Integration of Advanced Inverters for Increased PV Penetration

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Sandia document: SAND2015-1466 C

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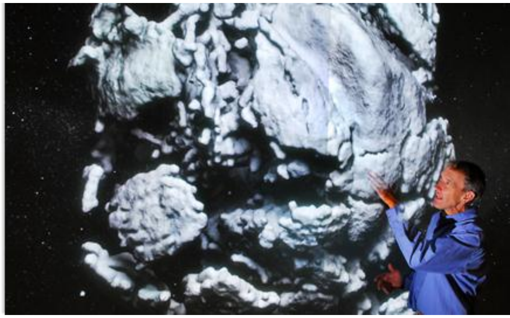

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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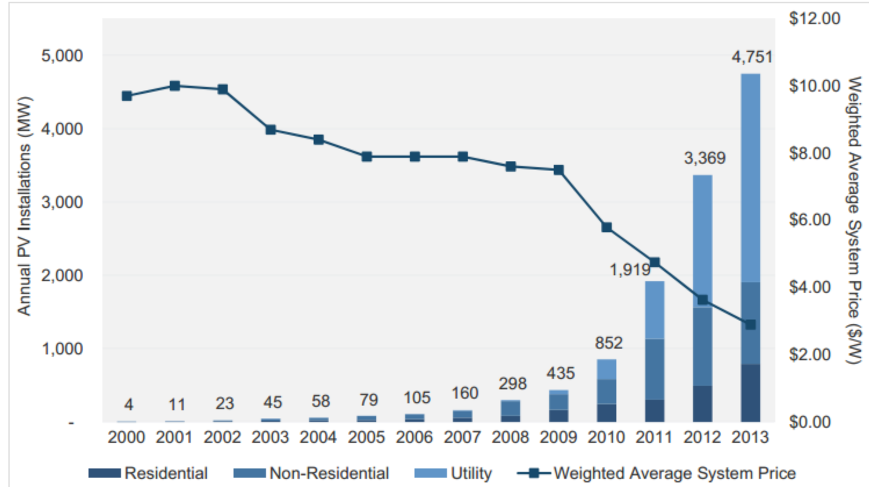
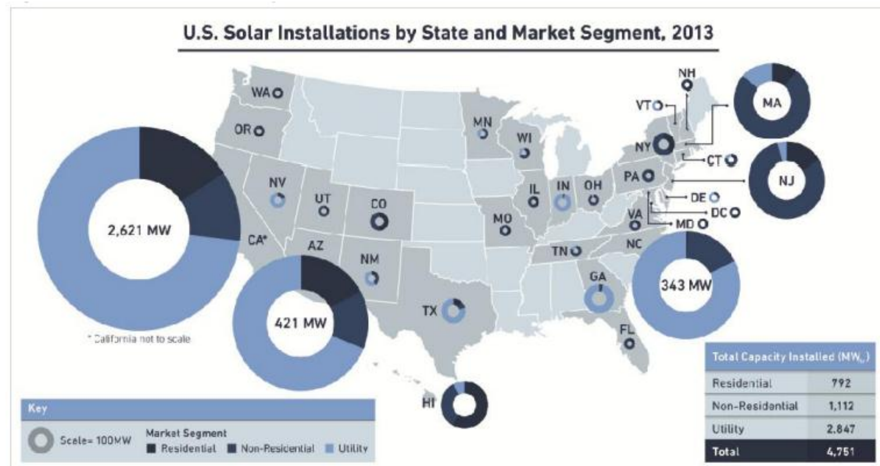
Outline

- The Challenge
  - Total installed capacity of PV is growing fast in the US, especially at the distribution level
  - Technical challenges exist for maintaining power quality & grid resiliency
  - Unless mitigated, these challenges will make it increasingly difficult and costly to continue adding renewable energy to the grid
- Advanced inverters are a big part of the solution in the U.S.
  - Situation in the U.S., IEEE 1547
  - California's Electric Rule 21 new proposed requirements
  - Projects:
    - Development of Standardized Test Protocols
    - Anti-islanding research at Sandia
    - Distributed Controls research at Sandia

PV capacity is growing fast in the US

- 4.7 GW in 2013, 12.1 GW total
  - Installed capacity is projected to triple by 2016!
  - Highest growth rate expected in distribution-connected PV
- High-Pen PV Areas
  - California
    - ~2 GW of distribution-connected PV
    - Aiming for 12 GW of DG (mostly PV) by 2020! [1-2]
  - Hawaii
    - Highest penetration at the balancing area level (island grids)
    - Half of distribution circuits are at 100% of daytime minimum load

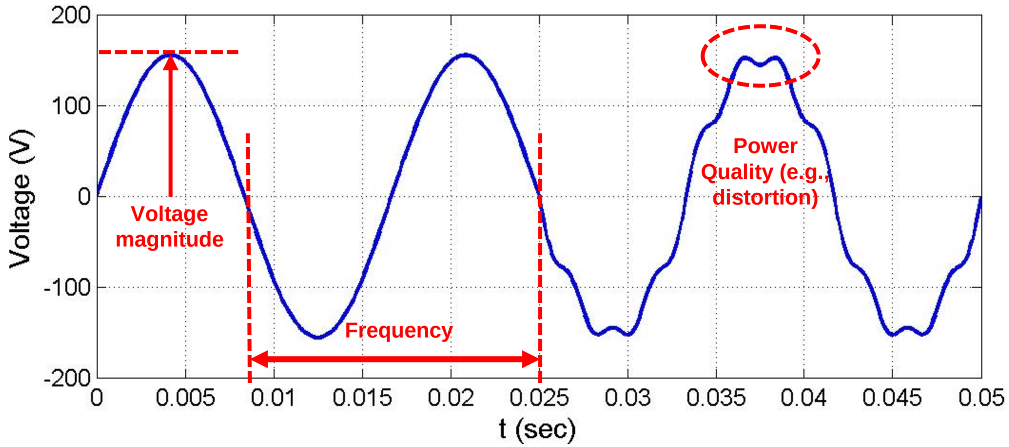


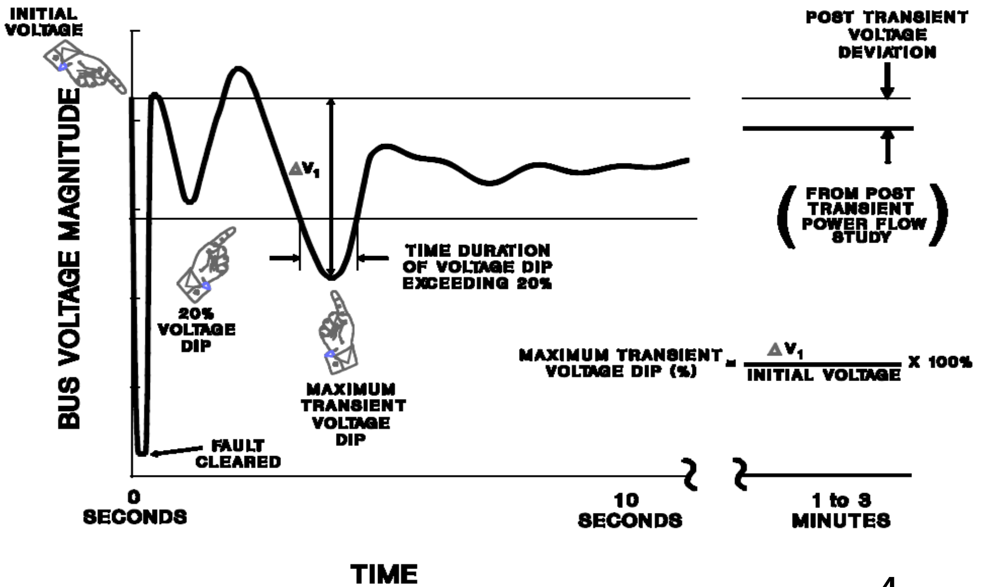


Source: SEIA/GTM Research, US Solar Market Insight 2013 Year in Review

Electric Power must meet performance requirements

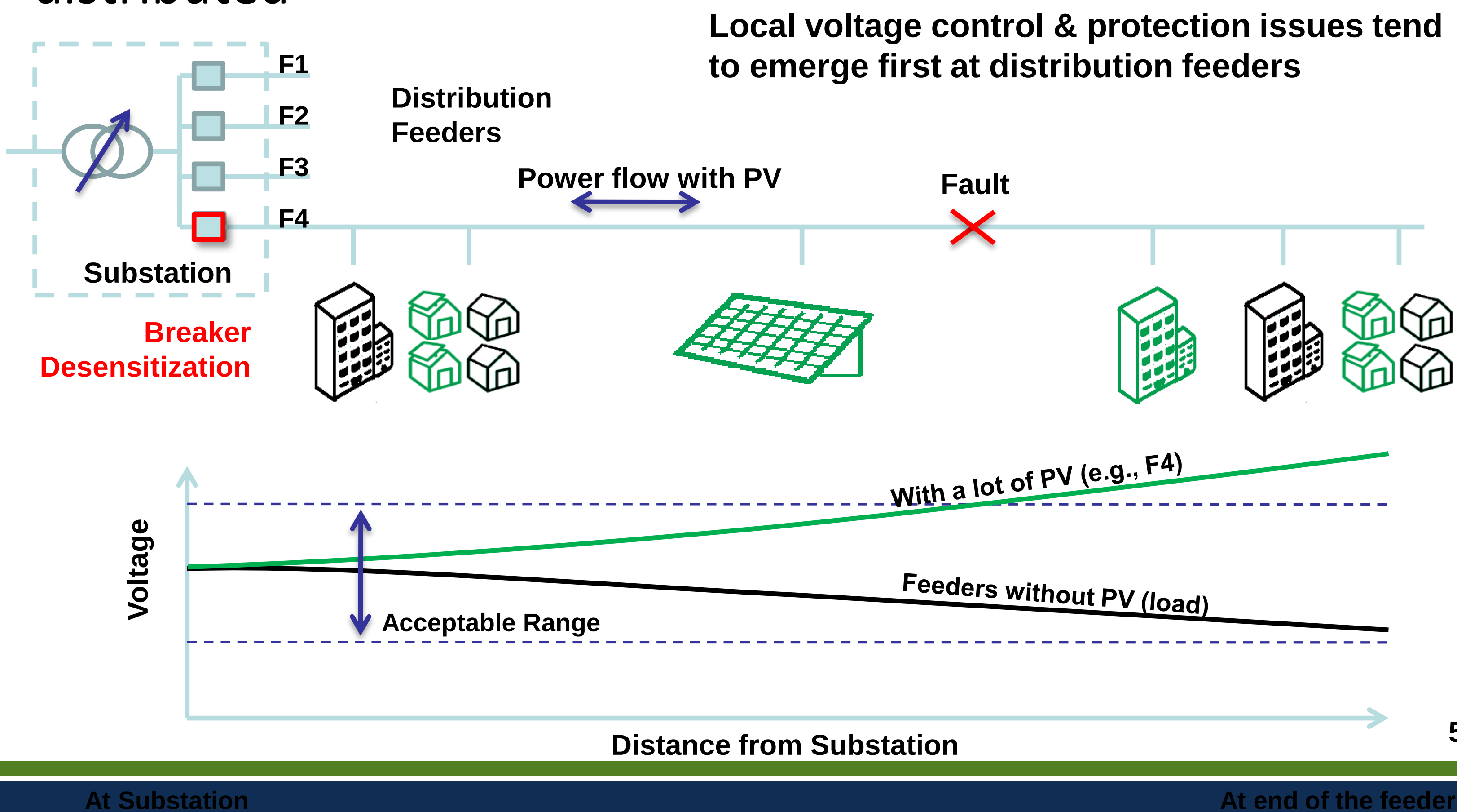
- Voltage & frequency control
- Protection
  - How to tell when/where there is a problem (e.g., fault)
  - Ensure safety, prevent damage to equipment, avoid cascading
- System stability
  - How voltage and frequency recover from a disturbance
- Continuity of service
  - Benchmark: 1-day cumulative outage per customer in a 10-year span (99.97% reliable)





High-Pen PV affects grid performance

- Synchronous Generator Characteristics: steady, dispatchable, includes inertia, speed governing, excitation control, centralized
- PV characteristics: variable, non-dispatchable, inverter-based, distributed



Advanced Inverters are up to the challenge

- It can become increasingly difficult and expensive to integrate high-pen PV [3-6]
- A big part of the solution: deployment of advanced inverters in future distribution-connected PV systems [7-8]
  - Mitigate high-pen impacts and enhance value of PV to owner and grid
- <u>Definition</u> [8-9]: Advanced inverters…
  - Actively support voltage and frequency by modulating the output
  - Have high tolerance to grid disturbances
  - Interact with the system via communications

...Faster than a tap changer

...More powerful than a rotating machine

...Able to leap deep voltage sags in a single bound

Courtessy of B. Lydic, Fronius

Advanced Inverters Enable High-Pen PV

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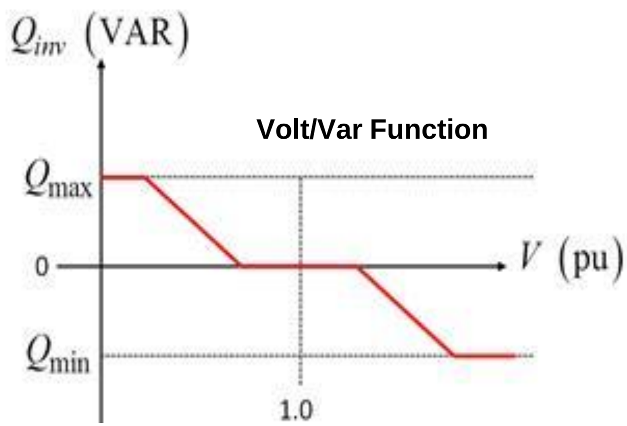
- Advanced inverters allow for higher PV penetration
  - It has been shown that PV inverters with Volt/Var capability can double a distribution circuit's PV hosting capacity (see illustration below) [10]
  - Voltage and frequency ride-through (V/FRT) capability is required to maintain bulk system reliability with high penetration PV [11]



➢ Sandia collaborates with EPRI and NREL to analyze the benefits of advanced inverters in California

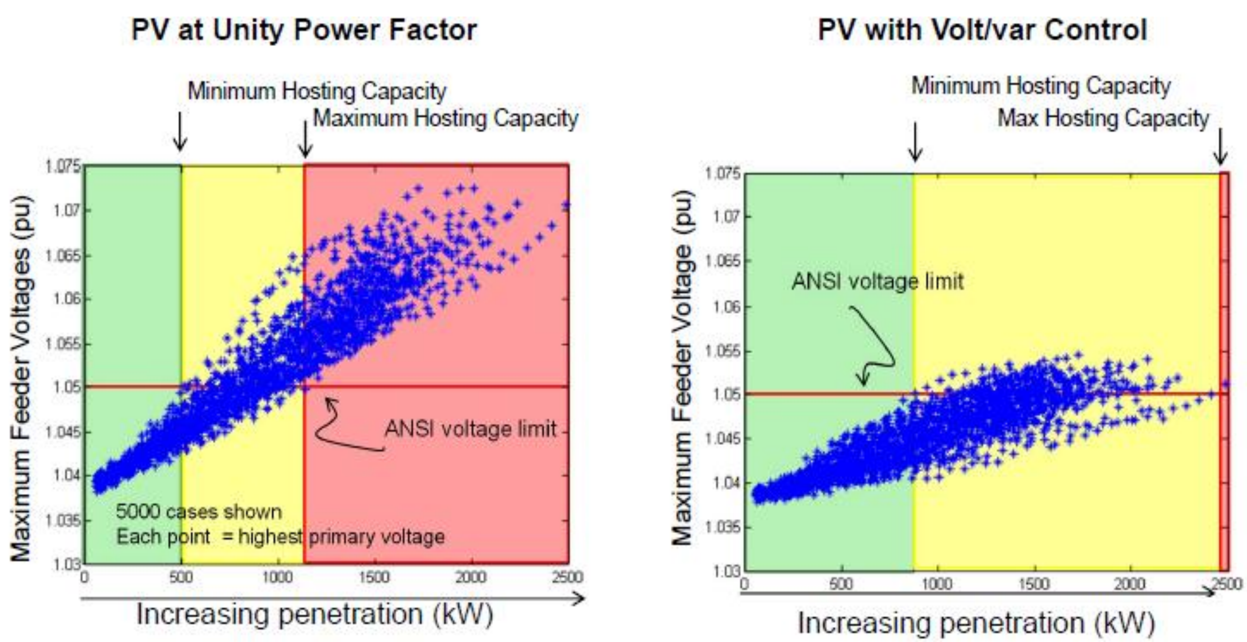
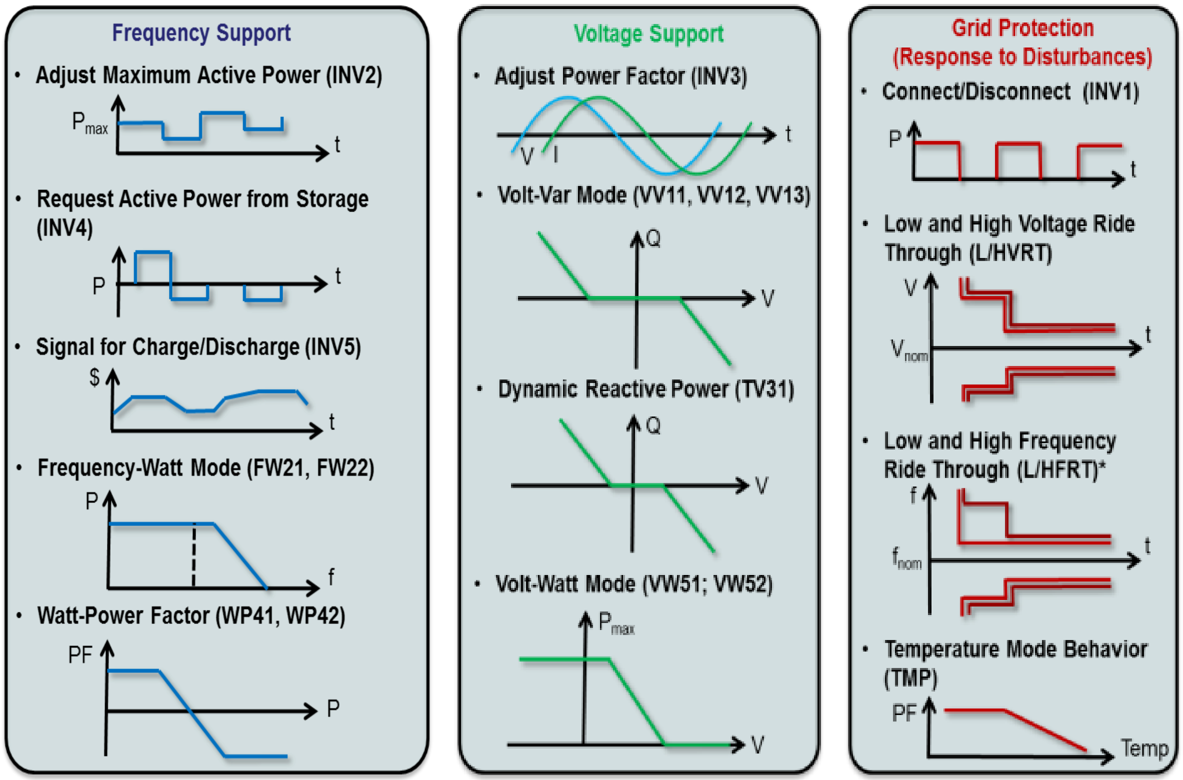


Illustration courtesy of B. Seal, EPRI [10]

Advanced Inverter functions must be defined and standardized

- Define functions (e.g., Q vs. V) and how they are specified
- Describe how the functions are implemented [8-9, 12]
  - Autonomous: Inverter response to local voltage and frequency conditions
  - Commanded: Remote control (e.g., on/off) & configure autonomous behavior



- In 2009, EPRI and Sandia initiated an effort to develop industry consensus on advanced inverter functions definitions, part of SEGIS effort
- Effort covers inverter-based DER (including PV and storage)
- The product became part of the IEC 61850-90-7 technical report

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

Advanced Inverter functions must be integrated into utility operations

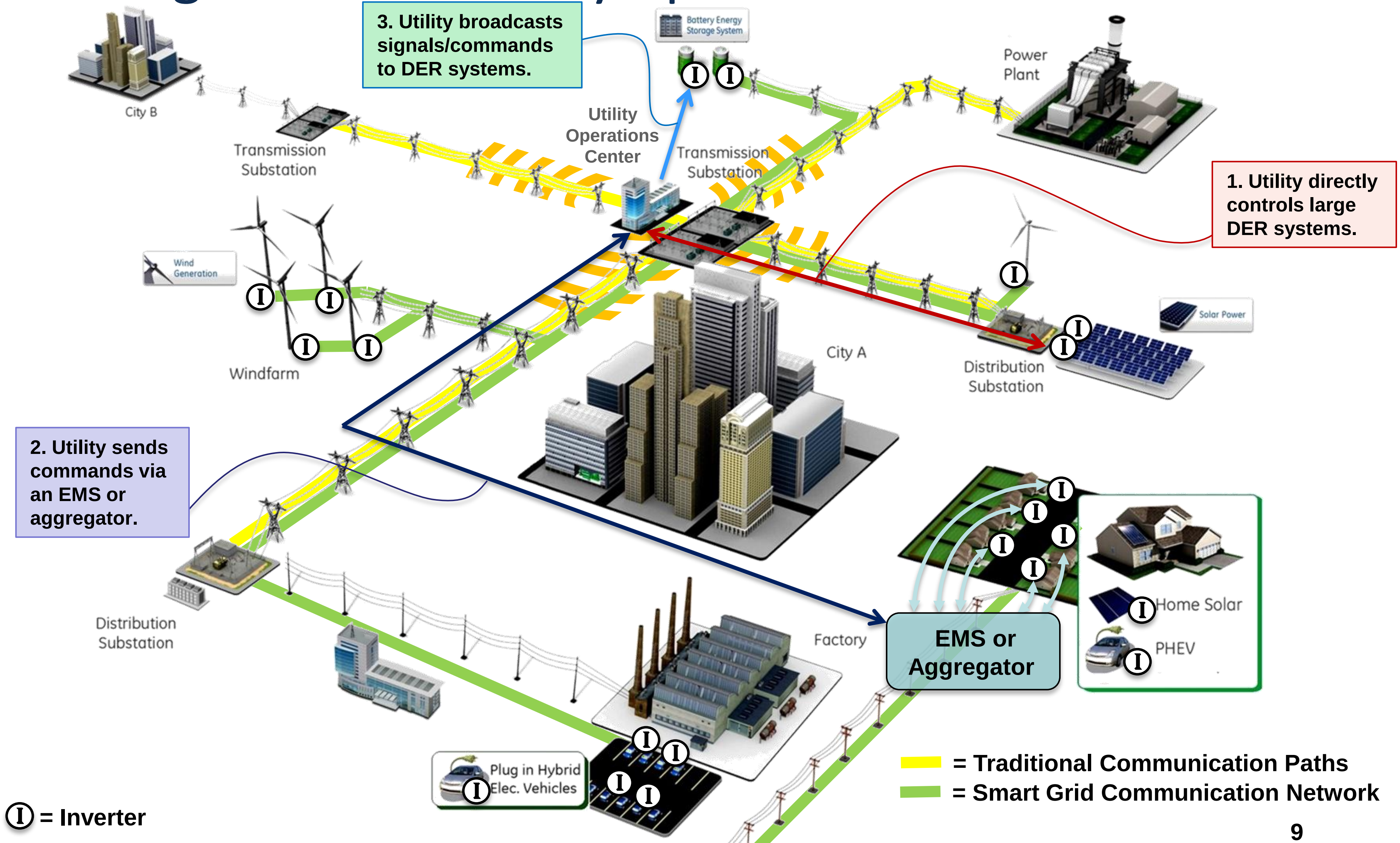
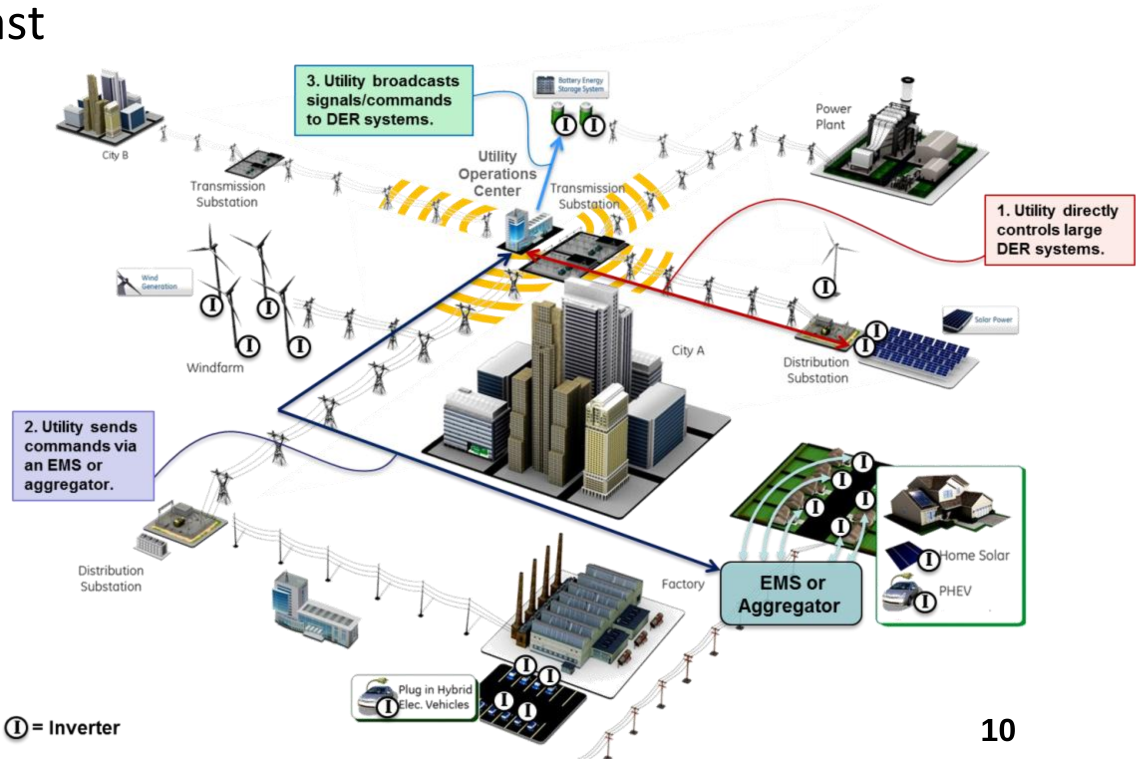


Image: Forbes India

Necessary communications/control architecture still presents challenges

- How will utility, aggregators, smart inverters interact?
- Competing communications solutions
  - Protocols: DNP3, SEP 2.0, IEC 61850, Modbus, OpenADR, SunSpec
  - Medium: Wi-Fi, PLC, Ethernet
  - Method: direct, broadcast
- Open challenges
  - Interoperability
  - Cybersecurity
  - Optimization
  - Utility Integration

➢ Sandia is collaborating with key stakeholders, including NIST, to address interoperability and cybersecurity gaps.



Adv. functions vs. Interconnection Stds.

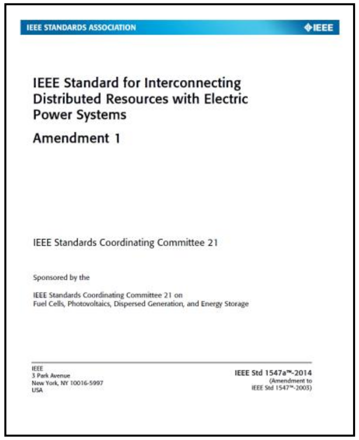
- IEEE Std. 1547 is the US-wide Distributed Resource (DR) technical standard

DER <u>must not participate</u> in V/f regulation ("get out of the way") when there are grid disturbances.

IEEE 1547-2008	IEEE 1547a-2014
Shall not regulate voltage [no volt/var allowed]	May participate in voltage regulation [no specification]
Shall not regulate frequency [no freq/watt allowed]	May participate in frequency regulation [no specification]
Restrictive voltage and frequency must-trip range [opposite of V/FRT]	More widely adjustable voltage and frequency must-trip range [No V/FRT requirement]

DER <u>*may* assist with voltage and frequency regulation</u> with Electric Power System Operator approval.

- Opens the door for jurisdictions to create different interconnection requirements
  - <u>Will likely lead to lack of harmonization</u> and over-specification
  - CPUC Electric Rule 21, PJM, HECO, others starting to develop standards addressing advanced functions


IEEE STANDARDS ASSOCIATION ◆IEEE

IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems

Amendment 1

IEEE Standards Coordinating Committee 21

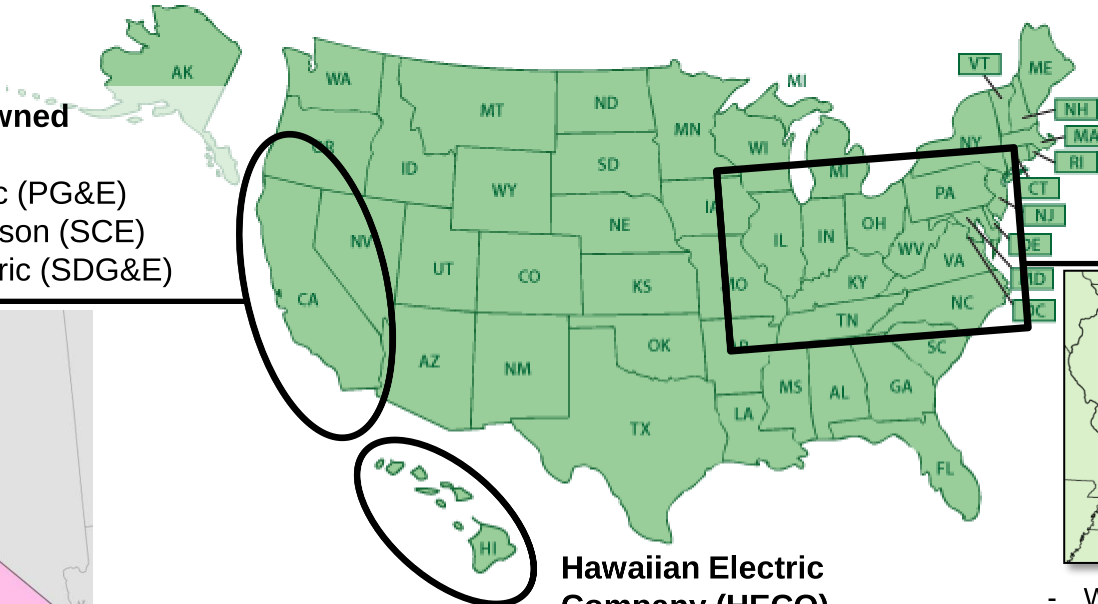
Sponsored by the

IEEE Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1547a™-2014
(Amendment to
IEEE Std 1547™-2003)

Smart Inverter Requirements in USA



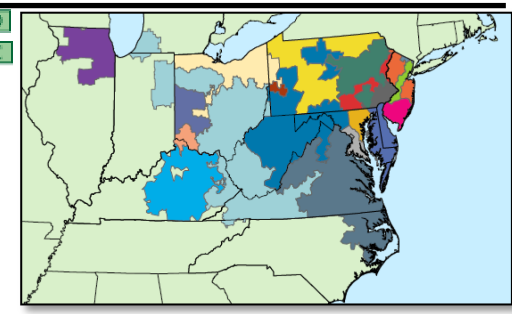
California Investor-Owned Utilities (IOUs):
Pacific Gas and Electric (PG&E)
Southern California Edison (SCE)
San Diego Gas & Electric (SDG&E)

- Serve ~68% of the load in CA
- Governed by California Public Utilities Commission (CPUC) and California Energy Commission (CEC) Electric Rule 21 statute which states the technical requirements for distributed-generation resources to interconnect to the California grid
- Likely to include MANY autonomous and communication-enabled advanced grid functions in the next 1-3 years

Hawaiian Electric Company (HECO)

- Serves 95% of the state's 1.4 million 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 voltage and frequency ride-through requirements

PJM Interconnection LLC (regional transmission organization)



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

All eyes on CA right now.

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

CA CPUC Rule 21 Status

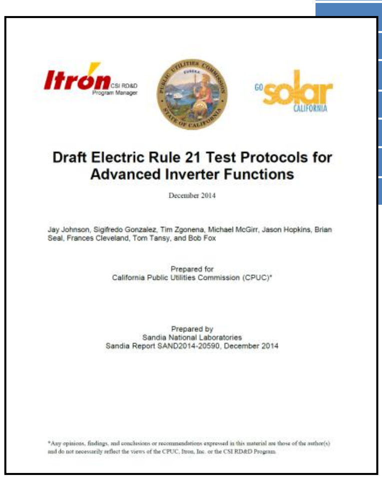
- Jan, 2014: Smart Inverter Working Group (SIWG) consisting of ~230 experts from gov., utilities, PV manufacturers, etc. created "Recommendations for Updating the Technical Requirements For Inverters in Distributed Energy Resources"
  - **Phase 1: Autonomous functions**, ride-throughs, ramp rates, volt/var, etc. **Approved by CPUC – Jan 2015.**
  - **Phase 2: Include communication capabilities**, add data model, cybersecurity, etc. **Submitted to CPUC – March 2015.**
  - **Phase 3: Add advanced inverter functionalities requiring communications**, status reporting, connect/disconnect, limit real power, etc. **Currently being edited by SIWG.**
- Phase 3 interconnection requirements contain the following advanced functions:
  - Anti-islanding
  - Low/High Voltage Ride-Through
  - Low/High Frequency Ride-Through
  - Dynamic Volt/Var operations
  - Normal Ramp rates
  - Fixed power factor
  - Reconnect by "soft-start"

Development of Rule 21 Certification Procedures

- Sandia is helping develop the **certification procedures** for the Rule 21 functions with the UL 1741 Standards Technical Panel.
- UL 1741 protocols are different than the original Sandia Test Protocols for IEC 61850-90-7 functions because they do not have interoperability requirements but they do have pass/fail criteria.

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

Rule 21 advanced inverter/DER functions, as recommended by the Smart Inverter Working Group in Jan 2014


Itron CSI RD&D Program Manager

Go Solar California

Draft Electric Rule 21 Test Protocols for Advanced Inverter Functions

December 2014

Jay Johnson, Sigifredo Gonzalez, Tim Zgonena, Michael McGirr, Jason Hopkins, Brian Seal, Frances Cleveland, Tom Tansy, and Bob Fox

Prepared for
California Public Utilities Commission (CPUC)*

Prepared by
Sandia National Laboratories
Sandia Report SAND2014-20590, December 2014

*Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the CPUC, Itron, Inc. or the CSI RD&D Program.

Draft Rule 21 Phase 1 certification procedures created with the UL 1741 STP

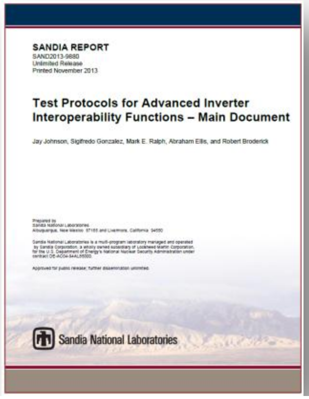
Development of Testing Standards is Critical

- **SIRFN collaboration on testing standards is important to accelerate the deployment of renewable energy around the world.**

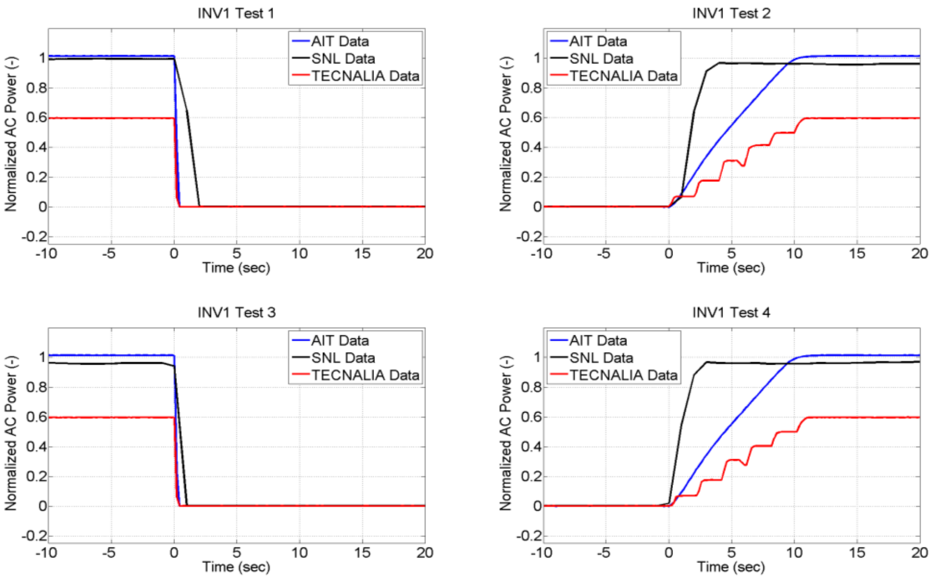
  - Urgency in U.S. to certify inverters for new requirements – both electrical performance and communications
    - Need advanced inverter test protocols for CPUC/CEC California Rule 21
    - Sandia protocols act as basis for updates to UL 1741
  - **Final product:** robust consensus certification procedure for advanced inverter functions for adoption by international standards organizations
  - *Note: this is similar to another Sandia project with the Korea Electrotechnology Research Institute in Changwon, Korea.*

Example Test Protocol (Procedure)

- The Sandia Test Protocols test matrix for the connect/disconnect (INV1) command.
  - Seven tests with different operating points and parameters.

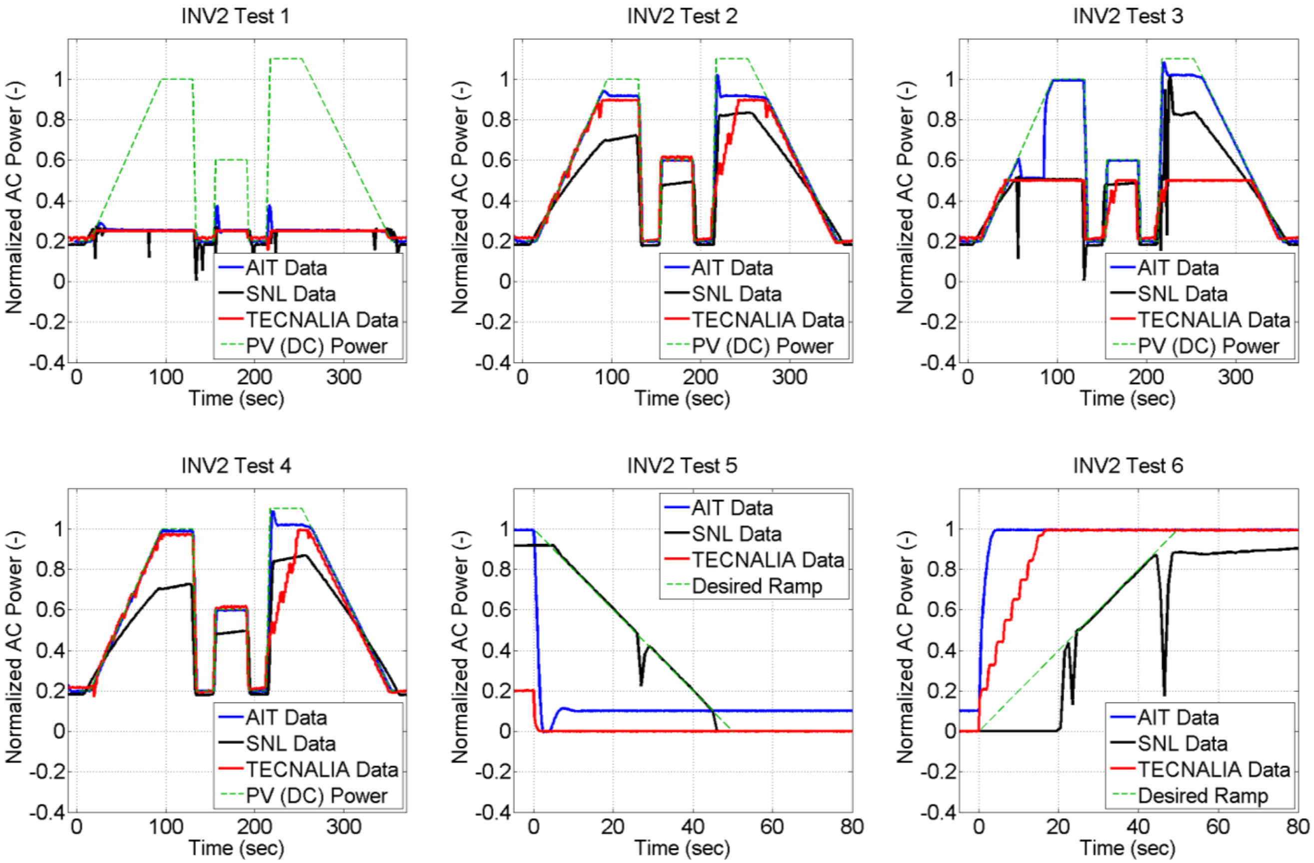


Test	EUT Initial Operating State	Command	Time Window (sec)	Timeout Period (sec)
1	>50% rated power, unity power factor	Disconnect 1	Default (e.g., 0)	Default (e.g., 0)
2	Inverter off	Connect 1	Default (e.g., 0)	Default (e.g., 0)
3	>50% rated power, unity power factor	Disconnect 2	0	Default (e.g., 0)
4	Inverter off	Connect 2	0	Default (e.g., 0)
5	>50% rated power, unity power factor	Disconnect 3	90	30
6	>50% rated power, unity power factor	Disconnect 4	60	0 (No Timeout)
7	Inverter off	Connect 4	60	0 (No Timeout)



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.

Real Power Curtailment (INV2) Results



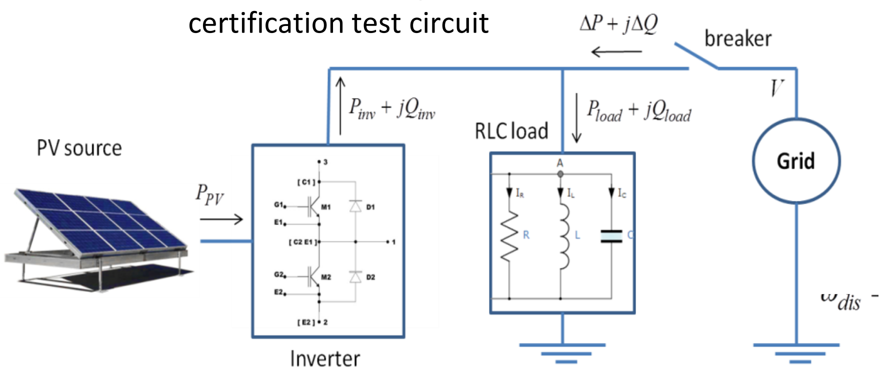
Test	WMax (% nameplate)	Ramp Rate (% nameplate watts/sec)	Time Window (sec)	Timeout Period (sec)	PV Power Profile
1	25	0	0	0	Fig. A2- 1
2	90	0	300	0 AIT:60	Fig. A2- 1
3	50	20	60	30 AIT:60	Fig. A2- 1
4	100	0	0	0	Fig. A2- 1
5	0 AIT:10	2	0	0	Const.
6	100	2	0	0	Const.

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.

Protection Coordination

- Some advanced functions can affect protection coordination
  - One example: Degradation of anti-islanding (AI) performance [13]
    - V/FRT capability can increase run-on times during AI certification test
    - Volt/var and freq/watt functions counter positive feedback AI methods

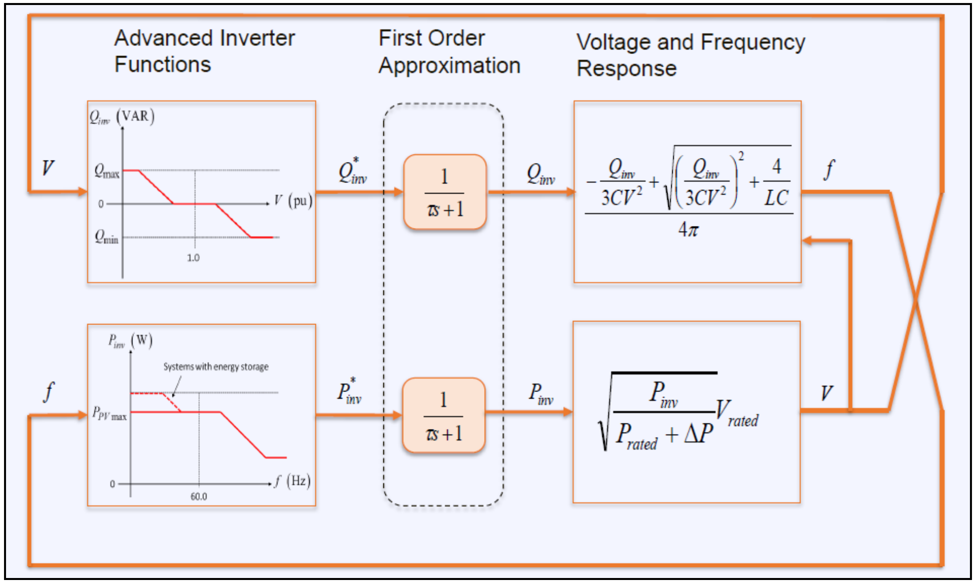
Anti-islanding certification test circuit



Voltage and frequency after the breaker opens

$$V_{dis} = \sqrt{\frac{P_{inv}}{P_{rated}}} \cdot V_{rated} \quad (1)$$

$$\omega_{dis} = \frac{-\frac{Q_{inv}}{CV_{dis}^2} + \sqrt{\left(\frac{Q_{inv}}{CV_{dis}^2}\right)^2 + \frac{4}{LC}}}{2} \quad (2)$$

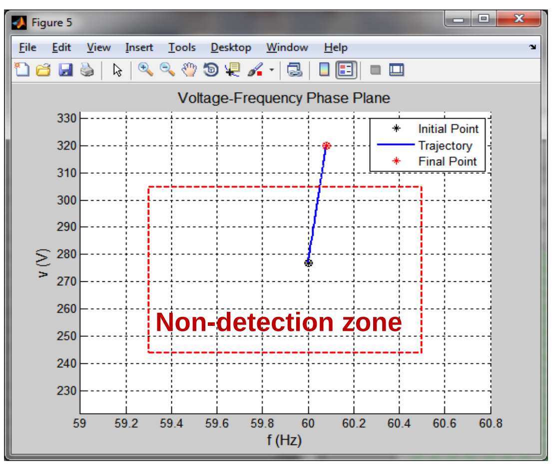


A simple model can be used to show how advanced functions (voltage and frequency support) could affect anti-islanding performance.

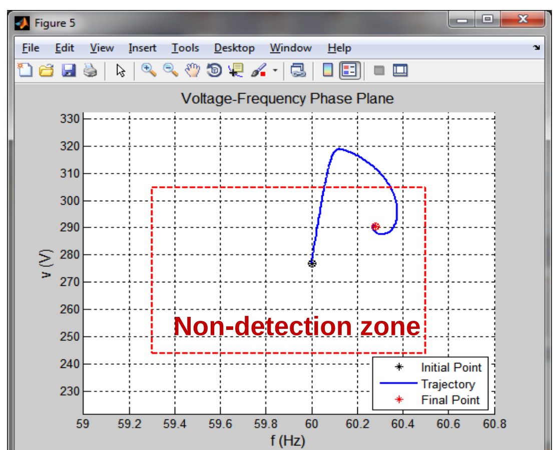
Example: anti-Islanding

- Analysis shows that volt/var & freq/watt functions can make certain anti-islanding methods less effective
  - Example below is for a 50 kW inverter using Sandia Frequency Shift AI method
  - AI is more difficult with V/FRT as well!

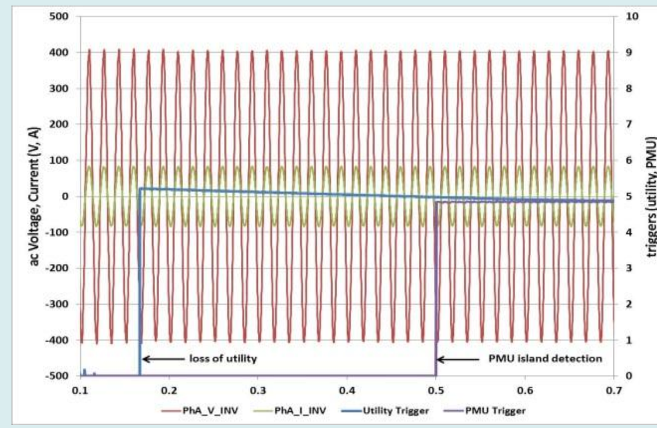
Without volt/var and freq/watt.



With volt/var and freq/watt.

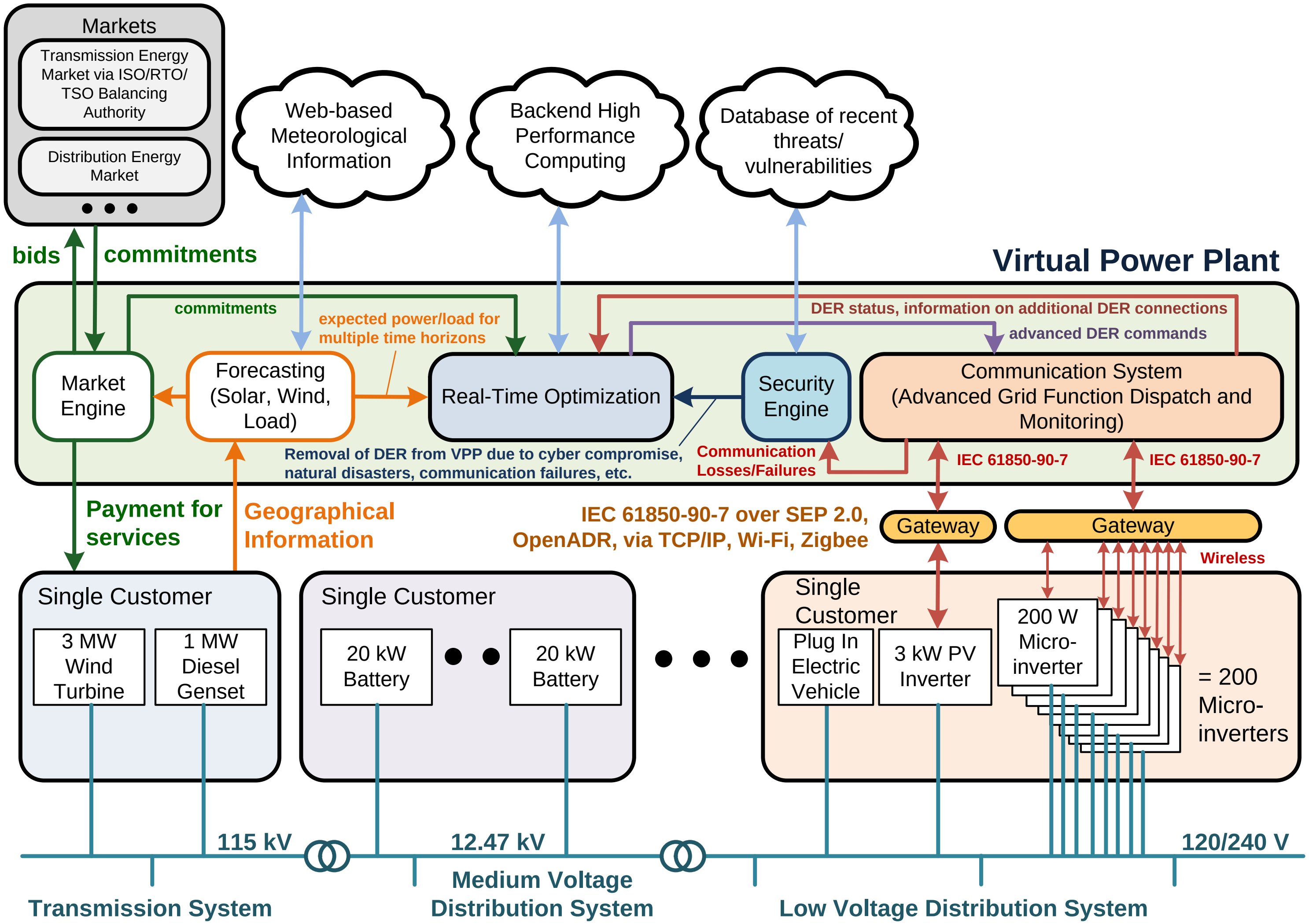


- Sandia is investigating control- and communication-based solutions to this problem
  - Optimization of control parameters (gains and delays) for a given anti-islanding scheme
  - PLC and synchrophasor "heartbeat" methods [14]



The illustration shows experimental results for a "failed" anti-islanding test conducted at Sandia, and effective synchrophasor islanding detection.

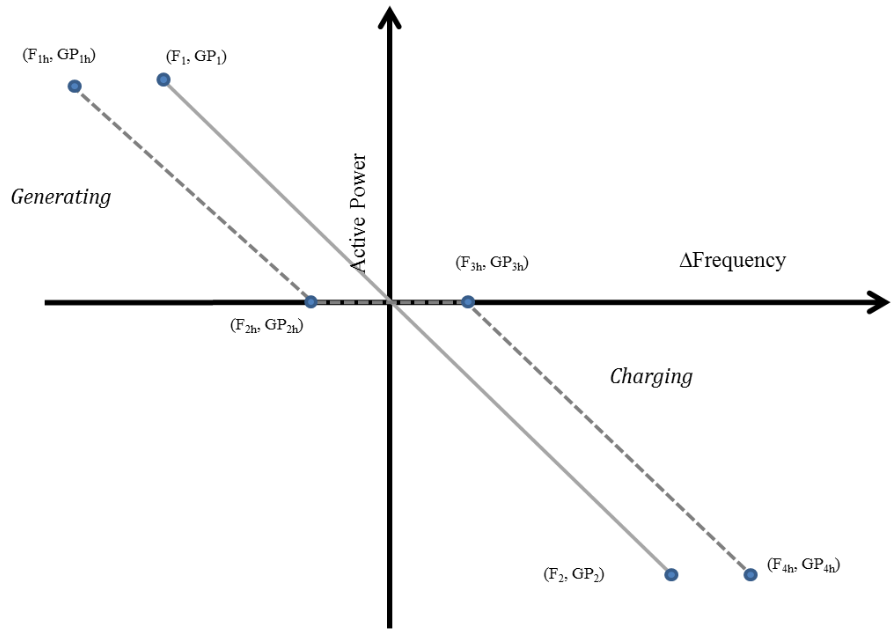
Virtual Power Plants allow resources to be aggregated, controls to be coordinated

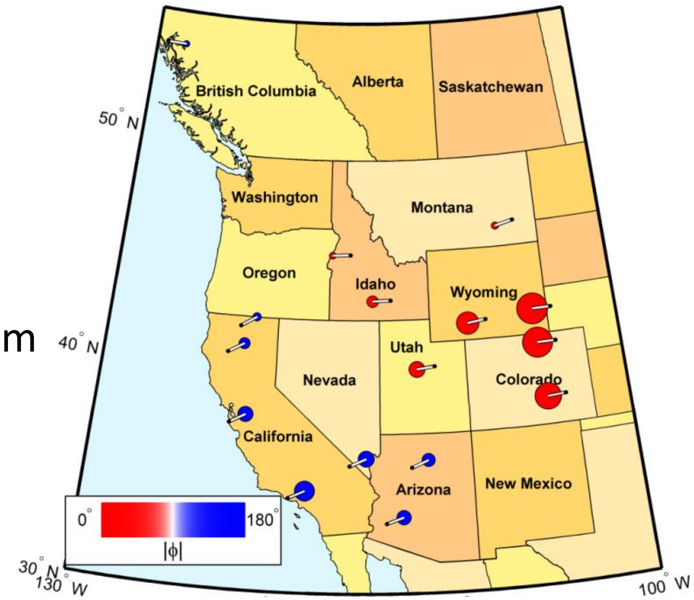


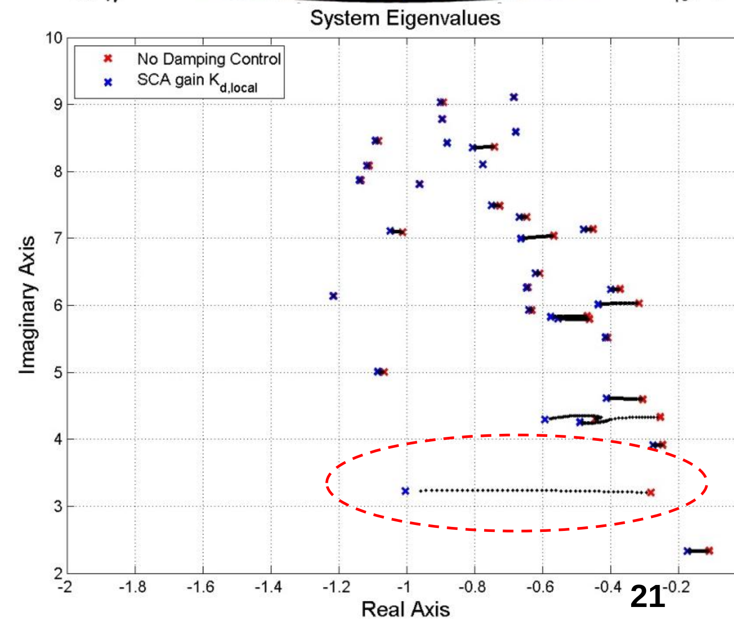
Real-time Optimal Control Algorithms are under development

- Example: frequency-Watt parameters are computed *optimally* based on:
  - location in western Interconnection
  - Frequency Response Objectives for the power system

Freq-Watt function







Conclusions

- PV inverters advanced functions help support the grid
- In the U.S., many jurisdictions are considering the implementation of smart inverters
  - Allowed with the adoption of IEEE 1547a
  - Regional differences could be an issue for manufacturers and certification laboratories
  - Autonomous functions will be rolled out first
  - Communications methods are not finalized, cybersecurity a big concern
- Sandia and collaborators are addressing technical issues:
  - Test protocol development to verify DER functionality
  - Development of Anti-islanding methods
  - Optimal/Coordinated selection of function parameters

Questions?

References

[1] T. Hsu, Los Angeles Times, “Gov. Brown pushes 12-gigawatt clean-power goal,” July 26, 2011.

[2] J.F. Wiedman, et al., Interstate Renewable Energy Council, “12,000 MW of Renewable Distributed Generation by 2020,” July 2012.

[3] Eltawil, Mohamed A., and Zhengming Zhao. "Grid-connected photovoltaic power systems: Technical and potential problems—A review." *Renewable and Sustainable Energy Reviews*, pp. 112-129, 2010.

[4] Enslin, Johan HR. "Network impacts of high penetration of photovoltaic solar power systems." Power and Energy Society General Meeting, 2010 IEEE. IEEE, 2010.

[5] J. Bank, B. Mather, J. Keller, and M. Coddington, “High Penetration Photovoltaic Case Study Report,” NREL Technical Report TP-5500-54742, Jan 2013.

[6] R. Elliott, R. Byrne, A. Ellis, L. Grant, “Small Signal Stability of the Western North American Power System with High Penetration of Photovoltaic Generation”(in development).

[7] E. Malashenko, S. Appert, W. al-Mukdad, Advanced Inverter Technologies Report, CPUC Grid Planning and Reliability Energy Division, 18 Jan 2013.

[8] International Electrotechnical Commission Technical Report IEC 61850-90-7, “Communication networks and systems for power utility automation–Part 90-7: Object models for power converters in distributed energy resources (DER) systems,” Edition 1.0, Feb 2013.

[9] Electric Power Research Institute (EPRI), Common Functions of Smart Inverters, Dec 2011.

[10] J.W. Smith, W. Sunderman, R. Dugan, B. Seal, "Smart inverter volt/var control functions for high penetration of PV on distribution systems," Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES , vol., no., pp.1,6, 20-23 March 2011.

[11] NERC Performance of Distributed Energy Resources During and After System Disturbance , Voltage and Frequency Ride-Through Requirements , IVGTF1-

[12] CEC/CPUC, Recommendations for Updating the Technical Requirements for Inverters in Distributed Energy Resources: Smart Inverter Working Group Recommendations, Jan 2014.

[13] J. Neely, S. Gonzalez, M. Ropp, D. Schutz, ”Accelerating Development of Advanced Inverters: Evaluation of Anti-Islanding Schemes with Grid Support Functions and Preliminary Laboratory Demonstration,” Sandia National Laboratories Technical Report SAND2013-10231; November 2013.

[14] M. Mills-Price, M. Scharf, et al., "Interconnection control of distributed generation with time-synchronized phasors," Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES , pp.1,8, 20-23 March 2011.