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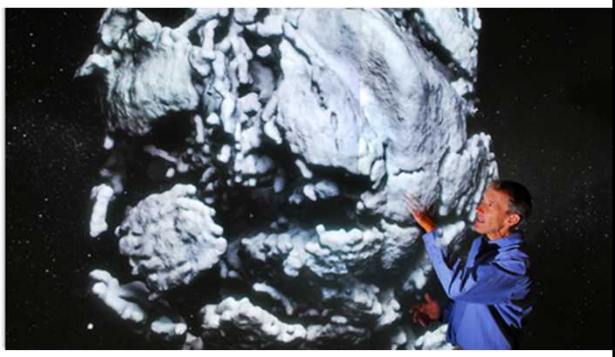

Testing Protocols for Emerging Interconnection Standards

UVIG Distributed Applications Users Group Meeting

Minneapolis, MN – April 21, 2015

Abraham Ellis, Jay Johnson, Sigifredo Gonzalez

Photovoltaic and Distributed Systems Integration

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Context:
  - Certification aspects of emerging grid codes
  - From testing protocols and certification standards
- Sandia Testing Protocols and Related Projects
  - California Solar Initiative Project
  - Smart Grid International Research Facility Network
  - Sandia-SunSpec System Validation Platform development

Types of Codes, Standards, Tests

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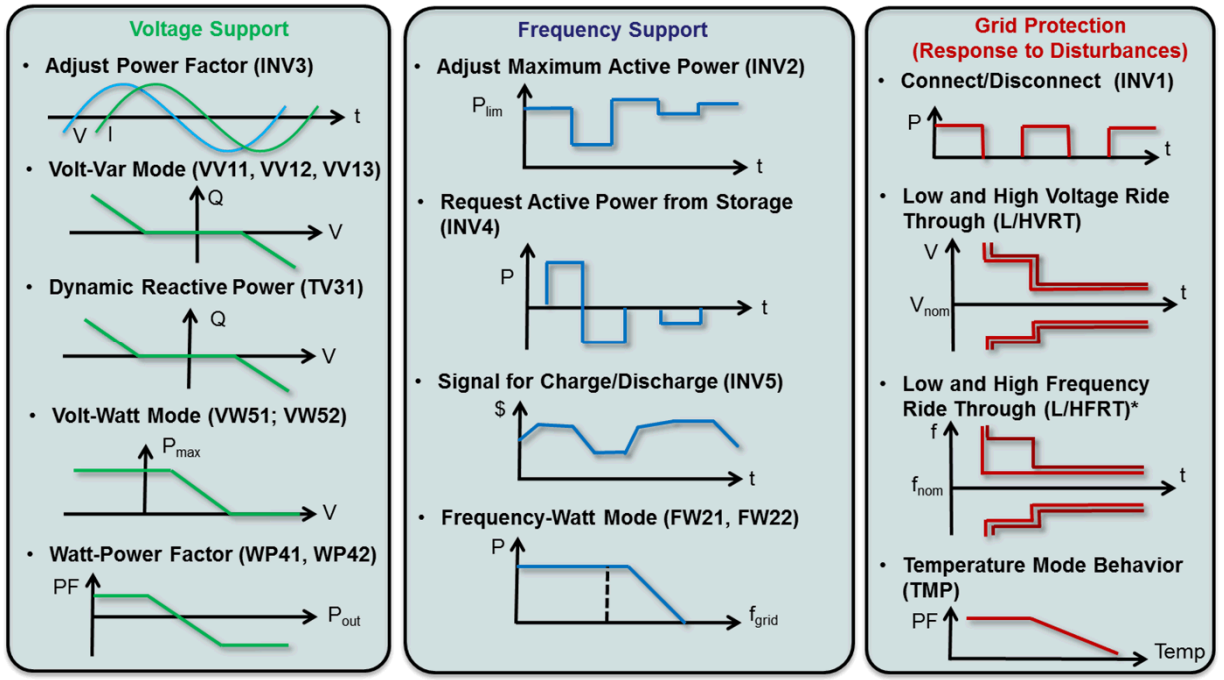
- Certification/Compliance/Conformance/Acceptance Standards
  - Detailed tests with pass or fail criteria (IEEE 1547.1, UL 1741).
  - Can be safety-, quality-, or performance-based testing.
  - In the US, Nationally-Recognized Testing Laboratories (NRTLs) certify.
    - Type testing certification valid for product line (same hardware & firmware)
  - In Europe, “self-certification” with heavy fines for non-compliance.
    - CE marking granted once manufacturer submits Declaration of Conformity
- Performance Tests
  - Quantitative metric of the quality of the product, e.g., CEC Inverter Performance Test Protocol (efficiency tests), PNNL Energy Storage Performance Protocol (PNNL-22010).
- Internal Manufacturer/Vendor Testing
  - Manufacturer/vendor tests as part of a quality assurance process.

Functional Definitions

- In 2009, EPRI and Sandia started a stakeholder effort to reach definition consensus on “advanced” inverter functions
- Result: EPRI’s *Common Functions for Smart Inverters* and eventually *IEC 61850-90-7 Technical Report*
- Types of grid support functions
  - Autonomous: In response to local voltage and freq.
  - Commanded (communication-enables): Remote controls & configuration of autonomous behavior



Advanced functions as defined in IEC TC 61850-90-7 [7].

Smart Inverter Requirements in USA

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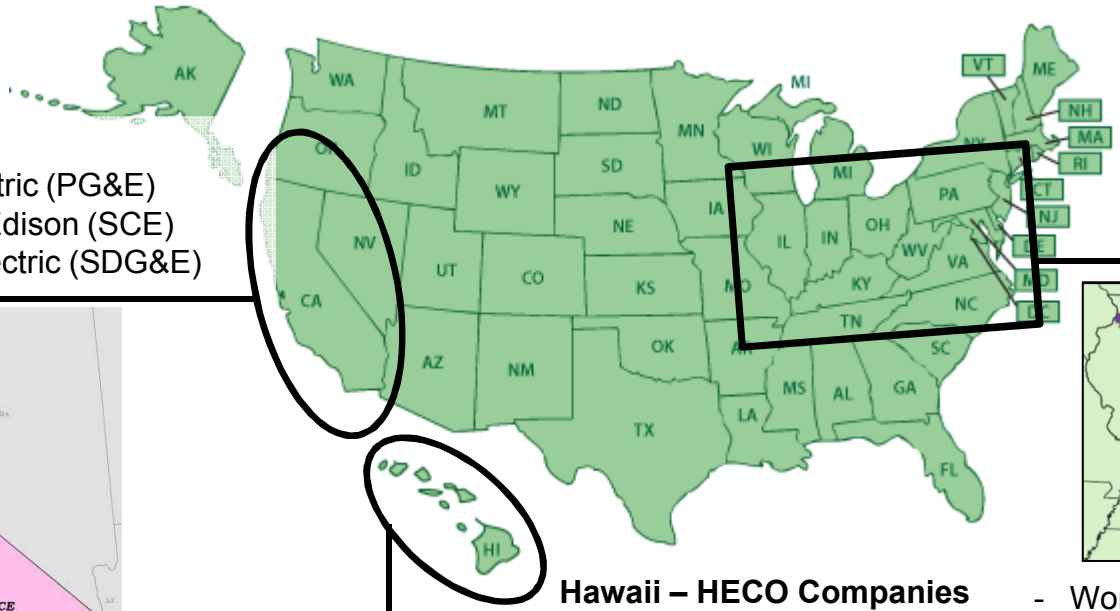


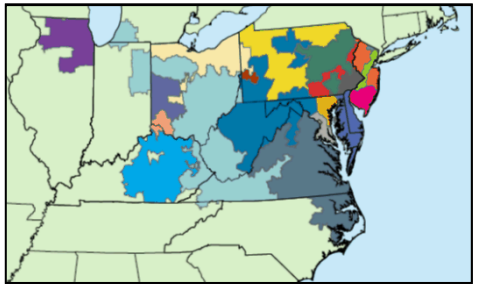
California IOUs
Pacific Gas and Electric (PG&E)
Southern California Edison (SCE)
San Diego Gas & Electric (SDG&E)

- Serve ~70% of the load in CA
- DER interconnection requirements governed by California Public Utilities Commission (CPUC) Electric Rule 21
- Likely to include MANY autonomous and communication-enabled grid support functions in phases over the next 3 years

Hawaii – HECO Companies

- Serves 95% of HI's 1.4M residents
- Many customers cannot connect their PV systems to the grid because the penetration levels are >100%*
- HECO investigating advanced functions in PV inverters, communications, and mandatory VRT/FRT
- Closely watching CA developments – expect to adopt many of the same DER interconnection requirements

PJM Interconnection LLC



- World's largest competitive wholesale electricity market
- 830 companies, 6M customers, 167 GW of generating capacity
- Closely watching CA developments in Smart Inverters – expected to adopt many of the same DER interconnection requirements

All eyes on CA Rule 21… and IEEE 1547 revision underway

*http://www.kitv.com/news/heco-says-its-trying-to-conect-more-customers-to-the-grid/28161878

CA CPUC Rule 21 Status

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- Jan, 2014: Smart Inverter Working Group (SIWG) produced Recommendations for Updating the Technical Requirements for Inverters in Distributed Energy Resources
  - Phase 1: Autonomous functions—V/FRT, ramp rate limits, volt/var, etc.
  - Phase 2: Communication capability—add data model, cybersecurity, etc.
  - Phase 3: Communications-enabled functions—status reporting, connect/disconnect, limit active power, etc.
- 2015: Phase 1 adopted; mandatory implementation is the later of..
  - 18 months after publication of revised Rule 21 (Jan 2015), or
  - 12 months after the UL approval of certification procedures

CA Rule 21 Phase 1 Functions

1	Anti-Islanding Protection (AI)
2	Low/High Voltage Ride-through (L/HVRT)
3	Low/High Frequency Ride-through (L/HFRT)
4	Volt-Var Mode with Watt-Priority
5	Ramp Rates
6	Fixed Power Factor
7	Soft Start

CA Rule 21 & UL Certification

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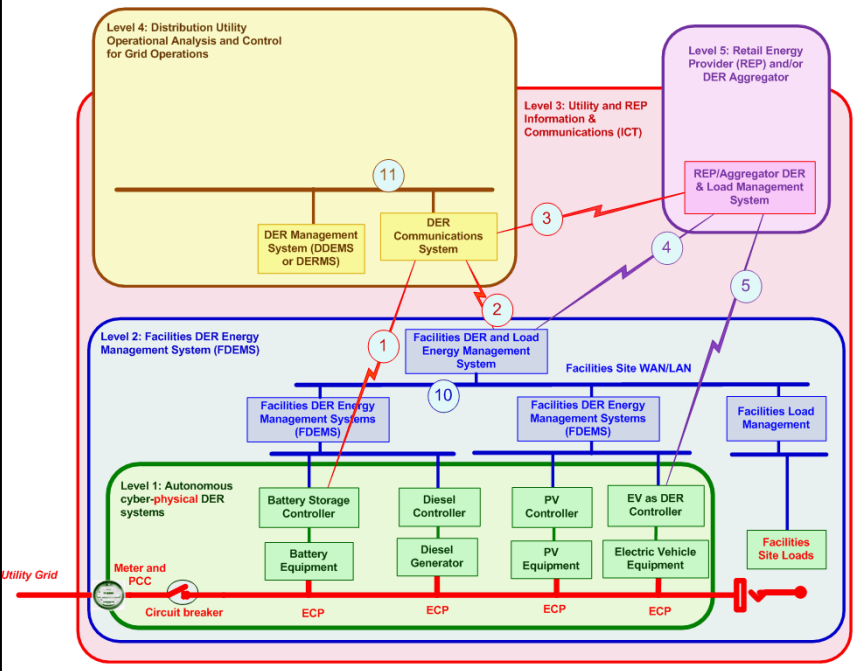
- UL 1741 Supplement A (SA) – *Grid Support Utility Interface Inverters and Converters* drafted by Standards Technical Panel (STP) Working Groups.
  - Appendix 1 – Anti-islanding Protection
  - Appendix 2 – Low and High Voltage/Frequency Ride-Through
  - Appendix 3 – Normal and Soft-Start Ramp
  - Appendix 4 – Fixed Power Factor and Volt/Var
  - Appendix 5 – Communications Interface (Optional)
  - Appendix 6 – Data Model (Optional)
  - Appendix 7 – Monitor Alarms (Optional)
  - Appendix 8 – Monitor DER Status and Output (Optional)
  - Appendix 9 – Frequency-Watt (Optional)
- Draft to be submitted to UL 1741 STP for approval ~Aug. 2015
  - IEEE Standard 1547.1 is next!

Communication Requirements??!!

- Wanted: Interoperability certification procedure and certification agency (UL?)
  - Electrical certification is well understood but certification of communications requirements is uncharted territory



Agreement that all Smart Inverter DER systems shall be *CAPABLE* of communications

Decision on which DER systems shall implement communications to be made during interconnection process

Communications Layers	Possible Communication Choices	Status	What Should Be Covered in Rule 21?
Utility DER-Related Applications and Databases	Cyber Security	← Cyber security requirements. Utility privacy agreement	Security requirements: policies & technologies
	Profile of Data Exchanges	← General agreement on monitoring and control data requirements. Grouping?	Data sets and performance required by utilities
Info Model	IEC 61850 Info Model	← Agreement on IEC 61850 as Info Model	Use IEC 61850 info model
"Application" Protocol	Utility Protocol	← Utility agreement on SEP 2 as default protocol, with SIWG SEP 2 profile	SEP2 Based on IEC 61850 Abstract Info Model
"Transport" Protocol	Internet Protocols:TCP/IP	← Agreement on Internet Protocols	TCP/IP
Communications Media	• Utility private WAN • Cellphone GPRS • Public Internet • AMI network • Telecomm provider	← Gateway/Translator to use utility-selected protocol	Not included
Gateway/Translator between protocols or Common Protocol		← No restrictions on media although media types can affect performance and security	Not included
Communications Media			
"Transport" Protocol	Internet Protocols: IP	← Agreement on IP	Not included
"Application" Protocol	Facility or DER Protocol	← For example, ModBus, GOOSE	Not included
Info Model	IEC 61850 Info Model	← Agreement on IEC 61850 as Info Model	Not included
DER Controller of Smart Inverter		← Testing details to be worked out	Not included

More information: *"Recommendations for Utility Communications with Distributed Energy Resources (DER) Systems with Smart Inverters, Smart Inverter Working Group (SIWG) Phase 2 Recommendations"*

Related Research at Sandia National Laboratories

Example Function: Volt/Var (VV11)

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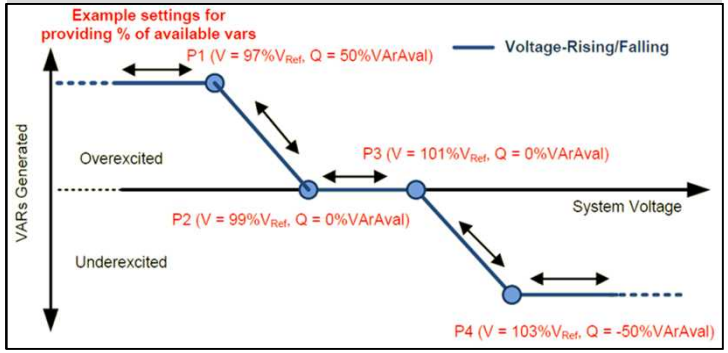
Volt/Var Curve



Test Parameters

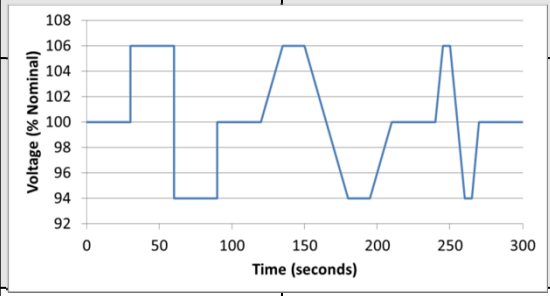
Volt/Var Initiation	Volt/Var [V,Q] Array				Requested Ramp Time (% VArAval/s)	Time Window for Randomization (seconds)	Timeout Period to Reach 95% of Target (seconds)
Binary, 1	V1	97	Q1	50	-	-	-
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			
Binary, 1	V1	97	Q1	50	25	-	-
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			
Binary, 1	V1	97	Q1	50	50	-	-
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			
Binary, 1	V1	97	Q1	50	-	60	-
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			

Data Collection

Command/Action	Command Send Time (seconds)	EUT Response (seconds)	Time Stamped Data from Volt/Var Test Profile and EUT Response
DS93 Request			
VV11 Parameter Set 1			
DS93 Request			
VV11 Parameter Set 2			
DS93 Request			
VV11 Parameter Set 3			
DS93 Request			
VV11 Parameter Set 4			
. . .			

Test Procedure

	Step	Task	Function	Notes
Communication	1	Utility requests status from EUT.	DS93 – Status Reporting	Log time sent.
	2	Utility receives response to the command.		Log time received.
	3	Utility issues a Volt/Var VV11 Command to EUT.	VV11 – Volt/Var	Log time sent. Command may include the following parameters: • Requested ramp rate (optional) • time window (optional) • timeout period (optional)
	4	Utility receives response to the command.	–	Expected response message: • Successful • Rejected (includes reason)
Electrical Behavior	5	If Success response received, verify command was successfully executed by varying the voltage profile according to Table A6-3 and Figure A6-2, using the grid simulator.		Monitor and record electrical output of EUT. • Voltage • Active power • Reactive power
	6	Repeat test with varying parameters as described in Table A6-2. Each test should be repeated until behavior of the EUT is reasonably understood. Test the time out period by rerunning the test profile in Figure A6-2.		
Analysis	7	Characterize EUT's response.		Determine if command was executed correctly.

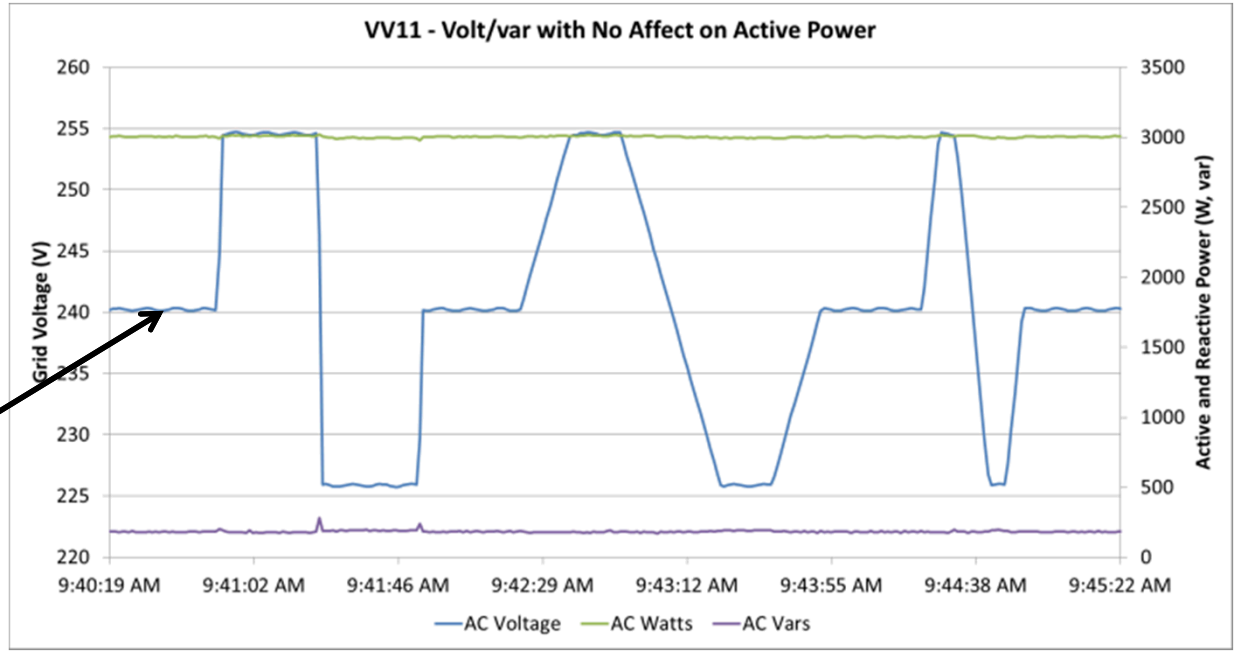


VV14 – Electrical Characterization Results

Baseline Test Case

- No change in vars to compensate for grid voltage changes
- No change in real power generation

Constant PF = 1.00



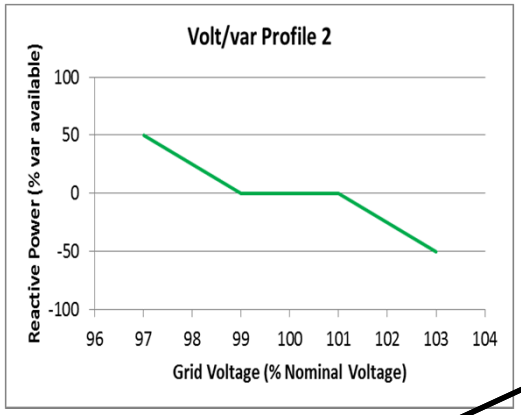
Ac line voltage

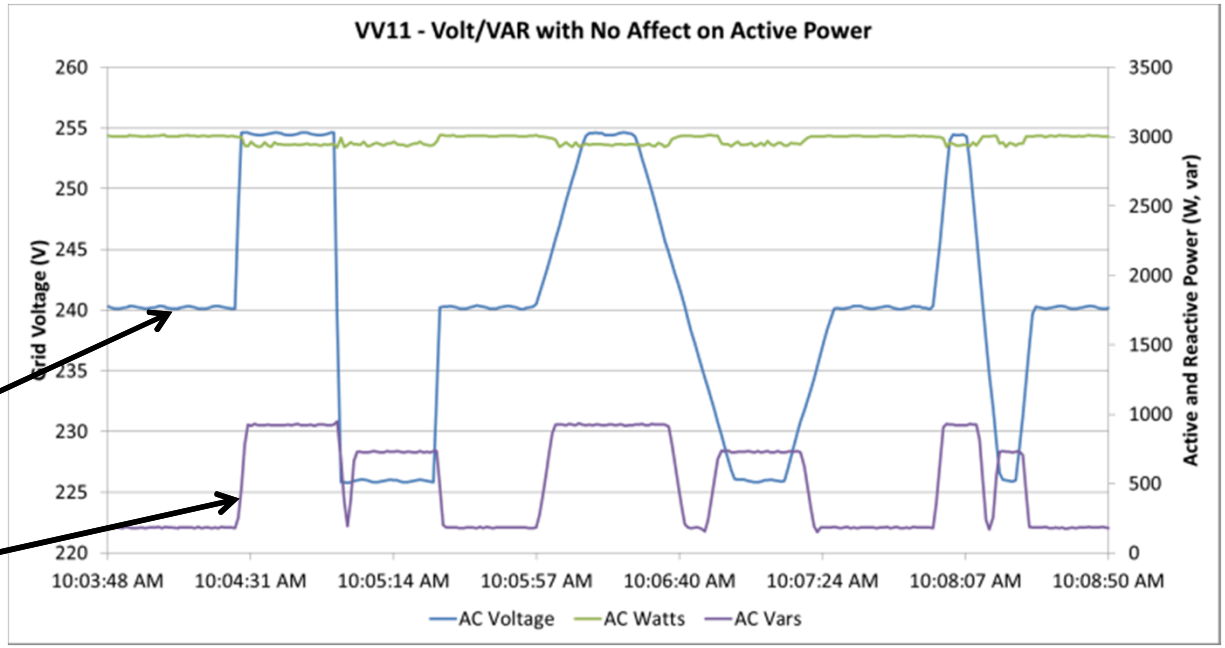
VV11 – Electrical Characterization Results

±50% VarAval Test Case

Small change in VArs to compensate for grid voltage changes.

Smooth transitions between cap/ind regions in the volt/var curve.





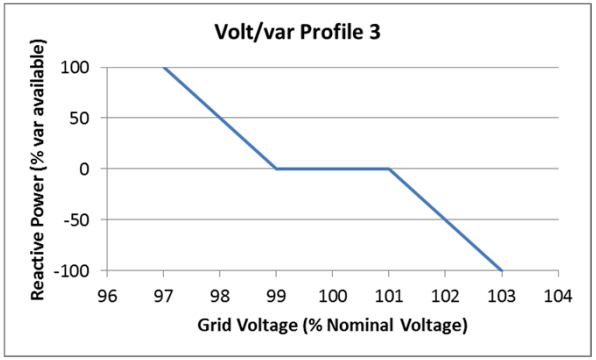
Ac line voltage

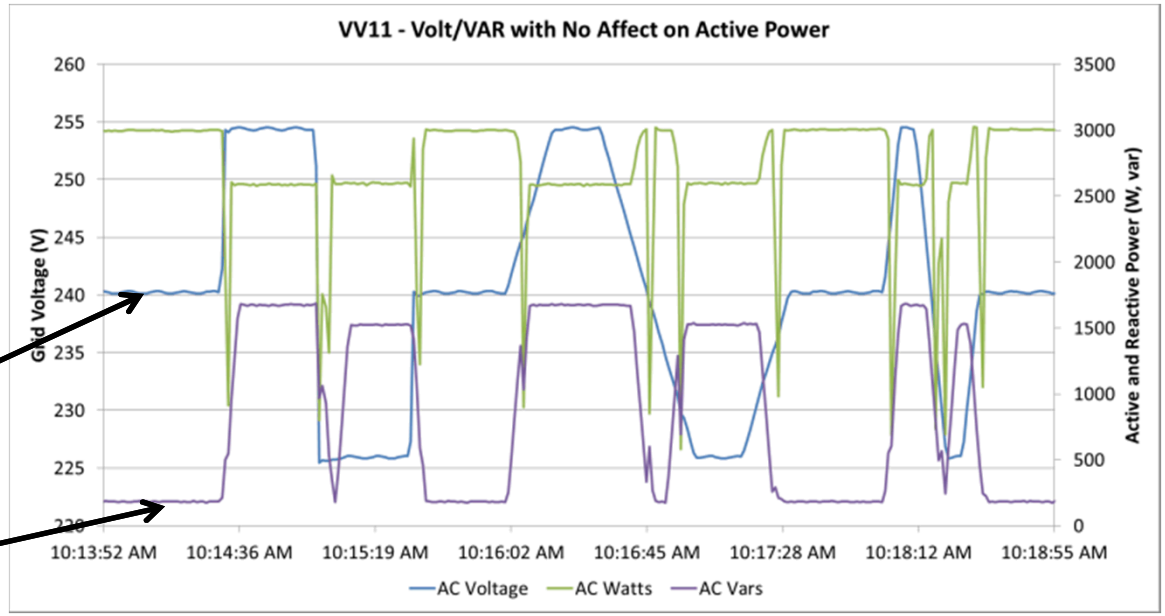
Var generation

VV11 – Electrical Characterization Results

±100% VarAval Test Case

- Larger reactive power production
- Inverter turns off (reduces output current to 0) frequently.
- Recommend tests at inverter limits to find possible issues.





Ac line voltage

Var generation

Grid Integration Pre-standardization

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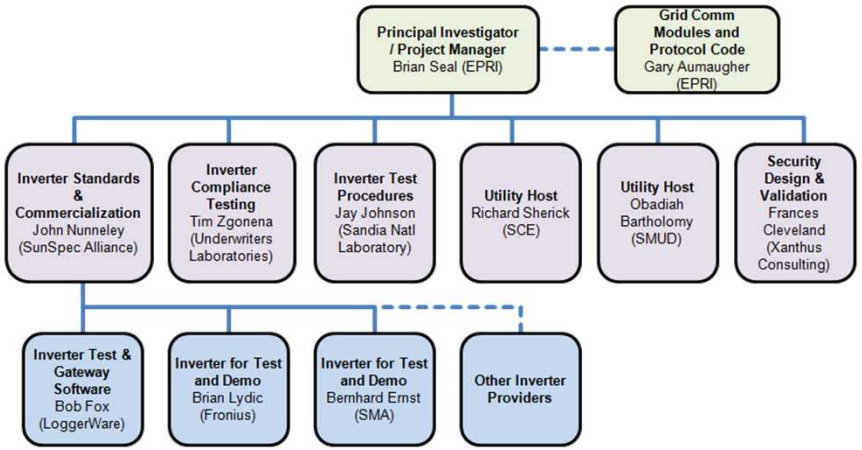
- EPRI-led California Solar Initiative Project *"Standard Communication Interface and Certification Test Program for Smart Inverters"*
  - Sandia contributing test procedures and cyber security recommendations



SunSpec Modbus + CEA-2045*

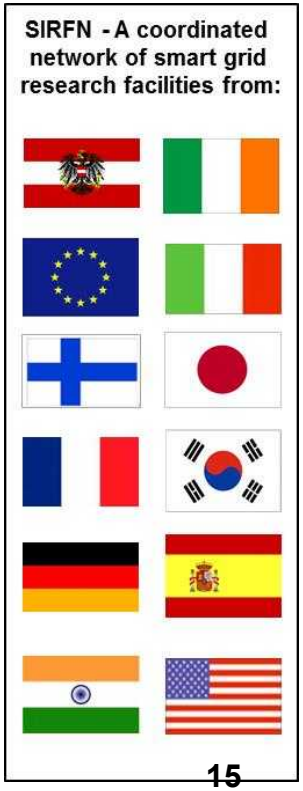
Function	Function or Communication Verification
1	Anti-Islanding Protection (AI)
2	Low/High Voltage Ride-through (L/HVRT)
3	Low/High Frequency Ride-through (L/HFRT)
4	Volt-Var Mode with Watt-Priority
5	Ramp Rates
6	Fixed Power Factor
7	Soft Start
8	Communication Interface
9	Transport Protocols
10	Data Model
11	Mapping to Application Protocols
12	Transport Cyber Security
13	User Cyber Security
14	Monitor Alarms
15	Monitor DER Status and Output
16	Limit Maximum Real Power
17	Connect/Disconnect
18	Provide DER Information at Interconnection/Startup
19	Initiate Periodic Tests of Software and Patches
20	Schedule Output Limits at PCC
21	Schedule DER Functions
22	Schedule Storage
23	Frequency-Watt Mode
24	Voltage-Watt Mode
25	Dynamic Current Support
26	Limit Maximum Real Power
27	Set Real Power
28	Smooth Frequency Deviations

Rule 21 Inverter/DER Functions

ANSI/CEA-2045 specifies a modular communications interface (MCI) to facilitate communications with residential devices for applications such as energy management.
ANSI = American National Standards Institute, CEA = Consumer Electronics Association

SIRFN Smart Grid Collaboration

- Goal: move toward international standard on advanced DER interoperability certification procedures
  - Conduct round-robin testing of advanced DER
  - Compare test results, methods, automation
  - Improve draft test procedures
- NEW! SIRFN now working on advanced energy storage test procedures



SNL, AIT, and TECNALIA Test-Bed Designs

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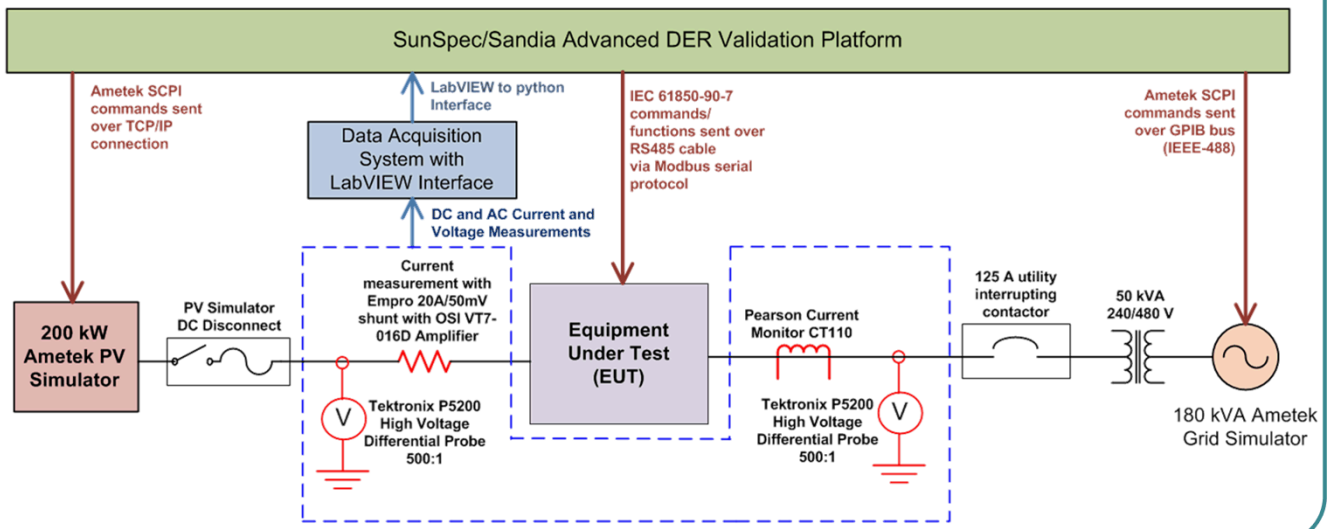
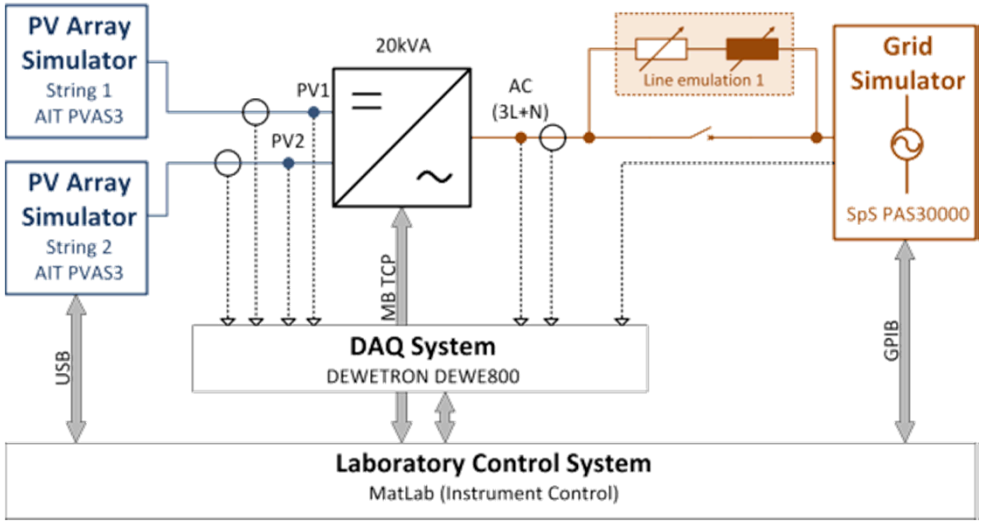


EUTs:
- SNL: 3 kW single-phase inverter
- AIT: 20 kW three-phase inverter
- Tecnalia: 5 kW single-phase inverter

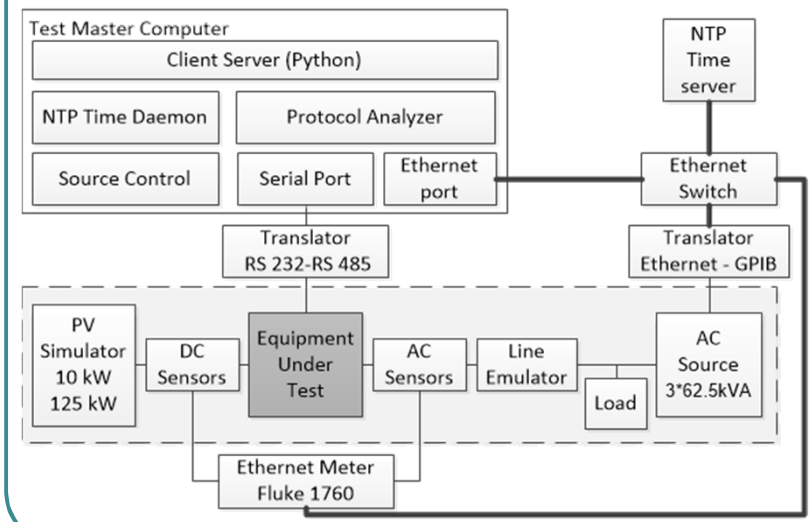
EUT Communications
- SNL: 61850-90-7 over serial
- AIT: 61850-90-7 over TCP
- Tecnalia: 61850-90-7 over serial

Control system
- SNL: SunSpec Test Tool (Python)
- AIT: Lab Control System (Matlab)
- Tecnalia: Master Computer (Python)

Austrian Institute of Technology

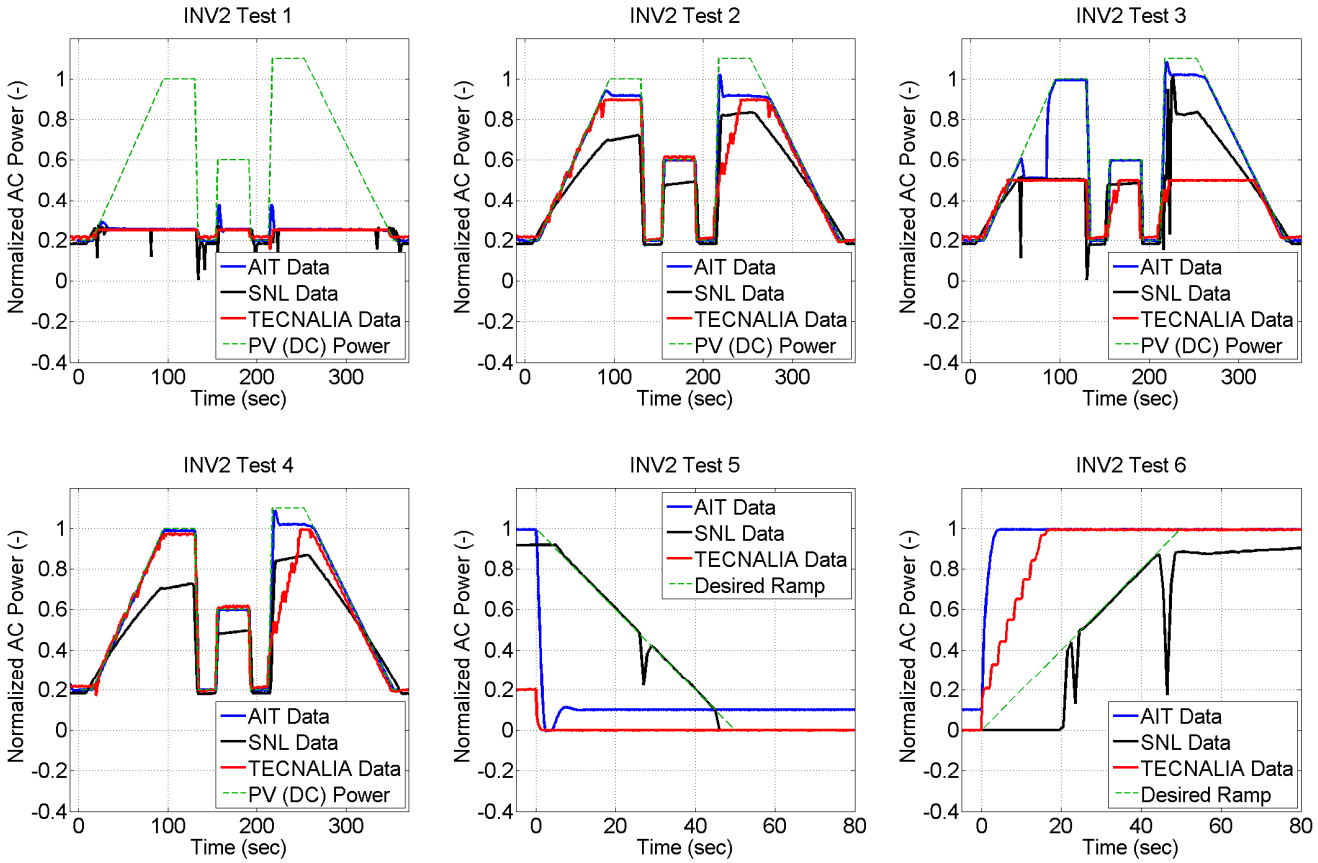


TECNALIA



J. Johnson, R. Bründlinger, C. Urrego, R. Alonso, "Collaborative Development Of Automated Advanced Interoperability Certification Test Protocols For PV Smart Grid Integration," EU PVSEC, Amsterdam, Netherlands, 22-26 Sept, 2014.

Real Power Curtailment (INV2) Results



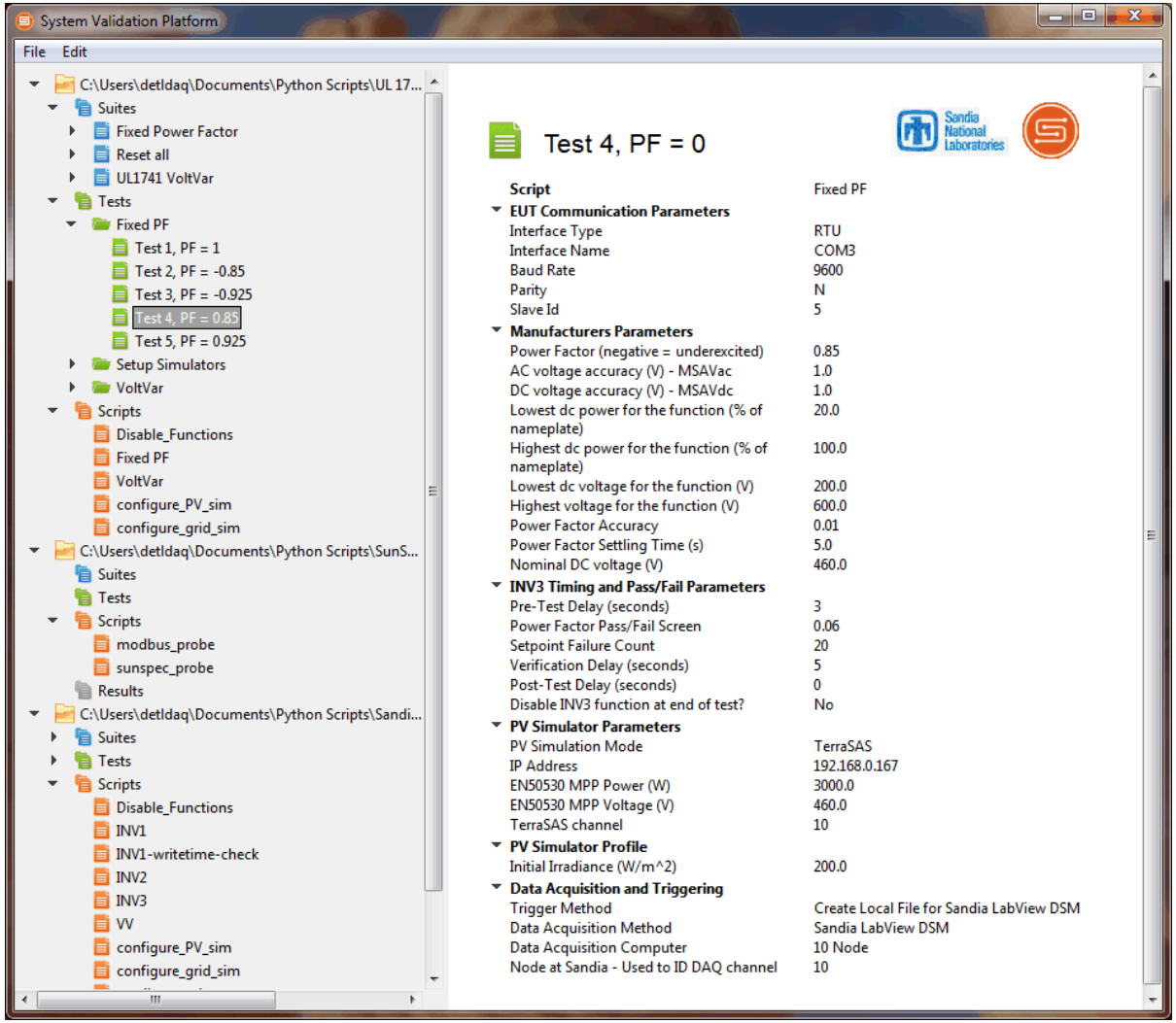
Test	WMax (% nameplate)	Ramp Rate (% nameplate watts/sec)	Time Window (sec)	Timeout Period (sec)	PV Power Profile
1	25	0	0	0	Fig. A2- 1
2	90	0	300	0 AIT:60	Fig. A2- 1
3	50	20	60	30 AIT:60	Fig. A2- 1
4	100	0	0	0	Fig. A2- 1
5	0 AIT:10	2	0	0	Const.
6	100	2	0	0	Const.

J. Johnson, R. Bründlinger, C. Urrego, R. Alonso, "Collaborative Development Of Automated Advanced Interoperability Certification Test Protocols For PV Smart Grid Integration," EU PVSEC, Amsterdam, Netherlands, 22-26 Sept, 2014.

SunSpec/Sandia System Validation Platform

Coming Soon!

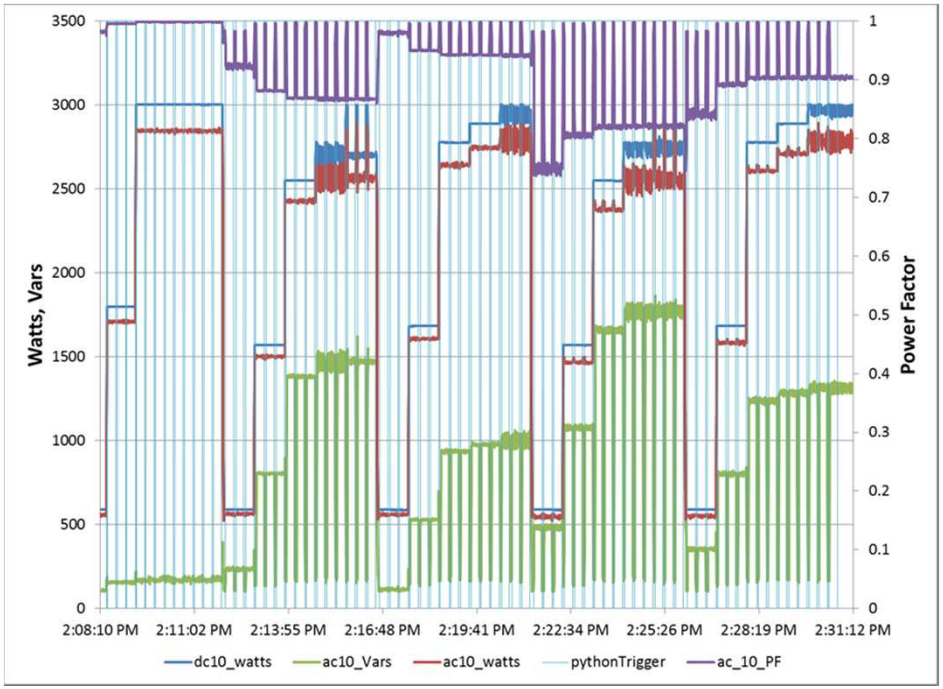
- System Validation Platform (SVP) is an automated certification interoperability platform
  - Fully scriptable
  - Interacts with DAQs, PV and grid simulators and SunSpec-compliant DER.



Power of Testing Automation

- UL 1741 SA test permutations are large due to the number of settings in each advanced DER function:
  - 75 measurements for fixed power factor - takes about 25 minutes with the SVP
  - 375 measurements for volt/var - takes about 90 minutes with the SVP

Proposed UL 1741 SA fixed power factor tests.



Proposed UL 1741 SA volt-var tests.

Conclusions

- Standards are being “rapidly” updated to require deployment of advanced DERs
- Certification of advanced DER functions has become a pressing industry need
  - Electrical performance – have some experience to draw on
  - Interoperability (communications + cyber) – New challenge!
- Critical efforts currently underway
  - New UL STP to address CA Rule 21 Phase 1 requirements
  - Revision of IEEE Standard 1547.1 will be the next major effort
  - US and International R&D efforts focused on refining testing procedures and creating automated tools as precursors to standards
  - Also addressing international harmonization (Sandia/SIRFN)

Questions?

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DER Interoperability Function Testing

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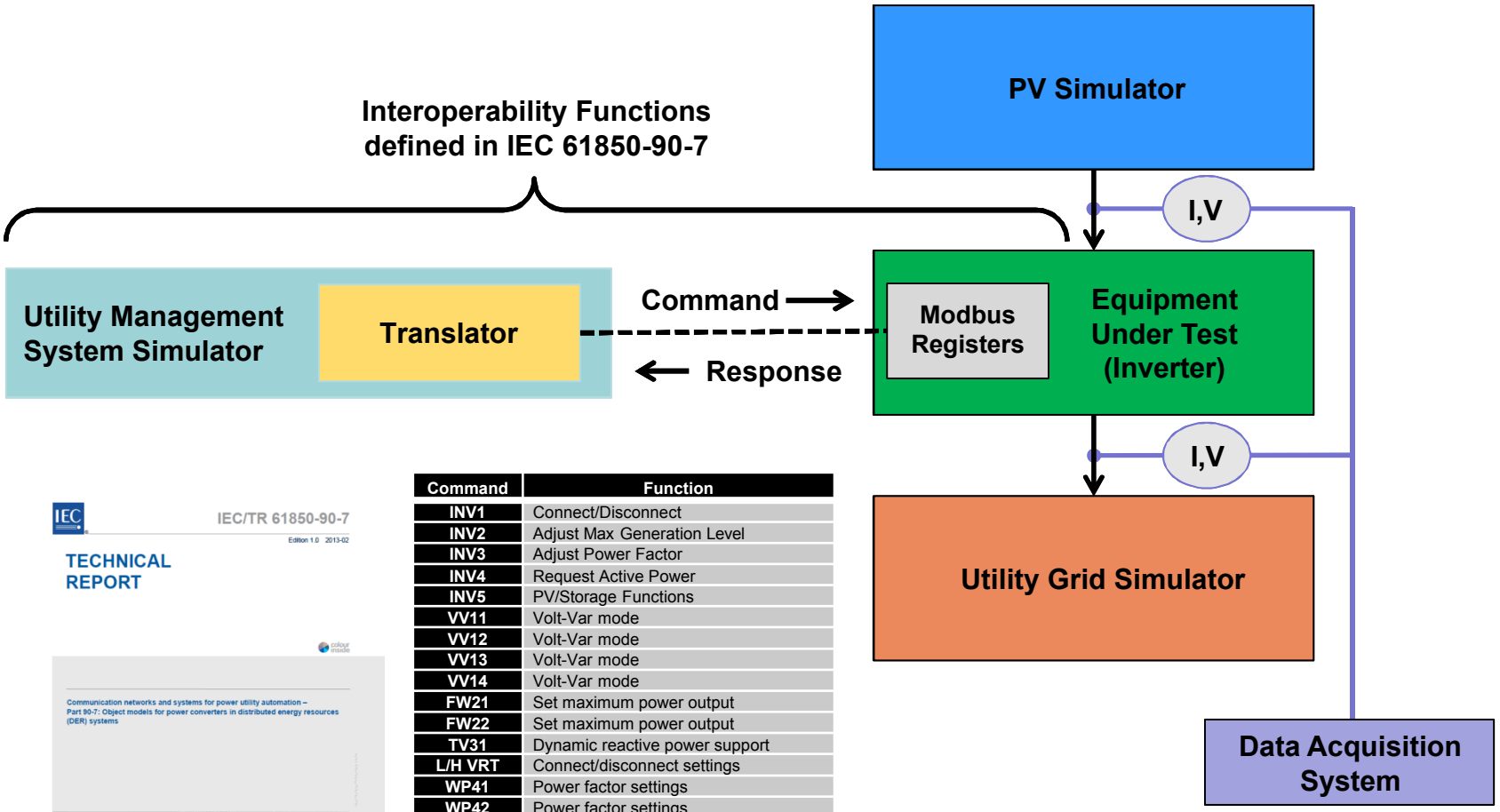


Command	Function
INV1	Connect/Disconnect
INV2	Adjust Max Generation Level
INV3	Adjust Power Factor
INV4	Request Active Power
INV5	PV/Storage Functions
VV11	Volt-Var mode
VV12	Volt-Var mode
VV13	Volt-Var mode
VV14	Volt-Var mode
FW21	Set maximum power output
FW22	Set maximum power output
TV31	Dynamic reactive power support
L/H VRT	Connect/disconnect settings
WP41	Power factor settings
WP42	Power factor settings
VW51	Set output to smooth voltage
VW52	Set output to smooth voltage
TMP	Temperature mode behavior
PS	Signal mode behavior
DS91	Modify DER Inverter Settings
DS92	Event/History Logging
DS93	Status Reporting
DS94	Time Synchronization

DER Interoperability Testing

Sandia National Laboratories

Interoperability Functions defined in IEC 61850-90-7

PV Simulator

I,V

Utility Management System Simulator

Translator

Command →

← Response

Modbus Registers

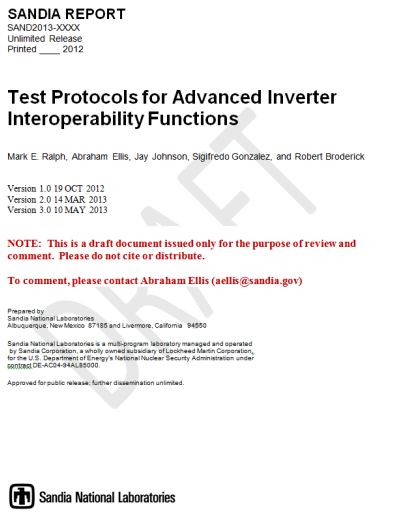
Equipment Under Test (Inverter)

I,V

Utility Grid Simulator

Data Acquisition System

Electrical testing defined by Sandia Test Protocol



SANDIA REPORT
SAND2013-XXXX
Unlimited Release
Printed ____ 2012

Test Protocols for Advanced Inverter Interoperability Functions

Mark E. Ralph, Abraham Ellis, Jay Johnson, Sigifredo Gonzalez, and Robert Broderick

Version 1.0 19 OCT 2012
Version 2.0 14 MAR 2013
Version 3.0 10 MAY 2013

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Approved for public release; further dissemination unlimited.

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Composed of main document and individually printable interoperability testing appendices

Appendix 1 – Connect/Disconnect (INV1)
Appendix 2 – Adjust Maximum Generation Level Up/Down (INV2)
Appendix 3 – Adjust Power Factor (INV3)
Appendix 4 –Request Active Power from Storage (INV4)
Appendix 5 –Signal for Charge/Discharge Action (INV5)
Appendix 6 – Volt/Var Mode (VV11; VV12; VV13; VV14)
Appendix 7 – Frequency/Watt Mode (FW21; FW22)
Appendix 8 – TV Dynamic Reactive Power support (TV31)
Appendix 9 – Low and High Voltage Ride Through (L/HVRT)
Appendix 10 – WP Power Factor Settings (WP41; WP42)
Appendix 11 – VW Set Output to Smooth Voltage Variations (VW51; VW52)
Appendix 12 –Temperature mode Behavior (TMP)
Appendix 13 – Utility Signal Mode (PS)
Appendix 14 – Event History/Logging (DS92)
Appendix 15 – Status Reporting (DS93)
Appendix 16 –Time Synchronization (DS94)
Appendix 17 – Time Window & Random Time Delay
Appendix 18 – Ramp Rate
Appendix 19 – Command Timeout

DER Interoperability Testing

Sandia National Laboratories

Interoperability Functions defined in IEC 61850-90-7

PV Simulator

I,V

Utility Management System Simulator

Translator

Command

Response

Modbus Registers

Equipment Under Test (Inverter)

Electrical testing defined by Sandia Test Protocol

SunSpec Models

I,V

Utility Grid Simulator

4x40001	Common Block
4x40070	Inverter Model
4x40122	Nameplate Ratings
4x40140	Basic Settings
4x40170	Extended Meas.
4x40207	Immediate Controls
4x40229	Other Control Block
4x40xxx	Other Control Block
4x40xxx	End Block

SunSpec_ID SunSpec_DID (1)
SunSpec_DID (103)
SunSpec_DID (120)
SunSpec_DID (121)


SunSpec Alliance Interoperability Specification
Inverter Controls Model
SunSpec Alliance Inverter Workgroup
Bill Randle, John Nunneley, Bob Fox, Christian Cox, Greg Madianos, John Blair, John Daharsh, Soonwook Hong, Martin Beran, Brian Lydic, Jose Gomez, Lu Jiang, Motoko Furukawa, Ralf Kaisler, Andreas Schacht, Søren Bækhøj Kjær
Version Draft 10
SUNSPEC ALLIANCE
ABSTRACT
This document describes the inverter controls model of the SunSpec Alliance interoperability specification.

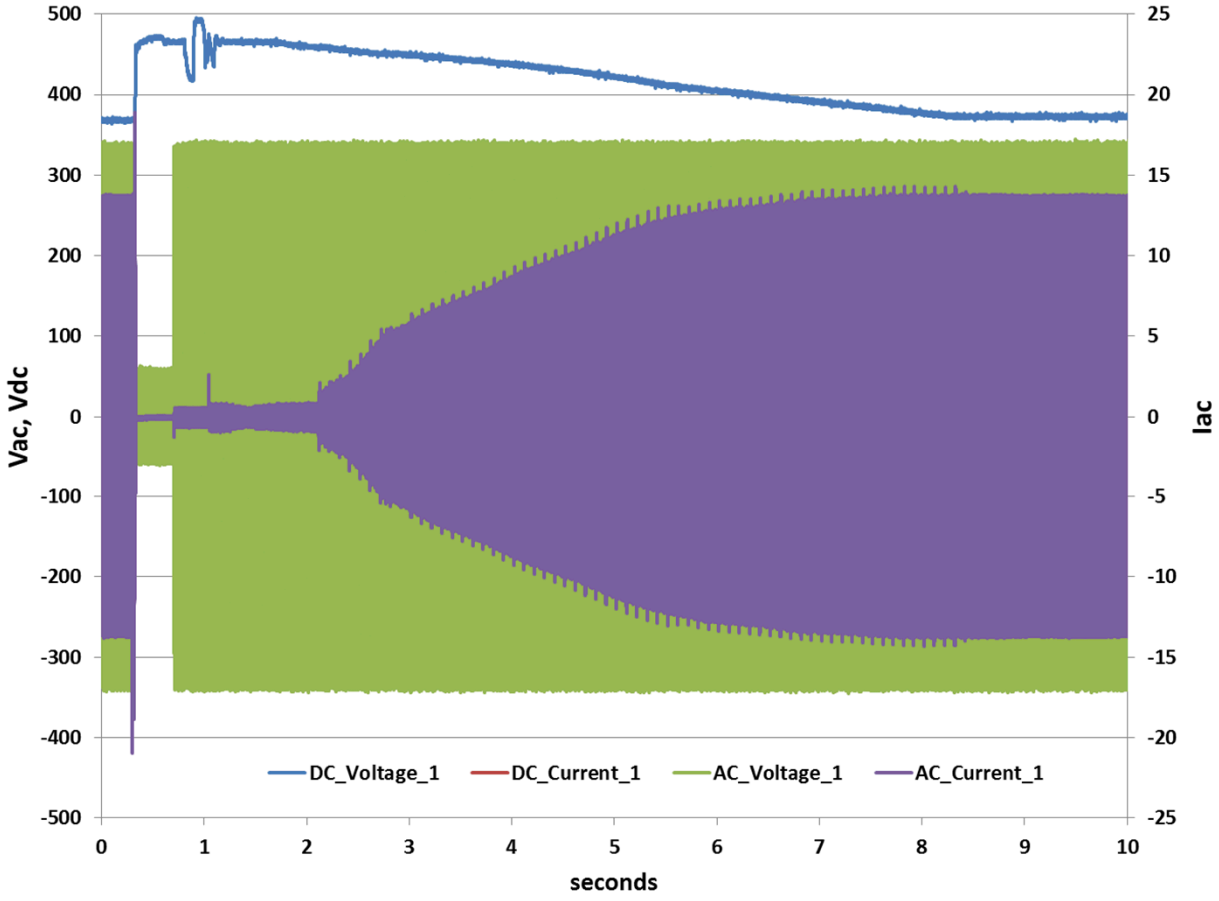
The SunSpec Alliance has published an inverter control specification that maps 61850-90-7 Inverter Interoperability Functions to Modbus and SEP2.0. Manufacturers are encouraged to adopt this standard so utilities do not need multiple translators to communicate to the inverters on their grids.

Data Acquisition System

Data collection, sampling rates, etc.

Low Voltage Ride-Through

Region	Voltage (% Nominal Voltage)	Ride-Through Until	Operating Mode	Maximum Trip Time (s)
Low Voltage 3 (LV3)	V < 50	1 sec.	Momentary Cessation	1.5 sec.



Low Voltage Ride-Through

Region	Voltage (% Nominal Voltage)	Ride-Through Until	Operating Mode	Maximum Trip Time (s)
Low Voltage 2 (LV2)	50 ≤ V < 70	10 sec.	Mandatory Operation	11 sec.