Sensing & Measurement Research Activities Portfolio Overview

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Oak Ridge National Laboratory

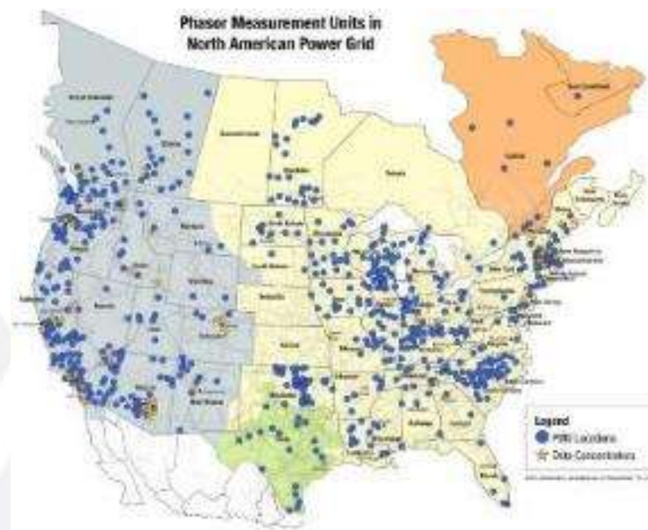
DOE GMLC Peer Review September 4-7th, 2018

Sensing and Measurements

Objective: Sensor development and deployment strategies to provide complete grid system visibility for system resilience and predictive control

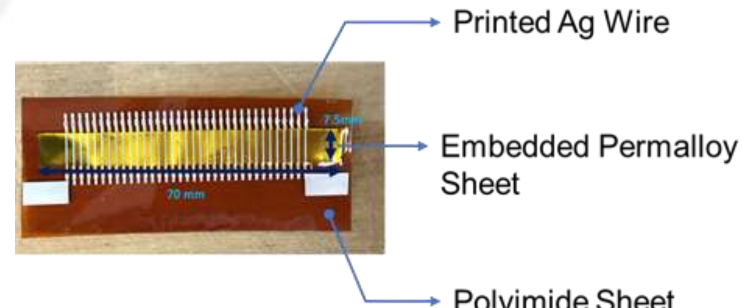
Expected Outcomes

- ► Advance and integrate novel, low-cost sensors to provide system visibility
- ► Develop next-generation low-cost sensors that are accurate through disturbances to enable closed-loop controls and improved system resilience
- ► Develop real-time data management and data exchange frameworks that enable analytics to improve prediction and reduce uncertainty



Federal Role

- ► Utilize unique capabilities to advance sensor development and transferring technology through public private partnerships
- ► Common approach across labs and industry test-beds for effective validation of emerging technologies
- ► Develop common interoperability and interconnection standards and test procedures for industry / vendor community



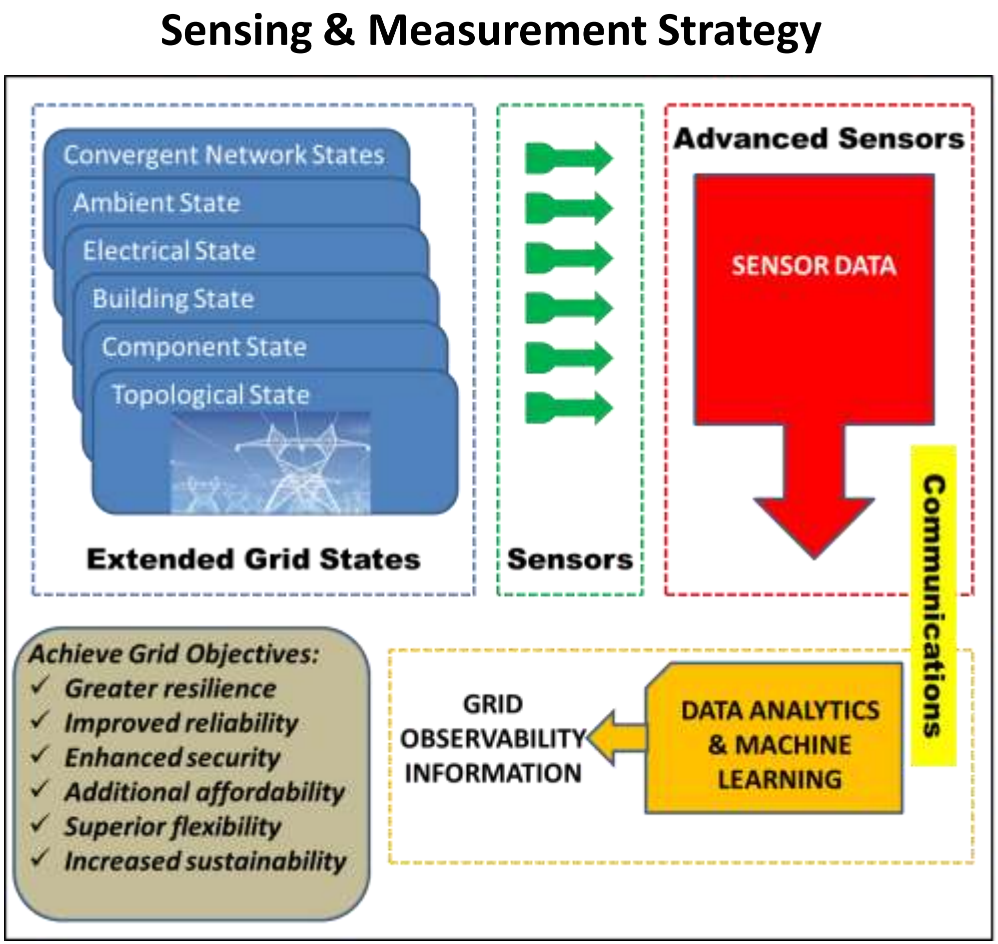
Grid Sensing & Measurement Activities & Technical Achievements

MYPP Activities	Technical Achievements by 2020
Improve Sensing for Buildings & End-users	Develop low cost sensors (under $10 per sensor) for enhanced controls of smart building loads and distributed energy resources to be “grid friendly” in provision of ancillary services such as regulation and spinning reserve while helping consumers understand benefits of energy options.
Enhance Sensing for Distribution System	Develop low cost sensors (under $100 per sensor) and ability to effectively deploy these technologies to operate in normal and off-normal operations Develop visualization techniques and tools for visibility strategy to help define sensor type, number, location, and data management. Optimize sensor allocation for up to 1,000 non-meter sensing points per feeder.
Enhance Sensing for the Bulk Power System: Develop Agile Prognostics and Diagnostics for Reliability & Asset Management	Develop advanced synchrophasor technology that is reliable during transient events as well as steady state measurement. Develop low cost sensors to monitor real-time condition of electric grid components. Using novel, innovative manufacturing concepts, develop low-cost sensors to monitor electric grid assets
Develop Data Analytic and Visualization Techniques	Provide real-time data management for the ultra-high velocities and volumes of grid data from T&D systems. Enable 100% visibility of generation, loads and system dynamics across the electric system through the development of visualization techniques and software tools Develop measurement and modeling techniques for estimating and forecasting renewable generation both for centralized and distributed generation for optimizing buildings, transmission, storage and distribution systems.
Demonstrate unified grid-communications network	Create a secure, scalable communication framework with a coherent IT-friendly architecture that serves as a backbone for information and data exchange between stakeholders and decision makers.

Foundational GMLC Projects

- Sensing & Measurement Strategy
- Advanced Sensor Development
  - End-use devices
  - Transmission & Distribution
  - Asset Monitoring
- Integrated Multi Scale Data Analytics and Machine Learning for the Grid

Project - Sensing & Measurement Strategy



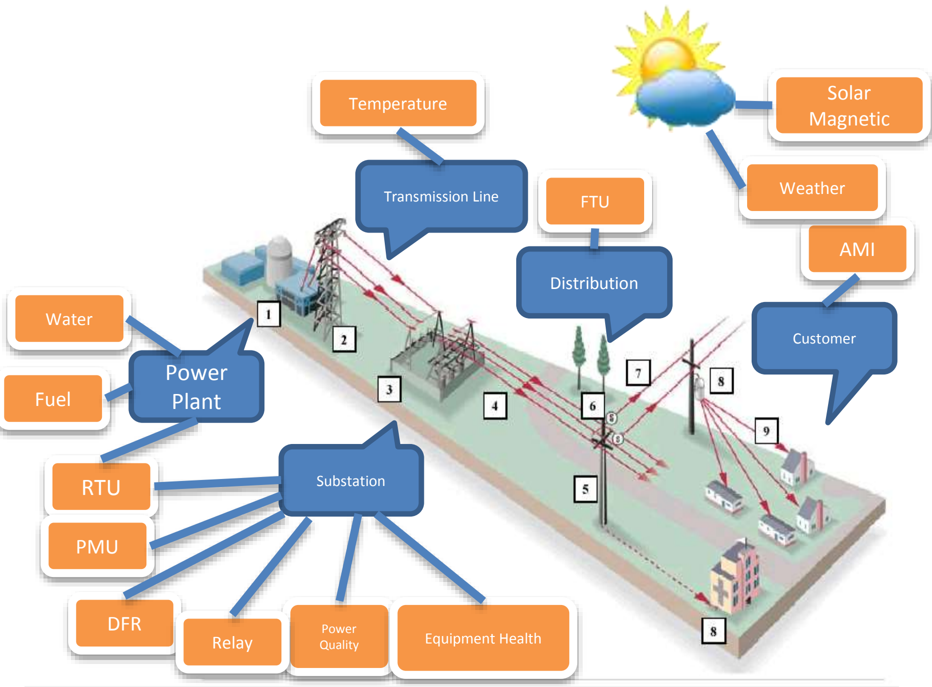
Develop an overall strategy for sensing & measurement including grid states, sensors, communications and data management & analytics. *Without an understanding of the true state of the system, these goals will never be realized.*

This methodology includes: 1) defining the grid state, 2) developing a roadmap and 3) framework to determine sensor allocation for optimal results.

Labs: ORNL, PNNL, NETL, LLNL, ANL, NREL, SNL, LBNL, LANL

Partners: EPRI, Southern Co, EPB, Entergy, OSIsoft, Dominion, TVA, CommEd, NASPI

Project – Advanced Sensor Development



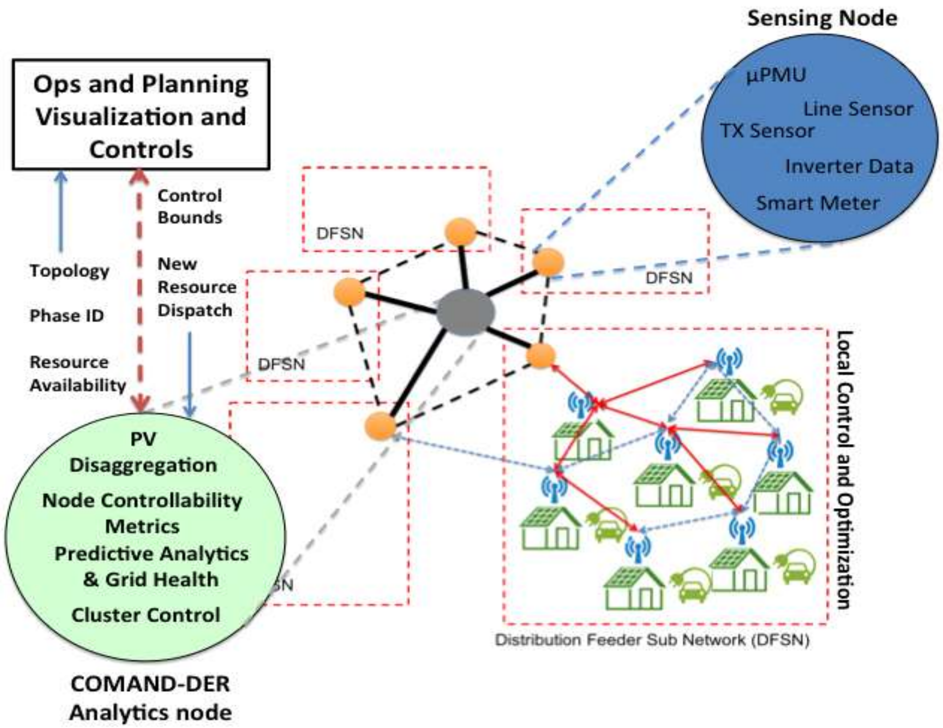
Modified from Duke Energy
https://www.progress-energy.com/florida/home/safety-information/storm-safety-tips/restoration.page?

Increase visibility throughout the energy system including transmission, distribution and end-use by developing low-cost, accurate sensors. Additionally, next generation asset monitoring devices will help determine state of grid components prior to failure.

Labs: ORNL, PNNL, NETL, NREL, SNL, LBNL

Partners: EPRI, University Tennessee, Southern Co, EPB, Entergy, Eaton, SmartSense, National Instruments, Dominion, TVA, ComEd, NASPI

Project – Multi-Scale Data Analytics & Machine Learning



Road Map of 1.4.9 (ML for distribution grids)

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

Labs: LANL, SNL, LBNL, ORNL, LLNL, NREL, ANL

Partners: OSIsoft, Duke Energy, PG&E, PingThings, PSL, City of Riverside, Hawaiian Electric, Pecan Street, Smarter grid solutions

Accomplishments and Emerging Opportunities

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Accomplishment

- 1.2.5 Developed Extended Grid State (EGS) framework and definitions incorporating industry feedback. Technology Roadmap (including key use cases) with industry feedback submitted to DOE. Sensor placement tool demonstrated within use case
- 1.4.4 End-use & Asset Monitoring sensor development has four invention disclosures & 2 patent applications; Developed algorithm for improved PMU under transient conditions;
- 1.4.9 Completed White Papers on technology gaps. Established three use cases. Developed supervised training dataset, EventDetect.

Path Forward

- 1.2.5 Continue EGS, roadmap outreach; Establishing DOE sensor program plan with technology roadmap. Optimization Tool (SPOT Tool) development to be demonstrated with other utilities
- 1.4.4 Evaluate performance of developed algorithms in hardware; continue research on promising approaches including integration using optical transducers & demonstrate benefits
- 1.4.9 Integration of multiple users to the developed framework; report on improvement over state of the art; continue development of datasets

Connections and Collaborations

Foundational and Program Projects

13 Partnership Projects between National Labs – Industry – Universities

MYPP Area	Foundational Projects	Program Specific Projects
Develop Low-cost advanced sensors	1.2.5 Sensing & Measurement Strategy 1.4.4 Advanced Sensor Project	GM0073 - HVDC and Load Modulation for Improved Dynamic Response using Phasor Measurements
Data Management & Analytics & Visualization	1.4.9 Distributed analytics	GM0070 - Discovery through Situational Awareness (DTSA) GM0072 - Suite of open-source applications and models for advanced synchrophasor analysis GM0077- Advanced Machine Learning for Synchrophasor Technology SI-1728 - Solar Resource Calibration, Measurement and Dissemination SI-1758 - Frequency Response Assessment and Improvement of Three Major North American Interconnections due to High Penetrations of Photovoltaic Generation WGRID-59 - WindView: An Open Platform for Wind Energy Forecast Visualization
Communications	1.2.5 Sensing & Measurement Strategy 1.3.5 SE Regional Project	SI-1586 - Opportunistic Hybrid Communications Systems for Distributed PV Coordination

Summary

Outreach & Commercialization

- ► Publications: over 30 publications with technical reports, journals (8) and conference proceedings, presentations (20+)
- ► Intellectual property developed: invention disclosures (8), patents (4).
- ► License of sensor suite technology
- ► R&D 100 award finalist – winners to be announced in November

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LABORATORY CONSORTIUM

Thank you

For More Information

http://energy.gov/under-secretary-science-and-energy/grid-modernization-initiative

GRID MODERNIZATION INITIATIVE
PEER REVIEW

GMLC 1.2.5 – Sensing & Measurement Strategy Project

D. TOM RIZY, ORNL (PI)
PAUL OHODNICKI, NETL (PLUS ONE)

September 4–7, 2018

Sheraton Pentagon City Hotel – Arlington, VA

U.S. DEPARTMENT OF ENERGY

Sensing & Measurement Strategy

High-Level Project Summary

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

- A cohesive strategy to develop and deploy sensing & measurement technologies for the modern grid is lacking.
- Project focuses on such a strategy to define measurement parameters, devices for making measurements, communications to transfer data, and data analytics to manage data and turn it into actionable information.

Value Proposition

✓ Grid is undergoing a major transformation (integration of new devices, major shift in generation mix, aging infrastructure, added risk of extreme system events (both manmade and climate).

✓ A need exists to characterize the state of the grid at much higher fidelity/resolution to maintain system reliability and security.

Project Objectives

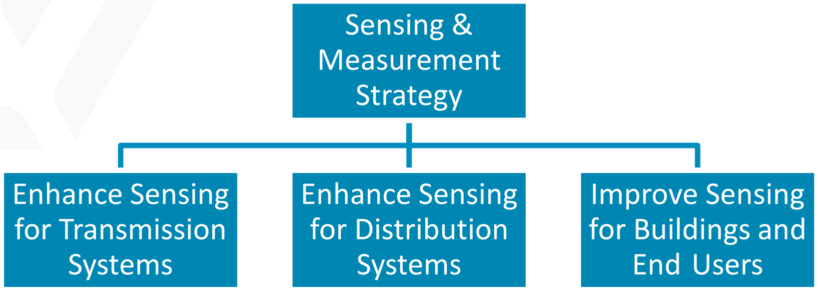
✓ Create extended grid state model.

✓ Develop a sensor technology roadmap.

✓ Develop a sensor placement optimization tool (SPOT).

✓ Outreach to technical & standard groups.

Sensing & Measurement Technologies are foundational needs of the GMI MYPP.



Sensing & Measurement Strategy

Relationship to Grid Modernization MYPP

Sensing & Measurement

- **Enhance Sensing for Transmission Systems**
  - 3.3.1 Develop advanced synchrophasors reliable during transient events
  - 3.3.2 Examine Sensor placement strategies as well as measurement accuracy requirements
  - 3.3.3: Develop novel inexpensive sensors for component health monitoring and low cost grid state monitors.
  - 3.3.4 Develop diagnostic and prognostic algorithms based on computationally efficient methods that interface with and use a suite of sensors
- **Enhance Sensing for Distribution System**
  - 3.2.1 Extended Grid State Framework
  - 3.2.2 Validated Visibility Strategy and Sensor Allocation Software Tool
  - 3.2.4 New, Low Cost Sensors for Distribution Level Electrical State and Asset Condition Monitoring
  - 3.2.5 Demonstrate low cost synchronized voltage and current sensors
- **Improve Sensing for Buildings and End Users**
  - 3.1.1 Advanced Sensors
  - 3.1.2 New Methods for Secure Wireless Sensor Communications
- **Develop Data Analytics and Visualization Techniques**
  - 3.4.3: Develop & demonstrate a tool for acquiring heterogeneous sensor data/ populating extended grid state
  - 3.4.1: Develop real time streaming analytics & machine learning paradigms for grid visibility, control, resilience, and security

Sensing & Measurement Strategy

Relationship to Grid Modernization MYPP

- **Project focuses on a strategy for sensing & measurement technologies to:**
  - ✓ Meet the challenges of integrating new technologies, such as renewable sources and storage, and new types of loads (EV, responsive loads).
  - ✓ Provide the visibility needed to operate the modern grid to deliver resilient, reliable, flexible, secure and sustainable electricity.
  - ✓ Identify sensor R&D needs, priorities, and sensor allocation.

- **Project is a crosscutting effort of the three thrusts of the GMI MYPP including**:
  - ✓ Technology – identifies grid states that need measurements, roadmap of sensor R&D needs, and how to allocate sensors in the system.
  - ✓ Modeling and analysis – identifies communications and data analytics requirements for sensing and measurement technologies.
  - ✓ Institutional and business – working with industry to identify needs and priorities and with technical and standards organizations to identify enhancements and new standards needed.

Sensing & Measurement Strategy

Project Team

Project Participants and Roles

Ten National Laboratories make up the project team:

- ✓ ORNL, PI and Task 3 & 4 Leads
- ✓ NETL , Plus One and Task 2 Lead
- ✓ PNNL, Task 1 Lead
- ✓ Total of ten labs involved in Task 1-4
- ✓ Multiple Labs served as working group leads to the sensor R&D roadmap development
- ✓ Others include: NREL, SNL, ANL, LBNL, LLNL, LANL, INL
- ✓ Industry partners include: Entergy, EPRI, Southern Co., EPB, OSIsoft, Dominion, TVA, ComEd, NASPI
- ✓ Industry Stakeholders include multiple organizations from industry (utilities, vendors, NASPI), academia, and other relevant government organizations.

PROJECT FUNDING				
LAB	**FY16 $**	**FY17$**	**FY18 $**	**Subtotal $**
ORNL	350	375	425	1,150
NREL	100	100	150	350
PNNL	150	145	45	340
NETL	100	100	100	300
LLNL	100	95	95	290
SNL	50	100	100	250
ANL	100	50	50	200
LBNL	50	15	15	80
LANL	0	20	20	40
TOTAL	1,000	1,000	1,000	3,000

Sensing & Measurement Strategy

Project Integration and Collaboration (Industry Outreach)

Utility Industry, EPRI, & NASPI

- ✓ Three industry meetings hosted by EPB, ComEd and Southern Co. Most recent was held at Georgia Power HQ in Atlanta.
- ✓ EPB and Duke Energy provided data for SPOT use cases
- ✓ EPRI – provided update on their current sensor activities
- ✓ NASPI Synchrophasor Task Teams: Performance, Standards & Verification and Distribution Systems

Vendors

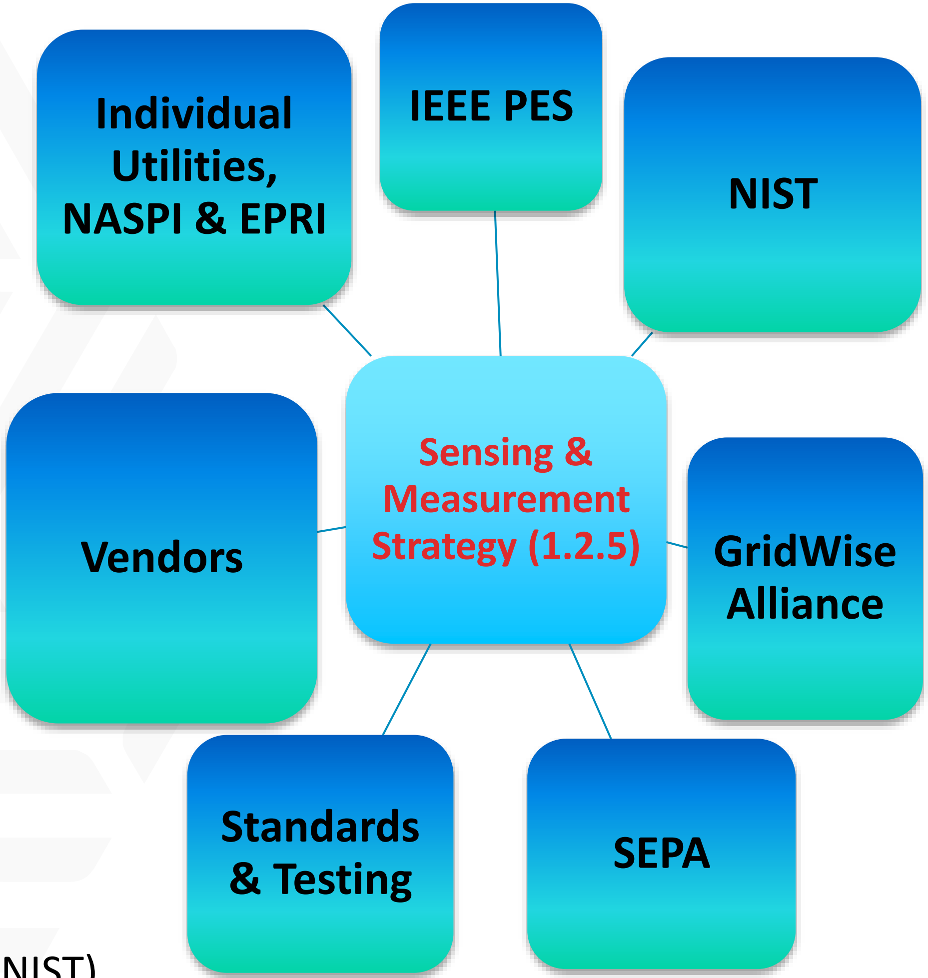
- ✓ EATON, Alstom, OSIsoft, Quanta, GE

IEEE PES

- ✓ IEEE Smart Distribution Working Group

Standards & Testing Organizations

- ✓ GridWise Alliance
- ✓ Smart Electric Power Alliance
- ✓ National Institute of Standards and Technology (NIST)



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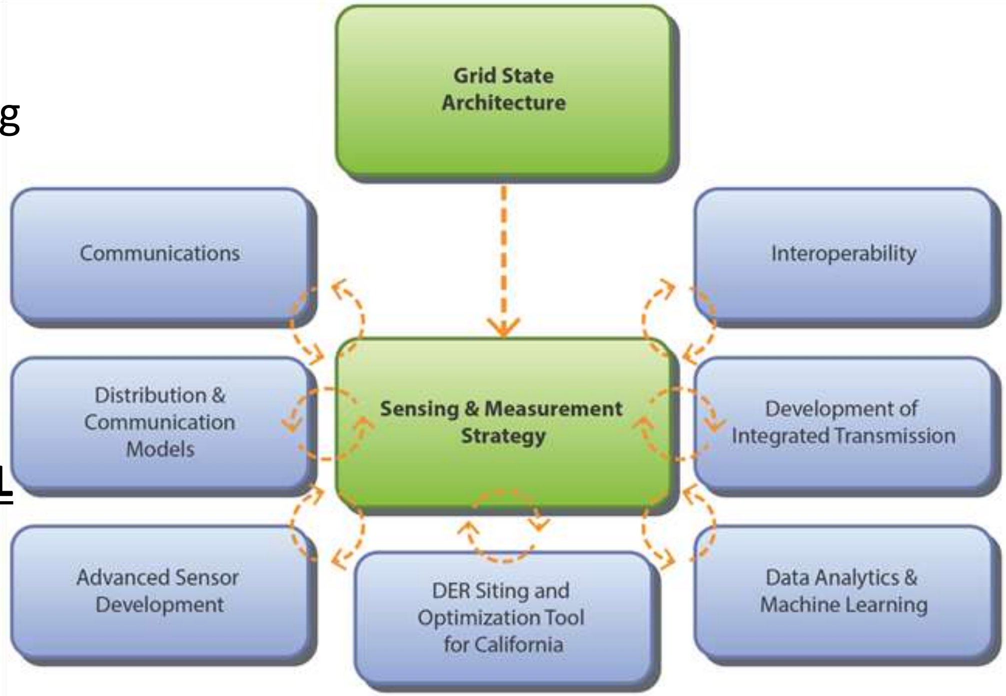
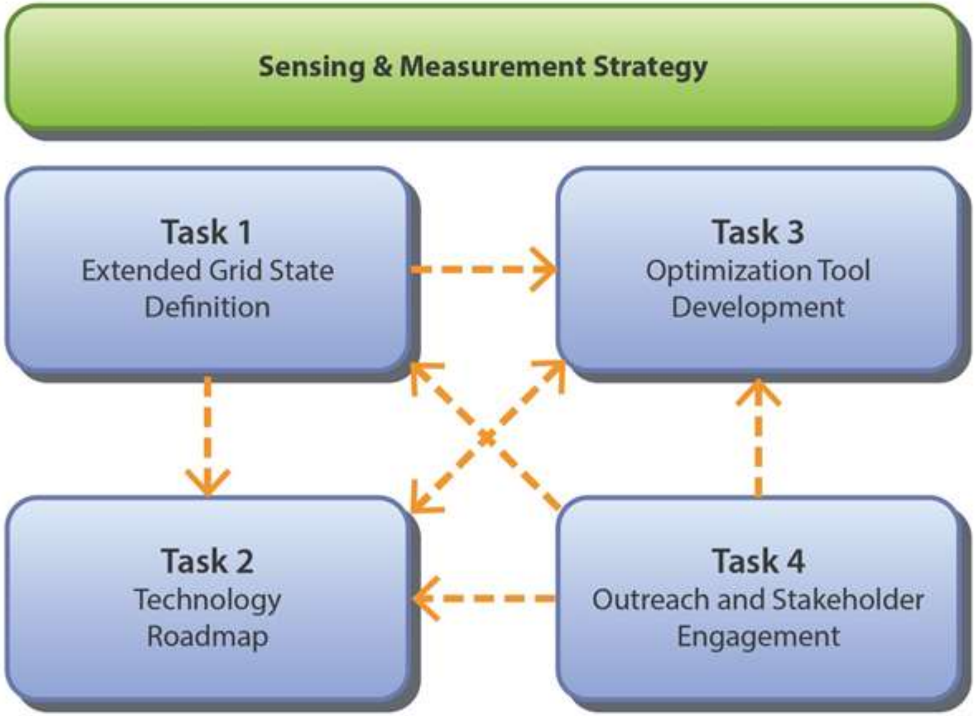
Project Integration and Collaboration (within GMLC)

- **<u>Grid Architecture (1.2.1)</u> –** What needs to be incorporated into EGS development?
- **<u>Interoperability (1.2.2)</u> –** Determine sensing & measurement interoperability needs.
- **<u>DER Siting and Optimization Tool for CA (1.3.5)</u> –** Approaches, methods or lessons learned that may be helpful to accelerate optimization tool development.
- **<u>Advanced Sensor Development (1.4.4)</u> –** New functionality of advanced sensors.
- **<u>Data Analytics and Machine Learning (1.4.9)</u> –** Data analytics needed for sensing and measurement.
- **<u>Development of Integrated T&D and Communication Models (1.4.15)</u> –** Communication models needed for sensing and measurement.
- **<u>Communications Roadmap Project by INL</u> –** INL completed draft report and participates in team meetings.



Sensing & Measurement Strategy
Approach

- **The project created an overall sensing and measurement strategy to:**
  - ✓ Bring together various stakeholders to define the "extended grid state".
  - ✓ Create technical a roadmap for sensors and measurement technology, including communications requirements, data management and analytics requirements.
  - ✓ At the same time considering MYPP goals (i.e., reliability, security, etc.).



Sensing & Measurement Strategy

Approach

- **Tasks are:**

1. **Extended Grid State (EGS)** – define the EGS reference model, drive extensions in standards, support development of strategy frameworks, and enhance interoperability.
2. **Technology Roadmap** – identify technical objectives, sensor functionality, measurement requirements, and associated data management/analytics and communication requirements.
3. **Optimization Tool** – provide/develop a tool for sensor allocation and placement and to enable creation of individual strategies by utility stakeholders.
4. **Outreach to Technical and Standards Organizations**
   - Work/coordinate with them and industry to incorporate ESG framework/definitions and sensing/measurement requirements in domestic and international standards.
   - Identify roadmap gaps and prioritize roadmap R&D objectives and ensure the usefulness of both of these and the optimization tool for industry.

Sensing & Measurement Strategy
Accomplishments to Date

Webinars & Working Groups
- ✓ Well attended webinars held in 2016-2018 to share the EGS and Roadmap with industry and to get their input/feedback.
- ✓ Direct participation by industry partners/stakeholders on roadmap WGs led by the Labs.

Industry Meetings
- ✓ Held at EPB in 2016, at ComEd in 2017, Southern Co. in 2018.
- ✓ EGS, Roadmap and SPOT status/progress and drafts were shared with industry at these meetings.

Reports Produced
- ✓ Produced EGS framework and definitions document which has been shared with NIST, NASPI, IEEE and IEC.
- ✓ Technology Review and Roadmap documents published as GMLC reports (Aug./Sep. 2018).

Sensing & Measurement Strategy

Extended Grid State Framework

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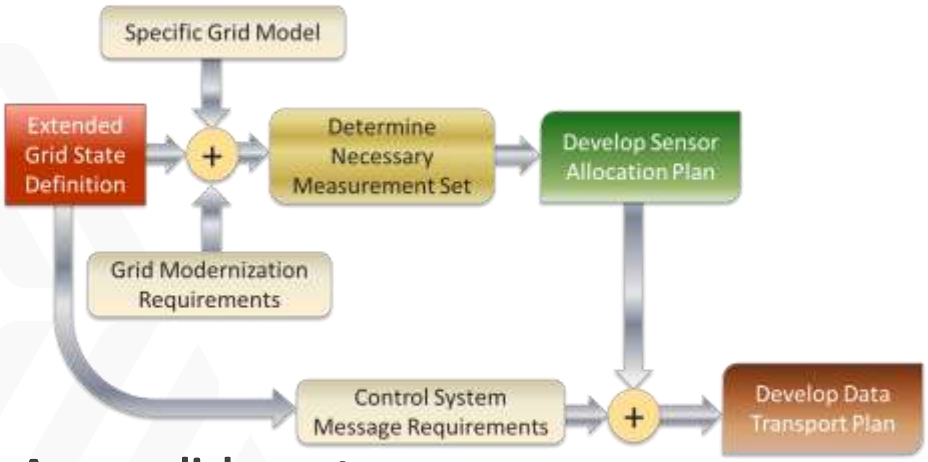
U.S. Department of Energy



YR 1: Define and Validate Extended Grid State Definition

- ✓ V0: proposal as starting point
- ✓ V1: developed by the team; get initial input from industry experts via meetings
- ✓ V2: updated V1 with inputs from external reviews
- ✓ Engaged key SDOs to work out alignment and harmonization
- ✓ V3: Update V2 with input from key Standards Development Organizations (SDOs)

YR 2: Test, Validate, Standards

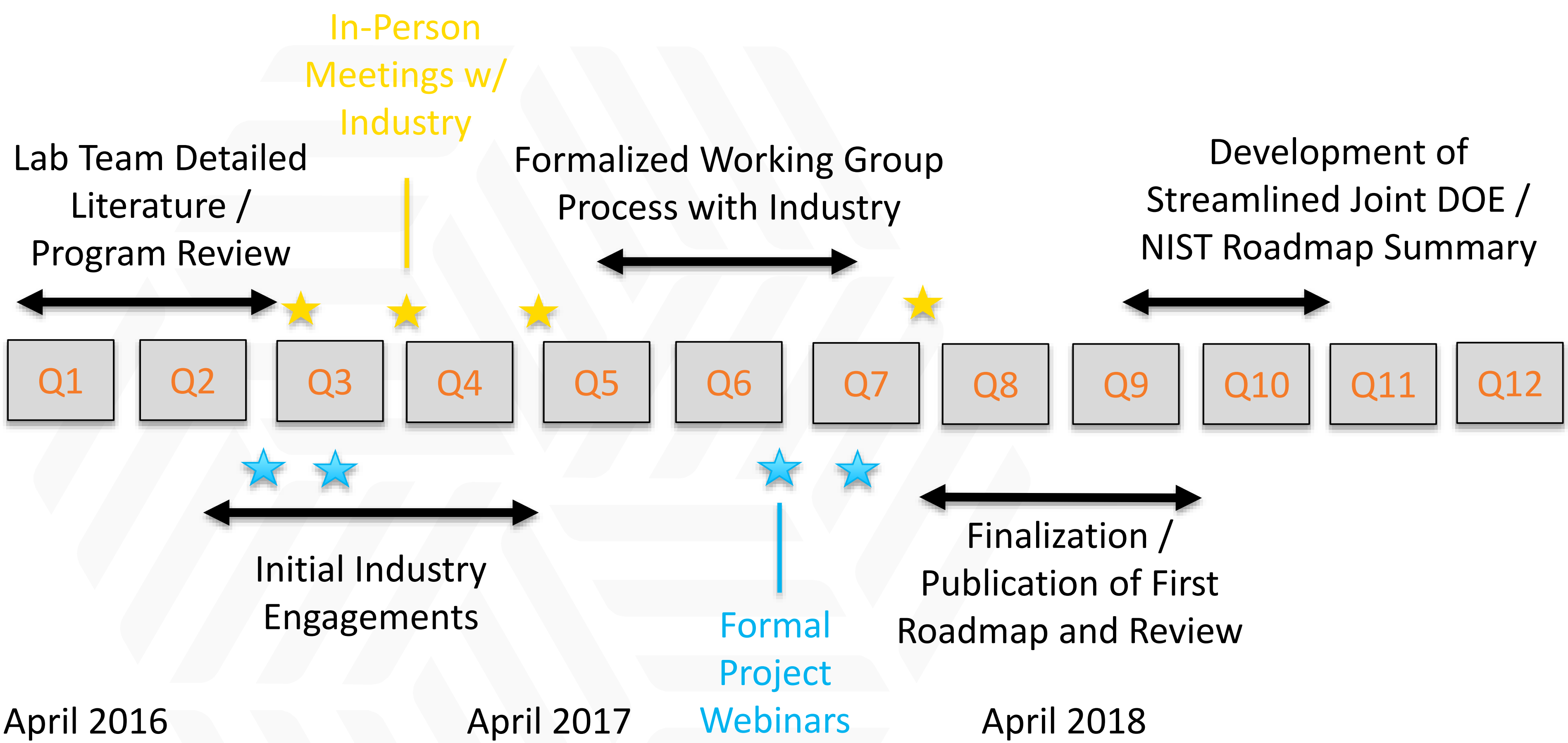
- ✓ Perform analyses and work with SDOs

Key Accomplishments

- ✓ EGS includes more than just traditional power states. (e.g. asset health and stress accumulation, thermal and other environmental states, and the states of grid connected assets)
- ✓ Document has been reviewed and received well by numerous utilities looking to define their sensing and measurement "needs"
- ✓ Follow-on is extension to new projects outside of GMLC in cyber-physical measurement space

Sensing & Measurement Strategy

Technology Roadmap Development



➢ **Process and timeline for development of the technology roadmap**

Sensing & Measurement Strategy

Accomplishments to Date - Roadmap: Example & Structure

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Suggested Focus Area with Description

Grid Asset Health Performance Monitoring – R&D Thrusts

Monitoring for determining the heath condition of assets can be applied to all those within the electrical power system. Benefits derived from improved visibility of their condition and health include increased reliability and resilience through prevention of catastrophic failures of critical assets and implementation of condition-based maintenance programs as a substitute for run-to-failure or time-based applications. It is desirable, with the movement toward a modern electric power system, to develop improved sensor device technologies at sufficiently low cost to monitor assets' health and performance in greater quantity with higher visibility. In regards to electrical parameters measurements, please refer to the the Novel sensors area on R&D thrusts.

Direct Links to GMI MYPP / EGS

Attributes: Reliability, Resiliency, Security

EGS Level: Component State, Convergent Network State

Scope of Activity: Conduct sensor device technology development at laboratory scale, followed by pilot-scale deployment and testing, and ultimately technology transition to industry.

Individual Research Thrusts with Key Parameters and Quantitative Metrics

#2: Grid Asset Internal Temperature

Internal temperature is a key parameter which serves as an early indicator of fault conditions in essentially all electrical grid assets, including centralized thermal generators. Temperature measurements tend to provide insights into natural degradation and failures of electrical grid assets including aging, arcing, etc. Lower-cost temperature probes that can be deployed internal to electrical grid assets need to be developed including multi-point sensor technologies. High-temperature, harsh-environment sensor technologies also need to be developed for centralized thermal generator applications.

High-Grade/Transmission Level:

Cost: Fully Installed Cost < $2,000
Performance:
- Temperature (Ambient to ~100ºC)

Geospatial: Multi-point, > 10 Individual Nodes

Low-Grade/Distribution Level:

Cost: Fully Installed Cost < $100
Performance:
- Temperature (Ambient to ~150ºC)

Geospatial: Single Point

High-Grade/Centralized Thermal Generator:

Cost: Fully Installed Cost < $10,000
Performance:
- Temperature (Ambient to as High as 1500ºC)

Geospatial: Multi-point, > 10 Individual Nodes

Sensing & Measurement Strategy

Accomplishments to Date - Roadmap: Example & Structure

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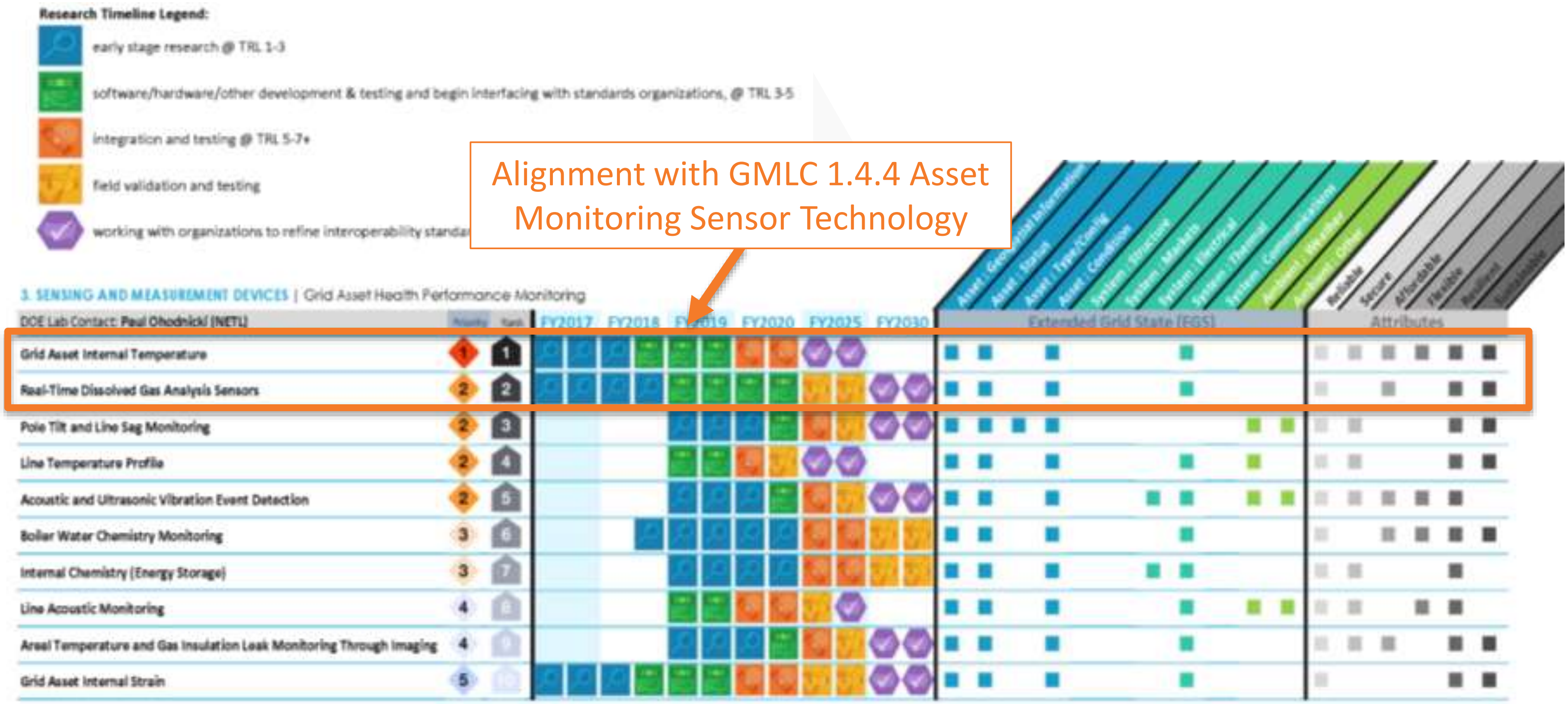

Research Thrusts

Graphical Timelines, Prioritization, and Ranking

Intersection with EGS and Grid Attributes From MYPP

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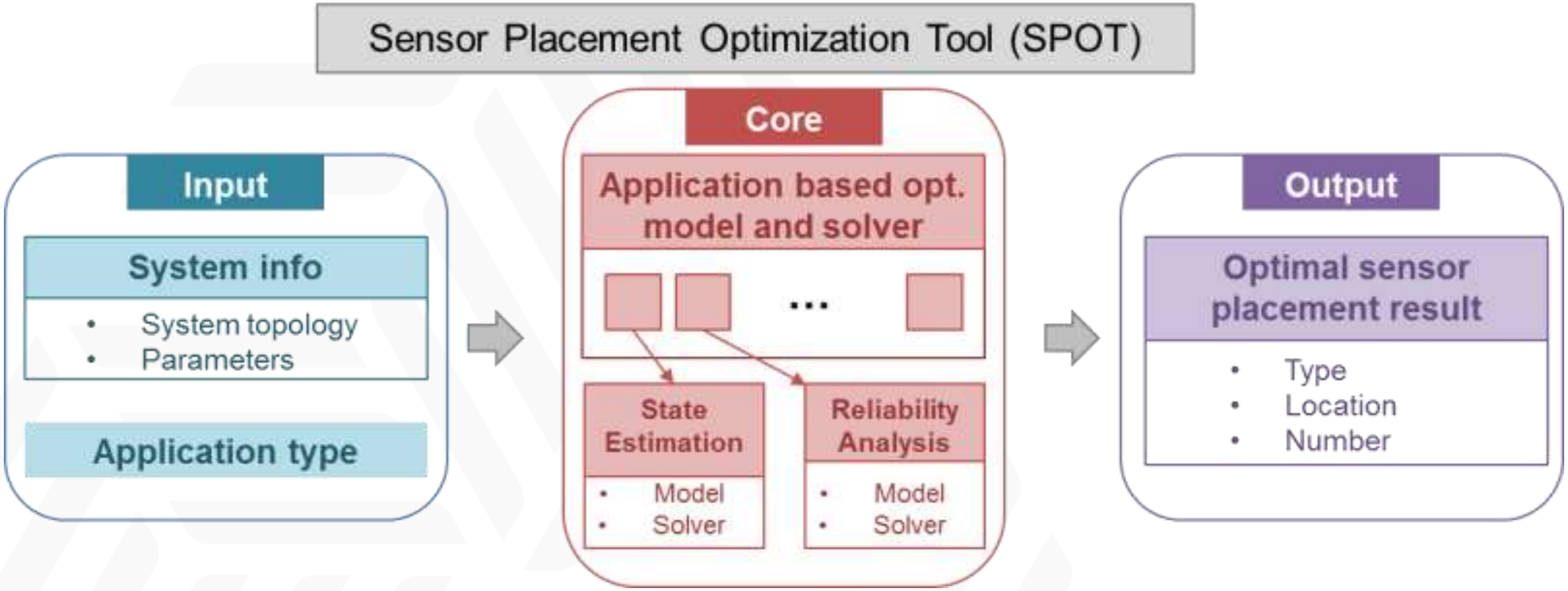
Accomplishments to Date – Tool Developed



- ✓ SPOT provides sensor placement strategy for distribution systems.
- ✓ Two distribution system applications (DSE and recloser placement for feeder reconfiguration) and optimization algorithms have been developed.
- ✓ SPOT has been tested against three different IEEE test feeders.
- ✓ Two utility (EPB and Duke) use cases have been conducted. In discussion with Southern Co. for another use case.
- ✓ The tool leverages the CYME tools of EATON.

Sensing & Measurement Strategy

Accomplishments to Date – Tool Case Study Example

Case Study

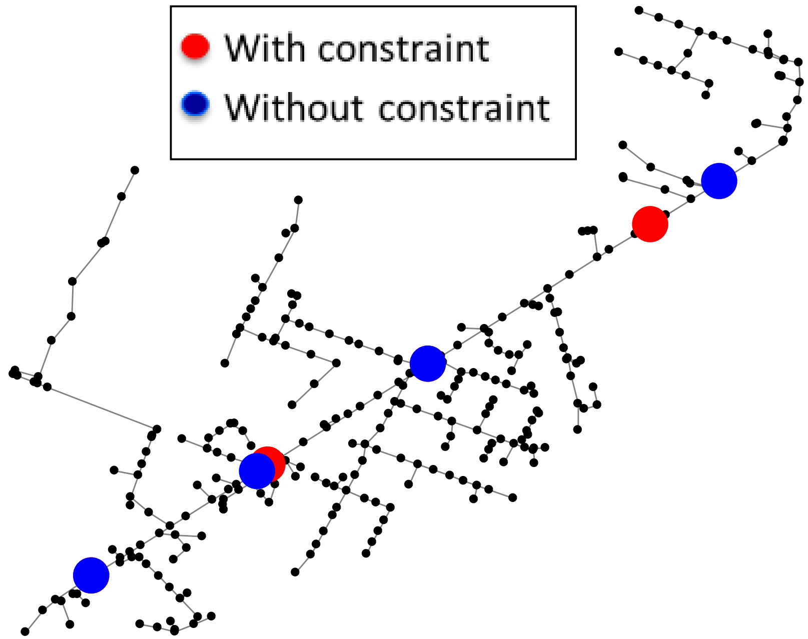
- ✓ Optimize recloser locations to improve the system reliability indices, e.g., System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI).

Practical constraint implementation

- ✓ Length constraint along the main trunk, 3000 ft
- ✓ Power constraint in each zone, 750 kW
- ✓ Customer constraint in each zone, 150 customers

Value assessment for improving reliability

- ✓ ICE calculator – An LBNL tool designed for estimating interruption costs/benefits associated with reliability improvements.
- ✓ **Input**: states/locations; number of customers; SAIFI; SAIDI.
- ✓ **Output**: Total benefit; without improvement (baseline); with improvement; benefit of each customer category.



Metric	Without Constraint	Constrained
SAIFI	1.3769	1.4172

Sensing & Measurement Strategy

Next Steps and Possible Future Work

- **Extended Grid State**
  - Gather feedback on EGS draft version from the IEEE/IEC (2018/2019)
  - Incorporate feedback into the EGS reference model and definitions (Future Plan, 2018 to 2019)
  - Conduct modeling of the EGS based on the final document (Future Plan, 2019)
- **Technology Roadmap**
  - Create streamlined version of the roadmap for DOE (Sep./Dec. 2018)
  - Share the findings and recommendations of the roadmap with technical and standards organizations including the IEEE and IEC (Future Plan, 2018/2019)
- **Optimization Tool**
  - Complete the technical report and user guide for the tool (Dec. 2018)
  - Complete case study with Duke Energy (2018/2019)
  - Conduct a case study with Southern Co. (Future Plan, 2019)
  - Work with vendors to transition the tool to industry (Future Plan, 2019)
- **Outreach**
  - Identify vendors that can support SPOT beyond the project period (2019)
  - Develop a PAR with the IEEE/IEC to develop/enhance technical standards to lay the groundwork for sensor technology developments (Future Plan, 2019)

Sensing & Measurement Strategy

BACKUP SLIDES

Sensing & Measurement Strategy

Project Objectives Expanded

- **Creation of an Extended Grid State (EGS) reference model**
  - ✓ Identifies information needed to understand states of the extended electric grid.
  - ✓ Provides a framework to identify sensing and measurement technology needed.
- **Development of a technology roadmap**
  - ✓ Identify the gaps and needs for sensor technology R&D for the electric grid.
  - ✓ Leads to the development of technologies to measure the electric grid parameters.
- **Development of a sensor placement optimization tool (SPOT)**
  - ✓ Develop a tool for optimal sensor placement while taking into account the various physical and budgeting constraints and use case objectives.
  - ✓ Leads to approaches for placing the technology to measure these parameters.
- **Outreach to technical groups**
  - ✓ Coordinate with industry for input, feedback, and ultimately acceptance.
  - ✓ Leads to identification of standards (new & enhancements) for sensing & measurement technology and needed crosscutting requirements.

Sensing & Measurement Strategy

Industry Partners & Stakeholders

- Utilities
  - Bonneville Power Administration
  - ComEd
  - Dominion Power
  - Duke Energy
  - Electric Power Board of Chattanooga
  - Entergy
  - ISO New England
  - NYISO
  - PEAK
  - PG&E
  - PJM
  - SMUD
- Utilities (cont.)
  - Southern California Edison
  - Southern Co.
  - Tennessee Valley Authority
- Gov't Organizations
  - Army Research Laboratory
  - NCAR
  - NOAA
  - Joint Research Centre, Italy
- Industry Organizations
  - Electric Power Research Institute
  - GEIRINA
  - IEEE

Sensing & Measurement Strategy

Industry Partners & Stakeholders (cont.)

- NASPI Task Teams
  - Distribution
  - Performance, Requirements, Standards & Verification
- Universities
  - Colorado State University
  - Florida State University
  - Michigan Tech
  - University of Albany-Sunny
  - University of CA- Berkeley
  - University of CA-Riverside
  - University of CA-San Diego
  - University of Oregon
  - University of TN-Knoxville
  - Virginia Tech
- Vendors
  - Bosch
  - Brixon
  - Eaton
  - Eppley lab
  - Ground Work Renewables
  - Irradiance
  - ISO-CAL North America
  - Kipp & Zonen USA Inc.
  - Ping Thing
  - Opal-RT
  - OSIsoft
  - Schneider Electric
  - Wi-Sun Alliance
  - Yokogawa Electric Company

Sensing & Measurement Strategy

Relationship with Advanced Sensors and Data Analytics

Sensing & Measurement Strategy

- ✓ Overall strategy for sensing & measurement including grid states, sensors, communications and data management & analytics.
- ✓ Identify sensor R&D gaps/priorities and optimize sensor placement.

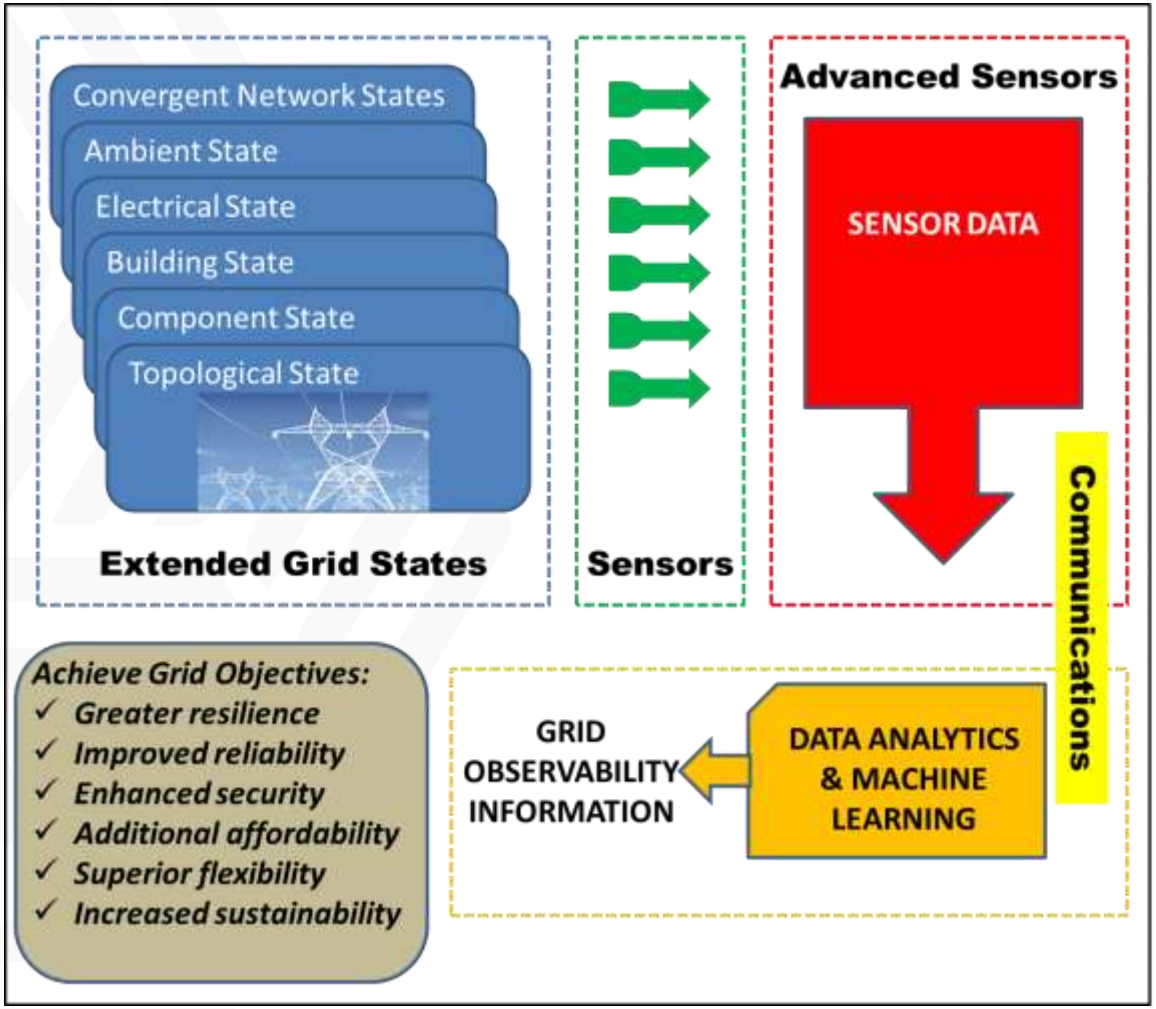
Advanced Sensors

- ✓ Develop new sensors to fill the gap needed for modern grid.

Data Analytics & Machine Learning

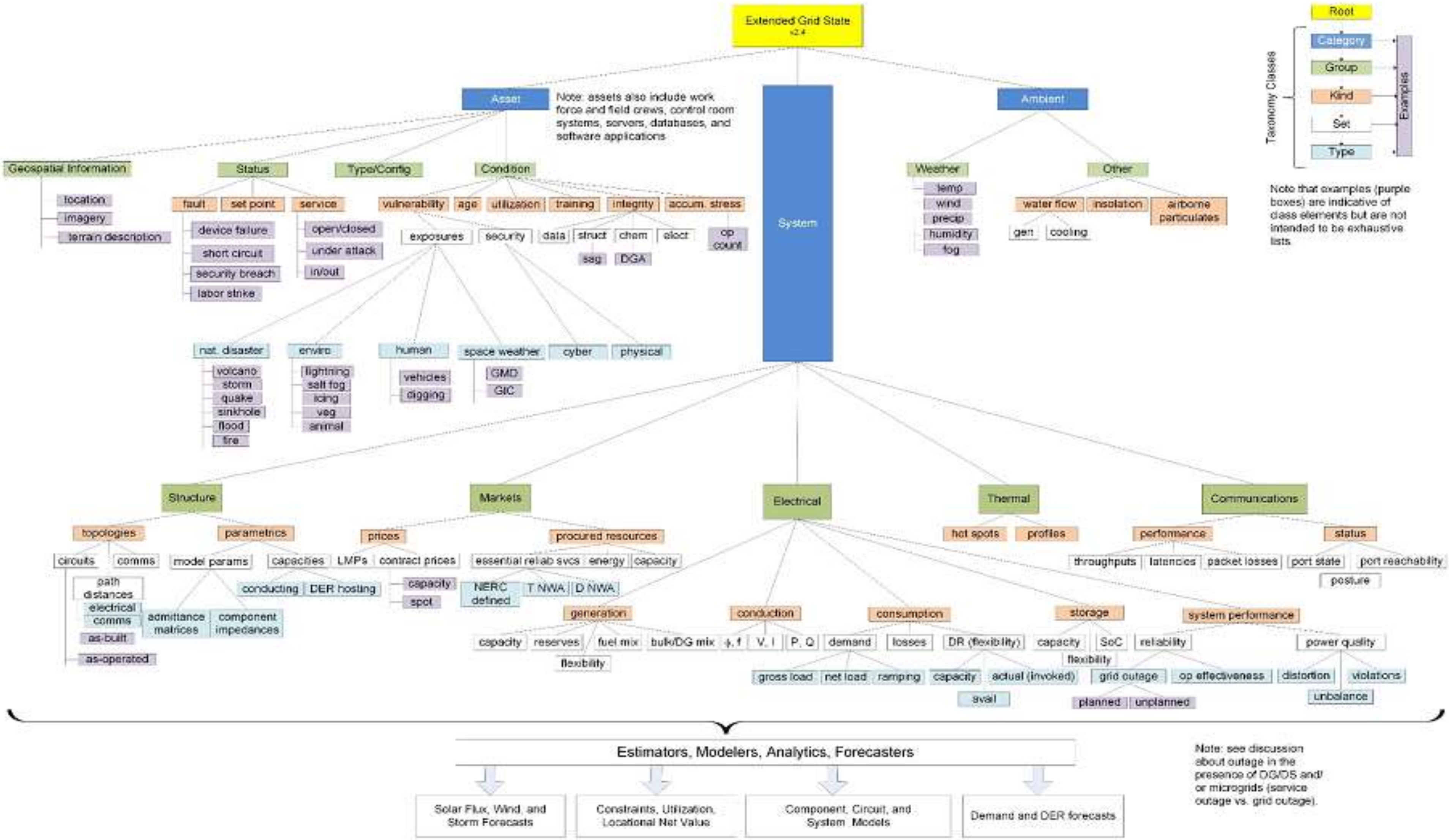
- ✓ Identify gaps in data analytics and develop machine learning algorithms.
- ✓ Turn sensor data into useful information to meet modern grid objectives.

Sensing & Measurement Strategy



Sensing & Measurement Strategy

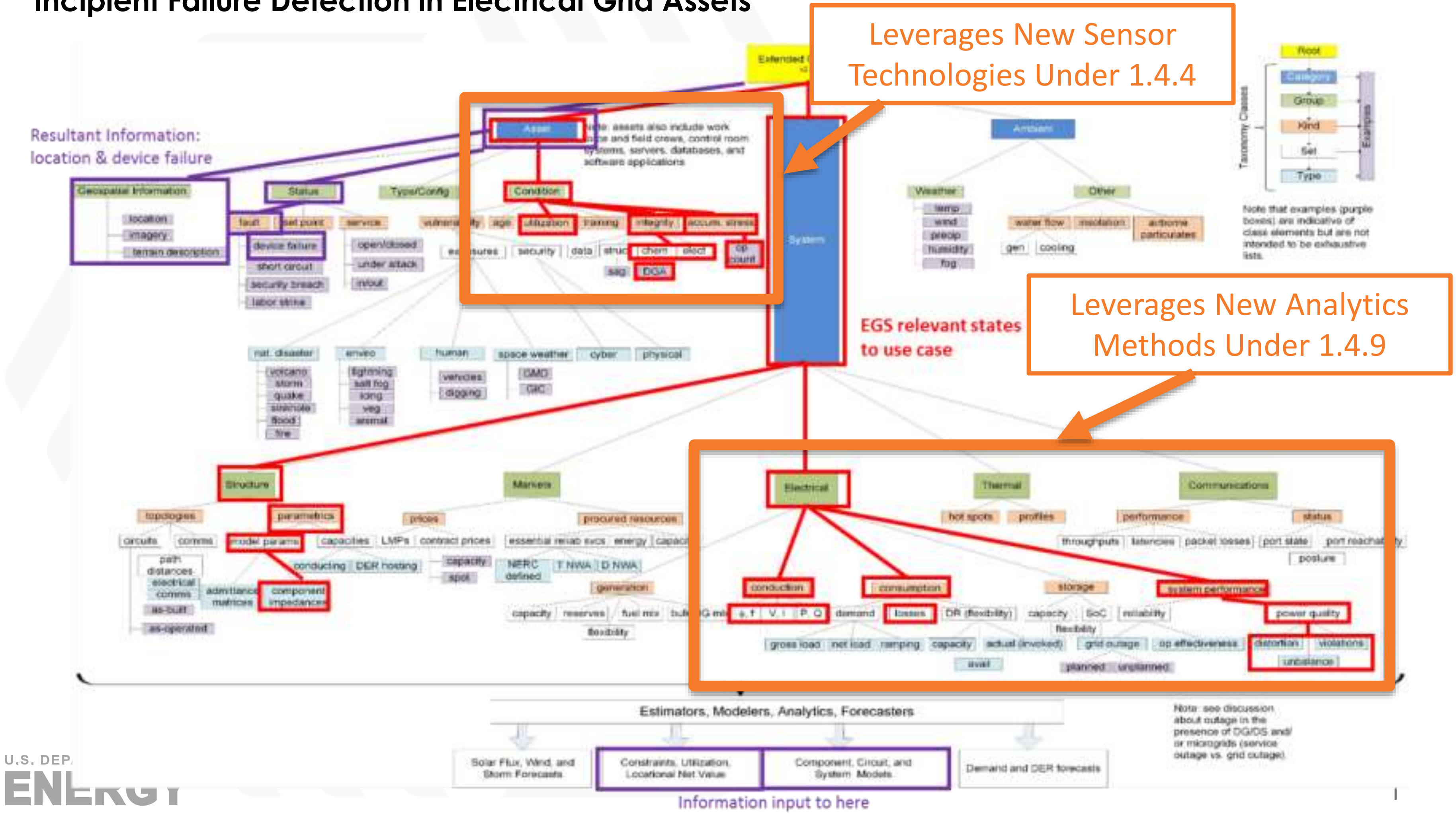
Extended Grid State Framework



Sensing & Measurement Strategy

Accomplishments to Date - Roadmap: Example & Structure

Example EGS Representation of a High Value Use Case :
Incipient Failure Detection in Electrical Grid Assets

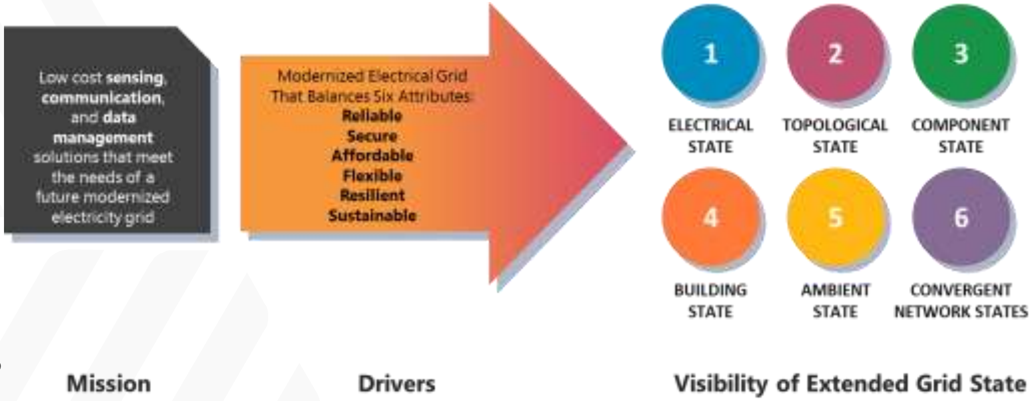


Sensing & Measurement Strategy

Accomplishments to Date - Roadmap

Sensor & Measurement Roadmap

LINKAGES TO DRIVERS & EGS



Crosscutting Initiatives

- ✓ Cyber-physical Security
- ✓ Standards and Testing
- ✓ Valuation of Sensing and Measurement
- ✓ Support for Industry and Utility Partners

Devices

- ✓ Harsh Environment Sensors
- ✓ Grid Asset Health Performance Monitoring
- ✓ Phasor Measurement Units
- ✓ Novel Electrical Parameter Sensors
- ✓ End-Use/Buildings Monitoring
- ✓ Weather Monitoring & Forecasting

Communications Requirements

- ✓ Distributed Communications
- ✓ Communications & Networking

Data Analytics & Modeling Requirements

- ✓ Big Data Management
- ✓ Analytics Support & Integration
- ✓ Weather Sensing Data

Sensing & Measurement Strategy
Some Key Gaps Identified

1) **Uses & Sensing Technology**
   - √ Parameters that require improved visibility via advanced sensor technology development
   - √ Technology to support the successful realization of advanced sensor devices
   - √ Characteristics of advanced sensor device technologies, including low cost and multi-parameter functionality

2) **Communications & Networks**
   - √ Optimized spectrum utilization and ease of integration of new technology platforms into various communications networks
   - √ Overall architecture characteristics
   - √ Standards as well as protocols for communications and networking technology

3) **Data Management & Analytics Including Grid Modeling**
   - √ Data management, standards, and utilization.
   - √ Data analytics development and applications for grid modeling, operations and real-time security assessments, and deployment.
   - √ Data and analytics tools for ease of visualization for operators.

Sensing & Measurement Strategy

Some Key Roadmap Targets Identified (Sensors)

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1) **Things to Monitor**

- √ Proxy sensors, i.e. vibration or acoustic.
- √ Tilt sensors to monitor pole and line orientation.
- √ Internal parameter measurements, i.e., temperature, chemistry of assets.
- √ High frequency/bandwidth and frequency selective responses.

2) **Advanced Materials & Techniques**

- √ Advanced sensing material R&D to support the development of sensor transducing elements that have optimal characteristics for a particular application.
- √ Advanced packaging and sensor device approaches and materials which are compatible with both electric grid and thermal generator applications.

3) **Needed Advancements**

- √ Dramatic cost reductions of existing sensor technology platforms and deployment.
- √ Development of ultra-low-cost sensing technologies with reduced but acceptable levels of technical performance.

Sensing & Measurement Strategy
Some Key Roadmap Targets Identified (Communications)

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1) **Utilization & Integration**
   - √ Hierarchical networks with distributed intelligence.
   - √ Distributed communications scheduling schemes.
   - √ Regular engagements with utilities, standards, and regulations to integrate advanced communications protocols such as 5G cellular and OpenFMB .
   - √ Sensor technologies with onboard data assimilation, analytics and communications, and distributed intelligence to alleviate information flow burdens.
   - √ Framework for cybersecurity, privacy implications and rules for variety of data and data uses.

2) **Architecture**
   - √ Compilation of latency & throughput requirements for existing/key emerging sensor platforms as well as a compendium of IoT/IIoT vendor & industrial group recommended architectures.
   - √ Integration of smart connectivity managers within a network architecture.

3) **Standards & Protocols**
   - √ Techniques for predicting interference/utilization impacts of non fully interoperable devices.
   - √ Device solutions which are agnostic to communications technology.
   - √ Solutions to ensure new devices are fully interoperable and compatible with existing standards.

Sensing & Measurement Strategy
Some Key Roadmap Targets Identified (Analytics / Data)

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1) Data Management

- √ Establish consortium focused on standards development/application for data acquisition, distribution, sharing, and exchanging subject to cybersecurity/privacy considerations.
- √ Development of clarified metrics around the impact of data quality on various algorithms/analytics methods to be applied for the modern grid domain.
- √ Relevant techniques, such as AI and big data analytics that have been applied to PMU data, could be adapted and applied to broader array of modern grid data types.

2) Data Analytics

- √ Development/application of geospatial analytical methods and incorporation of multiple types of disparate sources of data from distinct locations and sensing platforms.
- √ Advanced analytical techniques in conjunction with ubiquitous electrical parameter measurements from a wide range of data sources such as for rapid detection of low-probability/high-consequence events.
- √ Advanced data analytical methods applied to an array of weather and other environmental-related sensor and measurement devices such as for accurate forecasting of DER generation..

Sensing & Measurement Strategy
Proposed Needs for Crosscutting Support

1) **Cyber-Physical**
   - √ Recommend development of clear, standardized methodologies for assessing the cyber-physical security of emerging sensing and measurement technologies.
   - √ Awareness of cyber-physical security as key elements of new R&D efforts focused on sensing & measurement technologies.

2) **Standards & Testing & Standardization**
   - √ Development of formalized partnership between GMI/GMLC and relevant SDOs to enable collaborative interactions to ensure that the needs of sensing and measurement technology within the electric grid application domain are properly addressed.

3) **Value Proposition**
   - √ Standardized testing approaches as well as improved understanding of full sensing and measurement costs via industry surveys and maintenance of an cost information database (i.e., details of installation, operation and maintenance)
   - √ Standardized and well-accepted methods for valuation of innovative technologies, including grid modeling in conjunction with sensor placement and allocation tools.
   - √ An example is SPOT that has been developed under task 3. It is an application-based tool to optimize placement (number/location) of sensors subjected to application-specific objectives and constraints of physical placement, and cost/budget.

Sensing & Measurement Strategy
Proposed Needs for Crosscutting Support (cont.)

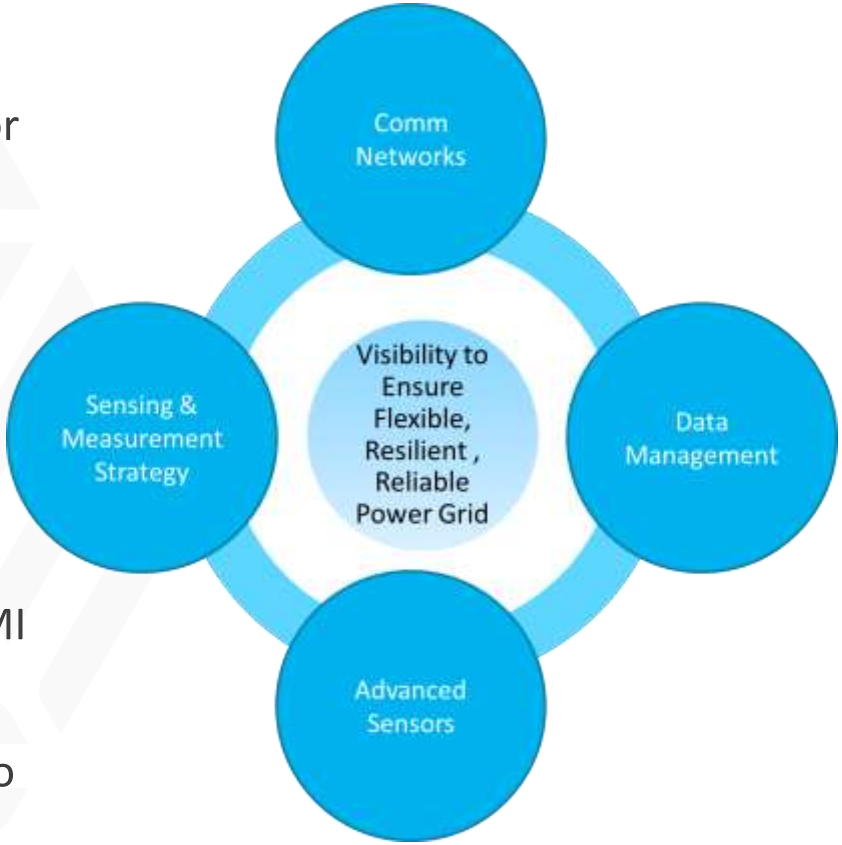
4) **Facilitating Deployment of New Technologies**

- √ Establish formalized group for the broader array of sensing and measurement technology moving into the future through the GMI/GMLC.
- √ A venue for voicing such concerns, lessons learned and other business challenges for new technology development and deployment can better inform regulatory bodies regarding the relevant trade-offs, and benefits of advanced sensing & measurement.
- √ Development of new course curricula focused on such sensing & measurement topics.
- √ Collaborations between researchers and operators/industry focused specifically on simplifying user interfaces for emerging technology platforms

Sensing & Measurement Strategy

Lessons Learned

- ✓ Industry is very interested in all aspects of the project.
- ✓ Industry recognizes the need for R&D priorities for sensor technology with the grid transformation.
- ✓ Industry recognizes need for sensor placement tool/strategy.
- ✓ In addition to R&D needs, industry also sees the need for support with mining of large sets of existing data such as synchrophasor data.
- ✓ There is concern about resiliency of sensors to EMI type events as well as cybersecurity.
- ✓ Sensing & Measurement is also an interest area to non-US entities such as the UK per a UK-US grid modernization collaboration workshop.



Sensing & Measurement Strategy

Key Future Project Milestones (CY2 & CY3)

Milestone (FY16-FY18)	Status	Due Date
Roadmap - Complete with inclusion of subtasks 2.4 (data management & analytics) to 2.5 (functional requirements).	**On track**	**10/1/2018**
SPOT - Draft report on distribution system cases studied and tool refinements.	Ontrack	10/1/2018
Outreach – Report on requirements for standards modifications (and new standards).	**On track**	**10/1/2018**
SPOT – Deliver final report on case studies and results of applying tool.	On track	4/1/2019
Outreach – Facilitate creation of a PAR/task force/working group to respond to sensor & measurement requirements.	**On track**	**4/1/2019**
SPOT - Validated framework of tool based on utility partner/stakeholder field testing.	On track	4/1/2019

GRID MODERNIZATION INITIATIVE PEER REVIEW
1.4.4 ADVANCED SENSOR DEVELOPMENT

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September 4–7

Sheraton Pentagon City Hotel – Arlington, VA

Advanced Sensor Development
Project Summary

GRID MODERNIZATION INITIATIVE
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Sensing and Measurement

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 proposal is organized around three major segments: end-use, transmission and distribution (T&D), and grid assets health monitoring

Expected Impact:
Increased visibility throughout the future electric delivery system.
Increased accuracy and fidelity of detection of faults, failures and other events.
Demonstrate approaches to data analysis, including machine learning, for baseline operation and anomaly recoverie(s)

Objective

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 transducers.

Asset Monitoring: sensing platforms with attributes for broad applicability across the grid asset monitoring application areas. Focus is on very low cost gas and current sensors for asset monitoring with the purpose of incipient failures or faults detection.

Advanced Sensor Development
Project Team

Project Participants and Roles

National Labs: ORNL, PNNL, LBNL, NREL, NETL, SNL
UTK: improve sensor algorithms
EPRI: technical input on sensing areas and demonstration of advanced sensors for monitoring transformer bushings and arresters.
Genscape: develop dynamic line rating approach using wireless monitoring devices
Southern Co., TVA, ComEd, EPB: advisory role to ensure the research is aligned with utility needs
National Instruments: provide hardware platform
SmartSenseCom Inc.: integrate the developed phasor estimation algorithms, GPS timing, and communication module

PROJECT FUNDING			
Lab	**FY16 $K**	**FY17 $K**	**FY18 $K**
ORNL	660	745	1,165
LBNL	145	145	150
NREL	145	145	150
SNL	250	250	250
NETL	150	150	150
PNNL	75	75	
Non-lab Team	650	550	
Total	**2,075**	**2,060**	**1,865**

Advanced Sensor Development

Relationship to Grid Modernization MYPP

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- Sensing & Measurement is a fundamental technical activity with linkages throughout the entire MYPP
- Limited activity in sensing technologies in the DOE portfolio prior to the GMI and GMLC

Devices and Integrated System Testing

- MYPP Activity 1
  - MYPP Task 2.1.4
- MYPP Activity 2
  - MYPP Task 2.2.4
  - MYPP Task 2.2.5

Design and Planning Tools

- MYPP Activity 2
  - MYPP Task 5.2.1
  - MYPP Task 5.2.2
  - MYPP Task 5.2.5
  - MYPP Task 5.2.6

Sensing and Measurements

- MYPP Activity 1
  - MYPP Task 3.1.1
  - MYPP Task 3.1.3
- MYPP Activity 2
  - MYPP Task 3.2.2
  - MYPP Task 3.2.5
- MYPP Activity 3
  - MYPP Task 3.3.1
  - MYPP Task 3.3.2
  - MYPP Task 3.3.3
  - MYPP Task 3.3.4
  - MYPP Task 3.3.5
- MYPP Activity 4
  - MYPP Task 3.4.1
  - MYPP Task 3.4.2
  - MYPP Task 3.4.3
  - MYPP Task 3.4.4
- MYPP Activity 6
  - MYPP Task 3.6.2
  - MYPP Task 3.6.3

System Operation, Power Flow and Control

- MYPP Activity 1
  - MYPP Task 4.1.1
  - MYPP Task 4.1.2
  - MYPP Task 4.1.3
- MYPP Activity 2
  - MYPP Task 4.2.1
  - MYPP Task 4.2.3
- MYPP Activity 3
  - MYPP Task 4.3.1
  - MYPP Task 4.3.2
  - MYPP Task 4.3.3

Problems & Needs addressed by the Project

- Nation's electric power system is going through a major transformation:
  - Major shift in generation mix - more non-firm renewable resources.
  - More connected devices: DG, electric vehicles, and energy storage.
  - Greater customer participation: transactive control, demand responsive loads/programs.
- The Grid transformation requires greater power system determination ("visibility") to manage assets ideally to:
  - Determine the real-time power system state of the power system
  - Forecast future states with enough accuracy and lead time to avert deviations from normal operations (i.e., self-heal for disturbances)
- Drives the need for better sensing and measurements of the grid:
  - Accurate measurements to characterize the power system state from generation, to transmission and distribution to finally end-loads.
  - At much higher fidelity and resolution than ever before.
- Meeting the objective of greater visibility requires advanced sensors, accurate measurements, communications, and data analytics. This project addresses the development of low-cost sensors

Bottom line: You can not detect or control what you can not accurately "observe"

Advanced Sensor Development

Approach

- Focus on key challenges identified in industry roadmaps and DOE multi-year program plans that are critical to increased visibility throughout the energy system.
- The project is organized around three major segments: 1) end-use, 2) transmission and distribution (T&D), and 3) grid asset monitoring

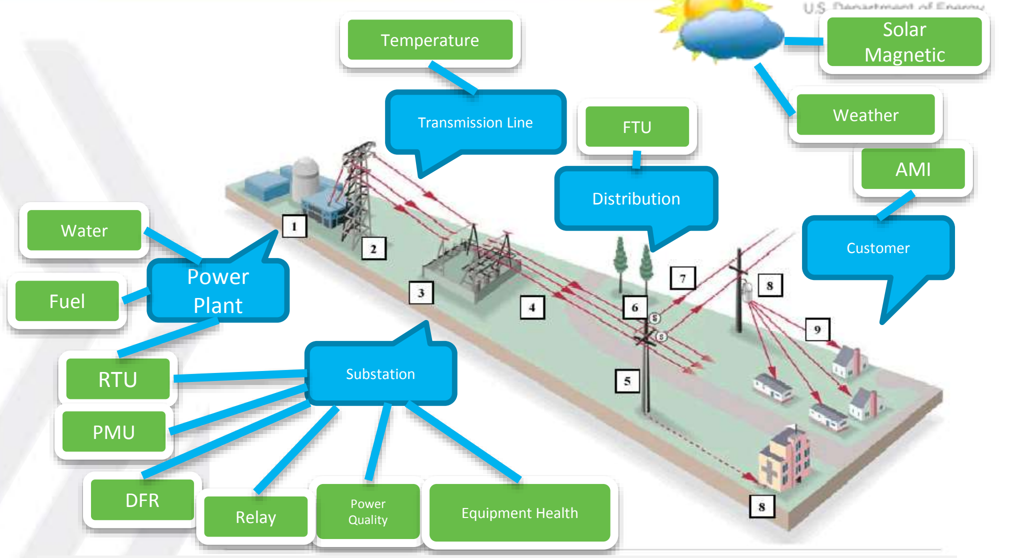
Value Proposition

Increased visibility throughout the electric delivery system.

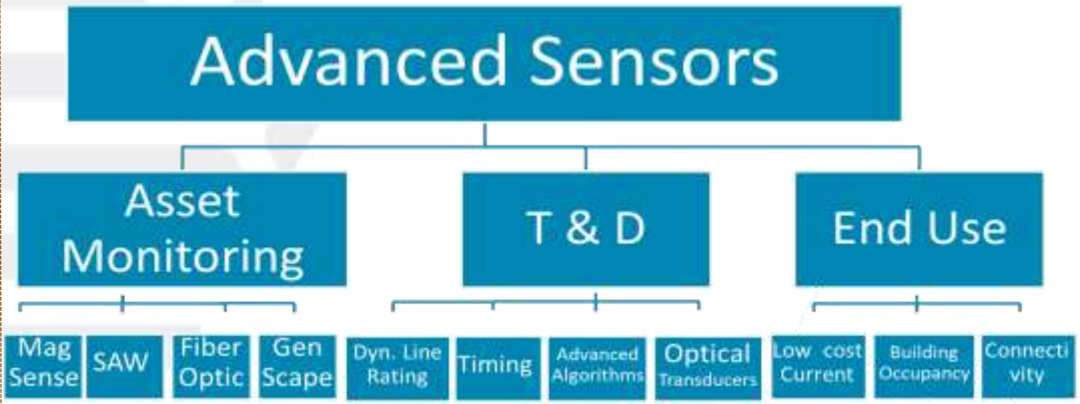
<u>End-use</u>: (1) develop low-cost sensors, exploiting additive manufacturing techniques, to monitor the building environment and electrical characteristics of building equipment, and (2) develop algorithms to use building-level data to provide utility-scale visibility and localized weather monitoring.

<u>T&D</u>: Extend the resolution of transmission grid visibility orders of magnitude higher than current technologies by developing ultra fast phasor algorithms, new GPS backup timing method, and optical transducers technologies.

<u>Asset Monitoring</u>: sensing platforms with attributes that are best-suited for broad applicability across the entire current and future grid asset monitoring application space.



Modified from Duke Energy
https://www.progress-energy.com/florida/home/safety-information/storm-safety-tips/restoration.page?



GRID MODERNIZATION INITIATIVE PEER REVIEW
1.4.4 ADVANCED SENSOR DEVELOPMENT
ASSET HEALTH MONITORING

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JAMES 'TRIP' HUMPHRIES, KOFI KORSAH, TOLGA AYTUG, RICHARD MAYES, CHRISTI JOHNSON, BRUCE WARMACK, JORDAN BESNOFF
Oak Ridge National Laboratory
PAUL OHODNICKI, CHENHU SUN
National Energy Technologies Laboratory

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Advanced Sensors – Asset Monitoring

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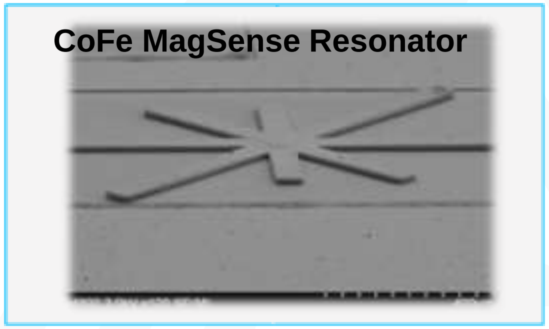
Value Proposition: Asset monitoring is critical for utilities as they deal with an aging infrastructure and a change in generation mix. In consulting with utilities, the GMLC identified three areas to emphasize while an overall roadmap was being developed.

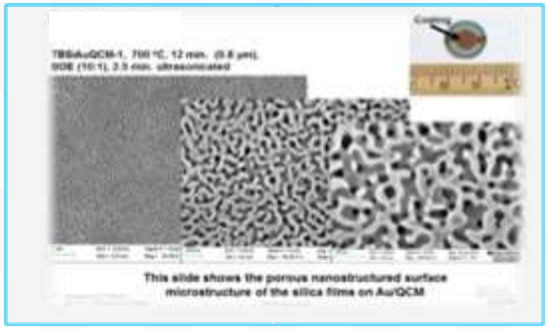
Work is organized in three sensor projects:



MagSense Sensor Development

Fast and frequency-selective electric current measurements are necessary for accurate asset health, failures and faults detection;

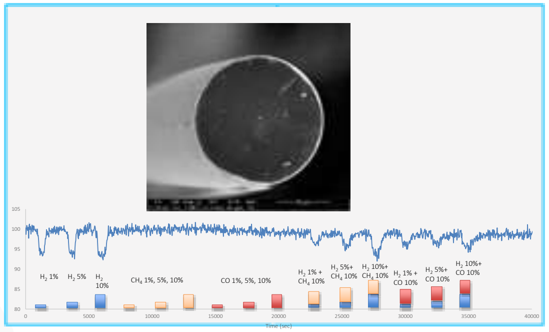
First of its kind: Low cost, frequency selective, very fast response time electrical current sensor



SAW Sensor development

Completely passive integrated chemical-species-and-temperature detector appropriately connected to the transformer

Small, solar powered interrogator (less than half the size of a smartphone) interrogates the sensor and transmits information to utility



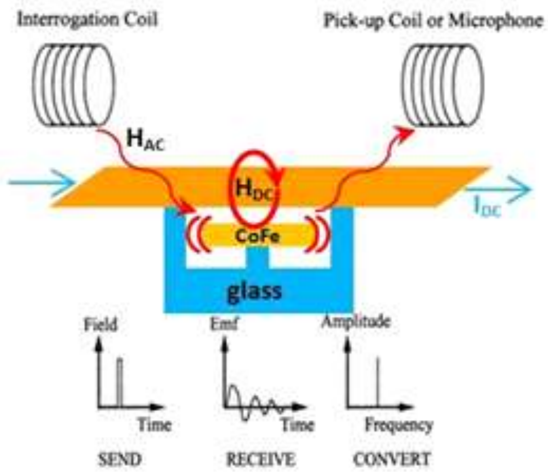
Nano Enabled Optical Fiber Sensor Development

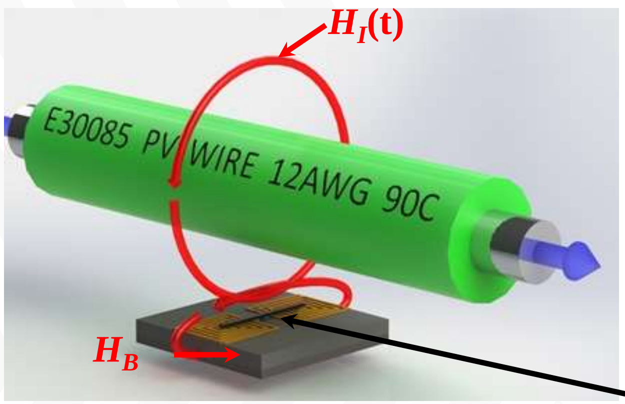
Integrated Nanomaterial with Optical Fiber Platform for Selective H_2 Chemical Sensing; Demonstrated Real-Time Temperature Monitoring for Operational Transformer Core;

Will Pursue Sensing Materials to Achieve Improved Selectivity and Sensitivity at Relevant Levels (H_2, CH_4, CO <~2000ppm)

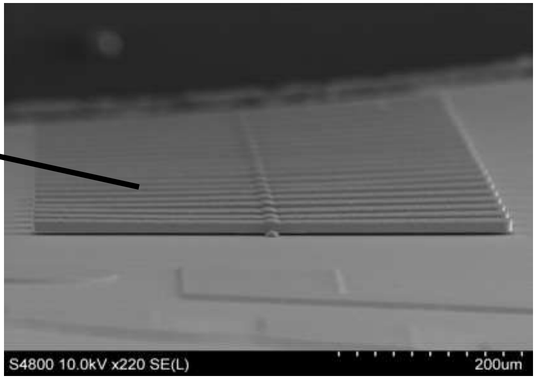
MagSense Sensor Approach

Goal: Develop and tailor a MagSens Sensor for temperature and/or current abnormalities





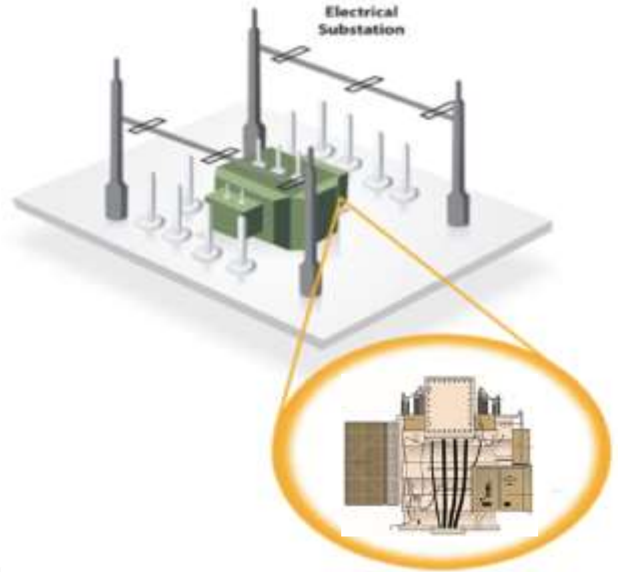
CoFe 5 MHz Resonator Array

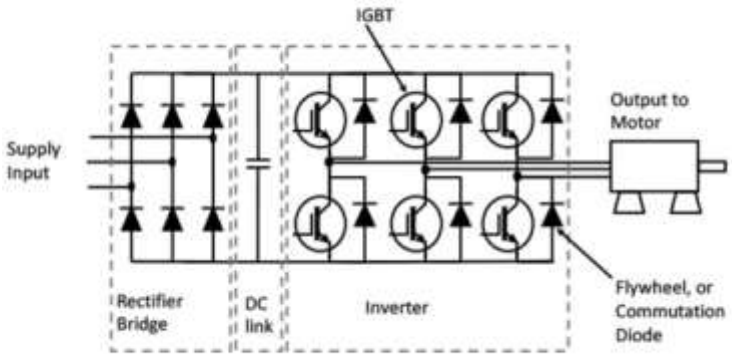


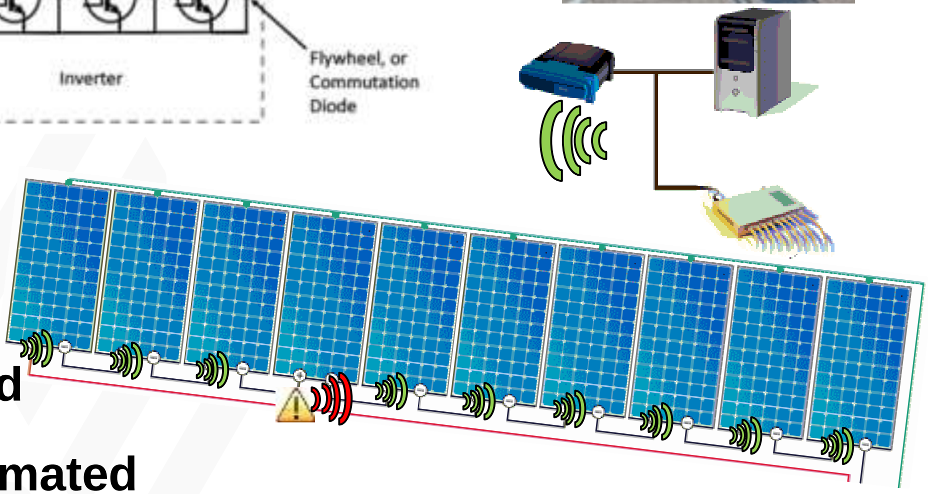
- Single, passive sensor to detect fault currents and/or temperature excursions
  - Inexpensive (¢/module)
  - Sensitive (I_{fault} = µA) current levels
  - Fast (µs response)

► MagSense can be tailored to sense a variety of abnormalities, including fault currents, temperature runoff in battery packs of EVs and large-scale storage, and many other applications

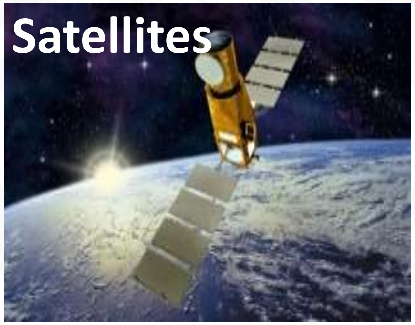
MagSense Sensor: potential applications







- Sensors can be wirelessly interrogated
- Data collection can be manual or automated (UAV, ground-based robots, etc)



Temperature sensing for Electric vehicle and other batteries

MagSense Sensor:
Current Sensing concept

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- A -first-of-its-kind electrochemically deposited (ECD) cobalt iron (CoFe) alloy with a high degree of magnetostriction was developed by SNL;
- CoFe resonating frequency changes, depending on current (***Js***) present, and frequency change/shift can be detected:

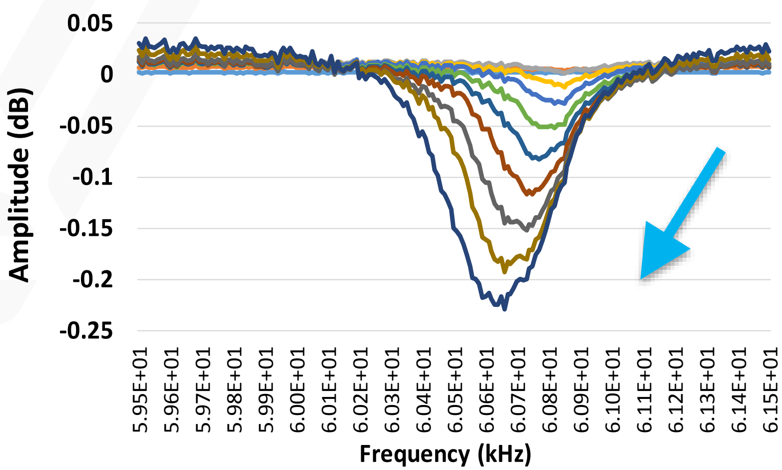
$$f_r = \frac{1}{2L}\left[\sqrt{\frac{\rho}{E_0} + \frac{9\lambda_s^2 \rho\left((|H_B + H_{DC}(t)| \cos(\beta))\right)^2}{J_s H_A^3}}\right]^{-1}$$

- We have fine-tuned process parameters to result in higher magnetic sensitivity parameters

- **We have demonstrated sensing of current for several important applications:**

1. Detection of DC and AC currents
   a. Application: detection of high impedance faults or ground faults in DC circuits
2. Detection of DC and AC faults
   a. Application: detection of "traditional" faults but with greater accuracy and precision
3. Detection of grid asset performance degradation or other abnormalities

Frequency shift and amplitude increase:



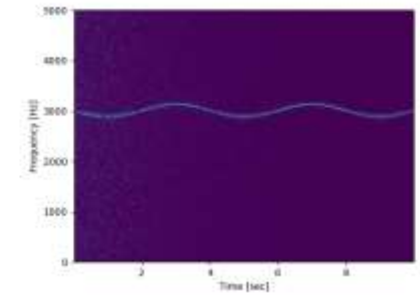
MagSense Sensor:
Sensor Design:

Two types of interrogation / information readout are possible:

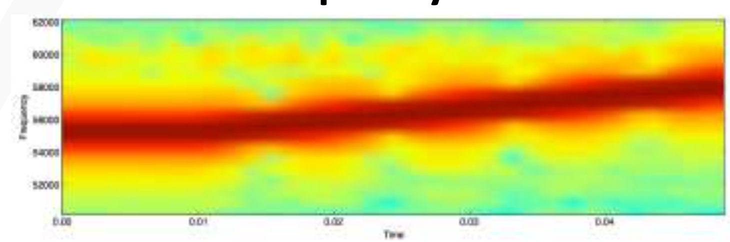
1. Passive
   - Device is interrogated manually or semi-manually
   - Lower cost option ($10 - $50 range)
2. Active
   - Device is actively “listening” and will transmit an alarm as soon an event is detected
   - Slightly more expensive option ($100 - $300 range)

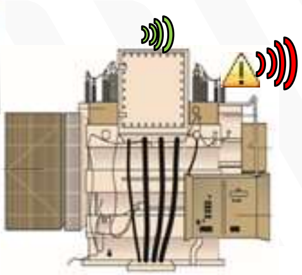
- We are working on both options, and will evaluate both of the cost/benefit trade-offs and gauge stakeholder’s interest in both of the solutions.

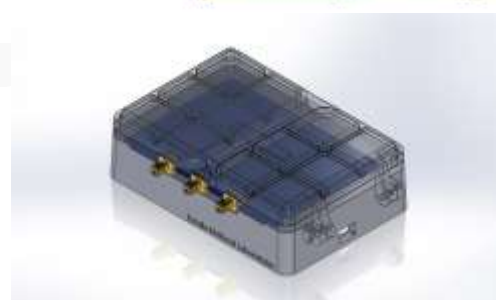
Sample frequency output: Spectrogram



Real operation output: Frequency wavelet:





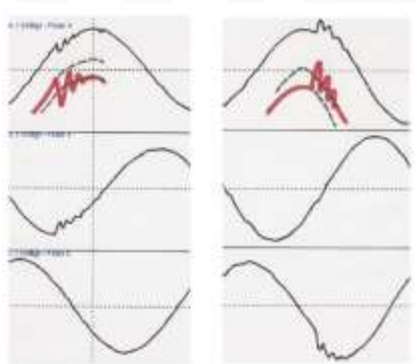


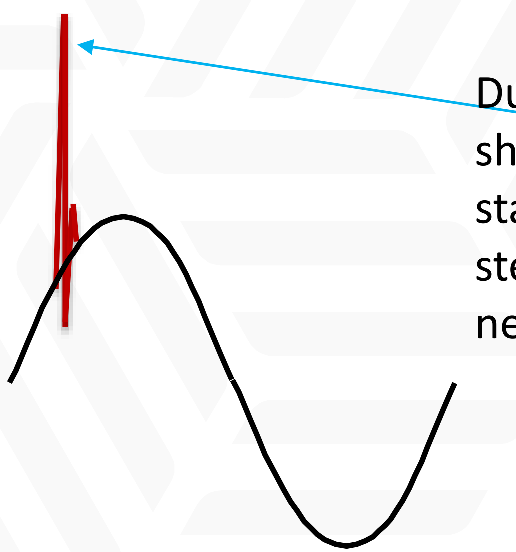
MagSense Sensor:
Housing and Software: Design Steps

- Using microprocessor (Rasp Pi, Arduino) and FPGA to demonstrate frequency shift detection
- Developed local alarm indicator; remote alarm communication software under development
- Other remote administrative software functions are finalized
- Finalize housing design to accommodate new FPGA dimensions (88x125x40mm)
- Working on NEMA-rated enclosure as an additional option

Next steps:

- Design and fabrication of higher magneto-strictive sensors to get higher Signal-to-Noise ratio
- Finalize housing and software design
- Demonstrate passive and active MagSense field unit designs
- Further demonstration tests:





During Transients or faults, frequency shift should be significantly above the steady state levels. Such difference from the steady state levels is the signal that we need to detect

Future work:

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- Demonstrate specialization of sensors for different events detection
  - Voltage/current droops/surges
  - Equipment harmonics due to degradations
  - Power/energy theft
  - Other, etc
- Environmental reliability/sensitivity of MagSense
- Finesse communication/reporting designs – based on stakeholder feedback
- Work with data integration and machine learning to:
  - Incorporate events/abnormalities detection into analytical methods for better visualization and controls
  - Analyze local data storage vs data transmission options for ML
  - Integrate with other applications (power electronics, other transmission and distribution infrastructure)
  - Integrate other peripheral sensors (thermocouple) for added information
  - Combine uPMU and communication infrastructure to realize better cost points

Accomplishments to Date : MagSense

- **When commercialized, this sensor will drastically reduce the costs associated with sensors manufacturing and deployment, as well as enable fundamentally more precise sensing and detection of faults and abnormalities**
- **Two patent applications:**
  - US Appl 14/876,652 "Electrodeposition processes for magnetostrictive resonators".
  - Disclosure: "Passive Magnetoelastic Smart Sensors For A Resilient Energy Infrastructure"
- **Presentations:**
  - "Optimized Co-Fe-B and Co-Fe-P Alloy Films for Electroformed Resonators" Jamin Pillars, Eric Langlois, Christian Arrington, Isaac Dyer, Patrick Finnegan, Christopher St. John, Todd Monson, presented at Electrochemical Society conference, 10/7/16
  - "Cobalt-Iron-Manganese Electrodeposition for High Performance Magnetoelastic Resonators", J. R. Pillars, E. D. Langlois, C. L. Arrington, and T. C. Monson, prented at Electrochemical Society conference, 10/4/18

SAW Sensor Concept:
Innovative SAW-Based Online System for Dissolved Gas Analysis for Power Transformers

Project Objective:

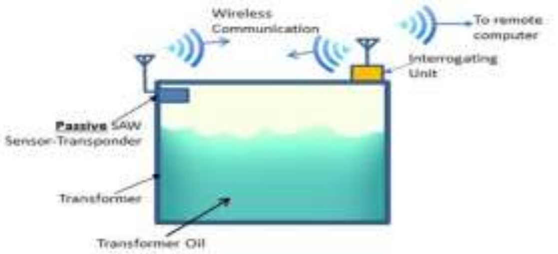
Develop a low cost, in situ, dissolved gas analyzer for incipient failure monitoring of power transformers

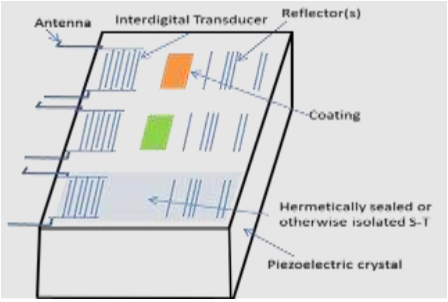
- Dissolved Gas Analysis (DGA) of power transformers typically employs offline methods and takes a relatively long time. Online methods exist, but costs ~ $30-50K per (DGA) system.
- Develop baseline highly selective chemical coatings (Methane (CH4) and Carbon Monoxide (CO) for proof of concept

Sampling port (possible location of test chamber for device)

Expected Outcome & Benefits:

An in-situ DGA system that costs an order-of-magnitude lower than the state of the art





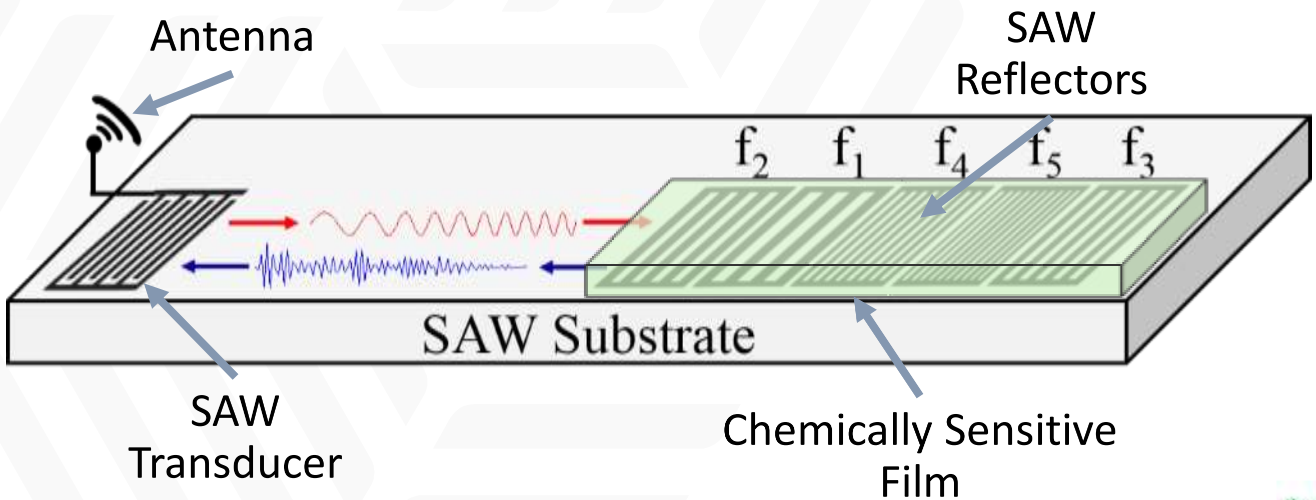
Value Proposition / Approach

- Dissolved Gas Analysis (SAW Gas Sensing)
  - Design SAW methane sensor for DGA application (500ppm)
  - Design SAW hydrogen sensor for DGA application (1000ppm)
  - Investigate nano-structured films for increased sensitivity for SAW gas sensing

- Field Validation (Remote Temperature Monitoring of Power Transformers Using Passive SAW Transponder Technology)
  - Design and test SAW temperature sensor
  - Design and Test Wireless Interrogator with Embedded Processing
  - Perform laboratory "field tests" by exposing temperature to expected temperature conditions in the field (0-100°C)

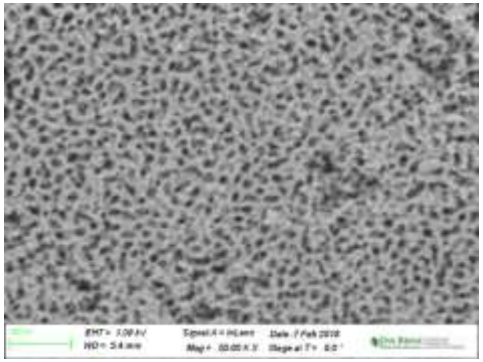
SAW Sensor Concept / Approach

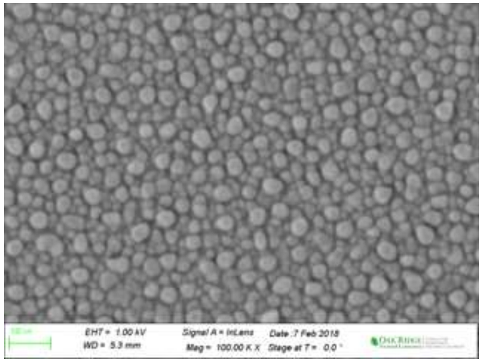
- One Port Device
  - Measure reflected interrogation signal (S_{11}); passive operation
  - Post-processing to determine how frequency, phase, delay of reflected signal is changing
  - “Cooperative RADAR target”
- 10MHz-3GHz Operation
  - Fabrication tolerances limit; sensor size dominated by antenna in wireless config.
  - Common to operate at 915 MHz or 2.4 GHz range
- Variety of Device Embodiments
  - Temperature, strain (pressure), chemical and gas detection
  - Resonant, delay line (narrow or wideband)
  - Radiation hard



Methane Sensing Concept

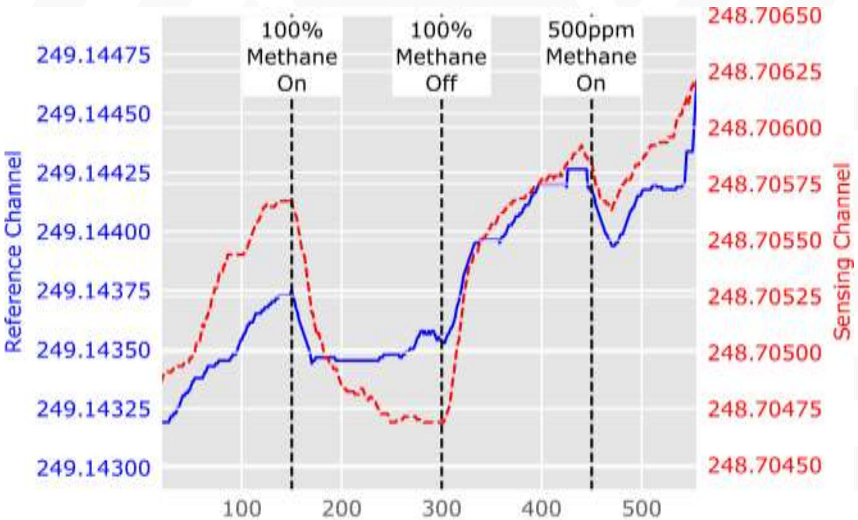
- SAW device as sensing platform
  - Deposit methane sensitive film on surface and track frequency shift due to mass loading
  - Wireless and passive operation
  - Low-cost to manufacture
- Nano-structured interstitial films
  - Deposited before applying methane sensing film
  - Increase surface area for methane/SAW interaction
  - Promote uniform sensing film application
- Methane Sensitive Molecule (Sensing Film)
  - Cryptophane-A
  - Trapping molecule, methane fits into cavity





Initial Methane Sensing Experiments

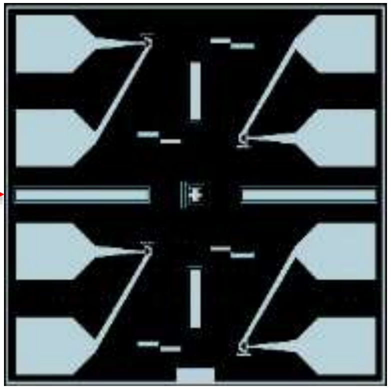
- Initial SAW device operated at 250 MHz
- Exposed sensor to 100% and 500ppm (desired sensitivity) methane
- Sensor has reference (temp) and sensing (methane) channel
  - Sensing channel shows larger freq. shift than reference channel when exposed to 100% methane.
  - 500ppm shows similar shift for both channels, most likely dominated by temperature; sensitivity to methane too low
- Increasing device frequency will increase sensitivity to mass on surface
  - Redesigning device for 915 MHz operation, predict 500-1000% increase in sensitivity



$$\Delta f = (k_1 + k_2) f_0^2 h p_f - k_2 f_0^2 h \left\{ \frac{4\mu'(\lambda' + \mu')}{v_0^2(\lambda' + 2\mu')} \right\}$$

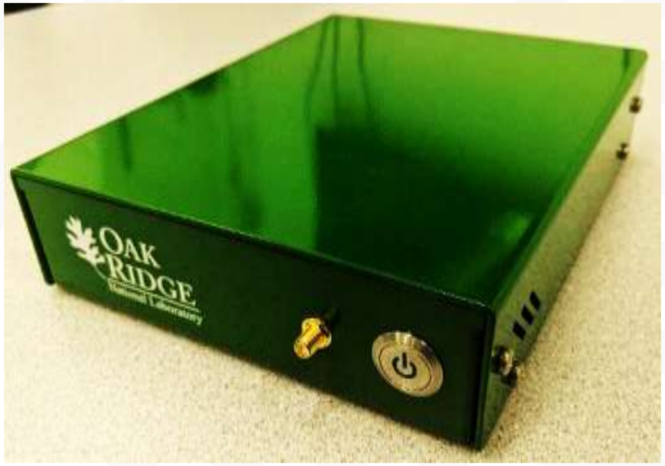
915 MHz Sensor Design

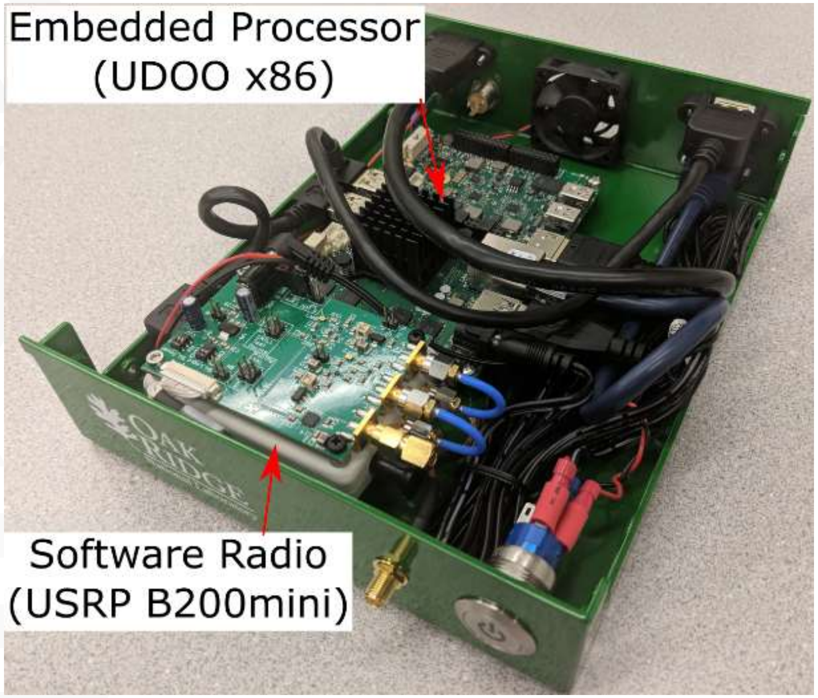
- 915 MHz Sensor Design current in progress
- New Test Fixture for Rapid Testing
  - Old design required wire bonding and adhesive bonding to PCB
  - New fixture routes RF signal to pogo pins; chip is placed into chamber and pogo pins make direct connection
- Wide-band, multi-chip (reflector) design for improved SNR (pulse compression gain)
- Laser cut shadow mask for nano-structure and cryptophane application



Embedded Interrogator

- ► Built prototype embedded interrogator system
- ► Custom enclosure that incorporates SDR, Udoo x86 embedded CPU, and cables
- ► 225×175×50 mm (9×7×2 in.)
- ► 1.2 kg (2.6 lbs.)





Current Efforts (DGA)

- Nano-structure integration experiments with 915 MHz devices
  - SAW very sensitive to thin film morphology and thickness
  - Determining optimal film thickness and process conditions
- Preparing for methane sensing test with 915 MHz devices
- Investigating hydrogen sensing methods on SAW
  - Some tests with palladium have been performed to observe palladium interaction with SAW
- Ruggedized interrogator design
  - Ready interrogator for field deployment / testing
  - Moisture / Dust resistant
- Package SAW sensor for field deployment and integration
  - Address attachment to utility asset
- Testing of Ruggedize system in ORNL Technical Testing & Analysis Center (TTAC)
  - Expose interrogator and sensor to moisture, dust, and temperature extremes

Accomplishments to Date : SAW Sensor

Advanced Sensor Development Project #1.4.4

- New laboratory facilities have been established for optical fiber based sensor fabrication and testing in conditions relevant for asset monitoring.
- A fiber optic sensor array has been fabricated for simultaneous detection of H_2 and temperature using multi-wavelength interrogation.
- Low-cost optical devices employing off-the-shelf LEDs and photodiodes have been developed for future field deployment efforts.

Field Validation Task "Add-On"

- Commercial interrogator systems have been used to characterize temperature distributions in operational transformer cores.
- A multi-point optical fiber based temperature sensor has been packaged and tested for energized cores under application relevant excitation conditions.
- Integration and testing in a distribution transformer is planned for the upcoming project year.

Asset Monitoring: Fiber Optic Sensors

Background:
Commercial Devices for Gas / Temperature Monitoring

- Survey of commercial technologies
- Review article developed by team members
- Transformer monitoring solutions exist
- Current monitoring approaches include:
  - Dissolved gas analysis (DGA): sampling
  - On-line DGA techniques
  - Transformer bushing sensors
  - Thermography
  - Winding resistance measurements
- <u>Costs limit deployment, particularly distribution assets</u>

“Chemical Sensing Strategies for Real-Time Monitoring of Transformer Oil: A Review” C Sun, PR Ohodnicki, EM Stewart, IEEE Sensors Journal 17 (18), 5786-5806

MODEL	COST
Market interest	< $100
Single Gas solid-state sensor	$6,500-7,500
Fuel cell gas sensor for key gases and moisture	$8,500-23,000
Non-dispersive infrared DGA sensor for key gases and moisture	$15,000-25,000
Gas Chromatography monitor for key gases and temperature	$25,000-45,000
Photo-Acoustic Spectroscopy monitor for key gases	$46,800
Fiber optic temperature monitor	$5,000-25,000
Electronic temperature monitor	$4,000
SAW temperature sensors	$3,000

Fiber Optic Sensors : Oil Temperature and Chemistry Monitoring

- Thermal and electrical faults result in aging and degradation of the transformer insulation.

- For temperature > 90ºC, the aging rate of insulation grows rapidly, resulting in a deterioration of transformer life expectancy.

- Temperature rise should be controlled to minimize risk of failure and extend lifetime.

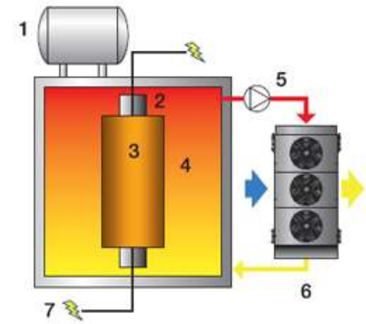
- Dissolved gas analysis can provide information about current and prior faults.

- Hydrogen is key chemical parameter to monitor:
  - Produced in most transformer faults
  - Conditions can be diagnosed (relevant range 100 to >1800 ppm)

Transformer cooling

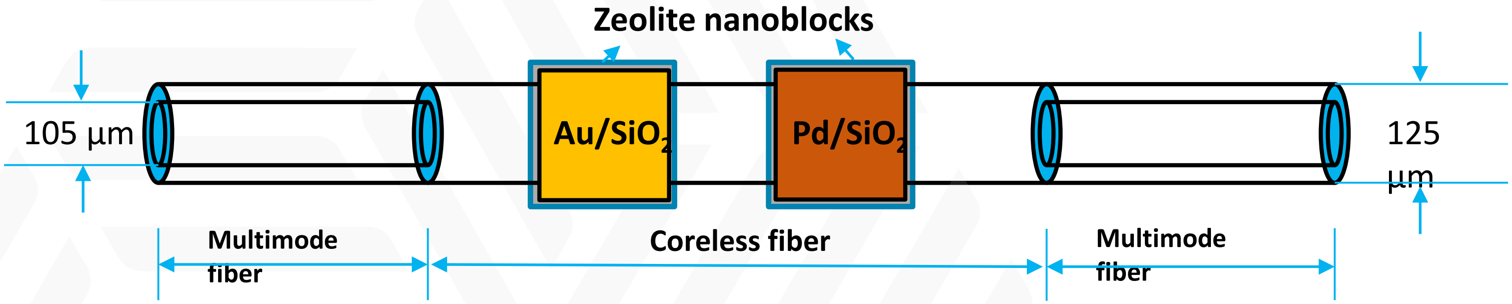
Schematic illustration of transformer oil cooling by air

1. Oil expansion tank
2. Transformer iron core
3. Transformer windings
4. Transformer oil
5. Oil pump
6. Dry cooler
7. Electricity in/out

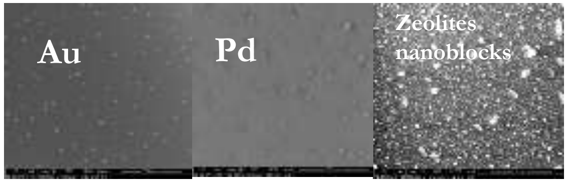


NETL Approach : Functionalized Optical Fibers

- Low-cost Fiber Optic Sensor Array for Simultaneous Detection of H_2 and Temperature



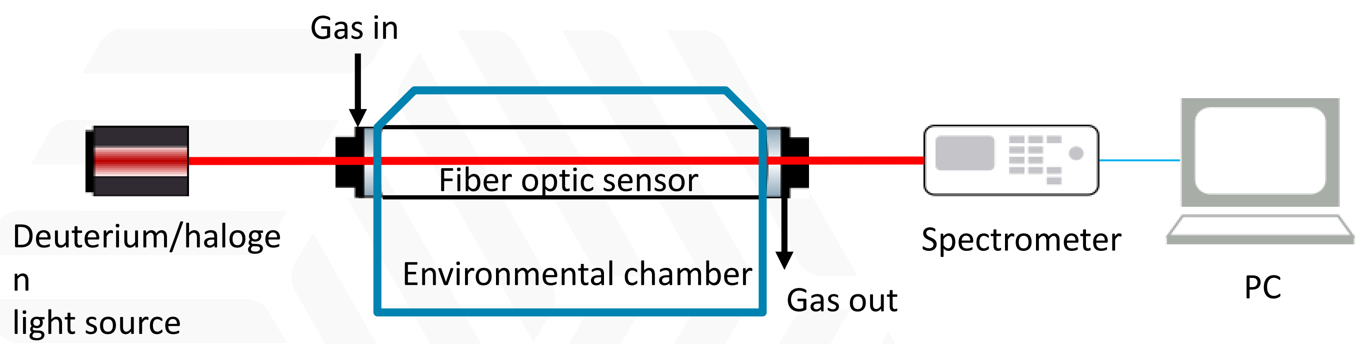
- Pd/SiO_2 and Au/SiO_2 nanocomposites thin film sensing elements.
- Zeolitic filter overlayers to improve selectivity
- Pd/SiO_2 → selective to H_2
- Au/SiO_2 → selective to temperature
- All concepts have been covered in awarded / submitted US patent applications
- Multi-wavelength interrogation enables simultaneous monitoring of T and H_2

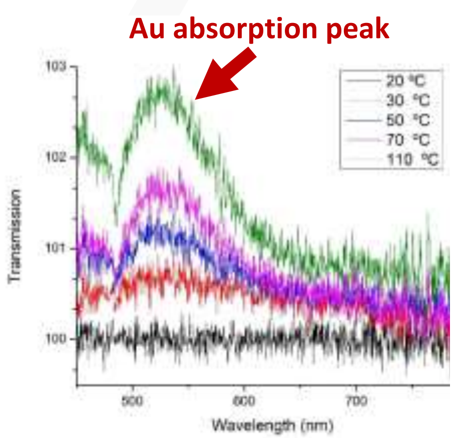


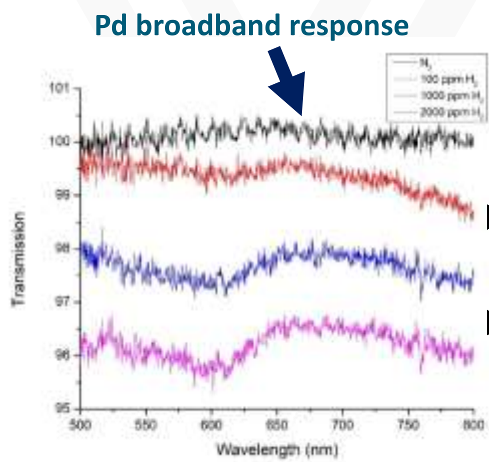
5–30 nm noble metal NPs

Zeolites filter layer

Fiber Optic Sensors: Experimental Setup and Results







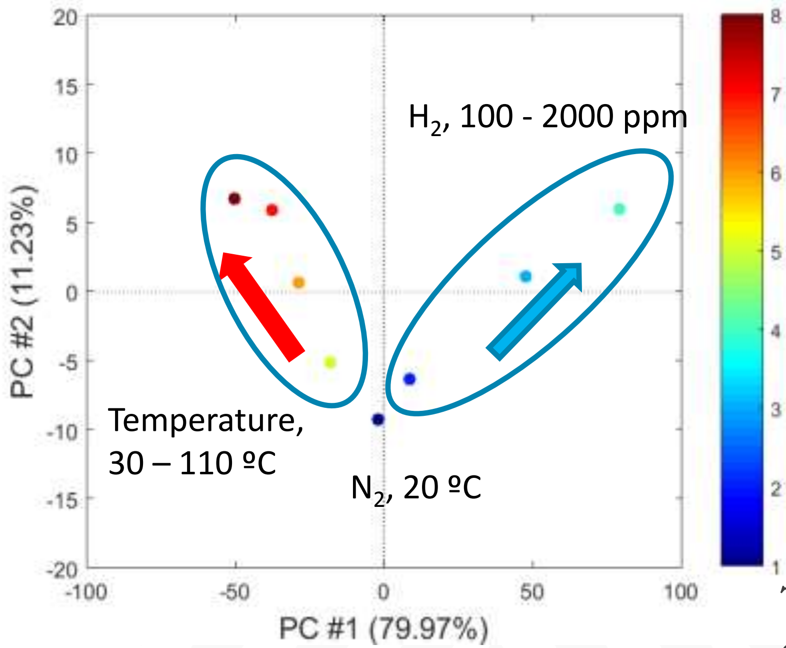
Broadband wavelength interrogation

- Unique wavelength dependences observed in response to Temp. and H_2 for each sensor element.
- Data analytics techniques can discriminate by multiple wavelength interrogation.

Fiber Optic Sensors : Temperature and Gas Dependent Response

Data Analytics: Principle Component Analysis

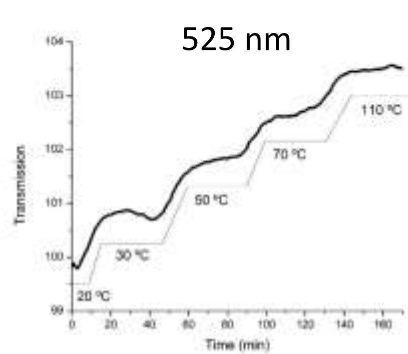
Generalized principle component space

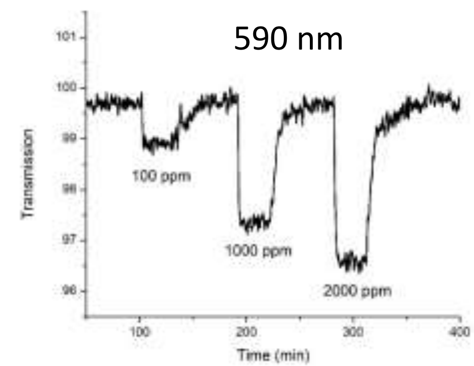


Discrete-wavelength interrogation

enables low cost multi-parameter sensors

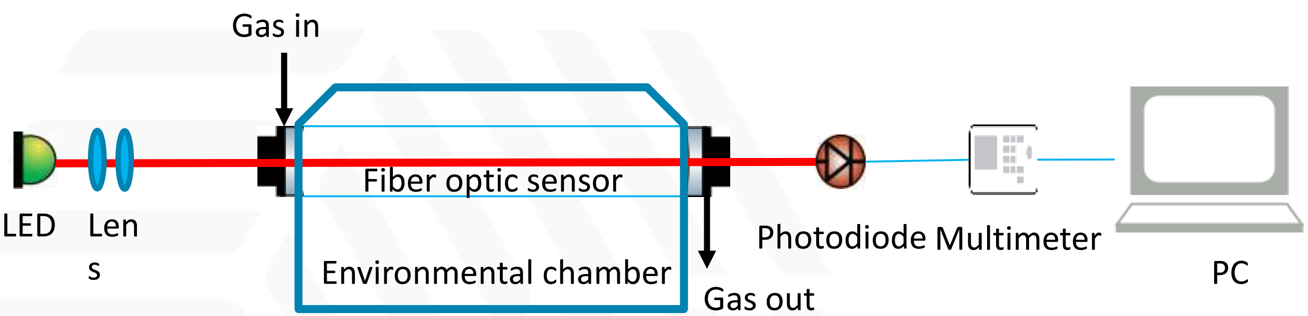
- ➢ temperature between ambient to 110 ºC
- ➢ H_2 between 100 to 2000 ppm at RT

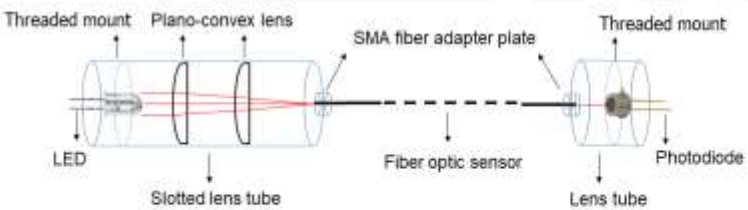




Two dominant principle components (PCs) = two wavelengths can be monitored simultaneously for unique information

Fiber Optic Sensors : Low-Cost Prototype Device Fabrication

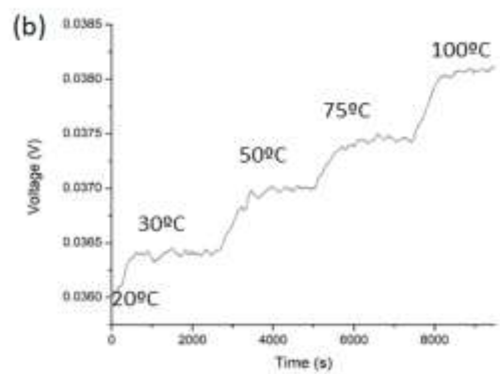


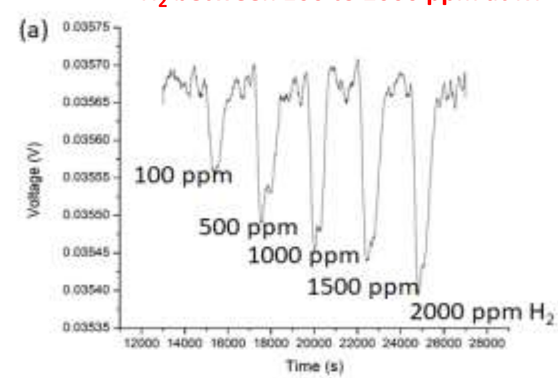


LED Input

Photodiode Output

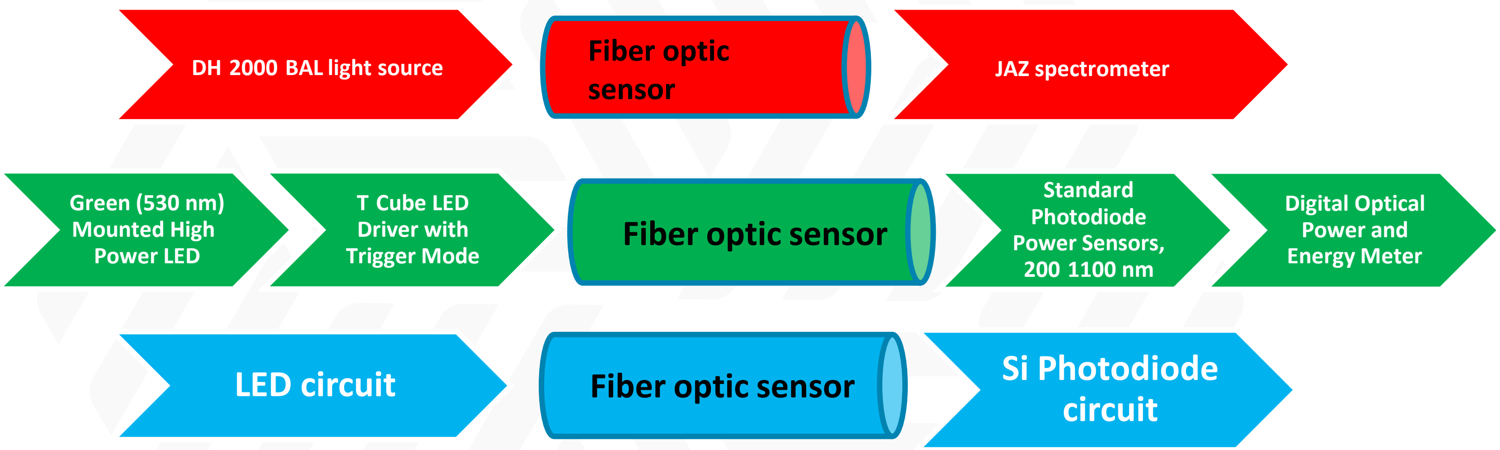
- temperature between ambient to 110 ºC
- H_2 between 100 to 2000 ppm at RT





Fiber Optic Sensors :
Prototype Developments and Cost Reductions

- Low-cost components have been developed to generate robust sensing signals
- Potential applications exist for economical deployment in transformer monitoring systems



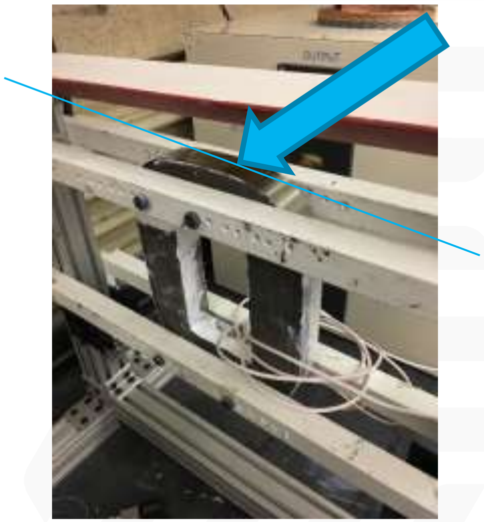
Setup	Cost
Deuterium halogen source + spectrometer	$12,000
Mounted LED + power meter	$2,100
Unmounted LED + photodiode circuit	~$100

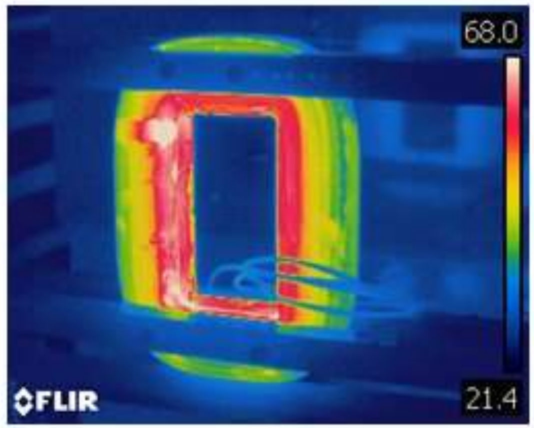
Cost reductions pursued over the project are approaching commercially relevant targets.

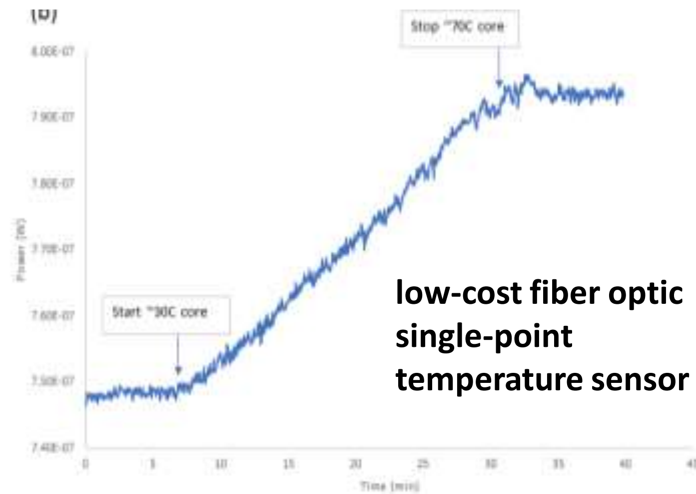
Fiber Optic Sensors : Temperature Monitoring of Transformer Core

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Mounted fiber optic sensor



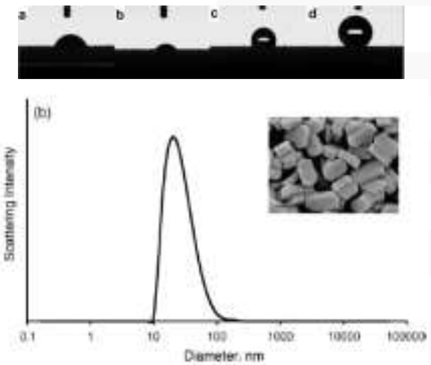




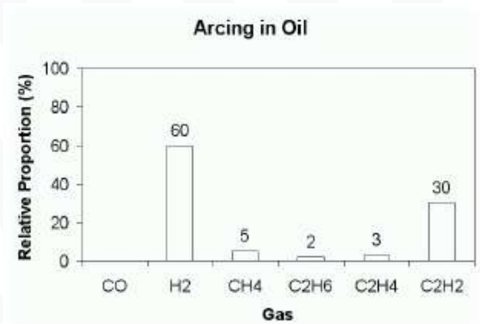
- Au/SiO_2 nanocomposite-based optical fiber sensor mounted on outside face of core
- Monitored real-time temperature change of a high frequency solid state transformer core
- Thermal imaging compared to the optical fiber sensor shows good agreement

Fiber Optic Sensors :
On-going Studies and Future Plans

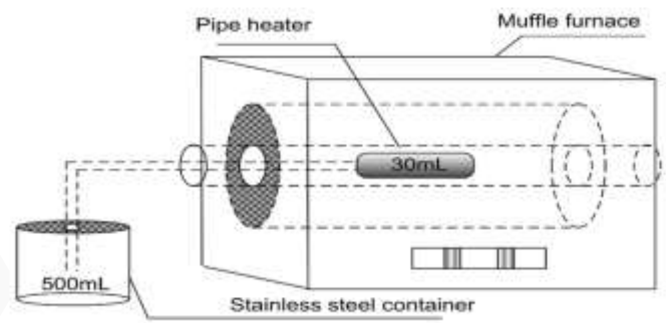
Hydrophobic Filter Layers



Acetylene Produced in Electrical Faults



Simulated Fault Condition Testing



- Explore mitigation of humidity effect on the sensing performance
- Novel materials for DGA-related gas sensing of other gases (e.g. acetylene)
- Testing in gas streams representative of simulated thermal faults
- Deployment internal to an energized distribution transformer

Fiber Optic Sensors: Accomplishments to Date

Advanced Sensor Development Project #1.4.4

- New laboratory facilities have been established for optical fiber based sensor fabrication and testing in conditions relevant for asset monitoring.
- A fiber optic sensor array has been fabricated for simultaneous detection of H_2 and temperature using multi-wavelength interrogation.
- Low-cost optical devices employing off-the-shelf LEDs and photodiodes have been developed for future field deployment efforts.
- Commercial interrogator systems have been used to characterize temperature distributions in operational transformer cores.
- A multi-point optical fiber based temperature sensor has been packaged and tested for energized cores under application relevant excitation conditions.
- Integration and testing in a distribution transformer is planned for the upcoming project year.

GRID MODERNIZATION INITIATIVE PEER REVIEW

1.4.4 ADVANCED SENSOR DEVELOPMENT - T&D

LINGWEI "ERIC" ZHAN, DAN KING, HERRON DREW, HAROLD KIRKHAM, YILU LIU

September 4–7

Sheraton Pentagon City Hotel – Arlington, VA

Advanced Sensor Development
- Transmission & Distribution Sensors

Project Objectives

Extend the resolution of grid visibility and focus on dynamic response and data resolution as well as innovative ways to estimate electrical parameters from optical transducers.

Wide Area Monitoring System (WAMS)

Problems Being Solved

- Slow measurement dynamic response and poor system transients capture. (Emphasized in Chap. 3.3 of DOE MYPP)
- Poor measurement reliability. (Identified and prioritized in GMLC 1.2.5 – Sensing and Measurement Strategy)

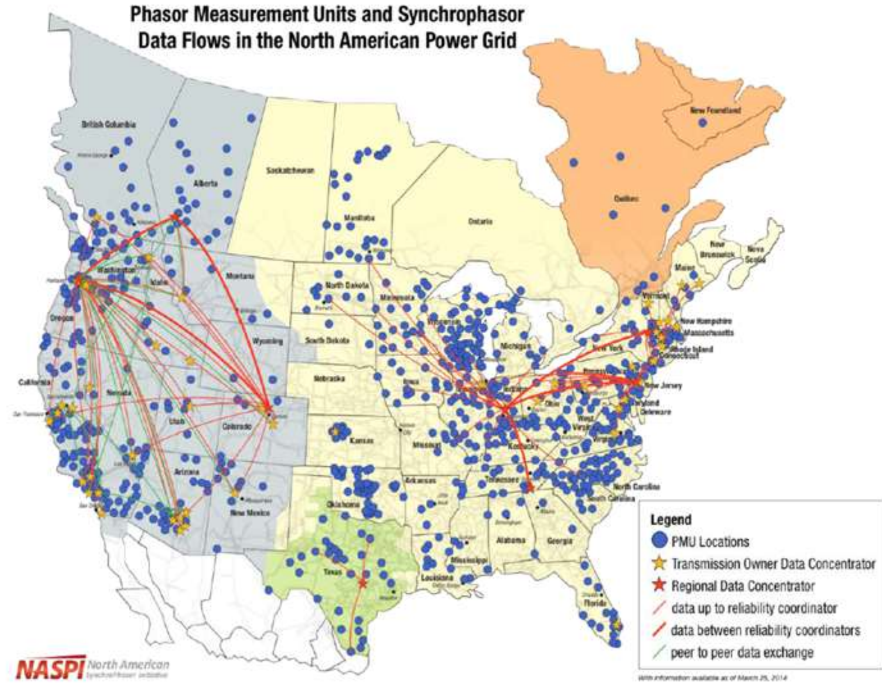
Value

- Improved grid visibility will allow timely and precise grid anomalies detections.
- Ultimately contributes to fast system transients capture, highly reliable 100% grid visibility, and real-time grid control.

Wide Area Monitoring System (WAMS)

- ► Definition: Based on GPS synchronized measurement instrument of Phasor Measurement Unit (PMU) and allow monitoring transmission system conditions over large areas.

- ► Application and benefits:
  - ✓ Situational awareness and wide-area monitoring
  - ✓ Real-time operations
  - ✓ Power system planning
  - ✓ Forensic event analysis



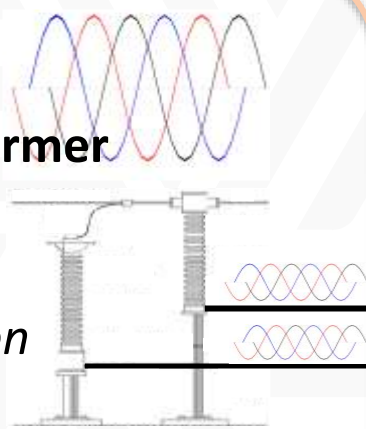
<u>PMU-enabled visibility could have prevented the 2003 Northeast and the 1996 Western blackouts.</u>

Key Issues

Timing

- *Poor timing reliability*
- *Short holdover capability*

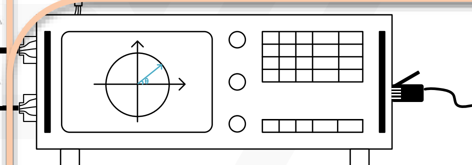
GPS receiver



Instrumental transformer

- *Errors*
- *Non-linearity*
- *Magnetic saturation*

PTs, CTs



PMU

Measurement device

- *Slow dynamic response*
- *Low data rate*
- *Data quality under faults*

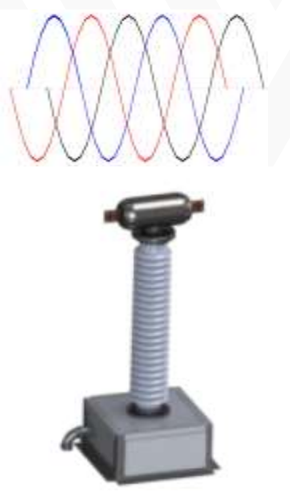
Project Approach and Uniqueness

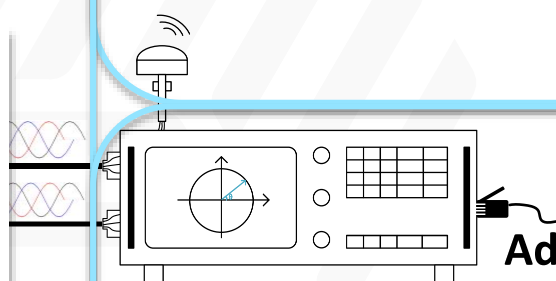
GPS Disciplined Chip Scale Atomic Clock (CSAC)

- *Complementary advantages*
- *High reliability*
- *Ultra high holdover capability*

Optical Transducers

- *Immune to magnetic saturation*
- *High linearity*
- *No temperature sensitivity*





PMU

Advanced Measurement Algorithms

- *Ultra fast response*
- *High steady-state accuracy*
- *High precision sampling*

GPS Disciplined CSAC
- Challenge and Approach

Timing Challenge

- ❖ Frequent GPS signal loss in over 60% of commercial PMUs*
- ❖ GPS holdover capability in commercial PMUs: < 20 seconds

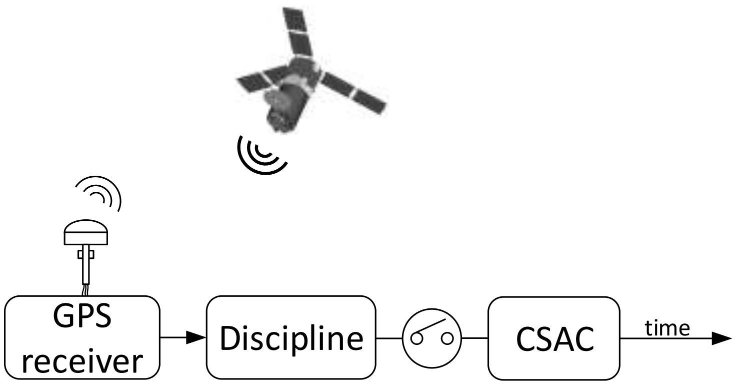
Approach: GPS disciplined CSAC

If GPS is available:

GPS continuously disciplines CSAC

else:

CSAC operates in standalone mode



* W. Yao, et al., "Impact of GPS signal loss and its mitigation in power system synchronized measurement devices", *IEEE Trans. on Smart Grid*, 2016.

GPS Disciplined CSAC
- Performance and Impact

Performance:

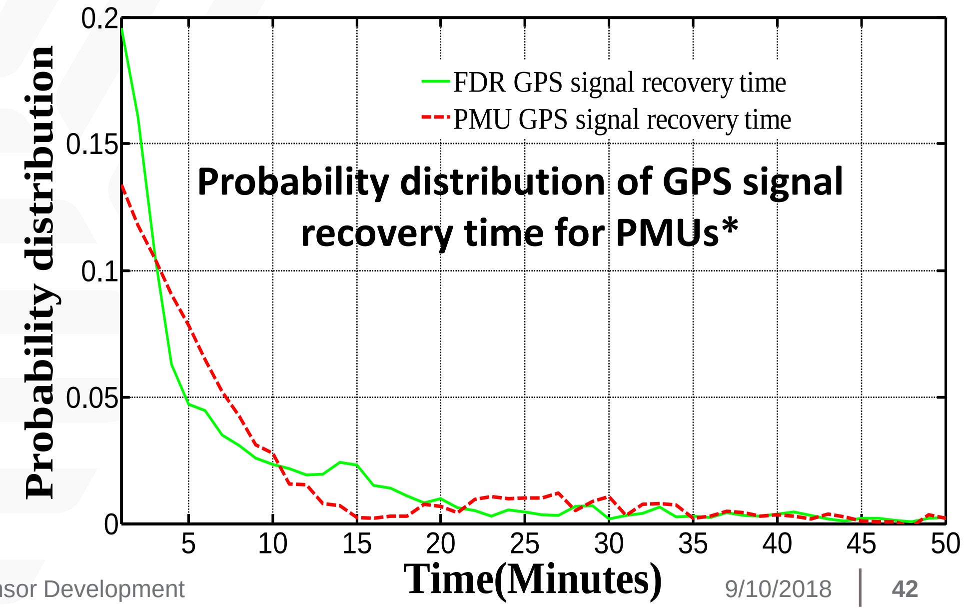
- Holdover capability improved by three orders of magnitude.
- Measurement errors are ignorable in 12 hours after GPS signal is lost.
- GPS receivers rarely lose GPS signal over 12 hours.

Impact:

- ***Tremendously mitigate the impact of timing loss on grid measurements.***
- ***Grid measurement reliability will be significantly improved.***

Experimental Results

	GPS disciplined CSAC	GPS only
1 us holdover capability	12 hours	~10 seconds
Phase angle error in 12 hours	0.0216 degree	~90 degree
Time to exceed 1% TVE (IEEE Std. requirement)	~13 days	~5 minutes



* W. Yao, et al., "Impact of GPS signal loss and its mitigation in power system synchronized measurement devices", *IEEE Trans. on Smart Grid*, 2016.

Advanced Measurement Algorithms
- Measurement Challenge and Approach

Challenge

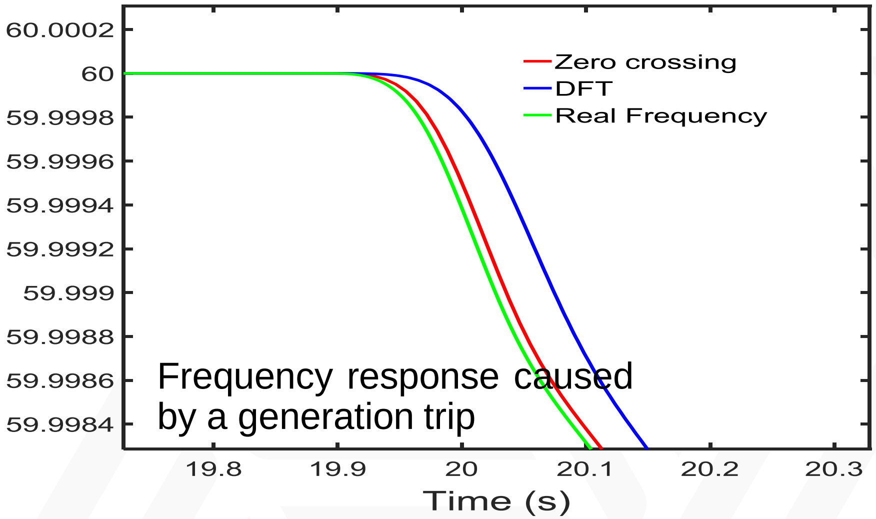
- Existing measurement algorithms are slow to measure system transients.
- System transients capture is at the cost of measurement accuracy.

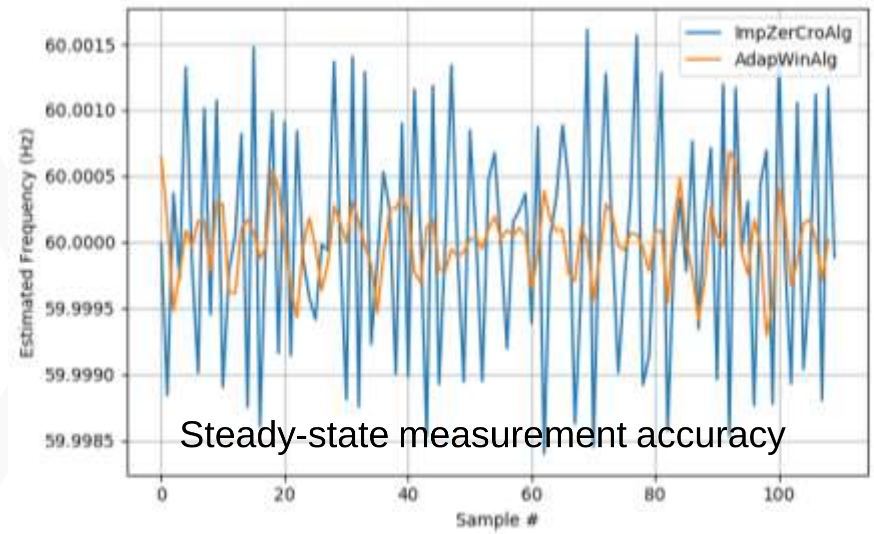
Approach: ultra-fast + adaptive window algorithm

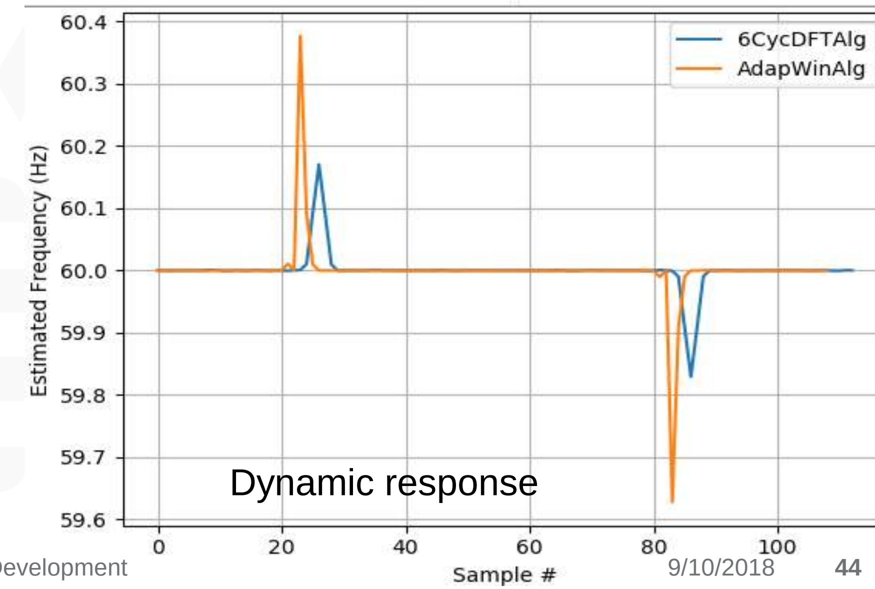
- Ultra-fast one cycle algorithm to capture system transients.
- Adaptive window algorithm to maintain measurement accuracy.

Adaptive window algorithm

Advanced Measurement Algorithms
- Measurement Performance and Impact







Performance:

- Ultra-fast algorithm captures system transients fast in one-cycle.
- Adaptive window algorithm achieves both fast dynamic response and high measurement accuracy.

***Impact:* Outperforms existing algorithms and allows timely grid protection and stability control (i.e. first swing stability).**

Optical Transducers
- Challenge of Magnetic Transducers and Approach

Challenge

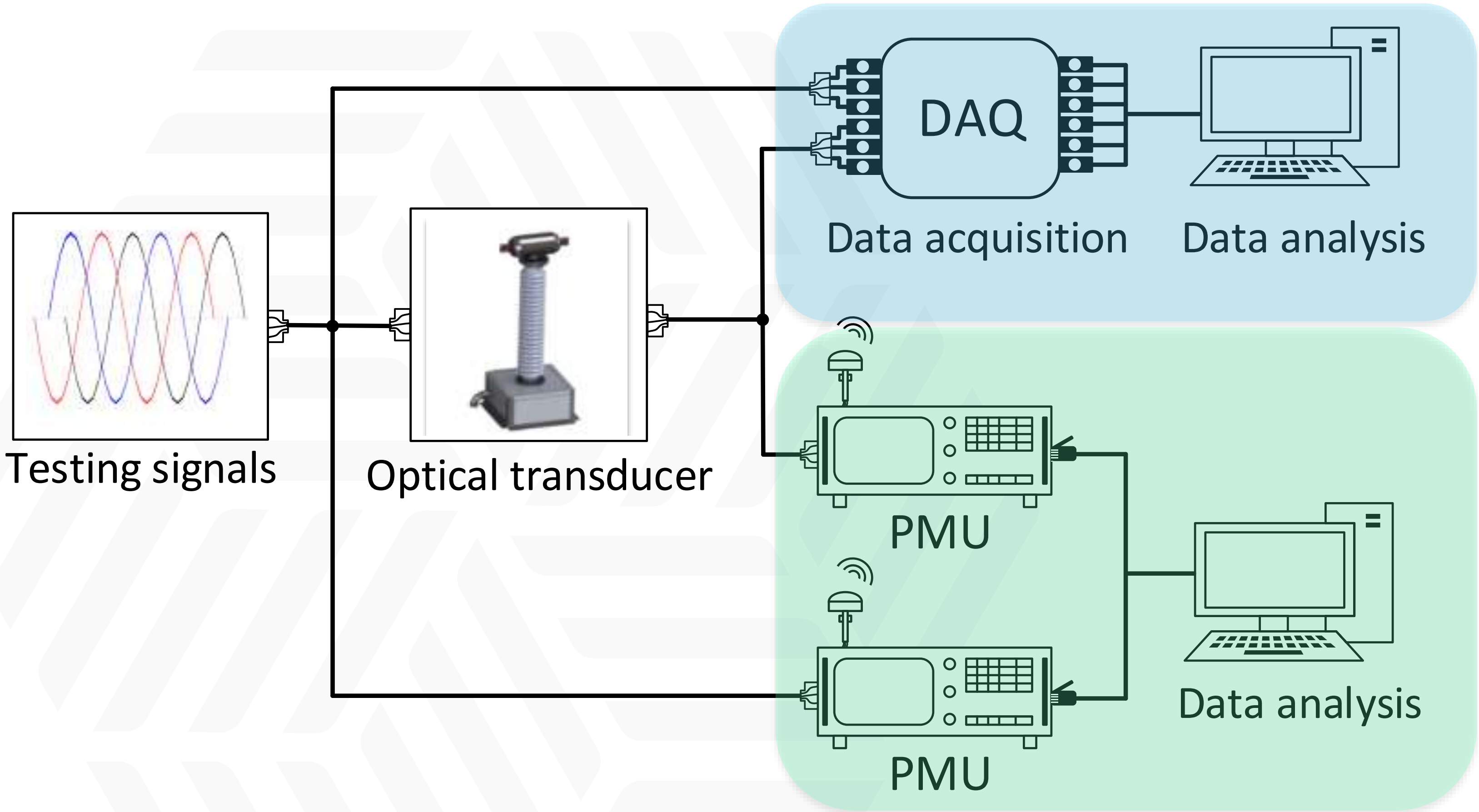
- Existing magnetic transducers (potential transformers (PTs) and current transducers (CTs) have poor linearity, magnetic saturation, etc.
- Optical transducers are believed to be the future of electric grid but less user familiarity, lack of successful demonstration, etc.

Approach: Improve grid measurement accuracy with optical transducers and demonstrate its linearity for system transients capturing.

- Developed optical transducer testbed.
- Tested and evaluated the performance of optical transducers in synchrophasor measurements.
- Demonstrate the advantages of optical transducers over magnetic transducers. (i.e. linearity for transient capturing.)

Optical Transducers

- Optical Transducers System Testbed

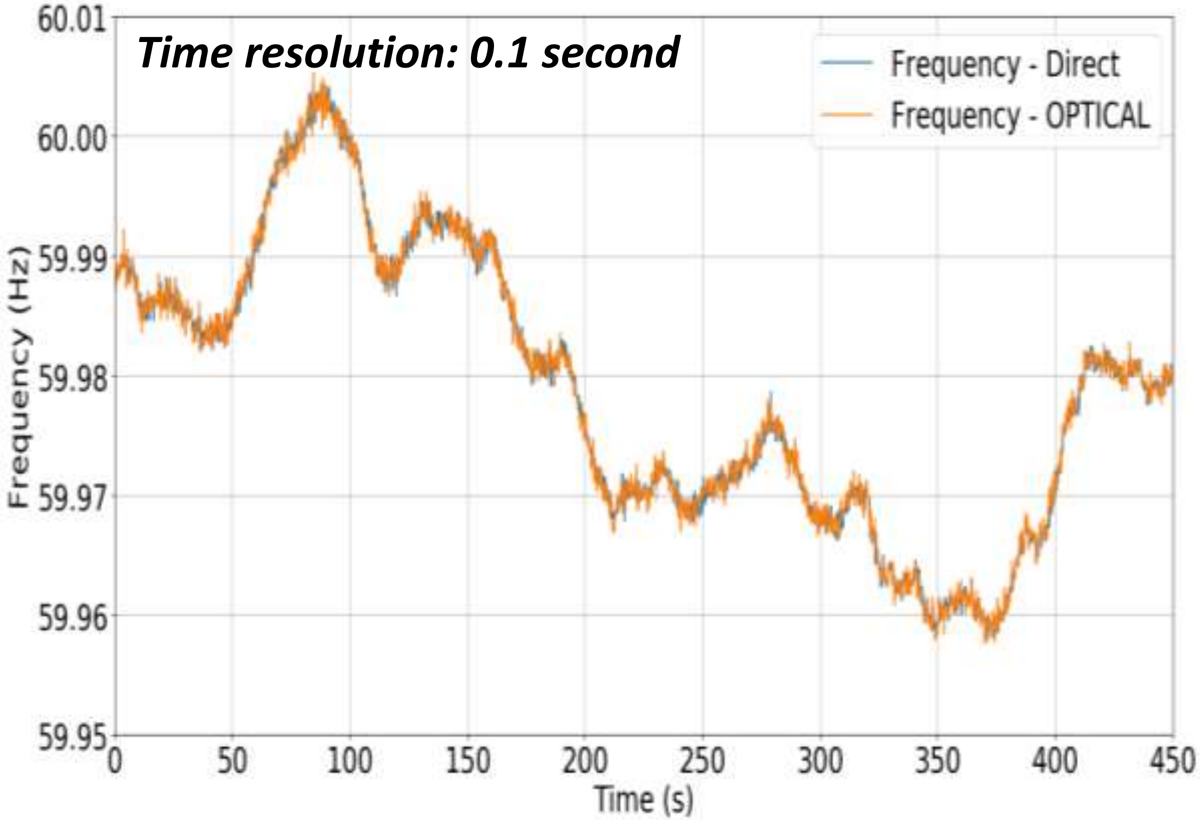


Optical transducers system testbed

Optical Transducers
- Performance and Impact

Performance and Impact:

- ❖ Electric power system frequency measured through optical transducers matched well with the frequency measured directly.
- ❖ Demonstrated the optical transducer for the first time in high-accuracy grid measurement.
- ❖ Laid a good foundation for next step research to demonstrate its advantages over magnetic transducers.



Frequency – Direct: frequency measurements by PMU w/o optical transducer
Frequency – OPTICAL: frequency measurements by PMU with optical transducer

Project Accomplishments to Date

- Improved reliability of grid measurements with the GPS disciplined Chip Scale Atomic Clock (CSAC) method.
- Developed a suite of measurement and sampling algorithms to achieve fast and accurate grid measurements.
- Developed optical transducer testbed and demonstrated good measurement performance.
- A patent disclosure “a method to generate high precision and time synchronized pulse” was filed. A patent will be filed.
- The team won R&D 100 Awards Finalist for the work of “Mobile Universal Grid Analyzer”.
- Published a journal paper “utilization of optical sensors for phasor measurement units” in the journal of Electric Power Systems Research.

Next Steps and Future Plans

- Experiments and validation of the advanced measurement algorithms in PMUs.
- Demonstrate the grid measurement accuracy improvement (i.e. system transients non-linearity capturing) by using optical transducers.
- Demonstrate the advantages of optical transducers over magnetic transducers by performing A/B testing.

Contact Information

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Publications

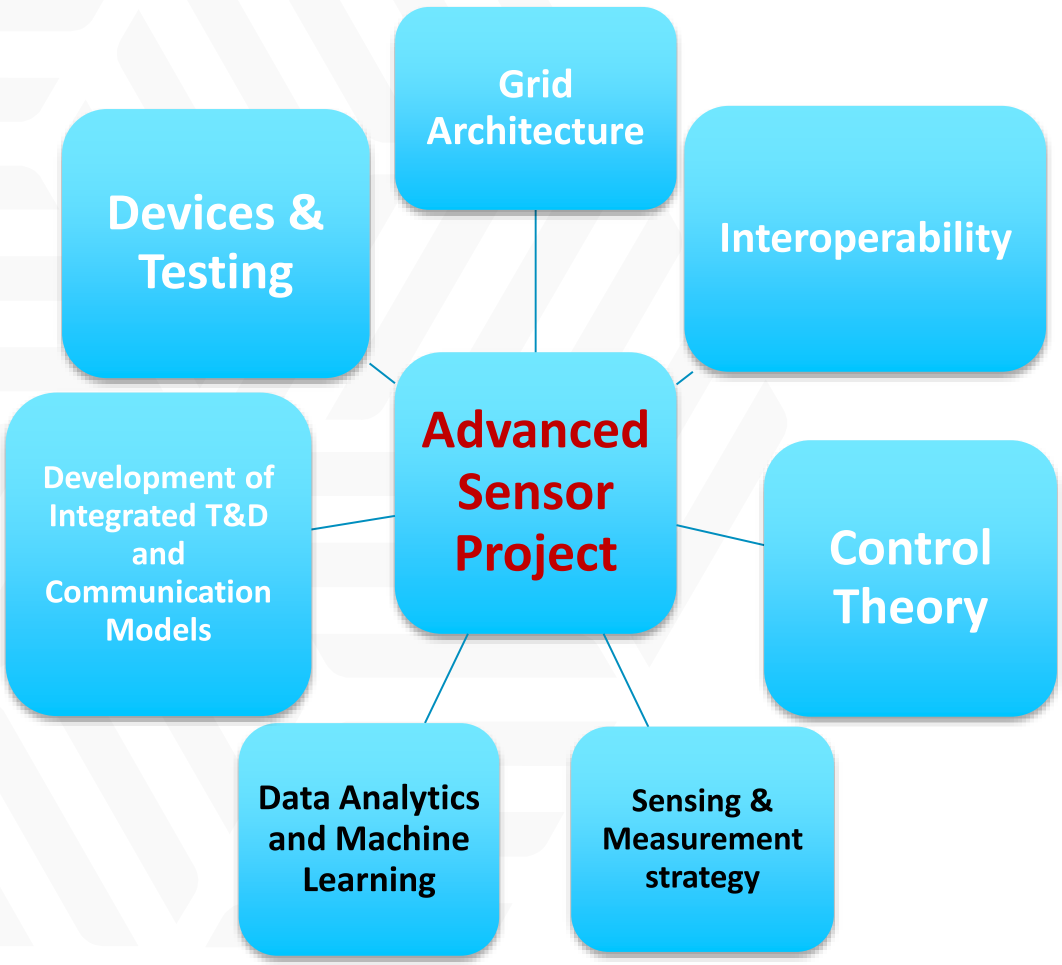
Publications:

- Low-cost fiber optic sensor array for simultaneous detection of hydrogen and temperature. C Sun, P Lu, R Wright, PR Ohodnicki. Proc. SPIE, Fiber Optic Sensors and Applications XV 10654, 1065405, 2018.
- Double-Layer Zeolite Nano-blocks and Palladium-based Nanocomposite Fiber Optic Sensors for Selective Hydrogen Sensing at Room Temperature. C Sun, PR Ohodnicki, Y Yu. IEEE Sensors Letters 1 (5), 1-4, 2018.
- Chemical Sensing Strategies for Real-time Monitoring of Transformer Oil: A Review. C Sun, PR Ohodnicki, EM Stewart. IEEE Sensors Journal 17 (18), 5786 – 5806, 2017.
- Cruickshank, Robert F., et al. "Characterizing Electric Grid System Benefits Of Mpc-Based Residential Load Shaping." *2018 Building Performance Analysis Conference and SimBuild.* ASHRAE and IBPSA-USA, 2018.
- Ueno, Tsuyoshi, Marco Pritoni, and Alan Meier. "Using Data from Connected Thermostats to Track Large Power Outages in the United States." In *Proceeding of Annual Society Conference of the Institute of Electrical Engineers of Japan*, Division of Electronics, Information and Systems, IEEJ, 2018.
- Cruickshank, Robert F., et al. "Empirical Investigations of the Opportunity Limits of Automatic Residential Electric Load Shaping." *2017 Ninth Annual IEEE Green Technologies Conference (GreenTech)*. IEEE, 2017.
- Cruickshank, Robert F., et al. "Quantifying the Opportunity Limits of Automatic Residential Electric Load Shaping." *IEEE Transactions on Industry Applications*. (In Review)
- Wang, Fei, et al. "Clustering of Residential Load Patterns Based on an Improved Gravitational Search Algorithm." *IEEE Transactions on Smart Grid*. (In Review)
- Yao, Wenxuan. (2017). Utilization of Optical Sensors for Phasor Measurement Units. Electric Power Systems Research. 156. 10.1016/j.epsr.2017.11.004.
- "Optimized Co-Fe-B and Co-Fe-P Alloy Films for Electroformed Resonators" Jamin Pillars, Eric Langlois, Christian Arrington, Isaac Dyer, Patrick Finnegan, Christopher St. John, Todd Monson, presented at Electrochemical Society conference, 10/7/16
- "Cobalt-Iron-Manganese Electrodeposition for High Performance Magnetoelastic Resonators", J. R. Pillars, E. D. Langlois, C. L. Arrington, and T. C. Monson, prented at Electrochemical Society conference, 10/4/18

Patents and Disclosures

- Palladium and platinum-based nanoparticle functional sensor layers and integration with engineered filter layers for selective H2 sensing. PR Ohodnicki, C Sun, JP Baltrus, TD Brown. US Patent App. 15/641,193, 2017.
- Palladium and platinum-based nanoparticle functional sensor layers for selective H2 sensingPR Ohodnicki, JP Baltrus, TD Brown, US Patent 9,696,256 (2018).
- Nanocomposite thin films for optical temperature sensingPR Ohodnicki, TD Brown, MP Buric, C Matranga, US Patent 9,568,377 (2017).
- S-138,534, Joshi, Pooran, et al.: "High-Performance Airflow Sensor Exploiting 2D/3D Manufacturing Techniques for Energy Efficient Smart Buildings." 2017.
- S-138,775, Joshi, Pooran, et al.: "Flexible Current Sensor for Load Monitoring to Enhance Building Energy Efficiency and Grid Reliability." 2018.
- ORNL No. 3763, "Gas Sensors Enabled by Phase-Separated Nanostructured Metal-Oxide Thin Films',
- ORNL No. 3764, "'Innovative three-dimensional nanostructured thin film scaffolds for gas sensors'
- DOE S-138,823, L. Zhan, et al., "A method to generate high precision and time synchronized pulse", disclosure failed

Project Coordination with related GMLC Activities



Questions/Comments

BACK UP SLIDES

Significant Milestones

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. − Achieved 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 of 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 ultrafast and adaptive window algorithms. Successfully captured system transients while maintaining high measurement accuracy. − Developed high-precision data synchronization algorithm and demonstrated GPS disciplined Chip Scale Atomic Clock timing method. Provides 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: - Demonstrated the performance of SAW sensors to meet design specification. Deployed physical sensors in ORNL flexible research platforms with ground truth measured using calibrated sensors. - Demonstrated the performance of MagSense sensors to meet design specification. Validated process repeatability, which is capable of detecting currents in the 1–1000 A range. - Demonstrated the performance of optical fiber sensors for detection of transformer performance degradation and temperature deviations.	07/31/2018

GRID MODERNIZATION INITIATIVE PEER REVIEW
1.4.4 ADVANCED SENSOR DEVELOPMENT
END-USE

POORAN JOSHI, ALAN MEIER, ANTHONY FLORITA

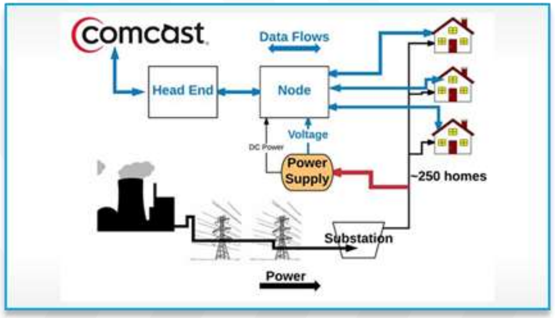
September 4–7, 2018

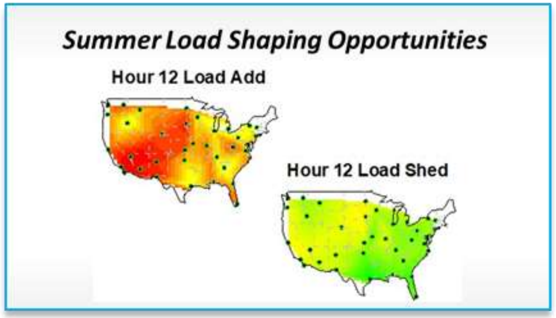
Sheraton Pentagon City Hotel – Arlington, VA

Advanced Sensor – End Use Accomplishments to Date

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description: Fundamentally revolutionary technologies that are inherently low-cost are required to increase visibility in End-Use Systems, such as Buildings. Advanced sensors and controls will enable enhanced controls of smart building loads and distributed energy resources to be "grid friendly."





Low Cost Sensors

Develop low-cost sensors, exploiting additive manufacturing techniques, to monitor the building environment

Developed a flexible current sensor hardware using a combination of direct-write printing and 3D additive manufacturing techniques. Battery operated sensor unit incorporates in-field calibration capability.

Internet-Connected Devices to Track Power Outages

Internet-connected devices (such as modems and thermostats) to act as sensors

Demonstrated that the thermostat (and cable box) networks could provide consistent national grid reliability data which could be used to track the Improvement of the smart grid. This data could be available almost immediately and at a low cost.

Buildings as Sensors

Load-side data analytics for Autonomous Grids, including load flexibility, state estimation, and forecasting applications

Feasibility of computational approach established: Co-simulation of tens-of-thousands of residential homes, thousands of distribution grid feeders, and hundreds of generators and their supporting transmission-scale infrastructure is feasible.

ENERGY

End-Use Team Focus

Objective

(1) Develop low-cost sensors, exploiting additive manufacturing techniques, to monitor the building environment and electrical characteristics of HVAC equipment

(2) Develop algorithms to use building-level data to provide utility-scale visibility of grid reliability and localized weather monitoring.

Roles

- ***ORNL**:* Low-cost sensors driven by advanced manufacturing technology to enable end-use observability
- ***LBNL**:* Wide-area outage monitoring using internet connected end-use loads in partnership with original equipment manufacturers
- ***NREL**:* Utilize weather correlated building load activity as sensors to facilitate utility-scale load shape estimation for planning ancillary services

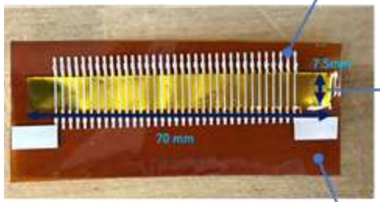
Direct-Write Printing to Realize Low-Cost Sensors (1/5)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Low Cost Electrical Current Sensor Concepts

1. Motivation
   - Buildings consume 74% of electricity.
   - Economical electric current measurements are necessary to enable building loads as grid resources.
2. Technology - A current transformer approach was determined that is compatible with low cost manufacturing techniques.
3. Progress
   - Direct-write printed sensor and prototype sensing hardware designed to test various coil designs, sensing algorithms, as well as to allow data collection in the field.
   - In the present configuration, the low-cost printed current sensor unit can be powered through USB or 4 AAA batteries to allow data collection and sensor calibration in the field.

Printed Sensor



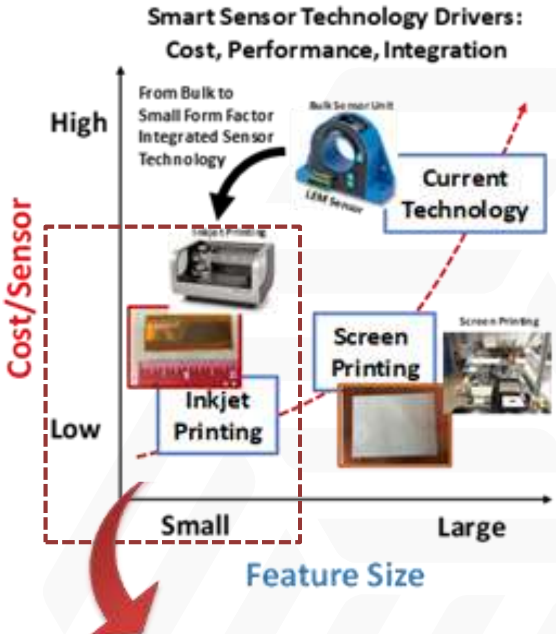
Flexible Prototype

Battery Driven Prototype

3D Printed Enclosure

Complete Prototype Hardware

Low-Cost Sensor System Using 3D Additive Manufacturing Techniques (2/5)



Flexible Current Sensor Development: Core Components

- Flexible Substrate
- Thin Permalloy
- Printed Conductor
- Integrated Prototype
- Performance Evaluation

Core Enabling Components	Key Characteristics
Flexible Substrate	Polyimide sheets: **7.5-100µm**
Permalloy	Thickness: **12.5µm**, Permeability>60,000
Direct-Write Conductor	Additive Printing: Line-width control ~**10µm**

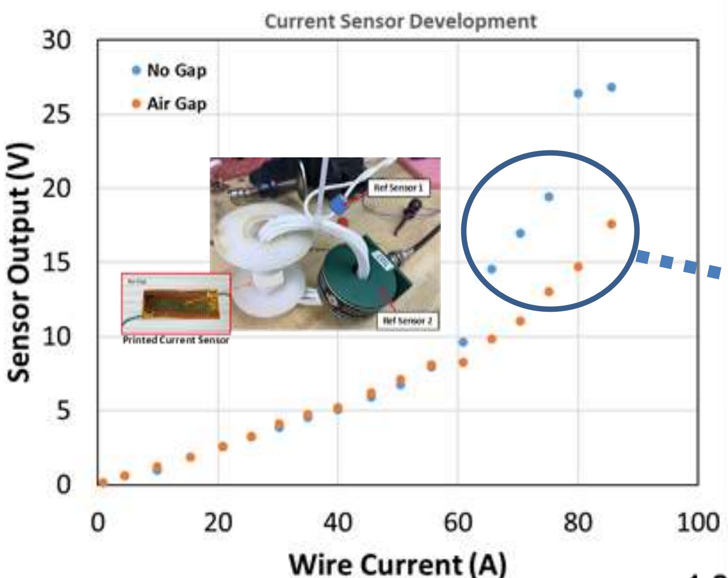
Prototype Hardware Capabilities

- Signal generator for in-field calibration
- microSD card slot for data collection
- Keyboard and Display to facilitate user interaction and real-time display
- Powered through USB or 4AAA batteries, coin cell to maintain internal RTC

Prototype Hardware

3D Printed Enclosure

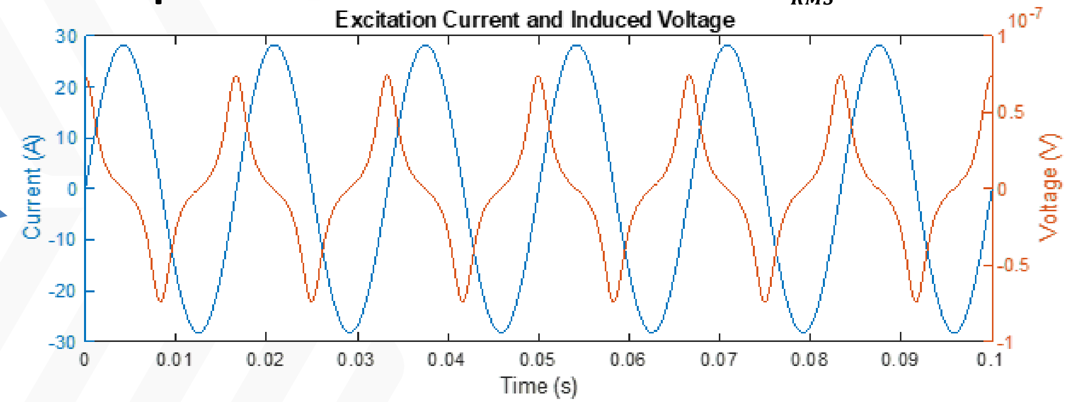
Low-Cost Sensor Design and Performance Consistent with Model (3/5)



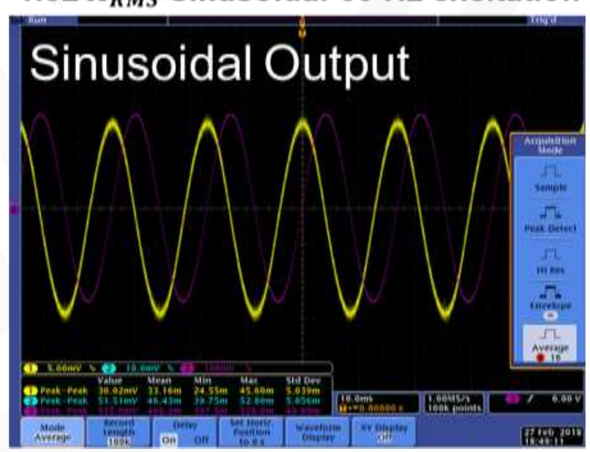
Model Development

$$v_s = \frac{d\Phi}{dt} = \mu_c \rho A_c \frac{di}{dt}$$

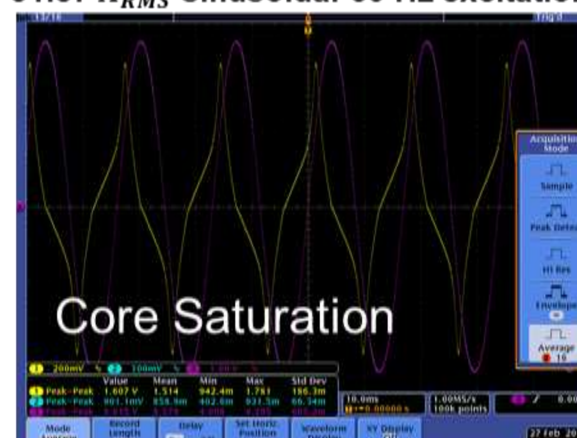
$\mu_{c,r} = 60000$,
$B_{SAT} = 0.77\ T$,
$\rho = 164.5\ turns/m$.
$20\ A_{RMS}$ excitation



1.82 A_{RMS} sinusoidal 60 Hz excitation



31.87 A_{RMS} sinusoidal 60 Hz excitation



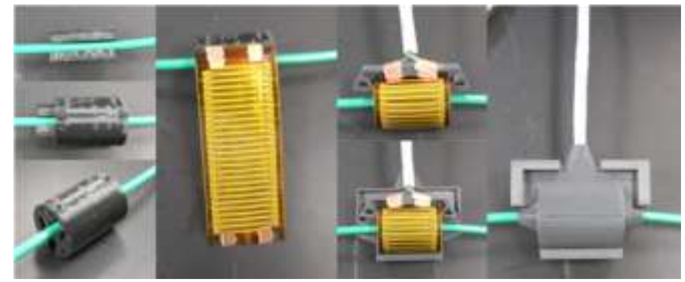
- Linear Sensor Response at least up to 50A peak-to-peak ac current
- Design flexibility employing direct-write printing technique

Low-Cost Portable Sensor System: Battery Operated with In-Field Calibration Capability (4/5)

Field Portable Current Sensor Unit Accommodating Different Wire Gauges

3D Printed Part

Installation of Sense Coil onto a Conductor



In-field Coil Calibration Capability

In-field Coil Calibration Capability

- 3D printed fixture slides directly into the loop for testing
- Known current through sense loop is generated for in-field calibration
- Unit can account for changes in power supply voltage, manufacturing tolerances, and design changes

Low-Cost Portable Sensor System: On-going Studies and Future Plans (5/5)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Next Step

- Performance evaluation in ORNL Flexible Research Platforms (FRPs)
- Establish scenarios for field portable current source for test and calibration
- Extend performance range through modeling, design, and direct-write printing

Flexible Research Platform (FRP) Installation

Integrated Prototype Characteristics

- Direct-write Flexible Sensor
- 3D Printed Enclosure
- USB/Battery Powered
- Data Storage
- In-field Calibration

Contact: Pooran Joshi, ORNL | joshipc@ornl.gov, 865-576-4718

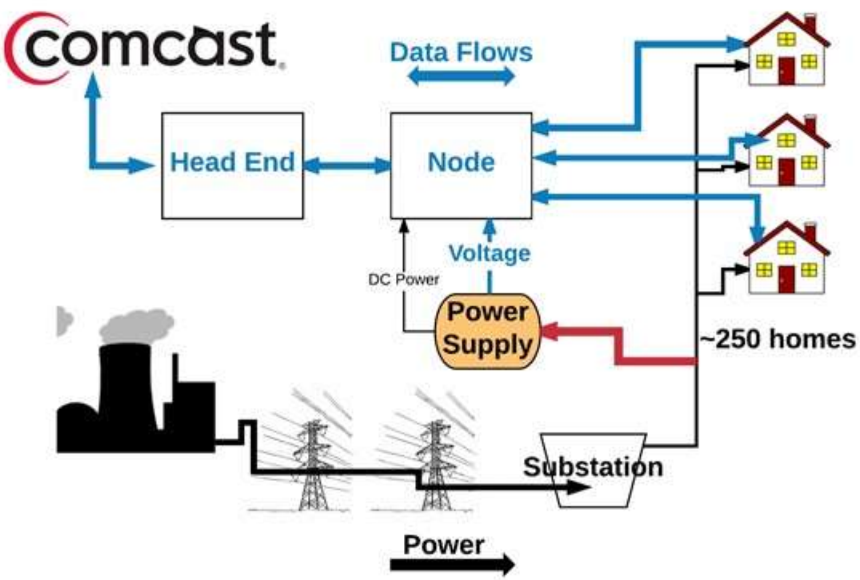
Using Interconnected Devices to Track Power Outages – (1/7)

GRID MODERNIZATION INITIATIVE U.S. Department of Energy

Tracking Power Outages with Internet-Connected Devices

Goals

- Demonstrate that existing Internet-connected devices can give grid authorities enhanced, real-time visibility during outages or cyber attacks
- Develop algorithm to distinguish between power outages and network outages
- Develop tools to track outages and grid status



Data and energy flows in cable TV network

Status

- Worked with cable boxes to demonstrate feasibility of outage tracking
- Developed algorithms to distinguish power outages from data network outages
- Obtained and evaluated 5-minute thermostat data from 20,000 homes across USA
- Developed procedures to identify power outages and applied to recent major outages

Project Retrospective*: *Tracking Power Outages with Internet-Connected Devices*

This project's goal was to demonstrate and commercialize a method for tracking power outages using Internet-connected devices. The project was a qualified success. Comcast adopted our idea and algorithms and converted them into a product to give utilities real -time visibility into outage conditions. However, Comcast was unable to sell the service to utilities because they typically obtained services from vendors of "Outage Management Systems (OMS)". Comcast then sought to sell this service to OMSs. Unfortunately, these vendors preferred to rely on their own, often fragmented, detection procedures. LBNL continued to work with Comcast on alternative solutions but has been hampered by data privacy and regulatory concerns.

In parallel, LBNL obtained 5-minute data from Ecobee thermostat's "Donate Your Data"(DYD) program for 30,000 homes around the USA. We showed that this thermostat network had sufficient density to accurately track outages caused by hurricanes and other major weather events and to supply actionable information to grid operators, emergency management authorities, and insurance companies.

Finally, we demonstrated that the thermostat (and cable box) networks could provide consistent national grid reliability data which could be used to track the Improvement of the smart grid. This data could be available almost immediately and at a low cost.

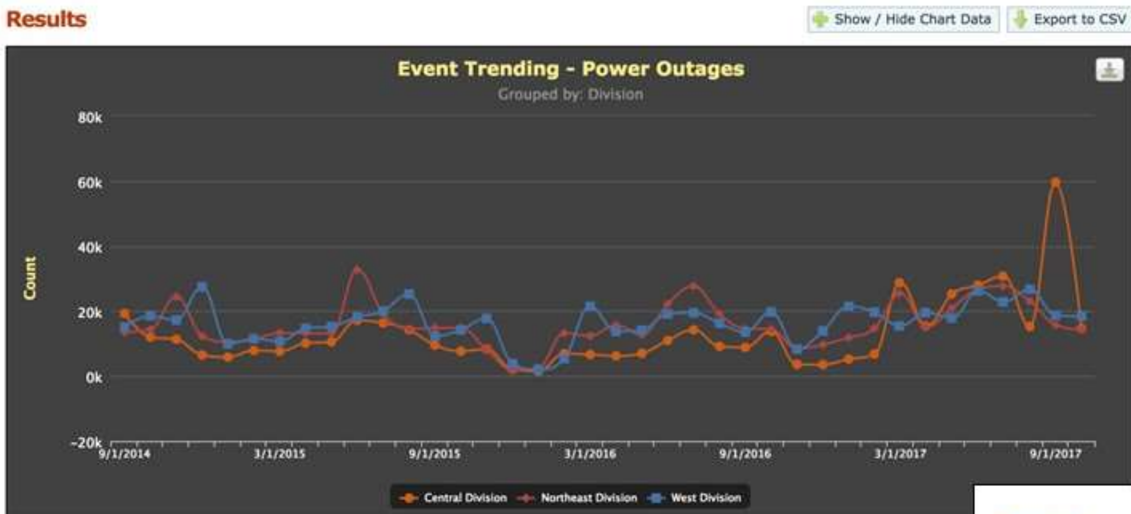
This project also Identified a potentially more valuable source of grid health data: the neighborhood cable TV node. These nodes offer a highly granular–groups of 150 homes–view of voltage (and potentially other grid characteristics). With NREL, LBNL submitted a proposal to develop this sensor but GMLC ultimately decided not to fund it.

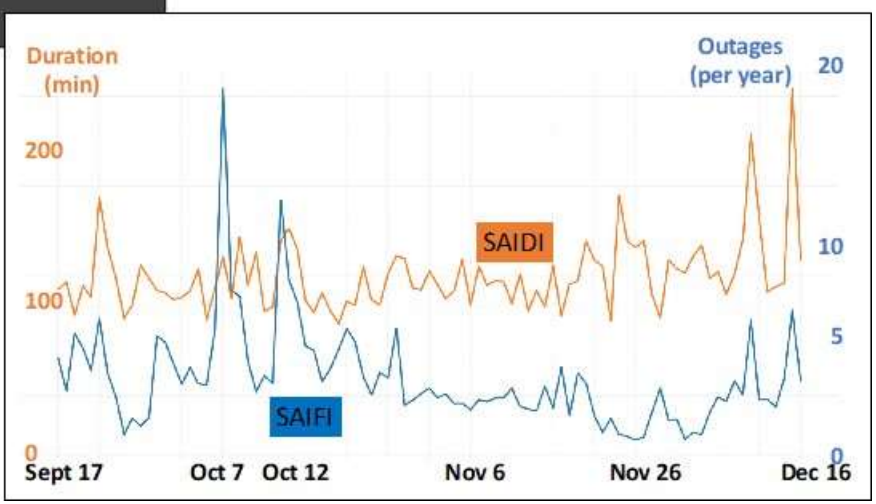
Through this GMLC-supported research., we successfully introduced Comcast, ecobee, Nest, and other firms to new applications of their products as grid sensors. At least one will pursue further opportunities.

*This project was incompletely funded in the second year and terminated in Year 3.

Using Interconnected Devices to Track Power Outages – (3/7)

Comcast Used LBNL Algorithms to Estimate Outages and SAIDI/SAIFI



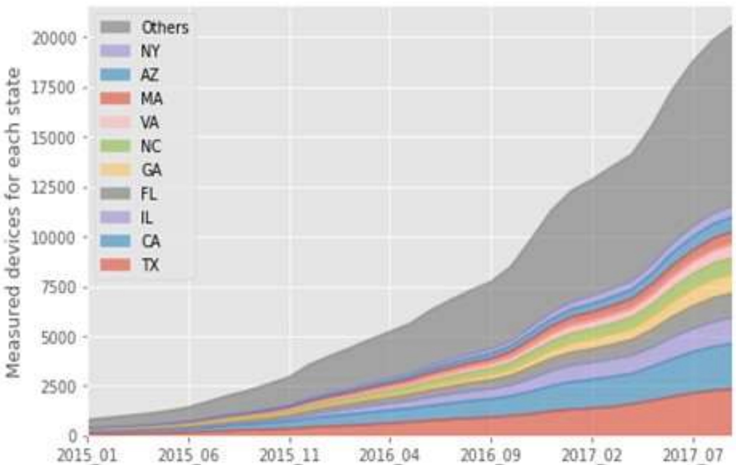


BERKELEY LAB

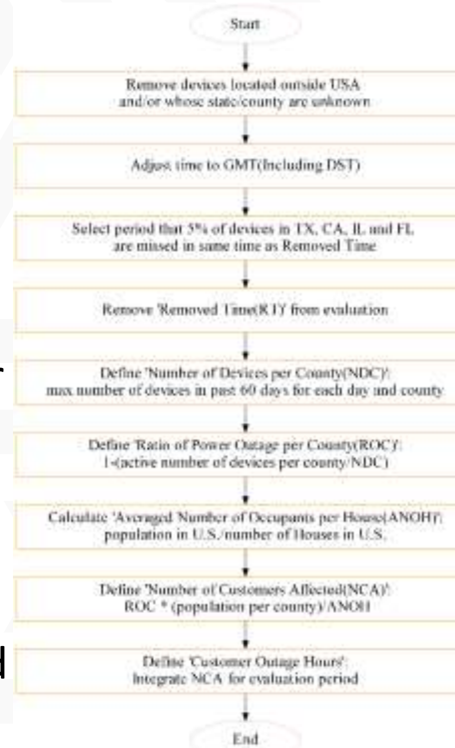
Using Interconnected Devices to Track Power Outages – (4/7)

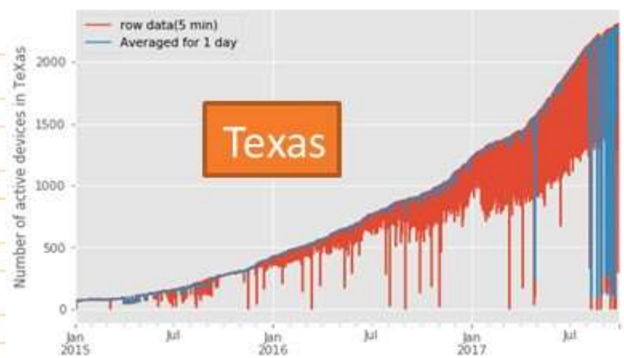
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

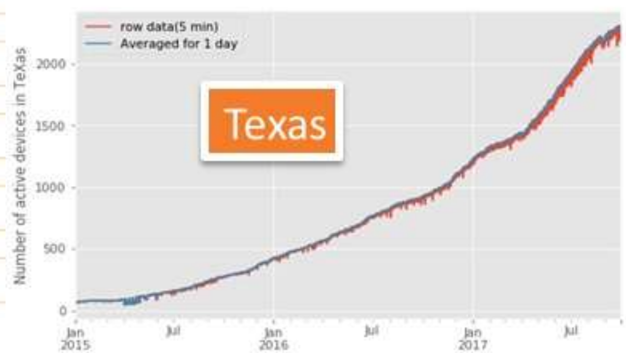
The "Donate Your Data" Data Set



We developed procedures to remove data outages in order to identify power outages.







Ecobee customers may "donate" their data for research

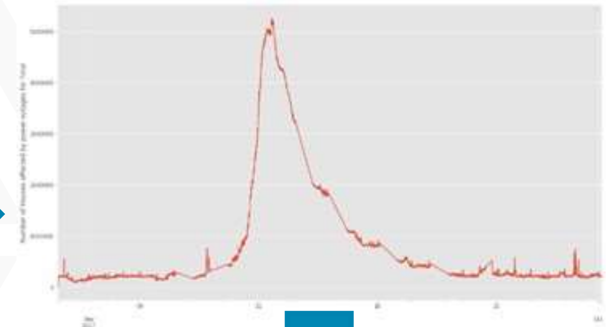
Program started program in January 2015 and participation is growing exponentially.

Updated analysis will probably exceed 50,000 devices.

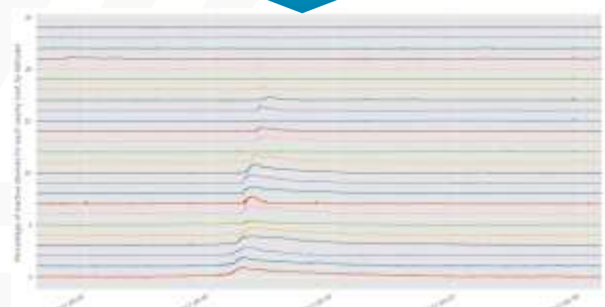
Using Interconnected Devices to Track Power Outages – (5/7)

Tracking Power Outages from Hurricane Irma

Path of Hurricane Irma

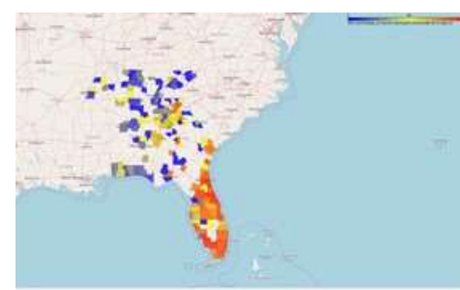


Disconnected (and then re-connected) thermostats during Hurricane Irma



Fraction of disconnected thermostat by county, stacked south-to-north. Note time progression.

Maximum number of disconnects in each county

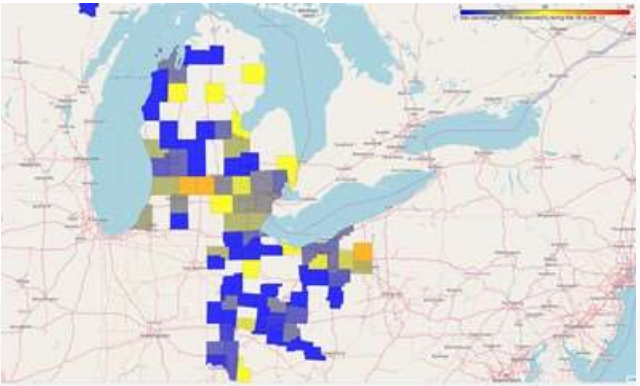


About 1000 thermostats in Florida acted as outage sensors during Irma’s passage. They stopped transmitting when the power failed and began transmitting when power was restored.

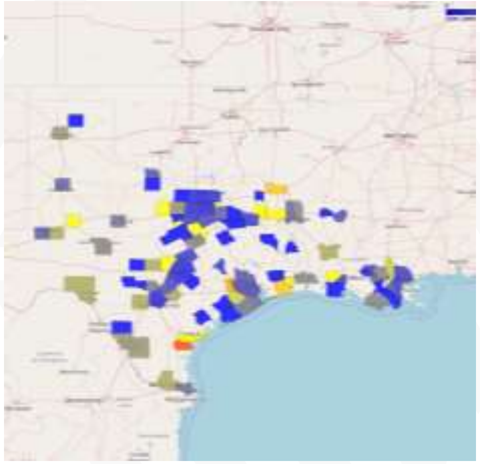
This data provides a consistent, regional assessment of grid conditions across 50+ utilities and two states.

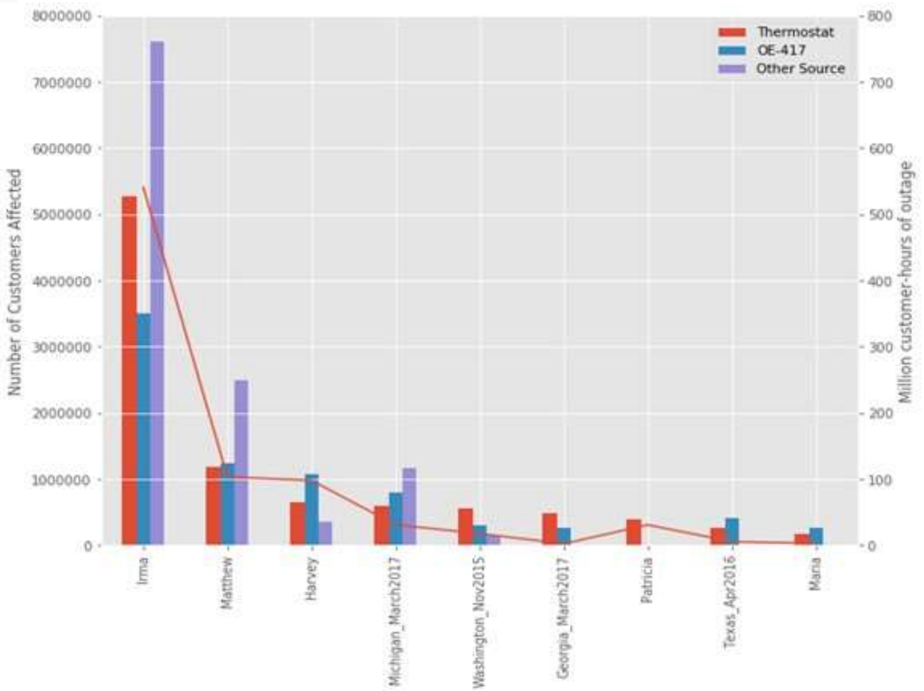
Using Interconnected Devices to Track Power Outages – (6/7)

Other Events and Consumer Outage-Hours



We evaluated over 10 separate outage events.





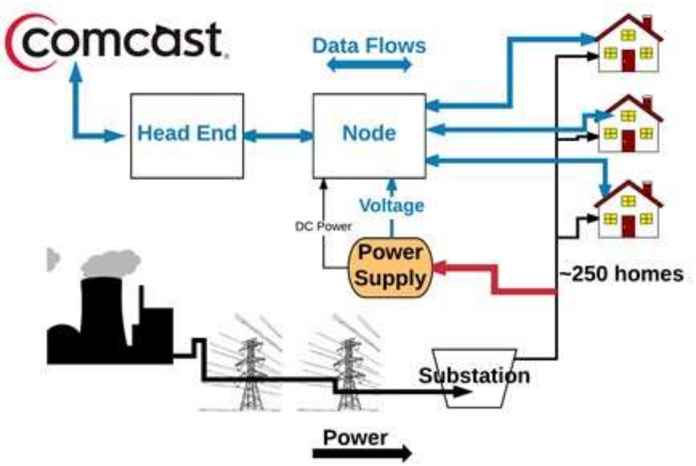
We calculated consumer outage-hours for each event.

Our estimates are similar to published values (and probably more reliable).

Using Interconnected Devices to Track Power Outages – (7/7)

Problems & Opportunities

- **Set-top boxes**
  - Proved concept
  - Comcast now trying to commercialize service but utilities & Outage Management Services not yet interested
- **Thermostats**
  - Demonstrated concept on real outage events
  - Unable to estimate outage metrics (SAIDI) because of high data outage rates
  - Estimated consumer outage-hours by county across many utilities and 2 states in a consistent way → valuable for emergency authorities, insurance, others.
- **Opportunities**
  - Identified better grid sensor: Comcast node → future GMLC project with NREL?
  - Wifi routers may be better data source
  - Several commercialization opportunities possible



The cable network node is potentially a better grid (and environmental) sensor

Contact: Alan Meier, LBNL | akmeier@lbl.gov, 510-486-4740

Background: Buildings as Sensors Value of Automatic Load Shaping/ Modulation – (1/5)

- Importance: Load-side data analytics for *Autonomous Grids*, including load flexibility, state estimation, and forecasting applications
- Project significance:
  - Value of load shaping ancillary service at scale
- Technical approach:
  - Device-to-Interconnection model & simulation
  - Distributed Model Predictive Control of homes on distribution feeders including "plug-in" capabilities for transmission grids
  - Existing IP communications / networks
- Potential risks and factors affecting project success:
  - No standards risks; in-place communications to thermostat-based controllers
- Journal paper submitted to IEEE TIA and conference paper to ASHRAE BPAC

Variable & Uncertain: Weather, Generation, Load, Transmission, Markets

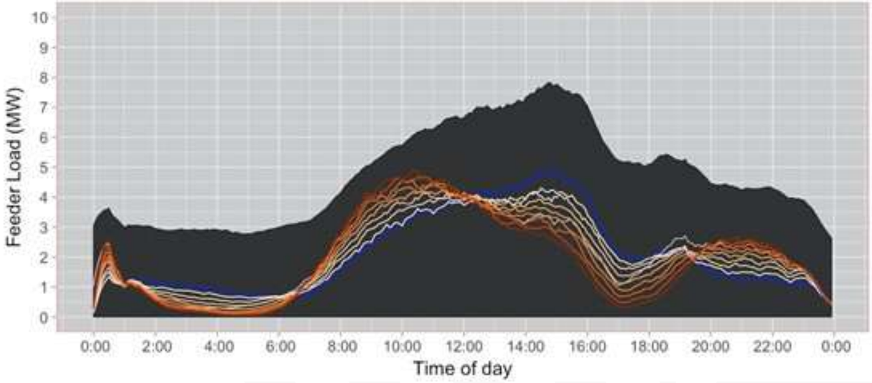
Adapted from: http://newsroom.cpsenergy.com/blog/energy-101/distribution-transmission

Buildings as Sensors: Computation Feasible 100,000+ Homes, 204 Feeders, 35 Cities – (2/5)

Load shaping limits of distributed model predictive control of residential HVAC

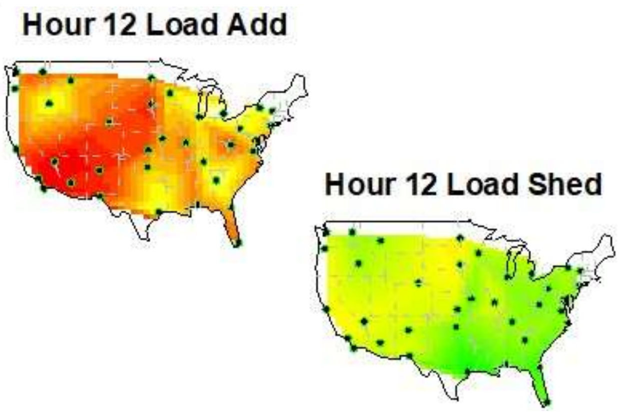
MPC Load Shed Opportunities, Houston 20 July 2012, 2,146 Homes , Total Load in black, A/C Load in Blue

Reduced load in white. Target reduction in other colors



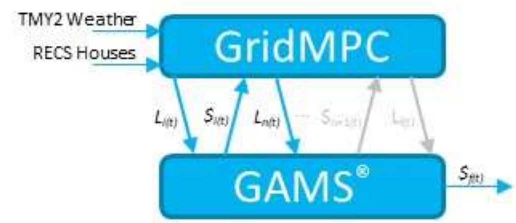
Regional Quantification

Summer Load Shaping Opportunities

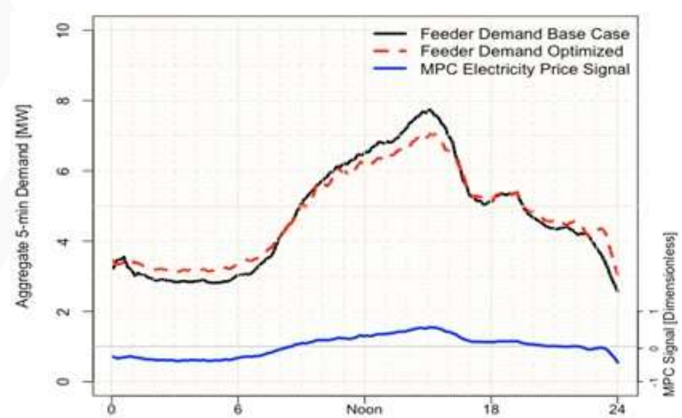


Buildings as Sensors: Computation Feasible Co-simulation of Generation & End Use – (3/5)

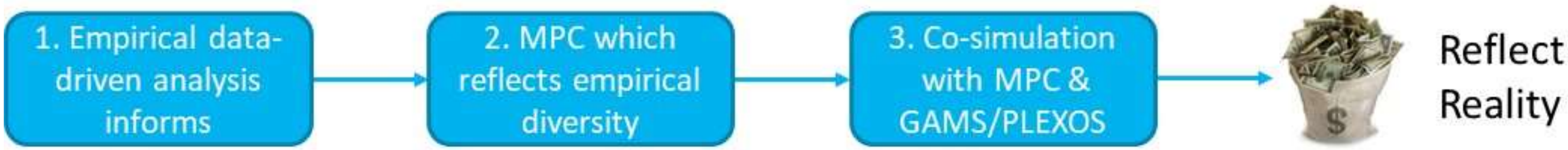
Test Case: Monetary savings of automatic residential load shaping (ARLS)



1. **GridMPC reads weather and houses and simulates base case energy usage, $L_{i(t)}$**
   - Passes *Load(t).csv* to GAMS
2. **GAMS optimizes initial cost w/ 3 generators, no transmission**
   - Calculates min production cost of $194,667/day, and $\$_{i(t)}$
   - Passes *MPC price signal(t)* to GridMPC
3. **GridMPC creates *new optimized load(t)* given**
   - Passes *new load(t).csv* to GAMS
4. **GAMS calculates new min cost of $190,849/day and $\$_{f(t)}$**
   - **Preliminary result is possible 2% reduction in generation cost = $(\sum \$_{i(t)} - \sum \$_{f(t)}) / \sum \$_{i(t)}$**



Buildings as Sensors: Next Milestone(s) Aggregate Value of Load Shaping – (4/5)

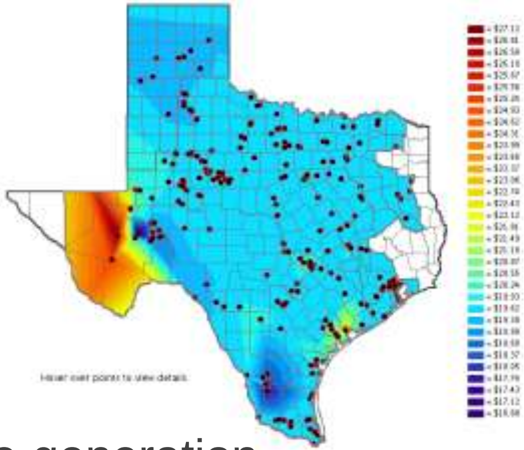


- ► Co-simulate generation & load for large geographic area
- ► Develop and incorporate additional MPC thermal/physical models for
  - Hot water heaters
  - Battery storage
  - Dispatchable Rooftop Solar PV
- ► Calculate reduced production costs and emissions due to MPC
  - Based on high-fidelity weather including uncertainty

Buildings as Sensors Future Project Activities & Impact – (5/5)

ISO-level monetary savings calculations covering ½ of U.S. Electricity

- Estimating the spatiotemporal value of jointly optimized electric power generation and residential electrical use across large electric grids
  - Electric Reliability Council of Texas (ERCOT)
  - California Independent System Operator (CAISO)
  - Midcontinent Independent System Operator (MISO)
  - PJM Regional Transmission Operator



- Production cost model based on realistic generation
  - Minimize ops cost of utility-scale thermal and renewable generation

- Future: Design of markets with grid-interactive efficient buildings (GEB)

Contact: Anthony Florita, NREL
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Publications

Conference Papers

- Cruickshank, Robert F., et al. "Characterizing Electric Grid System Benefits Of Mpc-Based Residential Load Shaping." *2018 Building Performance Analysis Conference and SimBuild.* ASHRAE and IBPSA-USA, 2018.
- Ueno, Tsuyoshi, Marco Pritoni, and Alan Meier. "Using Data from Connected Thermostats to Track Large Power Outages in the United States." In *Proceeding of Annual Society Conference of the Institute of Electrical Engineers of Japan*, Division of Electronics, Information and Systems, IEEJ, 2018.
- Cruickshank, Robert F., et al. "Empirical Investigations of the Opportunity Limits of Automatic Residential Electric Load Shaping." *2017 Ninth Annual IEEE Green Technologies Conference (GreenTech)*. IEEE, 2017.

Journal Articles

- Cruickshank, Robert F., et al. "Quantifying the Opportunity Limits of Automatic Residential Electric Load Shaping." *IEEE Transactions on Industry Applications*. (In Review)
- Wang, Fei, et al. "Clustering of Residential Load Patterns Based on an Improved Gravitational Search Algorithm." *IEEE Transactions on Smart Grid*. (In Review)

Disclosures

- S-138,534, Joshi, Pooran, et al.: "High-Performance Airflow Sensor Exploiting 2D/3D Manufacturing Techniques for Energy Efficient Smart Buildings." 2017.
- S-138,775, Joshi, Pooran, et al.: "Flexible Current Sensor for Load Monitoring to Enhance Building Energy Efficiency and Grid Reliability." 2018.

Wireless Precision Measurements

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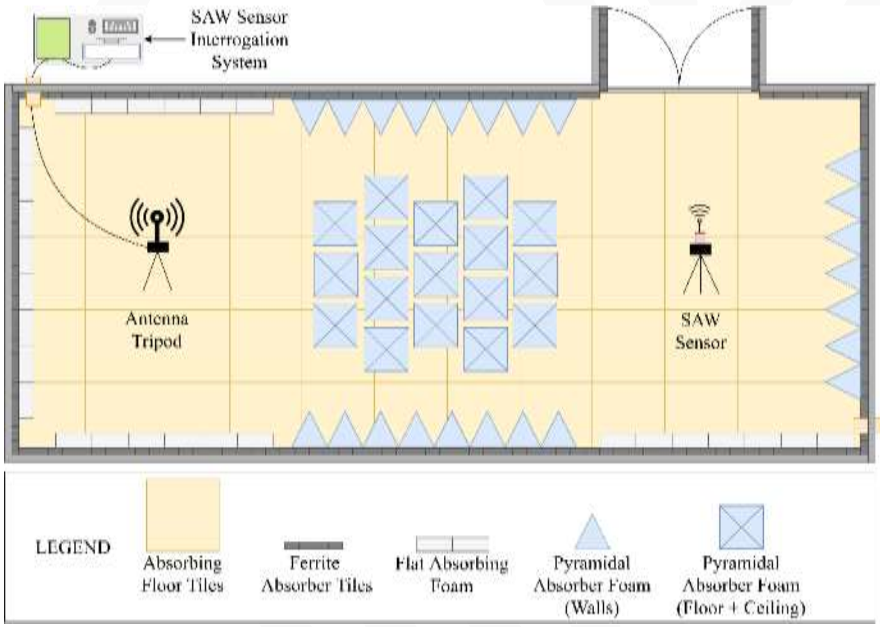
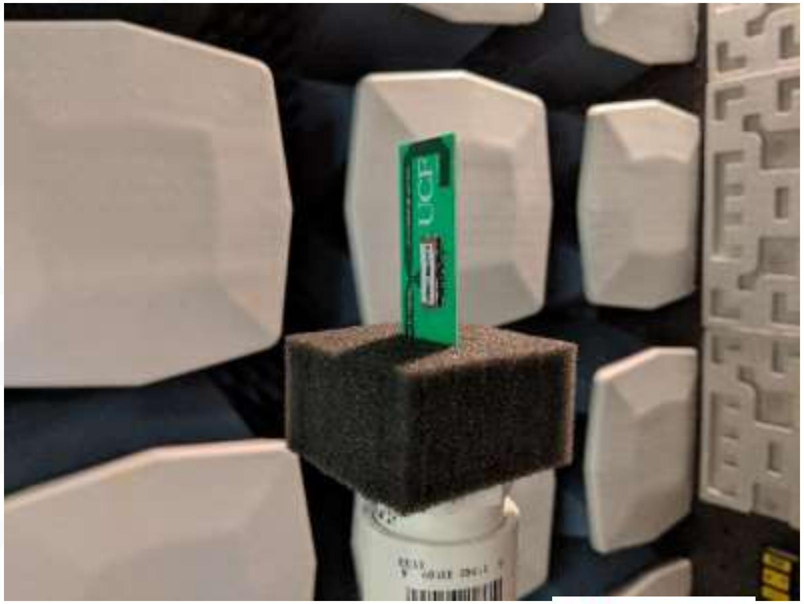
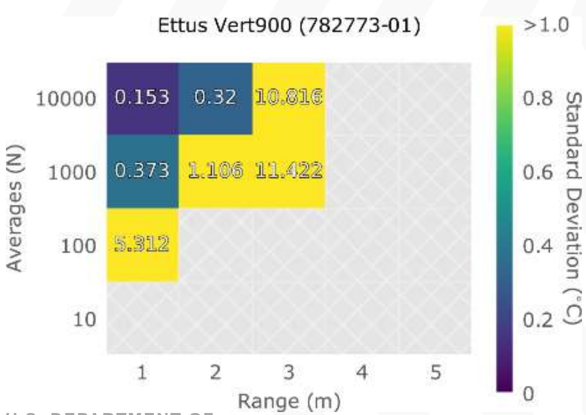
- SAW temperature sensor tested in anechoic chamber (22×7.4×8.5 ft)
- Observed sensor performance with varying wireless range, antenna type, and number of post-processing averages (multiple sweeps)
- Calculate temperature standard deviation (at constant temperature)

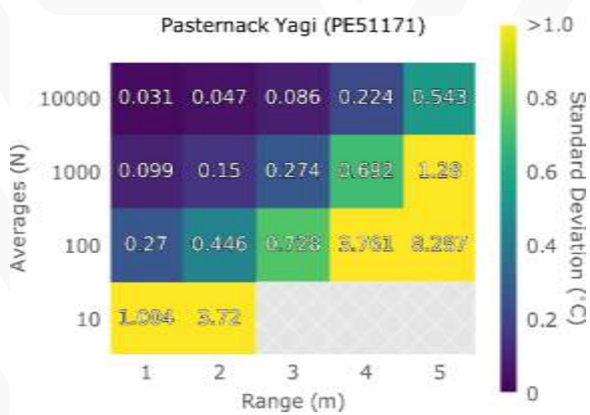


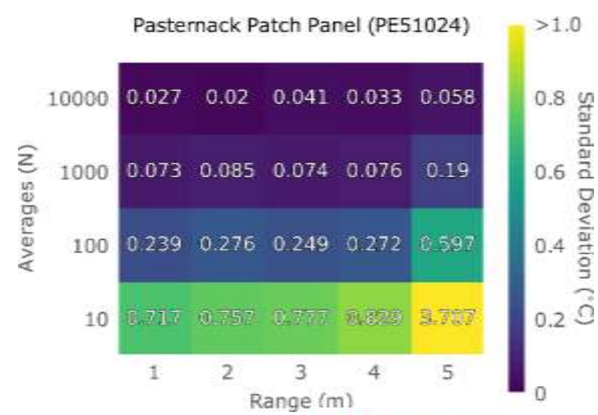


Anechoic Chamber Results

- Monopole, Yagi, and Patch Panel antennas tested
- Sensor can operate up to 5 meters (Limited by chamber length)
- Measurement precision down to 0.027°C observed
- Best performance observed with Patch Panel antenna

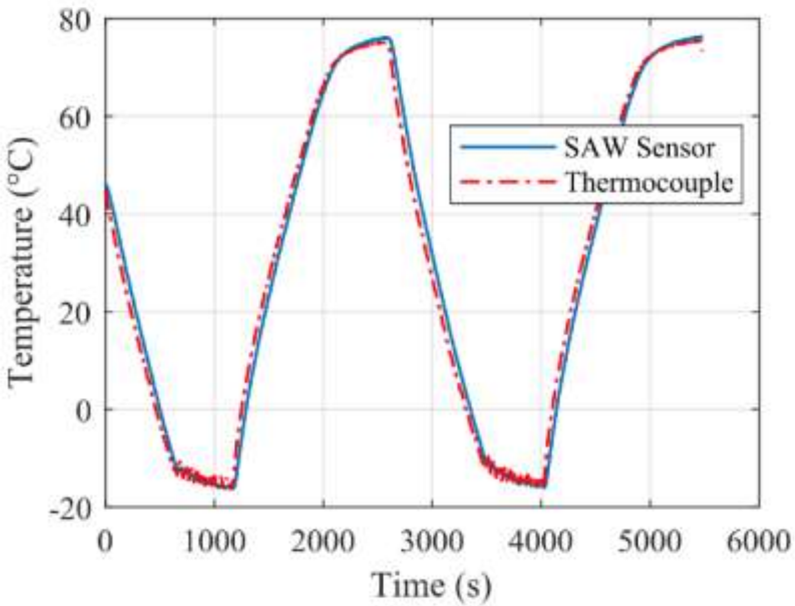


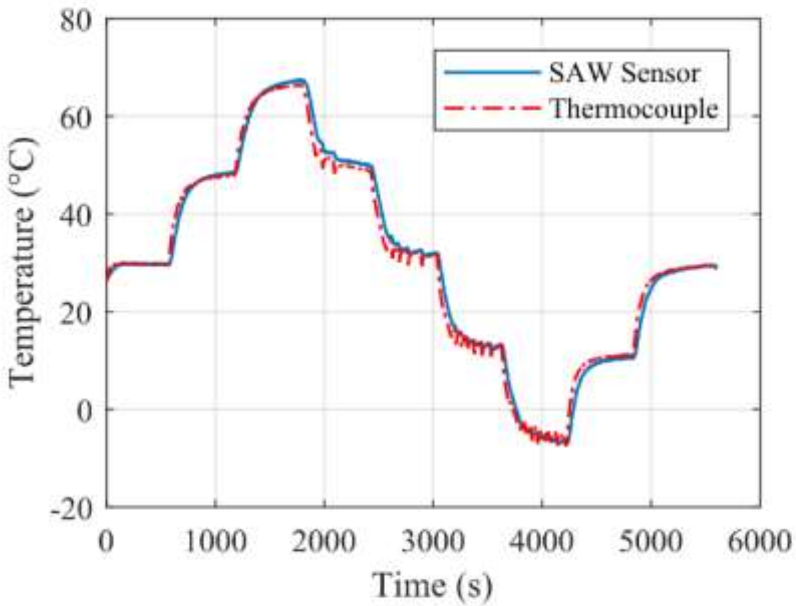




Temperature Accuracy Experiments

- SAW temperature sensor exposed to temperature extremes in temperature chamber (Tenney TJR), (Approx. -15°C to 75°C)
- Thermocouple (TC) for performance reference; SAW tracked closely
- TC reacted to heat/cool cycling at extremes and steps (low thermal mass)





Advanced Sensors

- **Asset Monitoring**
  - Mag Sense
  - SAW
  - Fiber Optic
  - Gen Scape
- **T & D**
  - Dyn. Line Rating
  - Timing
  - Advanced Algorithms
  - Optical Transducers
- **End Use**
  - Low cost Current
  - Building Occupancy
  - Connectivity

GRID MODERNIZATION INITIATIVE PEER REVIEW

Integrated Multi-scale Data Analytics and Machine Learning for the Grid 1.4.09

EMMA M. STEWART (LLNL)

September 4–7, 2018

Sheraton Pentagon City Hotel – Arlington, VA

Integrated Multi-scale Data Analytics and Machine Learning for the Grid 1.4.9

High-Level Project Summary

Project Description

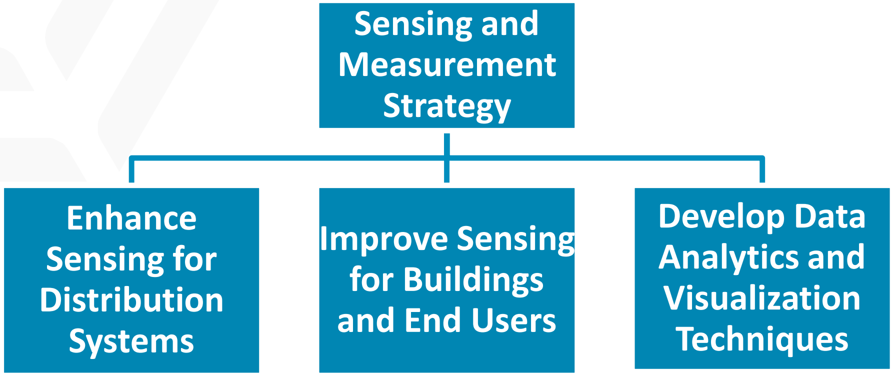
Develop and demonstrate distributed analytics solutions to building-grid challenges, leveraging multi-scale data sets, from both sides of the meter. Evaluate and demonstrate the application of machine learning techniques to create actionable information for grid and building operators, and derive customer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

Value Proposition

- ✓ Solving fundamental challenges for transitioning ML and data analytics into the grid industry
- ✓ Enabling the transition from data to actionable information at the building to grid interface
- ✓ Increased revenue streams for resource utilization for customers
- ✓ Proactive and efficient asset management for operators/planners

Project Objectives

- ✓ 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
- ✓ Improve grid health and data utilization



Integrated Multi Scale Data Analytics and Machine Learning

Relationship to Grid Modernization MYPP

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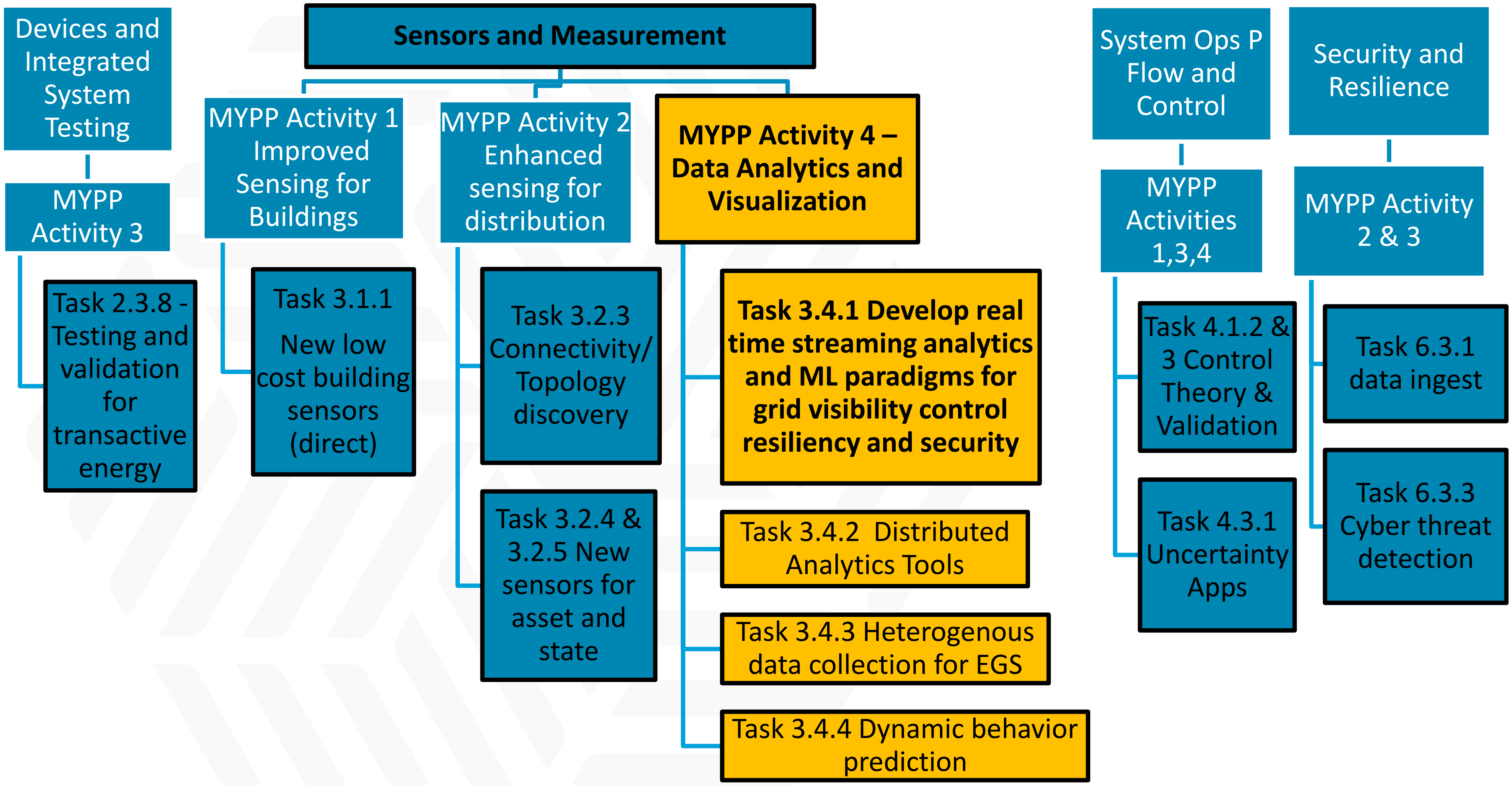


Integrated Multi-scale Data Analytics and Machine Learning for the Grid 1.4.9

Project Team

PROJECT FUNDING				Tasking
Lab	FY16 $	FY17$	FY18 $	
LLNL	83k	270k + 75k subs	270k + 75k subs	Lead Lab Data Collection, Application definition, data quality analysis, baysian framework for transformers
LANL	220k	240k	240k	+1, Anomaly Detection and platform integration
LBNL	267k	175k	175k	Platform detection, incipient failure
SNL	41.5k	75k	75k	Application Development, Topology Detection
ANL	83k	45k	45k	Resiliency Apps
NREL	41.5k	45k	45k	Application definition, ML for DER verification
ORNL	104k	75k	75k	OpenFMB integration

- Approach:
  - Application of both existing and evolved techniques of machine learning to grid data sets for moving the state of the art in grid applications forward.
  - Improve methods by which machine learning can be applied to streaming distributed datasets, and evaluate impacts of key grid issues such as data quality, and labeling
  - Address fundamental challenges with development of platform, expertly labeled datasets, and effective application and integration of ML techniques to streaming distributed grid data
- Key Issues:
  - many data analytics packages exist, but there has not been true translation to the grid and building space.
  - We see advancements in many industries rapidly. Must address developing and enhancing techniques in both the technical machine learning aspects, and the functional mechanisms by which it is applied
- Distinctive Characteristics:
  - Integrated approach which is considering both the source of data, and its path to the end user through a web of ML, platforms and data streams

Integrated Multi-scale Data Analytics and Machine Learning for the Grid 1.4.9

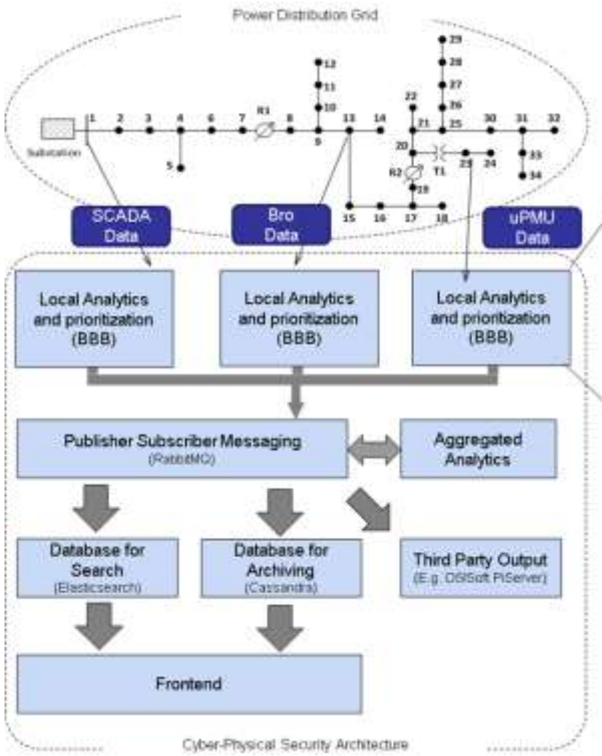
Accomplishments to Date

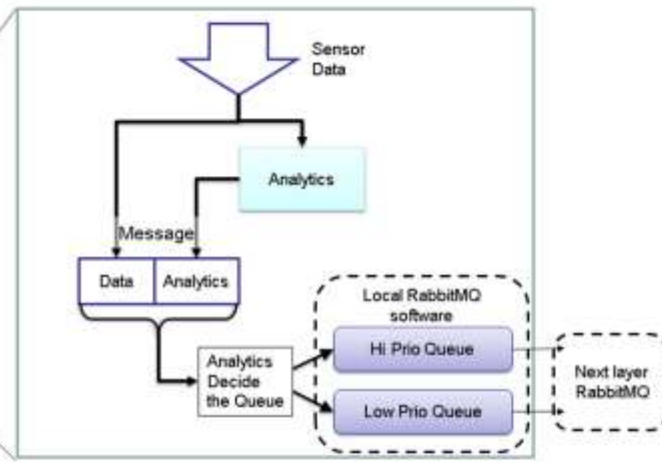
- Reviewed the white space
  - What is really stopping the application of advanced machine learning algorithms becoming common place in the grid space?
  - Do we need new algorithms, better application of those, or better supporting infrastructure
- Findings:
  - There is some room for new algorithm development, but there are key issues in how data is ingested, analyzed, stored, and interpreted
  - Addressing both algorithmic work and 3 key support areas:
    - Local platforms and distributed analytics
    - Data quality and impact on algorithms
    - Dataset labeling and ground truthing
  - In last year of work will also address:
    - Analytics valuation
    - Validation and benchmarking against SOA

Accomplishments
Use Case Framing (Year 1)

Use Case	DR & DER Local Availability & Verification	Incipient Failure Detection in Distribution	Topology & Parameter Estimation
Present State of Art	Estimated forecast and manual communication	Local sensing, smoke signals, outage management	Successful applications in highly sensed environments,
Present Granularity	Sub or Individual Customer, Day+	Limited prior to outaged component	Sub or Individual Customer, Day+
Future Requirement	Cust & Dist XFRMR Real time and Hrs Ahead	Dist XFRMR/ component level Real time, Months and Hrs Ahead	Switch, Distribution Component Planning and Event Driven
Useful Data	AMI, Irradiance, Green/Orange Button, PMU, model	AMI, Model, PMU, GIS	AMI, Model PMU, GIS, Model

SPARCS: Platform development, algorithm integration and testing

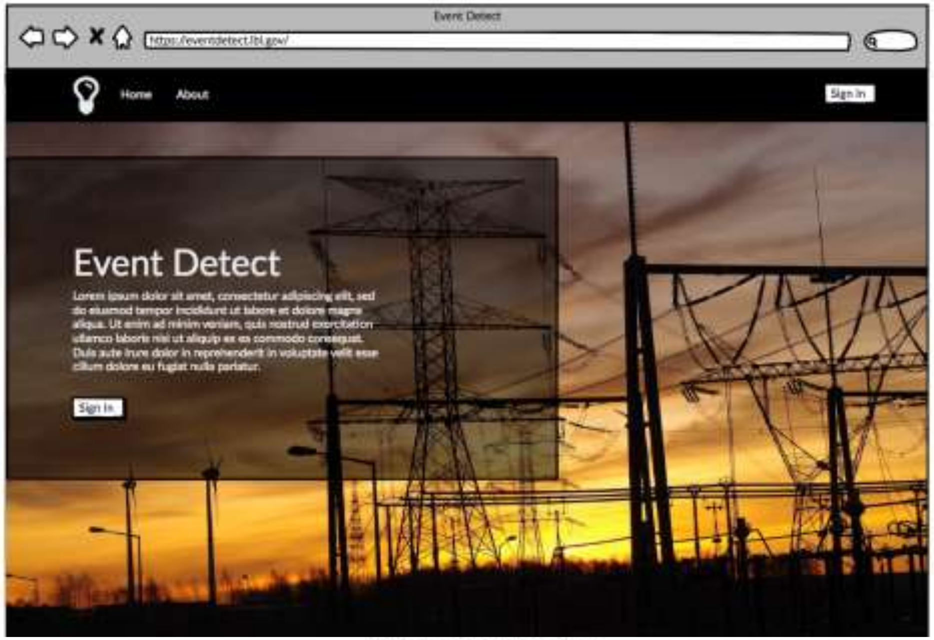


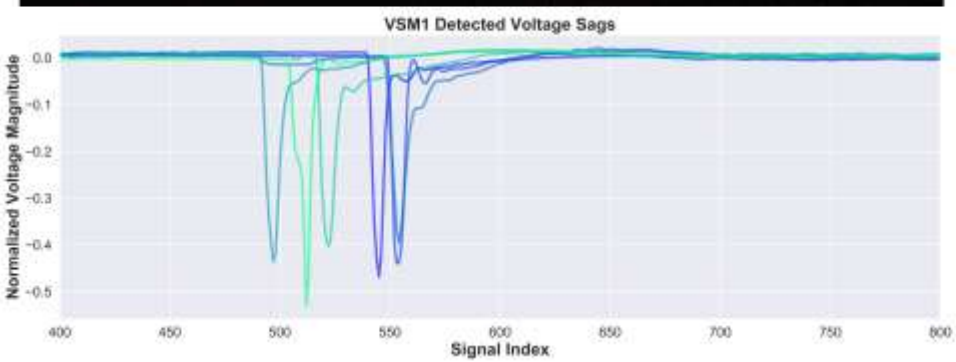


For GMLC 1.4.9, we have augmented the platform to support a "hierarchy" of storage and analysis — local sensors pass data to intermediate layers (next slide), to enable robustness to network connectivity issues — before ultimately being stored in a central system for archival and broader situational awareness.

For GMLC 1.4.9, this data framework has been made available via database APIs to GMLC 1.4.9 partner labs. LANL's and LBNL's fault-detection algorithms developed for GMLC 1.4.9 currently successfully run against the database API. (Demonstrated July 2018)

Development of a Supervised Training Dataset with expert user input





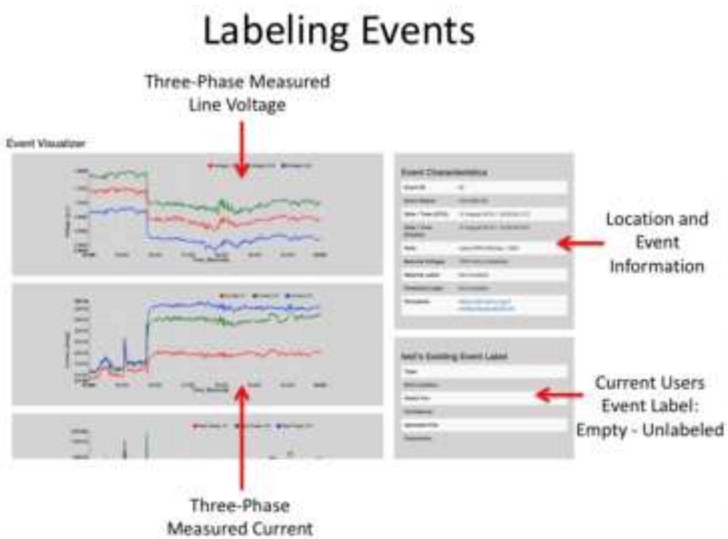
Answering a key "need" for application of supervised ML to grid data

- "what are the events and how do we label them"
- "we don't know what we are looking at"
- "I need a dataset labeled by knowledgeable power systems engineers"

Reduce need for large volumes of historical data and very complex unsupervised algorithms

No way for engineers to view "anomalous" events in a systematic manner for labeling – especially in new datasets

EventDetect Functionality

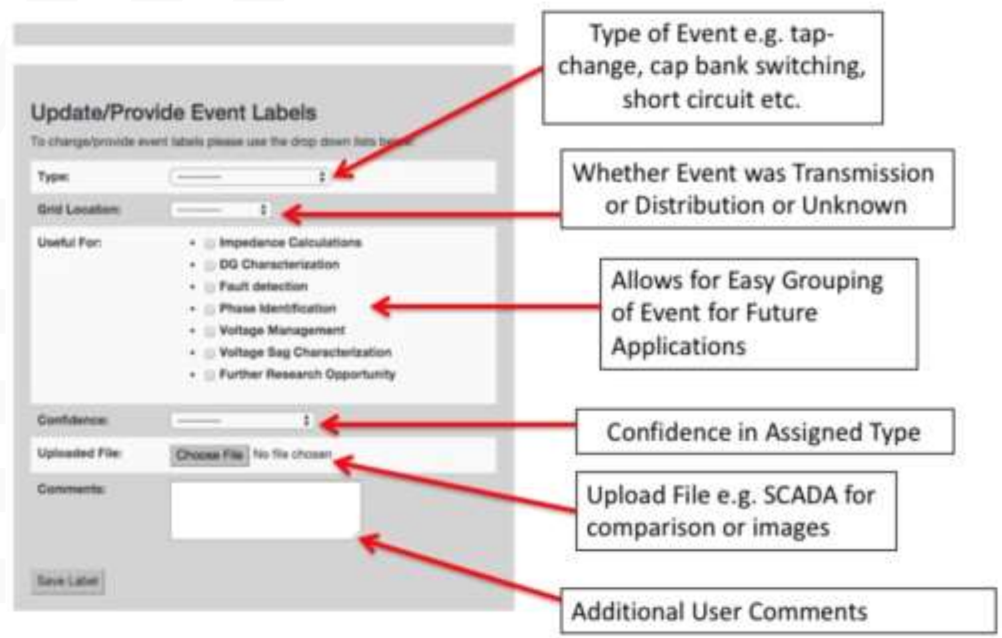


<u>Outcome: Large labeled (ground truthed) PMU & Other dataset for future ML apps</u>

<u>Online: Oct 2018</u>

Classifications:

- voltage sag
- tap change
- known voltage event
- known current event
- known frequency event
- unknown voltage event
- unknown current event
- inconclusive



Online Anomaly/Event Detection in Distribution Grids: a PMU measurement based study: Results and comparison of ML techniques

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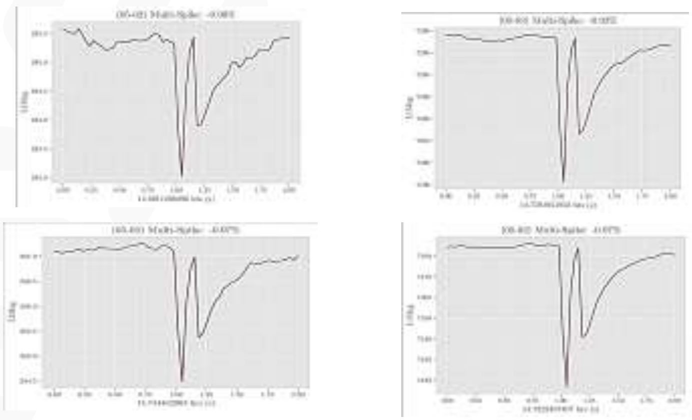
Time-series of measurements from multiple PMUs are received

- 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

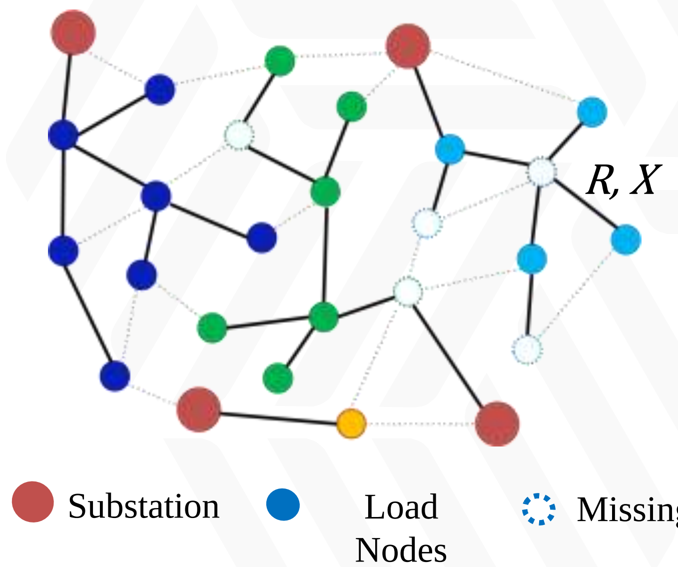
Cross-Validation/In-sample Accuracy on LANL Data			
Learning Algorithm	5 Features	12 Features	Raw Signal
Decision Tree	78.0% / 85.0%	84.8% / 88.5%	N/A
Random Forest	77.2% / 100%	80.26% / 100%	N/A
Neural Net	78.7% / 90.3%	82.0% / 91.3%	80.7% / 90.8%



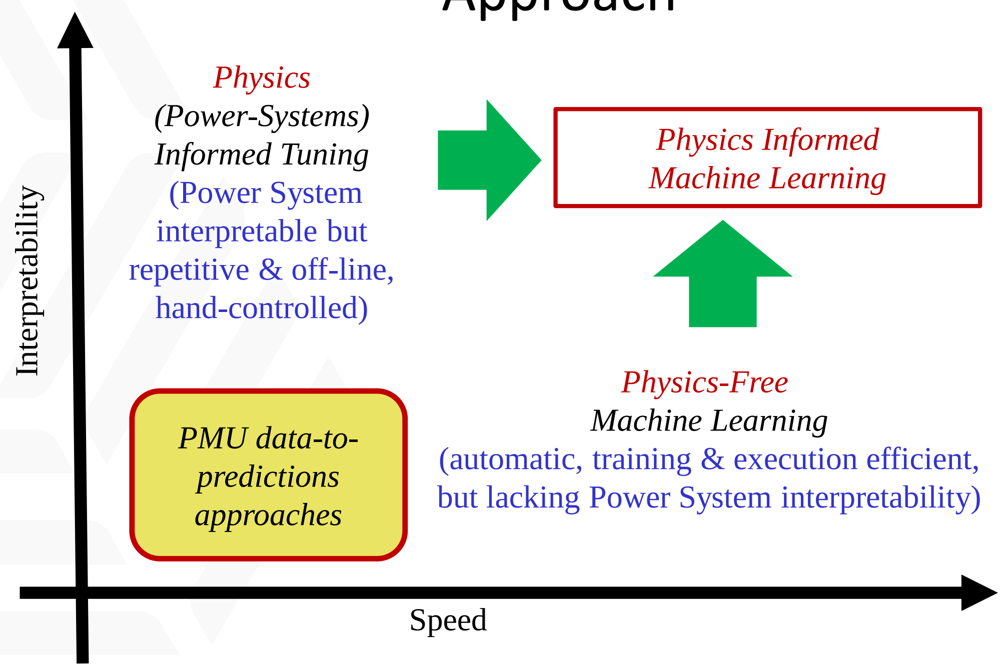
- Localization using relative time-stamps (preliminary)

Learning in distribution grids: Topology & parameter estimation with missing nodes

- Structure Learning
- Learning Line Impedances
- Incomplete observations



Approach



- Advantage: Provable results, Missing data extensions

Deep multi-dimensional GPs/stick breaking processes for heterogeneous temporal data

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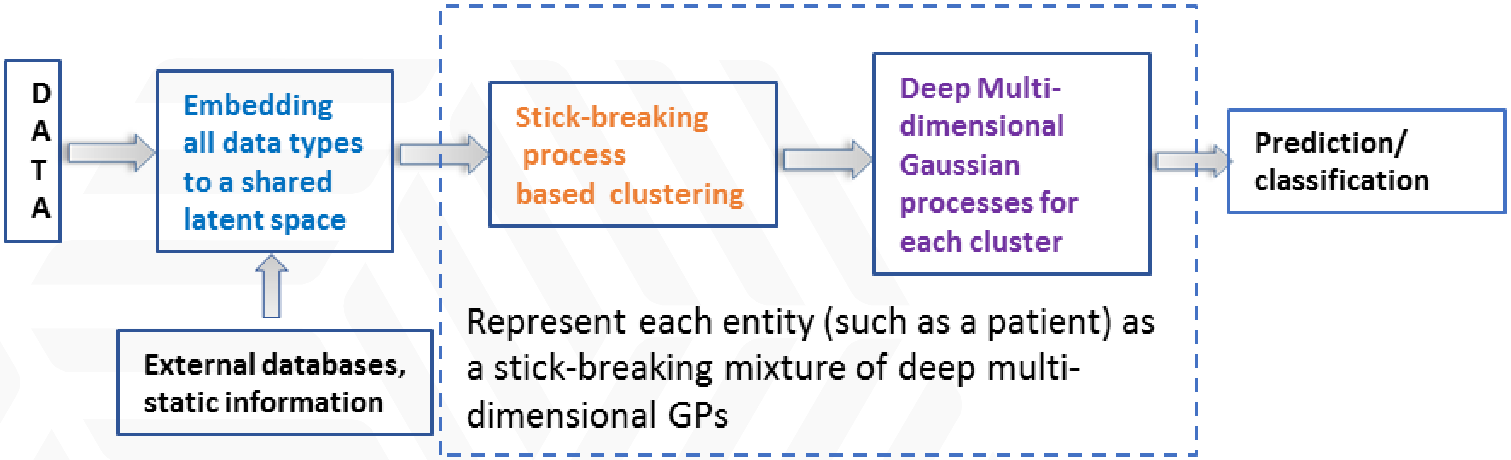

Application of temporal multi-modal learning
Fuse Information from different sources + Capture spatio-temporal structure within the data

- Multi-modality
- Heterogeneity, adapt model complexity as driven by data
- High-dimensional, irregularly sampled time-series data, uncertainty quantification
- Leverage on the recent success of deep learning

Medical	Transformer Analytics
Patient vital signs	uPMU data/SCADA
Clinical diagnosis	Known fault database
Test results	DGA, infrared
Medications	Maintenance and repairs
Visit notes	Repair records

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Benchmarking

- Why?
  - "Everyone is working on ML"
  - Determine the white space and limitations of existing approaches
  - Where ML is useful and not
  - Where existing industry techniques can be applied to the same problem
  - Compare direct sensing with analytics

- Structure
- Part 1: Describe
  - Brief Description
  - Actors
  - Information Objects
  - Step by step description
  - Post condition and Outcomes
- Part 2: Evaluate
  - ML technique applied
  - Data required
  - Data type limitations
  - Real or Simulated
  - Data accuracy/precision requirements
  - Temporal/spatial requirements for data input
  - Data Availability Requirement
  - Latency–between data ingest and visualization of result
  - Accuracy/RMSE
  - potential for algorithm distribution
  - Challenges for platform deployment (algorithm onto platform)
  - Is there a sensor type which can perform this analysis independently

We need targets…from MYPP S &M Roadmap

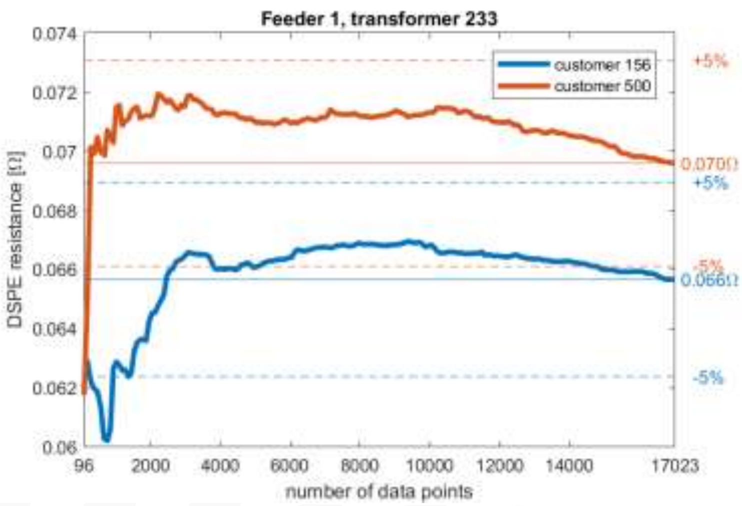
Level | Time	Retrospective (Past)	Real time (Present)	Predictive (Future)
Local	Data Acquisition Latency: minutes Computational Budget: moderate Solution time: minutes Nodes: 1 Scalability: 100k Precision: single node/device Accuracy: <5% RMSE	Data Acquisition Latency: 0 to us Computational Budget: low Solution time: <us Nodes: 1 Scalability: 1 Precision: single node/device Accuracy: <5% RMSE	Data Acquisition Latency: ms Computational Budget: moderate Solution time: seconds Nodes: 1 Scalability: 1 Precision: single node/device Accuracy: <10% RMSE
Distributed	Data Acquisition Latency: minutes Computational Budget: moderate Solution time: Minutes Nodes: 100k Scalability: 1M Precision: high (local decision making) Accuracy: <5% RMSE	Data Acquisition Latency: 0 to us Computational Budget: low Solution time: <us Nodes: 100k Scalability: 100k Precision: single node/device Accuracy: <5% RMSE	Data Acquisition Latency: ms Computational Budget: high Solution time: seconds Nodes: 100k Scalability: 100k Precision: single node/device Accuracy: <5% RMSE
Centralized	Data Acquisition Latency: minutes Computational Budget: high Solution time: minutes Nodes: 1M Scalability: 10M Precision: single device Accuracy: <5% RMSE	Data Acquisition Latency: 0 to us Computational Budget: high Solution time: <us Nodes: 500k Scalability: 500k Precision: regional Accuracy: <5% RMSE	Data Acquisition Latency: 0 to us Computational Budget: high Solution time: seconds Nodes: 500k Scalability: 500k Precision: regional Accuracy: <10% RMSE

Data Quality Assessments

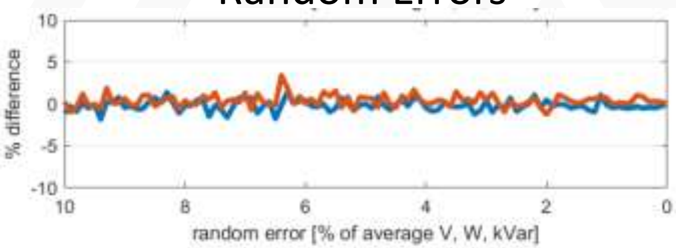
- Applications of ML to data can be both heavily influenced/degraded by poor data, or used to account for the bad data in itself
- Data quality is assessed in terms of impact of measurement accuracy, zero values, repeated or missing values
- Evaluated performance of key ML techniques with a specific dataset:
  - Example: logistic regression and decision trees may be significantly impacted by zero measurements or oor, but not to missing measurements or repeated values due to in range
  - Bayesian Analysis may mitigate OOR values, and is not impacted by zero values

DSPE Sensitivity Analysis (SNL Topology with AMI resolution)

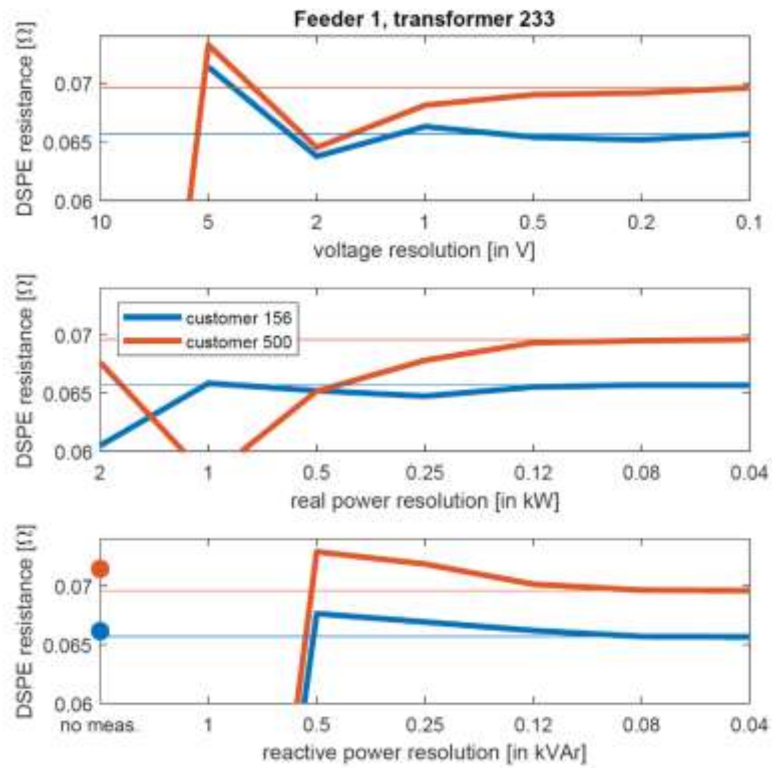
Amount of Data



Random Errors



Data Resolution



- 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; low kVAr sensitivity
- Random errors in measurements => random errors in DSPE

1.4.9
Next Steps and Future Plans

- 6 months of project remains.
- Key Next Steps to be achieved
  - EventDetect:
    - Integrate at least 10 users to the framework, provide initial data set to industry and research community on signatures (November 2018)
  - Benchmarking complete
    - Report on improvement over state of art (April 2019)
  - Streaming algorithm implementation
    - Test two algorithms in SPARC framework, benchmark against metrics (January 2019)
  - Further development of incipient failure algorithms Bayesian framework and reporting (March 2019)
  - Industry review meeting, technology transition and publication (April 2019)
- Is there an improvement over existing statistical methods?
  - By how much must the technique provide an improvement for it to be worth the extra cost?
  - Review for year 3 – where is there a real critical advance needed
- Future plans
  - Project technology and algorithms are being integrated to follow on projects (CSDERMS, SETO Lab Call FY19 Projects, CEDS Projects)
  - Developing useful datasets is critical for expansion and integration
  - Industry partnerships should be grown

Comparison and Benchmarking

Name	Learning Dynamical Models of Distribution Systems (combination of supervised and unsupervised machine learning)	Subsequence time series clustering (The U C employs multi dimensional clustering)	Outage Detection in Radial Distribution Networks (Utilize maximum likelihood detector and decoupling of it over subtrees)
Use Case	Anomaly detection for all use cases	Failure detection in equipment	Failure detection
Data Type Limitations	The D-ML Engine and AD require both current and voltage phasors, but do not need a circuit model The C-ML Engine uses Anomaly Events generated by the D-ML Engines and a circuit model	U-C requires voltage magnitude and active and reactive power measurements No circuit model	Requires prior knowledge of circuit model of the distribution feeders Errors of nodal load forecasts is modelled as Gaussian noise with zero mean and known covariance matrix
Latency between digest and visualization	D-ML Engine and AD—No visualization is provided at this distributed level C-ML Engine—approximately 10 seconds	Real-Time comparison of RTO to STSC: 1-2 Seconds Computation of STSC by U-C: minutes to 10s of minutes (this analysis can be run offline)	Depend on the size of the distribution network; is scalable
Data accuracy and precision dependency	D-ML Engine and AD—Standard D-PMU data accuracy and precision is anticipated to be sufficient C-ML Engine—The circuit model and possible topologies should be an accurate representation of the physical system	U-C - accuracy of cluster assignment dependent on clustering technique and distance metric (i.e. accuracy is somewhat tunable)	No explicit requirements for nodal load forecasts errors, since the probability of detection depends on this error. So if there is requirements on the probability of detection, we can derive the corresponding load forecast errors The power flow measurement from sensors (e.g., D-PMU) is assumed to be accurate to D-PMU standards
Data availability requirement	D-ML Engine and AD—Steaming ML applications and require continuously available data C-ML Engine—Off line computing application that executes only when Anomaly Events are reported	U-C requires access to historical D-PMU data as well as streaming	Power flow measurements: the reporting rate of the measurement data should be the same with application refresh rate (depending on time requirements of other applications, e.g., state estimation). Nodal load forecasts: Can have errors or missing data of measurements

Publications, Reports, Presentations and Workshops

- Publications FY18: 7 journals, 2 technical (lab) reports, 8 conference presentations/publications
- Features: IEEE PES GM 2018 Panel on Big Data and IoT, Panel presentation on parameter and topology estimation
- Stakeholder meeting in conjunction with the Sensors and Measurement Roadmap Stakeholder meeting

- Linked follow on work:
- SETO PV Estimation
- CleanStart DERMS
- BTO: CUBE

Integrated Multi Scale Data Analytics and Machine Learning for the Grid – Task OpenFMB

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1 Establish sensor-to-sensor communication

Using micro PMUs (µPMU) and other devices establish communication between sensors via secure communication channel

2 Establish connection to cloud database

Understand API for PingThings and establish OpenFMB-compliant communications to cloud server via secure communications channel

3 Finalize full process

Trigger the sequence of processes on alert
Verify entire process works
Verify data integrity
Verify OpenFMB compliance

4 Perform experiments & create framework

Create datasets with various categories and types of faults/failures:

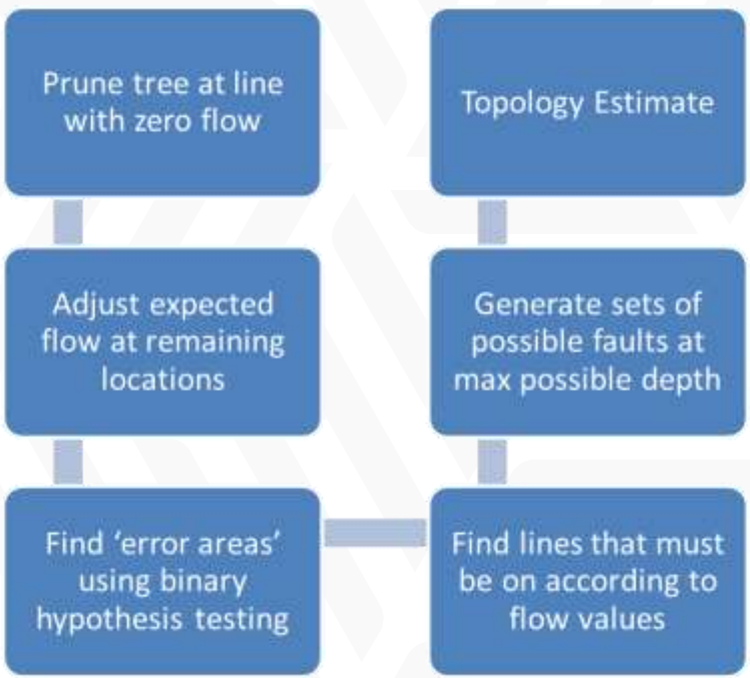
- Electric
- Cyber
- Hardware failures

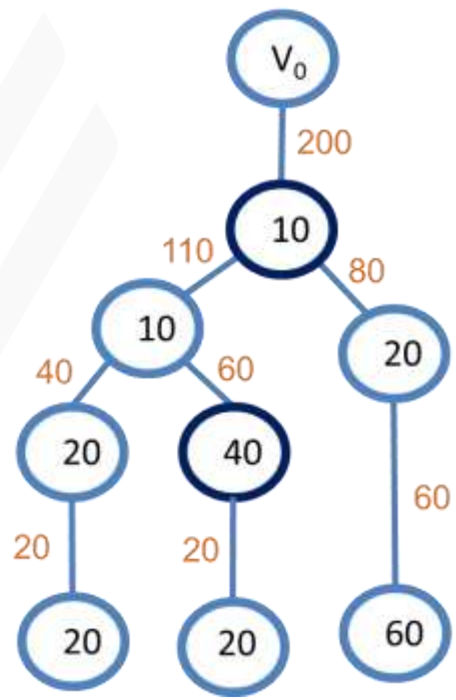
5 ML algorithm and feature selection

Perform pre-processing of data
Dimensionality-reduction
Feature selection
ML algorithm selection
Benchmark AI techniques for anomaly detection
How to enter quarantine state
(Stable safe state to prevent propagation of virus into other parts of the system)

Outage Detection in Radial Distribution Networks (ANL)

- Solutions
  - Given load demand estimation/forecast, power flow measurement from sensors, and error-free topology, design a maximum likelihood detection scheme
  - Optimal sensor placement to ensure all detectable outages are identifiable
  - Design a sequential detection scheme to reduce computational complexity



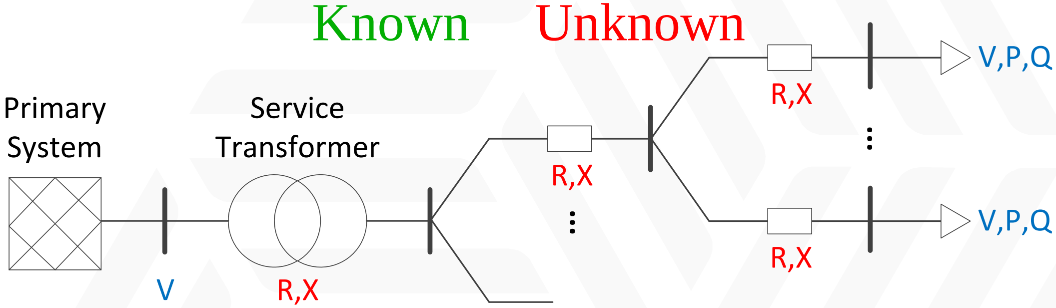


AMI Data for Parameter and Topology Estimation (SNL)

Low-Voltage Secondary System Parameter and Topology Estimation

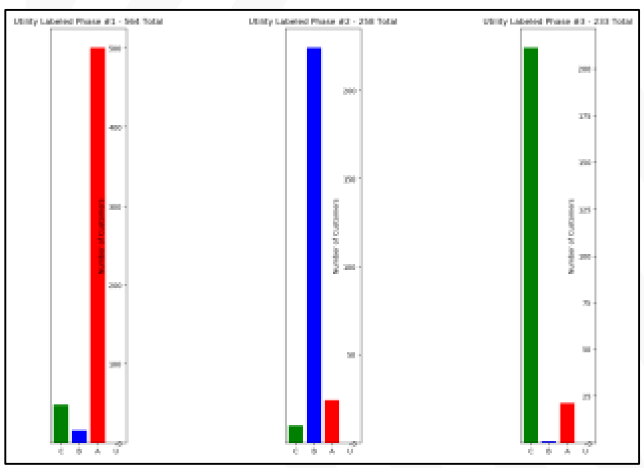
$$V_1 - V_2 = I_{R1}R_1 + I_{X1}X_1 + I_{R2}R_2 + I_{X2}X_2 + \epsilon$$

Known Unknown



Validated Results

Phase Identification



3 Utility Feeders Analyzed