SUNSPEC ALLIANCE

CASE STUDY

SMART INVERTER PERFORMANCE TESTING TO UL 1741 SA AND CA RULE 21 CRITERIA: RESULTS FROM THE UC SAN DIEGO SMART INVERTER LABORATORY

Performance Testing of Smart Inverters According to UL 1741 SA / CA Rule 21 Criteria is the final Task 2 report for the *Smart Inverter Interoperability Standards and Open Testing Framework to Support High-Penetration Distributed Photovoltaics and Storage project, CEC EPC-14-036,* conducted by the SunSpec Alliance.

The information from this project contributes to Energy Research and Development Division's EPIC Program.

The full report can be found at SunSpec.org.

MARCH 2019

CONTENTS

LIST OF FIGURES

TEST CONTEXT

Inverters are electrical devices that convert Direct Current (DC) power generated by Distributed Energy Resource (DER) systems to alternating current (AC) power that can be accepted by the electrical grid. Pre-2017 inverter technology is basic in nature: it does not actively support grid health and is considered unsafe when installed on circuits where the fraction of energy generated by DER systems is more than 15% of energy consumption.

With the success of California's renewable energy policies, by 2010 it was anticipated that DER generation levels would soon exceed the 15% limit. To address the challenge of overcoming the 15% limitation, the State of California and Underwriters Laboratories (UL) collaborated on the development of the UL 1741 SA standard to define advanced functionality and safety requirements for so-called "smart inverters" that would enable these devices to be installed in far greater density. This standard was subsequently utilized to support the implementation of the latest revision of California interconnection Rule 21 (CA Rule 21).

The smart inverter functions defined in UL 1741 SA enable DER systems to play a role in supporting the stable and reliable operation of the electric grid. Some functions, such as low- and high-voltage ride-through, take advantage of the ability of the smart inverter to remain connected to the system during certain types of disturbances, allowing the inverter and its connected energy source to contribute to grid stability and reliability—rather than disconnecting at the slightest hint of trouble, thus exacerbating the disturbance. During the course of this project, the concepts worked out here were incorporated into the national DER standard IEEE 1547-2018.

During the course of this project, the concepts worked out here were incorporated into the national DER standard IEEE 1547-2018.

The objective of this aspect of this project task was to construct a smart inverter testing laboratory at University of California San Diego for the direct testing of inverters according to the criteria for the advanced functions set forth in UL 1741 SA and CA Rule 21. Inverters compliant with this new standard were supplied by the manufacturers and tested in the laboratory with controlled testing protocols according to the requirements of the tests. The tests address the "Phase 1" set of functions of CA Rule 21[1].

1 A related CEC EPIC project EPC 16-079 leverages the UCSD smart inverter test lab to validate "Phase 3" functions of CA Rule 21 and to perform simulated end-to-end functional testing of DER systems.

PROJECT PURPOSE

The objectives of this part of the EPC 14-036 project were three-fold:

1 Determine the effectiveness of utilizing a standard data communication protocol to change settings of CA Rule 21 Phase 1 functions of DER systems that incorporate energy storage;

2 Determine the readiness of the smart inverter industry to meet future CA Rule 21 requirements;

3 Develop an open, software-based framework for testing and evaluating smart inverters for functional performance and communication interoperability.

With the exception of exercising energy storage in the lab (this was covered in the field trial portion of the project) all three objectives were achieved in a complete and robust manner.

PROJECT PROCESS

1. Recruit Smart Inverter Manufacturers

The first step of the process was to recruit smart inverter manufacturers to participate in the program.

Firms were selected based upon the vendor's:

- Intention to achieve UL 1741 SA compliance,
- Plan to incorporate a standard SunSpec Modbus communication interface in their smart inverter, and
- Ability to support the project over a four-year term. Seven initial vendors met program criteria and were welcomed to the project.

2. Construct Smart Inverter Test Laboratory

The second step was to construct a smart inverter test laboratory at the University of California San Diego (UCSD) using off-the-shelf hardware components (i.e. PV simulator, grid simulator, data acquisition device, networks, computing hardware) and an open source, smart inverter validation software platform called SunSpec System Validation Platform ("SunSpec SVP").

The open source aspect of SunSpec SVP was critical because, although a substantial number of software-based test scripts had been developed, additional test capabilities needed to be developed and refined over the course of the project.

The SunSpec SVP developer community, including experts from national energy laboratories, academic institutions, the DER industry, and SunSpec personnel, were enlisted to develop software test scripts.

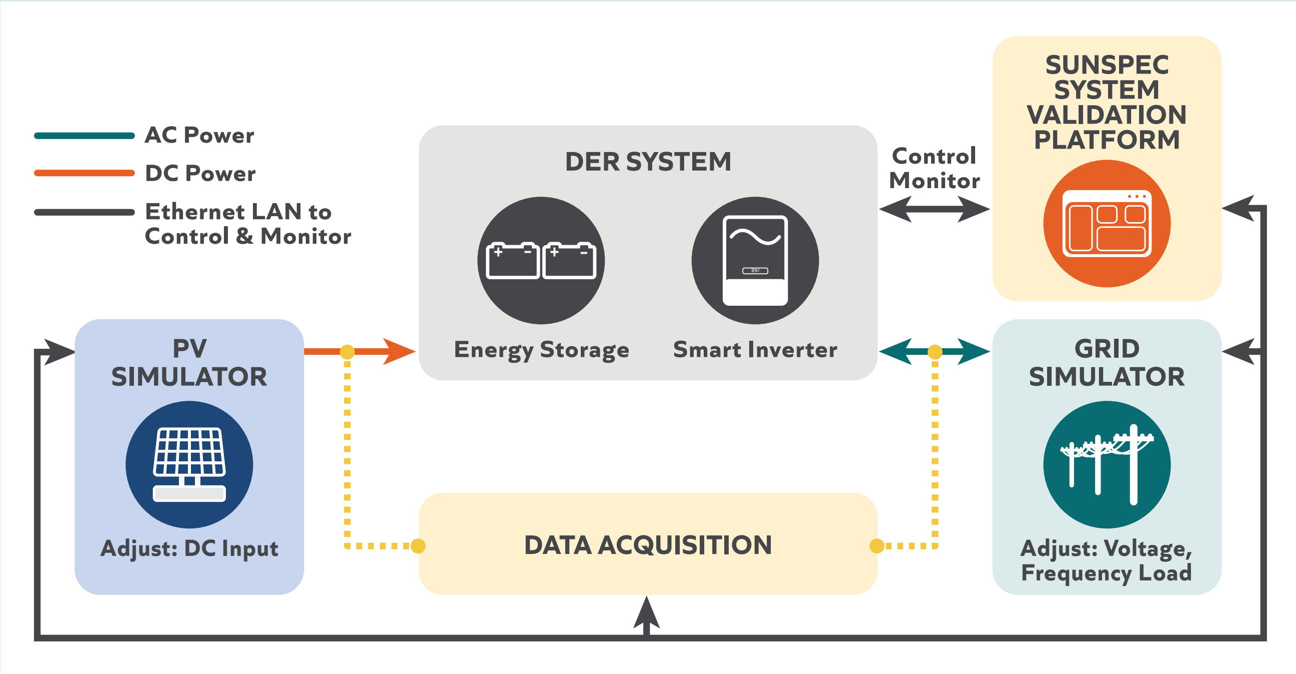


Figure 1. SunSpec System Validation Platform (SunSpec SVP)

3. Test and Evaluate Smart Inverters

The third step was to test and evaluate inverters in the smart inverter test laboratory at UCSD.

Testing was performed on a First In, First Out (FIFO) basis, in which CA Rule 21 Phase 1 tests were performed. When defects were discovered, testing was paused to allow the vendor to correct issues and a different vendor's equipment was put under test. This process was repeated iteratively for the duration of the project.

Data from all tests was captured by SunSpec SVP, which generated the results and graphs for each function analyzed in this report.

4. Manual Manipulation of Test Settings as Needed

As several vendors did not present a standard communication interface, a fourth step was added to the process to accommodate smart inverters lacking this capability.

The fourth step substituted smart inverter settings changes via data communication with settings changes via manipulation of the inverter front panel. This step was time consuming but increased the population of smart inverters that were evaluated.

TESTING OBJECTIVES

The UCSD smart inverter testing laboratory was designed to provide a controllable environment in which to test inverters to the CA Rule 21 standards to evaluate the ability of the inverters to perform the smart functions. Testing needed to be consistent, repeatable, reproducible, and low cost. Data collection needed to be accurate, comprehensive, and sufficient to enable all stakeholders to accurately evaluate the performance of an inverter, and either to recognize compliance with the test criteria, or to identify shortcoming in the performance that could be rectified by software, firmware or hardware updates, or through adjustment of the inverter's parameters.

The UCSD smart inverter testing laboratory was designed to provide a controllable environment in which to test inverters to the CA Rule 21 standards to evaluate the ability of the inverters to perform the smart functions.

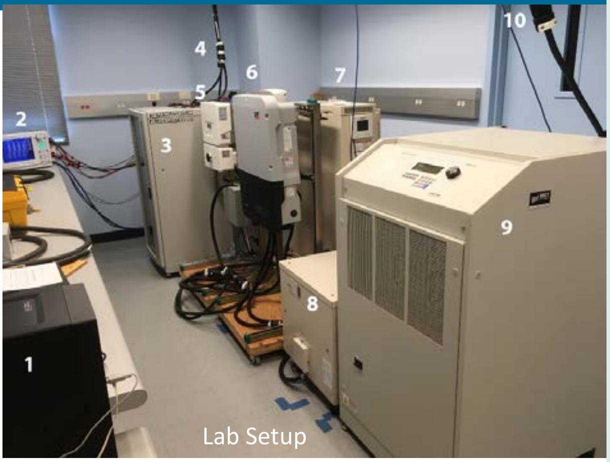
Compliance Testing of Smart Inverters

California Rule 21 and UL 1741 "Phase 1" Standards

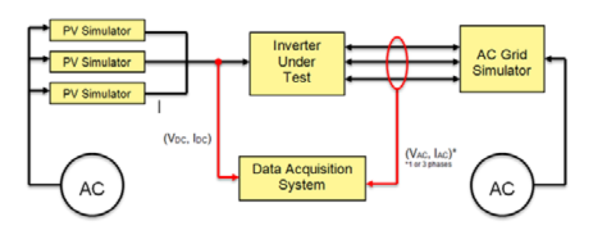
UC San Diego
JACOBS SCHOOL OF ENGINEERING
Center for Energy Research

UC San Diego is testing smart inverter functionalities to meet the new requirements of California Rule 21 and UL 1741 "Phase 1" standards for grid-connected inverter systems in a project funded by the California Energy Commission. Phase 1 includes the inverter functionalities described below right; additional advanced functions will follow in Phases 2 and 3 (TBD).

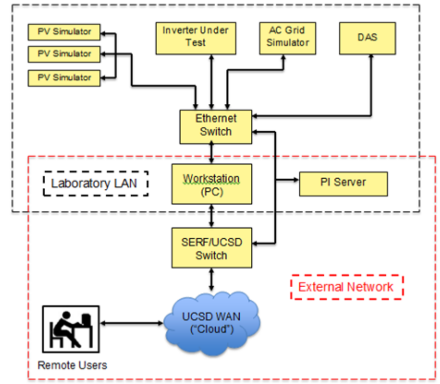
- The SunSpec Validation Platform (SVP) software, resident on the Lab Workstation PC (not visible in picture), controls all test equipment through the local area network (LAN), runs standardized tests, and manages data acquisition, data archiving and retrieval.
- Three PV simulators provide up to 30 kW of DC power to the Inverter Under Test (IUT), with the ability to program and simulate a wide range of PV scenarios, including the impacts of intermittent and variable PV supply.
- A 30 kW AC Grid Simulator receives the output power of the IUT and injects it back into the grid. The simulator is fully programmable and can simulate any of the AC Grid conditions required for the tests, including voltage and frequency excursions, and unbalanced phases conditions.
- The Data Acquisition System (DAS) monitors and records in real time all aspects of the tests, including AC and DC voltages, currents and power on both sides of the IUT; status commands and readings from the AC and DC simulators; and status and response times of the IUT.
- An OSIsoft PI Archive system, simulated on a PI Server Workstation, archives the completed test results datasets, and provides client access and application software for data retrieval, (



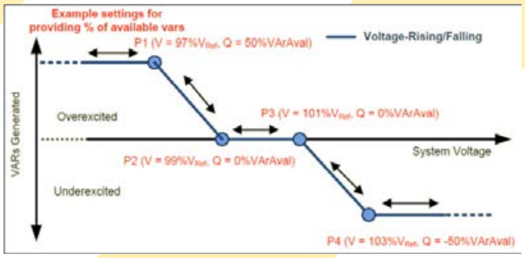
1 – PI Data Server
2 – Yokogawa DAS
3 – PV Simulators
4 – AC Supply to PV Simulator
5 – SolarEdge Inverter
6 – SMA Inverter
7 – Tabuchi Inverter
8 – Tabuchi Battery
9 – Grid Simulator
10 – AC Supply to Grid Simulator



Testing Schematic



Data & Communications Schematic



Inverter Performances Specs for Volt-VAR Control

Testing of Phase 1 Inverter Functions

- **Anti-Islanding Protection:** The IUT, with and without smart inverter functions enabled, must trip (disconnect from the grid) in the specified time when exposed to an AC grid outage.
- **Low and High Voltage Ride-Through:** The IUT must cease to energize, but not trip, during AC voltage excursions of specified duration outside the normal operating range.
- **Low and High Frequency Ride-Through:** The IUT must cease to energize, but not trip, during AC frequency excursions of specified duration outside the normal operating frequency of 60 Hz.
- **Normal and Soft-Start Ramp Rates:** Normal Ramping is employed for routine operation, as when the inverter is following the output of a PV system. Soft-Start Ramping is intended for smoothing transitions from one power level to another.
- **Specified Power Factor:** Default setting for inverters is PF of 1.0 (real power only). The IUT should respond to system commands to change its power factor in the range of œ0.85 to output VARs for support of grid voltage.
- **Volt-VAR Control:** The IUT should respond to AC grid voltage fluctuations by supplying or absorbing VARs to help maintain AC voltage within specified limits (see figure, left).

Contact: wtorre@ucsd.edu
Contributor: William V. Torre, Bob Fox, Lloyd Cibulka,
Balu Karthikeyan, Changfu Li

CER

Figure 2. UC San Diego Compliance Testing of Smart Inverters

PROJECT RESULTS

The results of this part of the project were substantial and punctuated by achievements in three specific areas:

- Confirmation that smart inverter manufacturers are ready to serve the market,
- Significant technological advancement in the area of smart inverter test automation, and
- Validation that commercial smart inverters perform as intended.

Manufacturers Are Ready to Serve the Market

The key question of whether manufacturers would produce smart inverters with UL 1741 SA certification in time for CA Rule 21 Phase 1 (September 2017) was answered resoundingly in the affirmative. A total of eleven (11) smart inverter manufacturers participated in the project and five submitted their products for testing. Several of these manufacturers started the project using older product models but ultimately switched to new hardware designs as the project progressed.
Ten (10) of the eleven (11) vendors that participated offer UL 1741 SA compliant products and have done so since CA Rule 21 Phase 1 took effect.

Technological Advancement of Smart Inverter Test Automation

The smart inverter test lab at UCSD became fully operational in the first year of the project. The lab design is based on the SunSpec Advanced Function Inverter Test Lab Specification[2]. This specification calls for low-cost, off-the-shelf components and is driven by the open source SunSpec SVP software platform[3]. The design of the test lab is very efficient (total set up budget was less than $300,000) and can be replicated at other research facilities or academic institutions. A version of the test lab specification that incorporates hardware-in-the-loop capabilities is being developed to further reduce set up cost.

2 https://sunspec.org/wp-content/uploads/2018/05/SunSpecADVANCEDFUNCTIONINVERTERTESTLABSPECIFICATION-2.pdf

3 https://sunspec.org/sunspec-system-validation-platform-2/

The foundation of the smart inverter test lab is SunSpec SVP. This cutting-edge DER system validation software has been continuously improved over years. Enhancements made in this project have resulted in a complete suite of UL 1741 SA/CA Rule 21 test scripts. These scripts are available to the public in open source form thus enabling free access and rapid innovation[4].

Given the complexity of testing CA Rule 21 related functionality, development and delivery of the open SunSpec SVP software to the market is one of the project's most important outcomes. The availability of this open platform means that DER vendors, DER asset owner/operators, and academic institutions, including other UC's, California State University campuses, and California Junior Colleges, can adopt the technology to develop their own DER research facilities and train the next generation of workers that will be required by the market.

Smart Inverters Perform as Intended

The five smarter inverters evaluated in this project have all been certified to the UL 1741 SA functional standard, thus qualifying them for installation under CA Rule 21 Phase 1. This project verified each inverter's compliance with CA Rule 21 Phase 1 requirements by exercising function setting changes in the UCSD smart inverter lab. While test coverage was inconsistent across manufacturers and there is still much smart inverter R&D to be done, all inverters evaluated produced results that demonstrate compliance. Evidence of verification is shown in CHAPTER 4: Smart Inverter Test Results and in Appendices A through E of this report[5].

Given the complexity of testing CA Rule 21 related functionality, development and delivery of the open SunSpec SVP software to the market is one of the project's most important outcomes.

4 https://sunspec.org/download/

5 https://sunspec.org/cec-pon-14-303/

OBSERVATIONS

Lab testing helped prove two points:

- Smart inverters can support the CA Rule 21 Phase 1 physical function setting changes
- The addition of data communication substantially reduces the cost of manipulating smart inverters in the field. In this step as well, SunSpec SVP captured data and generated results and graphs for each function evaluated.

Though the lab testing was a success, there is room for improvement in the Smart Inverter test program. During the course of testing, three aspects were identified as needing improvement: test scripts, test specification, and communication interfaces of the smart inverters themselves.

Second, a late start for some vendors was due to unclear CA Rule 21 communication requirements during most of the project. Inverter manufacturers react to local requirements associated with each country market they serve around the globe. In a four-year R&D project with no clear commercial deadline, manufacturers had shifting priorities with some vendors withdrawing prior to completion. Others submitted products that were still in development.

Third, there was a lack of a standard communication interface on some of the products which made testing difficult and caused delays. Specialized technical support was needed to resolve issues with proprietary interfaces. Support was sometimes delivered slowly as some manufacturers are based in foreign countries and have American field offices that are not prepared to support R&D projects. The need to consult with the home office resulted in delays in debugging and resolving issues.

Fourth, there is a need to ensure that inverters shipped for testing are production units. One manufacturer sent a unit that apparently was incomplete, lacking a communication interface card (which took weeks to get), and hadn't been tested in-house before being sent. A possible remedy is to purchase the inverter outright rather than ask for a loaner; inverters are becoming less costly, so the impacts to project budget are not that great.

BENEFITS TO CALIFORNIA

This aspect of the project delivered several important benefits to the state of California.

California Sets Technology Agenda for Smart Inverters

First, it harnessed significant technical and intellectual resources from the world's leading inverter manufacturers thus enabling California to set the technology agenda for smart inverters.

Smart Inverters Compliant with CA Rule 21 Phase 1 Can Safely be Installed at DER Penetration Levels of 100% or Higher

Second, the project proved conclusively that smart inverters compliant with CA Rule 21 Phase 1 requirements can be installed safely at penetration levels of 100% or higher while eliminating the reverse energy flow and thermal problems associated with non-smart inverters. The implication here is that there are no known technical barrier imposed by smart inverters that would preclude California from reaching its 100% renewable energy goals.

Automated Smart Inverter Testing Can be Leveraged for Years to Come

Third, research into the effects of Distributed Energy Resources is in its infancy and this project delivers a new technology (smart inverter test automation) that can be leveraged by California for years to come. With the breakthroughs this project has yielded in the areas of capital equipment cost reduction for smart inverter testing, DER simulation, and test automation, it is conceivable smart energy laboratories may one day be affordable to the likes of California high schools and primary schools.

ABOUT SUNSPEC ALLIANCE

Global alliance of Distributed Energy Resource (DER) industry participants

Driver of industry growth and efficiency via open communication and information standards

Active programs for system- and device-level communication, financial and operational data exchanges, and cybersecurity

CONTACT

www.SunSpec.org