Sensing & Measurement Strategy

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

National Labs: ORNL, NETL, ANL, INL, LANL, LBNL, LLNL, NREL, PNNL, SNL
Industry Partners: ComEd, Dominion, Entergy, EPB, EPRI, NASPI, NIST, OSIsoft, Southern Co., TVA

Project Description

The Electric Grid is undergoing a major transformation (integration of new devices, major shift in generation mix, aging infrastructure, added risk of extreme grid events) which presents new and greater challenges for effective grid operation and management requiring greater grid visibility through sensing and measurement. A Sensing & Measurement Strategy (measurement parameters, devices for making measurements, communications to transfer data, and data analytics to manage data) is needed to allocate and turn grid measurements into actionable information.

Expected Outcomes

- Creation of an Extended Grid State Reference Model to identify the information needed to understand how to instrument the modern grid with conventional sources/loads and renewables, storage, EVs, etc.
- Development of a Technology Roadmap to identify the state of sensors and to determine sensor R&D needs/priorities needed to measure grid measurements and provide actionable information.
- Development of a Sensor Placement Optimization Tool (SPOT) to assist utilities in deciding what sensor & measurement technologies to use and how to allocate them to achieve effective grid observability.
- Outreach to technical groups to coordinate with industry needs/priorities and identify new standards and enhancements needed.
- Value Proposition: A cohesive strategy for sensing & measurement will provide what is needed to characterize the state of the grid at much higher fidelity/resolution to maintain system reliability and security.

SIGNIFICANT MILESTONES	STATUS	DATE
Fully compiled report outlining roadmap and gap analysis to DOE.	*Complete*	10/1/2017
Development of prototype sensor placement tool.	*Complete*	4/1/2018
Publish completed sensor technology state-of-the-art review and roadmap reports.	*On track*	10/1/2018
Complete final report of sensor placement tool on case studies and results.	*On track*	4/1/2019
Facilitate creation of a PAR/task force/working group for standards to respond to sensor and measurement requirements.	*On track*	4/1/2019
Complete validated framework of sensor placement tool based on utility partner field testing.	*On track*	4/1/2019

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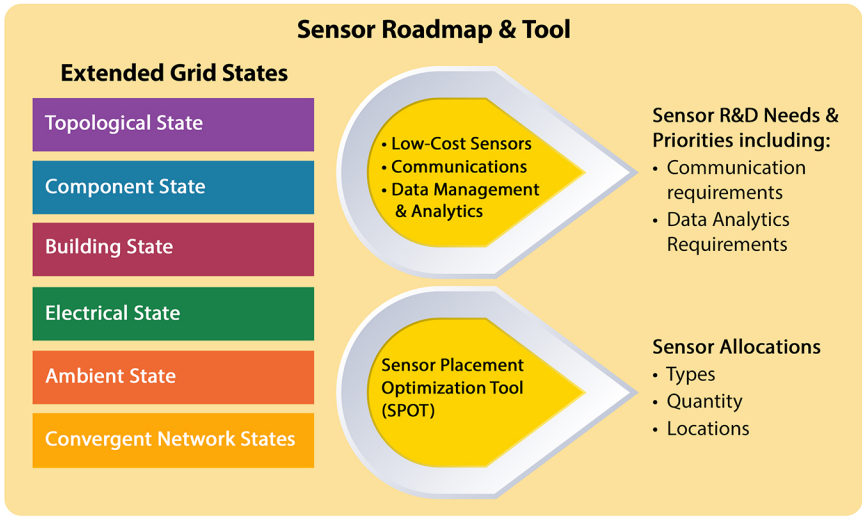

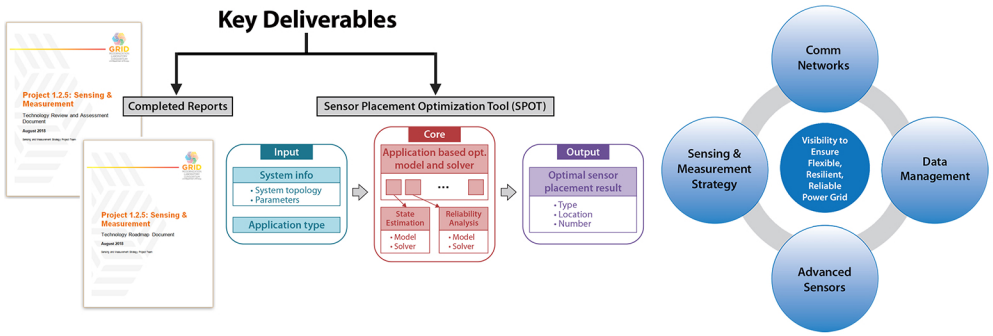

Progress to Date

- Well attended webinars held in 2016-2017 to share the EGS and Roadmap with industry and to get their input/feedback.
- Industry meetings held at EPB (Chattanooga, TN, 2016), ComEd (Oak Brook, IL, 2017) and Southern Co. (Atlanta, GA, 2018).
- EGS, Roadmap, and SPOT status/progress and drafts shared with industry at these meetings/webinars.
- Direct participation by industry partners/stakeholders on roadmap working groups led by the Labs.
- Produced EGS framework and definitions report which has been shared with NIST, NASPI, IEEE and IEC.
- Produced sensor technology review (state-of-the-are) report that was first drafted in 2016.
- Produced sensor technology roadmap.
- Developed SPOT tool for sensor placement on distribution systems and tested against three different IEEE test feeders. Conducted two utility use cases.

ORNL 2017-G003848/toc

Advanced Sensor Development

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Project Description

Focus on key challenges previously identified in industry roadmaps and DOE programs that are critical to increased visibility throughout the energy system. The project is organized around three major segments: end-use, transmission and distribution (T&D), and asset monitoring.

Expected Outcomes

End Use: (1) Develop low-cost sensors, exploiting additive manufacturing techniques, to monitor the building environment and electrical characteristics of HVAC equipment, and (2) Develop algorithms to use building-level data to provide utility-scale visibility of grid reliability and localized weather monitoring.

T&D: Extend the resolution of transmission grid visibility orders of magnitude higher than current technologies. Focus is on dynamic response and data resolution as well as innovative ways to estimate electrical parameters from optical sources.

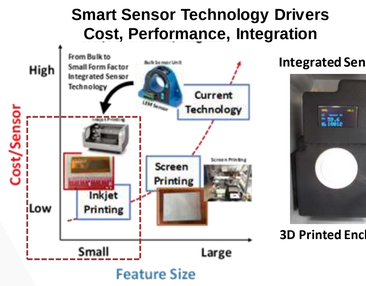
Asset Monitoring: Sensing platforms with attributes that are best-suited for broad applicability across the entire grid asset monitoring application areas. Focus is on very low cost gas and current sensors for asset monitoring.

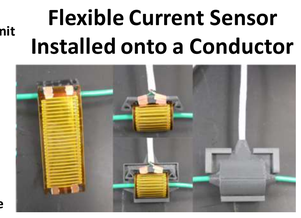
Significant Milestones	Date
End Use: − Developed a field portable flexible current sensor hardware using a combination of direct-write printing, 3D additive manufacturing, and laser processing techniques. Battery powered printed current sensor unit incorporates data collection and in-field calibration capabilities. − Geographical quantification of the value of aggregate building load shaping by coupling the 'Buildings as Sensors' production cost model of electrical generation to the model predictive control of distribution network residential air conditioning. − Developed highly-granular grid resiliency metrics (customer outage-hours) to capture impacts from hurricanes and other outage events based on Internet-connected devices.	**06/30/2018**
T&D: − Developed ultra-fast and adaptive window algorithms. Successful system transients capture while maintaining high measurement accuracy. − Developed high-precision data synchronization algorithm and demonstrated GPS disciplined Chip Scale Atomic Clock timing method. Provide high-precision and reliable time synchronization. − Developed optical transducers system testbed. Demonstrated the performance of optical transducers for high resolution frequency measurements.	**07/31/2018**
Asset Monitoring: - Demonstrate the performance of SAW sensors to meet design specification. Deploy physical sensors in ORNL flexible research platforms with ground truth measured using calibrated sensors. - Demonstrate the performance of MagSense sensors to meet design specification. Validation of repeatable process which is capable of detecting currents in the 1A - 1000A range. - Demonstrate the performance of optical fiber sensors for detection of transformer performance degradation and temperature deviations.	**07/31/2018**

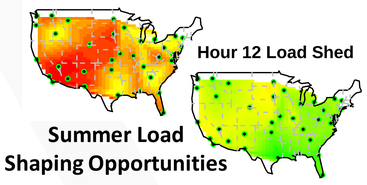
Progress to Date

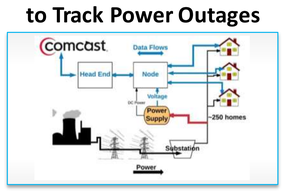
End Use

- **Direct-write Printing of Flexible Current Sensor** for improving building energy efficiency.
- **Internet-connected Devices as Sensors:** A data-driven outage map in partnership with a network company.
- **Buildings as Sensors**: An open-source package for load shape estimation & forecasting.



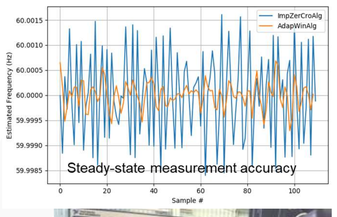


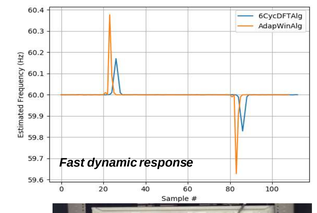




Transmission & Distribution

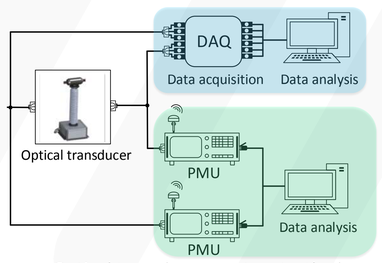
- **Ultra-fast and adaptive window measurement algorithms:** Achieve fast dynamic response and high measurement accuracy. Allow timely grid control (i.e. first swing stability).
- **High precision data synchronization algorithm and GPS disciplined CSAC timing method**: Grid data synchronized at a resolution of nano-second level with high reliability.
- **Optical transducers system testbed:** High resolution frequency measurement capability demonstrated. Laid a foundation for transient linearity evaluation.



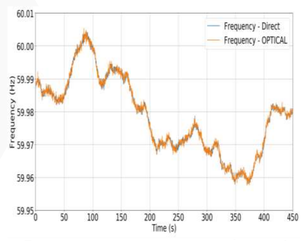


Optical transducers

Measurement testing system



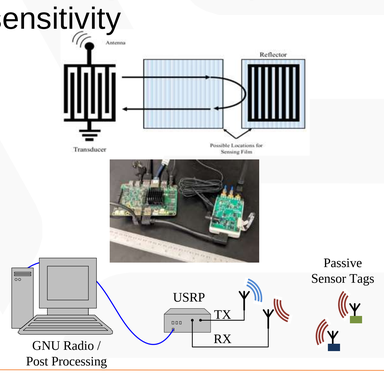
Optical transducers system testbed



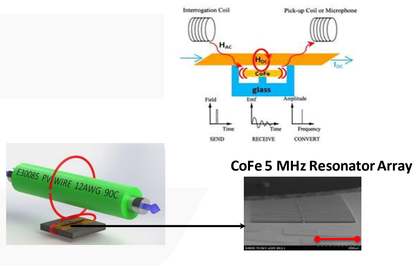
Frequency measurement by optical transducers

Asset Health Monitoring

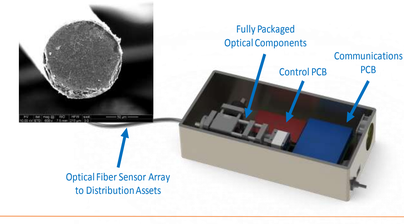
Surface-Acoustic Wave (SAW) sensor: for methane detection, and promising selectivity and sensitivity



Magneto-elastic sensor (MagSense): Single, passive sensor to detect fault currents and/or temperature excursions, Inexpensive (¢/module), Sensitive (Ifault = µA), current levels, fast (µs response)



Nano-Enabled Optical Fiber sensor: Selective H_2 chemical sensing as a proxy for Dissolved Gas Analysis. Demonstrated multi-point temperature monitoring for an energized transformer core. Low cost field deployable prototypes under construction.



4 patent applications, 6 patent disclosures, 2 journal paper, 1 conference paper, and 4 journal papers under review.

Integrated Multi Scale Data Analytics and Machine Learning (1.4.9)

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Project Description

Develop and demonstrate distributed analytics solutions to building-grid challenges, leveraging multi-scale data sets, from both sides of the meter. Evaluate and demonstrate the application of machine learning techniques to create actionable information for grid and building operators, and derive customer benefits from disparate data

Enabling the transition from data to actionable information at the building to grid interface

Team

Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Berkeley Lab, NREL, Oak Ridge National Laboratory, Sandia National Laboratories, Argonne National Laboratory, PG&E, Hawaiian Electric Maui Electric Hawai'i Electric Light, Riverside Public Utilities, Duke Energy, PSL, OSIsoft, Sentient Energy, OPAL-RT Technologies, PECAN STREET, smarter grid solutions, PingThings

Use Case Development

Phase 1: Application benchmarking and testing for existing state of art, benefits assessment

- Data Layer – Streaming AMI, PMU, Distribution Models, OMS
- **Platform & Initial Distributed Comms**
- Simple Anomaly Detection – Learning Baseline Behavior
- App 1: DR & DER Verification & Prediction
- App 2: Distribution Incipient Failure
- App 3: Topology & Parameter Estimation
- PV Disaggregation Load response Dependency (FIDVR)
- LTC failure analytics XFRMR Impedance detection
- Load Identification Inverter Estimation Topology ID
- Upper Supervisory Layer – OSISoft, PingThings OpenFMB integration

Significant Milestones	Date
White Paper Delivery and Review	9/1/17
Benchtop application demo	7/15/18
Data Quality Assessment	7/15/18
Framework Presentation & Project Workshop	3/1/19

Expected Outcomes

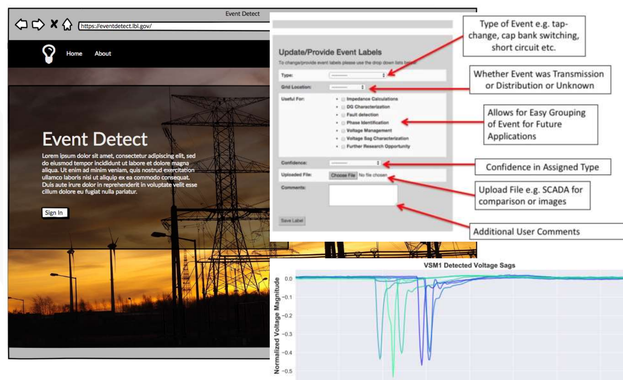
- Enable local nodal information exchange and high-performance, distributed algorithmic analysis
- Deploy local analytics integration at the grid edge, with a bridge to supervisory grid layers
- State-of-the-art distributed analytics strategies to thrive in an evolving distribution system

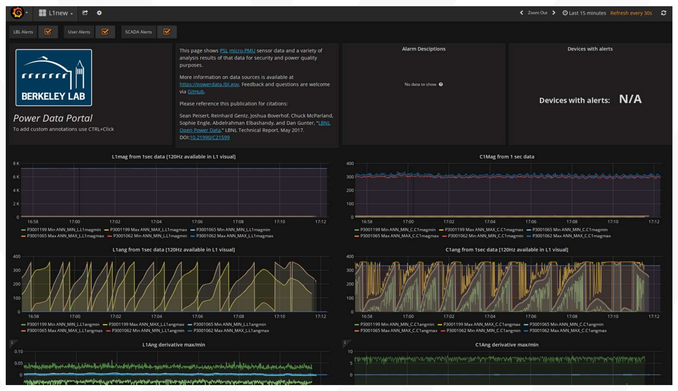
Approach & Progress to Date

Address fundamental challenges with development of platform, expertly labeled datasets, and effective application and integration of ML techniques to streaming distributed grid data

Expertly Labeled Data Sets

Answering a key "need" for application of supervised ML to grid data
"I need a dataset labeled by knowledgeable power systems engineers"
Tool integrating anomaly detection and uPMU data, to allow easy identification of known events





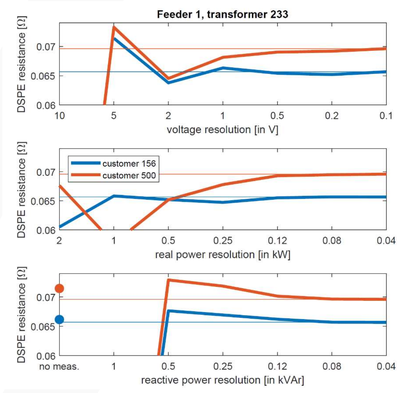
Platform Development

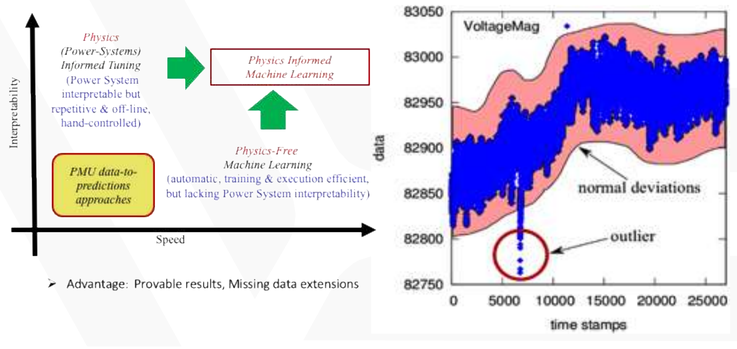
SPARCS platform development for hierarchical data ingest, distributed analytics and fusion

Data Quality Impact Assessment

Example: AMI for topology identification Over all customers, found ~8,000 data points (<3 months of 15-min data) sufficient to accurately derive parameters and topology.

- Need about 2V and 0.25kW or better resolution





Cross-Validation/In-sample Accuracy on LANL Data			
Learning Algorithm	5 Features	12 Features	Raw Signal
Decision Tree	78.0% / 85.0%	84.8% / 88.5%	N/A
Random Forest	77.2% / 100%	80.26% / 100%	N/A
Neural Net	78.7% / 90.3%	82.0% / 91.3%	80.7% / 90.8%

Algorithm Development

Example: Topology and feature Identification

Time-series of measurements from multiple PMUs are received

- Learn system dynamics using maximum likelihood estimation
- Classify event/anomaly types (9 types, some physically interpreted)
- Detection using voltage features

Time-series of states from PMU → Offline learning of event types → Real-time event detection from data → Event Localization

Prepared by LLNL under Contract DE-AC52-07NA27344

Discovery through Situational Awareness (GMLC0070)

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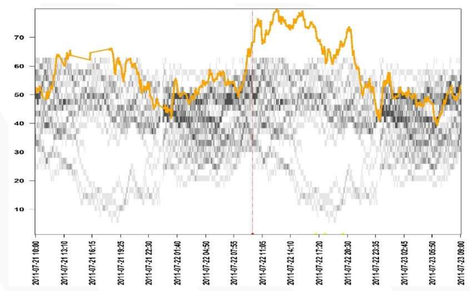
Project Description

Create and investigate statistical and machine-learning algorithms in the context of big data analytics to identify anomalies, events, and oscillations in near real-time

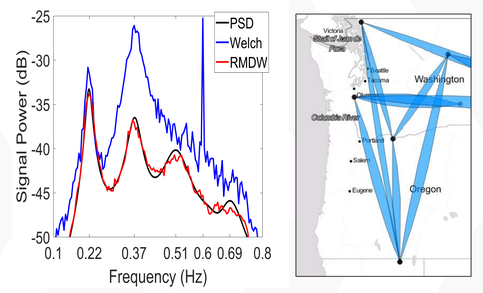
Expected Outcomes

- Anomaly and oscillation detection algorithms implemented and tested in the ESAMS tool (Eastern Interconnect Situational Awareness Monitoring System)
- FY18 technical report discussing new algorithms detecting anomalies, oscillations and events, and building classifiers to identify future events

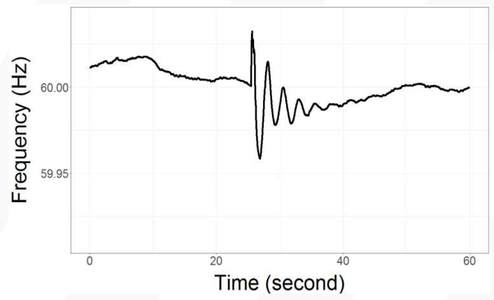
Significant Milestones	Date
ESAMS ready for install	4/15/2018
FY18 Technical Report Draft	6/11/2018
FY18 Technical Report Final	8/31/2018
ESAMS ready for participating ISOs	10/15/2018



Data driven algorithms identify wide area phase angle pair anomalies in near real-time



The RMDW estimates the ambient spectrum (PSD), even when other oscillations are present. It enables oscillation baselining and detection.



Frequency events in real PMU data were identified with over 99.1% accuracy
Previously unseen frequency events were classified as such with over 99.4% accuracy

Progress to Date

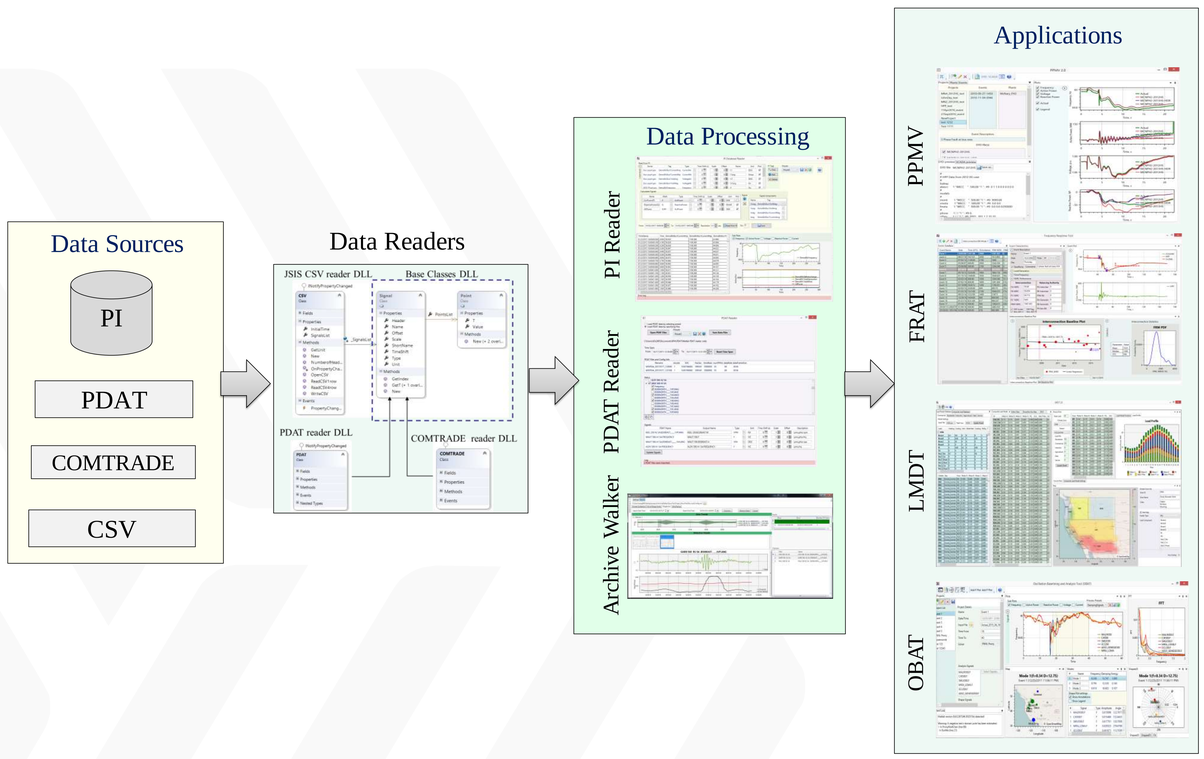
- ESAMS tool finished and ready for install at PJM
- Applied anomaly and event detection and machine-learning algorithms to 18+ months of PMU data (2.5 TB)
- J. Follum, T. Yin, and B. Amidan, "A New Spectral Estimator for Identifying Dominant Modes and Detecting Events in Power Systems," 2018 Probabilistic Methods Applied to Power Systems (PMAPS) Conference, Boise, ID, 2018, pp. 1-6
- Presented anomaly and event detection work (NASPI March 2018) and oscillation detection work (PMAPS June 2018)

GM0072: Suite of Open-Source Applications and Models for Advanced Synchrophasor Analysis

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

The goal of this research is to develop and advance applications of synchrophasor data from phasor measurement units (PMUs) for power system planning, modeling, and analysis.



Expected Outcomes

- Industry-grade, open-source power system analytical tools and software modules.
- Common open platform and data format structures.
- Building blocks and solutions for future and third-party applications.
- Address oscillation analysis, frequency response, model validation and calibration, load modeling, and other important power-grid-related issues.
- Enable adoption of PMU technology by a wider range of electrical utilities.

Significant Milestones	Date
Release new version of PPMV and FRAT tools	6/30/2017
Release the open source framework for PMU analysis	9/30/2017
Release enhanced version of the data readers	12/30/2017
Release LMDT 2.2	3/30/2018
Develop advanced statistical methods for oscillation baselining	6/30/2018

Progress to Date

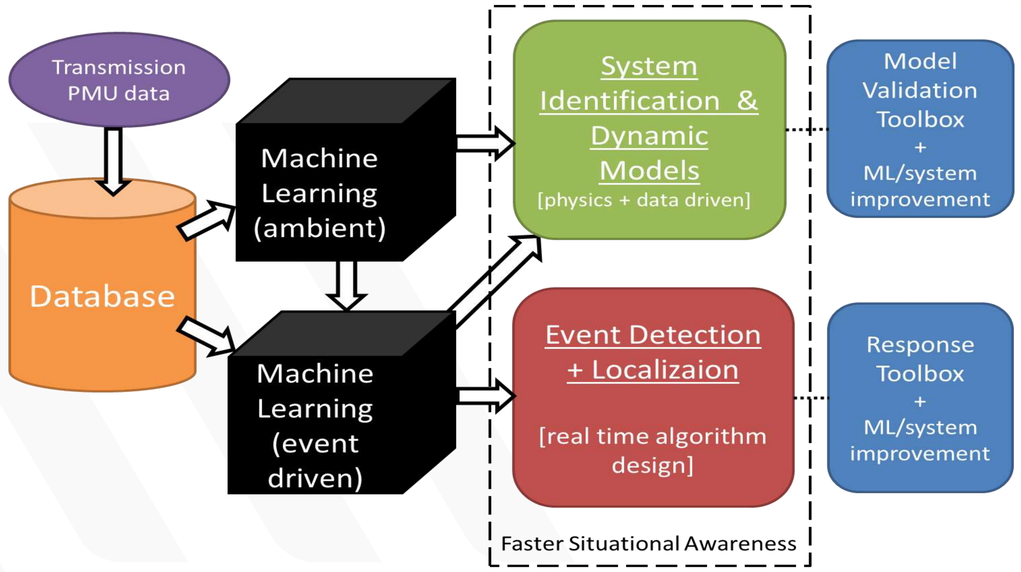
- New methodology for oscillation baselining based on a comprehensive set of statistical and machine learning analysis approaches.
- New versions of the OBAT, FRAT, PPMV and LMDT tools with enhanced capabilities have been released.
- Tools used by multiple leading electrical organizations, including NERC, WECC, BPA, SCE, PG&E, and many more.
- Tools presented at multiple events, including IEEE T&D conference panel presentation, NASPI, NERC and WECC working group meetings, and i-PCGRID workshop.
- Published one journal paper and four conference papers.

Advanced Machine Learning for Synchrophasor Technology (GM0077)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy
Transmission Reliability Program

Project Description

- Transmission systems are becoming more dynamic due to renewables.
- Operator situational awareness and decision making need enhanced support
- High sampled PMUs provide data that may help but current operator tools are *insufficient* to convert PMU data into actionable information
- Operator requirements:
  - Fast algorithms to convert PMU data into network-wide and equipment level **dynamical models**.
  - Accurate and Fast data-driven algorithms that leverage these models to **detect, characterize and localize** anomalies & events
  - **Advanced visualization** to aid decisions & situational awareness



Challenges

- PMU data is sparse
- PMU data is noisy

⇨ Algorithms should be robust to partial observability & bad data

- High frequency input data
- Decisions need to be real-time

⇨ Algorithms should take streaming data and have low complexity

- Events in transmission grid have big geographical spread

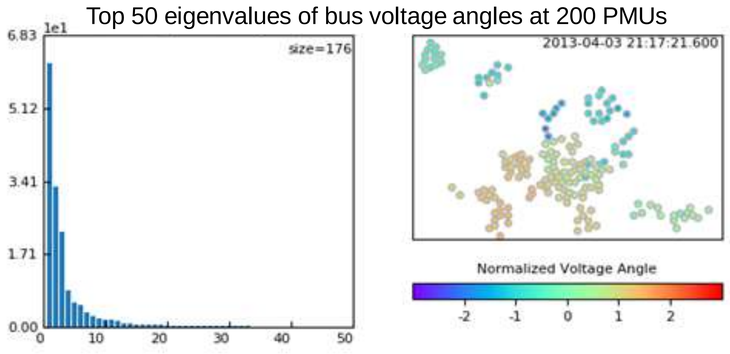
⇨ Visualization platform needs temporally and spatially scaling

Expected Outcomes

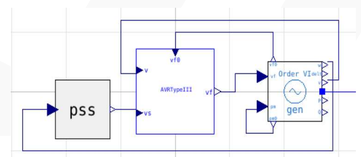
- Physics aware **Machine Learning & Analytics (MLA) toolbox** that is able to:
  - Estimate system-wide dynamic model parameters, monitor grid resources
  - Detect and localize events and anomalies in real time within seconds
- Industry grade **situational awareness big-data platform** that is able to
  - Receive real-time PMU and system state information
  - Incorporate Machine Learning algorithms for system analysis & decisions
  - Visualize results for decision support

Progress to Date

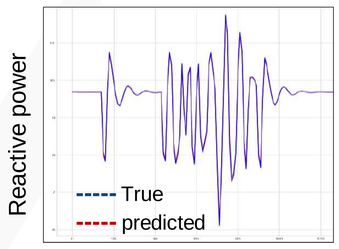
- Streaming Algorithm for **real-time monitoring** of features in high frequency large PMU data set using PCA (Principal Component Analysis) [1].



- Physics informed **reduced-order models** of bulk grids with limited data [2-3].
- **Dynamic models** for generators and loads using Neural Networks on time-series data [4].



OpenIPSL Generator (12th order)



- A **cloud-based machine learning platform** for (Big Data) analysis in power grids is being developed by PNNL using Apache Spark in an OpenStack cloud infrastructure [5-7].
- Estimation & **Cyber-Physical Attack** on power grids with low observability [8-9].
- Real-Time **Fault Localization** with Convolutional Neural Network (CNN) tested on 68-bus system in PST [10]

ARC: Average Rank of Correct faulted line

The ratio of measured buses	7 %	10 %	15 %
Total number of buses	5	8	10
ARC	2.3	1.8	1.5

Major Publications

[1] A. Shukla et al., “Non-Stationary Streaming PCA”, NIPS Time Series Workshop, 2017.
[2] D. Deka et al., “Physics informed Topology Learning in Network of Dynamical Systems”, Automatica 2018 (submitted)
[3] A. Lokhov et al., “Online Learning of Power Transmission Dynamics”, in Proceedings of PSCC, 2018.
[4] N. Stulov et al., “LSTM based generator learning using time-series data”, in preparation.
[5] P.V. Etingov et al., "Cloud Based Analytical Framework for Synchrophasor Data Analysis”, in CIGRE US National Committee Grid of the Future Symposium, 2017.
[6] H. Ren et al., “Pattern Mining and Anomaly Detection based on Power System Synchrophasor Measurements”, in Proceedings of 51st HICSS, 2018.
[7] H. Ren et al., “Online Anomaly Detection Using Machine Learning and HPC for Power System Synchrophasor Measurements”, PMAPS conference, Boise, Idaho, June 24-28, 2018.
[8] S. Soltan et al., “Power grid state estimation following a joint cyber and physical attack”, IEEE Trans. Control of Network Systems, 2018.
[9] S. Soltan et al., “EXPOSE the Line Failures following a Cyber-Physical Attack on the Power Grid,” IEEE Trans. Control of Network Systems (to appear), 2018.
[10] W. Li et al., “Real-time Faults Localization in Power Grids Through Neural Networks”, in preparation.

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BERKELEY LAB
Lawrence Livermore National Laboratory
COLUMBIA UNIVERSITY

Opportunistic Hybrid Communications Systems for Distributed PV Coordination (SuNLaMP)

P.I.: Bri-Mathias Hodge, National Renewable Energy Laboratory
Team members: S M Shafiul Alam, Jianhua Zhang, Tarek Elgindy, Anthony R. Florita (NREL)
Liuqing Yang (Colorado State University), and Jin Wei (University of Akron)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

This project is developing a hybrid architecture of communications that allows a fair utilization of both existing wired power system communications mediums and ubiquitous wireless communications devices at the point of distributed PV coupling. The opportunistic nature seeks the most reliable message route in real-time through the combination of wired and wireless networks. It renders a currently unattainable level of knowledge about distributed PV states, without additional communications system capital costs. Thus, a comprehensive view of the present state of transmission and distribution systems can be achieved with high distributed PV penetrations at any given moment.

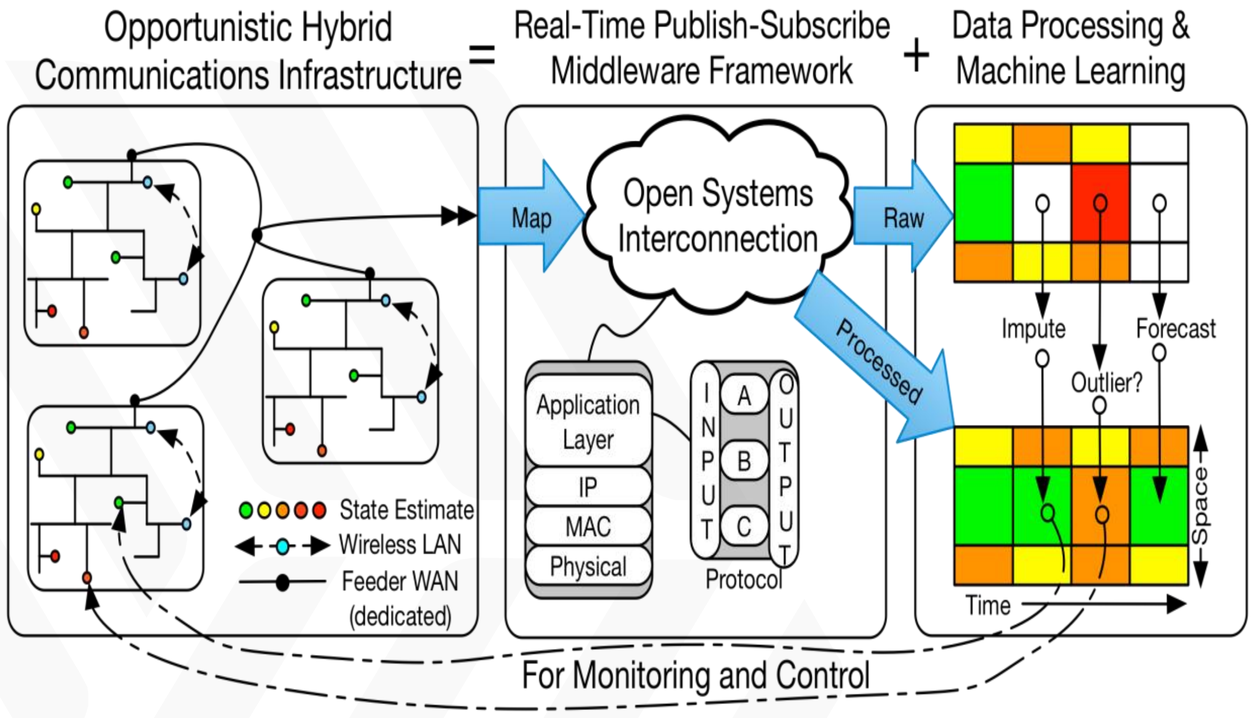
Expected Outcomes

- ✧ Design framework of opportunistic hybrid communication infrastructure including optimal node placement.
- ✧ Advanced distributed Quality of Service (QoS)-resilient middleware architecture extending the utilization level of existing communication systems.
- ✧ Distributed steady and dynamic state estimation techniques for both PV generation and multiple levels of the power grid.
- ✧ IGMS-based co-simulations and HIL experiments to validate and make the proposed technologies robust over 1000 combined transmission-distribution system buses.

Impacts:

- ❖ Easing the economic grid operation with high PV penetration.
- ❖ Enhancing efficiency and reliability of the modern power grid.
- ❖ Laying the foundation for more advanced applications (e.g., ENERGISE)

Significant Milestones	Date
✓ Development of QoS-resilient middleware architecture	3/31/2016
✓ Design distributed ladder iterative state estimation algorithm	9/30/2016
✓ Development of distributed PV state estimation algorithm	3/31/2017
✓ Development and Co-simulation of hybrid communication system models	9/30/2017
✓ Robustification and integration of the proposed distributed state estimation algorithms	3/31/2018
Hardware-In-Loop validation of opportunistic hybrid communication infrastructure	9/30/2018



The Full-scale and Operational Implementation of Opportunistic Hybrid Communications Systems will allow the current knowledge gap to be filled with representative measurements and robust inferences in terms of grid performance (e.g., reliability, scalability, interoperability).

Progress to Date

- ➢ Developed distributed QoS-resilient middleware architecture.
- ➢ Finished the design framework of opportunistic hybrid communications systems including communication node optimal placement and hybrid communication system simulation models.
- ➢ Developed distributed state estimation algorithms for both PV generation and multiple levels of the power grid.
- ➢ Publications

[1] A. Hasandka, J. Zhang, S M S. Alam, A. Florita, and B.-M. Hodge, “Simulation-based Parameter Optimization Framework for Large-Scale Hybrid Smart Grid Communications Systems Design", IEEE SmartGridComm 2018, October 29-31, 2018, Aalborg, Denmark.

[2] J. Zhang, A. Hasandka, J. Wei, S M S. Alam, T. Elgindy, A. Florita, and B.-M. Hodge, “Hybrid Communication Architectures for Distributed Smart Grid Applications", MDPI Energies, vol. 11, no. 4, 2018.

[3] Y. Wu, J. Wei, and B.-M. Hodge, “A Distributed Middleware Architecture for Attack-Resilient Communications in Smart Grids” IEEE International Conference on Communications, May 21-25, 2017, Paris, France.

[4] Y. Wu, G. J. Mendis, Y. He, J. Wei, and B.-M. Hodge, “An Attack-Resilient Middleware Architecture for Grid Integration of Distributed Energy Resources" IEEE 2016 GLOBECOM, December 4-8, 2016, Washington, DC.

[5] D. Wang, L. Yang, A. Florita, S M S. Alam, T. Elgindy, and B.-M. Hodge, “Automatic Regionalization Algorithm for Distributed State Estimation in Power Systems", IEEE GlobalSIP 2016, Dec. 7-9, 2016, Washington D.C., USA.

[6] Y. Wu. G. J. Mendis, Y. He, J. Wei, and B.-M. Hodge, “An Attack-Resilient Middleware Architecture for Grid Integration of Distributed Energy Resources“, IEEE CPSCom, December, 2016, Chengdu, China.

[7] Y. Wu, J. Wei, and B.-M. Hodge, “A Distributed Middleware Architecture for Attack-Resilient Communications in Smart Grids“, IEEE SmartGridComm 2016, November 6-9, 2016, Sydney, Australia.

Solar Resource Calibration, Measurement and Dissemination

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

NREL develops and disseminates foundational solar resource data and products, best practices, and national standards. This project reduces the cost of developing, financing, integrating, and operating solar energy projects.

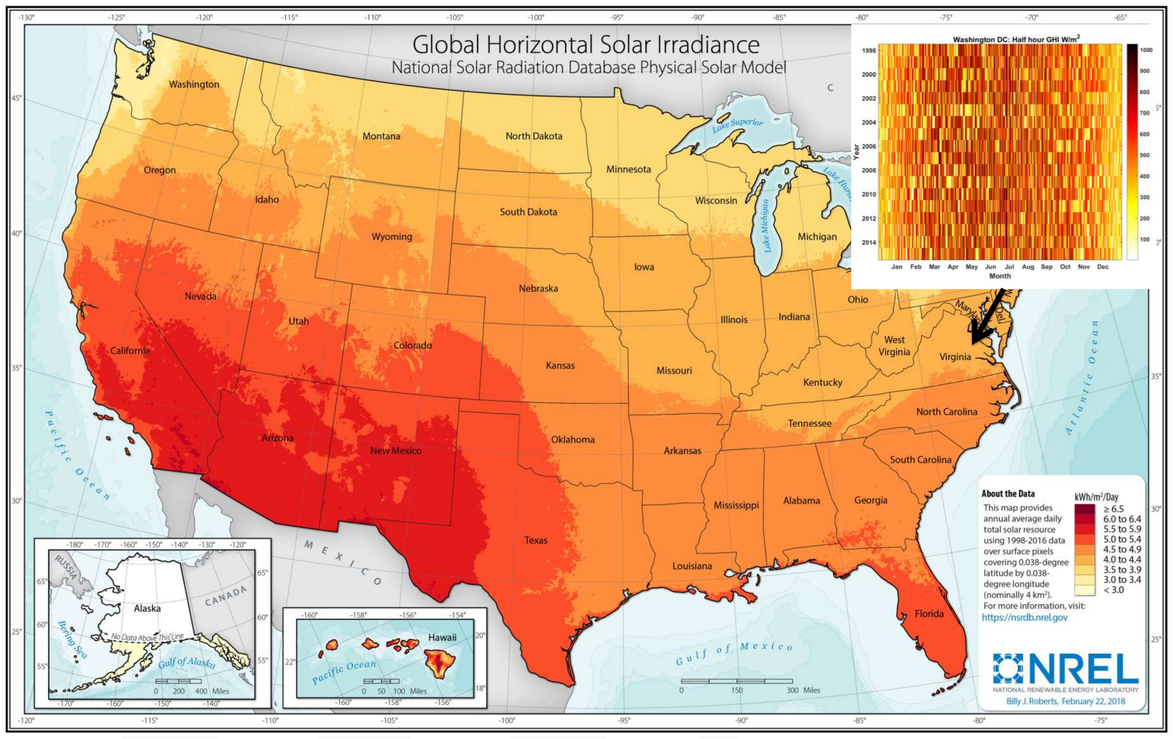
Expected Outcomes

Easy access to high quality, low uncertainty, solar resource data increases solar energy deployment and reduces project development and integration costs.

To achieve these goals, this project:

- Develops state-of-the-art models and creates high quality long-term solar resource data for the U.S. and distributes it through the **National Solar Radiation Database (NSRDB)**.
- Conducts research on **accurate, robust and low-cost solar radiation instrumentation and methods**.
- Uses new knowledge and technology to develop **consensus national standards and best practices** for solar energy.
- Provides **solar measurement reference to all instruments in the US** through the annual NREL Pyrheliometer Comparison conducted by the Solar Radiation Research Laboratory (SRRL).

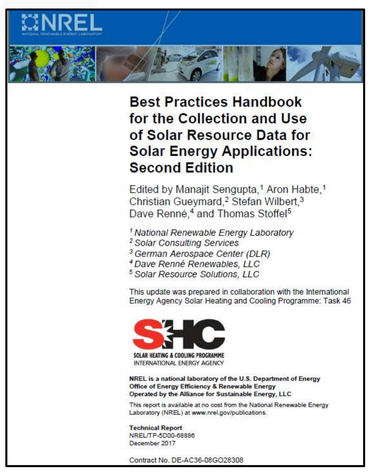
Significant Milestones	Date
Produced and delivered solar radiation data for 1998-2017 through the NSRDB	September 2018
Transferred world radiation standard to 45 Absolute Cavity Radiometers from national and international shareholders including calibration service providers	October 2017
Published the "Best Practices Handbook of Solar Resources for Solar Energy Applications: 2nd Edition"	December 2017
Published NSRDB article in high-impact journal. Impact factor 8.050	June 2018
Completed a Cooperative Research and Development Agreement (CRADA) with AccuFlux Inc. to characterize new radiometric devices for improved accuracy in long-term solar measurements.	December 2017
Incorporated advanced NASA MERRA-2 dataset in the NSRDB to improve aerosol characterization.	December 2017
Led technical contributions for the US to ISO-9060 standard on classification of radiometers.	May 2018



The freely-available data from the NSRDB is critical for solar energy development and integration across the US

Progress to Date

- The NSRDB data have been available as a free download to the public from https://nsrdb.nrel.gov, which now has around **5,000 users per month**. External users include kWh Anaytics, Southern Company, and First Solar. Major projects include the System Advisor Model (SAM) and the North American Regional Integration Study (NARIS).
- Published a manuscript that reviews the complete package of surface observations, models, and satellite data used for the latest version of the NSRDB as well as improvements in the measurement and modeling technologies deployed in the NSRDB during the years.
- Together with industry, the American Society for Testing of Materials, and International Standards Organization, NREL led the update and draft of **new standards** that promote knowledge, stimulation of research, reduce the uncertainty and cost of solar energy projects.



NREL sets standards for government agencies, academia, and industry, ensuring high-quality measurements in the U.S. (left). NREL's 35 years of experience is shared through best practices (right), standards, collaborations, and training.

Frequency Response Assessment and Improvement of Three Major North American Interconnections Due to High Penetrations of Photovoltaic Generation

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Lead: ORNL Yilu Liu **Team Members: UTK, NREL, GE**

Project Description

The project produces a series of high solar PV penetration scenarios from detailed and validated models of all three U.S. interconnections so that the effects of increased solar PV generation on frequency response can be fully quantified. Strategies to improve frequency response are developed and validated using both software and hardware test beds for a final recommended portfolio from available options.

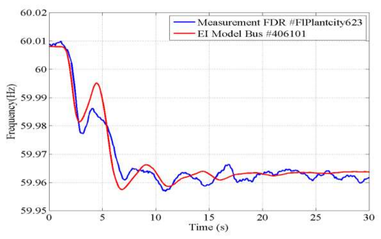
Expected Outcomes

- All levels of 20%, 40%, 60%, and 80% renewable penetration models are built and studied for three U.S. interconnections.
- Solar PV inverter inertia and governor controls are tested in hardware and three U.S. interconnection grid models.
- **<u>Impact</u>: By directly addressing the grid frequency stability challenge, this project helps meet the PV system integration goal (PV penetration level > 80% interconnection load and 100% of peak load locally).**

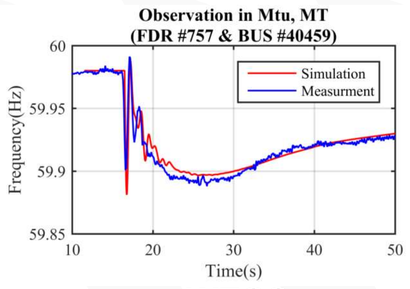
Significant Milestones	Date
1. Developed 20%-80% high PV penetration scenarios based on previously measurement-validated interconnection models and realistic PV distribution projections for each interconnection. √	12/31/2016
2. Quantified high solar PV generation's impact on each North American interconnection's frequency response. √	09/30/2017
3. Designed remedial schemes for the negative impacts of high PV on frequency response using multiple developed PV penetration scenarios. √	09/30/2018
4. Implement artificial inertia/governor/AGC schemes on a GE's utility-scale PV inverter product (the Brilliance series) and test their effectiveness in GE's RTDS laboratory.	12/31/2018

Progress to Date

Dynamic model validation



EI



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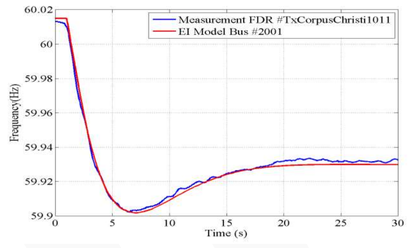
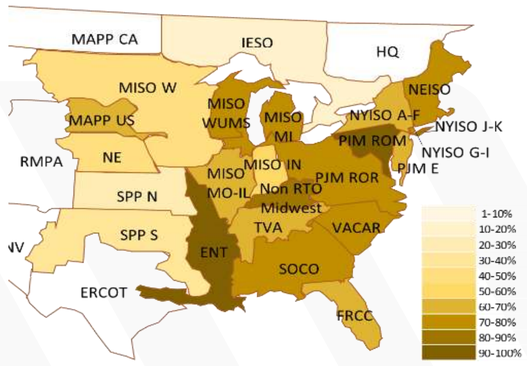


ERCOT

PV distribution



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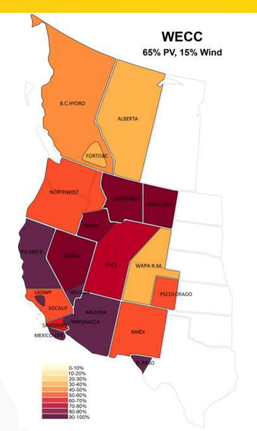

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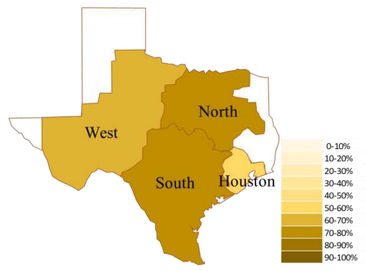
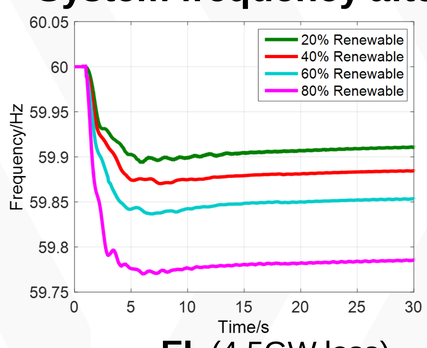
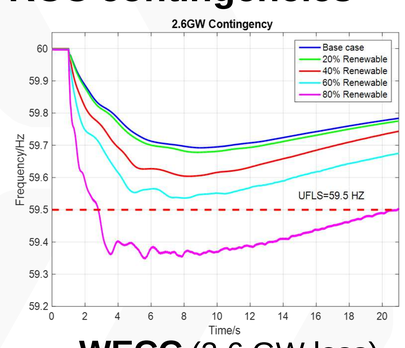


ERCOT

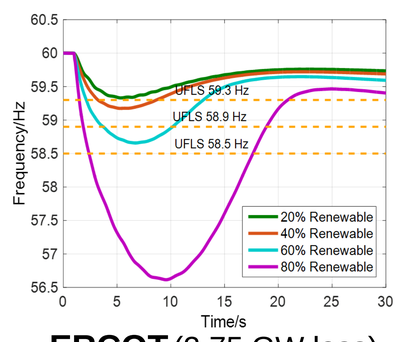
System frequency after RCC contingencies



EI (4.5GW loss)

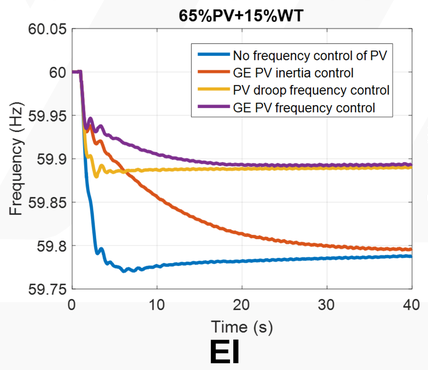


WECC (2.6 GW loss)



ERCOT (2.75 GW loss)

System frequency (w/wo PV primary frequency control)



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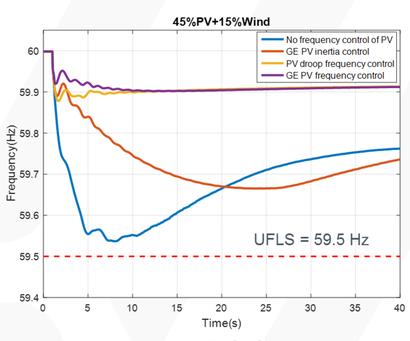

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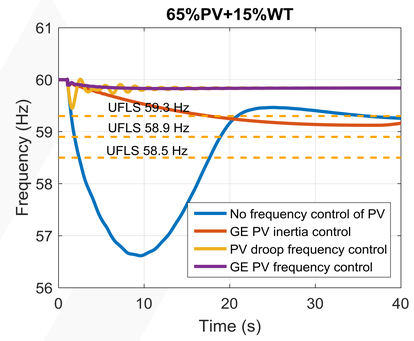


ERCOT

Hardware testing facilities for PV primary frequency control

GE PV inverter test facilities

Hardware room

Visualization & control room

CURENT Hardware Testbed

Publications and Industry Outreaches/Reviews

- 4 out 5 milestones and technical reports completed; 5 IEEE journal papers and 5 conference papers published.
- 1 face-to-face meeting and 2 teleconferences with technical review team, 3 presentations to industry in conferences, 1 presentation to NERC ERSWG.

Industry Partners: NERC, ISONE, ERCOT, MISO, Southern, TVA, PJM, Dominion, NYISO, PG&E, SCE, EPRI, PEAK RC, CAISO, FPL

WindView: An Open Platform for Wind Energy Forecast Visualization

Shrirang Abhyankar, Zhi Zhou, Andrew Ayers, Audun Botterud (Argonne National Laboratory)
Bri-Mathias Hodge, Erol Chartan, Paul Edwards (National Renewable Energy Laboratory)
Jie Zhang, Cong Feng, Mucun Sun (University of Texas at Dallas)

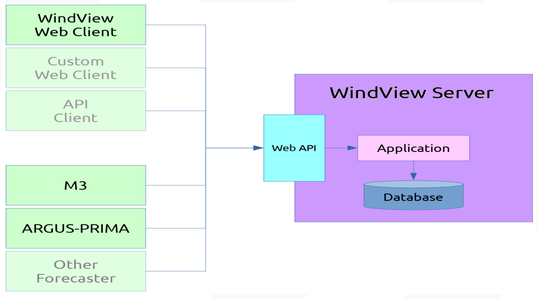
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

WindView is an open source situational awareness and decision support visualization platform for wind energy. It provides visualization of deterministic and probabilistic wind power forecasts with ramp detection capability at different horizons on a dynamic and interactive map to display the uncertainty information in an easy to understand manner

Expected Outcomes

- Open-source wind forecast visualization available to national labs, industry, and academic researchers.
- Visualization of probabilistic wind forecasts with different horizons, temporal and spatial correlations of wind power forecasts, ramp forecasting, and condensed view of uncertainties.
- Aid the operators to manage wind forecast uncertainty and variability and thereby enhancing system reliability, having better management of system reserves and reducing power outages
- Will increase power system operators' situational awareness and allow wider integration of wind power advancing the Wind & Water Power Technologies Office objectives
- Develop a production-level version of WindView for the Western Area Power Administration's network



Platform Architecture

Significant Milestones	Date
Advanced feature development of WindView with integration of wind forecaster	12/31/2017
Demonstration of WindView to Technical Review Committee and WAPA EPTC	03/30/2018
Incorporate TRC feedback and demonstration of WindView to Excel Energy	06/30/2018
Final release of WindView, including documentation and submit a paper on WindView	09/30/2018

Wind Energy Forecast Visualization with WindView

Progress to Date

- Feature enhancements for WindView including ramp alerts, multi-chart view, forecast aggregation, and others
- Presented a demo of WindView to technical review committee, and in-person visit to Excel Energy.
- Presented progress of WindView to system operators at the Western Area Power Administration.
- Hosted publicly accessible version of WindView available at https://windview-beta.nrel.gov/
- Integrated wind power forecaster M3 from UTD (M3) and preparing integration of ARGUS-PRIMA from Argonne
- Preparing a technical paper on WindView.