assessment includes DER communication interfaces "A" and "B", where interface "A" represents:

- Network connections between a utility and a communication modem/module
- Network connections between an aggregator/vendor and a communication modem/module

Figure 2-2, Cyber Security Areas of Assessment

And interface "B" represents the local interface between a communication modem/module and the remainder of the DER system.

Cyber security requirements for DER systems can be categorized according to importance:

- Authentication and integrity of data are the most important cyber security requirements, and were assessed to be critical for all types of interactions, including monitoring and control commands, to ensure that the data exchanged comes from known sources and has not been modified in transit.
- Authorization and non-repudiation are important to ensure that commands are authorized, executed as specified, and reported back accurately.
- Availability is less critical since DER systems usually operate autonomously and can be preset to perform the DER functions.
- Confidentiality is only important for select DER functions where either privacy or sensitive data is being exchanged, such as personal information or contractual data. For

residential DER systems, it is not expected that much confidential data will be exchanged.

2.2.1 Resilience

In the energy sector, two phrases are key in international and national policies: “grid resilience” and “cyber security of the cyber-physical grid”. Grid resilience responds to the overarching concern: *"The critical infrastructure, the Smart Electric Grid, must be resilient - to be protected against both physical and cyber problems when possible, but also to cope with and recover from the inevitable disruptive event, no matter what the cause of that problem is - cyber, physical, malicious, or inadvertent."*

Resilience relies on a combination of cyber security techniques to protect cyber assets, and the engineering design and operational strategies that keep the physical and electrical assets safe and functioning correctly.

All too often, cyber security experts concentrate only on traditional “IT cyber security” for protecting the cyber assets, without focusing on the overall resilience of the physical systems. At the same time, power system experts concentrate only on traditional “power system security” based on the engineering design and operational strategies that keep the physical and electrical assets safe and functioning correctly, without focusing on the security of the cyber assets. However, the two must be combined: resilience of the overall cyber-physical system must include tightly entwined cyber security technologies and physical asset engineering and operations, combined with risk management to ensure appropriate levels of mitigation strategies.

2.2.2 Interface A: Network Cyber Security Recommendations

Communication interface “A”, as depicted in Figure 2-2 is the outward, wide area network-facing interface of the communications modem/module. It is this interface that extends away from the DER site to utility, aggregator, and vendor system based on some routable control protocol, such as IEEE 2030.5 (SEP2), IEEE 1815 (DNP3), OpenADR 2.0b, etc.

The key recommendations/findings are:

- The IEEE 2030.5 and OpenADR 2.0b protocols used in this project, or others that may be considered for DER integration, must support authentication, and data integrity
- Authentication: Certificates, Passwords, PKI, TLS, security methods are included in the protocol standards (cyber security)
- Authorization: Role-Based Access Control (RBAC), Access Control Lists (ACL) (engineering design and operational strategies)
- Data Integrity: Protocol security for ensuring data integrity in transit (cyber security), application data validation for reasonability (engineering), time synchronization (engineering), logging (engineering)

- Confidentiality: Encryption of data if needed (cyber security)
- Key management for thousands of devices is a challenge (cyber security)

2.2.3 Interface B: Local Port Cyber Security Recommendations

Communication interface "B", as depicted in Figure 2-2, is the local, DER-facing interface of the communications module. It is internal - a wired interface that is only accessible when physically present at the DER. For typical residential DER systems (i.e. less than 10 kW capacity), the power impact to the grid from a single device is small (i.e. unlikely to impact the operation of the local distribution circuit). Physical security of the local port is the key security measure to be implemented for interface "B". The Modbus protocol utilized in this project does not have integrated security features.

The key recommendations/findings are:

- Physical security is the primary method for securing the local link between the DER and a communication modem/module
- Use of tamper-resistant bolts to secure the communication module is recommended
- Communication modules should perform integrity checks on Modbus messages for unauthorized types or values
- Communication modems/modules must be designed so that access on the local port does not provide access to other devices on the outside network – in other words, the exposure is limited to the local DER
- SunSpec has published a best practice document describing methods for mitigating security threats such as those listed above.

2.2.4 Cyber Security Recommendations Summary

Cyber security is becoming increasingly important and should be part of system designs from the initial stages, including in the CSI4 project. Without built-in security, DER systems, even at small residential installations, could have major impacts on the grid. Initially these impacts might just be to the residential DER owner, but in aggregate could impact the operation of the grid as increasing numbers of these small DER systems become interconnected. Therefore, implementation of the CSI4 communication module for residential inverter-based DER communications should comprise inclusion of industry standard best practices and the cyber security recommendations in this document as an integral part of design and development.

3 DEVELOPMENT OF COMPLIANCE TEST PROCEDURES

As part of this project, Sandia National Laboratories (Sandia), EPRI, Xanthus Consulting, Underwriters Laboratories, SunSpec Alliance, Loggerware, utilities, and PV inverter manufacturers drafted a certification protocol for advanced inverter and interoperability functions proposed by the Rule 21 SIWG. This effort was completed in collaboration with the UL 1741[3] Standards Technical Panel (STP) because they were concurrently drafting the UL 1741 Supplement A certification protocol to test advanced DER functionality. In fact, this project accelerated the development of many of the UL 1741 SA test procedures by drafting, refining, and compiling the test procedures in a single document.

The final report[4] consists of test protocols to evaluate the electrical performance and interoperability of DER inverters defined in the CA Rule 21 SIWG Phase 1 proposal and select functions from Phase 2 and Phase 3. Many of these functions are similar to those defined by the International Electrotechnical Commission (IEC) Technical Report (TR) 61850-90-7, so previous work[5-6] in designing testing protocols for those functions was heavily leveraged.

3.1 Advanced Inverter Functions Included in Protocols

The final report was structured with separate appendices for each of the Rule 21 advanced inverter functions. The functions included in this document are displayed in Table 3-1, however the Rule 21 Phase 2 and Phase 3 functions are not defined fully by the SIWG or the IOUs at the time of this project, so those certification protocols must be updated based on future SIWG discussions surrounding these functions. Abbreviations for the protocols are labeled R21-x-y, where x is the phase and y is the function designator; for instance, R21-1-AI is Anti-islanding Protection in Rule 21 Phase 1. The function designator is matched to IEC TR 61850-90-7 nomenclature when there is a synonymous function, e.g., L/HVRT, INV3, VV11, and DS93.

[3] Underwriters Laboratories 1741 Ed. 2, "Inverters, Converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources," 2010.

[4] J. Johnson, S. Gonzalez, T. Zgonena, M. McGirr, J. Hopkins, B. Seal, F. Cleveland, T. Tansy, and B. Fox, “Draft Electric Rule 21 Test Protocols for Advanced Inverter Functions,” California Solar Initiative report for California Public Utilities Commission (CPUC), Dec. 2014.

[5] J. Johnson S. Gonzalez, M.E. Ralph, A. Ellis, and R. Broderick, “Test Protocols for Advanced Inverter Interoperability Functions – Main Document,” Sandia Technical Report SAND2013- 9880, Nov 2013.

[6] J. Johnson S. Gonzalez, M.E. Ralph, A. Ellis, and R. Broderick, “Test Protocols for Advanced Inverter Interoperability Functions–Appendices,” Sandia Technical Report SAND2013-9875, Nov 2013.

Table 3-1: Phase 1 and Select Phase 2 and 3 Advanced DER Functions in the Test Protocols.

Appendix	Function or Communication Verification	Protocol Abbreviation
1	Anti-Islanding Protection (AI)	R21-1-AI
2	Low/High Voltage Ride-through (L/HVRT) and Low/High Frequency Ride-through (L/HFRT)	R21-1-L/HVRT R21-1-L/HFRT
3	Normal Ramp Rate and Soft-Start Ramp Rate	R21-1-RR R21-1-SS
4	Fixed Power Factor and Volt-VAR Functionwith Watt-Priority	R21-1-INV3 R21-1-VV11
5	Communication Interface	R21-2-CI
6	Data Model	R21-2-DATA
7	Monitor Alarms	R21-3-A
8	Monitor DER Status and Output	R21-3-DS93

3.2 Protocol Contents

Each of the appendices were broken into multiple sections. First, a general description of the function was provided along with the function's purpose (grid-support capability). This was followed by the technical specifications for certifying the DER, which included required information provided by the manufacturer, the test sequence, the test points or parameter sets, and the pass/fail criteria. For instance, the soft start ramp rate tested the equipment under test (EUT) with four different ramp rates (disabled, minimum ramp rate, average ramp rate, and maximum ramp rate), through a common test sequence. Mathematical rules for passing the test were provided in the pass/fail criteria section.

4 DEVELOPMENT OF OPEN PROTOCOL AND TEST SOFTWARE

The SunSpec Alliance provided three primary deliverables to this project:

A data communication interface definition for CA Rule 21 Phase 1

“C” driver software that is used to by module software to bridge the Field Bus protocol used by the inverters (Modbus) to the Wide Area Network protocols used by the utility network (IEEE 2030.5 and OpenADR).

Test Framework software, including test scripts and test lab automation technology, to accelerate testing of inverters complying with CA Rule 21 Phase 1

Each of these technologies was delivered on time, in open source form, and is available to the public at no charge in open source form. They comprise a major technological development that will immediately help to accelerate deployment of CA Rule 21 advanced inverters.

4.1 CA Rule 21 Phase 1 Communication Interface Definition

The first and most fundamental artifact delivered by the SunSpec Alliance is the “EPRI CSI4 Profile for CA Rule 21 Demonstration, a SunSpec Alliance Application Note.” This document is a CA Rule 21 Phase I Communication Interface Definition (CID), and includes a description of the SunSpec information models needed to enable remote manipulation of CA Rule 21 Phase 1 advanced inverter functions via the Modbus protocol. It is available for free downloading from SunSpec.org and from the California Solar Initiative web site.

Both Fronius and SMA implemented this CID during the CSI4 project. Substantial, though not complete, interoperability was demonstrated among equipment vendors in a number of ways.

- Both inverter brands respond consistently when probed by SunSpec Dashboard, a Microsoft Windows application used to interrogate products implementing the CID, and SunSpec System Validation Platform.
- Both inverter brands respond consistently when interacting with the SunSpec “C” driver, which is used in this project to translate requests from IEEE 2030.5 and OpenADR networks to the inverter protocol.
- Both inverter brands respond consistently when interacting with the independently-developed Kitu Systems IEEE 2030.5 gateway device.

The CID lays a solid foundation for the future expansion that will likely be required to support CA Rule 21 Phase 3 functionality. Partially as a result of the CSI4 effort, the CID is highly aligned with IEC 61850-7-420 and 7-520, IEEE 2030.5, IEEE 1815 (DNP3), UL 1741 SA, and with (future) IEEE 1547 communication definitions.

4.2 “C” Driver Software for Gateway Development

The SunSpec “C” driver is another important deliverable of the CSI4 project. The “C” driver is based on and CA Rule 21 Phase 1 requirements and is designed as an open source building block for creating gateway software functionality that can be deployed on CTA-2045 modules or other low cost, high volume industrial compute platforms.

As delivered, the “C” driver software is “pre-certified” to SunSpec standards and is known to be interoperable. The “C” language was chosen because it is broadly compatible with high-volume and embedded computing platforms.

The EPRI software development team successfully used the “C” driver to create gateway functionality to bridge IEEE 2030.5 and OpenADR protocols with the inverter protocol. IEEE 2030.5 is the “default CA Rule 21 Phase 2” protocol so validation with this system was essential. OpenADR is a likely choice for ancillary services enabled by CA Rule 21 Phase 2 so integration, once again, was serendipitous.

The “C” driver open source technology can be accessed and diffused at no cost via Github.com. SunSpec supports this repository as part of its ongoing commitment to building an open source ecosystem for Distributed Energy.

4.3 Test Framework Software

Expansion of the SunSpec System Validation Platform (SunSpec SVP) and supporting test framework is another important deliverable of this project.

Open source test scripts, based upon the functional test requirements developed by Sandia, are now available to support the full gamut of CA Rule 21 Phase 1 functionality plus other advanced inverter functions that will likely be considered for future CA Rule 21 phases.

The capabilities of SunSpec SVP delivered during the CSI4 program remove multiple barriers to CA Rule 21 adoption including: 1) providing an open source framework that manufacturers can use to validate products in the development lab, 2) providing a template for Nationally Recognized Testing Laboratories to develop their test framework capabilities, and 3) cutting down the time needed to test advanced inverter functions from days to minutes. This last benefit—automation—is perhaps the most important because it makes the test process highly efficient and because it enables nearly unlimited variation of test scenarios and non-stop, around-the-clock test sessions.

Open source SunSpec SVP test scripts are also available for free download and use from Github.com.

5 COMPLIANCE TESTING

5.1 UL1741 SA Evaluation Requirements

To provide a certification path for the new CPUC Rule 21 Test Protocols for Advanced Inverter Function requirements, Industry, Utilities, National Labs, EPRI and UL worked together to develop and publish US requirements to meet this need. The outcome of this group effort is a 60-page supplement to the UL Safety Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources, UL1741. This supplement A is designated as UL1741 SA which includes the test requirements, test methods and pass fail criteria needed to evaluate grid support/advanced utility interactive inverters for compliance with various source requirements documents (SRDs) including but not limited to CPUS Rule 21. A Grid Support Utility Interactive certification under the UL1741 SA standard (once published) will be necessary to address the certification needs defined by utility engineers under local grid codes as well as electrical inspectors for compliance with the NEC within the US.

The 1741 SA requirements are in addition to the other applicable requirements within the UL1741 standard. UL1741 SA defines the evaluation criteria for utility interactive inverters with grid support functions that are rated and specified as “Grid Support Utility Interactive Inverters”.

This new “Grid Support Utility Interactive” nomenclature is intended to differentiate these products from the traditional “utility interactive inverters” evaluated to the existing IEEE 1547 and IEEE 1547.1 (excluding the amendments). Those older utility interactive inverters have considerably less functionality built around basic voltage and frequency trip limits.

UL1741 SA is intended to be an interim solution to bridge the gap until IEEE 1547 and IEEE 1547.1 are revised to include the new grid support / advanced inverter requirements. The UL1741 SA was provided by UL to the IEEE 1547.1 committee as a seed document to speed the development of the IEEE 1547.1 standard.

The scope of UL1741 SA was intentionally limited to speed its development and address the needs of the first phase of the CPUC Rule 21, which only includes autonomous grid support / advanced inverter functionality. With this in mind the UL1741 SA does not include communications requirements related to grid support/advanced inverter functionality which are anticipated in the next phases of the Rule 21 requirements. As such, the critical communication element of this CSI4 project were incremental requirements, not addressed in the draft of UL1741 SA.

The testing performed by UL under this CSI4 project was focused on validation of the performance of the SMA model SB 5000TL-22-US and Fronius model IG Plus V 3.8-1 inverters with grid support utility interactive inverter functionality. The compliance criteria for this project was based on the performance of an interactive system of laboratory equipment and test samples which utilized communications via the SunSpec protocol over a CTA-2045 port to activate grid protection functions, adjust operating parameters, and measure grid support / advanced functionality performance of the samples being tested.

As of the publication of this report, the UL1741 SA draft is in its ballot period. The initial ballot results were positive and met the ANSI requirements for consensus although the draft received 224 ballot comments / proposed revisions. With an aggressive meeting schedule, the 1741 SA task group addressed and resolved the STP comments and it is anticipated that the ballot results will be positive which would allow for a publication date of September 8^{th} 2016. Publication of the UL1741 SA will start the new Rule 21 Grid Support / Advanced inverter compliance clock that will require new grid tied inverters to be compliant with and Listed to the UL1741 SA requirements.

5.2 UL Inverter Testing

5.2.1 Inverters

Under this project UL tested two different manufacturers' inverters with grid support / advanced functionality. Each inverter was tested as an assembly including a CTA-2045 communications interface.

Manufacturer	Model	Serial number	Firmware Version	
SMA	SB 5000TL-22-US	1913124411	02.63.33.S	
Fronius	IG Plus V 3.8-1	22240387	HW: 6.2.28 Communication: 2.1.21	

Figure 5-1, Inverters Tested by UL

Model	Pictures	
CEA 2045 AC to Ethernet (was used with SMA Inverter)		
CTA 2045 AC to RS-485 (was used with Fronius Inverter)		
CTA-2045 USB UCM AC Test Cable V1.0 (was used with Fronius and SMA Inverter)		

Figure 5-2, Inverter CTA-2045 Communication Interfaces

5.2.2 UL Test Equipment

The Inverters (EUTs) were connected to a grid simulator (programmable AC-power supply) and a photovoltaic simulator (DC power supply). The oscilloscope (high speed data acquisition system) was used for short duration measurements of AC-voltages and currents where we needed to evaluate cycle by cycle data. The power Analyzer was used for longer duration measurements of the AC voltages, currents, power-factor, active power, reactive power, apparent power and DC-voltages and currents. The inverter and CEA 2045 communications device were tested as an assembly which was connected to a computer to control and read-out parameters.

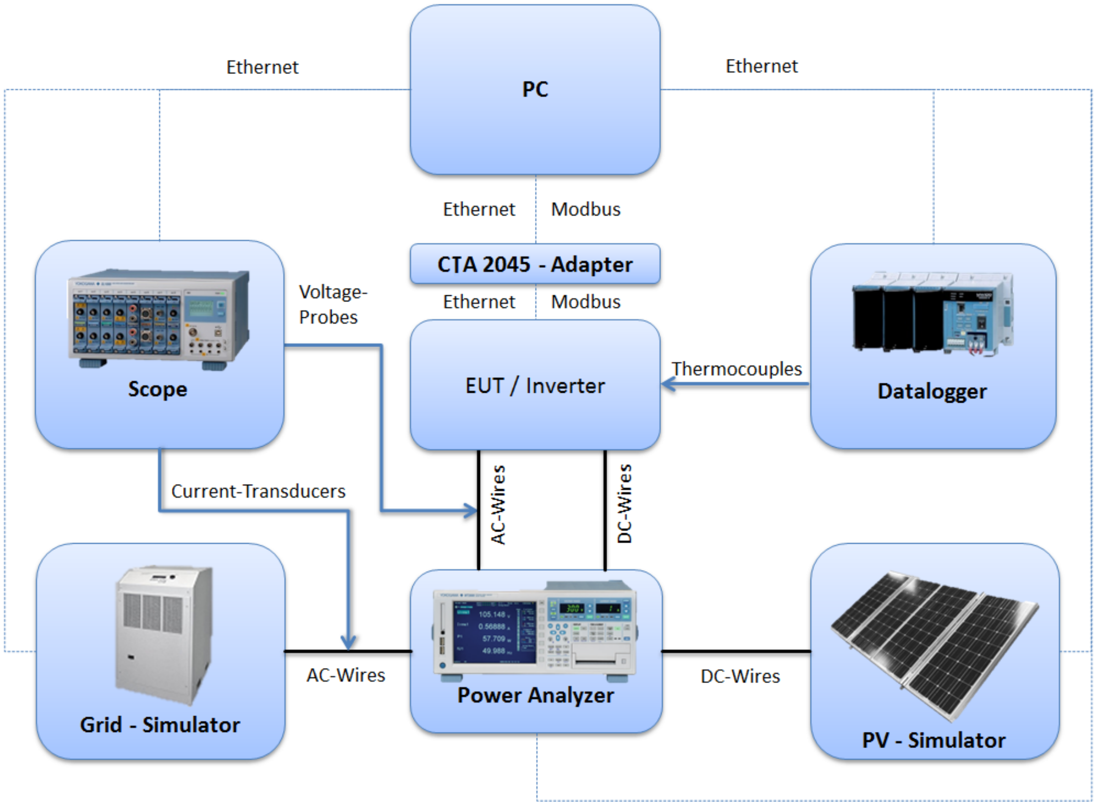


Figure 5-3, UL Test Configuration

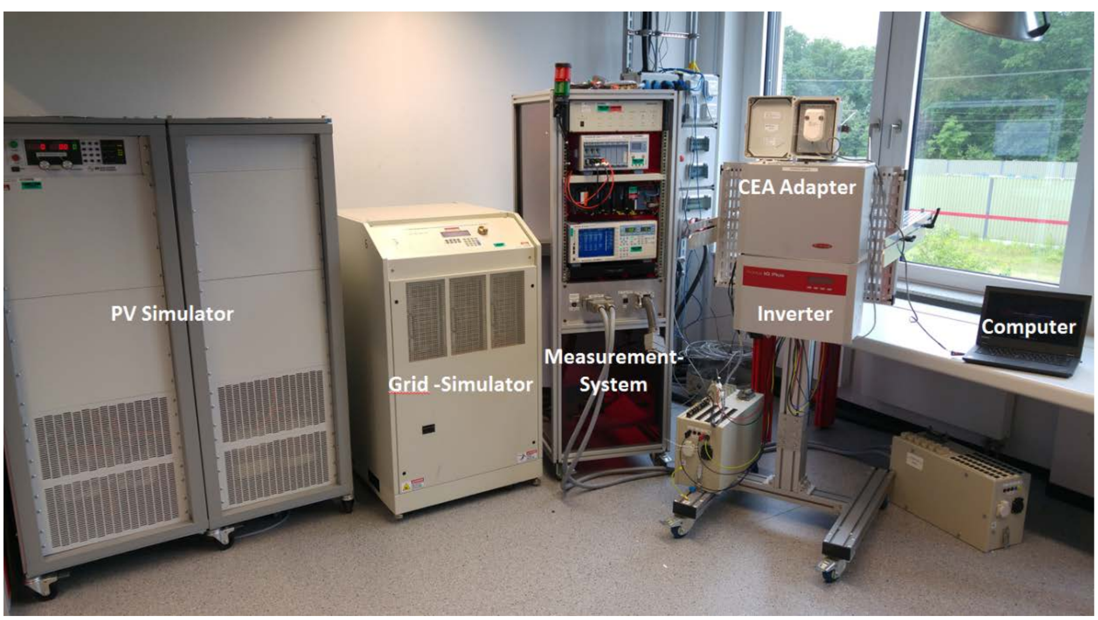


Figure 5-4, UL Inverter Test Lab

Table 5-1, UL Test Equipment List

Equipment	Manufacturer	Model
Grid simulator	Ametek / California Instruments	MX-45
PV Simulator	Magna Power	MT 100-1000
Scope	Yokogawa	SL1000
Power analyzer	Yokogawa	WT1800

5.2.3 Communications Software Interface

The communications with the inverters was performed through two SunSpec software interfaces. The SunSpec software was primary basis for communication with the EUT and compliance was judged based up on the ability of the EUT to receive and implement the commands via SunSpec software.

SunSpec SVP provides an environment that can manage and execute test scripts that utilize libraries that provide access to all the necessary components in the system. The SunSpec SVP Software was used to perform tests automatically where possible.

The SunSpec Dashboard is an application that enables interrogation and inspection of devices and documents using SunSpec technology.

UL Test Software An existing UL automated testing environment/system was also used to interact with the different devices and automate test-procedures.

5.2.4 Compliance Testing Results

At the time this project was performed, the two inverters that were tested did not include all of the advanced grid support functions that were evaluated under this project. Those functions that were not implemented were not able to be tested. During the project SMA provided new firmware that included increased functionality and aided in testing. The final test results reflect the available inverter functionality with the firmware version listed in the table above.

Table 5-2, Test Communication Capability via SunSpec Software and CTA-2045

Advanced Inverter Test	Functional Test Results Performed through SunSpec Software via the CEA 2045 Communications Interface	
	Fronius	SMA
UL 1741 SA9, L/HVRT	Not implemented in SunSpec model	Not implemented in SunSpec model
UL 1741 SA10, L/HFRT	Not implemented in SunSpec model	Not implemented in SunSpec model
UL 1741 SA11	Not implemented in SunSpec model	Yes

Advanced Inverter Test	Functional Test Results Performed through SunSpec Software via the CEA 2045 Communications Interface	
	Fronius	SMA
RR- Normal Ramp		
UL 1741 SA11, Soft Start Ramp	**Not implemented in SunSpec model**	**Yes**
UL 1741 SA12, INV3 Fixed Power Factor	**Yes**	**No, did not work with SunSpec software**
UL 1741 SA13, VV11 Volt/Var Mode	**Yes**	**Yes**
UL 1741 SA17, Optional: Frequency-Watt	**Not implemented in SunSpec model**	**Yes**
UL 1741 SA18, Optional: Volt-Watt	**Yes**	**Did not function with SunSpec Software**

Table 5-3, Inverter Test Results

Test	SMA	FRONIUS
UL 1741 SA9 L/HVRT	• The function worked with SMA software • Not implemented in SunSpec model, not required to do so	• The function worked with Fronius software • Not implemented in SunSpec model, not required to do so
UL 1741 SA10 L/HFRT	• The function worked with SMA software • Not implemented in SunSpec model, not required to do so	• The function worked with Fronius software • Not implemented in SunSpec model, not required to do so
UL 1741 SA11 RR- Normal Ramp	Fail: The function did not work with SunSpec protocol • SunSpec model includes the WGra parameter • Parameter WGra did not have an effect on the ramp-rate	Fail: The function did not work with SunSpec protocol • SunSpec model did not include the WGra parameter

Test	SMA	FRONIUS
UL 1741 SA11 **Soft Start Ramp**	Fail: The function did not work with SunSpec protocol • Function not included in SunSpec software or SMA firmware.	Fail: The function did not work with SunSpec protocol • Not included in SunSpec software. • Parameter "GPIS" startup-speed was in the mfr menu and worked.
UL 1741 SA12 **INV3 Fixed Power Factor**	Fail: The function did not work with SunSpec protocol • The function works when using the SMA tools	Pass: Function works with SunSpec protocol
UL 1741 SA13 **VV11 Volt/Var Mode**	Pass: Function works with SunSpec protocol	Pass: Function works with SunSpec protocol
UL 1741 SA17 **Optional: Frequency-Watt**	Pass: Function works with SunSpec protocol	Fail: The function did not work with SunSpec protocol • Function "GFPR" Grid frequency-dependent power reduction is present in display-settings and worked.
UL 1741 SA18 **Optional:** **Volt-Watt**	Fail: Characteristic is not programmable with the SunSpec protocol • Characteristic can be set with SMA tools and was measured	Pass: Function works with SunSpec protocol • Characteristic was measured
Inverter - monitor critical components for over temp.	• No observed over temperature or risk of fire hazard during testing.	• No observed over temperature or risk of fire hazard during testing.
Monitor DER Status	• Pass: Function works with SunSpec protocol	• Pass: Function works with SunSpec protocol

Test	SMA	FRONIUS
Connect Disconnect	Fail: The function did not work with SunSpec protocol	• Pass: Function works with SunSpec protocol
Limit Maximum Real Power Function	• Pass: Function works with SunSpec protocol	• Pass: Function works with SunSpec protocol
Anti-Islanding Protection	• Unknown - Due to an unrelated inverter sample failure this test could not be performed.	• Inverter complied with all Advanced functions enabled • Inverter complied with VRT, FRT and SPF enabled

5.2.5 Conclusions from UL Compliance Testing

1. The advanced inverter functionality is being introduced in the US and this significant change is taking time to implement. While many of the CA Rule 21 / UL1741 SA functions were implemented in the tested inverters and supported via the SunSpec protocol, not all were available at UL test time. UL notes that the remaining functions are under development for implementation in the near future.
2. Having a communications and control interface like the SunSpec (over CTA-2045) provides a common platform to support this testing and prevents the test lab from having to learn and use multiple unique communication and control interfaces provided by the individual inverter manufacturers.
3. Implementation of the communications interface is still in progress, but what is available now greatly enhances testing automation and data collection for inverters that use the SunSpec communication protocol. Reduction in test time speeds time to market and reduces cost.
4. This project benefited greatly from automated test software and further development of this automation software is necessary to match the upcoming functionality as defined in the UL1741SA document slated for publication in early September 2016.
5. As compared to the previous UL1741, IEEE 1547 and IEEE 1547.1 testing, this new advanced grid support testing is orders of magnitude more complex which results in significant increases in time and cost to implement. This new testing would appear to

be infeasible without the use of automation due to the increased complexity, number of tests and iterations per test.

6. During the testing of the advanced grid support inverter functions evaluated under this project, neither of the inverters demonstrated characteristics that would indicate that their safe operation was compromised.

6 SMART INVERTER DEVELOPMENT

Project partners Fronius and SMA developed the advanced inverters used in the evaluation. The project did not require the inverter manufacturers to commercialize products, and both ultimately chose to approach the development as prototype exercises. One reason for this was the lack of specific communication requirements in the approved California Rule 21 Phase 1 and ongoing process of the IEEE 1547 full revision during the timeframe of the project.

Both companies chose to use existing physical product designs, modifying firmware and adding an external communication interface (as shown in Figure 6-2 and Figure 6-3) in order to avoid making mechanical changes to the inverter housings during the project timeline. This simplified the compliance testing process. Going forward, communication modules could be directly plugged inside or onto inverters such as shown in the model shown in Figure 6-1 used in some of the project indoor/laboratory testing.

Figure 6-1, Example of Direct Communication Module Placement

6.1 Smart Inverter Vendor Approaches

As global market participants, Fronius and SMA approached this project as an opportunity to deepen their understanding of emerging U.S. market requirements and better engage with utility partners. Each executed a program that involved weekly or bi-weekly conference calls between company product/program managers, SunSpec Alliance personnel, and EPRI to determine project priorities; periodic calls between company engineers and engineers from SunSpec and Sandia to understand the detailed technical requirements implied by the Sandia test protocols; active participation at both business and technical levels within the Smart Inverter Working Group; and active firmware development within their respective R&D groups.

In general, the project progressed according to expectations and substantial CA Rule 21 functionality was achieved. Lack of a ratified UL 1741 SA standard remained a challenge throughout the project and ensured that CA Rule 21 requirements would remain ambiguous.

The hardware integration aspect of the project was exacting yet straightforward. The close correspondence between the RS-485 and CTA-2045 pin specifications is convenient and focused testing efforts in this domain. A module adaptor reference design was developed, refined, and published on the SunSpec.org web site for royalty-free use. Module adaptors were produced using this design and, with the exception of typical new product introduction issues, worked well in both the test lab and the field deployment.

Figure 6-2, Fronius IG Plus Advanced Inverter with Standard Communication Interface

Figure 6-3, SMA Sunny Boy Advanced Inverter with Standard Communication Interface

6.2 Smart Inverter Vendor Observations

To date, inverter communication protocols and hardware interfaces have tended to be vendor-specific. In contrast, this project introduces standard communication protocols and a standard hardware interface for the purpose of management and control. Given this context, and the mismatch of the status quo compared to the new requirements, the lessons learned by the vendors are similar.

A standard communication interface may have capabilities that are different from a vendor-specific interface, thus introducing integration hurdles. For example, data in a standard interface may be represented in different ways (e.g. Boolean, integer, floating point, or text string) or with different levels of precision from the vendor-specific interface. Similarly, the standard interface may be organized differently from the vendor-specific interface, thus requiring different design considerations or architectural approaches.

Features that may have been considered "value added" can become interoperability/implementation stumbling blocks. For example, a vendor-specific communication interface that auto-negotiates data transfer rate or implements individual security features may need to be modified in order to support a standard interface requiring specific settings.

The user experience of the inverter may change entirely. For example, while an inverter with a vendor-specific communication interface may require that the user access the front control panel to make settings changes, inverters with a standard communication interface may preclude user interaction with the front control panel entirely.

7 COMMUNICATION SYSTEM DEVELOPMENT

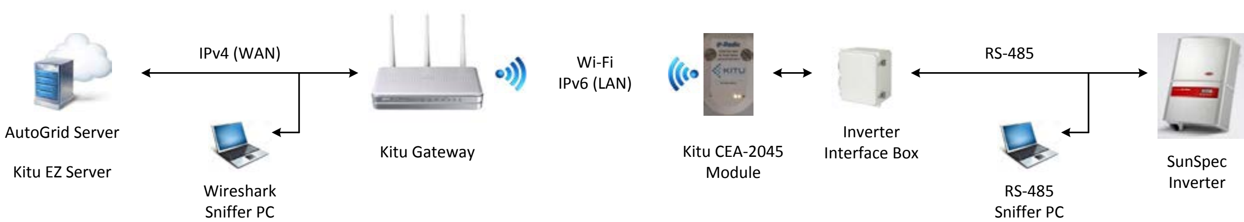
7.1 IEEE 2030.5 System

IEEE 2030.5 (formerly Smart Energy Protocol 2.0 or SEP 2.0) was chosen as one of the utility communications protocols as it includes native support for DER functions and is designated by the California Smart Inverter Profile (CSIP) Rule 21 activity as the default utility interface for smart inverter communications. For the IEEE 2030.5 portion of this project, Kitu Systems Inc. provided the 2030.5 Gateway and CTA-2045 modules for SCE and SMUD; Autogrid provided a cloud based 2030.5 DER Server for SCE; and Quality Logic provided their 2030.5 test harness for SMUD to use as a server. In addition, Kitu and Quality Logic (QL) supported Interoperability testing with the IEEE2030.5 Server and inverters.

This project used two test configurations depending on whether the IEEE 2030.5 Server was on the internet or on the local HAN.

7.1.1 Kitu/AutoGrid Test Configuration

The SCE test configuration completed by Kitu is shown in the figure below. The Kitu Gateway connects the 2030.5 server to the CTA-2045 module. A Wireshark Sniffer PC connected to the router WAN interface is used to sniff the Ethernet packets to/from the IEEE2030.5 Server. An RS-485 Sniffer PC is connected to the RS-485 interface of the inverter to sniff the Modbus commands and responses. All of the test cases were run without re-starting the IEEE2030.5 server or the CTA-2045 Module. Also shown is the Kitu EZ Server which is Kitu’s cloud based DER server and was used to support the testing.



7.1.2 QualityLogic Server Test Configuration

The QL server runs on a Windows PC. The test configuration for the QL server is shown in the figure below. A standard Wi-Fi Access Point is used to connect the QL server to the Kitu CTA-2045 module. The QL Server PC also runs Wireshark to sniff the Ethernet packets to/from the IEEE2030.5 Server. An RS-485 Sniffer PC is connected to the RS-485 interface of the inverter to sniff the Modbus commands and responses. Both the QL server and the CTA-2045 Module were restarted prior to each test because the QL server does not allow changing DER Control parameters without stopping and restarting the server.

7.1.3 Kitu Gateway

The Kitu Gateway is an enhanced Wi-Fi Router that mediates the communications between servers on the internet WAN and devices in the local HAN. In this position in the network, the Kitu Gateway can play many roles and functions (e.g. Site Aggregator, Energy Management System, Smart Bridging, etc.). In this project, the Kitu Gateway proxy's communications between the EZ-Server and the CTA-2045 module. Specifically, it contains an IEEE 2030.5 Client using IPv4 to communicate with the EZ-Server (or other internet servers) and an IEEE 2030.5 Server using IPv6 to communicate with the CTA-2045 module (or other HAN devices).

7.1.4 Kitu CTA-2045 Module

The Kitu CTA-2045 Module is an AC form factor Wi-Fi module that performs the following functions:

- Interfaces to the IEEE 2030.5 Gateway server using IPv6
- Performs all of the IEEE 2030.5 Client Functions
    - Secure all transactions using TLS as specified by IEEE 2030.5
    - Host and resource discovery using xmDNS
    - Time synchronization
    - Event management
    - Distributed Energy Resource Rule 21 functions
    - Status reporting
    - Metrology reporting
- Implements all of the relevant SunSpec Modbus models
- Detection and compensation for differences in behavior between the Fronius and SMA inverters

7.1.5 Autogrid 2030.5 DER Server

AutoGrid's Cloud-based 2030.5 server was used by SCE for the end-to-end lab and field testing

The server contains utility-defined DER programs, each of which has a default DER

Control setting. The server allows operators to create DER programs, define the default DER Control for a program, and assign DER devices to specific DER programs. These program assignments are managed through the 2030.5 Function Set Assignment. In addition to the default DER Control option, utility operators may store other user-saved DER Control options for each DER program, to use during DER Events. In each DER Event, utility operators may specify the DER Control base (i.e. saved DER Control setting, including DER Curves), Start time, End time, Start Randomization, End Randomization. In addition to the events, the server supports 2030.5 metering allowing the operator to collect data from the DER.

7.1.6 Quality Logic 2030.5 Test Harness

QualityLogic provides test tools for verifying client and server conformance to the IEEE 2030.5 standard. Their "*SEP20ClientTester*" program was used as the IEEE 2030.5 server in the configuration where both the IEEE 2030.5 server and client exist on the same HAN network. The QL tool allows the operator to create DER programs and DER Controls & Curves within those programs. The tool supports IEEE 2030.5 security and xmDNS discovery. The tool performs real-time protocol validation and logs all transactions in a Wireshark-like text format.

7.2 OpenADR 2.0b System

To support the overall project and interoperability evaluation, EPRI provided an end-to-end communication system based on the OpenADR 2.0b protocol. The system is illustrated in Figure 7-1.

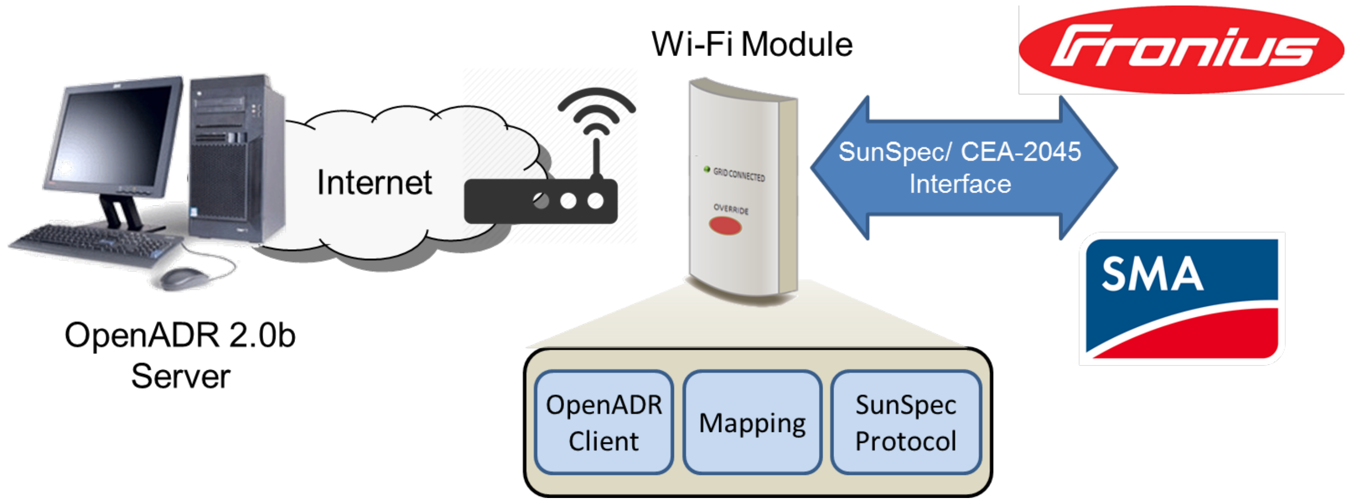


Figure 7-1, OpenADR 2.0b Communication System

The server, also called a "Virtual Top Node" or VTN, used in this project was an instance of EPRI's open source VTN. This source software and executables are freely available on SourceForge[7]. A modified instance of this software was setup to support the project on an EPRI server in Knoxville, TN and accounts were setup for SCE and SMUD to provide access for the testing.

A CTA-2045 form factor Wi-Fi communication module was developed and is shown in Figure 7-2. This module used the larger "AC Form Factor" option. As illustrated in Figure 7-1, this module housed the OpenADR 2.0b client, SunSpec protocol driver (developed by the SunSpec Alliance in a previous task) and the mapping between the two.

Both the server and the module were capable of the OpenADR 2.0b protocol's TLS1.4 security, but were operated in "Basic Authentication" mode during this project for convenience.

[7] https://sourceforge.net/projects/openadr2vtn/

Figure 7-2, EPRI OpenADR 2.0b Module

7.2.1 OpenADR 2.0b Adaptation to Support Smart Inverters

The OpenADR 2.0b protocol was developed primarily to support demand response uses. The range of messages that are rigidly-defined in this protocol accordingly support the basic needs of load control. The needs of solar inverters, however, are wider ranging and more extensive data models and message sets are needed. Nevertheless, it was interesting to the stakeholders in this project to demonstrate OpenADR 2.0b since it is in broad use for load management applications and there is technical interest in the future convergence of protocols for all types of distributed energy resources (generation, load, storage).

In addition to the rigidly-defined parameters (i.e. specific enough to ensure interoperability), The OpenADR 2.0b protocol includes a number of fields that allow additional parameters to be exchanged. To support the functional requirements of this project, EPRI utilized a combination of these capabilities and devised methods to support the project. A detailed report has been published separately that explains how the messages were encoded.

7.2.2 OpenADR 2.0b Smart Inverter Technical Approach

Individual DER functions supported were mapped to existing OpenADR EiEvent functions. These functions are all based on the oadrDistributeEvent function which allows a wide range of flexibility.

The oadrDistributeEvent message is designed to notify the end device of a DR event that is currently taking place or will take place in the future. The event can have a single or multiple signals, and each signal can have a single or multiple intervals.

To support control of the selected inverter functions, additional signal names were added to the EPRI OpenADR server. The OpenADR 2.0B client software was modified to recognize these new signal names. The OpenADR client polled the OpenADR server for new event updates rather than having the server push them down to the end devices. This approach eliminates the need to customize setting in the client side routers since all interactions are initiated by the OpenADR client.

In general, configuration parameters are applied to the connected inverter by the UCM on event start or if an event is modified. Actions that have a duration, such as enabling a volt/var curve or using the max watt limit function, follow the start time and duration parameters of the event. Events are triggered by the UCM module at a specific time and are terminated by the UCM at the end of the event duration or by aborting the event on the VTN. Configuration parameter events such as curve downloads are applied on event start or when modified.

Curve Download and Enable/Disable

Three curve types were supported, Volt-VAR, Volt-Watt, and Frequency-Watt. Each curve type had two functions, curve download, and curve enable/disable. The curve enable allowed the selection of desired curve if more than one was defined.

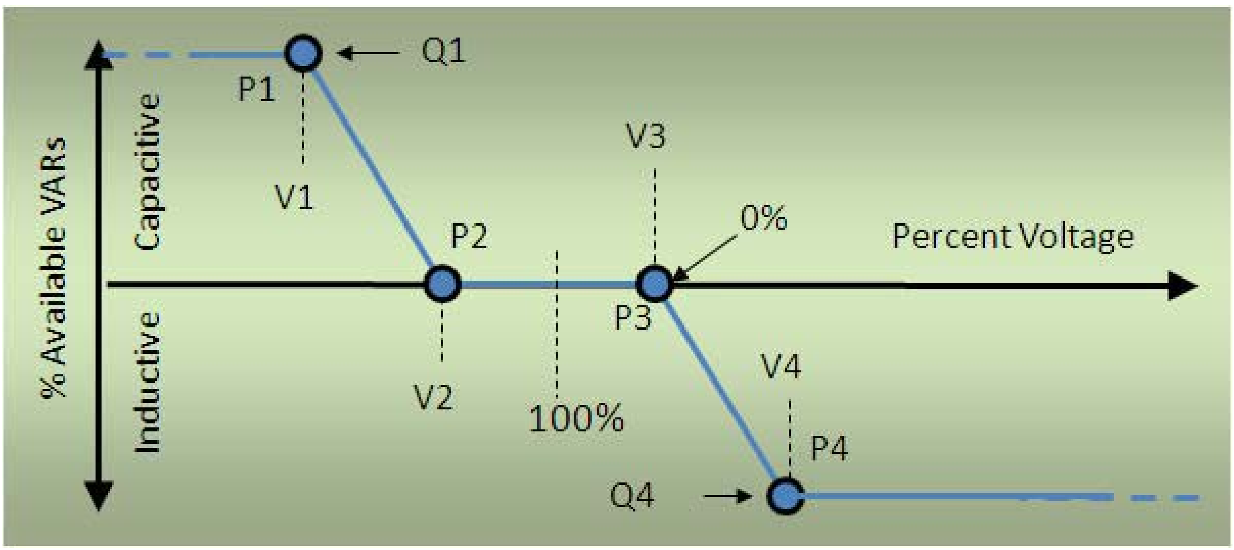


Figure 7-3, Example Volt-VAR curve

The curve download functions have the parameters start time, curve ID, and curve value pairs. The curve enable functions have the parameters curve ID, event start time, duration, randomize time, reversion timeout, and ramp time. Typical for all action events, the UCM uses event start time, duration, and randomizer time to trigger and terminate the event.

Ramp Rate Download

The parameter WGra is the default ramp rate of change of active power. This ramp rate value limits the rate of change of real power delivered due to either a change by a command or by an internal action such as a schedule change. This ramp rate is only used if an event is issued without a ramp rate. It acts as the default if no specific ramp rate is specified. WGra is defined as a percentage of WMax per second.

This function has only the ramp rate in seconds mapped to the inverter. The start time is used to trigger when the value is sent to the inverter.

Fixed Power Factor

This function provides a mechanism to set the power factor of a DER to a fixed value. This function has the mapped parameters power factor, and ramp time. Power factor type is not supported in this implementation.

Limit Maximum Real Power

This function is intended to provide a mechanism through which the maximum real power may be limited to a percentage of the DER maximum real power.

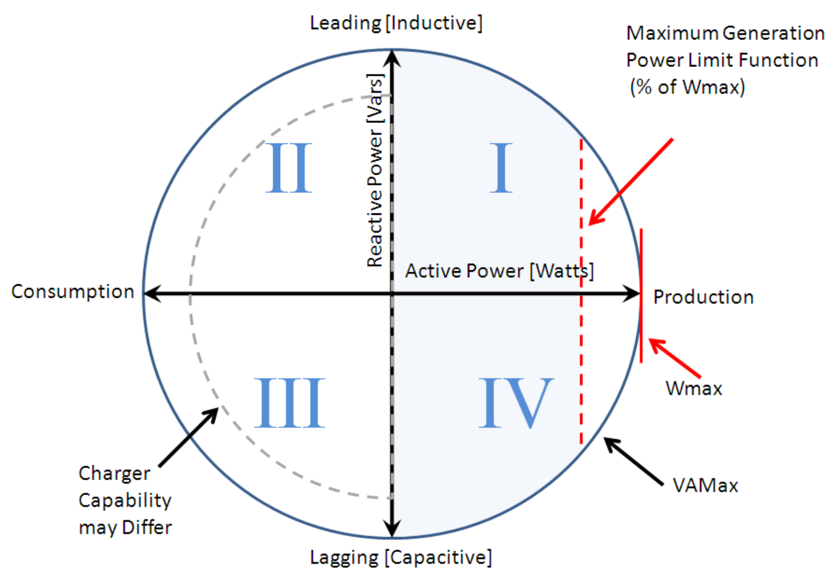


Figure 7-4, Limit maximum real power

This function has the parameters event start time, duration, power limit, randomizer time, and ramp time.

Connect/Disconnect

This function is intended to provide a mechanism to connect or disconnect the DER from local loads and the grid. Although this command was intended to control a physical disconnect, neither of the inverters tested incorporated such a device. Instead it was chosen to imitate a disconnect by setting the output to zero watts. This action is carried out by the inverter and was considered an acceptable solution for this project to demonstrate the concept.

This function has the parameters event start time, duration, and randomizer time. The connect event is typically generated with a zero duration which keeps the inverter connected indefinitely. Ending the event will disconnect the inverter until another connect event occurs.

Data and Status Reporting

Specific data points will be polled and reported based on the capabilities of the connected inverter. This data can include instantaneous real power, instantaneous power factor, totalized real power output, connection status, and alarm flags.

The inverter data capable of being reported by the VEN is:

- Totalized real energy output
- Instantaneous real power
- Instantaneous power factor
- Connection status
- Alarm flags
- AC amps
- AC amps Phase A
- DC amps
- DC voltage
- DC watts
- Frequency
- Phase voltage
- Volt-Amps
- VArs

The actual data reported is based on the particular inverter.

8 LABORATORY TESTING

The laboratory testing was led by project partners Southern California Edison (SCE) and Sacramento Municipal Utility District (SMUD). This testing brought together the smart inverters and communication systems and evaluated their functionality end-to-end. Prior to these tests, the components had been developed and assessed independently, but not as a system.

The original laboratory test plan intended to follow UL testing of the inverters so that any issues encountered would be known to relate to the communication systems or some subtle interoperability issue at the modular communication interface. However, because UL testing was delayed due to a longer-than-expected process for finalizing the UL 1741 SA test procedure, it was decided to run the laboratory testing in parallel with UL testing. This meant that there were more uncertainties, more unknowns, during the laboratory testing and problems encountered were more difficult to diagnose because the issues could be in the inverters, in the communication systems, or a combination of the two.

To help compensate for this challenge, EPRI performed supplemental laboratory testing with findings detailed in Section 6.3.

8.1 Southern California Edison Laboratory Testing

The objective of the utility laboratory testing was to evaluate the performance of the end-to-end system including the communication head-end, CTA-2045 modules, and smart inverters in a controlled environment. In order to test the interoperability of these components, it must be ensured that the DER command or event scheduled at the head-end communication server will produce the expected result at the inverter. Therefore a single utility communication system and communication module should be compatible with multiple inverters provided from different manufacturers. Additionally, a single inverter design should be compatible with the different utility head-end systems.

8.1.1 Communications Architecture

In order to perform this testing at SCE, two different cloud-based servers were used as the head-end to communicate via OpenADR and IEEE 2030.5 protocols. An internet gateway providing an IEEE 2030.5 client/server was used for IEEE 2030.5 testing, while the same gateway's routing functionality was used for OpenADR testing. Both the gateway and the router provided a Wi-Fi Access Point to connect with the CEA 2045 modules.

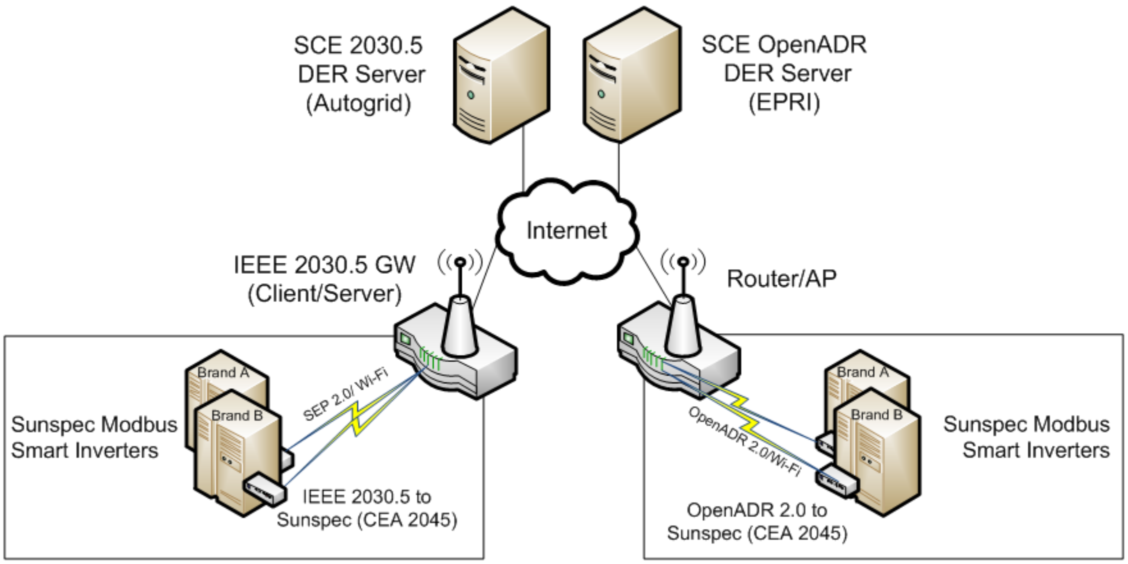


Figure 8-1, Communication Architecture used in SCE Labs

8.1.2 Lab Testing Equipment

Multiple pieces of equipment were used to energize the inverters under test as well as vary the electrical conditions in the setup to verify changes to some of the autonomous advanced inverter settings, such as programmable curves.

- Solar PV Simulator: This device is a programmable DC power supply (up to 90 kW) that will emulate the behavior of solar PV panels providing power to the inverter. It can be used to implement specific predefined I-V curves.
- Grid Simulator: This device is a programmable AC power supply (up to 90 kVA) that will provide the nominal grid voltage (240 V) and frequency (60 Hz) at the inverter output terminals. This voltage and frequency can be modified to assess the inverter programmable curves.
- Load Bank: This is an adjustable load that can be modified using a series of multiple resistive and inductive impedances.
- Digital Oscilloscope: This device will be used along with multiple voltage probes and current transformers (CT) to record raw electrical data at a high sampling rate.

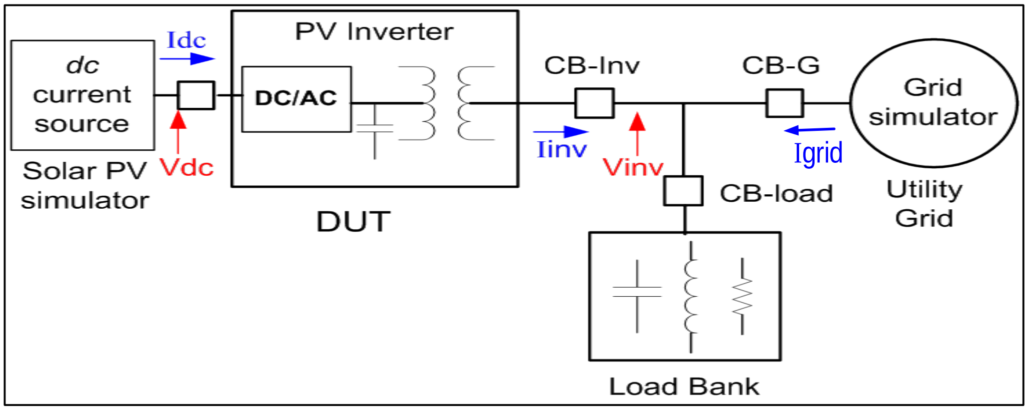


Figure 8-2, Diagram of Electrical Test Setup in SCE Labs

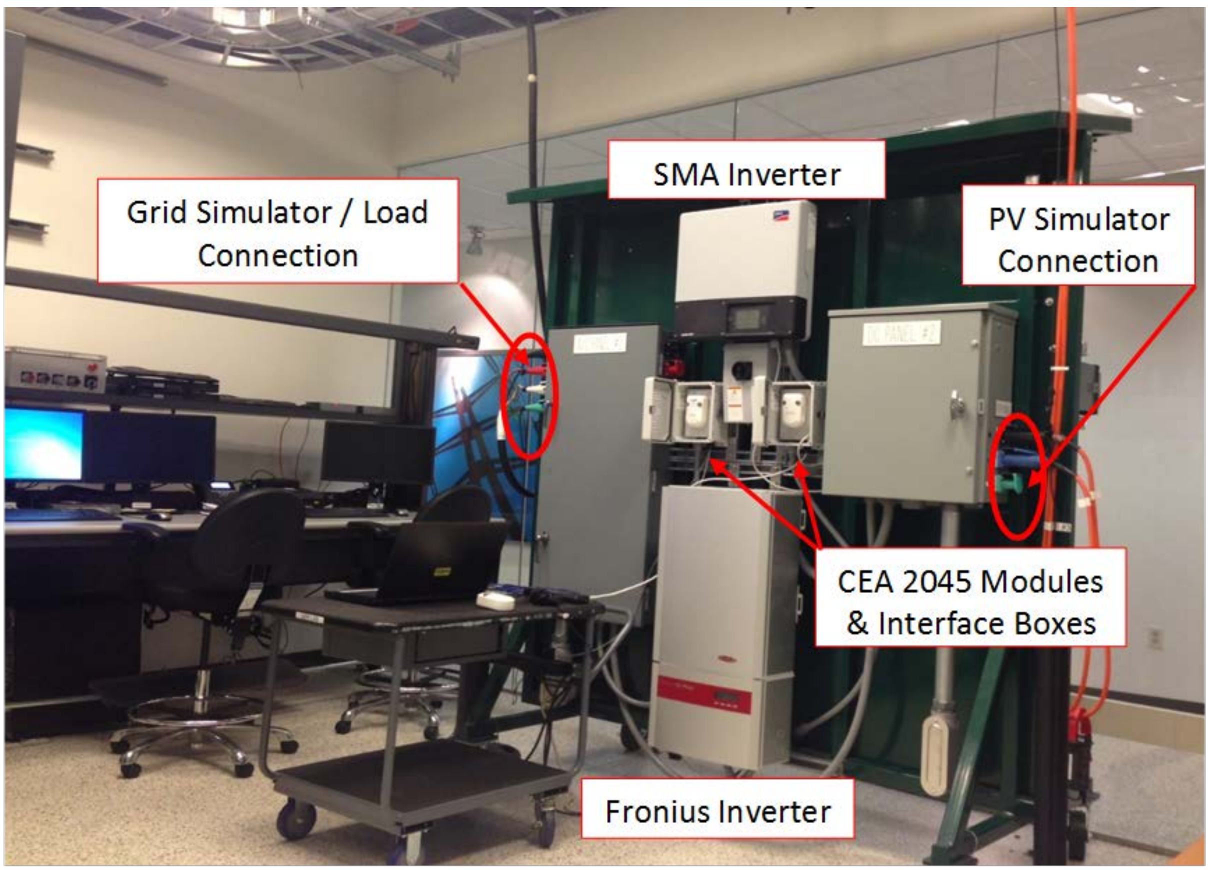


Figure 8-3, SCE DER Laboratory Setup – Inverters and Communication Modules

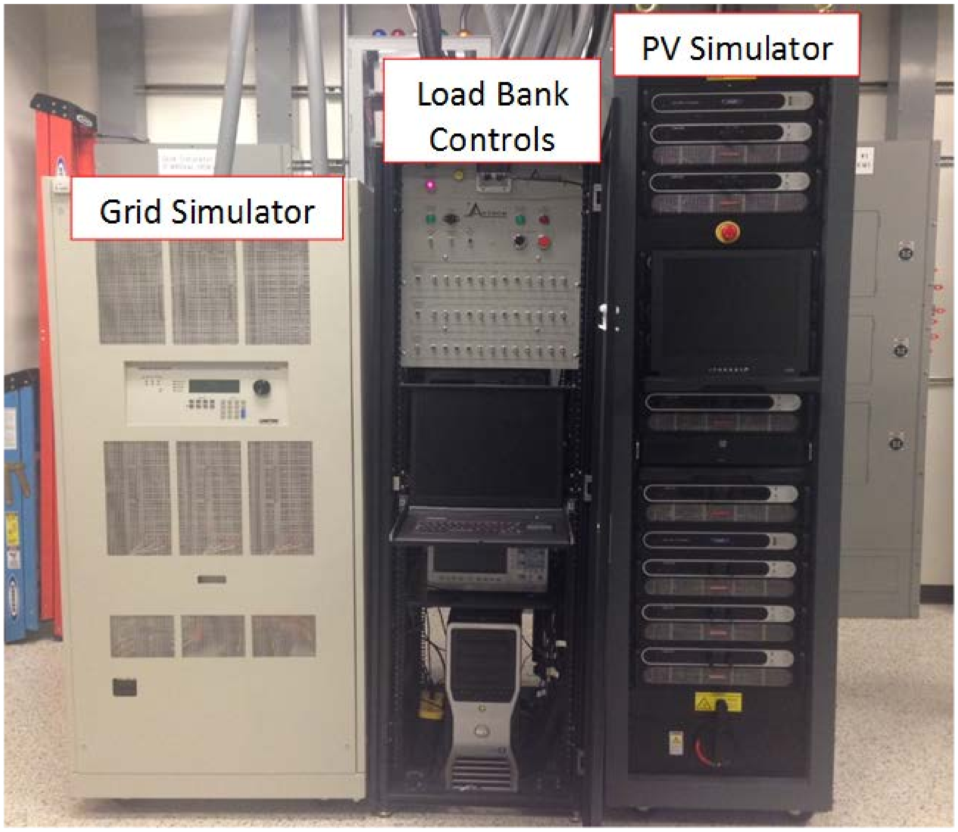


Figure 8-4, SCE DER Laboratory Setup – Power Supplies and Loads

8.1.3 Lab Testing Results

The following table provides a summary of SCE's laboratory interoperability testing to assess end-to-end compatibility of the communication systems, modules, and inverters. The list of smart inverter functionality demonstrated for both inverters was evaluated using multiple methods. A hardwired Modbus connection and the SunSpec Dashboard tool was used to directly change internal registers and act as a means of verification. Meanwhile, IEEE 2030.5 and OpenADR protocols were demonstrated over Wi-Fi using the corresponding communication modules and head-end systems as illustrated in Figure 6-1, the communications architecture.

Table 8-1, SCE Laboratory Test Results Summary

Test Case	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
Volt-VAR Mode	✓	✓	✓	✓	×	×
Fixed Power Factor	✓	✓	✓	×	×	×
Limit Max. Real Power	✓	✓	✓	×	×	×

Test Case	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
Volt-Watt Mode	✓	✓	✓	✓	×	×
Freq-Watt Mode	×	×	×	×	×	×
Connect/Disconnect	✓	✓	✓	✓	✓	×
Monitor DER	✓	✓	✓	✓	✓	✓

Test results indicate that both inverters are capable of supporting most of the advanced inverter functionality proposed in the procedure using a standard communication protocol. Nearly all of these functions were successfully implemented by changing the standard Modbus registers directly, with the exception of frequency-watt function for both inverters and the fixed power factor setting for a single inverter. Direct settings (i.e. fixed power factor and limit maximum power) behaved exceptionally well, remaining within 1.5% of the intended value. Autonomous curve functions (i.e. volt-var and volt-watt) remained within 1.5% as well with the exception of one inverter's volt-watt function which displayed a 5% error between the programmed curve and measured parameters.

As for the end-to-end system testing with the two internet-based protocols, the results varied for the different inverter and module combinations. The Fronius inverter successfully demonstrated nearly all of the smart inverter functions using both IEEE 2030.5 and OpenADR protocols. However, some of these functions did not always behave exactly as expected. For example, one inverter restarted each time the volt-watt function was re-configured. The SMA inverter supported only a limited number of test cases, caused by read-only registers as well as Modbus error messages observed that resulted in no change to the inverter settings during testing. Therefore, several inverter limitations were observed and documented regarding the interoperability with the two communication systems.

Volt-VAR Function

Although the intention was to test volt-var curves with watt priority (using percentage of available reactive power), neither inverter supported this particular volt-var mode. Instead the inverters acted in a var priority mode (using the maximum amount of Vars possible). The following table summarizes the results of the various volt-var tests:

Table 8-2, Volt-VAR Communication Results Summary

Volt-VAR	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
Curve #1	✓	✓	✓	✓	×	×
Curve #2	✓	✓	✓	✓	×	×
Curve #3	✓	✓	✓	✓	×	×

The Fronius inverter successfully demonstrated autonomous volt-var functionality with var priority after scheduling the DER event using either communication system. The SMA inverter acknowledged the write of the volt-var curve values, but only updated the first voltage parameter resulting in an unsuccessful test.

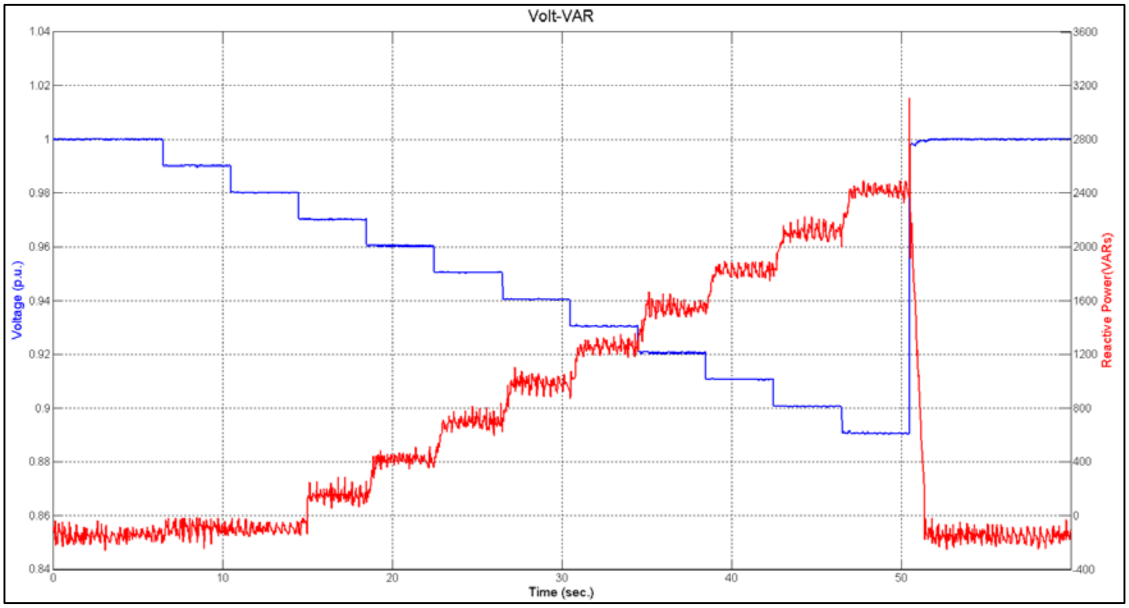


Figure 8-5, Sample Volt-VAR Under-Voltage Test

Fixed Power Factor Function

Based on performance observed during testing, the positive sign convention (+) resulted in inductive behavior while the negative sign convention (-) resulted in capacitive behavior. Table 6-3 summarizes the results of these fixed power factor tests while using different the different head-end applications:

Table 8-3, Fixed Power Factor Communication Results Summary

Fixed PF	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
+ 0.90	✓	✓	✓	×	×	×
+ 0.95	✓	✓	✓	×	×	×
1.00	✓	✓	✓	×	×	×
- 0.95	✓	✓	✓	×	×	×
- 0.90	✓	✓	✓	×	×	×

Table 8-4, Fixed Power Factor Functionality Results Summary

Fixed PF Setting	Fronius PF Measured Values	SMA Measured PF Values
+ 0.90	+ 0.892	N/A
+ 0.95	+ 0.945	N/A
+ 1.00	+ 1.000	N/A
- 0.95	- 0.955	N/A
- 0.90	- 0.905	N/A

Maximum Real Power Limit Function

Properly implemented, the Maximum Real Power Limit Function is to be controlled via specific Modbus registers (WMaxLimPct (%)). With one of the tested inverters, this function was not properly supported. In this case, SCE proved that the product was physically capable of reducing its real power output by editing the nameplate real power rating (WMax (watts)) to reduced power levels. Table 6-5 summarizes the results and Table 6-6 summarizes the resulting measurements.

Table 8-5, Maximum Power Limit, Communication Results Summary

Limit Max. Real Power	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
100%	✓	✓	✓	×	×	×
80%	✓	✓	✓	×	×	×
60%	✓	✓	✓	×	×	×
40%	✓	✓	✓	×	×	×
20%	✓	✓	✓	×	×	×

*Power reduction achieved by writing the inverter nameplate rating

Table 8-6, Maximum Power Limit, Functionality Results Summary

Limit Maximum Power Setting	Fronius Measured Power Values (% Wmax)	SMA Measured Power Values (% Wmax)
100%	99.3%	98.9%
80%	79.5%	78.7%
60%	59.3%	59.1%
40%	39.8%	39.5%
20%	19.9%	19.8%

Voltage Watt Function

Table 6-7 summarizes whether or not the autonomous volt-watt functionality could be enabled and updated using the different communication systems and corresponding head-end applications:

Table 8-7, Volt-Watt Function, Communication Results Summary

Volt-Watt	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
Curve #1	✓	✓	✓	✓	×	×
Curve #2	✓	✓	✓	✓	×	×

The Fronius inverter only supported 3-point Volt-Watt curves as opposed to 4-point curves. After receiving the appropriate commands from the IEEE 2030.5 application, the Fronius inverter went into a “Sync” mode where it ceased to generate until the grid side conditions were appropriate for 5 minutes. However once it returned to normal operation, the inverter demonstrated autonomous volt-watt functionality. The SMA inverter acknowledged the write of the volt-watt curve values, but only updated the first voltage parameter resulting in a failed test.

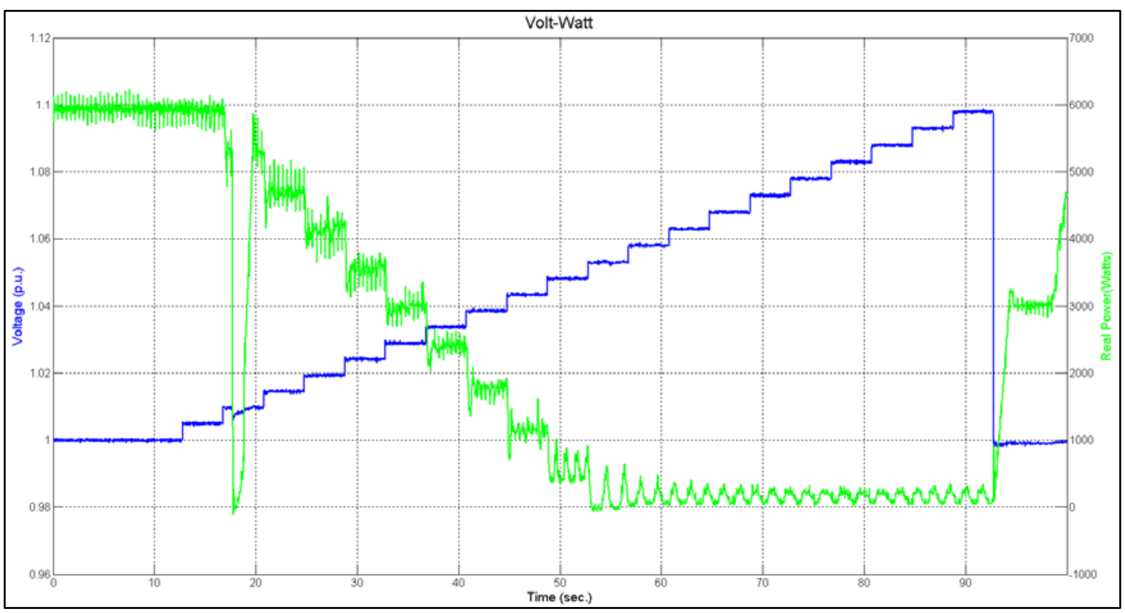


Figure 8-6, Sample Voltage-Watt Test with the Fronius Inverter

Frequency-Watt Mode

The frequency-watt functionality was ultimately not supported by either inverter manufacturer using open communication protocols, and therefore could not be tested accordingly in the lab.

Table 8-8, Frequency-Watt Function, Communication Results Summary

Freq-Watt	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
Curve #1	×	×	×	×	×	×
Curve #2	×	×	×	×	×	×

Connect/Disconnect Function

Although intended to have created physical disconnection from the electric grid, the inverters tested merely used existing functionality to reduce power output. Therefore the real power output was reduced to near zero, demonstrating something similar to a cease generation capability.

Table 8-9, Connect-Disconnect Communication Results Summary

Disconnect	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
0%	✓	✓	✓	✓	✓	×

Table 8-10, Connect-Disconnect Functionality Results Summary

Ideal Watt Setting	Fronius Measured Power	SMA Measured Power
0 W	11.3 W	22.1 W

Monitor DER Status and Output

Table 6-11 summarizes the monitoring capabilities of the inverters and the ability to read DER output information from the different communication head-end systems.

Table 8-11, Monitoring Communication Results Summary

Monitoring	Fronius Inverter			SMA Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR)
V, A, W, etc.	✓	✓*	✓	✓	✓*	✓

*These pass/fail indicators are not absolute and must be understood through the corresponding text

Though the Autogrid IEEE 2030.5 server did not provide an interface to view or download data, Wireshark traces confirmed the capability of the IEEE 2030.5 systems to post all 7 data points collected by both the Fronius and the SMA inverters. The EPRI OpenADR VTN provided an interface to view and download the data points provided by each of the inverters.

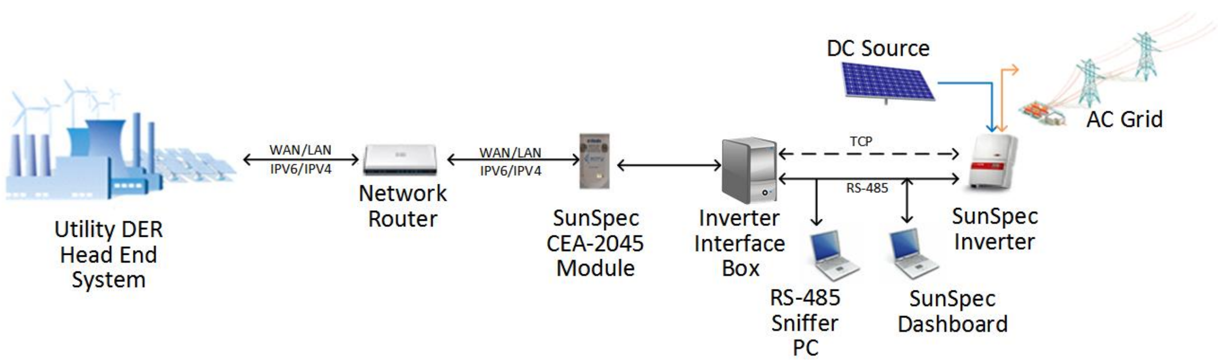
8.2 Sacramento Municipal Utility District Laboratory Testing

The objective of the utility laboratory testing was to evaluate the performance of the end-to-end system including the communication head-end, CTA-2045 modules, and smart inverters in a controlled environment. In order to test the interoperability of these components, it must be ensured that the DER command or event scheduled at the head-end communication server will produce the expected result at the inverter. Therefore a single utility communication system and communication module should be compatible with multiple inverters provided from different manufacturers. Additionally, a single inverter design should be compatible with the different utility head-end systems.

8.2.1 Test Environments and Configuration

The following hardware and software components are required to demonstrate the successful exchange of messages between the utility head end and the inverter.

8.2.1.1 Architecture Overview



- **Utility DER Head End System** manages and creates the intended DER programs that will be communicated to the Smart Inverters and/or aggregators that will act upon the created programs using IEEE 2030.5 (SEP 2.0) or OpenADR 2.0 protocols.
- **WAN/LAN Network** provides the private/public wide area network (or LAN for laboratory usage case) connectivity which will allow the Utility DER Head End System to connect to the grid connected DER devices.
- **Wi-Fi Access Point/Router** provides the local network connection for the utility's DER Head End System using the required IPV6 or IPV4 protocol.
- **SunSpec CTA-2045** module provides the network connectivity for the target SunSpec based Smart Inverters. This module has the IEEE 2030.5/OpenADR application logic and converts these message exchange protocols to the SunSpec/Modbus register based commands required by the end Smart Inverter DER device.
- **Inverter Interface Box** provides the adapter necessary for the SunSpec CEA -2045 module to connect to the end Smart Inverter DER device. This interface box will connect to the end DER device through typically a RS-485 or TCP Modbus connection.
- **RS-485 Sniffer PC** – A PC along with serial interface capture and decoding software was used to collected Modbus data exchanges between the CEA 2045 module and the inverters under test.
- **SunSpec Dashboard** – A PC running the SunSpec Dashboard application provided a way to browse register content in the inverter and to make ad hoc changes to those register settings as needed to validate functional behavior.
- **SunSpec Smart Inverter(s)** provide the set of Smart Inverter functionality required by the CA Rule 21 (CSI4 project). Examples of such inverters being tested by the CSI/SMUD project include Fronius and SMA smart inverters.
- **DC Source** - This testing includes used a DC Power Supply as a representation of a PV array.

8.2.1.2 SMUD's Test Environment

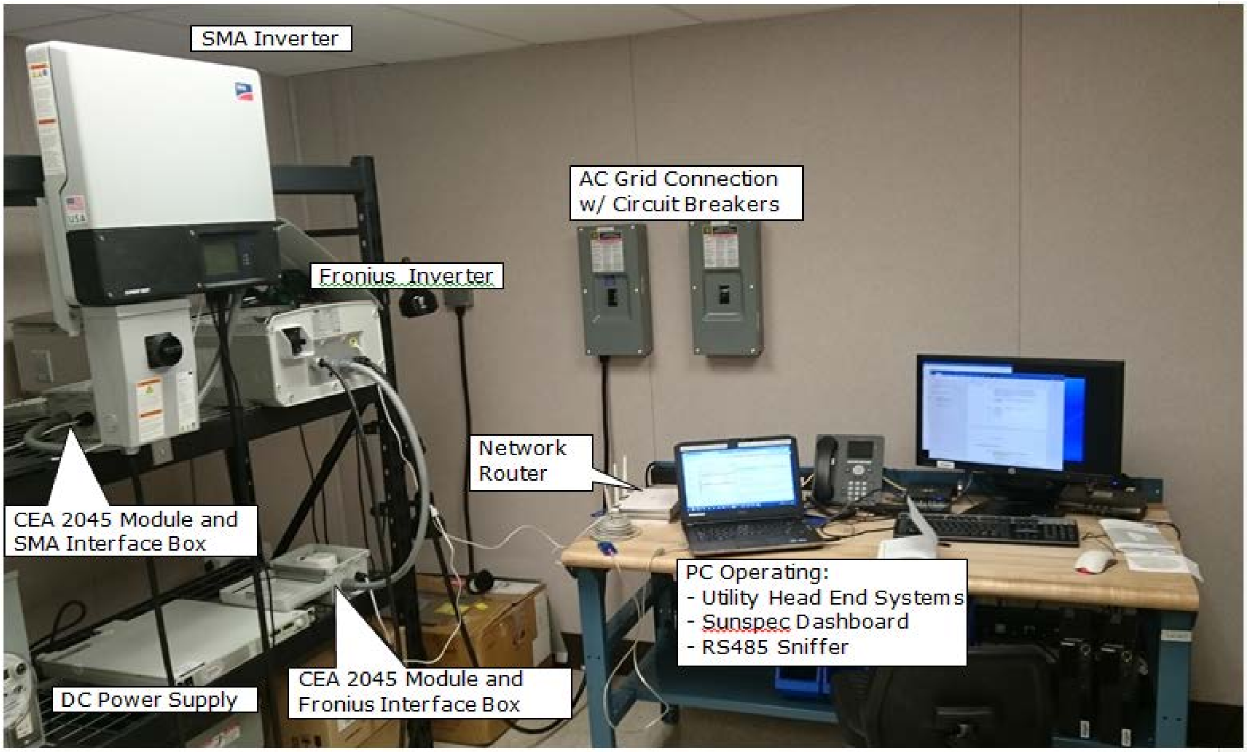


Figure 8-7, SMUD Laboratory Testing Setup

8.2.2 Utility DER Head End System

A utility owned DER Head End System is the central system that will manage the DER events that will occur in its distribution and residential grid networks. This system will manage the individual inverters and aggregators that will be part of its grid connected inverters/PV systems. The following software was used to simulate the Head End interactions with the Smart Inverters:

- QualityLogic IEEE 2030.5 (SEP 2.0) Ad-Hoc Tester
- EPRI OpenADR Virtual Top Node (VTN) Application Server, with helper dialogs for inverter specific functions

The following components were used to create DER programs and events that were communicated to the participating Smart Inverters.

	IEEE 2030.5 (SEP 2.0)	**OpenADR 2.0b**
Product Name	QualityLogic IEEE 2030.5 Ad-Hoc Tester	EPRI OpenADR VTN
Software Version	Version 1.1 (Feb 18, 2016)	v0.9.5-2

	IEEE 2030.5 (SEP 2.0)	OpenADR 2.0b
Technical Reference	QualityLogic Ad-Hoc Tester Description Note 1	SunSpec-Modbus-Usage_CARule21-Req_Final.pdf Note 2

1) https://www.qualitylogic.com/tuneup/uploads/docfiles/SEP2-ad-hoc-tester.pdf
2) http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004788

8.2.3 SunSpec based Inverters

Fronius Inverter

A Fronius Smart inverter is one of the two inverters that are the subject of the CSI4 testing. The Fronius Smart Inverter specifications are below:

Hardware Model	IG+V6, 0U
Software Version	6.2.28
Options	2.1.21 Modbus Card with RS-485 Interface ModbusRTU to CTA-2045 Adapter
Device Address	1
Technical Reference	Fronius Modbus Card, *Fronius Modbus Register Tables.pdf* http://www.fronius.com/Applikationen/contentserverdownload/downloadcsitem.aspx?id=361552

SMA Inverter

A SMA Smart inverter is one of the two inverters that are the subject of the CSI4 testing. SMA Smart Invert specifications are below:

Hardware Model	SB5000TL-US-22
Software Version	40050949
Options	9201 Modbus Protocol with Ethernet TCP Interface Modbus TCP to CTA-2045 Adapter
Device Address	126
Grid Guard	Kitu's Grid Guard was used.

Technical Reference	http://russellpacific.com/wp-content/uploads/2015/09/Tech_Description_SunSpec_Modbus-TB-US-en-14.pdf

8.2.4 CTA-2045 Module(s)

The CTA-2045 modules transform the IEEE 2030.5/OpenADR 2.0 messages into the necessary Modbus register read/write commands to effect the requested inverter function change. The CEA -2045 modules are configured to connect to a wireless Wi-Fi Access point.

The table below documents the developers of the four CTA-2045 modules used during testing along with identifying information, if any, on the modules.

	IEEE 2030.5 (SEP 2.0)	**OpenADR 2.0b**
SMA Inverter	Kitu CEA-7001 Module	EPRI HW: PiZ16.01.26 FW:TBD
Fronius Inverter	Kitu CEA-7001 Module	EPRI HW: PiZ16.01.26 FW: PIZ16.02.03

8.2.5 Local Area Network Router

A wireless router provides the interconnection between inverter CTA-2045 modules and the utility head end applications. The following Router Model is used during SMUD's testing.

Hardware Model	ASUS RT-N16 Wireless-N 300 Router (DDWRT Compatible)
Software Version	Tomato-K26USB-1.28.RT-MIPSR2-131-Mega-VPN.trx
IP Protocol	With IPV6 support

The wireless access point on router is preconfigured with a well-known SSID and Password. The CTA-2045 module, QualityLogic DER Head End System and other network connected devices and sniffers are connected with this router to communicate SEP 2.0 and OpenADR messages.

8.2.6 Modbus Browsing Software and Hardware

In order to validate that the message exchange between the head end and the inverter was successful, selected inverter Modbus registers were examined. The following applications and associated hardware were utilized to independently inspect and validate the Modbus registers of the inverters:

Item	Product	Supplier
SunSpec/Modbus Browser	SunSpec Dashboard	SunSpec Alliance
USB to RS-485 Adapter	RS-485 to USB Converter is required to connect the SunSpec Dashboard or any Modbus sniffing software from a PC laptop	Any RS-485 to USB converter manufacturer

An Ethernet cable or wireless interface is required to connect the PC running the Modbus TCP browser to the SMA inverter's Modbus TCP RJ45 connector.

8.2.7 Electrical Setup

The Smart Inverters being tested were connected electrically to a DC power supply (Agilent N5771A 300VDC, 5A Power Supply) to simulate the Photovoltaic Arrays. The inverters were not attached to the AC power grid.

8.2.8 Summary of SMUD's Test Observations

The following highlights some of the more significant observations during testing. Please refer to each detailed test section as well as the test logs in the appendix for more information on the behavior of the inverters, CTA-2045 modules, and the applications simulating the Head End events.

- Not all of the required CSI inverter modes are supported by either of the Smart Inverters tested.
- Frequency Watt curve function is not supported in both Fronius and SMA inverter models.
- Current inverters have some limitations on the ability to write certain Modbus registers, ex. OutPFSet_Ena register for SMA which enables/disables Fixed Power Factor mode.
- The CTA-2045 modules for Fronius inverters do not have sufficient torque on fasteners and individual pin insertion depth.
- Both inverters require a DC power to be provided in order for a client to more fully read its SunSpec based registers.
- IEEE 2030.5 does not have a way to issue connect/disconnect commands in the current standard. It is only a state information as part of the DERSettings attributes.

- EPRI OpenADR 2.0b module successfully received inverter function events from the Headend VTN, but in most cases the module failed to send the required Modbus values to the SMA inverter.
- The communication systems did not always return the smart inverter to its previous state at the end of an event, such as modifying power factor.
- Unexpected behavior when attempting to enable some inverter functions, such as entering into startup mode when enabling Voltage-Watt Function (Fronius)

8.2.8.1 Registration

Summary:

Registration encompasses all communication set up procedures and is a pre-condition for the remainder of the test cases. Registration comprises the registration of devices on servers, automated server and resource discovery processes, network commissioning, and provisioning of server information on clients (IP Addresses, URLs, program information, etc.). The purpose of this test case is to ensure interoperability of various technologies, architectures, and standards, and is fundamental to meeting the objectives of the CSI4 project.

Results:

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Registration	√	√	√	√

Test Observations:

- Communication between the OpenADR EPRI CTA-2045 (OpenADR) modules and the VTN used HTTP communication with basic authentication rather than TLS 1.2 security with client server x.509 certificate exchange used in most deployments. EPRI reports that the module is capable of both, and was operated in basic authentication mode for this project in order to work with an existing basic OpenADR server instance.

8.2.8.2 Volt-VAR Function with Watt Priority

Summary:

The Volt/var function allows DER systems to counteract voltage deviations from the nominal voltage level (but still within normal operating ranges) by consuming or producing reactive power. Volt/var curves can specify the changes in Vars in response to changes in the local voltage measured at the inverter terminals.

Results:

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Volt-Var	√*	√*	√*	X*

* These pass/fail indicators are not absolute and must be understood through the corresponding text

Test Observations:

- Fronius: inverter does not support %VArAvail (Mode 3) which is the method by which CSI Test Plan recommends for controlling Volt-VAr inverter control. It supports use of %VArMax (Mode 2), The Kitu CEA 2045 (SEP 2.0) module for this test case attempts to write mode 2 to the DeptRef register, while the EPRI OpenADR 2.0b module attempts to write mode 0 (N/A) to the DeptRef register. Volt-VAr:DeptRef register is read only and fixed at DeptRef=2 (%VArMax), so neither of these write attempts had an effect on the mode used.
- SMA: Although the inverter allows writing of 8 curve points along with setting the enable bit by the CEA 2045 (SEP 2.0) module, it only updates the first curve point coordinates and the enable bit does not get set.
- SMA: inverter does not support %VArAvail (Mode 3) which is the method by which CSI Test Plan recommends for controlling Volt-VAr inverter control. It supports use of %WMax (Mode 1) which is used by the Kitu CTA-2045 (SEP 2.0) module for this test case. Volt-VAr:DeptRef register is read only and fixed at DeptRef=1 (%WMax) according to the SMA technical documentation. However, the SunSpec dashboard reads the value as 0.02 and CEA 2045 module reads it as 2, which made no impact on the test itself.
- SMA: Modbus sniffer log indicates that EPRI CTA-2045 (OpenADR) module does not attempt to read or write any Volt/Var settings.

8.2.8.3 Fixed Power Factor Function

Summary:

The purpose of utilizing fixed power factors in an inverter-based DER system is to help compensate for any reactive load and/or other DER systems that generate reactive power. Ideally, the most efficient operation of an electric power system is if it has zero reactive power and a unity power factor. However different types of loads and DER systems can generate/consume reactive power, adjusting the power factor on the circuit and limiting real power flow over conductors. If the inverter’s fixed power factor can be modified to meet reactive power demand, then this will allow circuit feeders to maintain optimal real power flow.

Results:

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Fixed Power Factor	√*	X*	√*	X*

*These pass/fail indicators are not absolute and must be understood through the corresponding text

Test Observations:

- Fronius (SEP 2.0): Inverter appears to always behave in the default mode of unity Power Factor operation as the specific enable register (OutPFSet_Ena) is left clear.
- Fronius (OpenADR): After event, inverter doesn't return to original OutPFSet, or clear OutPFSet_Ena. Modbus trace indicates Modbus Error 3 when the CEA module attempts to write a value of 0 to the OutPFSet register at the end of the event. The trace indicates that the CEA module does not try to write any other registers at the end of the event.
- SMA: Inverter does not allow turning off the Power Factor Enable register (OutPFSet_Ena) as it always remains at 1. Attempting to turn it off results in a Modbus error 1.
- SMA: Inverter does not support setting a user specified Power Factor value at all. Attempting to write to the appropriate inverter register results in a Modbus error 2.

8.2.8.4 Limit Maximum Real Power

Summary:

While solar photovoltaic generation is dependent on solar irradiance and can therefore be intermittent throughout the day, the DER system settings can be modified to place a maximum limit on amount of real power generated. Limiting maximum real power may be necessary in response to unusual or emergency conditions that are causing reverse flow into the feeder's substation or because the total DER real power output on the feeder is greater than some percentage of total load, which can potentially result in higher voltages on the distribution feeder.

This test case will cover the above use case by initiating a series of Limit Maximum Real Power commands from the Utility DER Head End system to the target smart inverter device using the values from Table 4 below.

Results:

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Limited Max Real Power	√*	√	√*	X*

*These pass/fail indicators are not absolute and must be understood through the corresponding text

Test Observations:

- Fronius (SEP 2.0): The Kitu CTA-2045 modules forces the inverter to go into sleep mode if it detects the value of WMaxLimPct to be 0 (checks it before/after the actual test). It is uncertain if this is the intended functionality.
- Fronius: Although Fronius allows writing into Setting:WMax register, it is actually read-only and does not change the value.
- Fronius (OpenADR) - At completion of the event, CTA module sets WMaxLimPct to 0, instead of 100%. This is acceptable, but the expected post-event setting is ambiguous. WMaxLim_Ena left clear, perhaps appropriate since 100% isn't really imposing a limit.
- SMA: WMaxLimPct register is write only, so unable to verify that setting is applied by inverter because reading is not allowed.
- SMA: Unable to clear WMaxLim_Ena using SSDash, so it is always 1.
- SMA: When limiting Max Real Power using OpModFixed Flow event mode, the CTA-2045 (SEP 2.0) module attempts to write to the Wmax nameplate rating setting instead of the WMaxLimPct and WMaxLim_Ena event controls.
- SMA: Modbus sniffer log indicates that the EPRI CTA-2045 (OpenADR) module does not attempt to write to the WMaxLimPct, WMaxLim_Ena, or WMax register settings.

8.2.8.5 Voltage-Watt Function

Summary:

The DER system autonomously modifies real power output in order to dampen voltage deviations. The purpose of voltage-watt operations is to use DER systems to help maintain voltage levels within their normal ranges as an alternative to emergency tripping in cases where an abundance of generation is resulting in higher voltages on the feeder. These higher voltages could be the result of reverse power flow on small conductors. The inverter would follow a voltage-watt curve that would specify the maximum real power output in response to the measured voltage at the inverter terminals.

Results:

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Voltage-Watt	√*	√	X*	X*

*These pass/fail indicators are not absolute and must be understood through the corresponding text

Test Observations:

- Fronius: Inverter has registers for only three curve points instead of the 4 points required by the test case. CEA2045 module does not attempt to write 4th point.

- Fronius - When a Volt-Watt curve is enabled, ModEna gets set to 1 and the inverter immediately stops generating and goes into startup mode. After 5 minutes it starts generating again.
- SMA: Although inverter allows writing of 8 curve points along with setting the enable bit by the CEA 2045 (SEP 2.0) module, it only updates the first curve point coordinates and the enable bit does not get set.
- SMA: Modbus sniffer log indicates that the EPRI CTA-2045 (OpenADR) module does attempt to write the curve points, but fails with Modbus error 1. No attempt is made to set ModEna enable bit.

8.2.8.6 Frequency-Watt Function

Summary:

The DER system autonomously modifies real power output to counter frequency deviations. This action may be taken during emergency conditions or during normal operations to smooth minor frequency variations. The inverter would follow a frequency-watt curve that would specify the maximum real power output in response to the measured frequency at the inverter terminals.

This test case will cover the above use case by initiating a series of Frequency-Watt curve inverter control commands from the Utility DER Head End system to the target smart inverter device using the values from the table below.

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Freq-Watt	X*	X*	X*	X*

*These pass/fail indicators are not absolute and must be understood through the corresponding text

Test Observations:

- Fronius: No Frequency-Watt Information Model or Modbus registers on DUT to support this functionality. CTA-2045 modules do not attempt to write event settings to Modbus.
- SMA: No Frequency-Watt Information Model or Modbus registers on DUT to support this functionality. CTA-2045 modules do not attempt to write event settings to Modbus.

8.2.8.7 Connect/Disconnect

Summary:

This particular function causes the DER system to electrically connect or disconnect from the grid. This may be implemented in response to an unusual or emergency condition requiring the

DER system to be de-energized. The DER equipment may be disrupting the grid due to malfunctioning behavior or the resource may need to be disconnected for maintenance.

This test case will cover the above use case by initiating a Connect/Disconnect inverter control commands from the Utility DER Head End system to the target smart inverter device.

Results:

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Connect/Disconnect	√*	√*	√*	X*

*These pass/fail indicators are not absolute and must be understood through the corresponding text

Test Observations:

- Fronius: Remains disconnected after event expires, but enters Sync Mode and automatically Connects after 5 minutes.
- Fronius: Event works, but causes DUT to enter sync mode. After 5 minutes in Sync mode it reconnects.
    - *Question: Should a disconnect command have a predetermined time limit after which it causes the inverter to reconnect? If disconnected for safety reasons, shouldn't it remain so until conditions are determined safe and a Connect command supersedes it? For that matter when is it ever safe to Connect an inverter remotely, given that ground crews may not expect it? Should connect/disconnect be a static setting or time based event?*
- SMA: WLimMax_Ena is always 1 and cannot be cleared by the SunSpec Dashboard. Causes a Modbus exception 1.
- SMA: Modbus trace indicates that the CEA Module successfully clears the Connected register, clears WMaxLimPct, and sets WMaxLim_Ena. The SunSpec Dashboard is unable to read the write-only Connected register. The inverter reduces its generation output, but the inverter display panel and DC Power Supply are still indicating production of 300V at .1A.
- SMA: Modbus sniffer log indicates that the EPRI CTA-2045 (OpenADR) module does not attempt to write to Conn, WMaxLimPct, or WLimMax_Ena registers with event settings. No change to AC output power of inverter.

8.2.8.8 Monitor DER Status and Output

Summary:

DER systems connected to the utility distribution system will be required to have monitoring capabilities that provide operational state data. This may include the system status (i.e. connected/disconnected) as well as various power system measurements (watts, Vars, voltage, etc.).

This test case will cover the above use case by initiating a set of inverter monitoring commands from the Utility DER Head End system to the target smart inverter device.

Results:

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045		OpenADR 2.0 EPRI VTN/EPRI CTA-2045	
	Fronius	SMA	Fronius	SMA
Monitor DER Status	√*	√*	√	√

*These pass/fail indicators are not absolute and must be understood through the corresponding text

Test Observations:

Modbus traces indicates that the Kitu CTA-2045 (SEP 2.0) module is not requesting Current(A) and Voltage (V). Posts are fixed at 655350 and 21300 respectively.

8.3 EPRI Supplemental Laboratory Testing

The results from utility testing differed in some regards from the expectations of the inverter and communication system providers. This raised a flag for the project team because in interoperability testing there should be consensus on whether a given function is supported or not. Any difference between expectations and test results identifies a likely lesson to be learned.

It should be noted that the OpenADR 2.0b module used a library that was created by the SunSpec Alliance in an early step of this project. The IEEE 2030.5 module used a library created by Kitu Systems. These independent developments created an improved opportunity to identify any ambiguities in the SunSpec/CTA-2045 specifications that resulted in differences in how they were interpreted and implemented.

Where differences were noted during utility lab testing, the project team wanted to identify the root causes so EPRI conducted supplemental testing to better understand the results. The tests included investigating specific differences observed between the SunSpec Dashboard, AutoGrid/Kitu IEEE 2030.5 system, and EPRI OpenADR 2.0b systems. The summarized results of the testing are shown in Table 8-13. The supplemental investigation focused on the five functions in which results differed across all tests. These include connect/disconnect, frequency/watt, limit max real power, volt-var curves, and volt-watt curves. The differences observed were primarily with the SMA inverter therefore most of the content in this section focuses on that inverter. This investigation required a detailed look into the implementation of the SunSpec protocol in the inverters, CTA-2045 modules, and the SunSpec specification.

8.3.1 Test Conditions

The following sections summarize the support of each inverter for the registers defined in the SunSpec specification. The results do not reflect the functionality of any non-SunSpec registers or manufacturer specific functionality. The Fronius inverter was fed from a DC Power supply in testing. The SMA inverter was fed from a PV simulator. Both inverters were connected to the local grid on their AC interfaces.

The following systems were used to administer commands to the inverters.

- EPRI's OpenADR CTA-2045 Module
- SunSpec Dashboard – Test Tool
- Miscellaneous Modbus Utility Tools

Note: EPRI did not have access to an AutoGrid headend/Kitu module to allow testing with this system.

A new firmware was released by SMA during the EPRI's supplemental testing. All of the utility and UL testing was performed using FW Pack 2.63. The newly released version was FW Pack 2.65. The new firmware had only minor changes and did not significantly affect the results reported in Table 6-13 or the functions summarized below. Where noted, it appeared the differences were improvements. All of the supplemental testing was performed using the most recent firmware – FW Pack 2.65.

Table 8-12 Model number and software version for the two inverters tested.

	Fronius	**SMA**
Model	IG Plus 3.0-1	SB5000TL-US-22
Software Version	2.1.21	2.65.03

It should be noted that the SMA inverter required a "Grid Guard Code" to be entered before operational parameters could be changed in the inverter. This is a vendor-specific characteristic and is not part of the SunSpec specification. This was effectively an across-the-board lack of interoperability – in other words, unless the communication systems implemented a vendor-proprietary step, the product would not perform any of the required functions. In order to progress in the project, software was added to the EPRI and Kitu modules to accommodate the "Grid Guard Code". For tests conducted with the SunSpec dashboard, this code was entered manually using a Modbus utility tool. Unlocking SMA's Grid Guard code lasts for 10 hours or until the inverter is powered off.

A high-level summary of the EPRI supplemental lab test results is shown in Table 6-13. It is important to understand that per the SunSpec specification, each function involves reading and writing a series of parameters. This potentially includes timers (randomized start window, reversion timer), ramp rates specific to the function, activation/deactivation, and other input parameters. Not all of these parameters are mandatory for the function to operate. In EPRI's testing, a function was considered supported if it had enough of these parameters to create the intended electrical response (watts, Vars). Timers and function-specific ramp rates were not a focus of the supplemental testing. It is noted that the specific parameters required in field scenarios may differ from what was tested, as stipulated by local grid codes and the requirements of utilities and DER owners.

Table 8-13 Summary of results from SCE, SMUD, and EPRI Testing of Inverters and Modules.

Inverter Function	Fronius Inverter								SMA Inverter							
	SunSpec (Modbus)			EPRI (OpenADR 2.0b)			Kitu (IEEE 2030.5)		SunSpec (Modbus)			EPRI (OpenADR 2.0b)			Kitu (IEEE 2030.5)	
	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD
Connect / Disconnect	✓		✓	✓	✓	✓	✓	✓	✓		×	×	×	×	✓	✓
DER Monitoring Points	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Fixed Power Factor	✓		✓	✓	✓	✓	✓	✓	×		×	×	×	×	×	×
Frequency-Watt Curve	×		×	×	×	×	×	×	×		✓	×	×	×	×	×
Limit Max Real Power	✓		✓	✓	✓	✓	✓	✓	×		×	×	×	×	×	✓
Ramp Rate (WGra)			×			×					✓			✓		
Volt-Var Function	✓		✓	✓	✓	✓	✓	✓	✓		✓*	×	×	×	×	✓
Volt-Watt Function	✓		✓	✓	×	✓	✓	✓	✓		✓*	×	×	×	×	✓

*Volt-Var and Volt-Watt functions worked only if the curves were programmed one point at a time. This prevented the EPRI modules from working. See full test results for more details.

8.3.2 Connect/Disconnect Function

Table 6-14 shows that there was some contention on whether the SMA inverter implemented the connect/disconnect function in SunSpec. EPRI's supplemental testing found that when accessing the SunSpec registers on the SMA inverter for Connect/Disconnect the unit returned a value mapped to "Not Supported". The specific parameters included connect/disconnect enable (Conn) and the timers (Comm_WinTms, Conn_RvrtTms). Because the parameters were not supported neither of the modules, EPRI or Kitu, should be able to set these variables.

Table 8-14 Results for Connect/Disconnect on the SMA Inverter – An Excerpt from Table 8-13

Test Case	SMA Inverter							
	SunSpec (Modbus)			EPRI (OpenADR 2.0b)			Kitu (IEEE 2030.5)	
	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD
Connect / Disconnect	✓		×	×	×	×	✓	✓

Upon investigation, the project team found that in all cases where the Connect/Disconnect function was reported as supported with the SMA inverter (Table 6-14), the WMax parameter was used instead of the connect/disconnect function parameters.

Connect/disconnect is a function that allows a user to connect or disconnect an inverter from the grid. A disconnect can take two forms: 1) physical operation of a switch and 2) setting output to 0 / ceasing to energize. Early in the project the team agreed that the manufacturers of these residential products could set output to zero upon receiving a disconnect command.

The Kitu modules succeeded with the SMA inverter by setting the nameplate parameter "WMax" to zero. While this produced a similar result, it is not the intended use of the WMax nameplate rating parameter and results in a couple of issues as discussed in the "Limit Maximum Real Power" section below. Interoperability requires that all inverters are controlled in a consistent way, and communication standards aim to define a singular, unambiguous way.

Key Takeaway: One inverter implementation was not complete. Parties involved in communication integration discovered an alternate way to achieve the desired electrical result. Though both produced the same result, only one method was per the SunSpec specification.

8.3.3 Frequency-Watt Function

Table 6-15 shows that frequency/watt was not supported by either module but there was contention on whether it supported this function through SunSpec. EPRI's supplemental testing found that the SMA did support Frequency/Watt but not the correct mode.

Table 8-15 Results for Frequency-Watt function on the SMA Inverter – An Excerpt from Table 8-13

Test Case	SMA Inverter							
	SunSpec (Modbus)			EPRI (OpenADR 2.0b)			Kitu (IEEE 2030.5)	
	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD
Frequency-Watt Function	✗		✓	✗	✗	✗	✗	✗

According to the IEC 61850-90-7 standard, the Frequency-Watt function may be implemented in two ways. Mode 1 uses settings to achieve a particular Frequency-Watt response in reference to deviation from nominal frequency. Mode 2 is involves the use of an array of X-Y points to create a user-determined "curve" response. This project plan required Mode 2, the curve approach, and all of the modules and tests were designed for this mode. The SMA implemented mode 1 which is the parameter based approach.

Key Takeaway: To achieve interoperability, functions must be implemented in the same way. Wherever standards like IEC 61850-90-7 identify multiple choices, grid codes must make specific selections.

8.3.4 Limit Maximum Real Power

Table 6-16 shows the results from the supplemental testing of the Limit Maximum Real Power function. Early testing at EPRI and utility laboratory test results were varied for this function and the causes for these variations are worth noting. EPRI's supplemental testing found a few items that were causing the varied results.

Table 8-16 Results for Limit Maximum Real Power on the SMA Inverter – An Excerpt from Table 8-13

Test Case	SMA Inverter							
	SunSpec (Modbus)			EPRI (OpenADR 2.0b)			Kitu (IEEE 2030.5)	
	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD
Limit Max Real Power	✗		✗	✗	✗	✗	✗	✓

Upon investigation, it was determined that SMA did not implement the Limit Maximum Real Power function as defined by the SunSpec specification. The function is unsupported but the register to turn the function on and off (WMaxLim_Ena) reads as supported and the parameter to set the output power limit (WMaxLimPct) reads as unsupported but is still writable if attempted. This parameter WMaxLimPct can be written to but not read. EPRI confirmed that writing to this parameter produces an electrical response. It is important to note that because SunSpec specification requires it to be readable and writable this function is deemed unsupported by the library. This was one source of confusion in testing.

In addition, it was determined that during some tests the nameplate rating WMax parameter was managed instead of the WMaxLimPct. Discussions with the utilities found that WMax was used to change the output power of the inverter. WMax is the nameplate rating of the inverter. Reducing the rating will cause the inverter to limit output to a reduced level, but other inverter functions are also affected because they refer to WMax as 100% real power output. It was also noted by the manufacturer that WMax was not designed to be changed often (if at all) and may memory-wearout consequences if used for power control.

EPRI was not able to directly assess how the Kitu module was implemented but discussions with Kitu revealed that the module wrote to the WMaxLimPct register and likely ignored the SMA's unsupported flag for this parameter causing the function to work. The EPRI module design did not attempt to use the function after receiving the "unsupported" response.

Key Takeaway: Utility lab testing used two different methods and arrived at the same result. In one case an incorrect parameter was used and in the other an "unsupported" flag was ignored. Certification testing, when available, is expected to catch such differences and ensure consistent implementation.

8.3.5 Volt-Var Function

Table 6-17 shows that the team agreed that the volt-var function was supported by both inverters but there was contention regarding whether the two communication systems worked with the SMA. This was unexpected because the implementation of the volt-var function should be the same in any inverter using the SunSpec protocol. EPRI's supplemental testing found a few items that were causing the varied results.

Table 8-17 Results for Volt-Var Function on the SMA Inverter – An Excerpt from Table 8-13

Test Case	SMA Inverter							
	SunSpec (Modbus)			EPRI (OpenADR 2.0b)			Kitu (IEEE 2030.5)	
	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD
Volt-Var Curve	✓		✓*	×	×	×	×	✓

During the investigation of this issue, EPRI and SunSpec found a firmware bug in the SunSpec library. It was corrected before EPRI's final testing. In addition, it was discovered that SMA implemented the DeptRef flag incorrectly. According to the IEC 61850-90-7 standard, the values on the dependent axis of the Volt-Var curve settings can be defined in several ways. This is controlled by the DeptRef flag. In the case of the Volt-Var function, the options include percent of maximum VARs (rating), percent of VARs available (only produces as many VARs as available at the current real power output – prioritizes real power generation over VARs), and percent of wattage rating. Each of these are communicated by passing either 1, 2, or 3 to the DeptRef variable. The SMA only supported maximum VARs. This was fine and is specified as the preferred method for this project. The issue identified was that the SMA implemented this register as read-only where the SunSpec protocol specifies it as read/write. The reason this was an issue is because if a system wrote any value to this register the SMA returned a Modbus error. This would cause all information for this function to be ignored by the SMA inverter. In addition, the EPRI module had a bug where it wrote an invalid deptref value. The bug has since been corrected. To continue testing EPRI modified the OpenADR 2.0b module with a workaround to accept the default DeptRef value. Note that this is not an acceptable practice because each DeptRef puts the Volt-Var curve into a new mode and by accepting the default the user is not aware of which mode it is in.

Another issue identified with this function was that the SMA did not accept curves written with multiple points at the same time which is the common practice for both modules. The inverter's software would only allow a user to write one point of the curve at a time, one x-coordinate or one y-coordinate. Per the Modbus standard, a user can write to Modbus registers in two ways: one register at a time or write a block of sequential registers. The SMA accepts both of these approaches for writing to registers and no Modbus errors were generated if a user tried to write to more than one curve coordinate. However, the SMA inverter as-tested only wrote the first coordinate to the SunSpec register. If a curve was entered one point at a time (using a write single register command) the user could successfully set the curve.

Key Takeaway: Even when the correct registers are used to control a function, design differences can exist in relation to the order or method by which the registers are written. Execution of certification testing using a standard communication platform can prevent subtle implementation differences from blocking interoperability.

8.3.6 Volt-Watt Function

and Table 8-19 shows similar results to volt-var. The team agreed volt-watt was supported by both inverters but there were some issues with the modules functioning with the two inverters. EPRI's supplemental testing found a few items causing the varied results.

Table 8-18 Results for Volt-Watt Curve on the Fronius Inverter – An Excerpt from Table 8-13

Test Case	**Fronius Inverter**							
	SunSpec (Modbus)			**EPRI (OpenADR 2.0b)**			**Kitu (IEEE 2030.5)**	
	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD
Volt-Watt Curve	✓		✓	✓	×	✓	✓	✓

Table 8-19 Results for Volt-Watt Curve on the SMA Inverter – An Excerpt from Table 8-13

Test Case	**SMA Inverter**							
	SunSpec (Modbus)			**EPRI (OpenADR 2.0b)**			**Kitu (IEEE 2030.5)**	
	SCE	SMUD	EPRI	SCE	SMUD	EPRI	SCE	SMUD
Volt-Watt Curve	✓		✓*	×	×	×	×	✓

Two noteworthy items were found on the SMA inverter. First, and similar to the Volt-Var function, the SMA had a DeptRef issue for the Volt-Watt function. In the case of the Volt-Watt function, the options include percent of maximum watts (WMax) and percent of watts available (WAvailable). Each of these are communicated by passing a 1 or 2 to the DeptRef variable. The EPRI module only supported WMax while the SMA only supported WAvailable.

Second, the Volt-Watt curve on the SMA inverter had to be written one point at a time. The same behavior was experienced for the Volt-var function and is more extensively explained in that section.

Four noteworthy items were found with the Fronius inverter in relation to this function. First, SMUD identified an issue with DeptRef and how the EPRI module worked with the Fronius. The Fronius inverter implemented the DeptRef register as read/write but ignores all values written to it. The EPRI module would try to change this register to WMax but the register remained set to WAvailable.

Second, testing revealed that in order to make changes to the Fronius' Volt-Watt function parameters, a particular order of operations had to be followed. Certain parameters had to be turned off in order to make changes to others. If this order was followed, the function operated as expected. If the order was not followed, the function disabled itself or ignored the values entered.

Third, whenever the Volt-Watt function settings were altered, the inverter went into standby mode and then reconnected. This happened if the curve was turned on or off using the ModEna register (Volt-Watt Curve – Enable/Disable) or if any of the four curves were changed while ModEna was set to 1 (Curve Enable).

Fourth, the Fronius inverter required that the first two wattage values (of three total) were set to 100% for the Volt-Watt function. Writing anything other than 100% did not produce errors but the value was replaced by 100% when read.

8.3.7 Key Findings

- The inverters successfully supported some of the functions in an interoperable way, but had certain issues with others.
- The Fronius inverter began the project with substantial SunSpec Modbus protocol capabilities and added others. The resulting product interoperated with the two communication systems extensively.
- The SMA inverter began the project with little of the SunSpec Modbus protocol implemented but made significant progress in adding these capabilities and was able to demonstrate interoperability with the two communication systems for certain functions.
- Many of the functions did not behave ideally, but once understood, worked with a few adjustments.
- In the course of this project many changes were made to the firmware, each one advancing the inverter a bit further forward. The Fronius had a couple issues but it appeared that the functions that were implemented were implemented fully.

  Future Research Opportunities: In both cases, conformance testing and interoperability events will help identify these issues over time.
- DeptRef is a parameter that specifies how the dependent variable (Y-Axis) of curve functions is scaled. For example, the Y-axis of a Volt-Var curve can be defined as % of maximum Vars or %of available Vars according to communication standards. The intended setting of this parameter should be specified by grid codes because functionality is substantially different based on how DeptRef is set. The two inverters tested did not implement the same DeptRef for all functions.

  Future Research Opportunities: A dashboard or top node should either make it clear to users what DeptRef is default or provide users with a choice. The inverters should also be able to communicate which modes are supported or provide meaningful error messages back to the user. It is likely that grid codes and utilities will require specific deptref values in interconnection agreements. If this is the case, the supported DeptRefs across management tools and inverters will converge on these requirements.
- SMA's Grid Guard® feature locks out communication and is not part of the SunSpec specification. Any features that are unique to a single manufacturer impede interoperability and must be addressed in compliance standards.

Future Research Opportunities: the members of the SunSpec Alliance may consider if access protection keys (Grid Guard Code) should be part of the SunSpec specification.

- The SMA inverter only allows curves to be written one point at a time. This is an example of why certification testing should be conducted using the intended communication standard – ensuring implementation in a particular way.
- The Fronius power cycles at the beginning and end of volt-watt operation and when changes are made to the parameters. The function also requires an order of operation to enable volt-watt curves. This is an example of why communication and functional testing should be linked. In other words, it is not sufficient to simply communicate properly, the communication must result in the expected power response. Restarting is not acceptable in response to a variable control signal that might be continuously managed.

9 FIELD TESTING

The laboratory testing was followed by field testing by both SCE and SMUD. The purpose of the field testing was to re-assess the communication systems and inverters in actual environments. Specifically:

- The communication system signal strengths may be ideal in laboratory environments but weak in field environments. This is of particular concern when small communication modules are used because their antenna geometries typically do not have the gain or range that larger equipment has.
- Communication system noise levels may be higher. Laboratory tests can inadvertently create ideal circumstances that are not common in the field.
- Communication system activity may be higher. In field environments, the communication systems may be active supporting other uses and this activity could impact the test results.
- Inverter operation may differ when fed from actual PV panels instead of a PV simulator.
- Inverter operation may differ when connected to an actual AC grid voltage (e.g. voltage variability, noise) rather than a grid simulator.

Per the project scope and plan, the scale of the field tests was the same as the laboratory testing. Multiple inverters at multiple sites would have provided more insight into the field communication scenarios.

9.1 Southern California Edison Field Testing

This section of the report outlines the field integration testing for comparison with the end-to-end system testing performed in the lab. This testing was performed using the Fronius inverter. The field test task was originally intended to include evaluation of real-world communication system latencies to the inverters, but the internet-based systems that were ultimately chosen by SCE for this project made latency less of a concern. Therefore the field testing performed by SCE focused on the communication systems ability to update the Fronius inverter settings and evaluating the corresponding smart inverter response given the variability of real solar photovoltaic panels as well as an actual grid connection in the field setup.

9.1.1 Communications Architecture

Similar to the laboratory testing, two different cloud-based servers were used as the headend to communicate via OpenADR and IEEE 2030.5 protocols. Also, the same gateway/access point was used to join the CTA-2045 modules to the Wi-Fi network and to point back to the servers residing on the internet.

9.1.2 Field Testing Equipment

Unlike the laboratory setup, the Fronius smart inverter is connected to a real 3.3 kW solar PV array located on the roof of the SCE facility where field testing was performed. Additionally, the inverter was connected to the actual grid with loads at the local facility.

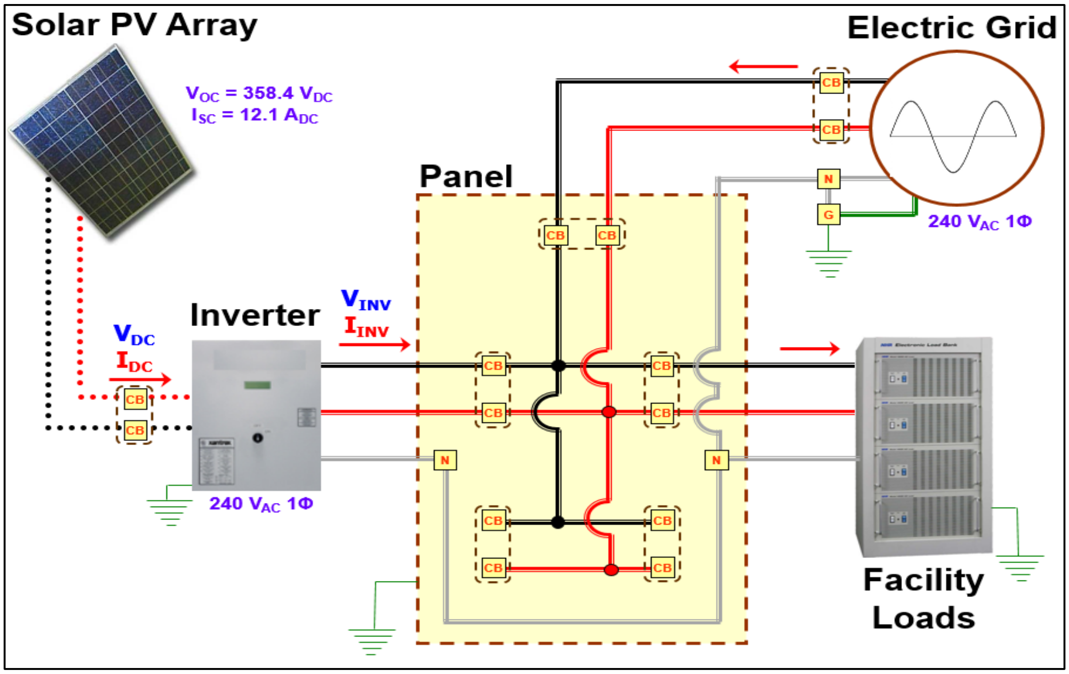


Figure 9-1, Diagram of Electrical Test Setup for SCE Field Testing

Figure 9-2, SCE Field Setup - Rooftop Solar PV Array

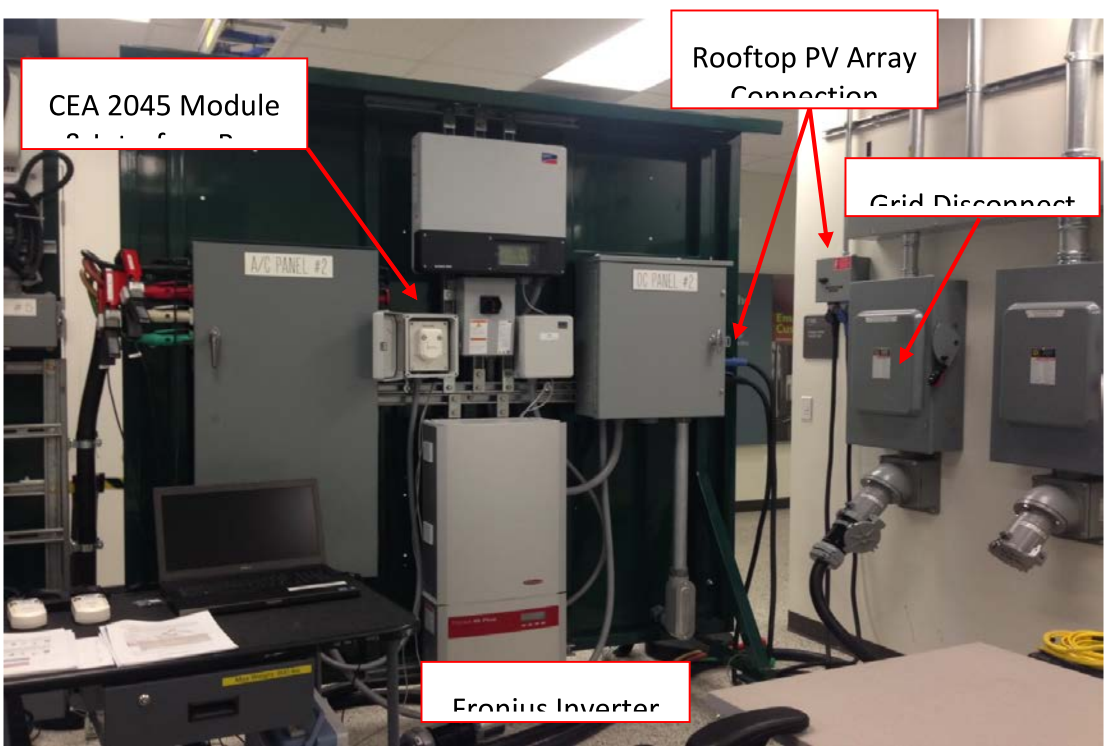


Figure 9-3, SCE Field Setup – Inverters & Communication Modules

9.1.3 Field Testing Results

The following table provides a summary of SCE's field integration testing of the Fronius inverter using different communication protocols, including a hardwired Modbus connection and the SunSpec Dashboard tool to verify the internal registers. The IEEE 2030.5 and OpenADR protocols were demonstrated over Wi-Fi using the corresponding communication modules and headend systems for comparison with the lab testing results.

Table 9-1, SCE Field Test Results Summary

Test Case	Fronius Inverter		
	SunSpec (Modbus)	**AutoGrid (2030.5)**	**EPRI (OpenADR2.0b)**
Volt-VAR Mode	✓	✓	✓
Fixed Power Factor	✓	✓	✓
Limit Max. Real Power	✓	✓	✓
Volt-Watt Mode	✓	✓	✓
Freq-Watt Mode	×	×	×
Connect/Disconnect	✓	✓	✓
Monitor DER	✓	✓	✓

Field test results indicate that the Fronius inverter successfully demonstrated nearly all of the smart inverter functions using both IEEE 2030.5 and OpenADR protocols, similar to what was observed during lab testing. Several secondary issues were observed which includes the inverter restarting each time the volt-watt function was re-configured. Additionally, there were several instances in which the inverter did not return to its default values after changing the fixed power factor. However the inverter and communication systems behaved as expected, successfully demonstrating most the advanced inverter functionality tested.

Volt-VAR Function

Due to the static nature of the grid voltage at the SCE test site, no significant changes in Var production were observed at the output of the inverter when performing a volt-var function test. For this reason, the Modbus registers were observed via the SunSpec Dashboard tool to verify that the Fronius inverter successfully updated and enabled its volt-var settings after scheduling the DER event using either communication system. No abnormal behavior from the inverter was observed while communicating to the inverter or while operating in this mode while connected to the grid. The following table summarizes the results of the various volt-var tests:

Table 9-2, SCE Volt-VAR Function Field Results Summary

Volt-VAR	Fronius Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR 2.0b)
Curve #1	✓	✓	✓
Curve #2	✓	✓	✓
Curve #3	✓	✓	✓

Fixed Power Factor Function

The Fronius inverter successfully demonstrated the fixed power factor function of operation using a variety of values. In some cases while using OpenADR, the inverter did not revert back to its default power factor setting after the scheduled DER event ended. The following table summarizes the results of these fixed power factor tests while using the different headend systems:

Table 9-3, Fixed Power Factor Function Field Results Summary

Fixed PF	Fronius Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR 2.0b)
+ 0.90	✓	✓	✓
+ 0.95	✓	✓	✓
1.00	✓	✓	✓
- 0.95	✓	✓	✓
- 0.90	✓	✓	✓

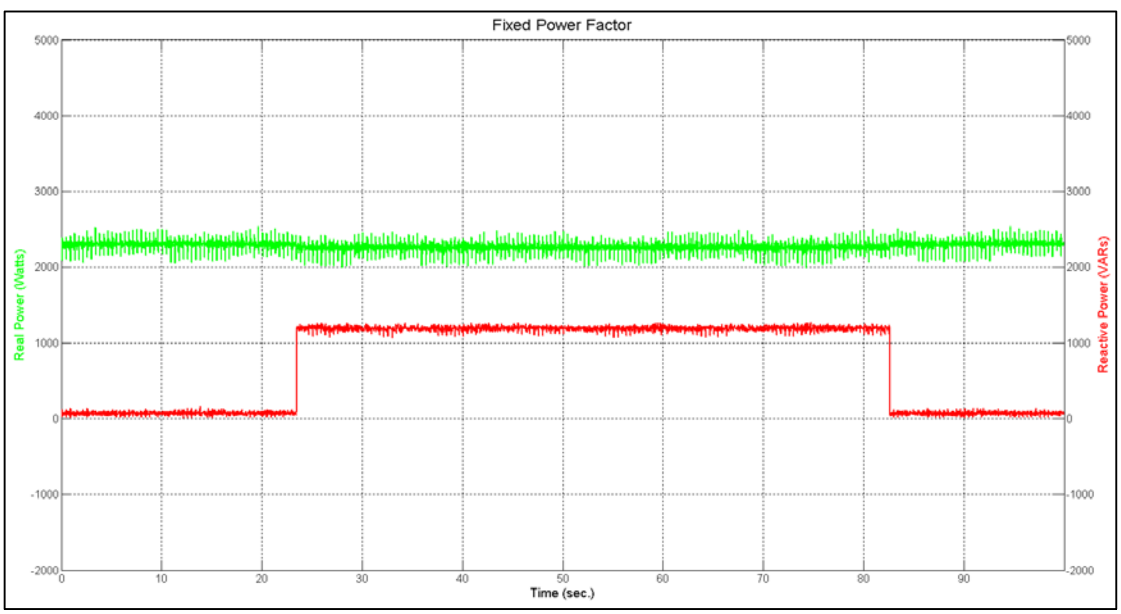


Figure 9-4, Sample Fixed PF Test (-0.90)

Maximum Power Limit Function

In a field setup with a real PV array, the inverter may not always be generating at full output and therefore the limit maximum power values must be adjusted accordingly to perform the test under the current operating conditions. The Fronius inverter successfully demonstrated limiting the maximum real power output just as it did during lab testing. The following table summarizes results for a variety of WMaxLimPct values using different protocols:

Table 9-4, SCE Maximum Power Limit Function Field Results Summary

Max. Real Power Limit	Fronius Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR 2.0b)
100%	✓	✓	✓
20%	✓	✓	✓
15%	✓	✓	✓
10%	✓	✓	✓

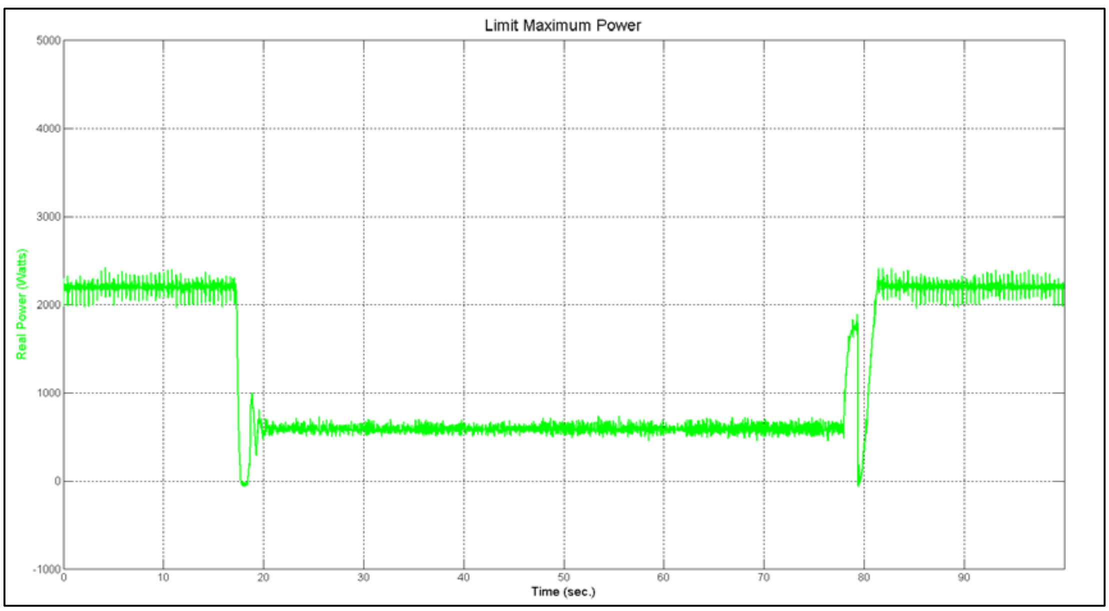


Figure 9-5, Sample Limit Maximum Real Power Test (10% Rated Power)

Voltage-Watt Function

Due to the static nature of the grid voltage, no changes were observed at the output of the inverter when performing an autonomous volt-watt function test. The Modbus registers were observed via the SunSpec Dashboard tool to verify that the Fronius inverter successfully updated and enabled its volt-watt settings after scheduling the DER event.

Similar to the observations during a lab testing, the Fronius inverter went into a “Sync” mode where it ceased to generate until the grid side conditions were appropriate for 5 minutes after the DER event was enabled/disabled. The following table summarizes the volt-watt results using the different communication systems:

Table 9-5, SCE Volt-Watt Function Field Results Summary

Volt-Watt	Fronius Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR 2.0b)
Curve #1	✓	✓	✓
Curve #2	✓	✓	✓

Frequency-Watt Function

The frequency-watt functionality was not supported by the Fronius inverter and therefore could not be tested accordingly in the field setup.

Table 9-6, SCE Frequency-Watt Function Field Results Summary

Freq-Watt	Fronius Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR 2.0b)
Curve #1	×	×	×
Curve #2	×	×	×

Connect/Disconnect Function

The Fronius inverter successfully reduced the real power output to near zero during field testing with the different communication systems. Similar to the observations during laboratory testing, the inverter demonstrated a function better described as "cease generation" rather than a physical disconnection from the electric grid.

Table 9-7, SCE Connect-Disconnect Function Field Results Summary

Disconnect	Fronius Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR 2.0b)
0%	✓	✓	✓

Monitor DER Status and Output

As mentioned in the lab testing section, the Autogrid IEEE 2030.5 server did not provide an interface to view or download data, but Wireshark traces confirmed the capability of the IEEE 2030.5 systems to post all 7 data points collected by the Fronius. The EPRI OpenADR VTN provided an interface to view and download the data points. The following table summarizes successful monitoring of the Fronius inverter using the different communication systems.

Table 9-8, SCE Monitoring Field Results Summary

Monitoring	Fronius Inverter		
	SunSpec (Modbus)	AutoGrid (2030.5)	EPRI (OpenADR 2.0b)
V, A, W, etc.	✓	✓*	✓

9.2 Sacramento Municipal Utility District Field Testing

This section of the report outlines the complete end-to-end integration testing of the Fronius and SMA inverters at SMUD. Both inverters were tested on an actual grid-connected PV system at SMUD's facilities connected to building and EV charging loads. The PV system was chosen because it is a real world installation that was close to the size of the rated inverters. Because of the fully safety tested nature of the inverters, SMUD felt that it was safe to do testing on a real system, but because full listing was not acquired, testing was temporary. It was limited to the length of two days. One day was reserved for each inverter. The field testing included real-world communications through internet-based system. This was chosen because our AMI system is an IP-based system, but it was not implemented over our enterprise system because integration costs were too high. The main focus of the field testing was to evaluate the commands and responses between the head-end and the inverters.

9.2.1 Communications Architecture

The field testing used the same IP-based server that was used in the laboratory testing. It utilized the IEEE 2030.5 protocols. The same router and CTA-2045 modules from the laboratory testing were used in the field.

9.2.2 Field Testing Equipment

Both inverters were connected to a 10 kW PV array. Panels from the PV array were safely disconnected to reduce the DC output to 3 kW. The inverters were feeding power into the AC power grid. The two inverters were alternately installed and tested in the same electrical system.

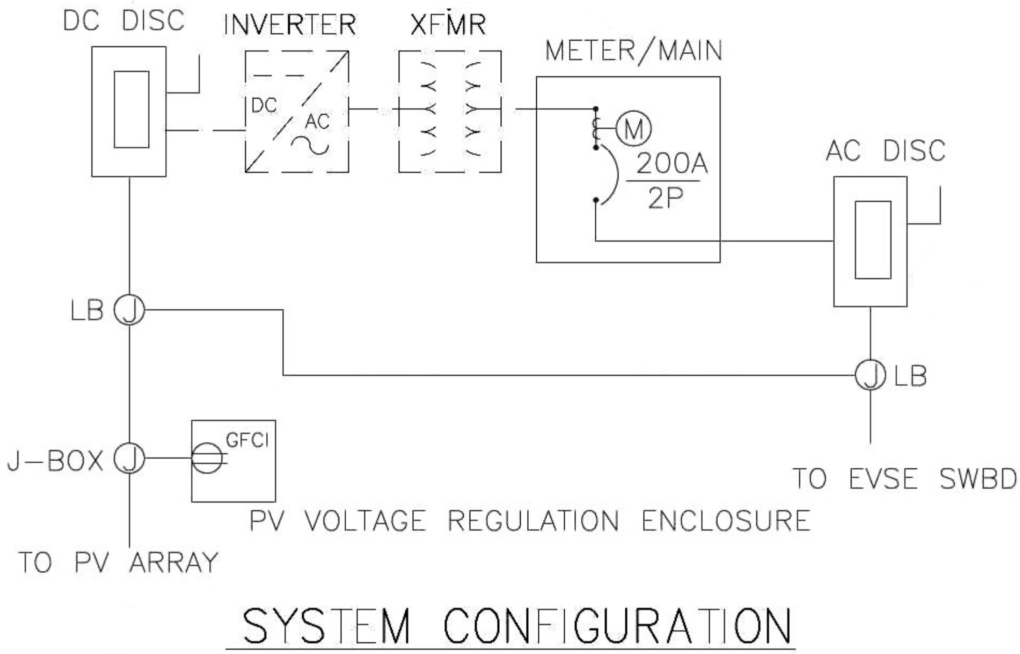
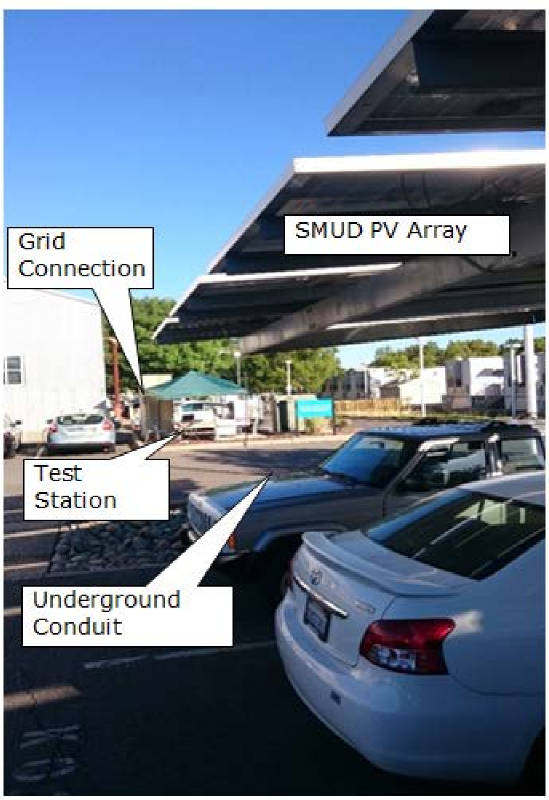


Figure 9-6, Diagram of Electrical Test Setup for SMUD Field Testing



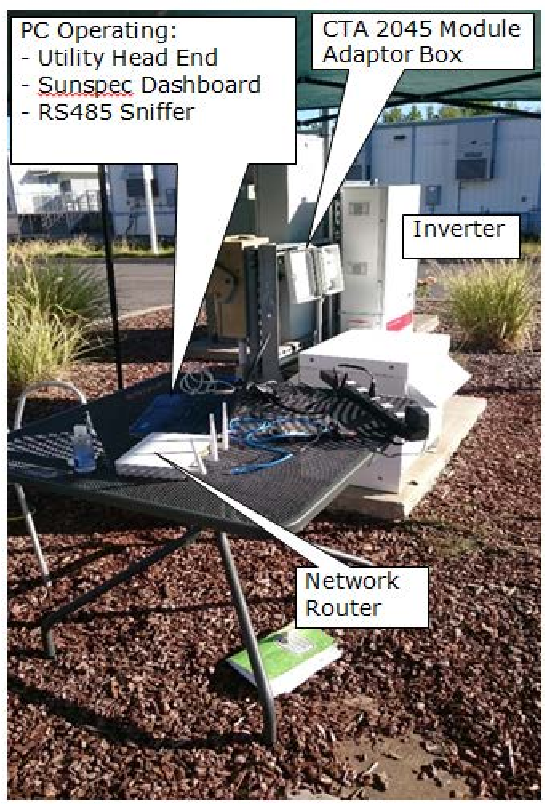


Figure 9-7, SMUD Field Setup - Rooftop Solar PV Array (Left) & Field Testing Station (Right)

9.2.3 Field Testing Results

Table 9-9, SMUD Field Testing Results Summary

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CEA-2045			
	Fronius		SMA	
	Lab	Field	Lab	Field
Registration	√	√	√	√
Volt-Var	√*	√*	X*	X*
Fixed Power Factor	√*	√*	X*	X*
Limited Max Real Power	√*	√*	√*	√*
Voltage-Watt	√*	√*	X*	X*
Freq-Watt	X*	X*	X*	X*
Connect/Disconnect	√*	√*	X*	X*
Monitor DER Status	√*	√*	√*	√*

Legend:

√=Passed

X=Did Not Pass

*=Issues Found (explained in each test case below)

Registration

Registration encompasses all communication set up procedures and is a pre-condition for the remainder of the test cases. Registration comprises the registration of devices on servers, automated server and resource discovery processes, network commissioning, and provisioning of server information on clients (IP Addresses, URLs, program information, etc.). The purpose of this test case is to ensure interoperability of various technologies, architectures, and standards, and is fundamental to meeting the objectives of the CSI4 project.

Table 9-10, SMUD Registration Test Results

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045	
	Fronius	SMA
Registration	√	√

Volt-Var Function with Watt Priority

Dynamic volt/var operations allow DER systems to counteract voltage deviations from the nominal voltage level (but still within normal operating ranges) by consuming or producing reactive power. Dynamic volt/var curves can specify the changes in Vars in response to changes in the local voltage measured at the inverter terminals.

Table 9-11, SMUD Volt-Var Mode with Watt Priority Test Results

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045	
	Fronius	SMA
Volt-Var	√*	X*

Test Observations:

- Field test was performed for the Volt-Var mode with Watt priority curve #1 set ((88,100)(99,0)(101,0)(110,-100), Watt). Other curves were not tested.
- SMA does not appear to update any of the values when observed by the SunSpec Dashboard. This is slightly different from laboratory tests which indicated first curve points were updated but not rest.
- The list of issues identified for this test is identical to the laboratory based tests.

Limit Maximum Real Power Function

While solar photovoltaic generation is dependent on solar irradiance and can therefore be intermittent throughout the day, the DER system settings can be modified to place a maximum limit on amount of real power generated. Limiting maximum real power may be necessary in response to unusual or emergency conditions that are causing reverse flow into the feeder's substation or because the total DER real power output on the feeder is greater than some percentage of total load, which can potentially result in higher voltages on the distribution feeder.

This test case will cover the above use case by initiating a series of Limit Maximum Real Power commands from the Utility DER Head End system to the target smart inverter device using the values from Table 9-12 below.

Table 9-12, SMUD Limit Maximum Real Power Test Results

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045	
	Fronius	SMA
Limited Max Real Power	√*	√*

Test Observations:

- Field test was performed for the Limit Maximum Real Power #5 value (20%). Other values were not tested.
- The list of issues identified for this test is identical to the laboratory based tests.

Voltage-Watt Function

The DER system autonomously modifies real power output in order to dampen voltage deviations. The purpose of voltage-watt operations is to use DER systems to help maintain voltage levels within their normal ranges as an alternative to emergency tripping in cases where an abundance of generation is resulting in higher voltages on the feeder. These higher voltages could be the result of reverse power flow on small conductors. The inverter would follow a voltage-watt curve that would specify the maximum real power output in response to the measured voltage at the inverter terminals.

Table 9-13, SMUD Voltage-Watt Mode Test Results

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045	
	Fronius	SMA
Voltage-Watt	√*	X*

Test Observations:

- Field test was performed for the Voltage Watt Curve #1 value ((90,100)(106,100)(110,0)(120,0)). Other curves were not tested.
- The list of issues identified for this test is identical to the laboratory based tests

Frequency-Watt Function

The DER system autonomously modifies real power output to counter frequency deviations. This action may be taken during emergency conditions or during normal operations to smooth minor frequency variations. The inverter would follow a frequency-watt curve that would specify the maximum real power output in response to the measured frequency at the inverter terminals.

This test case will cover the above use case by initiating a series of Frequency-Watt curve inverter control commands from the Utility DER Head End system to the target smart inverter device using the values from the Table 9-14 below.

Table 9-14, SMUD Frequency-Watt Mode Test Results

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045	
	Fronius	SMA
Freq-Watt	X*	X*

Test Observations:

Neither Fronius nor SMA support curve based Frequency -Watt mode. This is same limitation as observed during laboratory tests.

- Fronius: No curve based Frequency-Watt Information Model or Modbus registers on DUT to support this functionality. CTA-2045 modules do not attempt to write event settings to Modbus.
- SMA: No curve based Frequency Watt Information Model or Modbus registers on DUT to support this functionality. CTA-2045 modules do not attempt to write event settings to Modbus.

Connect/Disconnect Function

This particular function causes the DER system to electrically connect or disconnect from the grid. This may be implemented in response to an unusual or emergency condition requiring the DER system to be de-energized. The DER equipment may be disrupting the grid due to malfunctioning behavior or the resource may need to be disconnected for maintenance.

This test case will cover the above use case by initiating a Connect/Disconnect inverter control commands from the Utility DER Head End system to the target smart inverter device.

Table 9-15, SMUD Connect/Disconnect Test Results

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045	
	Fronius	SMA
Connect/Disconnect	√*	X*

Test Observations:

Both Fronius and SMA have issues related to Connect/Disconnect tests. This observation and the list of issues are identical to the laboratory tests that were performed.

Monitor DER Status and Output

DER systems connected to the utility distribution system will be required to have monitoring capabilities that provide operational state data. This may include the system status (i.e.

connected/disconnected) as well as various power system measurements (watts, Vars, voltage, etc.).

This test case will cover the above use case by initiating a set of inverter monitoring commands from the Utility DER Head End system to the target smart inverter device.

Table 9-16, SMUD Monitor DER Status and Output Test Results

Test Case	IEEE 2030.5 QLI DER Head End/Kitu CTA-2045	
	Fronius	SMA
Monitor DER Status	√*	√*

Test Observations:

Modbus traces indicates that the Kitu CTA-2045 (SEP 2.0) module is not requesting Current(A) and Voltage (V). Posts are fixed at 655350 and 21300 respectively.

10 CONCLUSIONS

10.1 Benefits to Ratepayers

The multiple activities and outcomes of this project directly benefit California utility ratepayers in several ways, including:

Enabling Consumer Solar Energy. The primary driver of communication-connected solar inverters is to enable distribution circuits to accommodate more PV systems. This project proved that residential scale solar inverters could perform the grid-supportive functions identified in California's Rule 21 revision process. This makes it possible for more consumers to own and operate grid-tied PV systems, to employ them at greater scales, and to do so with minimal limitations.

Providing Consumer Choice. The project proved the viability of inverters being integrated through multiple (and by extension, any) communication system. If this technology is adopted in the marketplace, it will provide California ratepayers with flexibility and choice in terms of how their PV systems are integrated. For example, if a PV system was originally deployed with a communication connection directly to the inverter manufacturer, and the consumer later decided to purchase a smart home automation system, the PV system could be readily connected into the home system to help manage variability, peak load, etc.

Enabling New Value Streams for Solar PV Owners. The smart inverters with open communication interfaces that were developed and tested in this project support a wide range of functionality beyond simple real-power generation. The result, from the perspective of the California ratepayer, is to be able to provide a wide range of services for which markets may exist. For example, a residential PV system could potentially provide variable regulation services to an ISO or reactive power services to a local DSO. The openness of the communication interface means that should such opportunities exist, the ratepayer would not be prevented or blocked from participating due to a limitation of a given communication interface.

Enabling Marking/Identification of Device Openness. The certification/compliance-test aspect of this project involved linking the functional and communication aspects of inverter products (i.e. UL testing using the SunSpec protocol). To the extent that such relationships are reflected in products in California, ratepayers benefit from clarity at the time of product purchase regarding the communication options they will have over the life of the system.

Enhancing Marketplace Competition and Innovation. The interoperability demonstrated in this project naturally encourages competition among both inverter manufacturers and communication integration providers. When products are open and interoperable, more business opportunities exist, barriers to market entry are reduced, and consumers benefit from the improved set of options they are presented.

Avoiding Product Obsolescence. The open interoperable approach that was demonstrated in this project provides the ratepayer a path for upgradeability – the ability for inverter owners/operators to change communication systems over the life of the product. From a

California ratepayer perspective, this lowers the risk of obsolescence and enhances the likelihood that PV systems can remain compatible with grid-support opportunities that could involve economic benefits for the system owner.

10.2 Positive Outcomes

Supporting California's Renewable Energy Goals. This project was timely in that the execution ran in parallel with, and accelerated, important industry activities that are aimed to enable California's renewable energy goals. To the extent that they are achieved, these goals bring a range of identified benefits to California including environmental and business/economical.

- SIWG Recommendations
- CA Rule 21 Revisions
- IEEE 1547a Amendment
- IEEE 1547 Full Revision
- IEC 61850-7-420 and IEC 61850-7-520 revisions in TC57 WG17
- EPRI Common Functions, 4th Edition, 2016
- UL 1741 SA
- EPRI DER Group-Level Integration Initiative

Rule 21 Functionality is Achievable. The project found that the CA Rule 21 Phase 1 functionalities are practical and supportable, even by small scale residential inverters. This is an important finding and informs industry discussions regarding what sizes of DER might be able to provide grid support.

SunSpec Protocol Interoperability. The project found that the SunSpec Modbus protocol could be used to achieve interoperability of smart inverters based on a core set of monitoring and management functions. Project partners Fronius and SMA were able to produce products that supported required functionality and interoperated to varying degrees.

Communication Systems that Can Work with any Inverter. This project utilized a modular communication approach in which the inverters were made with a standard CTA-2045 port interface. Each communication system provider produced a single module design that could plug-into either inverter and bring it onto their network. This was accomplished without inverter-specific code in the modules, and so is extensible to many brands/types.

Network Manageability. The modular approach demonstrated in this project makes it possible for the communication modules/modems to be of a single type across a diverse set of inverters. This makes it practical for the network operator to push-out firmware upgrades to fix cyber security problems, to enhance system performance, and to improve reliability by deploying edge-processing and distributed intelligence throughout the system. It is not practical to perform system-wide security upgrades in an environment in which each node has unique firmware.

Solar Inverters that Can Work with any Communication Network. Each inverter manufacturer produced a single inverter design that could accept either of the communication system modules, without modification. This means that a consumer or business can have peace of mind when making inverter selection, knowing that it can be connected in any number of ways over the life of the system.

IEEE 2030.5 Protocol. The project successfully applied the existing IEEE 2030.5 protocol in one of the communication networks (from the utility head-end to gateway to communication modules on the Fronius and SMA inverters) to support the California Rule 21 control and monitoring functions.

OpenADR 2.0b Protocol. The project was able to adapt the OpenADR 2.0b protocol in order to support Rule 21 functionality. It is noted that OpenADR's specified Event types do not inherently support Rule 21 inverter functions. However, using OpenADR's flexible tool box of Event characteristics, it was straightforward to build conformant OpenADR Event payloads that could encapsulate the inverter function settings. The project team was able to show the network flexibility achieved by the SunSpec/CTA-2045 interface and that OpenADR 2.0b could be used to communicate information to the smart inverters.

10.3 Challenges

Timing of Parallel Industry Activities. When this project started in 2014, it was not possible to know the exact content and timeline of developments within the California Rule 21 revision and associated UL 1741 SA processes. The project plan was to be as adaptive as possible, tracking these activities and modifying the technical scope as long as possible. As it turned out, the approved California Rule 21 Phase 1 did not require communications, so the associated UL 1741 SA likewise does not require the use of any particular communication protocol. This resulted in the smart inverter requirements of this project meeting, but also exceeding, the present Rule 21 requirements.

General Complexity of Smart Inverter Integration. The project brought the project team deeper appreciation of the complexity of smart inverter functions and integration with utility systems. A strategy of small, incremental steps is advisable.

Levels of Interoperability. The developments and testing of this project underscored the fact that interoperability is multi-faceted. Communication system developers commonly work with the Open Systems Interconnection (OSI) model of 7 layers or the simplified 4 layers of the Internet model. But these layers only address the successful transfer of data from one entity to the other. Understanding of goals and intentions at other levels is also required to achieve the utility industry's goals in relation to solar integration.

The GridWise Architecture Council's eight-layer model shown in Figure 8-1 can be used to highlight the challenges noted in this project. The communication standards and specifications utilized addressed (or attempted to address) the lower "Technical" layers, with the CTA-2045 port definition and Wi-Fi media relating to Layer 1 and the SunSpec, IEEE 2030.5 and OpenADR 2.0b protocols relating to Layers 2 and 3.

The GWAC "informational" layers 4 and 5 relate to some of the interoperability challenges identified in the project:

- One inverter, upon each change to the Volt-Watt function setting, shutdown and restarted (a minutes-long process) before the change took effect. The communication protocol was correct and the functionality of the Volt-Watt function (once active) was correct.
- There were differences in the number of Volt-Var curve points that each inverter could accommodate. As a result, a control system that attempted to send a common 4-point curve to all DER in a group would succeed with some but fail with others. The communication protocol was correct, and the functionality of the Volt-Var function was correct within the limitations of each brand. This shows why grid codes and associated functional tests like UL1741 need to be specific in terms of capabilities within required functions.

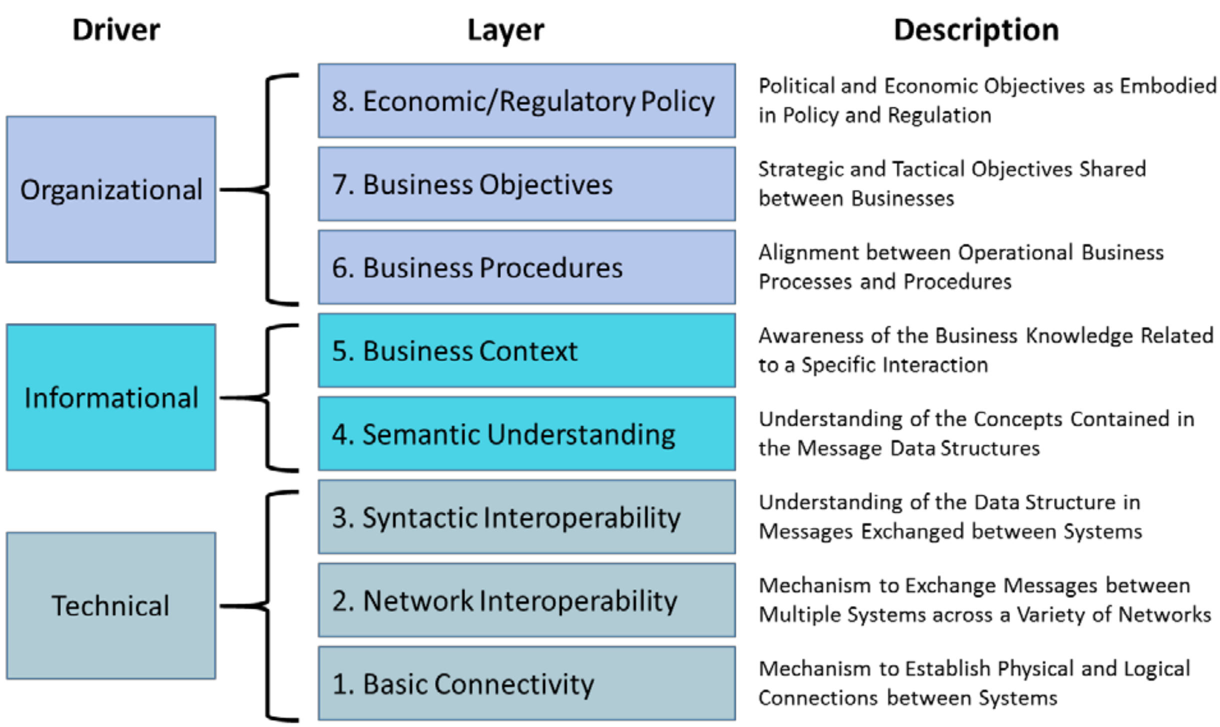


Figure 10-1, GridWise Architecture Council's Eight-Layer Interoperability Model

Issues that relate to the GWAC "Organizational" layers were also noted. For example, the original project plan was to implement Volt-Var control with Watt-priority, but both manufacturer's final implementations used Var-priority (% of Var,max). California Rule 21 Phase 1 requires Watt-priority by default, but notes that Var-priority may also be included by mutual agreement. California Rule 21 also adds further definition to the Volt-Var function, establishing power-factor ranges within which the function's behavior must remain. At the same time, a voltage-regulation sub-group within the IEEE 1547 full revision process was considering different requirements. The regulatory/policy uncertainty created by these ongoing developments made it difficult for manufacturers to finalize and implement their product designs.

New and Ongoing Product Implementations. Project execution was challenged by product designs (inverters and communication systems) that were new and ongoing. Implementation of the SunSpec protocol was an ongoing process throughout the project period.

Testing Complexity. Advanced inverter functionality defined in California Rule 21 and IEEE 1547 will result in an order of magnitude increase in the complexity of the testing of smart inverters. The utility industry has done a great job pulling together in this area, producing the UL 1741SA[8] test specification during the project. This specification is becoming the recognized certification process for the smart inverter functions but in-line with CA Rule 21 Phase 1, does not include any communications testing in the certification at this time.

Complete Communication Certification is a Necessity. Achieving interoperability is difficult, even for a short list of functions and a relatively simple protocol. Communication compliance testing is needed for both inverters and communication modems/modules. A strong supporting testing document and associated processes are needed - Interoperability requires steps beyond basic compliance.

The ideal scenario would be formal industry certification end-end (head-end to the SunSpec inverter interface) consisting of both conformance and interoperability testing by recognized 3rd party independent test labs. For communication networks that are internally based on open standards, such as the IEEE 2030.5 and OpenADR 2.0b used in this project, communication modules could be provided by multiple sources of supply, so additional certifications are also needed.

The OpenADR Alliance has a conformance certification program but it does not include specific smart inverter functionality or interoperability. The USnap Alliance does not currently have a certification program in operation while the SunSpec Alliance conducts a self-certification program that is only conformance oriented. Neither conduct interoperability testing as part of their certifications. There is a formal industry test specification for IEEE 2030.5 and approved test tools that implement it, but there is not yet a formal industry certification program in place nor does the current specification include interoperability testing, smart inverter specific tests or end-to-end testing.

[8] 1741SA passed initial ballot but with 175 comments. Draft made available to IEEE 1547 for augmentation of 1547.1