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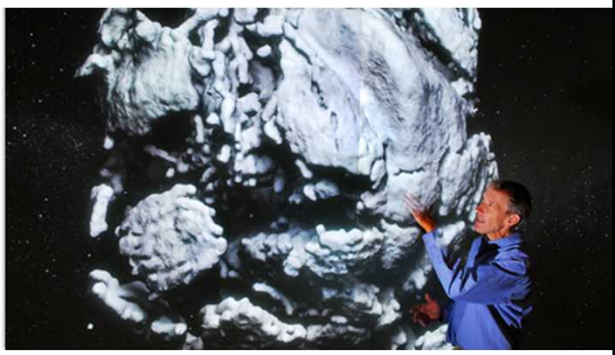

Evaluation and Optimization of Interoperable DERs to Provide Grid-Support Services

Georgia Tech Grid Modernization Workshop
Atlanta - 27 April, 2016

Jay Johnson

Photovoltaic and Distributed Systems Integration

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Agenda

- Advanced DER testing at the Distributed Energy Technologies Laboratory (DETL)
  - Test protocol development with the Smart Grid International Research Facility Network (SIRFN)
  - System Validation Platform (SVP)
- Creation of an integrated distributed energy/cybersecurity research platform across Sandia and external sites
- Virtual Power Plant (VPP) research

Distributed Energy Technology Lab (DETL)

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A Reconfigurable Smart Grid Testbed

- Optimization of new DG/DER components and systems
  - R&D and product development
  - Pre-commercial testing and characterization
  - Protocol and standards development
  - Demonstration

- Scenarios
  - Grid-connected and off-grid
  - Controllable loads simulate residential, commercial
  - Campus or base grids
  - Forward operating bases
  - Multiple sources
  - Energy storage
  - Home/building/network EMS

DETL Facility Features

- 150 kW PV
- 1 MW-hr storage capability
- 250 kW inverter capacity
- 3-Ø, 1-Ø µ-grids
- Communications infrastructure (ethernet, wireless, PLC)
- 10-node residential
- µ-inverter testbed
- 200 kW diesel genset

Links to smart grid field demos:

- **Mesa del Sol**
- **PNM Prosperity project**
- **NMSU campus microgrid**
- **Others (military microgrids, large PV plants)**

Large-scale hardware evaluations achievable with PV and Grid Simulators

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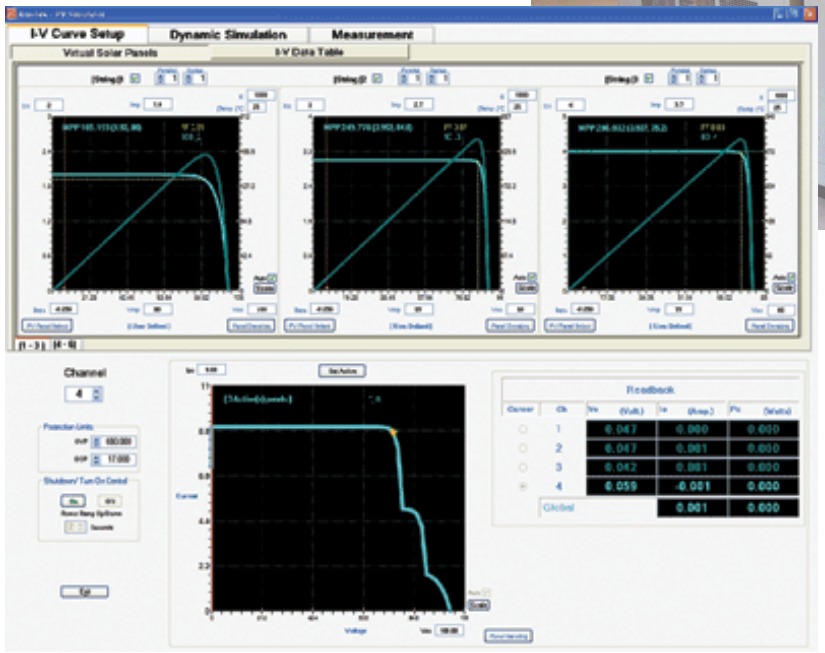
- State-of-the-art DC and AC simulators
- Regenerative programmable AC power supply, 200 kW
- Advanced DC power supply can be programmed to simulate PV arrays, based on data from any commercial PV module. Variable irradiance conditions can also be programmed.



Specifications:
Power: 200kW (20 outputs, 10kW each)
Voltage: 0-1000 Vdc/output
Current: 10A/output

Characteristics:
Individual I-V curve characteristics per output.
Outputs can be combined to mimic poor performing string.
Ideal MPPT evaluating source

High Penetration PV and Smart Grid Studies with 10-Node Platform

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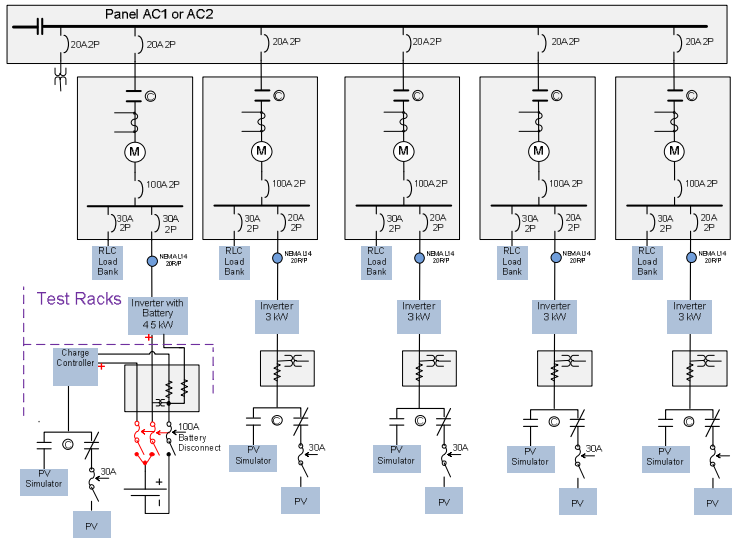
- Simultaneous testing of up 10 inverters with individual programmable load, energy storage, PV, Smart Meter, Home EMS
- 120V/240V service, up to 10 kW per node
- Can be isolated to grid or to programmable AC power supply to evaluate off-nominal or dynamic grid conditions
- Able to evaluate communication protocols and cyber security
- **New HIL capabilities with Opal-RT and Typhoon HIL simulators**



DER Certification Testing Background

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- Total installed capacity of renewables is growing fast in the US
  - The distributed and variable nature of these resources cause a range of challenges for grid operators
- Distributed Energy Resources (DERs) have the ability to help by:
  - **Supporting voltage and frequency** by modulating active and reactive power output
  - **Tolerating grid disturbances**
  - Interacting with grid operations via **communications**
- These capabilities are enabled through **multiple advanced DER functions**
  - They are being **codified in a number of standards development organizations** (SDOs)
  - It's necessary to **verify their functionality prior to wide-spread deployment** in the US
  - Testing will be conducted according to **UL 1741 SA**

Smart Grid Communications

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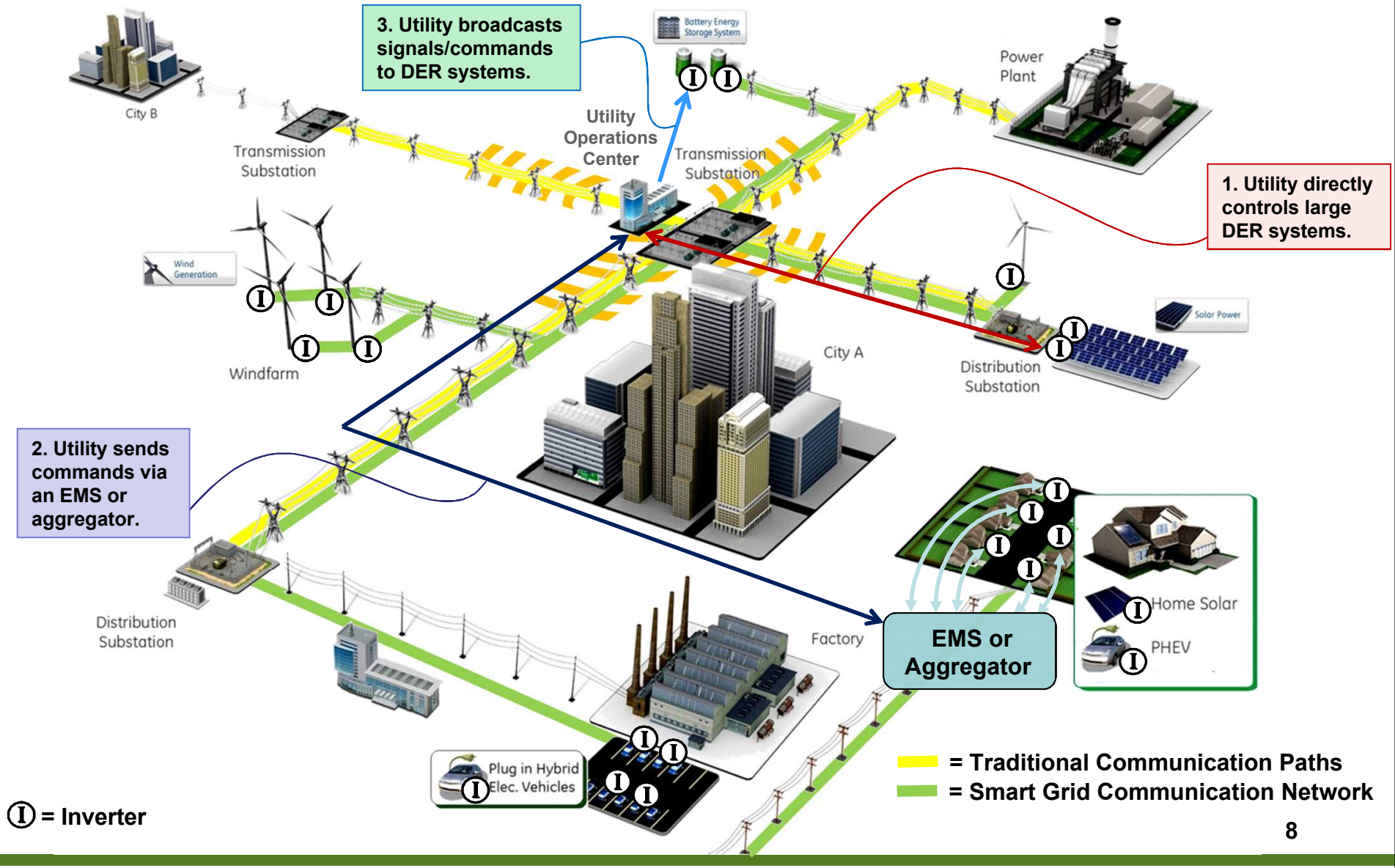
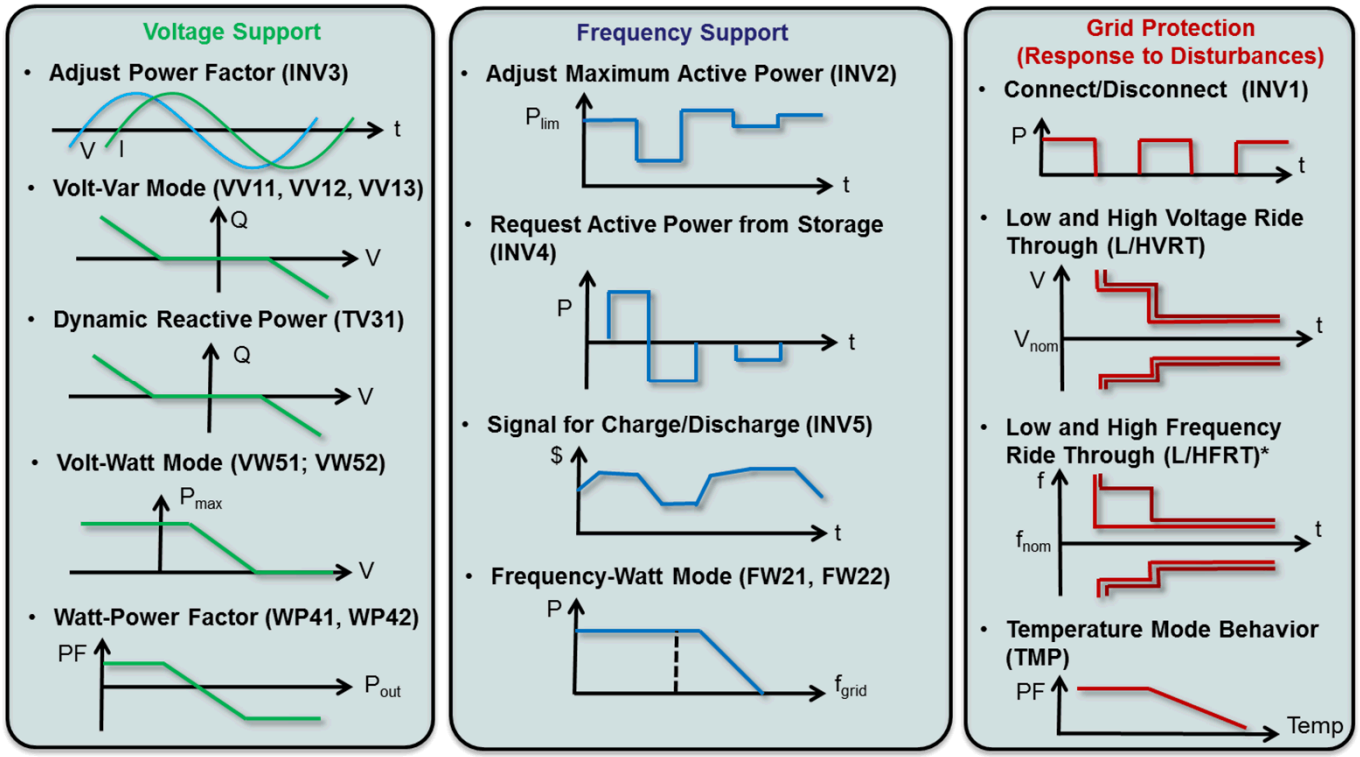


Source: Forbes India

Advanced Interoperability Functions

- New 'smart' inverters will include multiple advanced functions
  - Autonomous: Inverter response to local voltage and frequency conditions
  - Commanded: Remote control (e.g., on/off, set power factor)
- Utilities will modify distributed energy resource (DER) behavior using communications.



Similar functions are in California Electric Rule 21, UL 1741 SA, and IEEE 1547 full revision.

Many countries in Europe have defined similar functions.

Advanced functions as defined in IEC TC 61850-90-7, *with the exception of FRT.

SIRFN Smart Grid Collaboration

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- IEA (International Energy Agency)
  - Clean Energy Ministerial (CEM)
    - International Smart Grid Action Network (ISGAN)
      - **Smart Grid International Research Facility Network (SIRFN)**
        - Smart Grid Distribution Automation
        - Advanced Laboratory Testing Methods
        - Power Systems Testing
        - **Test Protocols for Advanced DER Functions**

SIRFN - A coordinated network of smart grid research facilities from:

- **Primary goal**: Develop and demonstrate a consensus-based interoperability certification standard for advanced Distributed Energy Resources (DERs).
  - Design and compare advanced interoperability test-beds.
  - Perform round-robin testing of advanced DER.
  - Compare test results, communications methods, and automation procedures.
  - Gradually improve draft test procedures for advanced DER with the goal of becoming an internationally-accepted standard.

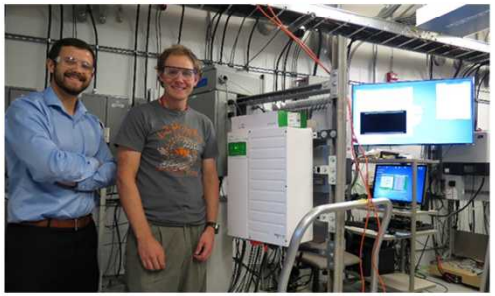
Some Experimental Results: J. Johnson, R. Bründlinger, C. Urrego, R. Alonso, "Collaborative Development Of Automated Advanced Interoperability Certification Test Protocols For PV Smart Grid Integration," EU PVSEC, Amsterdam, Netherlands, 22-26 Sept, 2014.

SIRFN Testing Laboratories creating and executing ESS Test Protocols

Team members at AIT Smart Electricity Systems and Technologies (SmartEST) PV Inverter Test Laboratory

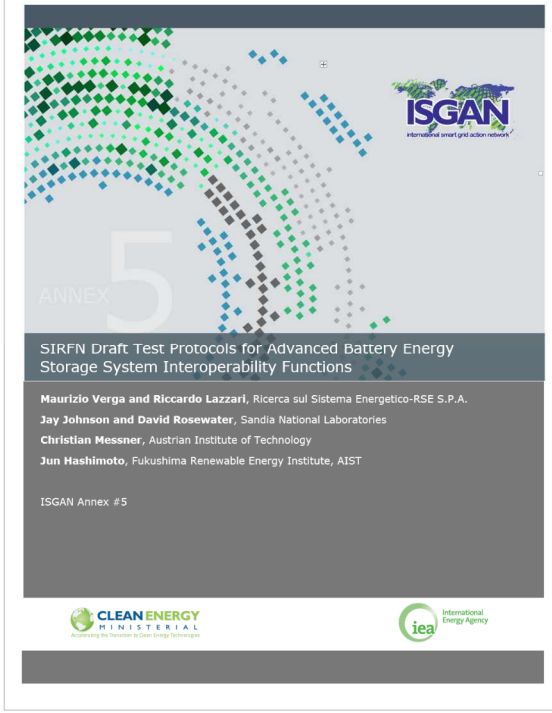
Team Members at RSE Distributed Energy Resource (DER) Test Facility

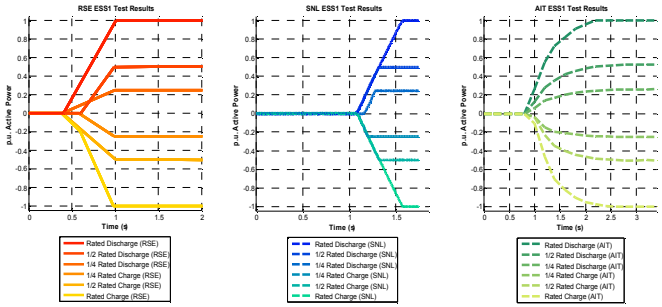
Team members at FREA Smart DER Research Facility

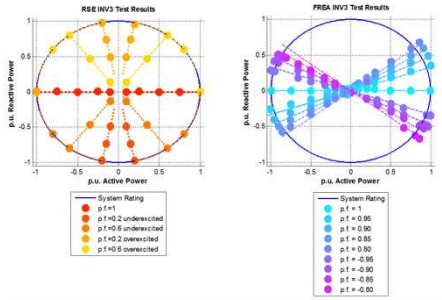


Team Members at Sandia's Distributed Energy Technologies Lab (DETL)

Protocols will be published soon for active power, reactive power, fixed power factor, volt-var, and frequency-watt.



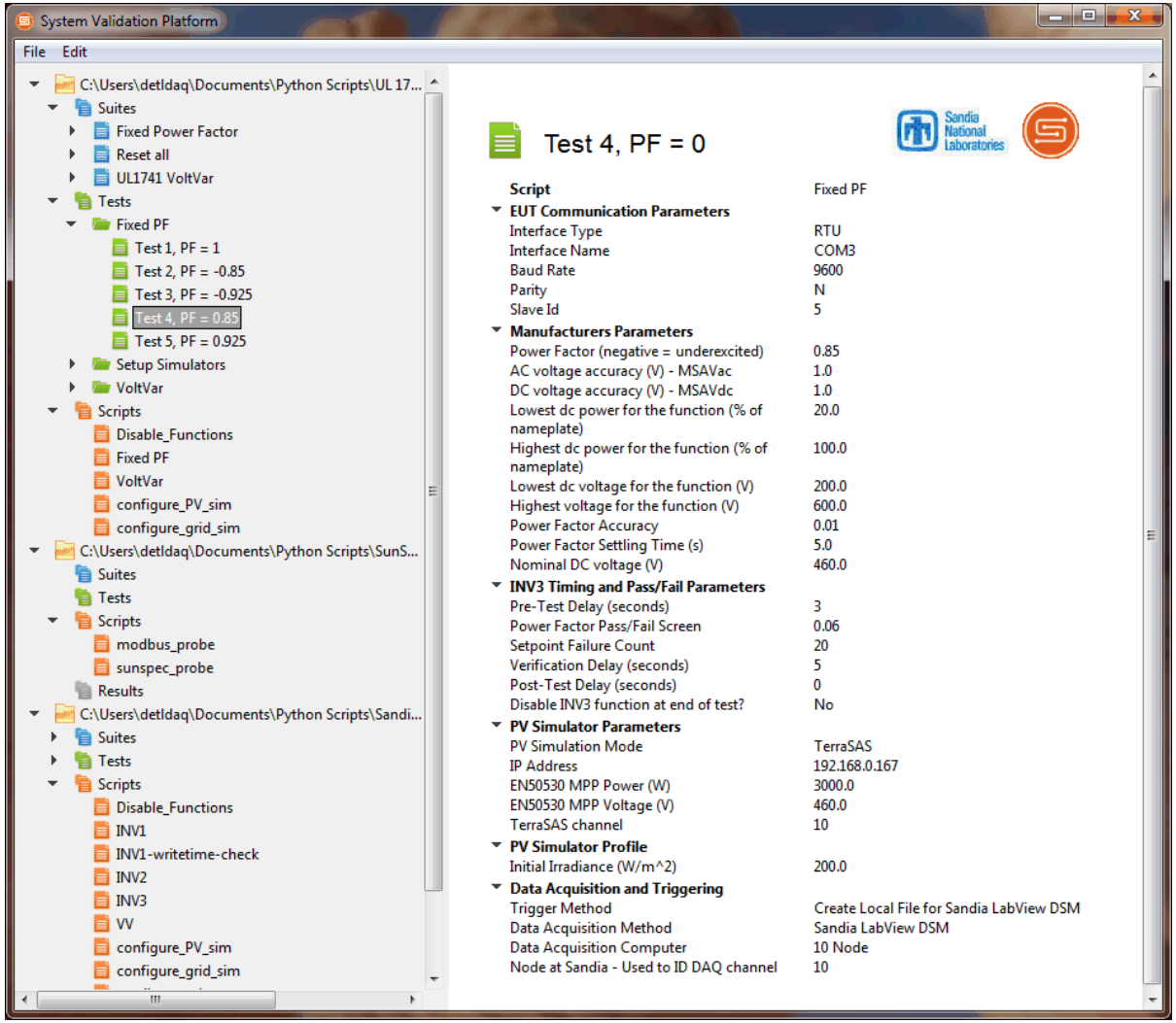




D. Rosewater, J. Johnson, M. Verga, R. Lazzari, C. Messner, R. Bründlinger, K. Johannes, J. Hashimoto, K. Otani, International development of energy storage interoperability test protocols for renewable energy integration, EU PVSEC, Hamburg, Germany, 14-18 Sept, 2015.

SunSpec/Sandia System Validation Platform

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

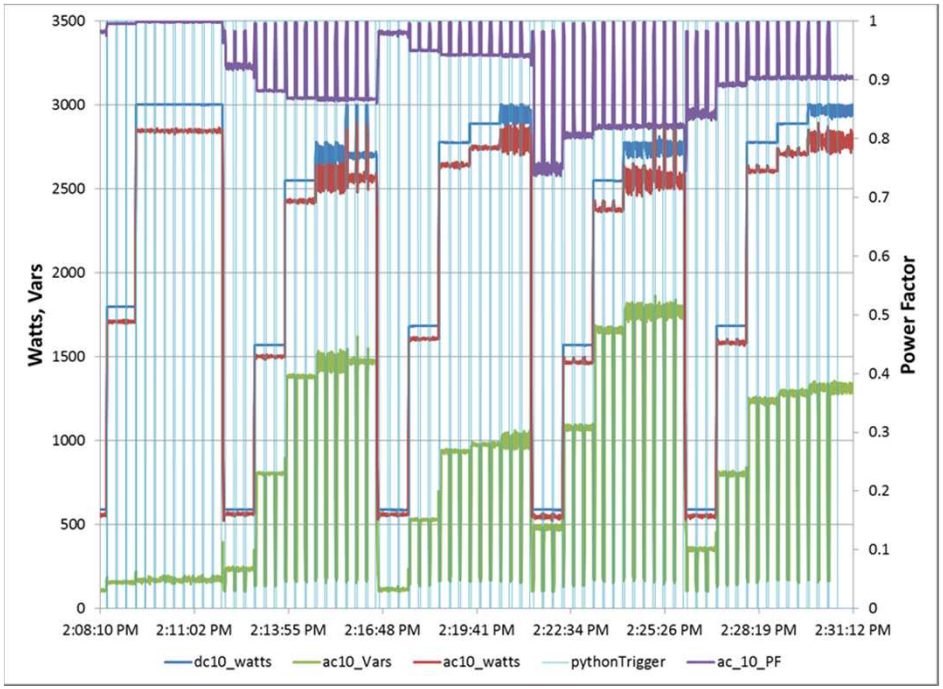


http://sunspec.org/sunspec-svp/
http://sunspec.org/download-svp/
https://github.com/sunspec/svp_directories

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.

More in: J. Johnson, B. Fox, "Automating the Sandia Advanced Interoperability Test Protocols," 40th IEEE PVSC, Denver, CO, 8-13 June, 2014.

Integrated R&D Capabilities

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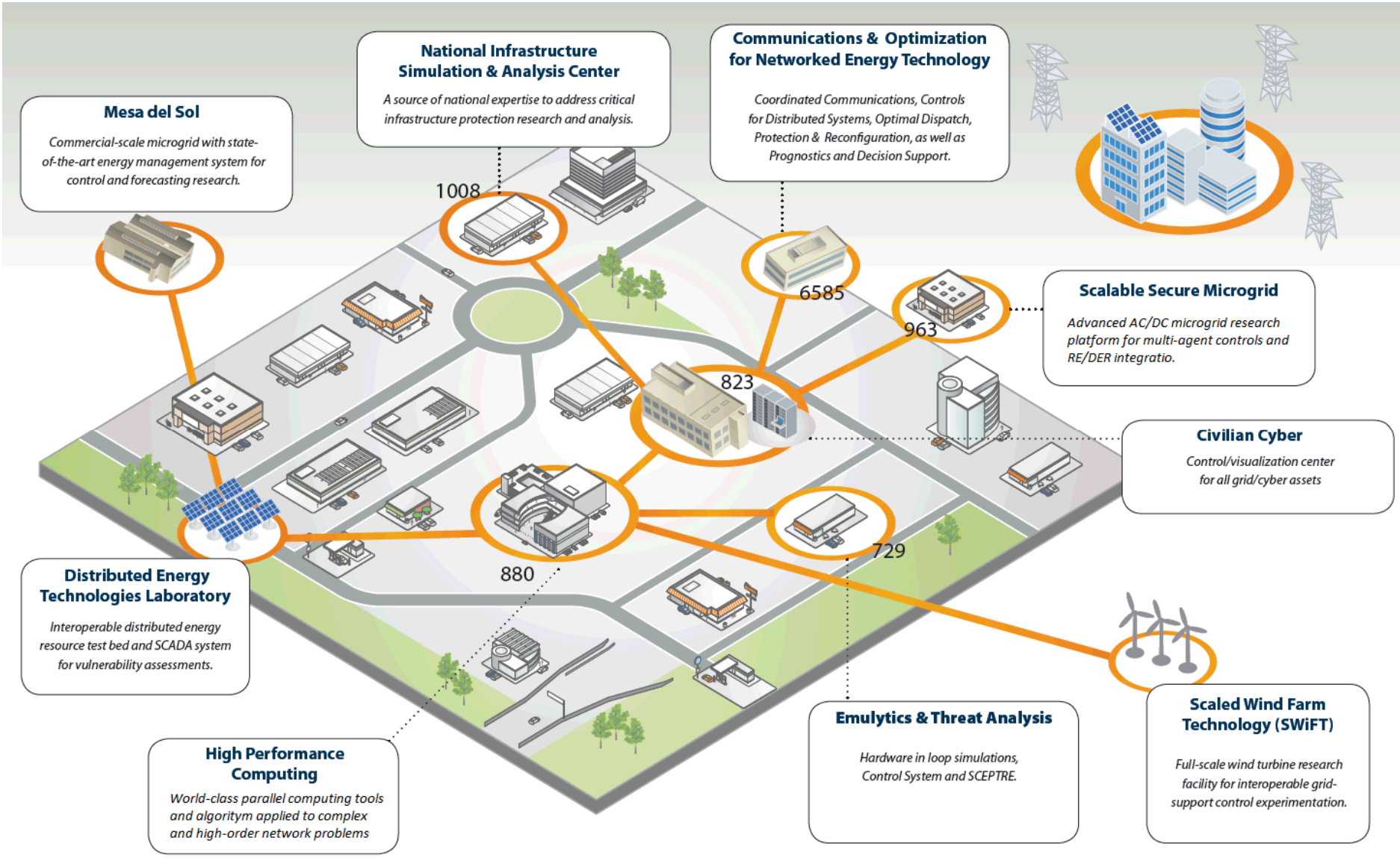

Cyber Security and Interoperability Demonstrations

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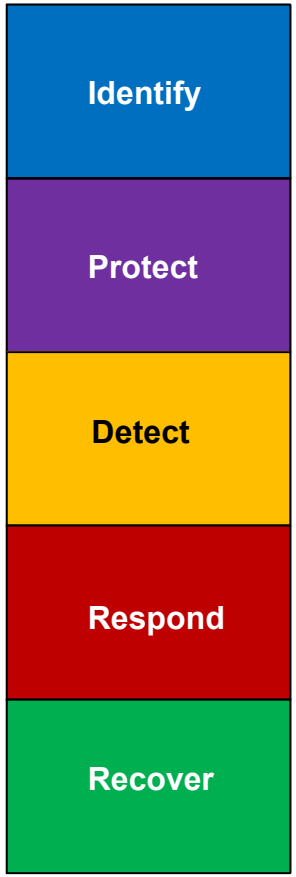
- Kali Linux penetration investigation of PV inverters
  - Search for additional issues with inverter interoperability capabilities.
- Intrusion Detection System (IDS) Penetration detection algorithm
  - Compare the data streams to see if there are indicators that the DER data is falsified.
- DER Control Network Red Teaming and Analysis
  - Working with major US aggregator to investigate cybersecurity weaknesses in their communication infrastructure.
- Collaborations with major PV manufacturers
  - SNL validating communication hardware and network security.
- HIL experiment for Bonneville Power Authority
  - Demonstrate wide-area damping with hardware-in-the-loop simulations of the WECC where frequency data is captured with 2 PMUs and power is injected according to a Sandia algorithm at the Pacific DC Intertie.
- Demand response control and modeling
  - Modeling MESA chiller to improve operational efficiency and provide DR via communications link.

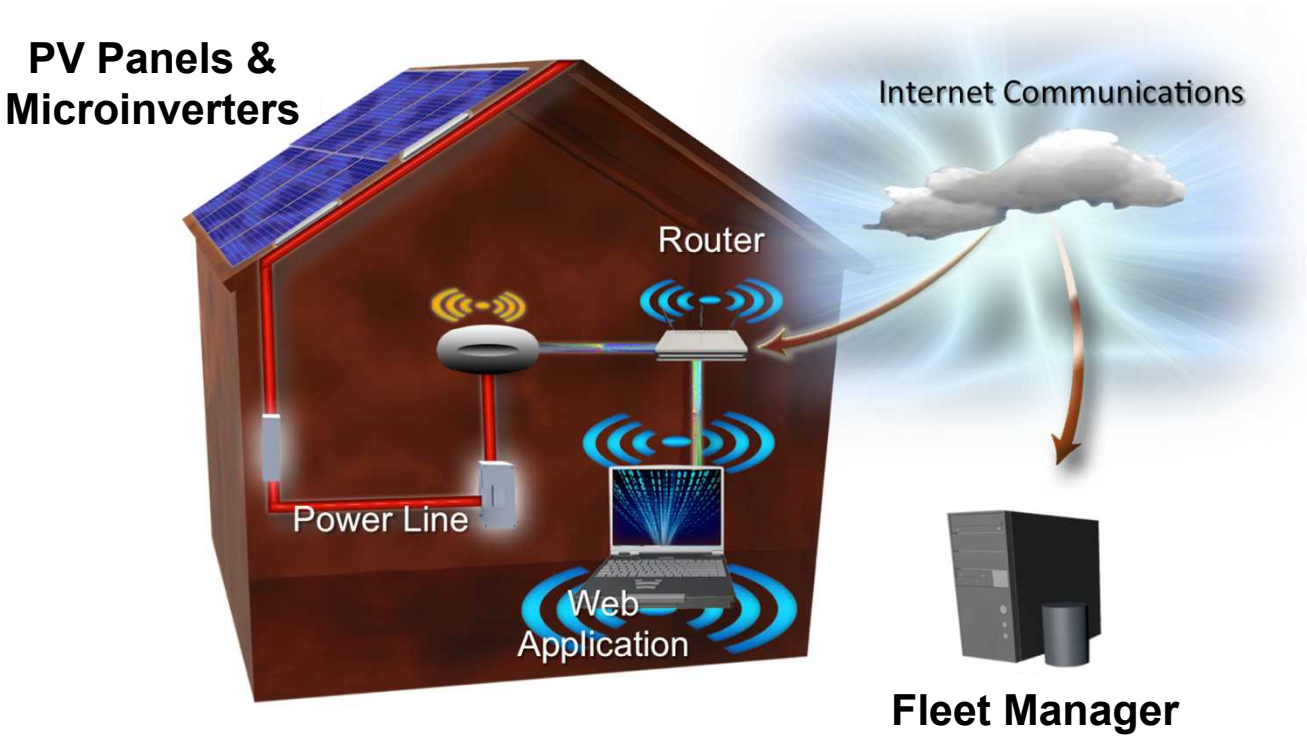


NIST Preliminary Cybersecurity Framework

http://www.nist.gov/itl/upload/preliminary-cybersecurity-framework.pdf

Example SNL Analysis: DER data manipulation

- Scenario: modify inverter performance data to cause billing problems and adjust control set points to impact grid stability
- Combines Sandia's cyber, power system, and critical infrastructure modeling and simulation capabilities



Exploitation – Impacting Business Operations

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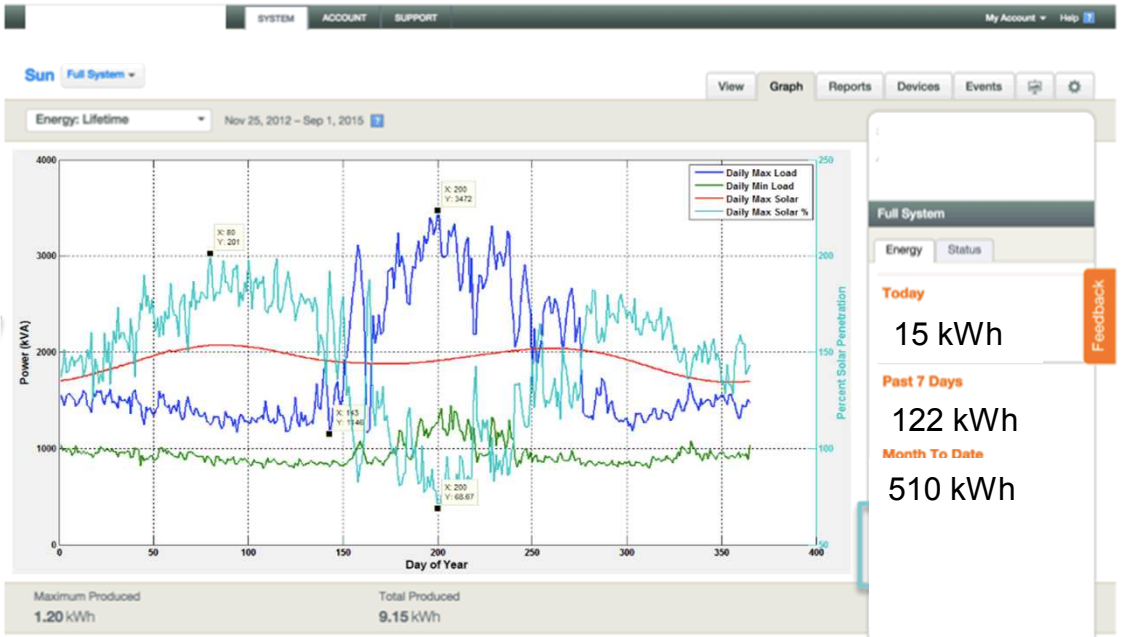
Modified data** used for **Billing, Marketing, and Consumer Monitoring



Weak Certificate Enforcement
+ Cyber Attack Against Encryption

Communication & Data Access

Sandia National Laboratories' Integrated Cyber Physical Impact Analysis (ICPIA) Framework

Virtual Power Plants

- VPPs are aggregations of DER assets controlled to provide identical (or superior) grid-support services compared to traditional generators.
  - Enables renewable energy, demand response, and energy storage to provide grid services
  - Improves grid reliability by providing additional operating reserves to utilities and ISO/RTOs
  - Removing renewable energy high-penetration barriers
- Goal: Develop a unified platform incorporating resource forecasting, standard communications, optimization, and control/dispatch to provide grid services with DERs.

Virtual power plant with communication network (EPRI)

>

Lake Side natural gas turbine power station in Vineyard, Utah. (Wikipedia Commons)

Sandia is optimizing advanced DER functions to provide grid support capabilities

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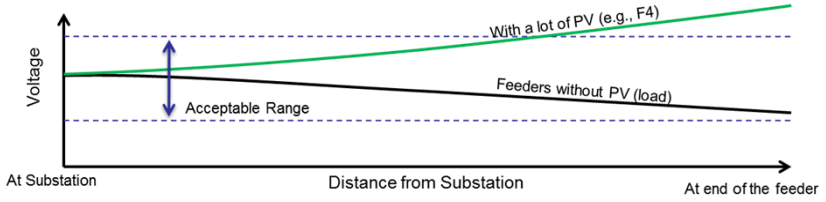
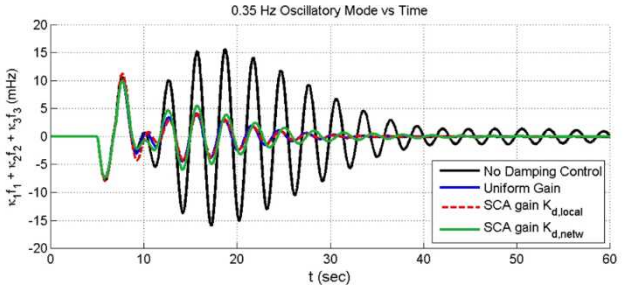
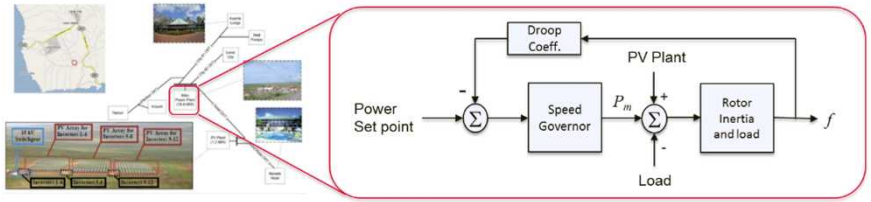
Distribution-Level Voltage Control[1]



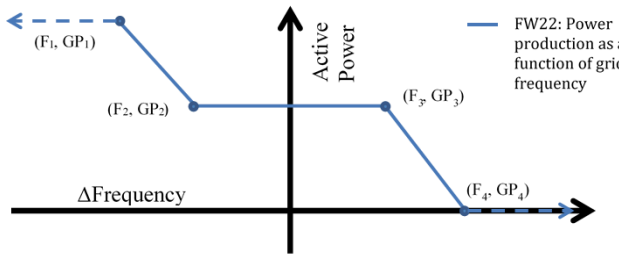
Wide-area damping[2]



Frequency Control[3]



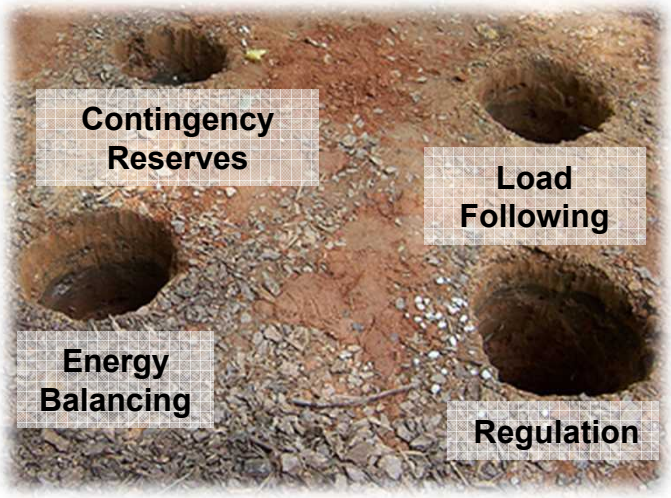
Ancillary Reserves[4]



1. J. Seuss, M.J. Reno, R.J. Broderick, R.G. Harley, "Evaluation of reactive power control capabilities of residential PV in an unbalanced distribution feeder," 2014 PVSC, pp. 2094-2099, 8-13 June 2014.
2. J. Neely, J. Johnson, R. Bryne, R. T. Elliott, Structured optimization for parameter selection of frequency-watt grid support functions for wide-area damping, DER Journal, vol. 11, no. 1, pp. 69-94, 2015.
3. J. Neely, S. Gonzalez, J. Delhotal, J. Johnson, M. Lave, Evaluation of PV Frequency-Watt Function for Fast Frequency Reserves, IEEE Applied Power Electronics Conference (APEC), Long Beach, CA, March 20-24, 2016.
4. J. Johnson, J. Neely, J. Delhotal, M. Lave, Photovoltaic Frequency-Watt Curve Design for Fast Contingency Reserves, IEEE PVSC, Portland, OR, 5-10 June, 2016.

VPPs will provide a range of grid services

DER resources to fill in utility/grid operator needs



VPP Software System

Multi-domain Optimization
Objective: Minimize Utility Cost

A co-optimization determines the service (or services) that the VPP will provide grid operators.

Domains:

- Regulation
- Following Reserve
- Energy Market
- Contingency Reserves*

VPP Participation Updated as Needed

* Current Research Focus

Optimization of DER Setpoints and Unit Commitment

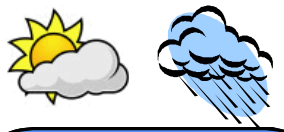
DER Feedback Control of DERs

Communications

DERs

VPP Architecture

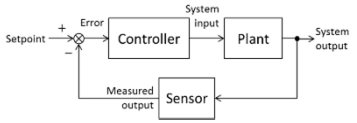
- Depending on the ancillary service(s) and the market, the VPP architecture and execution vary. Generally, there are 4 steps:



Forecasts of renewable energy generators and demand response units define a safe operating margin for the VPP.

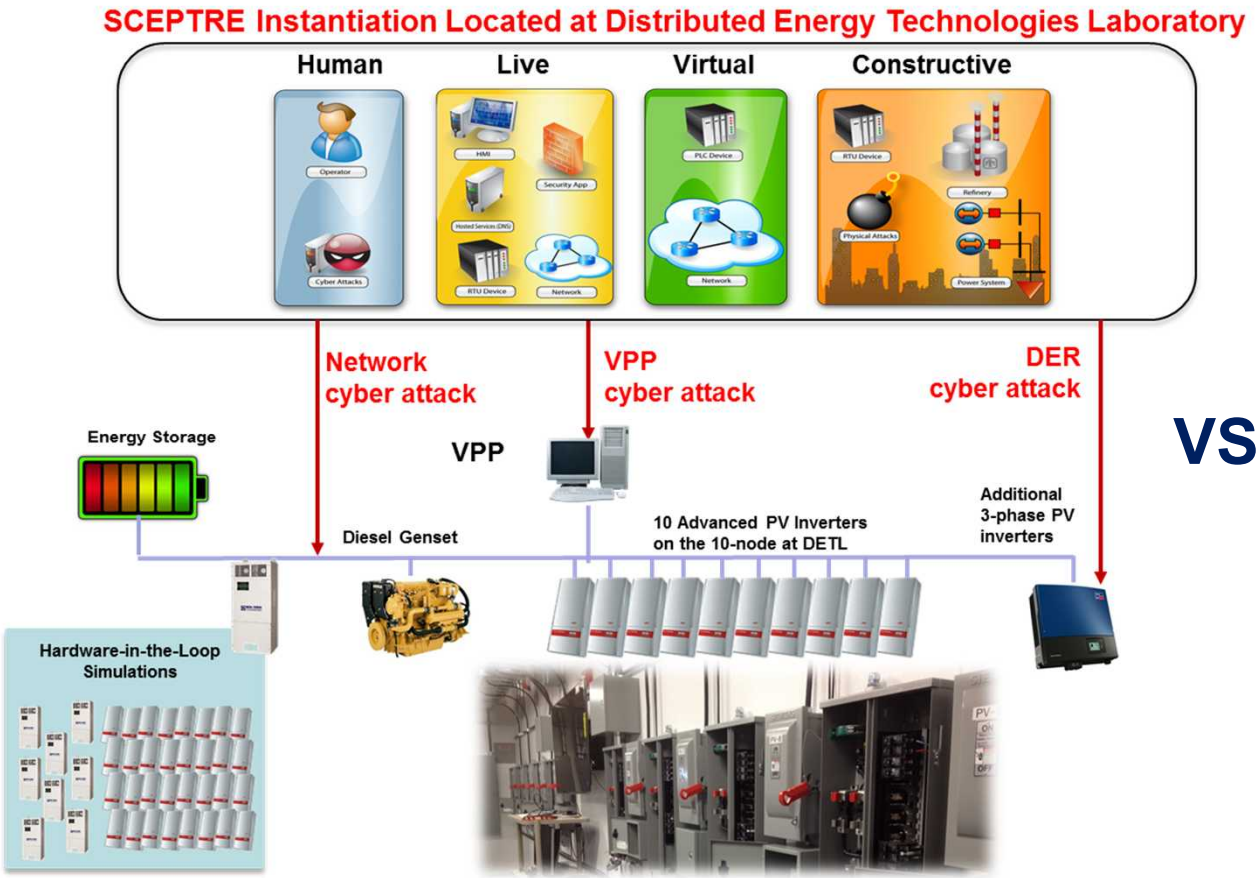
Stochastic optimization is run to determine market bids, precharge energy storage, and prepare demand response units.

Based on commitments and updated forecasts, unit commitment optimization adjusts DER operations and maintains sufficient headroom for contingency reserves.

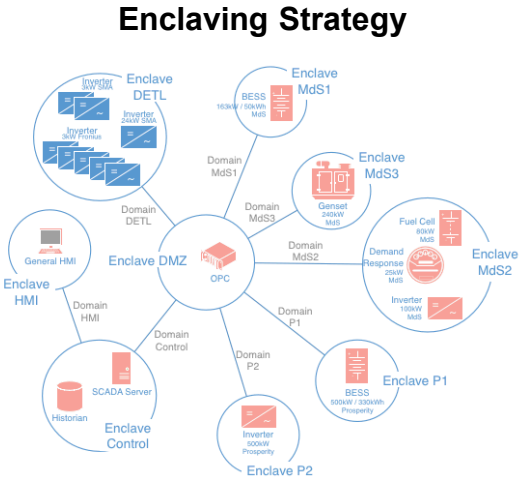


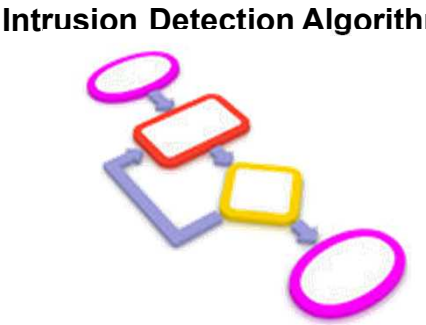
A feedback controller (possibly in combination with decentralized control) is used to reach the VPP commitment target.

Red Team Demonstrations at DETL



VS.





Goal: protect the VPP through enclaving of VPP DERs and intrusion detection algorithms.

Conclusions

- DETL is a **versatile, reconfigurable test lab** with extensive **power system** and **cybersecurity testing capabilities**.

- **Sandia, SIRFN, and SunSpec** are also **improving certification protocols and test capabilities** by:
  - Building test-beds for advanced inverter testing (electrical performance and interoperability).
  - Comparing advanced DER test results and improving draft certification protocols.
  - Recommending improvements to national and international codes and standards.

- Sandia is constructing a **lab-wise cybersecurity test network** and starting a number of programs in the cyber grid arena.

- The **virtual power plant** has the ability to **change market paradigms** and provide a range of **grid-support capabilities**.

- **What's the good word?**

To Hell with Georgia!

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