Advancement of Synchrophasor Technology

IN PROJECTS FUNDED BY THE AMERICAN RECOVERY AND REINVESTMENT ACT OF 2009

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Office of Electricity Delivery and Energy Reliability

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Eight of the synchrophasor-related grant recipients and one demonstration recipient voluntarily agreed to provide enhanced reporting of the status and impact of their projects, which significantly contributed to this report. These companies are:

- American Transmission Company
- Center for Commercialization of Electric Technologies
- Duke Energy Carolinas
- Idaho Power Company
- Independent System Operator New England
- Midcontinent Independent System Operator
- New York Independent System Operator
- Peak Reliability (previously part of Western Electricity Coordinating Council)
- PJM Interconnection, LLC

The remaining four synchrophasor-related grant recipients provided information in accordance with the requirements of their smart grid investment grants:

- Entergy Corporation
- Florida Power & Light Company
- Lafayette Consolidated Government
- Midwest Energy

All recipients worked with DOE to respond to requests for additional information and clarifications and to disseminate information on synchrophasor technology – particularly on sharing their experiences, lessons learned, and procedures developed – in order to advance the capabilities and facilitate further deployments of this important technology. The North American SynchroPhasor Initiative (NASPI), supported by DOE-OE, provided and continues to provide a forum for joint problem solving and information sharing among all members of the synchrophasor community. The materials posted to the NASPI web site by project participants and others also contributed to this report.

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EXECUTIVE SUMMARY

The American Recovery and Reinvestment Act (ARRA) of 2009 provided $4.5 billion to the Department of Energy (DOE), Office of Electricity Delivery and Energy Reliability (OE) to modernize the U.S. power grid, create jobs, and stimulate the economy. The majority of the funding went to competitively selected industry projects under the Smart Grid Investment Grants (SGIG) and Smart Grid Demonstration Program (SGDP)—in which participants matched or exceeded ARRA funds with private funding.

DOE and industry partners invested a total of more than $357 million to deploy synchrophasor technology that will provide grid operators with unprecedented wide-area visibility to better sense the behavior of the transmission system and improve reliability. Traditionally, supervisory control and data acquisition (SCADA) systems have been used to monitor and control power systems by measuring grid conditions every 2 to 4 seconds. Synchrophasor technology, however, uses high-resolution phasor measurement units (PMUs) that provide time-synchronized data at a rate of more than 30 times per second to detect disturbances that often cannot be observed with SCADA systems. For example, network oscillations that could destabilize the power grid are readily detected by synchrophasor technology. Connecting PMUs that are strategically located across the power grid with high-speed communications networks provides grid operators with wide-area visibility to better detect system disturbances, improve the grid's efficiency, and prevent or more quickly recover from outages.

DOE competitively selected 13 entities that invested $155 million of ARRA funding and $203 million of participant funding in synchrophasor technology. The participants included five Independent System Operators / Regional Transmission Organizations (ISO/RTO), seven owners and operators of transmission assets, and one Texas nonprofit corporation:

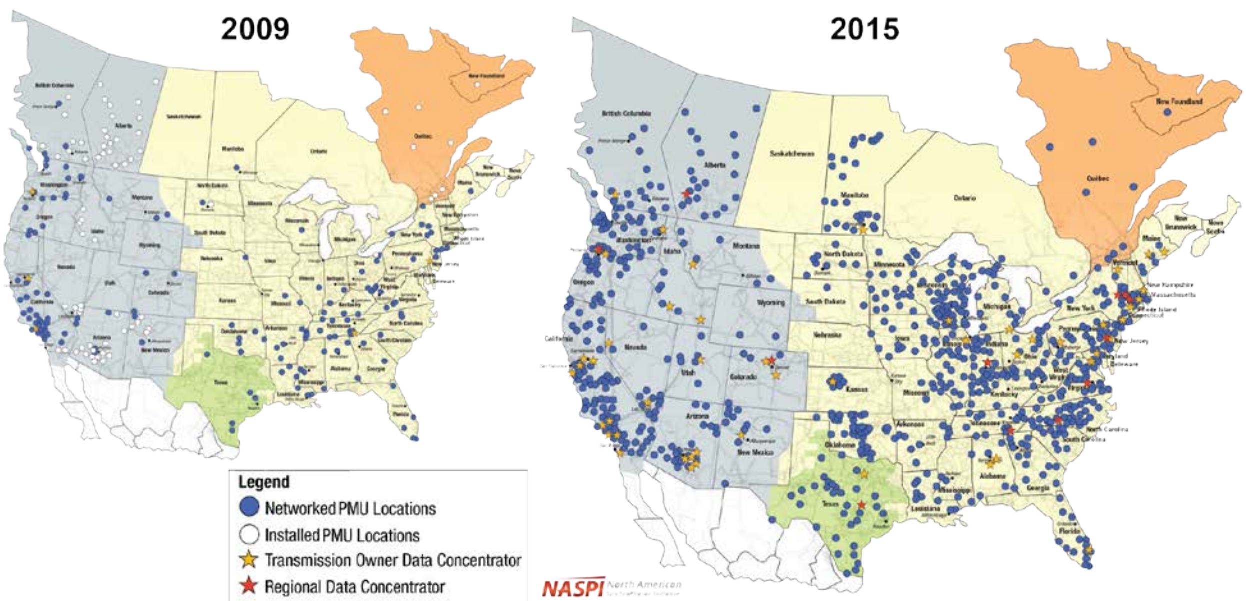
- American Transmission Company (awarded both a synchrophasor and a communications project)
- Center for Commercialization of Electric Technologies
- Duke Energy Carolinas
- Entergy Services, Inc.
- Florida Power & Light Company
- Idaho Power Company
- Independent System Operator New England
- Lafayette Consolidated Government
- Midcontinent Independent System Operator
- Midwest Energy, Inc.
- New York Independent System Operator
- Peak Reliability (original project with Western Electricity Coordinating Council)
- PJM Interconnection, LLC

OE managed the program from planning to closeout, monitored technical progress, and worked with the North American SynchroPhasor Initiative (NASPI) forum to review project status, progress, and share lessons learned. OE required all participants to develop and implement cybersecurity plans—which were reviewed by DOE and their subject matter experts—and to consider cybersecurity requirements as they developed procedures and deployed technologies.

KEY ACCOMPLISHMENTS FOR WIDE-AREA VISIBILITY

Operators now have near 100% visibility of the behavior of the entire U.S. high-voltage transmission network, due in large part to synchrophasor deployments by ARRA projects. In 2009, there were about 166 research-grade, networked phasor measurement units (PMUs) in North America, concentrated in a few areas within the grid.[1] By 2015, the ARRA projects had installed 1,380 additional networked PMUs and 226 phasor data concentrators that **provide operators with visibility into the transmission systems that serve approximately 88% of the total U.S. load** and covers approximately two-thirds of the continental United States. In total, there are now over 1,700 PMUs on the North American grid: the 166 original PMUs, the 1,380 PMUs installed with ARRA funding, and over 150 additional PMUs installed with private funding by either project participants or other utilities (see Figure ES.1).

Figure ES.1 Synchrophasor Advancements in North America



Networked PMUs in North America increased from about 166 in 2009 to over 1,700 in 2015

The ARRA projects not only designed and deployed the synchrophasor technology systems, they drove significant advancements in the technology itself, including technology performance, how the technology is used, design of communications networks, and development of cybersecurity requirements. They also significantly advanced critical institutional issues such as policies and procedures for sharing of data. For the first time, improvements in data quality provided operators with the necessary trust to use the technology for power system planning and operational activities on a large scale. Prior to ARRA, problems with PMU data availability and accuracy severely limited industry acceptance. Project participants also drove the development and upgrade of data standards and worked with contractors, or in some cases developed their own test platforms, to test synchrophasor equipment. As a result, the ARRA synchrophasor projects were able to procure and install modern, production-grade PMUs that met industry standards for conformance, reliability, and

[1] North American SynchroPhasor Initiative, "Synchrophasor Technology Fact Sheet," October 2014, https://www.naspi.org/documents.

data quality. The project participants also developed and implemented rigorous procedures for validating synchrophasor data, monitoring synchrophasor system performance, and restoring service to PMUs to maintain the required data quality. These procedures along with sharing of best practices in the NASPI forum will facilitate greater adoption in the future.

The ARRA synchrophasor projects also marked the first time that many ISOs and RTOs deployed region-wide synchrophasor-based applications and supporting communication networks, enabling unprecedented data sharing and visibility over large areas. The ARRA projects expanded communications systems and developed protocols and procedures for transporting PMU data. These data are now being shared to an unprecedented degree among ISOs, RTOs, and utilities. The West has developed a unified data sharing agreement, and data are shared across the entire Western Interconnection (WECC region), involving all balancing authorities, transmission owners, transmission operators, and reliability coordinators. The Electric Reliability Council of Texas (ERCOT) also shares synchrophasor data across the Texas Interconnection. Utilities in the Eastern Interconnection are transitioning to the Eastern Interconnection Data Sharing Network – a new network for sharing operating reliability data, including both SCADA and synchrophasor data, among appropriate entities.

KEY RESULTS FROM REAL-TIME AND PLANNING CAPABILITIES

The ARRA-funded synchrophasor projects transitioned synchrophasor technology from a research and off-line analysis tool to one that is beginning to inform the real-time operation of the power grid and improve system planning. Synchrophasor technology enhances, and in some cases enables, important capabilities for the reliable operation of the power grid (see Table ES.1):

The ARRA synchrophasor systems have been in operation for approximately two years—a relatively short amount of time for new power system technologies—yet the project participants have reported numerous tangible benefits:

- **Increased System Reliability**: Synchrophasor technology has prevented outages, detected and diagnosed failing or mis-operating equipment, enabled faster reenergizing of out-of-service transmission lines, and informed system operators of developing problems on the grid.

  For example, American Transmission Company uses PMU data to check the operation of their protection devices. Any problems identified with the protection system are corrected in order to ensure that the electrical system is protected appropriately to ensure reliability.

- **Increased Asset Utilization and System Efficiency**: Synchrophasor technology has enhanced the integration of renewable energy by enabling operators to more effectively model renewable energy generation, and thereby reduce curtailment of variable renewable energy sources. Participants have also been able to increase transmission flows in congested service areas, and validate/update generator models without having to take the generator units off-line.

  For example, Bonneville Power Administration used synchrophasor data to recalibrate the 1,100 MW Columbia Nuclear Generating Station without needing to take the unit off line, providing $100,000 to $700,000 in estimated savings for this type of generator outage.

- **Increased Organizational Efficiency by Expanding Operator and Engineer Capabilities**: By using PMU data and synchrophasor-based tools, program participants have effected a large reduction (as much as 75%) in the time, effort, and costs needed to analyze system disturbances, validate system models, and assess the status of the grid.

  For example, the Independent System Operator of New England's (ISO-NE) event analysis applications automatically collect and analyze synchrophasor data from PMUs all across New England, enabling engineers to quickly identify and analyze disturbances. With the improved efficiency, ISO-NE is able to analyze two or three events per week – up from two events per year – using the same resources.

Table ES.1 Synchrophasor Capabilities Create Tangible System Benefits

	Number of Projects	Increased System Reliability	Increased Asset Utilization & Power System Efficiency	Increased Organizational Efficiency
Real-Time Capabilities[2]				
Phase angle monitoring	12	✓	✓	
Oscillation detection and monitoring	11	✓		
Voltage stability monitoring	9	✓		
Event detection, management & restoration	9	✓		✓
Islanding detection, management & restoration	4	✓		
Equipment problem detection	9	✓		✓
Wide-area situational awareness	11	✓		✓
Study Mode Capabilities[3]				
Model validation and calibration	11	✓	✓	✓
Post-event analysis	11	✓		✓
Renewable resource integration	3		✓	
Operator training	6	✓		

FUTURE OPPORTUNITIES AND TECHNOLOGY OUTLOOK

Transmission system operators will continue to integrate synchrophasor data into planning and operating decisions and leverage unused capabilities to extract more value from the technology. While the ARRA projects demonstrated a host of new or enhanced capabilities from synchrophasor

[2] Real-time capabilities are employed in the minute-by-minute operation of the electric power grid. These are generally carried out by power system operators or operational engineers.
[3] Study mode/planning capabilities, which are generally carried out by power system engineers, are employed in planning for transmission system expansions, generation additions and retirements, system protection, and studying unexpected events or system behaviors.

technologies, not all participants tested every synchrophasor application. At this time, there is consistent, though not mandatory, use of PMU data:

- Twelve participants are using PMU data to inform their power system operations.
- Eleven participants are using PMU data to inform their power system planning.

Yet most participants can expand their applications of synchrophasor technologies as they continue to build familiarity and incorporate new procedures. Electric operating companies rely on specific, detailed procedures to guide their system planning and operations, and incorporating new procedures is an elaborate and time consuming process that involves thoroughly validating the procedure over time to account for seasonal changes of systems conditions. The extent to which system operators have revised or adopted new operating procedures to employ PMU data is an indicator of the degree to which operators have operationalized the synchrophasor system. Currently, 5 of the 13 ARRA synchrophasor participants have been able to formally implement procedures after only approximately two years of full operation of synchrophasor systems.

The synchrophasor vendor community will continue to enhance their product offerings to meet their customers' maturing needs and push for continuing development of enhanced and new standards to improve performance and ensure interoperability. While PMUs now provide nearly full coverage of the transmission system, they can also potentially play a role—though not yet specifically defined—in the distribution system. The increasing penetration of renewable generation, electric transportation, and energy storage connected to the distribution system will likely drive the need for advanced monitoring and control capabilities that PMUs may provide.

CONCLUSIONS

In summary, the ARRA projects resulted in a dramatic expansion in the use of synchrophasor technology (devices and capabilities), enabling the implementation of advanced capabilities that are improving power system planning and operations. These projects now provide real-time wide-area coverage of the entire nation[4] and have achieved capabilities not obtainable with traditional SCADA-based monitoring and control technology. The ARRA projects have greatly improved the maturity of the technology: upgrading and developing standards, and implementing synchrophasor-based tools throughout the industry. Although these synchrophasor systems have been in operation less than two years, they have provided benefits, increasing system reliability, asset utilization, and organizational efficiency. Going forward, the project participants are continuing to expand implementation of synchrophasor technologies and develop best practices that rely on synchrophasor data. OE will also continue to have a role in providing forums, such as NASPI, for sharing best practices and lessons learned with the broader synchrophasor community, and will continue to develop advanced applications for the technology.

In the Quadrennial Energy Review, the desired infrastructure characteristics are identified as: "reliability, resilience, safety, a minimal environmental footprint, flexibility, and affordability."[5] The ARRA synchrophasor projects have made a major contribution towards achieving these objectives.

[4] The synchrophasor systems cover two-thirds of the geographical region, but provide electrical coverage of the entire United States.

[5] U.S. Department of Energy, *Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure*, pp.1-20, April 2015, http://energy.gov/epsa/quadrennial-energy-review-qer.

1. INTRODUCTION TO SYNCHROPHASOR PROJECTS UNDER ARRA

The American Recovery and Reinvestment Act (ARRA) of 2009 provided $4.5 billion to the Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) to modernize the U.S. power grid, create jobs, and stimulate the economy. The majority of the funding went to competitively selected industry projects under the Smart Grid Investment Grants (SGIG) and Smart Grid Demonstration Program (SGDP)—in which participants matched or exceeded ARRA funds with private funding. As part of this effort, OE competitively selected 13 entities to carry out 13 synchrophasor-related projects as part of the SGIG program and 1 synchrophasor-related project under the SGDP program:

- American Transmission Company (ATC)—awarded both a synchrophasor and a communications project
- Center for Commercialization of Electric Technologies (CCET)—SGDP project
- Duke Energy Carolinas
- Entergy Services, Inc.
- Florida Power & Light Company (FPL)
- Idaho Power Company (IPC)
- Independent System Operator New England (ISO-NE)
- Lafayette Consolidated Government
- Midcontinent Independent System Operator (MISO)
- Midwest Energy, Inc.
- New York Independent System Operator (NYISO)
- Peak Reliability—original project with Western Electricity Coordinating Council (WECC)
- PJM Interconnection, LLC

Participants included five Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs), seven owners and operators of transmission assets, and one Texas nonprofit corporation. The synchrophasor-related costs of these projects totaled about $358 million, and over 50% of the funding was provided by the project participants (see Table 1.1).

The large public and private investments made under ARRA have accelerated smart grid technology deployments, providing real-world data on technology impacts and benefits along with valuable lessons learned and best practices. OE managed all aspects of the smart grid ARRA programs from planning to closeout, and designed a data collection process to measure both progress and outcomes.

Each of the SGIG and SGDP projects reported to OE key data to help determine the impact and value of the new technologies and systems they implemented. Projects reported two types of metrics: 1) **build metrics**, including the number of installed devices and their costs, and 2) a set of **impact metrics** that assessed the effects of the new technologies and systems on grid operations and business practices.

For the synchrophasor projects in particular, OE developed "**core metrics**," which replaced or augmented many of the original impact metrics after the projects were awarded. These core metrics were designed to allow OE to collect details on the state of specific synchrophasor technology implementations and to allow project participants to report cases where synchrophasor technology resulted in tangible, quantifiable benefits. Nine of the project participants agreed to report the Core Metrics, which are included in Appendix 3.

This report informs electric utilities, policymakers, and other key stakeholders of the qualitative and quantitative impacts, benefits, and lessons learned from SGIG and SGDP projects that implemented synchrophasor technologies. The majority of projects began in 2009 and were completed in 2015, making this the final report on synchrophasor project results from the ARRA smart grid investments.

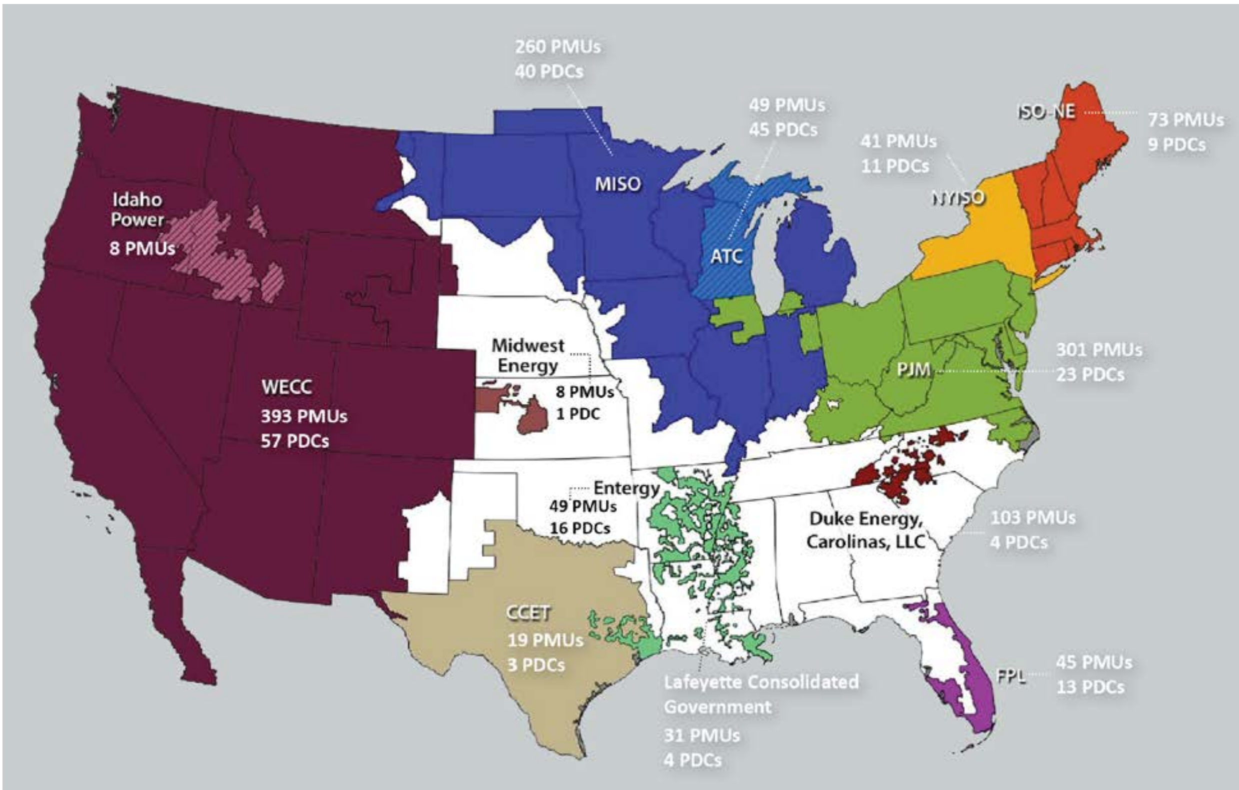
Table 1.1 ARRA Synchrophasor Total Project Costs and ARRA Funding

Project Participants	Project Title	Total Project Cost*	ARRA Funding*
Independent System Operators (ISO) & Regional Transmission Organizations (RTO)			
WECC/Peak Reliability	PMU deployment & advanced applications	$ 128,766,537	$ 53,890,000
NYISO*	PMU & capacitor bank installations	$ 70,336,403	$ 35,138,211
MISO	Improving operational reliability & efficiency with synchrophasors	$ 33,157,190	$ 16,578,595
PJM Interconnection	Synchrophasor technology deployment	$ 27,399,720	$ 13,688,509
ISO-NE	Synchrophasor infrastructure & data utilization	$ 13,894,847	$ 5,955,740
Transmission Owners & Utilities – Large Projects			
Florida Power & Light *	Advanced metering and monitoring installations	*$ 31,107,111	*$ 6,292,012
ATC/Communications	Enhanced SCADA & PMU communications	$ 21,780,312	$ 10,890,156
ATC/PMUs	Wisconsin PMU installations	$ 2,776,261	$ 1,330,825
Entergy Services	Deployment & integration of synchrophasor technology	$ 9,222,158	$ 4,610,383
Duke Energy Carolinas	PMU deployment & communication system modernization	$ 7,653,910	$ 3,826,955
Utility – Small Projects			
CCET (SGDP) *	Technology solutions for wind integration	*$ 6,606,209	*$ 484,589
Lafayette Consolidated Government*	Advanced metering, monitoring & distribution equipment	*$ 2,701,622	*$ 1,350,811
Midwest Energy	Relay replacement for Knoll substation	$ 1,424,514	$ 712,257
Idaho Power Company*	Customer systems, advanced metering infrastructure, distribution automation, advanced transmission system monitoring	*$ 1,074,838	*$ 575,928
TOTAL			
All 14 ARRA Synchrophasor Projects		**$357,901,058**	**$155,324,971**
* Only those project costs allocated to synchrophasors (and NYISO capacitors) are listed here. Some participants also received additional funding—not reported here—for advanced metering, distribution automation, or other smart grid technologies.			

Appendix 1 includes extensive descriptions of each project, and more information and past reports from ARRA-funded SGIG and SGDP projects can be found at: SmartGrid.gov.

The service areas of the project participants are shown in Figure 1.1, along with the number of phasor measurement units (PMUs) and phasor data concentrators (PDCs) each participant deployed. While the 13 project participants were the entities primarily responsible for the work, the five projects undertaken by ISOs/RTOs engaged many of the transmission owners (TOs) within their service area, and the SGDP project conducted by CCET engaged key players in the Texas energy community. TOs and key players on these projects are shown in Figure 1.2. Every one of these entities played a significant role in the design, build-out, and commissioning of the synchrophasor system infrastructure. Although the service areas of the ARRA-funded utilities cover approximately two-thirds of the nation, the visibility provided by the total PMUs deployed nationally (ARRA-funded and not) cover a wider geographic area.

Figure 1.1 Service Areas and Technology Deployments of ARRA Synchrophasor Project Participants



Geographic service areas of the synchrophasor project participants – shown in color – cover approximately 2/3 of the continental United States.

To ensure collaboration across projects and with key industry partners, OE also worked with the North American SynchroPhasor Initiative (NASPI)[6] forum to report on project status, progress, and lessons learned. This provided outreach and feedback with the general synchrophasor community, interested utilities, manufacturers, and other entities. Most of the ARRA-funded project participants participated in the NASPI general meetings and in various task team meetings. NASPI enabled project participants to learn from each other by sharing experiences related to unexpected problems, data quality and availability, PMU testing and evaluation procedures, applications development, standards, and more. The shared lessons learned helped reduce duplication of effort and accelerate the learning curve of project participants.

[6] In 2006, OE established the North American SynchroPhasor Initiative (NASPI), a public-private partnership whose mission is "to improve power system reliability and visibility through wide area measurement and control by fostering the use and capabilities of synchrophasor technology. NASPI is a voluntary group of practitioners with interest in synchrophasor technology from the utility industry, manufacturers and vendors, academia, national laboratories, government experts and standards-making bodies." More information can be found at https://www.naspi.org/.

Figure 1.2 ARRA Synchrophasor Project Participants

ARRA Synchrophasor Project Participants[1]

- **American Transmission Company (ATC)[2,3]**
- **Center for the Commercialization of Electric Technologies (CCET)[1]:**
  - American Electric Power
  - Electric Power Group
  - Electric Transmission Texas
  - ERCOT
  - Golden Spread Electric Cooperative
  - Intel/McAfee
  - Oncor Electric
  - Sharyland Utilities
  - Texas Tech University
- **Duke Energy Carolinas[2]**
- **Entergy Services, Inc. [2]**
- **Florida Power & Light Company**
- **Idaho Power Company[2]**
- **ISO-New England:**
  - Bangor-Hydro
  - Central Maine Power
  - National Grid
  - Northeast Utilities
  - NSTAR
  - United Illuminating
  - VELCO
- **Lafayette Consolidated Government**
- **Midcontinent ISO:**
  - Ameren
  - American Transmission Company (ATC) [2]
  - Duke Energy[2]
  - Entergy[2]
  - Great River Energy
  - Hoosier Energy
  - Indianapolis Power and Light
  - International Transmission Company
  - Manitoba Hydro
  - Minnesota Power
  - Montana Dakota Utility
  - Northern Indiana Public Services Company
  - Ottertail Power
  - Vectren
- **Midwest Energy**

Note 1: CCET was an SGDP project. All others were SGIG projects.
Note 2: These entities were prime grant recipients and also participants in RTO/ISO projects.
Note 3: ATC had 2 projects: PMU; Communications.

- **New York ISO:**
  - Central Hudson Gas & Electric Corporation
  - Consolidated Edison Company of New York, Inc.
  - Long Island Lighting Company doing business as the Long Island Power Authority (LIPA)
  - New York State Electric & Gas Corporation
  - Niagara Mohawk Power Corporation doing business as National Grid
  - Orange and Rockland Utilities, Inc.
  - Power Authority of the State of New York (NYPA)
  - Rochester Gas and Electric Corporation
- **Peak Reliability/WECC:**
  - Alberta Electric System Operator
  - Arizona Public Service
  - Bonneville Power Administration
  - British Columbia Hydro Authority
  - California Independent System Operator
  - Idaho Power Corporation[2]
  - Los Angeles Department of Water and Power
  - Northwestern Energy
  - NV Energy
  - Pacific Gas and Electric
  - PacifiCorp
  - Public Service of New Mexico
  - Salt River Project
  - San Diego Gas and Electric
  - Southern California Edison
  - Tri-State Generation and Transmission
  - Tucson Electric Power
  - Western Area Power Administration
- **PJM Interconnection:**
  - Allegheny Power
  - Baltimore Gas and Electric Company
  - American Electric Power Service Corporation
  - Commonwealth Edison
  - Duquesne Light Company
  - First Energy Corporation
  - PECO Energy Company
  - PEPCO Holdings
  - PPL Electric Utilities
  - Public Service Electric and Gas
  - Rockland Electric Company
  - Virginia Electric and Power Company

1.1. COMPLEMENTARY OE SUPPORT OF SYNCHROPHASOR DEVELOPMENT

OE has supported the development of synchrophasor technology from its inception. During the SGIG and SGDP projects, the OE Transmission Reliability Program made additional strategic research and development (R&D) investments in synchrophasor technologies—and continues to do so—conducted in concert with SGIG and SGDP participants or building on their experiences. These efforts include:

- Providing technical support for NASPI with management support beginning in 2014.
- Accelerating development and adoption of interoperability standards for various elements of synchrophasor technology.
- Developing and enhancing applications that can leverage PMU data for grid reliability, including generator model validation, oscillation detection, oscillatory mode meters, voltage stability monitoring, non-linear state estimation, and automated PMU-based protection and control schemes.
- Documenting lessons learned and best practices for synchrophasor technology by funding detailed technical reports on topics including:
    - Comparison of PMU data visualization tools
    - Use of synchrophasor technology for integrating renewable energy sources
    - Support for technical standard IEC 61850-90-5 activities
    - Factors affecting PMU installation costs
    - Model validation using synchrophasor data
    - Diagnosing equipment mis-operations using PMU data
    - PMU data quality, validation, and conditioning
- Conducting "big data analysis" of PMU data to identify baseline conditions on portions of the North American grids and developing early pattern recognition for potential disturbances.
- Developing academic programs to enhance engineering education on synchrophasor technology.
- Conducting pre-commercial prototype development, demonstration, and field-testing with a utility host committed to installing the production-grade[7] application on its system.
- Exploring further improvement of synchrophasor communications network design and PMU data management tools.
- Continuing research and providing guidance into the design and maintenance of a cyber-secure communications system.

In addition, OE and the National Science Foundation (NSF) co-sponsor the Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT)[8] at the University of Tennessee at Knoxville. This is an NSF Engineering Research Center performing leading-edge research and providing advanced education on electric grid topics including synchrophasors, PMUs, and applications based on this technology. It is a collaboration between academia, industry, and national laboratories.

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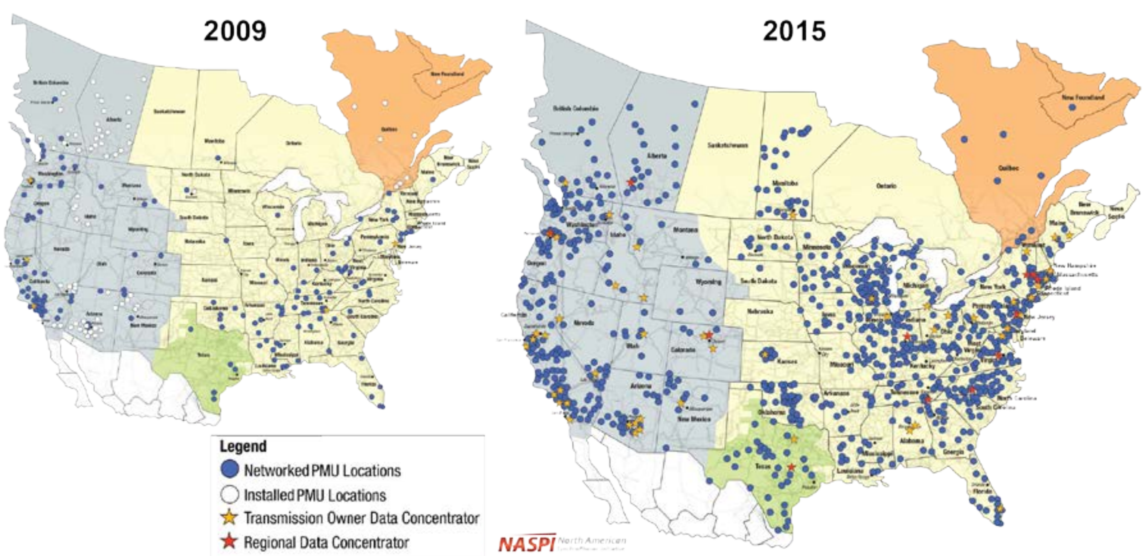
[7] "Production-grade" refers to meeting current industry standards for conformance, reliability, and data quality.
[8] Synchrophasor technology is a key part of building and managing an ultra-wide-area electric grid. More information is available at http://curent.utk.edu/.

2. SYNCHROPHASOR SYSTEM IMPLEMENTATION UNDER ARRA

Operators now have near 100% visibility of the behavior of the entire U.S. high-voltage transmission network, due in large part to synchrophasor deployments by ARRA projects. Synchrophasor technology encompasses high-resolution phasor measurement units (PMUs)—which report time-stamped data more than 30 times per second—and phasor data concentrators (PDCs) that collect and *synchronize* (or time align) PMU data to provide operators with precise grid conditions over wide areas.

In 2009 there were about 166 research-grade, networked PMUs in North America, concentrated in a few areas within the grid. By 2015, the ARRA projects had installed 1,380 additional networked PMUs and 226 PDCs that now provide grid operators and operations engineers with synchronized data across regions, enabling wide-area situational awareness. Project successes also encouraged project participants and other utilities to install hundreds of additional PMUs without government funding. The number of PMUs in North America has increased over tenfold from 2007, and more continue to be installed. Figure 2.1 shows the increase in PMU deployments from 2009 to 2015.

Figure 2.1 Synchrophasor Advancements in North America



Networked PMUs in North America increased from 166 in 2009 to over 1,700 in 2015.

PMUs installed by the ARRA synchrophasor projects provide significant system visibility. Participant PMUs **provide operators with visibility into the transmission systems that serve approximately 88% of the total U.S. load** and cover approximately two-thirds of the continental United States.[9] When the new ARRA project PMUs are added to existing PMUs and PMUs installed on other utilities' systems outside

[9] Eighty-eight percent of the total electric power delivered to U.S. consumers is provided by the ARRA synchrophasor project participants. The synchrophasor systems installed by these participants are able to observe ("see") this load. Source of load data: North American Electric Reliability Corporation, *2014 Long-Term Reliability Assessment*, November 2014, http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/2014LTRA_ERATTA.pdf.

the projects, the total North American PMU installations “see” the entire high-voltage transmission grid in the United States.

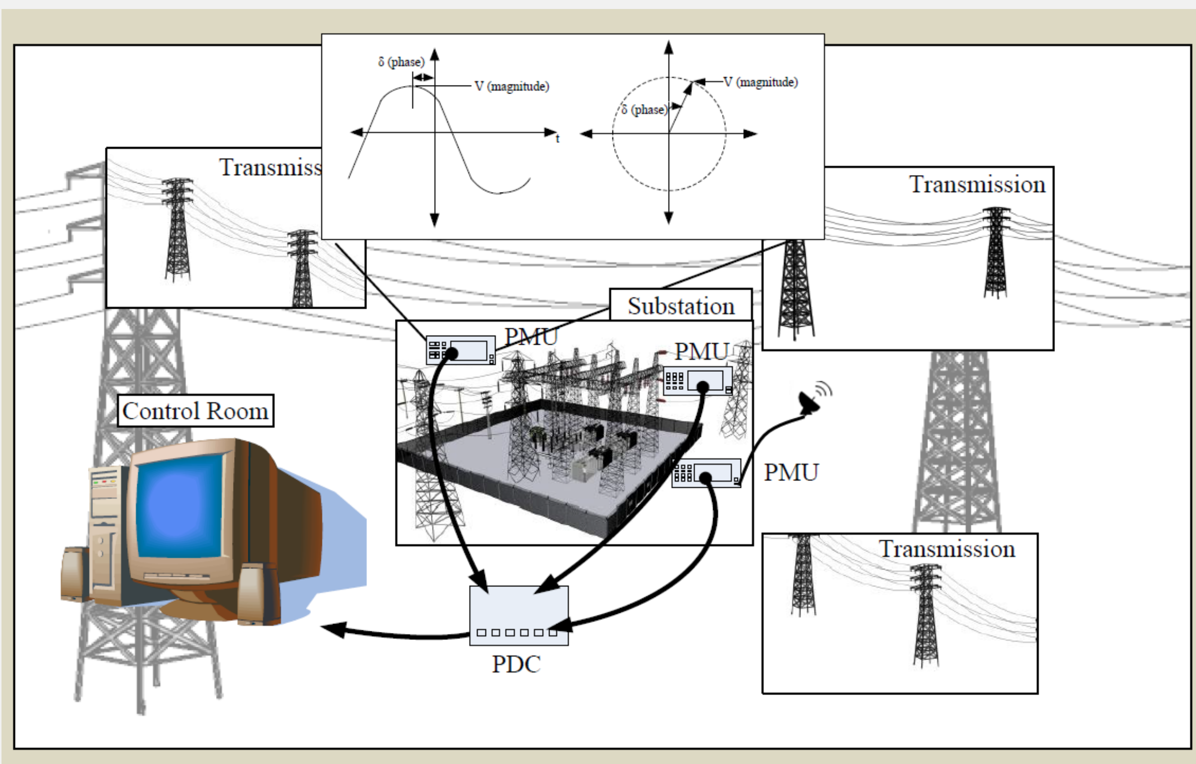
Synchrophasor Technology Fundamentals

Monitoring devices called phasor measurement units (PMUs) measure the instantaneous voltage and current, and calculate frequency, at specific locations in an electricity transmission system. These parameters represent the “heart-beat” and thus the power system’s health. Voltage and current are parameters characterizing the delivery of electric power from generation plants to end-user loads, while frequency is the key indicator of the balance between electric load and generation.

PMUs sample power grid conditions at a rate of several hundred times per second and convert the measured parameters into phasor values, typically 30 or more values per second. A phasor is a complex number (mathematical representation) that represents the magnitude and phase angle of the sinusoidal waveforms of voltage or current at a specific point in time. The cutout at the top of Figure 2.2 depicts the magnitude and phase angle in the time based waveform (in the left graph) and the same values in vector form (in the right graph). The PMUs also add a precise time stamp to the phasors based on the Global Positioning System (GPS) time signal. This turns phasor values into synchrophasors. The synchrophasor values provided by PMUs in different locations and across different power industry organizations are sent through communications networks to phasor data concentrators (PDCs) which collect and time-align the data.

The resulting PMU data provide transmission grid planners, operators, and engineers with a high-resolution “picture” of conditions throughout the grid, enabling capabilities such as wide area situational awareness, oscillation detection and monitoring, and detection of equipment problems not previously observable.

Figure 2.2 Collection and Flow of Synchrophasor Data

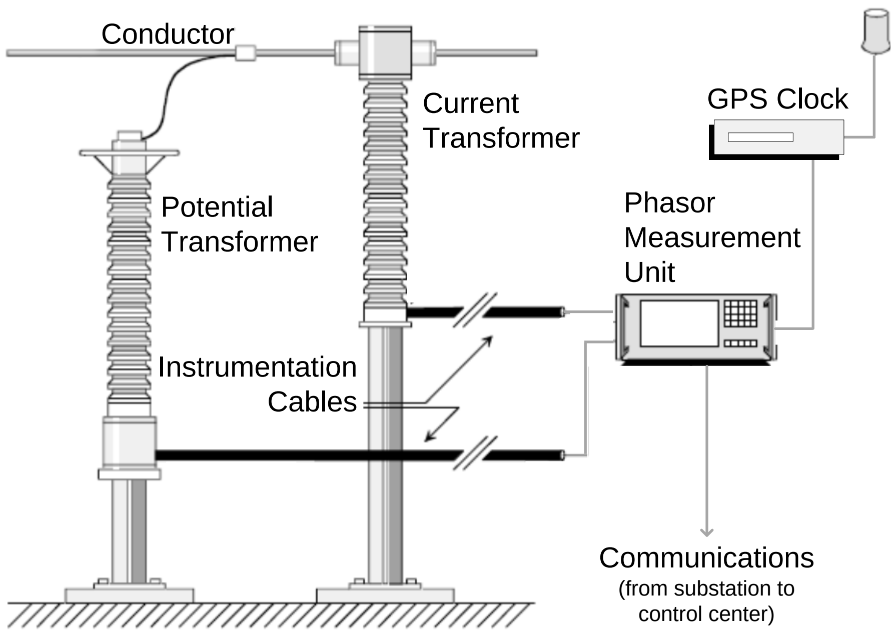


There are a number of references available that describe in detail the various components of a synchrophasor system. Some key references are:

- M. Paolone et. al., "Synchrophasor Fundamentals: from Computation to Implementation," Tutorial, IEEE PES General Meeting, July 21-25, 2013, https://www.naspi.org/File.aspx?fileID=1384.
- North American Electric Reliability Corporation, *Real-Time Application of Synchrophasors for Improving Reliability*, October 18, 2010, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.
- D. Novosel, "Tutorial on PMU Technology and Applications," June 5-7, 2006, http://www.ceb5.cepel.br/arquivos/artigos_e_documentos/med_fasorial/Damir.pdf.

Figure 2.3 depicts the installation of a PMU in a substation.

Figure 2.3. Representative PMU Installation within a Substation



The installation of synchrophasor systems required that each of the ARRA participants conduct a coordinated and comprehensive set of activities, including assessing synchrophasor requirements, developing procurement specifications, installing and commissioning PMUs, validating PMU data, and operationalizing their systems.

Sharing information through forums such as NASPI[10] provided a ready platform for project participants to support each other in developing best practices and sharing lessons learned. The activities involved in building out the synchrophasor infrastructure will be discussed in the following sections.

[10] NASPI was supported by NERC until 2013 and is now supported by DOE.

2.1. BUILDING THE INFRASTRUCTURE

Most of the pre-ARRA PMUs on the electric transmission grid were research-grade PMUs.[11] While useful, these devices did not perform to the standards required for the reliable operation of the power grid. Many of the devices were developed either internally by industry members, or by vendors working with industry members, as one-off, small-scale experiments. At that time, grid operators used synchrophasor technology primarily for research by academia and analysis by vendors. Networking and data sharing were generally limited to bilateral agreements between industry and its academic and industry partners.

The ARRA synchrophasor projects marked the first time that many transmission owners and operators had procured and installed modern, production-grade[12] PMUs on an operational scale. It also marked the first time that many ISOs and RTOs deployed region-wide synchrophasor-based data applications.

While the business of generating and delivering electricity is common, every electric utility is unique. Each utility has its own set of electrical assets – including generating stations, transmission and distribution (T&D) networks, control centers, and interconnections with neighboring systems. Each operates under a specific set of constraints – regulatory (e.g., FERC, NERC, and state public utility commissions), financial, and system operating limits. Each utility's customer base is different – residential; commercial; industrial; institutional; high priority customers such as communications centers, police, fire, and military bases; and customers that cannot tolerate extended outages such as hospitals. Each utility has developed its own procedures for operating and maintaining its power system and for mobilizing utility field crews. Thus, the synchrophasor systems deployed by the ARRA participants were tailored to their unique situations. Whatever the design approach taken, each utility identified and implemented appropriate cybersecurity measures to comply with all of their company's NERC Critical Infrastructure Protection (CIP) requirements.

Since the PMU devices drive all the other parts of the synchrophasor infrastructure, achieving a significant penetration of PMU devices on the electric transmission grid is critical to achieving tangible benefits from this technology. As a way to assess progress in building out the physical infrastructure, project participants reported on the number of PMUs installed and networked, number of substations where the PMUs were installed, number of signals provided by PMUs, and the number of phasor data concentrators (PDC). Table 2.1 illustrates the scale of the infrastructure installed by the synchrophasor projects.

The participants in total installed 1,380 PMUs. In addition to the large number of PMUs installed, project participants installed a total of 226 phasor data concentrators (PDC). PDCs, an intermediate component of the infrastructure, collect data from PMUs and from other PDCs and move the composite data to other parts of the synchrophasor system.

Two more measures of the scale of the ARRA projects are the number of substations equipped with synchrophasor equipment and the number of distinct synchrophasor signals produced (e.g. voltages, currents, and frequencies). Both of these metrics are indicative of the types of capabilities which may be

[11] Research-grade PMUs are not expected to meet firm, quantifiable service level requirements.

[12] Production-grade – meaning they meet current industry standards for conformance, reliability, and data quality.

deployed and the extent to which each of those capabilities is useful. The number of substations equipped with PMUs and the locations of those substations drive the capabilities that can be deployed.[13] Project participants installed PMU equipment in 778 substations. Project PMUs provided over 11,500 signals of high-definition electric grid data. Synchrophasor systems also required high-bandwidth communications to transport PMU data.[14]

Table 2.1 ARRA Synchrophasor Project Equipment

Recipient	Installed Equipment[15]			
	PMU Devices	PMU Substations	PMU Signals	PDC Count
ATC Comm.*	N/A	69	N/A	N/A
ATC PMU	49	45	620	45
CCET	19	16	19	3
Duke Energy	103	52	1,872	4
Entergy	49	49	≥ 49	16
FPL	45	45	≥ 45	13
Idaho Power	8	4	100	0
ISO-NE	73	40	383	9
Lafayette	31	31	≥ 31	4
Midwest Energy	8	1	≥ 8	1
MISO	260	166	1,928	40
NYISO**	41	41	759	11
PJM	301	85	2,698	23
WECC / Peak	393	134	3,032	57
TOTAL	**1,380**	**778**	**≥ 11,544**	**226**

*ATC Communications project installed 110 miles fiber optic cable.
** NYISO also installed 938 MVAR of switched capacitors.

[13] The location of PMUs in the grid determines the capabilities that can be enabled. For example, PMUs must be located close to the edges of the system to assess the stress that the grid is operating under. PMUs must be located close to the plant to monitor the performance of a generating station.
[14] For example, in the West, a low latency (less than 30 ms requirement) and high availability (greater than 99.99% requirement) network for synchrophasor communication systems has been established.
[15] Data reflects the final report provided by each project participant and is current as of September 30, 2015.

In addition to equipment, the ARRA funds were used to install communications networks, develop and deploy software enabled by synchrophasor data, and to train power system engineers and operators in the use of the software.

2.1.1 Major Factors in Design and Deployment of Synchrophasor Systems

Interviews of nine companies[16] that participated in the ARRA synchrophasor projects revealed several key drivers of costs and complexities for installing PMUs. In order of relative importance, these are:

- Communications
- Cybersecurity
- Labor
- Equipment

Communications: The availability of adequate communications to support the transmission of PMU data, including installations and upgrades, was the most significant factor affecting PMU acquisition and installation costs. Synchrophasor systems have greater transmission and data quality requirements than traditional or other grid monitoring systems. As a result, the communication requirements were a major factor for the selection of PMU locations, such as in the case of Entergy. Duke Energy reported that, absent adequate existing communications, upgrades to communications infrastructure increases the cost of installing PMUs by a factor of seven. However, the cost of installing additional PMUs is relatively low once a high-speed backbone communications network is in place.

Cybersecurity: Cybersecurity requirements were the second most significant cost driver. These requirements are directly related to how critical the PMU data are to utility functions:

- **Mission-critical systems:** Used for making operational decisions or to drive automatic control actions.
- **Mission support systems:** Used for monitoring system conditions and for offline capabilities that do not directly affect operations.

One utility estimated that deploying a mission-critical synchrophasor system increased its PMU installation costs by a factor of two over the amount required for deploying a mission-support PMU system.

Labor: Utilization of labor for installing and commissioning PMUs was the third most significant cost driver. Two approaches for labor deployment emerged:

- **Specialized crew:** Specialized training and tools were provided to a single crew which handled all of the installations (minimizes learning curve).

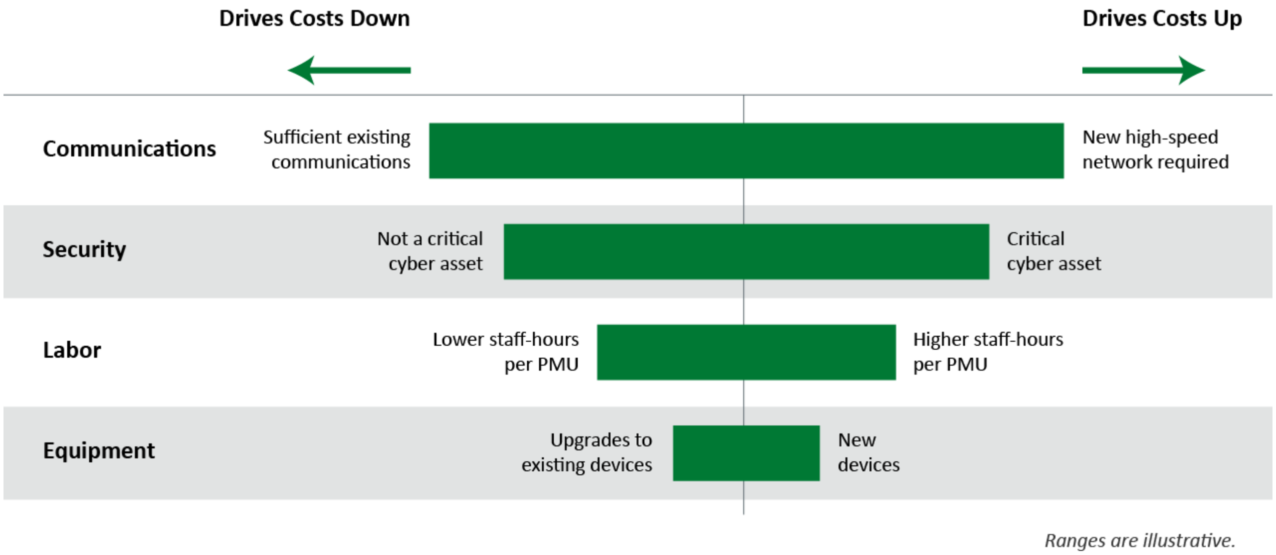
[16] The nine companies interviewed were American Transmission Company, Bonneville Power Administration, Duke Energy Carolinas, Entergy Corporation, Idaho Power Company, Manitoba Hydro, Midcontinent Independent System Operator, Oncor Electric Delivery Company, and Pacific Gas and Electric Company. The results of the interviews are documented in the report “Factors Affecting PMU Installation Costs,” October 2014, available on https://www.smartgrid.gov.

- **Decentralized crews:** Training was provided to technical personnel across the system where PMUs were being deployed (minimizes travel time to and from installation sites).

While labor was a significant cost driver, neither approach emerged as optimum. However, one approach that significantly reduced labor costs was to coordinate PMU installations with other planned substation outages.

Equipment: The least significant cost driver was the PMU hardware cost (see Figure 2.4). This was typically less than 5% of the total installed system cost. PMU equipment costs, even though relatively small, varied widely. On the low end, some participants implemented PMU capabilities by making software upgrades to electronic devices already in service. On the high end, some participants required the installation of new standalone PMUs.

Figure 2.4 Major PMU Acquisition and Installation Cost Drivers and Their Relative Impacts



A more complete description of the cost impacts – as well as other factors affecting the design of synchrophasor systems – is documented in the report "Factors Affecting PMU Installation Costs," available on smartgrid.gov.[17] As utilities gain more experience with synchrophasor technology and share experiences and insights, the relative cost of installing PMUs will continue to decrease.

2.1.2 Synchrophasor Data Quality

Fundamentally, the term "data quality" represents the extent to which data are accurate and timely. Accuracy refers to how well the data represent the physical phenomenon that is being measured. Timeliness refers to the data's being available in the timeframe required by the capabilities the data inform.

[17] U.S. Department of Energy, *Factors Affecting PMU Installation Costs*, September 2014, https://www.smartgrid.gov/document/factors_affecting_pmu_installation_costs.html.

The quality of data from synchrophasor systems has improved significantly as a result of the ARRA Smart Grid projects, setting the stage for production use of PMU data requiring standards, testing, and verification. Because the data were to be used for planning and operational activities, many of the project participants developed and implemented rigorous procedures for monitoring and validating the performance of the synchrophasor data systems and attendant data quality, and they shared information on these best practices among themselves and with the broader synchrophasor community.

Figure 2.5 Pacific Gas & Electric's Proof of Concept Testing Facility

Source: PG&E

Best Practices: Proof of Concept Testing Facility - PG&E developed a proof of concept facility for testing, process development, equipment trouble-shooting, and data impairment tests prior to field installation.

Each project participant was asked to report on their synchrophasor system's performance using the method most appropriate to their enterprise. Because the measurement techniques varied from project to project, it is not possible to calculate a quantitative measurement of the improvement in system performance. However, looking at the change in metrics each recipient reported over time, data quality – in terms of reliability and accuracy – increased significantly over the project timeframe, and the "trustworthiness" of synchrophasor-derived insights increased accordingly.[18]

Activities conducted by project participants for monitoring and improving the quality of the synchrophasor data include:

- Peak Reliability: The PMU to PDC communication is controlled by each member. 95% of the PMUs deliver data that meets all of their quality standards. The wide area network availability is 99.99%.
- Idaho Power Company: The PMU data are sent to the PDC over dedicated circuit through a private communications network, and the PDC output is sent to WECC through a firewall and a WECC edge router.
- ISO-NE: Transmission owners (TOs) have a communication link from their PMUs to their PDC, where their data are concentrated and forwarded to ISO-NE's PDC. Routers are located at both the TO and the ISO-NE connection endpoints. Firewalls are present at both ends, and PMU data are encrypted before going onto the communications network. The total data success rate is around 95%. The PMU failure rate has been similar to legacy SCADA equipment. Performance data on availability, latency, and quality is archived on the PDCs and can be reviewed.

[18] Poor data quality has been a long-standing issue in the synchrophasor community. Accordingly, until now the results and insights presented by PMU applications have generally been considered "suspect" until they were validated against other data sources.

- PJM: TOs send data over private networks to the PDC at PJM. The PJM PDC consolidates the inputs and sends out composite data to PJM's wide area monitoring system. PJM established a Phasor Data Quality Task Force to resolve issues and work toward common goals.
- NYISO reported about 86% availability in PMU signals. Data quality is continuing to improve with the inclusion of the data in disturbance reporting and other facets of grid operations, including data testing within the phasor-enhanced state estimation function.
- MISO reported its PMU data quality improved from an initial 91% availability to over 96% availability.

Participants have come to rely on synchrophasor data to inform planning and operating procedures. As a result, the consequences of the data not being available now represent unacceptable risks – to system reliability, costs, and/or efficiency. The project participants' efforts to maintain high-quality PMU data have resulted in more stringent maintenance requirements for the synchrophasor systems to ensure their accuracy and reliability are within prescribed limits.

2.2. EVOLVING THE TECHNICAL STANDARDS

The development of technical standards is a prerequisite for widespread adoption of synchrophasor technology in the operation of interconnected power systems. Interconnecting data systems of any type and achieving interoperability of devices from multiple manufacturers requires standardization of the various components and software. This necessitates development of formal standards for the device performance and communications protocols.

The ARRA projects accelerated development of broad-reaching domestic and international standards for synchrophasor technology.[19] The project schedules – driven by timelines in the ARRA legislation – necessitated a concentrated collaboration by standards-setting bodies such as the National Institute of Standards and Technology (NIST), the Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), and others. The primary technical standards that were updated include:

- IEEE C37.118.1: Standard for Synchrophasor Measurements for Power Systems.
- IEEE C37.118.2: Standard for Synchrophasor Data Transfer for Power Systems.
- IEC 61850-90-5: Synchrophasor Data Communications and Protocols.
- IEEE C37.238: Standard Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications.
- IEEE C27.242: Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMU) for Power System Protection and Control.
- IEEE C37.244: Guide for Functional Requirements for Phasor Data Concentrator.

The Energy Independence and Security Act of 2007 gave NIST the responsibility to develop a framework[20] of protocols and model standards to achieve interoperability of smart grid devices and systems. OE funded NIST, national laboratories, the Electric Power Research Institute (EPRI), and others

[19] The first standard for synchrophasors was IEEE 1344 after the introduction of phasors for power systems in the 1980s, which further developed into standard IEEE C37.118 in 2005.
[20] National Institute of Standards and Technology, *NIST Special Publications 1108: Framework and Roadmap for Smart Grid Interoperability Standards*, Release 1.0 to 3.0, http://www.nist.gov/smartgrid.

to accelerate the development and updating of synchrophasor technology standards for the ARRA-funded projects. Both NASPI and NIST provided forums for subject matter experts to identify requirements for synchrophasor functionality and collaborate in developing the standards.

The Performance Requirements, Standards & Verification Task Team (PRSVTT) was formed under NASPI to identify needed standards, standards updates, and harmonization requirements.[21] Its goal is to support the adoption of phasor measurement technology through standardization by providing a forum for discussing, developing, and monitoring system and component requirements. The Task Team includes chairs and members of the IEEE Power System Relaying Committee that developed earlier synchrophasor standards and other experts in synchrophasor technology development, deployment, and use. The Task Team created white papers and draft technical standards to socialize the new concepts. This in turn shortened the time required by the formal standards setting bodies to create new standards and modify existing standards. The PRSVTT worked to harmonize the IEEE C37.118 standard with the IEC 61850 standard.

Testing and certification protocols are also required to ensure that all PMU devices will perform to the currently approved standards. For this reason, the project participants and other industry leaders engaged with the IEEE Synchrophasor Conformity Assessment Steering Committee (SCASC) to develop a conformity assessment program (CAP) for PMU testing and certification. The CAP was adopted in 2014 to provide an unambiguous, systematic way of PMU testing according to IEEE C37.118. As a result of this program, PMU tests by labs that comply with the uniform test methods will provide certainty that a PMU either meets or does not meet the requirements in the approved technical standards regardless of the laboratory that conducted the tests. As of September 2015, the IEEE SCASC has published Version 2 of the IEEE Synchrophasor Measurement Test Suite Specification, which was modified as a result of findings during pilot tests.

These activities were crucial in building out the infrastructure in the ARRA synchrophasor projects, and will facilitate future sharing of PMU data across many, diverse operating entities.

[21] North American SynchroPhasor Initiative, "Performance Requirements, Standards & Verification Task Team," accessed February 2016, https://www.naspi.org/prsvtt.

2.3. CAPABILITIES PROVIDED BY SYNCHROPHASOR SYSTEMS

In addition to deploying the physical infrastructure, project participants implemented the processes and procedures and software that utilize the data provided by the PMUs to improve existing technical capabilities or to create new capabilities.

In electric transmission systems, capabilities are generally specific to one of two operational scenarios:

- **Real-time capabilities:** These capabilities are employed in the minute-by-minute operation of the electric grid. These are generally carried out by power system operators or operational engineers.
- **Study mode/planning capabilities:** These capabilities are employed in planning for transmission system expansions, generation additions and retirements, system protection, and studying unexpected events or system behaviors. These are generally carried out by power system engineers.

As the project participants began utilizing synchrophasor data, a set of commonly-adopted capabilities emerged. These are described in detail in Appendix 2 and summarized in Table 2.2.

Table 2.2 Recovery Act Smart Grid Investments in Synchrophasor Capabilities

CAPABILITIES	ATC[1]	CCET	Duke Energy	Entergy	FPL	Idaho Power	ISO-NE	Lafayette	Midwest Energy	MISO	NYISO	PJM	WECC / Peak Reliability
REAL-TIME CAPABILITIES													
Phase angle monitoring	In Development & Testing	Fully Implemented	Fully Implemented	In Development & Testing	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Oscillation detection and monitoring	In Development & Testing	Fully Implemented	Fully Implemented	In Development & Testing		In Development & Testing	Fully Implemented			Fully Implemented	Fully Implemented	In Development & Testing	Fully Implemented
Voltage stability monitoring	In Development & Testing	Fully Implemented		In Development & Testing	Fully Implemented	In Development & Testing	In Development & Testing	Planned		Fully Implemented	Fully Implemented		Fully Implemented
Event detection, management, restoration	In Development & Testing	Fully Implemented	In Development & Testing	Fully Implemented			In Development & Testing		Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Islanding detection, management, restoration	In Development & Testing			In Development & Testing						Fully Implemented			Fully Implemented
Equipment problem detection	Fully Implemented	Fully Implemented	Fully Implemented		Fully Implemented		Fully Implemented			Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Wide area situational awareness	In Development & Testing	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	In Development & Testing	Planned	Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
STUDY MODE CAPABILITIES													
Model validation and calibration	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented		Planned	Fully Implemented	Fully Implemented	In Development & Testing	Fully Implemented
Post-event analysis	Fully Implemented		Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Renewable resource integration		Fully Implemented	Planned	Planned		Fully Implemented							Fully Implemented
Operator training		Fully Implemented		In Development & Testing						In Development & Testing	Fully Implemented	Fully Implemented	Fully Implemented

KEY to status of capabilities development: Planned | In Development & Testing | Fully Implemented (real-time or study mode)

Note 1: ATC had two projects: a PMU project and a Communications project. The Communications project supports capabilities listed for the PMU project.

2.3.1 Real Time Capabilities

Phase angle monitoring: The angular (phase angle) differences in voltages between two locations on a transmission grid provide information on power system stress and stability.

The grid is said to be "stressed" when power transfers are high and critical components in the grid operate close to their physical (thermal) limit. In this state, the ability of the power system to adjust to an equipment outage or other failure is reduced.

System stability is the ability of the system to move to a secure and steady operating condition following a disturbance (equipment outage or other failure). Some systems have stability limits on certain transmission paths. In these systems, high power transfers across those paths cause instability somewhere on the system. Power transfers across those paths are therefore limited (to the "stability limit") in order to avoid putting the power system into an unstable configuration.

Knowing the extent to which the system is stressed and the proximity of the system to its stability limit lets operators know how much discretion they have in adjusting operating conditions and how much time they have to make the adjustments.

The phase angle difference is also a decisive factor for reclosing transmission lines. Traditionally, phase angles are calculated off-line with simulations and state estimation based on line flows. Now PMUs can measure phase angles directly, making them immediately available to system operators who can then monitor and remediate stressed power system conditions as they develop.

Oscillation detection and monitoring: When the electrical system is physically disturbed[22], the electrical characteristics (voltages, currents, and other parameters[23] derived from these) of the electrical system are also disturbed. Because these voltages, currents, frequencies, etc. tend to cycle quickly (analogous to physical vibrations), the disturbances are referred to as "oscillations." Oscillations become a concern when they grow over time instead of waning. Oscillations also occur due to problems with control systems – most significantly generator controls. A system's ability to damp oscillations is an important indicator of system stability. PMU data provide a way to detect the presence of oscillations, determine the extent to which an oscillation poses a threat to the electric grid, and monitor the oscillation to determine if conditions worsen.

Voltage stability monitoring: Maintaining voltage at levels that remain stable, even as demands from loads change and outages occur, is of paramount importance to a power system operator. PMU-enabled tools provide the system operator with insights as to the proximity of the system to its voltage stability limit.[24] Voltage problems can develop almost instantly, so the ability to quickly detect and diagnose voltage problems and develop remedial actions is extremely valuable.

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[22] The electrical system is considered disturbed when there is a sudden loss of one or more generators, transmission lines, or loads.

[23] Other parameters derived from voltages (in Kilovolts) and currents (in Amperes) typically include frequency (in Hertz), phase angles (in degrees or radians), power factor angles (in degrees or radians), real power (in Megawatts), reactive power (in Megavars), and apparent power (in Megavoltamperes).

[24] The voltage stability limit is the lowest voltage at which the power system will operate without blacking out loads. The blackout could be local or cascade to a wide-spread power outage.

Event detection, management, and restoration: When an event that perturbs the normal operation of the power system, such as a tripped transmission line or tripped generator occurs, operators must take action to mitigate its effects. Good event detection, management, and restoration allows system operators to understand the event, minimize its impact, and restore service as quickly as possible. PMU data provide early indications of grid stress, including abnormal voltages, phase angles, frequencies, and power flows. As the event occurs, PMU data provide high-resolution graphic displays that show the system operator how the system is reacting. These displays provide insights into the type of event taking place and its extent. The sooner an operator understands the event, the more options are available for mitigating the event.

Islanding detection, management, and restoration: Islanding is the separation of a part of the power system from the larger power grid. Islands can occur when multiple lines are forced out of service thus isolating a region of the grid. This usually happens as a result of a major storm. The synchrophasor technology provides participants with the ability to detect, monitor, and better manage islands when they occur. Synchrophasor technology can quickly identify an island, allowing operators to synchronize the island to the larger power grid and restore its connection to the rest of the grid.

Equipment problem detection: Detecting equipment problems early can prevent unplanned outages due to equipment failures. Equipment failures can cause customer outages, costly equipment replacement, and could even damage other equipment. Synchrophasor technology has provided the capability to detect and diagnose failing equipment (for example, being able to detect intermittent off-normal voltages undetectable by SCADA), allowing for replacement during planned outages.

Wide area situational awareness: Data from PMUs provide a high-resolution view of localized electrical phenomena. If PMU data are widely shared, conditions that develop across an entire interconnection can be detected and monitored. Wide area situational awareness is the capability for grid operators to see key parameters of the bulk electric power system beyond their service territory – across an entire interconnection with enough shared data. Wide area displays allow all operators in an interconnection to have a common understanding of the condition of the overall electric grid, resulting in better collaboration and better solutions to emerging problems.

2.3.2 Study Mode/Planning Capabilities

Model validation and calibration: Models are mathematical representations of power system components. Models are used in all aspects of power system planning and operations. Typical components that are modeled in the power industry include:

- Conventional generating units (nuclear, hydro, steam)
    - Generator dynamics
    - Exciters
    - Turbines
    - Governors
- Motors
- Wind generating units
- HVDC (high-voltage direct current) devices
- Electronically-coupled (i.e., inverter-driven) loads

- Power system stabilizers
- Power system components (transformers, circuit breakers, transmission lines, etc.)

The accuracy of these models drives the efficiency and effectiveness of long-term capital investments and real-time system operations. Therefore, the quality of grid operation is strongly dependent on the quality of these models. Model validation improves the mathematical representation of the various components of the electric grid, thus allowing analytical engines to provide more accurate insights. Synchrophasor data enable engineers to evaluate, validate, and improve their models more quickly, accurately, and frequently, and with less effort. With more accurate models, analysis tools provide better insights to decision makers. NERC standards – both existing and planned – require that the models used to plan and operate power systems be validated at regular intervals.[25] Synchrophasor data provide a mechanism for validating the dynamic performance of power system components – with the most significant being large generators – without the need to take these components offline.

Post-event analysis: After a system disturbance, utilities study the sequence of events that led to the problem in order to prevent it from reoccurring. The insights gained by these analyses allow operators and planners to learn what initiated the system event, how the system responded to the incident, and most importantly, what can be done to prevent similar events from occurring. PMUs provide high-resolution, time-stamped data so that an accurate, temporally aligned record of events can be constructed quickly. Synchrophasor technology has significantly reduced the labor and cost requirements for such analyses, allowing engineers to investigate many events that they previously would not have had time to analyze.

Renewable resource integration: Large-scale renewable generation plants are relatively new to the bulk electric system, so their plant characteristics and control algorithms need to be better understood in the context of the operation of the grid as a whole. This is especially true as they become a greater portion of the generation. Renewables can be challenging to manage in the grid due to the as-available nature of their production and the vendor specific characteristics of their control systems. Synchrophasor systems are particularly useful for monitoring, modeling, managing, and integrating distributed generation and renewable energy into the bulk power system. PMU data show in high-resolution how the renewable generation facilities affect the grid and respond to changes in grid conditions.

Operator training: Power system operators need to understand the electric grid's behavior in real time in order to know which procedure to apply and when to apply it. All of the ARRA-funded projects provided training to operators on the use and interpretation of PMU data and new synchrophasor tools. This included incorporating PMU data into Dispatcher Training Simulators so operators can gain first-hand experience with the new synchrophasor data displays and playback of the data and develop a more fundamental understanding of the effects of various dynamic power system phenomena and their effects on the power grid's operation as well as test alternative mitigation measures.

Each project participant deployed the specific capabilities appropriate to their enterprise. Table 2.2 shows the synchrophasor-enabled capabilities implemented by each of the project participants along

[25] North American Electric Reliability Corporation, "Project 2010-03 Modeling Data (MOD B)," accessed February 2016, http://www.nerc.com/pa/Stand/Pages/Project2010-03ModelingData(MOD-B).aspx.

with an indication of the status of the implementation (Planned; In Development & Testing; Fully Implemented). As a result of the ARRA projects, phase angle monitoring, wide-area situational awareness, model validation & calibration, and post-event analysis are the most widely deployed functions – and therefore the functions that are likely to mature most quickly.

2.4. OPERATIONAL USE OF SYNCHROPHASOR SYSTEMS

As part of the ARRA Smart Grid projects, project participants designed synchrophasor systems for their electric grids, built out the infrastructure (installed devices and tested PMU system performance), and evolved the technical standards. Once the infrastructure was built out, project participants set to transitioning the new assets to productive use. Activities for making synchrophasor systems operational fell into two categories:

- **Operating and Planning Procedures:** Creating new procedures or modifying existing procedures to leverage the newly-available PMU data.
- **Data Sharing Agreements:** Establishing agreements with outside entities that specify how PMU data are shared with outsiders and how outside data are handled internally.

2.4.1 Operating and Planning Procedures

Electric operating companies depend on specific, detailed procedures to guide their system planning and operations. The extent to which existing operating procedures are revised and new procedures adopted to employ PMU data is an indicator of the degree to which the synchrophasor system is being operationalized.

Incorporating a new procedure into power system operations is a time-consuming and elaborate process since it involves thoroughly validating the procedure over different systems conditions that are characteristic of different seasons of the year. Some of the ARRA synchrophasor projects have been able to implement procedures[26] even though these synchrophasor systems have only been in full operation approximately two years. Five project participants have reported adoption of new procedures:

- In recognition of the value that synchrophasors provide to grid operations, the Electric Reliability Council of Texas (ERCOT) created a Phasor Measurements Task Force and the ERCOT communications handbook was updated to include a section on synchrophasors.
- Idaho Power Company (IPC) developed and implemented a procedure for generator model validation using PMU data.
- MISO implemented internal procedures for the use of synchrophasor tools and data.
- NYISO developed one operating procedure that makes use of synchrophasor data to enhance wide-area situational awareness.
- WECC (Peak Reliability):
    - o California Independent System Operator (CAISO) implemented a procedure to monitor transmission path stress and to guide restoration for four major paths using phase angle differences between the ends of the transmission lines. These values are compared with the

[26] "Implementation" in this report refers to having a validated use of PMU data vetted for informing planning or operations processes.

energy management system's calculated values, displayed in the control room, and shared with three other WECC members.
    - Bonneville Power Administration (BPA) included information on PMU status within one of its operating procedures.

Two participants are far along in implementing additional PMU-based procedures:

- ERCOT (CCET) established a Phasor Measurement Task Force (PMTF) to define operator priorities and benefits, and to identify processes and procedures that would be enhanced by using PMU data. Language was prepared on disturbance monitoring and system protection for inclusion in the ERCOT Nodal Operating Guides that support the protocols that guide control room operations. Recommendations have been submitted to ERCOT stakeholders for review.
- WECC member BPA plans to train their operators on the use of oscillation detection software applications and is working on revisions to various dispatcher standing orders that address oscillation risks.
- WECC member Salt River Project is working on a synchrophasor manual to help operators understand frequency, voltage, and power flow graphs in the control room.

In addition to adoption of new procedures, there is consistent, though not mandatory, use of PMU data:

- Twelve participants are using PMU data to inform their power system operations.
- Eleven participants are using PMU data to inform their power system planning.

All of the project participants considered cybersecurity requirements as part of their procedure development process. They each developed and implemented plans that were reviewed at the project review meetings by DOE and their subject matter experts. Since the topics included business sensitive material, cybersecurity discussions are out of scope for this report.

2.4.2 Data Sharing Agreements

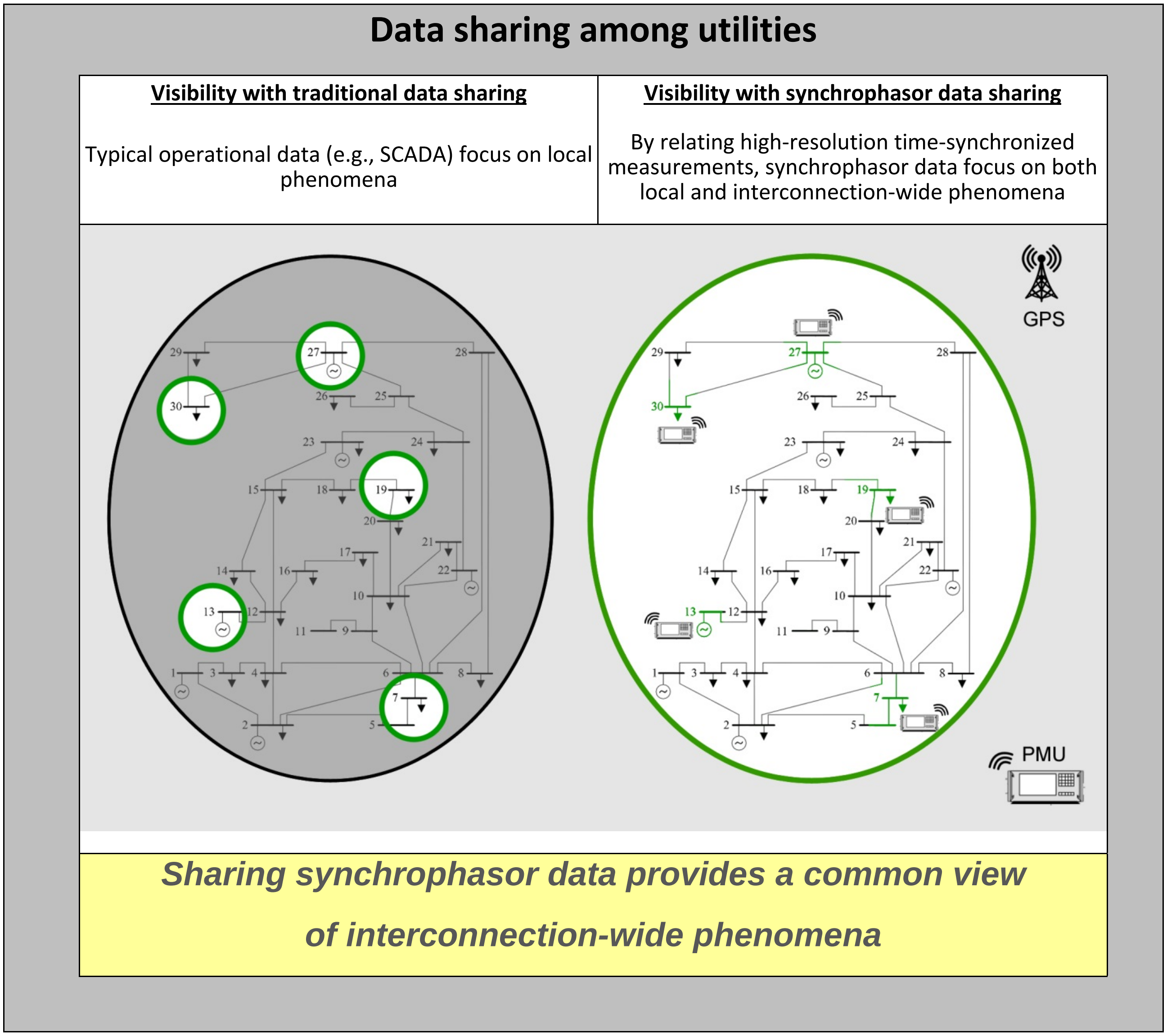
Synchrophasor data provide insights into both local and interconnection-wide phenomena (see Figure 2.6). Since there are many other sources of data for local phenomena, the extent to which data are shared across operating companies is a measure of the extent to which interconnection-wide PMU capabilities are being operationalized.

Under the ARRA projects, the sharing of synchrophasor data has greatly increased between TOs and their ISOs. To some extent, synchrophasor data sharing has increased between RTO regions. Within the three U.S. interconnections (Western, Eastern, Texas) the most significant example of improved data sharing is the Western Interconnection Synchrophasor Project (WISP). In addition to the technical infrastructure, WECC/Peak negotiated the WECC Synchrophasor and Operating Reliability Data Sharing Agreement.[27] Data are shared across the entire WECC region involving all balancing authorities, transmission owners and operators, and reliability coordinators.

ERCOT is also sharing synchrophasor data across the entire Texas Interconnection.

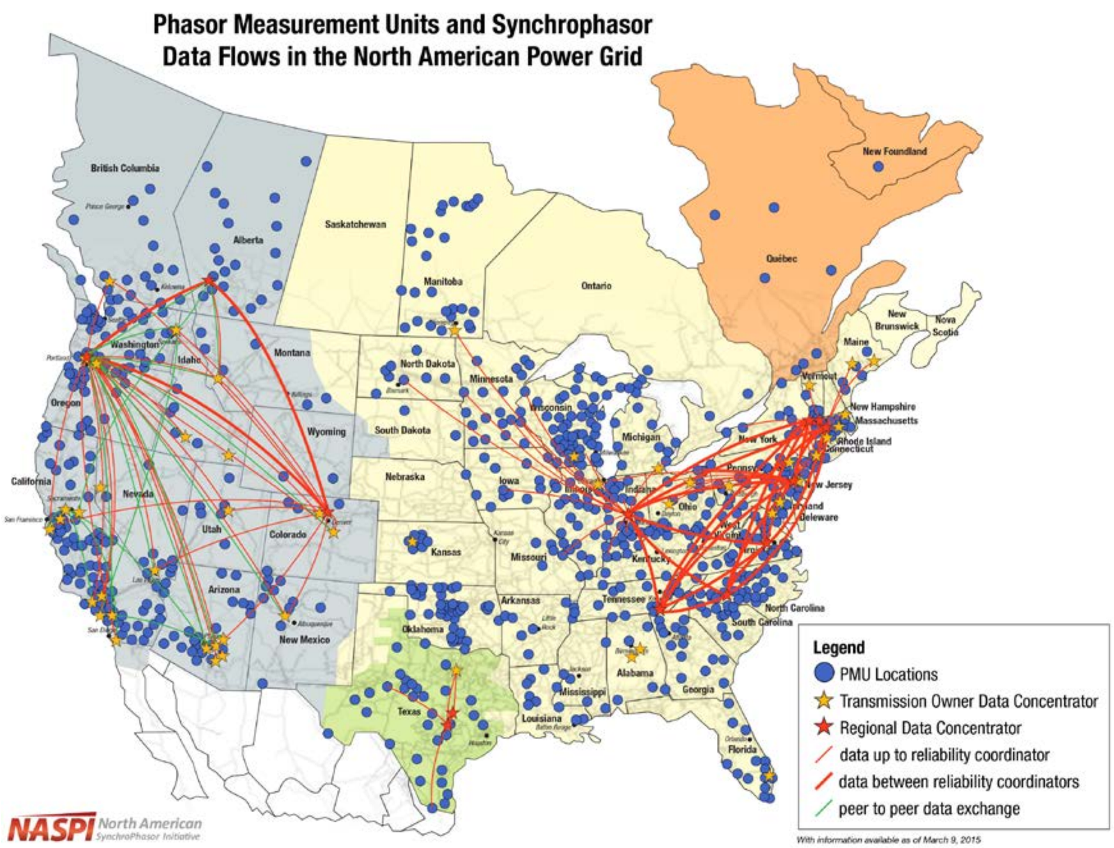
[27] Western Electricity Coordinating Council, "WECC Synchrophasor and Operating Reliability Data Sharing Agreement," March 6, 2012, https://www.peakrc.org/aboutus/Documents/UDSA%20Final%20%20v0.1_rs.pdf.

Figure 2.6 Data Sharing Increases Visibility among Utilities



Recognizing the importance of sharing operating reliability data including both SCADA and synchrophasor data interconnection-wide, utilities in the Eastern Interconnection are transitioning to the Eastern Interconnection Data Sharing Network (EIDSN)[28] – a new network for sharing operating reliability data, including both SCADA and synchrophasor data, among appropriate entities. The new network is a replacement for NERCnet, the legacy network over which pertinent operating reliability data has been shared. EIDSN is a nonstock, nonprofit corporation. The following project participants are already sharing synchrophasor data within the Eastern Interconnection: ATC (member of MISO), Duke Energy (member of PJM), ISO-NE, MISO, and NYISO (see Figure 2.7).

Figure 2.7 Phasor Measurement Units and Synchrophasor Data Flows in the North American Power Grid



All PMUs displayed are connected to their local network. Major data paths for sharing information among operating entities are shown here.

[28] "The mission of EIDSN is to develop a new, more efficient and effective network for the sharing of operating reliability data, including both SCADA and synchrophasor data, among appropriate entities to promote the reliable and efficient operation of the Eastern and Quebec Interconnections." Eastern Interconnect Data Sharing Network, Inc., http://eidsn.org/.

2.5. MATURING THE TECHNOLOGY

Prior to the ARRA Smart Grid projects, the market for synchrophasor technology was small and utility investments in communications and security were limited. The scope and scale of the ARRA Smart Grid projects prompted utilities to be more demanding of equipment vendors. This, in turn, motivated equipment vendors to improve the PMU devices and the standards-setting bodies to write new standards, update existing standards, and harmonize the standards with one another. The result has been a rapid maturing of the technology, as illustrated in Figure 2.8.

Synchrophasor technology was invented in the 1980s and documented in two IEEE Transactions Papers.[29] From that time until the launch of the ARRA Smart Grid projects, the technology proved to be useful in special circumstances, but had not yet matured into a widely-adopted suite of commercial products. By increasing the number of PMUs in North America by a factor of 10, encouraging disparate and independent companies to share PMU data with one another, facilitating communications about best practices and lessons learned, and reporting the benefits of using PMU data, DOE's ARRA projects moved synchrophasor technology into widely used commercial success.

[29] Phadke, A.G., J.S. Thorp, and M.G. Adamiak, "A New Measurement Technique for Tracking Voltage Phasors, Local System Frequency, and Rate of Change of Frequency," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-102, No. 5, May 1983, doi:10.1109/TPAS.1983.318043; Thorp, J.S., A.G. Phadke, and K.J. Karimi, "Real-Time Voltage Phasor Measurements for Static State Estimation," *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-104, No. 11, November 1985, doi:10.1109/TPAS.1985.318818.

Figure 2.8 Comparison of Synchrophasor Projects Pre- and Post-ARRA

Synchrophasor Technology

	Pre-ARRA (1980s to 2009)	Post-ARRA (2015)
PMU Devices	• Research-grade • Very limited system coverage	• Production-grade • Widespread system coverage
PDCs	• Research-grade • No standard	• Production-grade • IEEE standard
Communications Systems	• Limited bandwidth • Limited quality	• High-bandwidth • Production-grade
Data Sharing	• Primarily bilateral • With vendors and universities	• Universal in Western Interconnection • Transitioning in the Texas and Eastern Interconnections
Applications	• Research-grade • Study Mode	• Production-grade • Study Mode & Real-Time
Procedures	• Informal; ad-hoc	• Formal, vetted

The ARRA projects accelerated the maturity of synchrophasor technology.

3. REALIZED BENEFITS TO THE U.S. ELECTRIC GRID

The ARRA-funded synchrophasor projects have transitioned synchrophasor technology from a research and off-line analysis tool to one that is being deployed interconnection-wide into production use for operations and planning. Already, early successes have been reported by the project participants, as described in Appendix 1. The improved performance in grid operations and planning benefits both the operating companies and the nation, which depends on reliable, affordable and clean electric energy. The primary benefits of synchrophasor technology can be classified as:

- Increased system reliability
- Increased asset utilization and power system efficiency
- Increased organizational efficiency.

In this report, **reliability** is considered to reflect the extent to which the power system maintains delivery of electricity from generation sources to loads in the face of changing system conditions, while maintaining key system parameters (voltages, frequencies, etc.) within technically acceptable limits. Reliability improvements include:

- Avoiding (or reducing the probability of) an unintended interruption in service or out of limit voltages.[30]
- Reducing the magnitude (number of customers affected) of an outage[31] or out of service limit condition if one occurs.
- Reducing the duration of an outage or out of limit condition.

Asset utilization and power system efficiency is the ability to operate grid assets closer to their physical limits or to improve the efficiency (in terms of fuel use, cost, or environmental effects) with which the grid serves the load.

Organizational efficiency refers to the extent to which staff time and other resources are needed to operate and meet the company's obligations. Electric grid operating companies have processes and procedures that guide the way they carry out their duties.

Each synchrophasor technology capability in Section 2 can contribute to one or more of these benefits, as illustrated in Table 3.1.

The following sections describe how each of these eleven capabilities contributes to one of the three overall benefits identified. Included with each description is a specific example of a benefit realized by the ARRA project.

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[30] Excursions of voltage outside of specified limits – either too high or too low – can cause operating problems on the electric grid as well as with consumers' equipment. (Prolonged low voltage conditions are often referred to as brownouts.)

[31] An interruption of power is termed an outage.

Table 3.1 Synchrophasor Capabilities Create Tangible System Benefits

	Number of Projects	Increased System Reliability	Increased Asset Utilization & Power System Efficiency	Increased Organizational Efficiency
Real-Time Capabilities[32]				
Phase angle monitoring	12	✓	✓	
Oscillation detection and monitoring	11	✓		
Voltage stability monitoring	9	✓		
Event detection, management & restoration	9	✓		✓
Islanding detection, management & restoration	4	✓		
Equipment problem detection	9	✓		✓
Wide-area situational awareness	11	✓		✓
Study Mode Capabilities[33]				
Model validation and calibration	11	✓	✓	✓
Post-event analysis	11	✓		✓
Renewable resource integration	3		✓	
Operator training	6	✓		

The appendices provide more detail:

- Appendix 1, "Summary of Each Participant Project," documents the technology that was implemented and the impacts achieved.
- Appendix 2, "Synchrophasor Technology Capabilities," describes more fully each of the eleven capabilities listed in Table 3.1 and lists the projects that implemented the capability.

[32] Real-time capabilities are employed in the minute-by-minute operation of the electric power grid. These are generally carried out by power system operators or operational engineers.
[33] Study mode/planning capabilities, which are generally carried out by power system engineers, are employed in planning for transmission system expansions, generation additions and retirements, system protection, and studying unexpected events or system behaviors.

3.1. INCREASED SYSTEM RELIABILITY

The method by which system reliability is increased by deploying synchrophasor capabilities is briefly described below. Also listed is a specific example of an ARRA project's increasing system reliability by deploying that capability.

The following ten capabilities contribute toward increased system reliability:

- Phase angle monitoring
- Oscillation detection & monitoring
- Voltage stability monitoring
- Event detection, management & restoration
- Islanding detection, management & restoration
- Equipment problem detection
- Wide-area situational awareness
- Model validation & calibration
- Post-event analysis
- Operator training.

Each of these is discussed below.

Capability: Phase Angle Monitoring

Contribution to Reliability: The difference in phase angle between two points on the grid (e.g., between a substation and the end of an open transmission line) is a decisive factor for connecting those points to one another. This is the situation when a breaker needs to be reclosed – reconnecting an electrical island to the rest of the grid or re-establishing a transmission line path. Phase angles can also be used to monitor grid stress. Phase angles are usually estimated through off-line simulations. PMUs calculate phase angles directly, making accurate information immediately available to system operators and engineers, allowing more timely and precise operating actions.

Example: Phase angle monitoring enabled WECC to rapidly restore a critical tie line. Offline phase angle estimates indicated the need to re-dispatch generation before the line could be brought back in service. However, real-time PMU data showed the phase angle difference between the end of the tie line and the substation bus was within the limit for successful reclosing, allowing them to more quickly close the breaker. The time period with the line out of service was shortened because of the PMU data, thereby reducing the power system's vulnerability to a potential subsequent contingency.

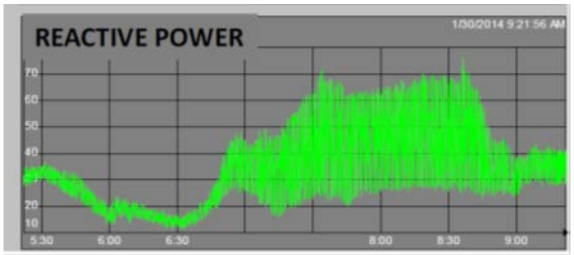
Capability: Oscillation Detection & Monitoring

Contribution to Reliability: Oscillations occur for many reasons including power system disturbances or malfunctioning control systems. Detecting and monitoring oscillations give insights into emerging system problems. PMUs have improved the utility industry's ability to detect and characterize oscillations, allowing operators and engineers to evaluate the potential impact of the oscillation and perform remedial actions as appropriate.

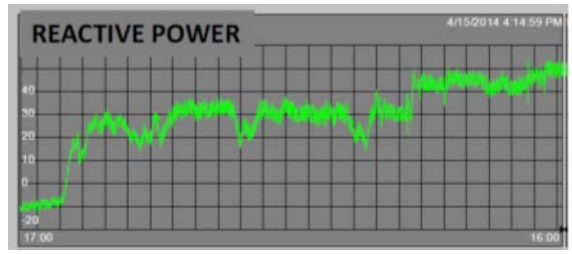
Example: Using PMUs, WECC member BPA observed potentially harmful oscillations and determined their cause to be a malfunction in a generator's controls. BPA notified the plant owner of the problem and the owner upgraded the plant controls, causing the oscillations to decrease significantly. Figure 3.1

shows the initial oscillations observed (a) and the improved waveform achieved after the generator's controls were upgraded (b).

Figure 3.1 BPA Wind Plant Oscillations before and after Control Upgrades



(a)



(b)

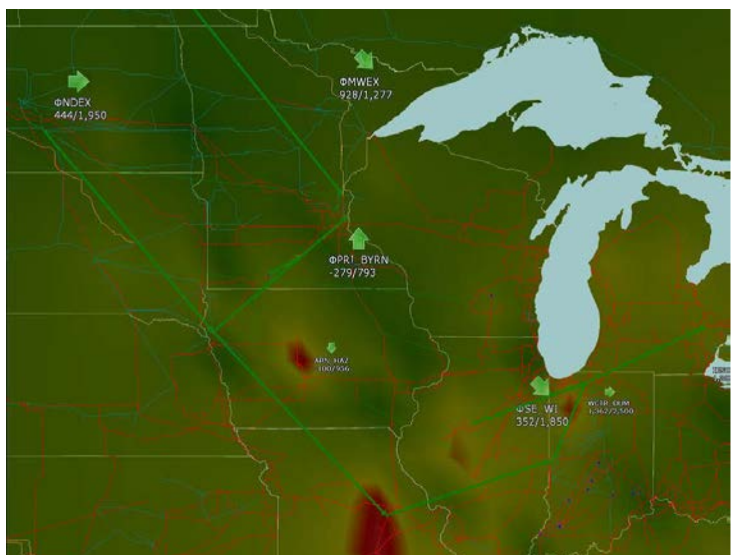
BPA wind plant oscillations (a) decreased significantly after upgrades to controls (b).

Capability: Voltage Stability Monitoring

Contribution to Reliability: Loss of voltage stability almost always results in a voltage collapse: the voltage drops to zero and the load can no longer be met at that location. PMU-enabled tools help system operators detect and diagnose voltage problems and identify actions to remediate problems.

Example: MISO correlates PMU data with energy management system (EMS) data and stability monitoring alerts, providing enhanced real-time displays for their system operators for monitoring voltage gradients and voltage angle pairs, allowing them to quickly detect voltage excursions and large amplitude oscillations (see Figure 3.2).

Figure 3.2 Visualization of MISO Control Room Voltage Gradients



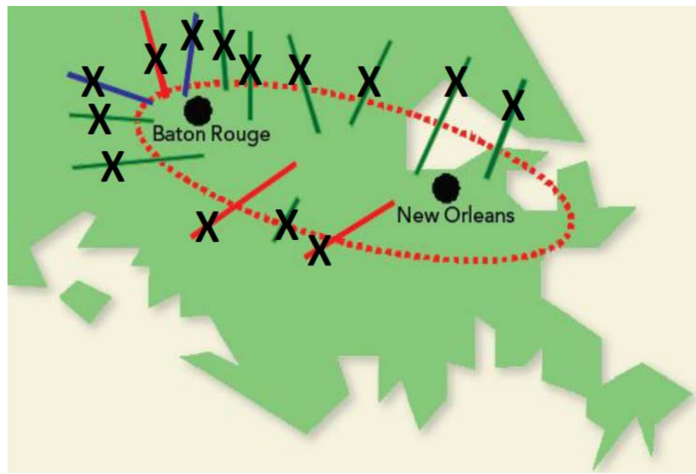
MISO control room's enhanced real-time visualization display of voltage gradients (red indicates areas of low voltage).

Capability: Event Detection, Management & Restoration

Contribution to Reliability: PMU data inform operators when parts of the system are stressed – even before an event occurs. This provides an opportunity to take early actions to mitigate the consequences of the event. If the event occurs, PMU data provide a view of the system's response to the event. The sooner and better an operator understands the event, the more options are available for mitigating the event.

Example: ATC uses PMU data to provide a check on the operation of protection devices, determining if faults are cleared properly and if all three phases open at the same time. Any operational problems are corrected in order to improve the system's response to future events.

Figure 3.3 PMU Data Used by ATC to Determine Operational Problems



Gustav isolated New Orleans and Baton Rouge in an unstable electrical "island."

Capability: Islanding Detection, Management & Restoration

Contribution to Reliability: PMU monitoring of voltages, currents, and phase angles can alert operators to the formation of an electrical island. The sooner an operator knows that an electrical island has formed, the greater the options available for avoiding a blackout.

Example: In 2008, fourteen transmission lines taken out of service by Hurricane Gustav formed an electrical island. Entergy's synchrophasors enabled operators to detect the island and then diagnose and mitigate instabilities within that island, preventing a blackout of New Orleans and Baton Rouge (see Figure 3.3). This was a motivator for Entergy to triple its number of PMUs and expand their synchrophasor system capabilities under their ARRA SGIG grant.

Capability: Equipment Problem Detection

Contribution to Reliability: PMUs' fast reporting rates make it possible to observe and analyze the condition of grid equipment at a level of detail not available with conventional SCADA technology. This detail is fine enough to detect unusual data –indicative of incipient equipment failures. Early detection and diagnosis of malfunctioning equipment allows for repairs or replacements to be made during planned outages – in most cases eliminating forced outages of equipment on the transmission grid or interruptions of service to customers.

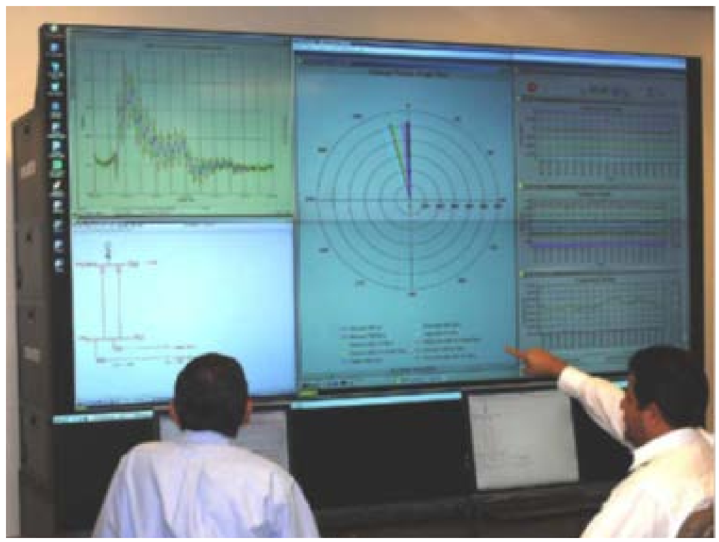
Example: Equipment monitoring enabled FPL to identify a damaged transformer before it failed. This avoided an unplanned outage of a large substation and an interruption of service to its customers.

Capability: Wide-Area Situational Awareness

Contribution to Reliability: Monitoring key electrical parameters over a wide area provides wide-area situational awareness. Synchrophasor systems provide early warning to operators of problems developing on the interconnection and allow them to take prompt action before the problem evolves. Synchrophasor data can provide a high-resolution view of power system and asset behaviors under a wide range of conditions across an entire interconnection. The lack of adequate situational awareness was identified as a major cause of the August 2003 Northeast Blackout.

Example: NYISO displays PMU-based information in its control center – alarming operators of abnormal conditions both inside and outside of the New York Control Area. Making operators aware of conditions outside their system enhances communication and coordination with operators in neighboring regions. (Figure 3.4 shows synchrophasor displays, developed by Southern California Edison, which represent the type of information that can be provided to control room operators.)

Figure 3.4 Various Synchrophasor Data Displays at Southern California Edison

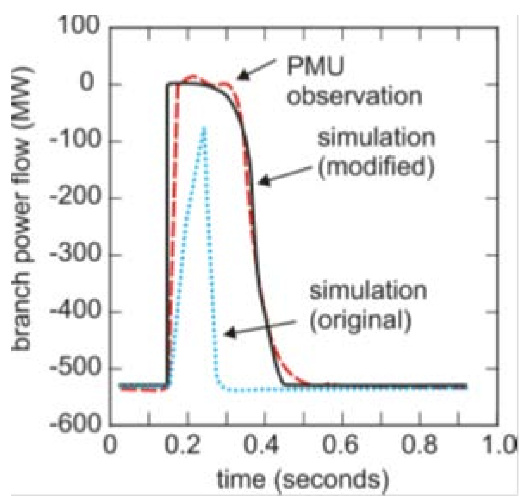


Capability: Model Validation & Calibration

Contribution to Reliability: Synchrophasors enable mathematical models of the power system and its components to be developed and validated more quickly and more accurately. With better models, the analysis tools used for short-term operational processes as well as long-term plans provide more accurate insights to utility personnel.

Example: ISO-NE quickly calibrated an HVDC model by using PMU data generated during a single-phase-to-ground fault on a transmission line. Adjusting their HVDC model quickly resulted in more timely improvements in the results of all subsequent simulations (see Figure 3.5).

Figure 3.5 Validation of HVDC Model



Capability: Post-Event Analysis

Contribution to Reliability: Analyzing system events is a critical part of learning what initiated the system event, how the system responded to the incident, and most importantly, what can be done to prevent another occurrence. PMUs provide high-resolution, time-stamped data so that an accurate time-aligned sequence of events can be constructed quickly, often within hours, and so that the root cause of the event can be determined.

Example: Entergy is utilizing PMU data for post-event analysis. By investigating historical disturbances and system events, they better understand the sequence of the events and their causes – providing insights into how the reliability of their system can be improved. Entergy is also looking to use pattern recognition techniques to identify PMU data signatures associated with specific instabilities or vulnerable conditions in order to provide pre-emptive guidance to their system operators.

Capability: Operator Training

Contribution to Reliability: Power system operators need to understand the electric grid's behavior in order to know which operating procedure to apply and when to apply it. Formal training on procedures is conducted using simulators of power system operation; PMU data, especially its playback of past events, enhance the breadth and quality of such training.

Figure 3.6 Synchrophasor Training Activities

Example: CCET and ERCOT staff provided training on their synchrophasor-based wide-area monitoring system to ERCOT's power system operators and those of ERCOT's member utilities, allowing operators to experience first-hand the new insights provided by PMU data (see Figure 3.6).

3.2. INCREASED ASSET UTILIZATION AND POWER SYSTEM EFFICIENCY

Improved asset utilization and power system efficiency is achieved through better understanding of the physical limits and operating characteristics of the devices and systems that make up the electric grid (better models), and by better understanding the grid's immediate operating state (better monitoring). Using PMU data for these purposes improves asset utilization and allows existing assets to operate closer to their true physical limits or capabilities. The following three capabilities contribute toward improved asset utilization and power system efficiency:

- Phase angle monitoring
- Model validation & calibration
- Renewable resource integration.

Each of these is discussed below.

Capability: Phase Angle Monitoring

Contribution to Increased Utilization and Efficiency: PMU-supplied phase angle data provide indications of the extent to which the system is stressed and the proximity of the system to its stability limit. This lets operators know how much discretion they have in adjusting operating conditions and how much time they have to make the adjustments.

Example: MISO operators use PMU data to display voltage angle differences between key bus locations in the power system. MISO now runs its transient stability assessment tool every 15 minutes instead of daily or hourly, enabling MISO to increase power flows in constrained areas while maintaining reliability margins.

Capability: Model Validation & Calibration

Contribution to Increased Utilization and Efficiency: Analysis of PMU data enables models of generators and other equipment to be validated without taking the equipment off-line.

Example: BPA used PMU data to calibrate the 1,100 MW Columbia Generating Station nuclear generator model without needing to take the unit off line, with $100,000 to $700,000 of savings estimated for this type of generator outage.

Capability: Renewable Resource Integration

Contribution to Increased Utilization and Efficiency: One of the challenges in integrating renewable energy resources is understanding how their control systems interact with the larger grid. Synchrophasor data are particularly useful for developing this understanding by improving the resolution of the data available for monitoring the behaviors of the control systems and their impact on the grid.

Example: ERCOT's synchrophasor system quickly identified a potentially damaging oscillation caused by a malfunctioning control at a wind farm. (The oscillation was undetectable by traditional SCADA.) The system operator constrained the unit to 40 MW to maintain the integrity of the system. After ERCOT linked the oscillation to a faulty wind farm plant software upgrade, the wind farm operator corrected the malfunction, ending the oscillation and the curtailment.

3.3. INCREASED ORGANIZATIONAL EFFICIENCY

All participants reported that the installed PMUs had improved their organizational efficiency. The following five capabilities contribute toward increased organizational efficiency:

- Event detection, management & restoration
- Equipment problem detection
- Wide-area situational awareness
- Model validation & calibration
- Post-event analysis

Each of these is discussed below.

Capability: Event Detection, Management & Restoration

Contribution to Increased Organizational Efficiency*:* Synchrophasor data analysis and display applications present information to system operators much more quickly and in far more detail. Compared to conventional SCADA applications, synchrophasors enable operators to understand the nature of the event quicker and focus more on mitigating problems.

Example: Figure 3.7 shows that the PMU clearly captured a slow acting breaker responding to a fault due to a lightning strike. (The PMU data shows the dynamic changes in the three phase voltages for the event.) Duke Energy's synchrophasor-based event analysis systems reduce the time required to analyze events by automatically recording the magnitude and time duration of the fault, making the analysis to diagnose and correct the problem more timely and efficient.

Figure 3.7 Lightning Initiated Event of Two Second Duration Recorded by a PMU

Capability: Equipment Problem Detection

Contribution to Increased Organizational Efficiency: Using PMU data to analyze equipment performance and diagnose operational problems reduces the time and staff required to commission new equipment.

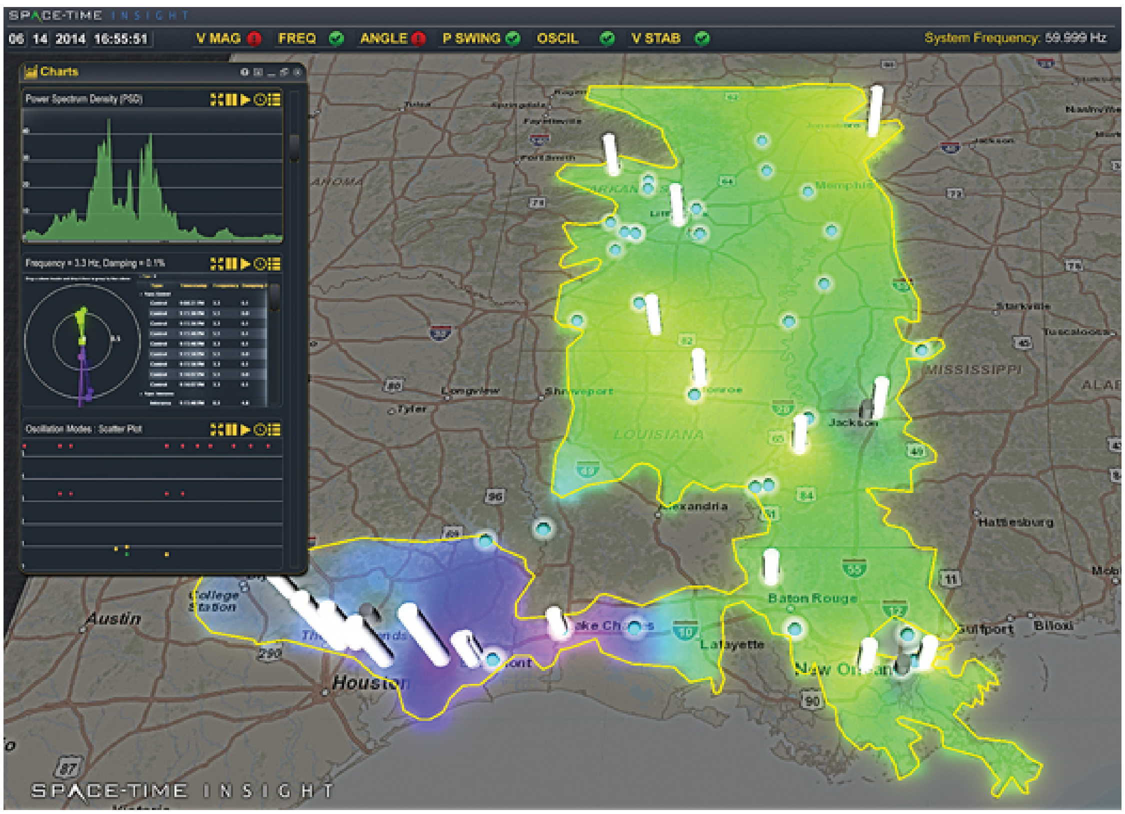
Example: PMU data provided instantaneous, high-resolution data to ISO-NE workers during the installation of a new power system stabilizer (PSS). The use of synchrophasor technology reduced the staff time required to commission the PSS and improved confidence in the PSS's operation.

Capability: Wide-Area Situational Awareness

Contribution to Increased Organizational Efficiency: PMU data enable display of real-time system conditions to system operators across a broad service territory and in a manner that is easy to comprehend and to act upon.

Example: Entergy's wide-area monitoring and visualization system enables the real-time observation of high-definition PMU data and results of analytic engines. Integrating this information onto geographical maps and analysis dashboards allows operators to monitor conditions across the entire Entergy service area.

Figure 3.8 Visualization of Oscillation and Voltage Stability on the Entergy System



The columns represent approximate PMU locations and are configurable based on context.

Capability: Model Validation & Calibration

Contribution to Increased Organizational Efficiency: Using PMU data to calibrate models reduces the staff time required to take equipment out of service and conduct performance tests. PMU data also enable observation of dynamic performance of a generation facility under conditions that may not be achievable under test conditions.

Example: IPC estimates that using PMU disturbance data reduces the time required to validate a wind turbine model by 75%, saving two to three days per generator when compared to traditional staged testing.

Capability: Post-Event Analysis

Contribution to Increased Organizational Efficiency: The time required to analyze an event is dramatically reduced with PMU-driven software. By automatically archiving data during system events, engineers can quickly locate, extract, and analyze the data to understand the event.

Example: ISO-NE event analysis applications automatically collect and analyze PMU data from all across New England, enabling engineers to quickly identify and analyze disturbances. With the improved efficiency, ISO-NE is able to analyze two or three events per week – up from two events per year – using the same resources.

4. CONCLUSIONS

Maintaining safe, reliable, and economical electricity is essential to the functioning of a modern society. Recognizing this, the American Recovery and Reinvestment Act (ARRA) legislation provided funding to launch a set of smart grid projects. This included funding for the Department of Energy (DOE) to implement the Smart Grid Investment Grants (SGIG) and the Smart Grant Demonstration Program (SGDP), expanding the deployment, advancement, and demonstration of synchrophasor technology for electric power transmission systems.

DOE's Office of Electricity Delivery and Energy Reliability competitively selected 13 organizations to conduct 14 synchrophasor-related projects. These organizations included 5 Independent System Operators / Regional Transmission Organizations (ISO/RTO), 7 owners and operators of transmission assets, and 1 Texas nonprofit corporation. These projects represent investments of $155 million of ARRA funding and $203 million of industry funding. Sixty-three other entities, under the aegis of the thirteen prime organizations, also participated, for a total of seventy-six organizations. 1,380 PMUs were installed or upgraded to production-grade quality across North America.[34] Another 150 PMUs were installed by project participants outside of ARRA funding. These enabled new and enhanced capabilities for planning and operating the electric grid.

Synchrophasor technology is now used in every North American Electric Reliability Corporation (NERC) region in the United States. Indeed, the service areas of the ARRA synchrophasor project participants represent 88% of all the electricity delivered in the United States. When combined with synchrophasor technology installed outside of the ARRA projects, the technology now monitors nearly 100% of the electricity delivered across the country.

4.1. OPERATIONAL USE

Once the infrastructure was built out, project participants set to transitioning the new synchrophasor and communication system assets to productive use.[35] Activities for making them operational fell into two categories: procedures and data sharing.

- **Procedures:** Five of the thirteen ARRA synchrophasor projects implemented new synchrophasor-informed procedures. For example, California Independent System Operator (CAISO) implemented a procedure to monitor transmission path stress and to guide restoration for four major paths using phase angle differences. These data are compared with the energy management system's calculated values, displayed in the control room, and shared with three other WECC members.
- **Data Sharing:** Interconnection-wide data sharing has been implemented in the West, but is still evolving in the rest of North America. Communications networks and cyber-security provisions will continue to evolve as the synchrophasor systems mature.

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[34] A total of 1,380 PMUs and 226 PDCs were installed with ARRA funding in 778 substations resulting in a total of 11,544 signals.

[35] Twelve participants are using PMU data to inform their power system operations. Eleven participants are using PMU data to inform their power system planning.

4.2. BENEFITS

The ARRA synchrophasor systems have been in operation for approximately two years—a relatively short amount of time for new power system technologies—yet the project participants have reported numerous tangible payoffs in reliability, asset utilization and power system efficiency, and organizational efficiency.

- **Increased System Reliability:** Ten of the eleven capabilities enabled by PMU data contribute to improving reliability. An example is Peak's using phase angle monitoring to rapidly restore a critical tie line. The shortened outage reduced the power system's vulnerability to a potential subsequent contingency, i.e., another line trip.
- **Increased Asset Utilization and Power System Efficiency:** Three of the eleven capabilities enabled by PMU data contribute to improving asset utilization and power system efficiency. An example is BPA's using PMU data to calibrate the 1,100 MW Columbia Nuclear Generating Station model without taking the unit off line. This saved an estimated $100,000 to $700,000.
- **Increased Organizational Efficiency by Expanding Operator and Engineer Capabilities:** Five of the eleven capabilities enabled by PMU data contribute to improving organizational efficiency. An example is ISO-NE's using synchrophasor-based event analysis software to automatically collect and analyze PMU data from across New England. The reduced cycle time enables engineers to identify and analyze two or three events per week – up from two events per year.

4.3. MOVING FORWARD

The scope and capabilities of PMU deployments continue to grow. As utilities become more familiar with the technology, they will increasingly use PMU data to inform a broader range of planning and operating decisions leverage unused capabilities to extract more value from the technology.

DOE will continue to foster the development and deployment of software that leverage the increasingly rich inventory of synchrophasor data. Continued development of technical standards and conformance testing guides will be needed to ensure device interoperability. DOE will continue to have a role in providing forums, such as NASPI, for sharing best practices and lessons learned with the broader synchrophasor community.

The specific roles for PMUs in the distribution system are still undefined, but the increasing penetration of renewable generation, electric transportation, and energy storage connected to the distribution system will likely drive the need for the advanced monitoring and control capabilities enabled by synchrophasor technology.

In the "Quadrennial Energy Review", the desired infrastructure characteristics are identified as: "reliability, resilience, safety, a minimal environmental footprint, flexibility, and affordability."[36] The ARRA synchrophasor projects have made a major contribution towards achieving these objectives.

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[36] U.S. Department of Energy, *Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure*, pp.1-20, April 2015, http://energy.gov/epsa/quadrennial-energy-review-qer.

APPENDIX 1: SUMMARY OF EACH PARTICIPANT PROJECT

Table A1.1 ARRA Synchrophasor Project Participants

ARRA Synchrophasor Project Participants[1]

- **American Transmission Company (ATC)[2,3]**
- **Center for the Commercialization of Electric Technologies (CCET)[1]:**
  - American Electric Power
  - Electric Power Group
  - Electric Transmission Texas
  - ERCOT
  - Golden Spread Electric Cooperative
  - Intel/McAfee
  - Oncor Electric
  - Sharyland Utilities
  - Texas Tech University
- **Duke Energy Carolinas[2]**
- **Entergy Services, Inc.[2]**
- **Florida Power & Light Company**
- **Idaho Power Company[2]**
- **ISO-New England:**
  - Bangor-Hydro
  - Central Maine Power
  - National Grid
  - Northeast Utilities
  - NSTAR
  - United Illuminating
  - VELCO
- **Lafayette Consolidated Government**
- **Midcontinent ISO:**
  - Ameren
  - American Transmission Company (ATC)[2]
  - Duke Energy[2]
  - Entergy[2]
  - Great River Energy
  - Hoosier Energy
  - Indianapolis Power and Light
  - International Transmission Company
  - Manitoba Hydro
  - Minnesota Power
  - Montana Dakota Utility
  - Northern Indiana Public Services Company
  - Ottertail Power
  - Vectren
- **Midwest Energy**

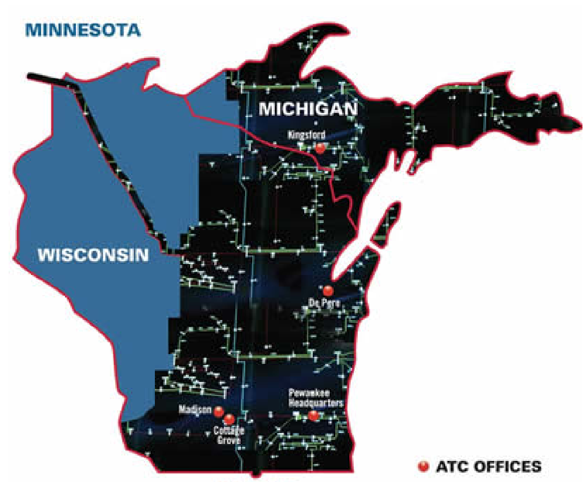
Note 1: CCET was an SGDP project. All others were SGIG projects.
Note 2: These entities were prime grant recipients and also participants in RTO/ISO projects.
Note 3: ATC had 2 projects: PMU; Communications.

- **New York ISO:**
  - Central Hudson Gas & Electric Corporation
  - Consolidated Edison Company of New York, Inc.
  - Long Island Lighting Company doing business as the Long Island Power Authority (LIPA)
  - New York State Electric & Gas Corporation
  - Niagara Mohawk Power Corporation doing business as National Grid
  - Orange and Rockland Utilities, Inc.
  - Power Authority of the State of New York (NYPA)
  - Rochester Gas and Electric Corporation
- **Peak Reliability/WECC:**
  - Alberta Electric System Operator
  - Arizona Public Service
  - Bonneville Power Administration
  - British Columbia Hydro Authority
  - California Independent System Operator
  - Idaho Power Corporation[2]
  - Los Angeles Department of Water and Power
  - Northwestern Energy
  - NV Energy
  - Pacific Gas and Electric
  - PacifiCorp
  - Public Service of New Mexico
  - Salt River Project
  - San Diego Gas and Electric
  - Southern California Edison
  - Tri-State Generation and Transmission
  - Tucson Electric Power
  - Western Area Power Administration
- **PJM Interconnection:**
  - Allegheny Power
  - Baltimore Gas and Electric Company
  - American Electric Power Service Corporation
  - Commonwealth Edison
  - Duquesne Light Company
  - First Energy Corporation
  - PECO Energy Company
  - PEPCO Holdings
  - PPL Electric Utilities
  - Public Service Electric and Gas
  - Rockland Electric Company
  - Virginia Electric and Power Company

A1.1. AMERICAN TRANSMISSION COMPANY (ATC)

Scope

American Transmission Company Service Area



ATC owns and operates the transmission grid across portions of Wisconsin, Michigan, Minnesota, and Illinois.[37] Under the American Recovery and Reinvestment Act (ARRA), ATC received funding for two projects: one to install phasor measurement units (PMUs) and a second to deploy an enhanced supervisory control and data acquisition (SCADA) and PMU communications backbone. ATC's objectives were to improve the reliability of the communications system and the electrical grid and to reduce the cost of operating and maintaining the transmission system. These projects have increased ATC's grid monitoring capabilities as PMUs provide sub-second data on the state of the grid and provide insights in event analysis that were not available with traditional SCADA systems. ATC shares its PMU data with Midcontinent Independent System Operator (MISO), its reliability coordinator, and with its member companies. ATC's ability to see beyond its interconnection points is valuable in understanding the full impacts of undesired system behaviors, improving post-event analysis, and validating its system models.

	# PMUs	# PDCs
ARRA Project Funded	49	45
ATC System (incl. ARRA)	107	58

ATC installed 31 stand-alone PMUs, upgraded 18 digital fault recorders (DFR) with PMU functionality, and deployed data collection software. Phasor data concentrators (PDCs) were installed at 45 substations to manage the data from the PMUs. ATC also enhanced its communications infrastructure by deploying 106 miles of new fiber optic cables and associated communications equipment across the company's Wisconsin footprint. The new fiber segments are interconnected with ATC's pre-existing fiber infrastructure and with leased fiber systems to form a communications backbone with the bandwidth and reliability to support enhanced SCADA and synchrophasor systems. The upgraded communications backbone interconnects 149 substations within the ATC system.

Goal: To increase grid monitoring capabilities and improve system reliability.

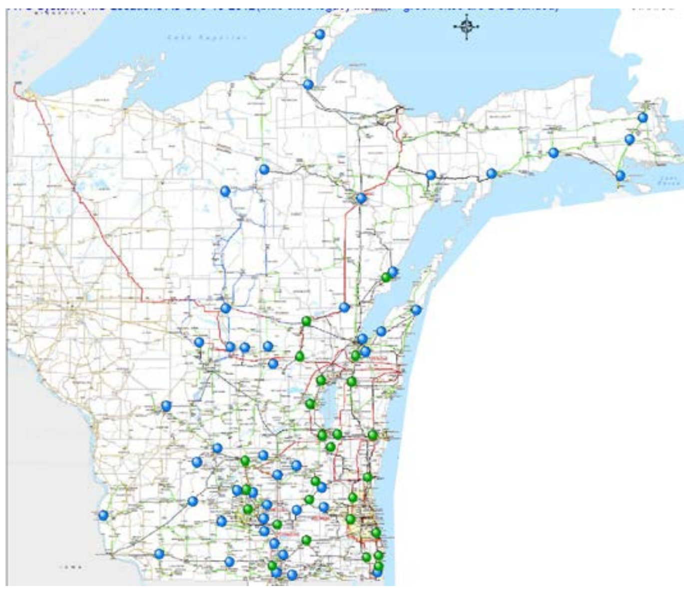
[37] http://www.atcllc.com/about-us/

Results Achieved

The synchrophasor system identified electrical component issues before they caused significant problems on the transmission system.

- ATC identified a failing potential transformer (PT) using PMU data. ATC determined that the PT should be replaced to avoid a failure. If the PT had failed, the outage to the customer would have been lengthy.
- Two generators unexpectedly tripped offline after lightning-caused transmission line faults had been cleared successfully. Precise measurements from nearby PMUs on the timing and sequence of operations verified that the generators should not have tripped. Working with the generation owner, it was determined that the plant's auxiliary protection systems were not operating as desired; the generation owner is correcting the problem. This diagnosis would have been difficult, if not impossible, prior to PMU installation. Because of this event and others where synchrophasor data have been shared, the generation owner plans to install their own PMUs to enable them to troubleshoot problems and validate generator models.
- Synchrophasor technology made it possible for ATC to identify several other issues within the transmission system, including: widespread effects on the system due to the failure of a surge arrestor, open and unbalanced phases due to improper relay settings or equipment failure, detection of low-frequency harmonics injected by equipment recently installed on the system, and improper switching of capacitor banks. In all of these instances, PMUs enabled ATC engineers to identify the cause and location of the issues.[38]

PMU Locations within ATC (blue sites are legacy installs; green sites are ARRA installs)



ATC applications translate PMU data into actionable information for system operators and engineers.

- ATC installed applications that use PMUs to identify islanding conditions and monitor frequency, phase angles, and voltages across the system. ATC is currently running the applications in test/study mode to evaluate the performance and integrity of the synchrophasor system. ATC plans to put them into production sometime in 2015.

[38] Source: "Diagnosing Equipment Health and Mis-operations with PMU Data" NASPI Technical Report, March 20, 2015.

- ATC has developed applications in-house to monitor the PMU data and extract data on incidents for post-event analysis.

PMU data are used by ATC to validate state estimation and system models.

- ATC is performing high-level validation of its state estimator model using PMU voltage angle data.
- Efforts are under way by ATC to develop applications that determine benchmarks for system models.
- ATC implemented its first high-voltage direct current transmission (HVDC) system in 2014. PMU data are being used to support analysis of the HVDC equipment operation and its impact on system frequency and voltage.

Enhanced communications resulted in improved reliability and operation of the transmission system.

- ATC's fiber backbone has increased communications reliability for SCADA, PMUs, and relays. This results in fewer unplanned outages, visibility of grid behavior in near real time, better physical security at substations, and the ability to remotely monitor and control.

"We routinely use the data to respond to customer event questions…. We can reliably answer what happened during an event."

Lessons Learned

Installing the devices and configuring the data flow were relatively easy, but costs of communications and challenges associated with managing a commercial synchrophasor system were higher than expected.

- Moving forward, ATC will use cost data for stand-alone optical fiber ground wire projects to provide more accurate cost estimates.
- Maintenance of the new synchrophasor technology was initially an issue as ATC had limited field support staff with good working knowledge of the holistic delivery system (i.e., how the entire system works – from the monitoring devices to the data concentrator located at the control center).
- The massive influx of information creates challenges in sorting and archiving the data to derive the information that supports operations and planning personnel.

Acceptance of the technology is increasing within the organization as operators and engineers see its use in helping to identify and solve problems, but nailing down exact applications has proved challenging.

- Every time ATC shares data with employees to help them solve a problem, demand and interest for the data and supporting applications grows. The quantity of data requests has escalated from once every month or two at project inception to after every significant system event.
- The post-event data analysis has been beneficial, but ATC has found it challenging to identify must-have applications for real-time operations personnel.

Future Plans

ATC will continue to use synchrophasor technology for post-event analysis to improve its understanding of the dynamic operation of the transmission system and to validate system models. Long term, ATC sees the PMU data "becoming increasingly integrated with ATC's existing processes so that operations, planning, system protection and asset maintenance personnel can analyze the data to determine how the system is performing." Currently, ATC and its project partners are developing model verification and improvement processes using analysis tools that can easily compare PMU event data to expected operation. In addition, ATC is evaluating PMUs for real-time monitoring and processes, including the use of synchrophasors to support voltage stability applications based on results from MISO and others.

ATC will use PMUs to validate its state estimator solution and investigate the use of synchrophasor data to improve state estimator results. ATC plans to put at least one of its applications into production in 2015 so that real-time PMU data are available to their operators.

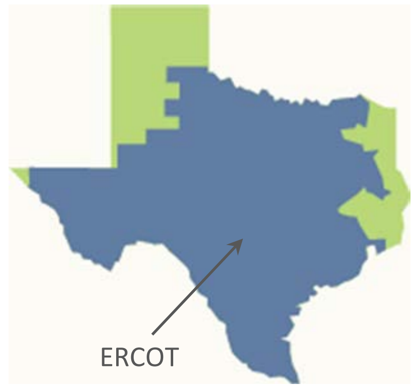
ATC's communications reliability program will strategically expand the use of the fiber network to improve data communications reliability. The program enhances ATC's control over communications of operating data, supports risk management by providing additional diversity in communications paths and media, and provides improved data security.

ATC will continue sharing knowledge with others to help gain wide-scale acceptance of the technology and continue to exchange data with transmission entities outside of its footprint. An immediate goal is to expand observability of the upper Midwest transmission system by requesting PMU data from entities outside of the ATC system. ATC will also look to expand its own PMU coverage at targeted sites as new projects are implemented.

A1.2. CENTER FOR THE COMMERCIALIZATION OF ELECTRIC TECHNOLOGIES (CCET)

Scope[39]

CCET[40] is a non-profit corporation comprised of utilities, retail electric providers, high technology companies, and research and development companies that operate within the Electric Reliability Council of Texas (ERCOT)[41] service area. CCET facilitates collaborations amongst these parties for the purpose of enhancing the safety, reliability, security, and efficiency of the Texas electric transmission and distribution system.[42,43]



ERCOT region in Texas

The State of Texas has an aggressive renewable portfolio standard to support wind generation growth. At the time of the American Recovery and Reinvestment Act (ARRA) initialization, Texas was (and still is) the nation's largest deployer of wind-powered generation – accounting for approximately 20% of total U.S. wind power capacity. As a result, Texas has invested heavily in the infrastructure needed to accommodate this renewable resource. Wind capacity in Texas was 12,470 MW as of December 2014, representing about 10% of the total ERCOT grid generation capacity. The growth in wind capacity in west Texas necessitated the development of 3,600 miles of transmission lines to move this power to the population centers in other parts of Texas.

	# PMUs	# PDCs
ARRA Project Funded	19	3
CCET (incl. ARRA)	109	6

The objective of CCET's smart grid demonstration project was to develop and demonstrate new mechanisms to help ERCOT manage fluctuations in wind generation. CCET accomplished this by utilizing better system monitoring capabilities, enhanced operator visualizations, and improved load management. The project helped define a new potential business model for managing wind resources through complementary synchrophasor technologies, residential solar energy resources, demand response, and storage. It demonstrated the value of combined, but separable smart grid components. ERCOT and other market participants will be

Goal: To manage increasing levels of wind power and demonstrate wide-area grid monitoring and visualization using synchrophasors.

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[39] http://www.ercot.com/about/profile/index.html

[40] In 2005, Texas utilities, technology companies and universities formed CCET in Austin, Texas, to advance technology developments in the electric utility industry of Texas.

[41] http://www.ercot.com/about

[42] http://www.electrictechnologycenter.com/pdf/CCET%20Fact%20Sheet.pdf

[43] ERCOT is a non-profit organization that serves as the independent system operator for approximately 85% of the state of Texas. http://www.electrictechnologycenter.com/aboutus.html

able to utilize the project's various tools to continue to meet reliability needs across the grid while responding to lapses in wind generation and other grid disturbances.

For the synchrophasor portion of the project, CCET implemented synchrophasor-based monitoring, visualization, and event reporting at ERCOT. CCET used the phasor measurement unit (PMU) data to calibrate a wind generator model, identify inter-area dynamics or oscillations, and detect and mitigate wind farm oscillations.

Results Achieved

> "Through this project, CCET demonstrated that new monitoring technologies can help integrate more wind resources while more effectively managing wind power's effects on the grid."

The project led an expanded deployment of synchrophasor technology in Texas beyond what had existed in 2009 as a "starter" system of three PMUs to over 100 PMUs in 2015. The ARRA project directly funded 19 of these additional PMUs. By providing data management systems, implementing PMU applications and visualization programs, and demonstrating the value of synchrophasor technology, those 19 PMUs motivated ERCOT members to network a total of 109 PMUs. The additional PMUs provide measurements across the entire Texas Interconnection and dramatically improved ERCOT's monitoring and early warning capabilities.

- ERCOT deployed a wide-area monitoring system using synchrophasor technology as an operator tool.
- In this role, synchrophasor data assist control room operators to more quickly and effectively diagnose and resolve potential grid stability issues due to intermittent wind farm output and transmission trips; these have been chronic and growing problems for the ERCOT grid.
- To enable the PMU system to be used in the ERCOT control room, ERCOT system operators and other staff members received training in the use and interpretation of the wide-area monitoring system.


Synchrophasor training activities

In recognition of the value that synchrophasors provide to grid operations, ERCOT created a Phasor Measurements Task Force and its members updated the ERCOT Communications Handbook to include a section on synchrophasors. It then prepared language on Disturbance Monitoring and System Protection[44] to be included in the ERCOT Nodal Operating Guides that support the protocols that guide control room operations.

ERCOT launched efforts to understand the impact of bad PMU data on system operations.

[44] http://www.ercot.com/content/wcm/current_guides/53525/06_060115.doc

- Data quality studies and lessons learned from mitigating PMU data loss activities led to reliability improvements for the control room's Real Time Dynamics Monitoring System (RTDMS).
- Synchrophasor systems will provide invaluable data for ERCOT control room grid management, and as a result, will need protection from cyber attacks in accordance with North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection (CIP) standards. Cybersecurity experts tested the integrated synchrophasor and Security Fabric system to verify that it complied with the relevant NISTIR-7628 (Guidelines for Smart Grid Cybersecurity) requirements. The testing identified a few vulnerabilities which the Security Fabric vendor corrected – thus improving the cybersecurity of its commercial offering, not only for synchrophasor systems, but also for any critical utility infrastructure.

ERCOT implemented synchrophasor-based applications that compare PMU measurements from key locations within the Texas grid and visualize the phase angle differences. The applications turn the PMU data into information that indicates grid performance and health.

- Wide-area monitoring applications focus on phase angle differences to assess grid stress.
- Small signal stability applications assess oscillation modes and damping, frequency instability, generation-load imbalance, power-angle sensitivity, and power-voltage sensitivity.
- ERCOT is using a synchrophasor-based application to validate and improve dynamic model parameters of both conventional generators and wind turbines. The improvement in generator parameters increases the accuracy of ERCOT generation forecasts and assists both generator owners and grid operators with NERC standards compliance.

Synchrophasor technology installed under the Smart Grid Demonstration Program (SGDP) project is beginning to reap value in terms of system performance by identifying undesirable events on the grid and providing information that helps ERCOT locate the problem's source. Additionally, synchrophasor data have been instrumental for validation of system models and quantifying the benefit of infrastructure expansion.

- Baseline performance measures were developed for wind generators by assessing the impact of wind generation on system inertia, governor frequency response, and low-voltage ride-through performance of wind generators.
- ERCOT's synchrophasor system quickly identified a potentially damaging oscillation from a malfunction at a wind farm in January 2014. The oscillation was undetectable by traditional supervisory control and data acquisition (SCADA). The operator stopped the oscillation by constraining the unit to 40 MW after which the wind farm operator quickly corrected the malfunction.
- PMU data measurements and analyses used to recalibrate engineering models include voltages, transmission line angle measurements, small signal stability monitoring results, and observations of damping behavior.

"Synchrophasor technology is here to stay, it has demonstrated numerous benefits, and it will soon become a very critical guide and asset in control rooms for grid operators."

- A wind generator model was determined to be inaccurate during a transmission line outage when the predicted behavior of the generator did not match the PMU measurements. Changes were made to the ERCOT models to correct the inaccuracy.
- System performance indicators, such as alarm limits, were identified by synchrophasor data/applications during an exhaustive baseline analysis. The analysis determined that grid conditions improved significantly with the addition of new transmission lines.

Lessons Learned

Acceptance of the technology requires interactions with industry stakeholders to show its value.

- Demonstration projects should be carried out on real operating electric grids in order to have sufficient perceived relevance to motivate change inside the utility.
- It takes constant effort to involve stakeholders and garner support to overcome constraints.

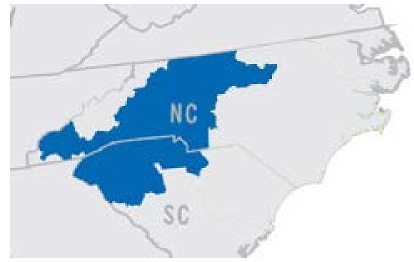
Future Plans

Better understanding of the challenges posed by the growth in wind generation in Texas underscores the need to establish new response mechanisms to wind variability. ERCOT will expand its use of synchrophasor technology to include voltage stability monitoring. ERCOT will transition PMU data systems and synchrophasor-based internal monitoring software into production so operators can take advantage of the alert features. ERCOT will continue to explore ways to assist generator owners and grid operators with NERC standards compliance through the improvements of tools for validating generator models.

A1.3. DUKE ENERGY CAROLINAS

Scope

Duke Energy Carolinas is an electric power holding company that serves over two million customers in North and South Carolina.[45] Under the American Recovery and Reinvestment Act (ARRA), Duke Energy Carolinas installed 103 phasor measurement units (PMUs) and four phasor data concentrators (PDCs) at 52 substations. Internet protocol-based communications were improved to deliver synchrophasor data from the PMUs to the PDCs and from the PDCs to the control center. Energy management systems were also upgraded.



Duke Energy Carolinas service area

The PMU network provides system operators with a more expansive view of the bulk transmission system and with the capability to understand dynamic system phenomena. Observing the nature of grid disturbances earlier, and more precisely, helps grid operators respond more quickly to disturbances and, thus, improves service reliability. Enhanced monitoring and diagnostic capabilities provide greater precision in daily operational decision making and improve overall system utilization and efficiency. This capability has helped prepare the transmission network in the Carolinas for the deployment of more distributed renewable generation sources.

	# PMUs	# PDCs
ARRA Project Funded	103	4
Duke Energy Carolinas System (incl. ARRA)	126	4

Goal: To observe the nature of grid disturbances earlier and more precisely; to prevent local disturbances from cascading into regional outages.

Results Achieved

Wide-area visualization is in use by operational engineering personnel and by operators in the control room.

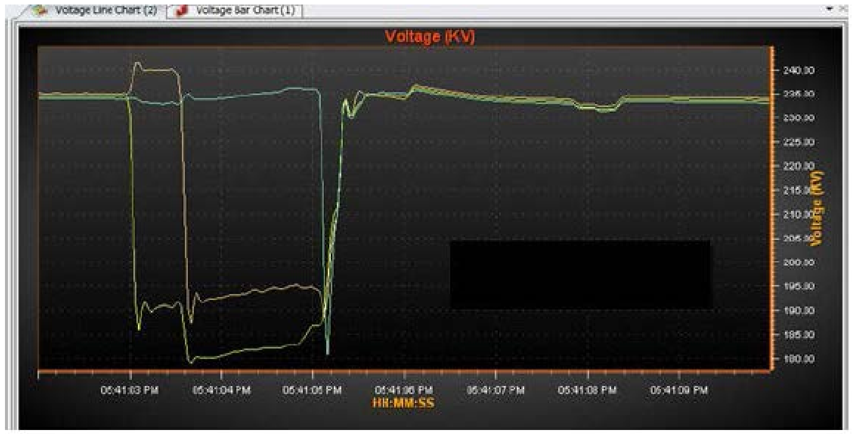
- The wide-area monitoring and visualization systems enable a broader view of the bulk transmission system for grid operators.
- Angle and frequency monitoring provide grid operators and engineers with detailed information regarding grid conditions, power flows, and dynamic phenomena.

Duke Energy is testing the use of synchrophasor data to improve state estimation, system model accuracy, and the time required for post-event analysis.

- Improved state estimation allows Duke Energy to better monitor parts of the transmission grid that lack angle measurements. This increases the accuracy of power systems network analysis calculations that are used to set various operational system parameters.
- PMU data are used for steady-state model benchmarking, increasing the fidelity of the models used to make planning and operational decisions.

[45] http://www.duke-energy.com/about-us/default.asp

- Duke Energy has implemented a synchrophasor-based event analysis application. The application reduces the time required to analyze events. For example, lightning initiated an event where a 100 Hz breaker was slow to trip, causing a fault to remain on the system for two seconds. As a result, the 230 kV to 100 kV transformers at the station tripped by overload and back-up protection was engaged. The PMU accurately recorded the magnitude and time duration of the fault (see the figure to the right), making the analysis to diagnose and correct the problem timelier and efficient.



Lightning initiated event recorded by a PMU

Duke Energy is using synchrophasors to detect oscillations and other phenomena within their service territory. Synchrophasor technology has enabled Duke staff to detect and locate problems before they significantly impact the system.

- A substation reported megawatt-level oscillations that were created on the transmission system when a 500/230 kV transformer at a nearby station was removed from service.
- PMU data was used to determine that a nearby hydropower unit was causing oscillations. The information enabled engineers to define the problem and implement a solution.
- An automatic voltage regulator at a power plant mis-operated as a result of a low voltage transformer fault.[46] Plant engineers needed to know the duration of the voltage dip, but supervisory control and data acquisition (SCADA) was unable to observe the fault. Using synchrophasors, engineers determined that the voltage on the 230 kV bus momentarily dipped to 150.6 kV, which is well outside the tolerances of the control system.

"Phasors provide a better indication of grid stress and can one day be used to help our system operators trigger corrective actions to maintain reliability."

Communications upgrades improved bandwidth and security to support PMU data delivery.

- Duke Energy upgraded its existing serial communications systems within substations to internet protocol-based communications.
- Adding a buffer to the input of the PDCs improved data availability.
- Communication improvements also included increased bandwidth across the network and reduced communications bottlenecks, upgraded secure communications from Duke Energy to

[46] Phillips, Evan. "Duke Energy Carolinas: Smart Grid Investment Grant Update", NASPI Presentation, October 2013.

the transmission substations, and upgraded communication capabilities to support transmission resources.
- Duke Energy is sharing data from 18 PMUs with PJM Interconnection.

Lessons Learned

Data quality plays a defining role in the effectiveness of synchrophasor technology. Also, acceptance of the technology will require effort to demonstrate the value to operations personnel.

- As the project moved from the installation phase to active use, it became increasingly important to test equipment to ensure that measurements and time stamps were accurate.
- To fully capitalize on the investment, operations personnel must be sufficiently engaged, trained, and committed to working with the new synchrophasor data and applications. Therefore, the project team must communicate a clear value proposition for embracing the technology at the operational level.

Implementation and management of synchrophasor systems present several challenges including:

- Designing and maintaining a low-latency communications system adequate for synchrophasor data delivery.
- Integrating multi-vendor systems and dealing with interoperability issues.
- Management of the large influx of data.

Future Plans

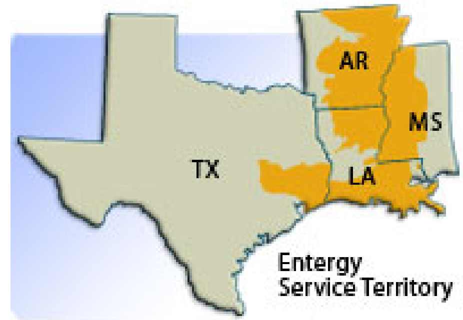
Duke Energy is interested in working with the U.S. Department of Energy to ensure that common visualization tools, language, and metrics for synchrophasor applications are broadly disseminated throughout the industry.

Duke has participated in meetings with the other synchrophasor projects funded by the ARRA to discuss lessons learned, impacts, and benefits from PMU installations, thereby increasing overall industry knowledge and effectiveness of synchrophasor technology. Duke Energy will continue to attend these meetings as PMU users become increasingly familiar with and begin to fully leverage the new technology.

A1.4. ENTERGY SERVICES, INC.

Scope

Entergy Services, Inc. (Entergy) is an integrated energy company that delivers electricity to approximately 2.8 million utility customers in Arkansas, Louisiana, Mississippi, and non-ERCOT portions of East Texas. Under American Recovery and Reinvestment Act (ARRA) co-funding, Entergy installed 49 phasor measurement units (PMUs), 16 phasor data concentrators (PDCs), six substation computers, and state-of-the-art decision support tools across the Entergy service area. The deployment of this technology provides global positioning system (GPS)-linked, time synchronized visibility of more than 20% of Entergy's 500 kV bulk electric transmission system. Additionally, the project included training and education of Entergy's operations and engineering groups to provide the foundational learning required to implement these advanced tools.[47,48]



Entergy service area

	# PMUs	# PDCs
ARRA Project Funded	49	16
Entergy System (incl. ARRA)	67	25

Entergy added several PMU data applications which enhance the visibility of Entergy's bulk power system in near real-time, enable detection of oscillatory and voltage disturbances, and facilitate sharing of information with neighboring regional control areas. All PMU data applications and visualization tools are implemented in a development, non-production environment, as they undergo benchmarking, testing, and evaluation for production readiness.

Goal: To enhance visibility of Entergy's bulk power system in near real-time, enable detection of oscillatory and voltage disturbances, and facilitate sharing of information with neighboring regional control areas.

Results Achieved

Entergy enhanced its PMU architecture to support the reliable and secure transfer of PMU data with the following additions:

- The Secure Information Exchange Gateway application (SIEGate) provides for the secure, scalable, and controllable exchange of high-bandwidth, high-frequency synchrophasor information between Entergy and other utilities.
- The open Phasor Data Concentrator (openPDC) serves as the core of Entergy's synchrophasor data architecture and gathers, time aligns, manages, and distributes the high-speed PMU data in real-time. These data, collected from PMUs, digital fault recorders and substation computers, are sent to analytics, visualizations, SIEGate, and OSIsoft PI, Entergy's long-term historian.

47 http://entergy.com/operations_information/

48 http://entergy.com/about_entergy/

- OSIsoft PI was implemented as Entergy's long-term data historian and holds over 30 terabytes of Entergy's historical PMU data.
- Entergy deployed the Substation Secure Buffered Gateway (SubstationSBG), an application that resides at the substation level and provides intelligence to manage PMU data locally. This software stores PMU data on the substation computer when communication networks are down, sends real-time data and resynchronizes locally stored data with the central openPDC when networks are active, easily connects to local substation PMU-capable devices, encrypts and securely transmits data between substations and central data centers, and minimizes PMU data loss between substations and the central openPDC.
- SIEGate, openPDC, OSIsoft PI, PMUs and their associated data, and the SubstationSBG are in the process of migrating to full production environments at Entergy.

Entergy installed synchrophasor-based applications including enhanced state estimation, oscillation monitoring and detection, and voltage stability monitoring. These applications have been implemented in a development, non-production environment, as they undergo benchmarking, testing, and evaluation for production readiness.

- A synchrophasor-assisted state estimator (SPASE) integrates network measurement based information with synchrophasor measurements into an off-line state estimator to assist in the observability of the Entergy system. In addition, SPASE detects erroneous data and identifies critical measurements in the system topology.
- A synchrophasor-based oscillation monitoring system identifies and evaluates oscillatory events in real time. Oscillation monitoring provides information about the characteristics and types of oscillations within the Entergy system and, if interconnection data is available, can provide information about inter-area oscillations across the Eastern Interconnection. The application enables early detection and mitigation of potentially harmful system oscillations, thereby enhancing the operational reliability of Entergy's transmission system. Persistent oscillatory modes can influence power quality and cause equipment fatigue, the disconnection of generators and loads, system islanding, and localized blackouts.
- Voltage stability monitoring applications provide voltage stability monitoring at PMU-enabled Entergy substations and for Entergy's Western Region. They also provide parameters for a model-based method to monitor the region's power imports and stability. Voltage stability analysis is a key function in system operation to help foresee critical grid conditions that may cause local and/or wide-spread voltage instability. These applications were developed to improve grid reliability by increasing the observability of changing grid conditions, especially during severe operating conditions. Voltage instability can result in blackouts in the stressed part of the transmission grid, which can cascade to other parts of the interconnection.

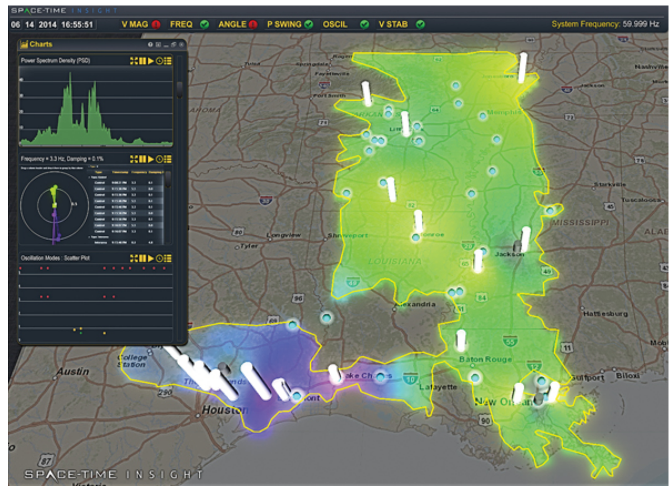
Entergy is using PMU data/analytics results to validate its system models, improve its post-event analysis, and to look for patterns in system behavior.

- Comparison of PMU measurement-based results and traditional model-based results may provide insight for validation of existing models and model assumptions. Entergy will continue to study the usefulness of these comparisons and explore their applicability in other engineering areas.

- Post-event analysis of PMU data enables investigations into historical disturbances and system events to better understand the sequence of the events and their causes.
- Pattern recognition analysis identifies patterns in PMU data and the potential value of these data signatures for improving grid operations.

Entergy has implemented real-time visualizations to show PMU data and application results.

- Entergy's wide-area monitoring and visualization system enables the real-time observation of high-frequency, high-bandwidth PMU data and analytic results. These include geographical mappings of PMUs, overlays of real-time weather trends, historical play-back of events, viewing and identification of real-time oscillations, visualization of unstable voltage areas, and integration of this information onto geographical maps and analysis dashboards.
- Entergy trained and educated over 500 personnel on synchrophasor fundamentals.



Visualization of oscillation and voltage stability

Lessons Learned

PMUs, and their associated intelligent components, evolve at much faster rates than more traditional transmission equipment and should be planned for accordingly.

- Establish metrics during project planning for measuring and understanding the PMU architecture's health.
- Make PMU applications scalable and adaptable as the technology becomes more commonplace and widespread.
- Evolve PMU analytics beyond simple real-time snapshots to include the use of statistical tools that provide longitudinal analysis of the data, projection of future trends, prescriptive actions to future trends, and the eventual business transformation enabled by these analytics and technology.

> "The completion of the DOE grant is really only the start of efforts to harness the power of these new tools... While Entergy has participated in the launch of PMU technology into the industry's mainstream, there is much exciting work still ahead."
>
> - Floyd Galvan, Entergy Program Manager

Management of PMU data and development of applications presented challenges to the project team.

- The high-bandwidth, high-frequency, and sheer volume of PMU data afford special requirements when implementing analytics, visualizations, and methods for information storage and retrieval.

- Applications of oscillatory/signal theory in real-world utility systems are novel and complex and will require much more education and training of engineers and operators and higher densities of installed PMUs before they can be viable tools.

Practical considerations are needed when migrating synchrophasor technology from a development environment into full operations production environments.

- The Department of Energy's (DOE's) Smart Grid Investment Grant projects have built an initial PMU framework; however, many more synchrophasor capable devices are needed to fully realize state-of-the-art grid control.
- The synchrophasor community needs to speak with a common vocabulary, agree on definitions and standardized testing of/use cases for synchrophasors, real-time analytics, visualizations, and data exchange.

Future Plans

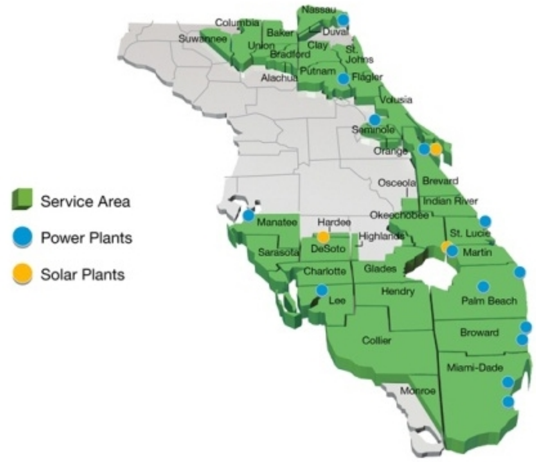
ARRA co-funding of PMU technology has made its adoption possible throughout the industry. Adoption, however, is only the first step in the integration of this technology into utility operations.

As an industry, we will need to outline a plan for the full utilization of this technology. This plan should include the retirement of aging communications assets which PMUs will replace, the growth of existing communications systems to accommodate significantly larger numbers of synchrophasor capable devices, and a realistic understanding of the long-term ramifications PMUs bring to grid operations.

A1.5. FLORIDA POWER & LIGHT COMPANY (FPL)

Scope[49]

Florida Power & Light Company (FPL), a subsidiary of NextEra Energy, is an investor owned electric utility that serves a large portion of the State of Florida.[50] FPL is the third-largest electric utility in the United States, serving approximately 4.8 million customer accounts in Florida. The FPL Smart Grid Investment Grant (SGIG) project, known as Energy Smart Florida (ESF), deployed advanced smart meters, distribution automation, an electricity pricing pilot, a mesh network communications system, and advanced monitoring equipment for the utility's transmission system. ESF applied advanced technology at all levels of the power system – customer (smart meters and demand response), distribution feeders (distribution automation), and bulk electric grid (equipment monitoring and phasor measurement units (PMUs) – to enhance the reliability and affordability of electric power for FPL's customers.



FPL service area

	# PMUs	# PDCs
ARRA Project Funded	45	13
FPL System (incl. ARRA)	45	13

FPL leveraged SGIG funding to install 45 PMU devices at 13 transmission substations throughout its service area. FPL deployed two types of phasor data concentrators (PDCs) to aggregate and time-align data from the PMUs. A local PDC at each substation manages the incoming data from PMUs at the site. A central PDC handles incoming PMU data from local PDCs in the FPL service area. The central PDC connects to the FPL Energy Management System (EMS) and the data historian. The data historian, in turn, provides the necessary PMU data to the FPL Power Delivery Diagnostic Center[51] (PDDC), a state-of-the-art diagnostics hub for monitoring power system equipment health and improving reliability.

Goal: To improve FPL's electric service reliability, power quality, and transmission system security using PMUs.

PMUs provide wide-area situational awareness of the FPL service area and help determine the transmission system stress points by monitoring synchrophasor data. The real-time information from wide-area monitoring using synchrophasor technology improves operation and reliability of the FPL transmission system by providing greater visibility of system conditions, improving diagnostic capabilities to prevent occurrence of outages, and assisting FPL system operators in system restoration

[49] http://newsroom.fpl.com/index.php?s=32039&item=978#assets_76:19475
[50] https://www.fpl.com/about/company-profile.html
[51] http://newsroom.fpl.com/2015-03-25-FPL-unveils-new-smart-grid-technology-center-a-state-of-the-art-diagnostics-hub-for-improving-reliability

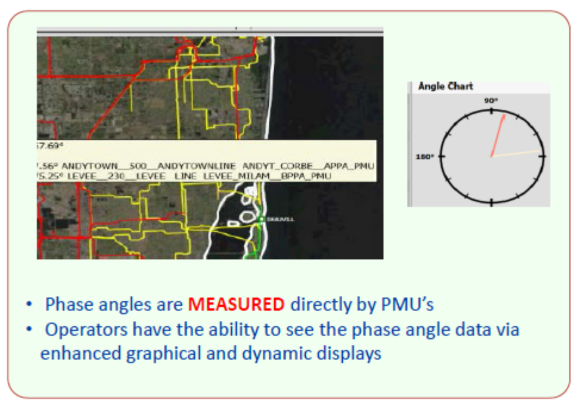
after events such as hurricanes. PMU measurements also enhance situational awareness for operators, especially during high load conditions that require large power transfers on the transmission network. FPL application areas include frequency response calculations, validation of state estimation, phase angle reclosing monitoring, voltage imbalance checks, post-event analysis, and model validation.

Results Achieved

PMUs, in conjunction with other monitoring devices, enhance the reliability and security of the FPL transmission system by detecting incipient failures and avoiding outages and equipment damage.

- In September 2012, data from equipment monitoring devices was used to identify a damaged transformer before it failed. This avoided an unplanned outage of a large substation and its customers.
- FPL is monitoring the transmission system and certain substations using PMUs, digital disturbance recorders, and other intelligent electronic devices. These data are being telemetered to the PDDC for assessment of health and status of power system equipment. For example, the health and status of capacitance voltage transformers (CVT) is inferred by measuring the voltage magnitudes of the CVTs' three-phase voltages and calculating the phase angles between these voltages. FPL developed a monitoring device-based algorithm to detect CVT degradation before it fails. The mitigation of CVT failures is important since this type of equipment failure results in a relay mis-operation which can cause a single-end line outage, a complete voltage loss, or loss of power line communications used for relay protection. These monitoring systems alerted FPL operators to three CVT events in 2014, all due to degraded or failing equipment. In all three cases, FPL had sufficient warning to take action before a transmission disturbance or Federal Energy Regulatory Commission (FERC)-reportable outage occurred.

FPL is using PMU-provided phase angle measurements to assess switching operations and to improve post-event analysis.



- Traditionally, phase angles in the system were calculated using the state estimator and the results were limited in time resolution and accuracy. Now, with PMUs, phase angles are measured and operators have visibility of the phase angle data via enhanced graphical and dynamic displays. Knowing the true phase angle differences between points enables system operators to close circuits with less risk.
- The improved data resolution provided by synchrophasor data from FPL's PMUs enhances the post-event analysis of power system events.

FPL has implemented or is piloting applications that monitor the health of the system across the service territory in order to enhance operational awareness.

> "PMU measurements enhance situational awareness for operators especially during high load conditions that require large power transfers using the transmission network."

- Angle measurement data from the PMUs are used as inputs to FPL's state estimator, thus expanding the state estimator measurement set. The angular measurements were not previously available and provide additional measurement data to estimate bus voltages and angles.
- The frequency monitoring application gathers data from PMUs located at key points on the bulk electric system. As necessary, the frequency monitoring application can trigger actions to aid in the system frequency response when a specified level of frequency excursion (as measured from specific PMUs) is experienced. FPL uses the PMU frequency measurements to validate the occurrence of frequency excursions and mitigate their effect by triggering short burst demand response actions.
- PMU data are being integrated into the EMS and voltage stability application to identify real-time power system conditions for critical elements within the grid. This enables operators to develop preventative and corrective actions to mitigate and prevent voltage instability. The enhanced quality of field measurements provided by PMUs improves FPL staff awareness of the actual stability margins of the system during any state of operation.

Lessons Learned

The biggest challenges at FPL have been:

- Building data interfaces and visualizations
- Transporting synchrophasor data from the PMUs/PDCs to a central PDC
- Integrating PMU data into a system historian

Data delivery requires careful design as engineers must recognize that the communications infrastructure must be as resilient as the power delivery infrastructure.

Future Plans[52]

FPL has plans to:

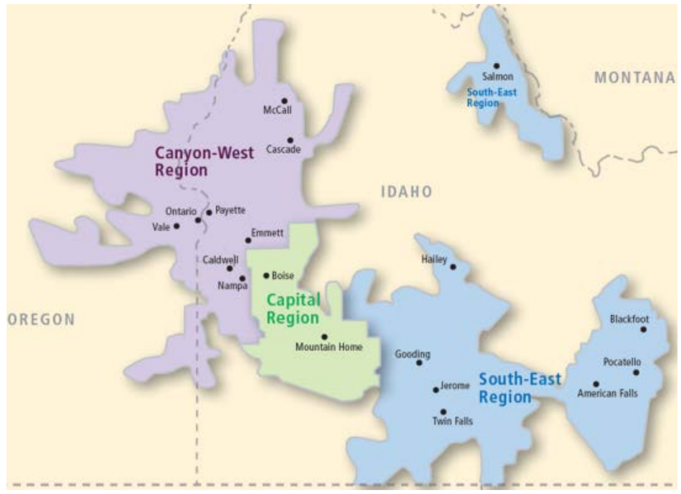
- Add control room visualization of synchrophasor applications. This capability will enable the operators to improve situational awareness.
- Evaluate the need for additional PMU coverage; FPL will determine if and where more PMUs are needed.
- Continue to offer synchrophasor training to its engineers and system operators to increase their technical awareness.

[52] McInnis, Don and Chenyan Guo. "Florida Power & Light Company Smart Grid Investment Grant Update." NASPI Work Group Meeting October 22-24, 2013.

A1.6. IDAHO POWER COMPANY (IPC)

Scope[53]

IPC is an investor-owned utility that serves customers across eastern Oregon and southern Idaho. IPC's smart grid project included deployment of advanced metering infrastructure (AMI), AMI-enabled customer systems, and advanced synchrophasor monitoring equipment for the transmission system. IPC has significant amounts of renewable generation available to its service territory in the form of hydroelectric and wind power. At times, wind power can provide up to 35% of IPC system demand. Installing phasor measurement units (PMUs) to assist engineers in validating wind turbine models has enabled IPC to better model, analyze, and operate the IPC system.



IPC service regions

	# PMUs	# PDCs
ARRA Project Funded	8	0
IPC System (incl. ARRA)	24	1

Through ARRA funding, IPC installed eight PMUs in four substations, bringing IPC's total to 24 PMUs in 14 substations. The PMUs monitor major extra high voltage (EHV) and high voltage transmission lines, tie lines, major load centers, renewable generation sites such as wind, geothermal generation, and major hydroelectric and natural gas generation sites. IPC used its existing phasor data concentrator (PDC) to aggregate and manage the data.

Goal: To provide greater visibility and awareness of transmission system conditions and to increase the overall reliability of the transmission system.

Dedicated circuits deliver the PMU data to the PDC through IPC's private communications network using a serial communications protocol. The PMU data are sent to three virtual servers on the IPC corporate network: 1) a dedicated PDC server to manage the data, 2) an application server that performs voltage stability and oscillation monitoring, and 3) a server that provides visualization and event analysis. All three servers archive their information on a remote disk array. IPC is evaluating applications including voltage stability and oscillation modal analysis and has implemented model validation that uses PMU data.

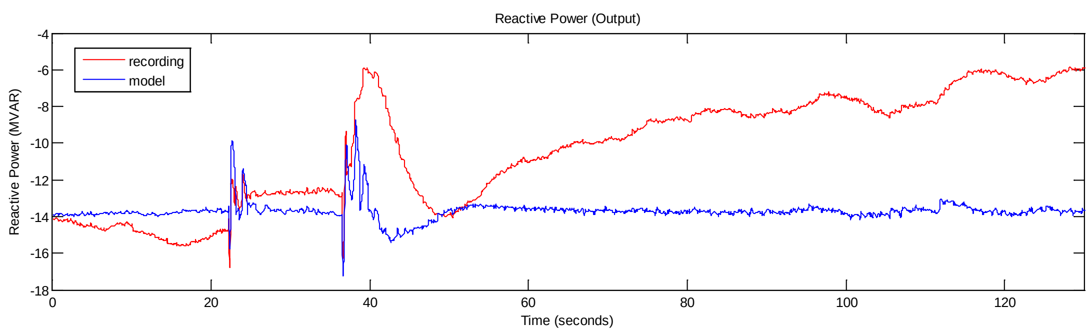
[53] https://www.idahopower.com/pdfs/AboutUs/CompanyInformation/OurCompany.pdf

Results Achieved

IPC and its partners developed tools that use synchrophasor data to improve the integration of renewable resources onto the transmission grid.[54]

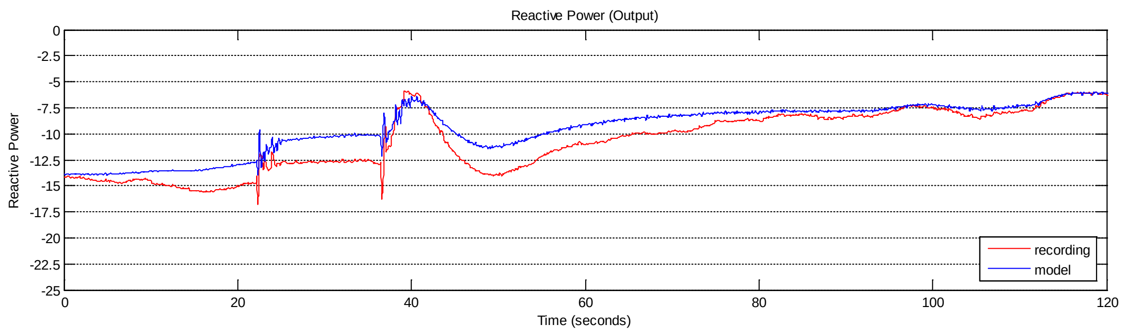
- One application enables IPC to visualize system disturbances so off-line PMU data can be exported for use in model validation applications. This application allows IPC engineers to investigate system disturbances – and be presented relevant PMU data – in a timelier manner.
- IPC developed an application to query archived PMU data and export the PMU data for use in model validation applications and for data sharing with interested entities.
- IPC validated dynamic models for select wind power plants using PMU data generated during disturbance events. IPC used new model validation applications for offline analysis to compare the dynamic model predictions to actual PMU disturbance data. Since sufficient test data for developing a reasonable baseline dynamic model has not been commonly available for wind generation, IPC believes that PMU disturbance recordings will provide the data needed to improve the models of wind power plants. An example is shown below.

Data on a system disturbance recorded by PMUs (red curve, first graph) showed that the predicted system behavior based on the dynamic model of a power plant (blue curve, first graph) was not accurate. IPC used the PMU data to modify and validate the model. The improved model's predictions of the power plant's behavior during a subsequent disturbance (blue curve, second graph) correlated much better with the PMU data (red curve, second graph).



Example of using PMU data (red curve) recorded during a disturbance to detect an inaccurate model (blue curve)

54 https://www.smartgrid.gov/project/idaho_power_company_ipc_smart_grid_program



The results of improving the model

IPC has shared its PMU data with research organizations for development and refinement of synchrophasor-based applications and with other utilities to improve grid visibility for the entire interconnection.

- Post-event PMU data is shared with the Electric Power Research Institute (EPRI) to explore the expansion of an existing tool for validating wind turbine generators. Currently, the tool applies only to a single turbine. This collaborative effort seeks to expand the functionality of the tool into a plant level model validation and calibration application.
- IPC is also sharing PMU data with Washington State University for developing real-time and post-event voltage stability and oscillation analysis applications.
- IPC is sharing (both sending and receiving) real-time PMU data with a number of entities including Peak Reliability (Peak), Bonneville Power Administration (BPA), and PacifiCorp. The increased monitoring of adjacent balancing areas provides better visibility of inter-area oscillations and angular differences.

"The PMU-based wide-area monitoring system provides IPC with real-time information about transmission system operation and reliability."

IPC is using synchrophasors to discover phenomena that were previously undetected with traditional technology. Synchrophasors are also leading to improvements in operational efficiency.

- Several oscillations have been observed by the oscillation monitoring application, including a well-damped oscillation at 0.2 Hz and three poorly damped modes at 0.6 Hz, 1.4 Hz, and 1.6 Hz. These modes are not persistent, but did appear in several analysis windows during the monitoring period. Using PMU data, IPC determined that the impact of these particular oscillations to grid reliability is negligible since their energy content is very low. However, IPC will continue to monitor these oscillation modes and their respective energy levels.
- Synchrophasor technology has reduced the time traditionally required to validate wind generator models by 75%. PMU data provide the ability to observe dynamic performance of a generation facility under conditions that may not be achievable under test conditions. IPC estimates that PMU disturbance data saves two to three days per generator as compared to traditional staged testing.

Lessons Learned

Managing the PMU installation project with other concurrent projects within IPC led to postponement or delay of certain tasks.

- The project involved multiple technology sub-projects, straining technical resources, and limiting how much could actually be accomplished.

Security and data integrity issues presented the team with tremendous time and resource-intensive obstacles.

- IPC has experienced data availability issues and total loss of PMU data from time to time due to issues including both hardware and application failure.
- IPC currently has no way to determine the performance of its PMU data network and is working with the PDC manufacturer to determine if using latency tracking at the PDC is a viable method for determining system performance.

Future Plans

IPC engineers see the value of synchrophasors and are installing additional PMUs to increase system observability.

- For example, after identifying oscillations during this project, IPC installed additional PMUs at generating stations to locate the sources of the oscillations.

Senior management is currently reviewing the completed projects and developing a vision for the next steps in smart grid for IPC.

- IPC will continue to work with its partners to develop new real-time and post-event voltage stability and oscillation detection/analysis applications that use PMU data.

IPC will continue to gather data to further refine the methodology used in both of these applications.

A1.7. INDEPENDENT SYSTEM OPERATOR NEW ENGLAND (ISO-NE)

Scope

ISO-NE is a regional transmission organization that oversees operation and planning of New England's bulk electric system and administers wholesale electricity markets across the six New England states. ISO-NE's transmission owners (TOs) include Bangor-Hydro, Central Maine Power, Northeast Utilities, National Grid, NSTAR, United Illuminating, and VELCO. Under the Smart Grid Investment Grant (SGIG) project, ISO-NE and its seven TOs installed 73 phasor measurement units (PMUs) and nine phasor data concentrators (PDCs) across the New England region, covering approximately 46% of the extra high-voltage system.[55] Point-to-point, high-speed communications circuits were utilized for streaming PMU data from substations to the TOs' PDCs and then to the ISO SuperPDCs.

ISO-NE service area

The goal of ISO-NE's Synchrophasor Infrastructure and Data Utilization (SIDU) project was to improve grid reliability and resilience while enabling more efficient use of grid resources. The SIDU project has already achieved benefits for New England by enabling power system engineers to monitor system dynamics that was previously not possible, achieving fast and accurate post-event analysis, and validating and improving power system models.

	# PMUs	# PDCs
ARRA Project Funded	73	9
ISO-NE System (incl. ARRA)	73	9

ISO-NE and its participating member TOs expect, in the future, enhanced monitoring capabilities and increased situational awareness provided by the new synchrophasor system. These, in conjunction with new applications, will improve the reliability of the transmission grid by enabling earlier detection of disturbances and preventing the spread of local disturbances into neighboring regions.

Goal: Improve grid reliability and resilience while enabling more efficient use of grid resources.

[55] The DOE originally approved a project grant of $18 million. However, the ISO and TOs identified over $4 million in cost savings opportunities as implementation of the project began. Without any significant changes to the original scope of project the final total amounted to $13.9 million.

Results Achieved

ISO-NE's synchrophasor system provides engineers with information to correct undesired system behaviors and improve system models. Grid planners and operation engineers rely on simulations of the dynamic behavior of the power system to make planning and operational decisions so they need to have confidence in their models. Inaccurate models could impact system security and result in under-utilization of transmission capacity and out-of-merit dispatch of generators.

- Engineers verified the accuracy of a generator model for a nuclear unit during a disturbance caused by a line trip and reclosing. The ISO simulated this event and compared simulation results with measurements from PMUs. The nuclear unit behavior as measured by the PMU compared well with the model-based simulation in terms of oscillation amplitude, oscillation frequency, and damping, demonstrating the model's accuracy.
- ISO-NE's use of PMU data to validate dynamic models also resulted in significant improvements to a user defined high-voltage direct current transmission (HVDC) model during a fault on a 345 kV line near the HVDC facility. The PMU data showed ISO engineers that the HVDC facility was temporarily blocked due to low alternating current (AC) voltages but simulation of this event did not produce the same behavior. ISO engineers re-tuned the HVDC model so that it provided results that were consistent with PMU measurements. The re-tuned HVDC model was verified using PMU data from a subsequent event.

The synchrophasor system has identified large oscillation modes that could not be detected by supervisory control and data acquisition (SCADA) measurements and which previous engineering simulations did not predict.

- Engineers are monitoring and performing off-line analysis of power system frequency, voltage angles, and line flows across the New England region to observe and detect oscillations within the system.
- The synchrophasor system recently alerted the ISO of an oscillation at 0.12 Hz that was sustained for about three minutes, reaching 100 MW peak-to-peak. Because simulations do not exhibit oscillations at this frequency, the ISO is now monitoring this specific oscillation mode and investigating methods to identify the source of this oscillation.
- Off-line analysis of PMU data also identified an oscillation at 0.95 Hz and pointed to a particular power plant as the potential source. ISO-NE is working with the power plant owner to investigate the oscillation. As a result, the plant owner has calibrated certain equipment and plans to install a power system stabilizer (PSS) to further reduce the impact this oscillation has on the grid and the power plant.

The synchrophasor system and its applications provide faster and more accurate information for post-event analyses, enabling engineers to understand what occurred and how the system behaved before, during, and after disturbances. The reconstruction of event sequences is particularly important for complex events where many elements can be involved in a short period of time.

- Without synchrophasor data, event analysis was a slow and tedious process, requiring at least a week of staff time and allowing analysis of only a few events each year. With PMU data now automatically collecting and synchronizing data from all across New England, engineers can quickly identify and analyze disturbances, enabling analysis of several events per week.

- One unusual system event resulted in the loss of two nuclear units for a total of 2,100 MW which was the single largest source loss ever experienced on the New England system. Using PMU data, engineers quickly assessed the system's behavior before, during and after the event. Furthermore, PMU data increased their confidence in simulation results.

ISO-NE is installing advanced synchrophasor applications that translate PMU data into actionable information for its engineers. These applications are currently processing data from PMUs and continue to be evaluated and improved by ISO-NE and its development partners.

- ISO-NE is exploring the use of PMU data in the state estimator along with conventional SCADA data. The goal is to assess the impact of PMU data on the performance of the state estimator in terms of robustness, accuracy, and reliability.
- The ISO is implementing an application that in the future could provide real-time alarms when the system operating point is close to the boundaries of secure operating regions in terms of voltage and thermal performance, and recommend corrective actions.
- ISO-NE is using synchrophasor data to help analyze primary frequency response provided by generators in the region. Using synchrophasor data eliminates errors in this calculation by providing high-resolution data with much better time accuracy than traditional SCADA data.

Lessons Learned

Installing PMUs in the New England region required significant coordination with TOs to achieve a comprehensive synchrophasor system. Efforts are needed to make engineers and operators aware that the technology is available and that it can be valuable to their mission.

- ISO-NE and its member TOs performed rigorous PMU data validation early on in the project, allowing the project team to resolve issues when the resolutions were least costly.
- Greater technical engagement between ISO-NE and TO staff earlier in the project would have been more effective in getting the entire project team aligned on project goals.
- More detailed PMU requirements and standards might have eliminated some technical issues that appeared during project implementation.
- Acceptance of the synchrophasor technology requires focus on formal training for engineers at ISO-NE and other stakeholders. Such efforts will also help to promote the benefits of synchrophasor technology to a wider audience.

> "Ultimately, the SIDU project is expected to provide the region with improved reliability through enhanced situational awareness, faster response to system events, and new system restoration capabilities."

Future Plans

ISO-NE continues to improve its understanding of the benefits obtained from synchrophasor technology with the objective of moving it from engineering to real-time operations. Currently, ISO-NE is conducting a feasibility demonstration of a PMU-based state estimation for the 345 kV network and evaluating a hybrid PMU/SCADA state estimator.

Real-time PMU data exchange with neighboring systems such as PJM and New York Independent System Operator (NYISO) could provide ISO-NE and the other areas with the ability to prototype wide-area monitoring displays and tools. ISO-NE is exploring using the Eastern Interconnect Data Sharing Network (EIDSN), a high-speed network for sharing power system data, including PMU data, in the Eastern Interconnection. Cloud-based hosting as a collaboration platform for PMU data exchange and central repository is also under consideration.

In addition to future real-time operations, ISO-NE will continue efforts to find innovative ways to use synchrophasors for system planning. Currently, ISO-NE is evaluating options to streamline their model validation processes by leveraging PMU, SCADA, and digital fault recorder data. ISO-NE is also working on an oscillation source study to diagnose the cause of the oscillations already discovered by the synchrophasor system.

A1.8. LAFAYETTE CONSOLIDATED GOVERNMENT

Scope[56,57]

Lafayette Utilities System (LUS) is part of the Lafayette Consolidated Government. This municipally-owned electric utility serves the City of Lafayette and surrounding areas – comprising a population of more than 120,000 people over 47.7 square miles in southwestern Louisiana. In 2012, LUS leveraged American Recovery and Reinvestment Act (ARRA) funding to install 31 relays with phasor measurement unit (PMU) functionality within its three 230 kV and one 138 kV substations. LUS also acquired a phasor data concentrator (PDC) for each substation and software for management and visualization of the data.

LUS coverage area in Lafayette Parish, Louisiana

Initially, LUS' plans for enhancing its transmission system automation included the deployment or upgrade of transmission protection devices at three substations and the upgrade of its supervisory control and data acquisition (SCADA) remote terminal units for improved transmission monitoring. LUS had already applied ARRA funds to install high-speed Ethernet communications between the substations. Once the dual-function relays were in place with the high-speed communications network, LUS engineers enabled the PMU functionality on the relays.

	# PMUs	# PDCs
ARRA Project Funded	31	4
LUS System (incl. ARRA)	31	4

Results Achieved

The PMU data system enhanced the capability of LUS engineers to perform post-event analyses of system disturbances.

Lessons Learned

Upgrading the digital relays to PMU functionality was relatively easy and inexpensive with support from the relay provider.

Goal: Increase observability of the grid's dynamic behavior in near real time by sending synchrophasor data to be monitored and archived.

[56] https://www.smartgrid.gov/project/lafayette_consolidated_government_lafayette_utilities_system_smart_grid_project/latest_data

[57] http://ilsr.org/wp-content/uploads/2012/04/muni-bb-speed-light.pdf

Future Plans

Currently, LUS stores PMU data at each substation, but the utility is exploring the possibility of feeding data to a central location and eventually sharing the data with its reliability coordinator – Midcontinent Independent System Operator – to support wide-area situational awareness. LUS is also exploring the use of PMU data for control room applications, voltage monitoring, and wide-area situational awareness.

A1.9. MIDWEST ENERGY, INC. (MWE)

Scope[58]

MWE is a self-regulated electric cooperative in central and western Kansas. With American Recovery and Reinvestment Act (ARRA) funding, MWE replaced eight electromechanical relays in its Knoll substation with digital relays that have phasor measurement unit (PMU) functionality. A phasor data concentrator (PDC) was installed at the site to aggregate and manage the PMU data. Prior to the ARRA-funded project, PMUs were not deployed in this area. Based on its experience with the Smart Grid Investment Grant (SGIG)-funded PMUs, MWE implemented PMU capability in four additional digital relays at another substation.

Midwest Energy service area

In addition to PMUs, the project deployed new communications equipment to transmit synchrophasor data to the MWE control center. All communications wiring at the Knoll substation was replaced.

	# PMUs	# PDCs
ARRA Project Funded	8	1
MWE System (incl. ARRA)	12	1

The primary application for the synchrophasors is post-event analysis to diagnose causes of system outages and identify design and operational measures to avoid similar outages in the future. Another application is to use the synchrophasors to improve system restoration. A third application is to use the PMUs to improve wide-area system visualization by providing grid operators and engineers with detailed information about grid conditions such as key angles, frequencies, power flows, and results of system stability calculations.

Goal: To improve power system models and analysis tools and increase grid reliability.

Results Achieved

MWE has established the value of synchrophasor technology on their system.

- PMUs provide a more expansive view of the bulk power system and reveal details about the dynamics of their system.
- MWE's system reliability has been enhanced by the use of PMU data to improve the protection schemes at Knoll substation.
- MWE uses PMU data for model validation and other applications.

[58] https://www.mwenergy.com/about/service-area

MWE plans to use synchrophasors to improve restoration procedures and is installing additional PMUs at other locations within the service area.

- Incorporating PMU data into its restoration procedures will enable MWE to re-establish service more quickly after an outage. MWE is also enabling fault location functionality for all 230 kV and 115 kV lines originating from the Knoll substation.
- MWE has installed four additional PMU-capable relays in another substation to further increase synchrophasor-enabled system visibility.

Lessons Learned

Installation of a synchrophasor system is only the first step in fully realizing the benefits of the new technology. Advanced application design, development, and deployment are necessary to provide operators with actionable insights in the control room.

Knoll Substation control house with PMUs and PDC

Future Plans

MWE will continue developing improved monitoring and visualization applications to fully leverage the new grid state data available from PMUs. MWE will also evaluate other uses of synchrophasors, including:

- Steady-state benchmarking.
- Compliance of operations with North American Electric Reliability Corporation (NERC) Standard PRC-005 on Protection System Maintenance.

MWE is considering improvements to state estimation using PMU data. These data would enable engineers and operators to better infer system conditions for parts of the transmission grid that lack monitoring equipment. MWE has also offered to share its PMU data with other utilities and system operators.

A1.10. MIDCONTINENT INDEPENDENT SYSTEM OPERATOR, INC. (MISO)

Scope

MISO region service area

MISO is a regional transmission organization administering wholesale electricity markets[59] in the Midwestern United States and Canada. MISO's seventeen members include Entergy, Ameren, American Transmission Co., Duke Energy, Great River Energy, Hoosier Energy, Indianapolis Power and Light, International Transmission Co., Manitoba Hydro, Minnesota Power, Montana Dakota Utility, Northern Indiana Public Services Co., Ottertail Power, Vectren, WAPA and Xcel. Sixteen of these members participated in the MISO Smart Grid Investment Grant (SGIG) project; Entergy participated under their own SGIG project. MISO's primary objectives under the SGIG project were to leverage synchrophasor technology to optimize the dispatch and operation of power plants and to improve the reliability of the bulk transmission system. Under the original scope of its SGIG project, MISO planned to install 150 phasor measurement units (PMUs), 40 phasor data concentrators (PDCs), and advanced transmission software applications. However, after project implementation had begun, MISO increased the number of project PMUs to 260 for the same budget. MISO leveraged its existing communications infrastructure to support PMU data collection and transfer.

	# PMUs	# PDCs
ARRA Project Funded	260	40
MISO System (incl. ARRA)	260	40

The PMUs provide a more expansive view of the bulk transmission grid while revealing dynamic operating details. The synchrophasor system's advanced applications use data collected from the PMUs for increased real-time situational awareness as well as improved post-event analysis. MISO is able to detect stress on the MISO system and identify potential stability issues before they occur, allowing MISO operators to take proactive measures.

Goal: To optimize the dispatch and operation of power plants and improve the reliability of the bulk transmission system through synchrophasor technology.

Results Achieved

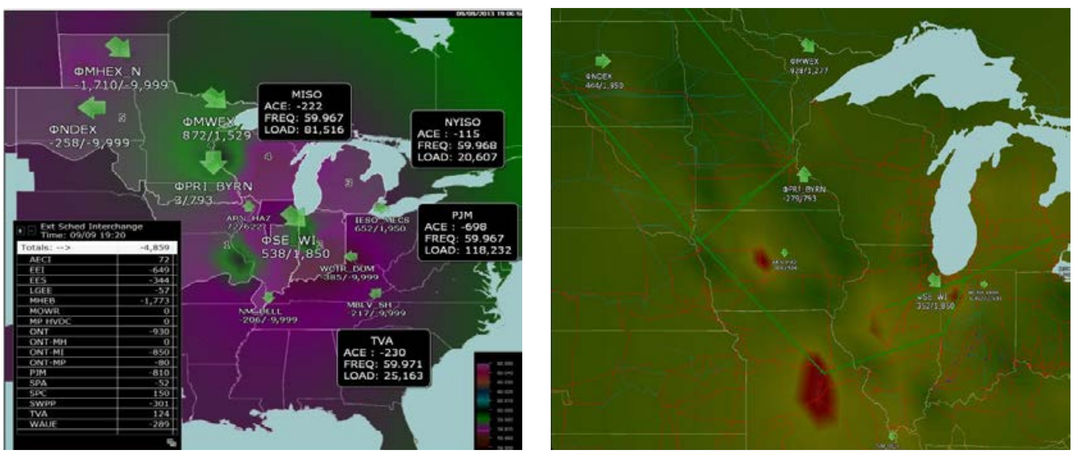
MISO developed enhanced real-time displays and deployed applications that use synchrophasor data to observe oscillatory behavior and display it in the control room.

- MISO's team of engineers pioneered a new feature for control room displays called enhanced Real-Time Display (eRTD) to give system operators a unique geospatial visualization of grid

[59] https://www.misoenergy.org/Library/Repository/Communication%20Material/Corporate/Corporate%20Fact%20Sheet.pdf

activity. This application also enables participating transmission owners to see the same displays as MISO control room operators.

- The eRTD allows operators to see voltage gradients and voltage angle pairs to determine phase angle differences.
- Synchrophasor data are correlated with the energy management system (EMS) and stability monitoring alerts, extending MISO capabilities and expanding functionality.
- Monitoring tools now exist in the control room, which display oscillatory behavior in the bulk electric system. They are enabled by the PMU reporting rate of 30 times per second, which provides observation of high-speed variations in voltage and frequency. The visual display can be used to identify oscillation characteristics including poor damping and large amplitudes, and to trigger alarms and alerts when oscillation characteristics surpass thresholds. When the system is disturbed, its ability to damp frequency oscillations is an important measure of system stability. Traditionally, these measures were based on steady-state power flow analysis. Now, PMU measurements make it possible to characterize oscillations as they develop.



Enhanced real-time visualization display: basic view (left) and voltage gradients (right)

MISO implemented applications that detect undesirable conditions on the system and automatically alarm MISO staff.

- New applications monitor PMU data for disturbances such as oscillations and islanding conditions. Event detection automatically notifies grid operators of real-time conditions that may affect grid stability.
- Assessment tools monitor the dynamic state of the grid and calculate angle limits. Operators can measure and display voltage angle differences between bus locations in the power system. An angle pair alarm corresponds to unusual system conditions, heightening operator awareness. MISO now runs its transient stability assessment tool every 15 minutes instead of daily or hourly, enabling MISO to increase power flows in constrained areas while maintaining reliability margins.

Offline tools provide MISO with the capability to validate system models and analyze system events.

- Synchrophasors are used to validate and calibrate models by comparing PMU data to simulation results. MISO uses operations models to predict potentially severe issues and contingencies across their system. PMUs enable more frequent and more accurate validation of these models, which improves MISO's ability to prepare for and mitigate such issues.
- MISO has also used PMU data to improve system planning models, including load composition models e.g., motors, electronics, lights; dynamic power plant models e.g., generator, exciter, turbine, and governor; and a model of their high voltage direct current transmission (HVDC) system.
- Other synchrophasor applications enable operators and MISO members to analyze event data using trending, statistics, spectral, modal/ambient, and ringdown capabilities. MISO has begun to archive data and has implemented down sampling of data for historical synchrophasor data storage.

"Incorporating these new technologies into real-time operations greatly increases our situational awareness of grid activity, and is essential to our effort to modernize the grid. Synchrophasor technologies provide us with unprecedented data on situations that could radically affect reliability of Operations and Corporate Services. With these devices, we've extended our ability to see ongoing system conditions, providing additional assurance that consumers are benefiting from improved reliability and predictability."

PMUs are providing MISO with a view of system behavior that was unavailable with traditional technology, enabling MISO to discover and locate phenomena on the system.

- Synchrophasors allow engineers to observe voltage drops in the MISO system that supervisory control and data acquisition (SCADA) is unable to detect.
- Oscillation analysis identified a generator governor control issue within the MISO region. PMUs enabled MISO engineers to determine the cause and location of the oscillations. MISO and the generation owner were able to resolve the control issue and mitigate the oscillations.

Lessons Learned

The acceptance of synchrophasor technology and management of the mass quantities of data are challenging issues for MISO.

- Given the status of synchrophasor technology development, operator acceptance and adoption of the technology is an ongoing challenge. MISO continues to train its staff and share its experiences to promote the technology; MISO expects it may take several years for the confidence of operators and engineers to reach the point of full acceptance.
- MISO began by maintaining all data and maximizing storage space, but has since begun to archive data and implement down-sampling of data for historical data storage. MISO is working to finalize its strategy for synchrophasor data storage.

Future Plans

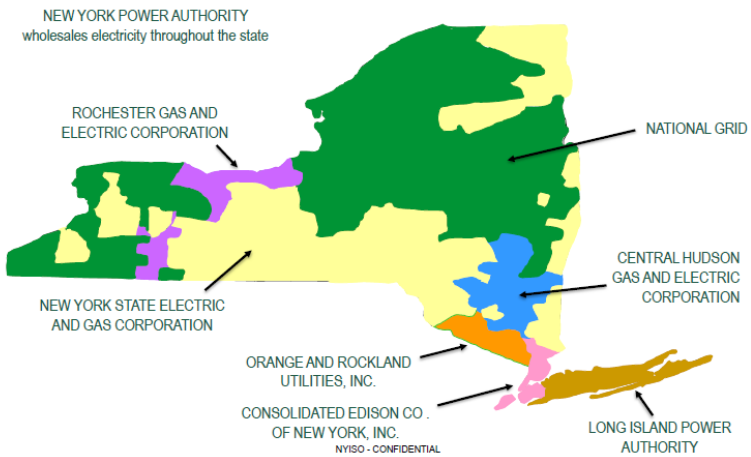
MISO intends to continue seeking new ways to extend the value gained from this technology by integrating it into their state estimator tool, deploying the new technology to additional transmission owners, and sharing data with the entire Eastern Interconnection.

- MISO has a three-year vision to support additional PMU installations and make synchrophasor usage routine in real-time operations.
- In line with this objective, MISO plans additional PMU measurements for bus-to-bus angle monitoring at key locations within the system.
- MISO expects to integrate synchrophasors into its state estimator within the next year with the objective that operators routinely use PMU data to support real-time decision-making.
- MISO will continue outreach efforts with the electric power industry and collaboration with TO members including continuing support to North American SynchroPhasor Initiative (NASPI) working groups and increasing real-time PMU data sharing.

A1.11. NEW YORK INDEPENDENT SYSTEM OPERATOR, INC. (NYISO)

Scope

The NYISO is a not-for-profit corporation that operates New York State's high-voltage transmission network, administers and monitors the wholesale electricity markets, and plans for the state's future electricity needs. NYISO's transmission owners (TOs) include Central Hudson Gas & Electric Corporation; Consolidated Edison Company of New York, Inc.; New York State Electric & Gas Corporation; Niagara Mohawk Power Corporation doing business as the National Grid; Orange and Rockland Utilities, Inc.; Rochester Gas and Electric Corporation; Power Authority of the State of New York; and Long Island Lighting Company doing business as the Long Island Power Authority. NYISO and these eight TO participants leveraged American Recovery and Reinvestment Act (ARRA) funding to deploy 41 substation phasor measurement units (PMUs), 11 phasor data concentrators (PDCs), and 938 MVAR of automated capacitor banks to support voltage stability in the New York Control Area (NYCA).



NYISO service region and transmission owner service territories

	# PMUs	# PDCs
ARRA Project Funded	41	11
NYISO System (incl. ARRA)	50	11

NYISO also installed a synchrophasor communications network, which delivers PMU data to the NYISO grid operations center through PDCs deployed across the participating TOs. This network includes systems to access, store, and process PMU data. Participant TOs also deployed software that uses the PMU data to assist staff by providing situational awareness displays.

Goal: To improve electric service reliability and power system stability.

The automated transmission system capacitors installed for the project are compatible with the monitoring capabilities provided by the PMUs and advanced applications. These capacitor banks improve the ability of the NYISO and the TOs to regulate transmission voltages.

NYISO's objectives for the synchrophasor system include increasing grid operator visibility of bulk power system conditions in near real time, enabling earlier detection of disturbances that could result in instabilities or outages, and facilitating the sharing of synchrophasor information with neighboring regional control areas. Access to better system operating information helps NYISO engineers improve power system models and analytical techniques, which improves the overall reliability of the NYCA transmission system. NYISO enhanced its state estimation application to accept synchrophasor data, deployed a voltage stability monitoring tool with real-time visualizations, and deployed an offline post-event analysis application.

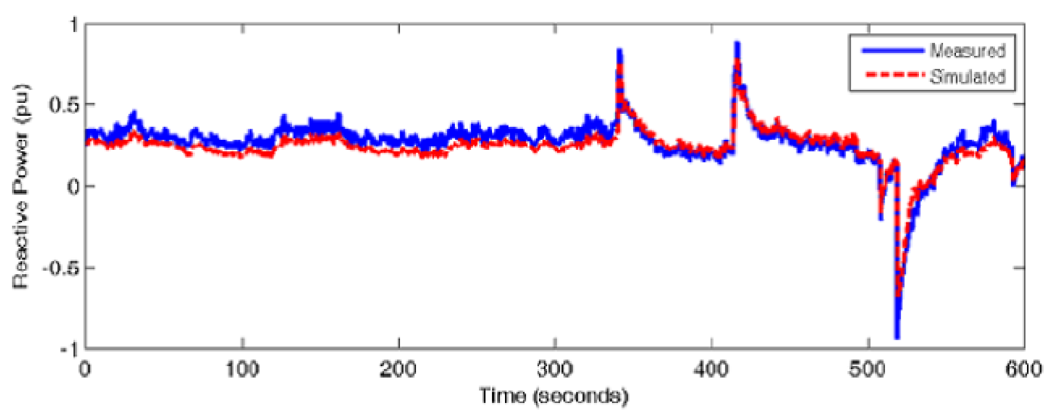
Results Achieved

NYISO implemented synchrophasor-based applications that enable engineers to see system behaviors not visible with traditional supervisory control and data acquisition (SCADA). It also uses synchrophasor data to improve the accuracy of existing applications. NYISO and its project partners view these capabilities as a key safeguard against future wide-scale blackouts, such as the major outage that affected NYISO and neighboring control areas in August 2003.

- Stability monitoring depicts system loading in real time and detects instabilities through phase angle relationships. Voltage stability monitoring provides grid operators and engineers with detailed information about grid conditions and system stability. This led to the detection of system oscillations in the range of 0.1 Hz to 5 Hz, which are currently monitored in real time.
- Synchrophasor data improve the accuracy of the state estimation function within NYISO's grid operations.

NYISO is incorporating PMUs into procedures for validating system models and into alarms for system operators.

- NYISO developed a model calibration procedure that compares PMU data captured during disturbances to simulated results using the models in their database. The procedure software recommends model parameter changes based on the result of the comparison.
- NYISO adopted an alarm procedure that provides instructions to system operators on steps to be performed in responding to certain PMU-based alarms. NYISO's alarming capability for the internal control area includes oscillation detection and limit violations for voltage magnitude, angle, and frequency. Alarming capability for external regions includes the angle differences across external regions and limit violations for voltage magnitude and frequency.



Successful model calibration using synchrophasors

Synchrophasor technology allows faster, more efficient analysis of system disturbances.

- PMUs enable grid operators to identify potential system events relatively quickly after they occur. This capability supports more rapid improvements to system models and operations.
- NYISO is using PMUs for fault analysis, significantly reducing the time required for event reporting and data collection. Traditionally, NYISO would have requested fault records from the TOs. However, PMUs provide most of the needed data directly to NYISO. The faster turn-around has improved NYISO operators' and engineers' ability to understand how the grid and equipment are responding to faults.[60]

PMUs are proving to be valuable for detecting and diagnosing issues before they become threats to the power system.

- PMUs made it possible to identify and locate oscillations caused by a malfunctioning voltage regulator at a NYISO generating plant. Traditional SCADA did not provide enough resolution to identify the oscillation characteristics or source.
- Engineers used synchrophasor data to analyze other voltage oscillations on the system. For example, they identified a large generating plant as the source of an oscillation, and plant staff subsequently determined the cause of the oscillation to be a malfunctioning power system stabilizer.

The capacitors provide much-needed reactive capacity to the NYISO system, reducing transmission loading and losses. The benefits reported on the NYISO system are:

- Avoided transmission losses: 36,447 megawatt-hours per year
- Generation cost savings: $7.7 million per year
- Avoided peak generation: 18.8 megawatts
- Avoided carbon dioxide emissions: 43,773 tons per year

Lessons Learned

Support from company leadership and detailed planning are significant factors for achieving success in deployment of synchrophasor technology in commercial power systems.

- Strong project management and dedicated executive sponsorship have proven to be critical to the project through various challenges, including delays due to natural disasters and the use of new, untested data sources in multiple new applications.
- The development of technical specifications and requirements in advance of field equipment installations was important to ensure consistency in project execution among the TOs and avoid integration issues. This also applies to synchrophasor applications implementation.

[60] "Diagnosing Equipment Health and Mis-operations with PMU Data," NASPI Technical Report, March 20, 2015.

Future Plans

- NYISO expects to continue to enhance its situational awareness through additional development of visualization applications.
- NYISO is currently working with neighboring regional control areas to share synchrophasor data and is currently sharing data with Midcontinent Independent System Operator & PJM. PMU data obtained from these entities supports NYISO's visualization and situational awareness.
- NYISO plans to participate in the recently created Eastern Interconnect Data Sharing Network (EIDSN), Inc.
- Beyond applications at NYISO, TOs within the NYCA plan to develop and deploy additional PMU-based situational awareness applications.

NYISO is studying whether synchrophasor system expansion would yield further electric grid efficiencies.

A1.12. PEAK RELIABILITY (FORMERLY THE WECC PROJECT)

Scope[61]

Peak Reliability (Peak) provides situational awareness and real-time monitoring as the Reliability Coordinator (RC) for the Western Interconnection. Peak was formed in 2014 when the Western Electricity Coordinating Council (WECC) bifurcated into a regional entity (WECC) and a Reliability Coordinator (Peak).[62] As a Reliability Coordinator, Peak is responsible for all or parts of 14 western states, British Columbia, and the northern portion of Baja California, Mexico.[63]

Peak Reliability coverage area

The Western Interconnection Synchrophasor Program (WISP), led by WECC/Peak and involving 18 partners, was established as an initiative to modernize operation of the transmission system in the Western Interconnection, increasing reliability and system performance, and enabling greater use of renewable resources such as solar, hydro, and wind. The eighteen partners include: Alberta Electric System Operator, Arizona Public Service, British Columbia Hydro Authority, Bonneville Power Administration (BPA), California Independent System Operator (CAISO), Idaho Power Corporation, Los Angeles Department of Water and Power, NV Energy, Northwestern Energy, PacifiCorp, Pacific Gas and Electric (PG&E), Public Service of New Mexico, Southern California Edison, San Diego Gas and Electric, Salt River Project, Tri-State Generation and Transmission, Tucson Electric Power, and Western Area Power Administration.

	# PMUs	# PDCs
ARRA Project Funded	393	57
Peak System (incl. ARRA)	584	77

The American Recovery and Reinvestment Act (ARRA) co-funded project, implemented as WISP, installed or upgraded 393 phasor measurement units (PMUs) at 134 substations. The project involved a total of 57 phasor data concentrators (PDCs), a wide-area communications network to support PMU data transfer, information technology infrastructure, and advanced transmission software. Control rooms and training facilities located in Vancouver, WA and in Loveland, CO were expanded to accommodate new synchrophasor applications.

Goal: To improve electric system reliability and enable better grid integration of renewable resources.

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61 http://www.nerc.com/AboutNERC/keyplayers/Documents/NERC_Interconnections_Color_072512.jpg

62 https://www.peakrc.com/aboutus/Pages/History.aspx

63 https://www.peakrc.com/aboutus/Pages/default.aspx

Peak stakeholders were familiar with the benefits of synchrophasors before the ARRA program due to their earlier adoption of PMUs in the 1990s, but Department of Energy (DOE) co-funding enabled expansion of the synchrophasor system using the latest in PMU technology, resulting in an infrastructure that would otherwise have taken at least 20 years to deploy.[64]

WISP facilitated the implementation of advanced wide-area monitoring, visualization, and control systems not previously available to transmission owners in the Western Interconnection. These systems provide a more expansive view of the western bulk power system and simultaneously reveal dynamic operating conditions. The synchrophasor applications include: angle and frequency monitoring; post-mortem analysis; voltage and voltage stability monitoring; oscillation energy and mode meter monitoring; reactive reserves monitoring and device control; model baselining, validation, and improvement; and path loading and congestion management techniques.

Results Achieved

Real-time measurements and detection tools based on synchrophasors are making their way into control rooms throughout the Peak RC area and are showing benefits in system operations.

- Phase angle differences between the ends of four major transmission paths are determined from the synchrophasor system, compared with the energy management system (EMS) calculated values, displayed in the CAISO control room, and shared with three other participants. Phase angle differences are used to monitor transmission line path stress and guide restoration in the case of a line outage. They were used to hasten restoration of the Imperial Valley – North Gila 500 kV tie line.
- PMU data have been used to detect and evaluate numerous events, including 18 under-frequency events; more than 30 events resulting from unit trips, faults, and remedial action scheme response; a generator controller problem; perturbations caused by probing signal tests; hydro-power generator oscillations; and a previously unknown forced oscillation from a wind plant that identified a problem with its control system.

WISP uses synchrophasors to improve and verify the accuracy of generator models. So far, the improvements in generator modeling are decreasing costs and increasing accuracy compared to previous validation methods. The increased accuracy improves system reliability through more accurate power system simulations in studies used to set path limits.

- At least 15 power plant models have been calibrated and validated using PMU data.
- PMU data enabled a recalibration of the 1,100 MW Columbia Generating Station nuclear generator without having to take the unit off line, saving $100,000 to $700,000 estimated for this type of generator outage.
- A model validation exercise for a Grand Coulee hydropower generator showed that the generator's power system stabilizer was not functioning because of an internal failure that could only be detected by the line PMUs near the generating unit.

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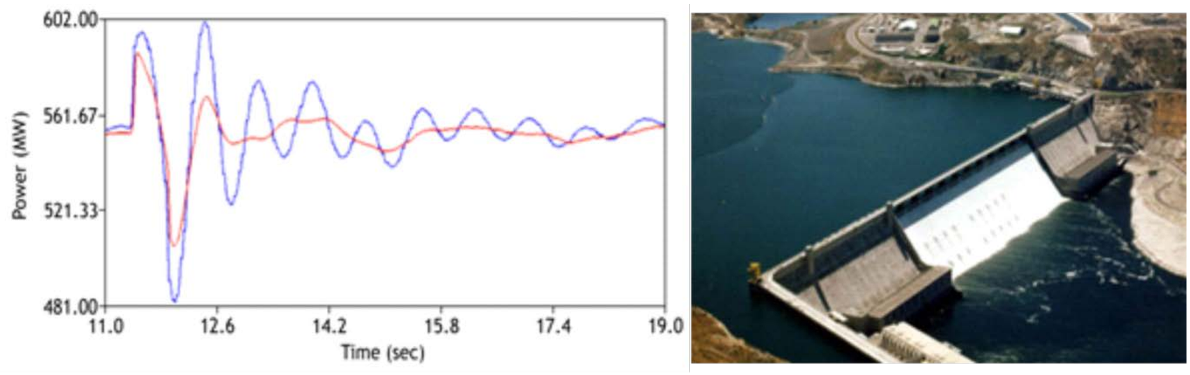
64 https://www.smartgrid.gov/document/peak_reliability_formerly_part_western_electricity_coordinating_council.html



Grand Coulee hydropower generator. Measured response (blue) differed from the baseline response (red). [Source: BPA]

The reliability data portal (www.peakrc.org) enabled by Peak streamlined the process for handling post-event disturbance analysis.

- WECC/Peak developed a data sharing agreement with reliability entities in the West and shares data through this reliability data portal. The portal is home to the registry, data archives, next-day studies, the West-Wide System Model (a power system model for the entire Western Interconnection), and the wide-area view. Peak has found wide-area data sharing to be essential in realizing the full benefits of synchrophasors.
- The reliability data portal eliminated the need to upload post-disturbance data as they are captured by the archival system. This increased organizational efficiencies by automating the process for post-event analysis.

WISP has established a wide-area network (WAN) that is centrally managed, fully redundant, dedicated, and secure, with 24/7 monitoring. WISP also monitors the quality of the PMU data.

- The WISP provided WAN maintenance and security up to, and including, the edge network routers in participant facilities. A majority of the PMU data is transmitted over the WAN to Peak control centers in Vancouver, WA and Loveland, CO. In addition, the WAN provides peer-to-peer sharing of synchrophasor data. Several of the participants have deployed synchrophasor applications on their own systems with fully redundant PMUs/PDCs and intra-utility communications for alternate data transmission routing.
- WISP has developed applications and methods to measure, monitor, and track the end-to-end quality of PMU data. Efforts remain focused on improving data quality and availability.
- All data transferred over the WISP WAN is encrypted.

WISP has developed criteria for choosing locations to install PMUs in an effort to optimize system observability and has implemented training to familiarize engineers and operators with the technology.

- The Joint Synchronized Information Subcommittee (JSIS) – formed to oversee WISP – has developed PMU placement criteria. WISP has developed training materials for selecting locations for PMU installations and these have been utilized by Peak and CAISO. WISP believes it has the PMU measurement locations needed to achieve 100% observability for the applications it developed and intends to deploy.

- BPA included synchrophasor familiarity in their seasonal dispatcher training, and PMU applications are exposed to the operators for evaluation. Power system island detection, frequency disturbance detection, wide-area angle summary, megawatt flow summary, mode meter summary, and relative amount of damping on inter-area oscillations are all under evaluation for display on the operators' video wall.
- PG&E has installed a test and simulation facility for PMUs that is also used for operator training.

"The strategic deployment of phasor measurement units and a state of the art wide area data sharing network made the use of advanced applications by planning, engineering and operations personnel possible. If not for the DOE grant, these advanced applications wouldn't have been deployed on the scale or in the timeframes we've experienced."

Synchrophasors in the Western Interconnection detect issues early and provide enough detail to identify the source of issues.

- Since the PMUs were installed, over 50 power system events every year in the Western Interconnection were detected and were only observable with phasor data.
- PMU data detected an oscillation on the California Intertie and the PMU data was used to determine its cause to be an oscillating steam generator turbine in Alberta, Canada.[65] The source of the problem turned out to be a malfunctioning steam extractor valve on the turbine, which caused the generator to throttle up and down.

Lessons Learned

Installing a synchrophasor system across an interconnection requires significant interaction among stakeholders to ensure that all components of the system perform their functions properly and interoperate to form a complete wide-area monitoring system.

- Common language and naming standards are needed among project participants for effective operation.
- Operations personnel should be engaged early in the process.
- Project teams should schedule adequate time for partnership agreements. Executing comprehensive data sharing agreements was harder to accomplish and longer in duration than expected.

The communications network and information technology (IT) equipment are vital for the timely delivery of PMU data, so it is important to ensure that the communications system meets project requirements at all points in the delivery chain.

- Factor in additional time and cost when in the planning stages to ensure vendors are or can be prepared to meet security requirements and handle high data volume requirements.
- Select a WAN communications vendor that will manage the entire network end-to-end.

[65] "Diagnosing Equipment Health and Mis-Operations with PMU Data", NASPI Technical Report, March 20, 2015.

Making a large number and variety of devices such as PMUs, PDCs, precise time clocks, and communications system components work together as a cohesive system is a challenging task. This task is further compounded when using equipment and protocols that do not meet accepted standards.

- Off-the-shelf hardware should be used whenever possible to improve system integration capability and reduce cost.
- Use standard, currently adopted and supported communications protocols whenever possible to improve integration with existing systems and streamline ongoing maintenance and support.

Gaps remain in synchrophasor technology that require further research and development. Peak identified some gaps in simulation and standards development.

- It is extremely difficult to simulate real-world loading of a synchrophasor data network.
- A comprehensive standard for PDCs should be developed.
- The original NASPInet[66] design needs to be modernized.

Future Plans

WISP is using a follow-up grant to support the Peak Reliability Synchrophasor Program, which will build on the momentum of the current synchrophasor system made possible by the ARRA-funded project. Peak's future plans include:

- Major initiatives to improve data accuracy and availability.
- Additional model calibration and validation, interconnection baseline analysis, and data transmission improvement through the use of true publish/subscribe messaging.
- Pre-commercial development in modal analysis, voltage stability, and wide-area view applications.

Real-time information and automated controls available from synchrophasor technology are expected to enable grid operators to eventually raise operating limits on the California-Oregon Intertie (COI) closer to its thermal limit. This will be accomplished by using the synchrophasor technology to:

- Detect voltage stability conditions.
- Provide input to response-based automatic controls.
- Quickly switch on capacitor banks to provide greater reactive supply at the head of the intertie and in the Portland and Willamette Valley load centers.
- Prevent contingency initiated voltage collapse.

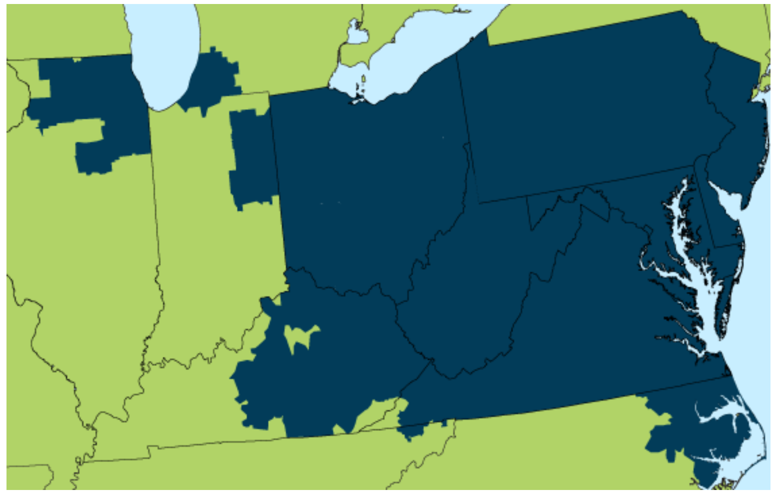
The resulting automated reactive compensation scheme is expected to allow up to 100 MW of operational capacity to be available more frequently on the COI. The scheme is currently operating in evaluation mode, so engineers can validate that the monitoring and controls are performing to their intended design.

[66] http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=5428363&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D5428363

A1.13. PJM INTERCONNECTION

Scope[67]

PJM Interconnection (PJM) coordinates the movement of wholesale electricity in 13 states and the District of Columbia.[68] The PJM transmission owners (TOs) that participated in this Smart Grid Investment Grant (SGIG) project include: American Electric Power Service Corporation, Allegheny Power, Baltimore Gas and Electric Company, Duquesne Light Company, Commonwealth Edison, First Energy Corporation, PECO Energy Company, PEPCO Holdings, PPL Electric Utilities, Public Service Electric and Gas, Rockland Electric Company, and Virginia Electric and Power Company. In coordination with the twelve TOs, PJM leveraged American Recovery and Reinvestment Act (ARRA) funding to deploy 301 phasor measurement units (PMUs) in 85 substations at the 345 kV, 500 kV, and 765 kV voltage levels. PJM installed 23 phasor data concentrators (PDCs) across the PJM system to form a robust data collection network. Centrally located PDCs at PJM aggregate data from the service area PMUs and PDCs. The resulting synchrophasor system covers ten states.



PJM service area

	# PMUs	# PDCs
ARRA Project Funded	301	23
PJM System (incl. ARRA)	386	26

PJM implemented advanced transmission software applications to translate PMU data into actionable information for staff at the regional transmission organization (RTO). These applications include synchrophasor data visualization and analysis software at PJM and synchrophasor visualization displays at the TO locations. The advanced monitoring and visualization system provides a more expansive view of the transmission system while revealing dynamic operating details that were previously undetected using traditional supervisory control and data acquisition (SCADA). Synchrophasor technology increases grid visibility for system operators in near real time, enabling earlier detection of problems that threaten grid stability or cause outages, and facilitating information sharing with neighboring control areas. Access to high-resolution system operating information allows

Goal: To improve electric system reliability and restoration procedures and prevent the spread of local outages to neighboring regions.

[67] https://www.pjm.com/about-pjm/who-we-are/territory-served.aspx
[68] https://www.pjm.com/about-pjm.aspx

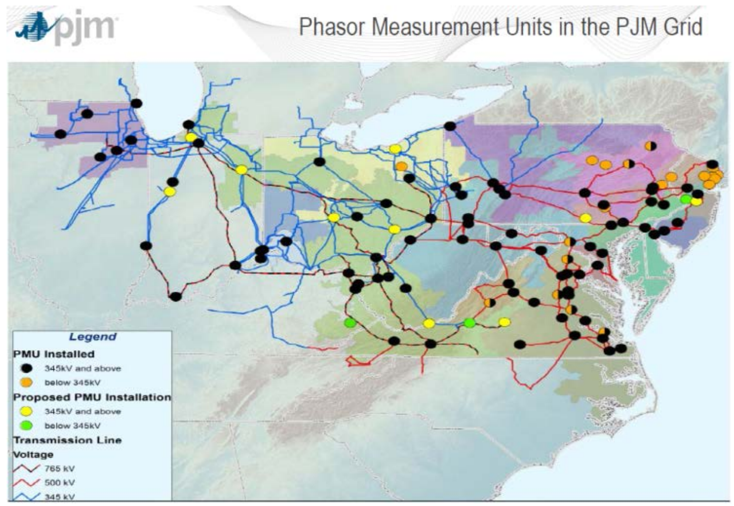
PJM engineers to improve power system models and analysis tools for better reliability and operating efficiency. Access to wide-area monitoring may also help optimize the dispatch of power plants.

The ARRA-funded project complemented existing equipment within the PJM footprint to enhance the information technology infrastructure required for wide-area monitoring and coverage of the PJM system. The project also supported further development of advanced applications based on synchrophasor data.

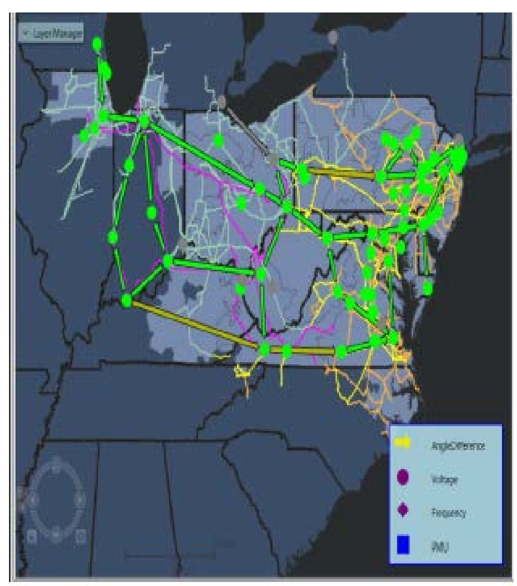
Results Achieved

PJM implemented synchrophasor applications that enable staff to monitor system conditions and observe system behaviors as they develop and unfold.

- Power Plant Parameter Derivation is a generator, exciter and turbine-governor-model validation tool using PMU data.
- Real-Time Dynamic Monitoring System provides real-time, wide-area situational awareness and analysis of the grid.
- Phasor Grid Dynamics Analyzer is an offline analysis tool for system health and dynamics.
- Linear State Estimator assists with data quality assessment and may be incorporated into the non-linear state estimator that PJM is developing.
- Energy Management System - State Estimation with PMU Data incorporates synchrophasor data as a highly weighted input to the state estimator.
- ePDC is a PDC configuration, monitoring, and diagnostic tool.
- The PI application is a visualization, monitoring and diagnostic tool used to compare real-time phasor data with SCADA/remote terminal unit (RTU) and state estimator data.
- PI-Fast Fourier Transform is an additional means to detect oscillations.



PMU installations within the PJM footprint



Visualization using PMU data

The applications give PJM operators and engineers the ability to visualize PMU data and quickly respond to problems.

- Angle and frequency monitoring provide PJM grid operators and engineers with detailed information about grid conditions and power flow.
- The visualization capability of the PJM wide-area monitoring enables operators to quickly determine real-time phase angles and compare them to typical phase angles.
- Visualization also helps identify trouble spots, monitors them more closely, and enables PJM to take action more quickly.

PJM has incorporated synchrophasor data in its process of operations and event analysis.

- Event alarming enables operators to detect oscillations, abnormal phase angle pairs, and damping events in a centralized alarming application and to perform additional analysis as needed.
- Post-event analysis enables operators to visualize historical data trends, obtain temporal and spatial information about a disturbance, determine the root cause of the disturbance, and assess its impact on system reliability.

Synchrophasor technology has enabled PJM staff to observe and correct adverse conditions before they cause system contingencies to occur, thus increasing the reliability of the PJM system.

- PMU data has enhanced system reliability. In the past, PJM did not have detailed data from disturbances. By analyzing PMU data associated with disturbances, PJM has been able to determine oscillation frequency signatures. These signatures enable PJM to better detect events before they cause interruptions.

> "This project is providing the foundational infrastructure upon which future advanced technologies can be deployed."

- Synchrophasor data also enabled PJM to find inaccurate generation models and to update them.
- Dominion Virginia Power used the synchrophasor data to detect a failing voltage transformer and to identify un-damped oscillations at one of its power plants.[69] Both issues were corrected prior to any significant impacts on system performance.

PJM is sharing data with its neighbors.

- PMU data are being sent to the New York Independent System Operator, Midcontinent Independent System Operator, Virginia-Carolinas (VACAR) subregion (which includes Duke Energy) and Tennessee Valley Authority.
- PJM exchanges data with independent system operators (ISO)/RTOs via the Eastern Interconnect Data Sharing Network (EIDSN) system.

Lessons Learned[70]

PJM and its members have formed collaborations to share their synchrophasor data and experiences.

[69] "Diagnosing Equipment Health and Mis-Operations with PMU Data," NASPI Technical Report, March 20, 2015.
[70] http://sites.ieee.org/isgt2014/files/2014/03/Day2_Panel1B_Liu.pdf

- PJM set up a task force consisting of PJM and member transmission owner staff to increase visibility of synchrophasors and to give stakeholders a pool of experience upon which to resolve issues and work toward common goals.
- Sharing data with its neighbors, including surrounding ISOs and RTOs, allows PJM to improve its wide-area monitoring capabilities and event analysis.

Because of challenges with technology acceptance and management of the synchrophasor system, proving the value provided by the data is critical to ensuring acceptance and adoption of synchrophasor technology.

- PJM found integrating PMU data into its processes and introducing new applications to be a challenge. To promote acceptance, PJM incorporated PMU data into existing applications and implemented a PMU technology training schedule for system operators.
- It is often difficult to schedule the PMU maintenance outages necessary to improve data quality.
- Not all PMUs are created equal. Some transmission-owner vendors are still performing firmware updates and resolving issues to achieve data quality goals established for the project.

Future Plans

Installation of a synchrophasor system is only the first step in fully realizing the benefits of the new technology. Advanced application design, development, and deployment are necessary steps towards providing operators with actionable insights and procedures for the control room.

PJM plans to incorporate synchrophasor-based wide area monitoring into the control room via the reliability engineer desk.

- Wide-area monitoring will be deployed in operations to evaluate system response following planned/unplanned outages on the 765 kV system, giving operators real-time visibility to system stress conditions.
- PJM will continue to incorporate PMU data into its linear state estimator to assist with improving data quality.
- PJM also may incorporate the PMU-related enhancements into its non-linear state estimator.

PJM will apply synchrophasors to determine system operations functions.

- Synchrophasor data will be used to calculate frequency bias.[71]
- Because PMU data are time-synchronized, they will continue to be used for post-event analysis.
- PJM's transfer limit calculator (TLC) takes approximately five minutes to perform contingency analysis and calculate operating limits to ensure reliability of interconnected operation with neighboring RTOs. The PMUs are expected to give the operators enhanced visibility when the system is in a secure state and avoid unnecessary actions to guard against contingencies while the TLC is updating the reliability-based operating limit calculations.

The use of PMUs in model validation and event analysis will continue to expand.

[71] http://www.nerc.com/docs/oc/rs/NERC%20Balancing%20and%20Frequency%20Control%20040520111.pdf

- PJM developed a generator, exciter, and turbine-governor model validation tool using PMU data. Implementation of the tool is awaiting PMU data from new generator locations of 100 MW or greater; the tool will become active in 2016.
- PJM has been incorporating PMU data into event analysis for oscillations near large generators and line trips on the 765 kV system. This has been on an ad hoc basis, but PJM is working to formalize the process.

PJM will continue to work to improve data quality and availability in its synchrophasor system. PJM also will continue to share data with its neighbors and look to expand such collaborations across the Eastern Interconnection.

APPENDIX 2: SYNCHROPHASOR TECHNOLOGY CAPABILITIES

A2.1. PHASE ANGLE MONITORING

The timing or angular (phase angle) differences in voltages between locations in a power system provide information on power system stress. The differences in phase angles between ends of a transmission line grow with loading of the line. The phase angle difference is not only useful for determining the stress on the transmission line, but also is a decisive factor for reclosing transmission lines. Information on voltage phase angles assists in operating the power system in a reliable fashion without impacting stability.

Traditionally, phase angles are calculated off-line with simulations and state estimation based on line flows. Now PMUs can measure phase angles directly, making them immediately available to system operators and enabling them to monitor and remediate stressed power system conditions as they develop.[72]

Examples of benefits realized by participants' using synchrophasors to monitor phase angles are:

- FPL uses PMUs to monitor phase angles directly when switching in transmission lines, with operators seeing the angles via enhanced graphical and dynamic displays. Previously, FPL calculated these system phase angles using their state estimator.
- WECC/Peak uses PMU data to monitor phase angle differences between the ends of four major transmission paths. The data are compared with the energy management system (EMS)-calculated values, displayed in the CAISO control room and shared with three other WECC participants. The synchrophasor values are used to monitor transmission path stress and guide any remediation needed. Phase angle monitoring also enabled WECC to reclose an important tie line between the Imperial Valley and North Gila substations[73], as the PMU data showed the phase angle difference between the ends of this tie line was well within the limit for successful reclosing. Operators reclosed the line successfully without requiring a change in the Imperial Valley generation output. This use of the Western Interconnection Synchrophasor Program (WISP) infrastructure resulted in a more rapid restoration of a critical tie line than would have otherwise been possible, limiting the time the line was out of service and reducing the power system's vulnerability to subsequent contingencies.

Other SGIG participants that use PMU data for phase angle monitoring include:

- ATC
- Duke Energy
- Entergy

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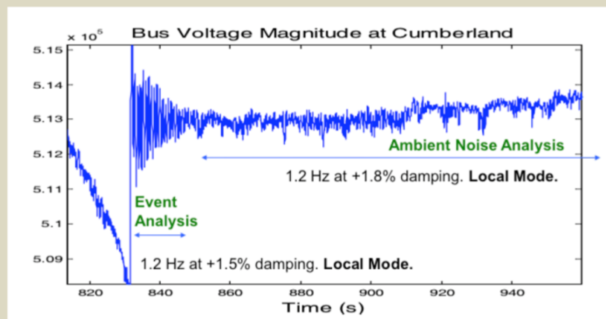
[72] P. Kundur et. al., "Definition and Classification of Power System Stability," IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, IEEE Trans. Power Systems, Vol. 19, No. 2, May 2004.
[73] Peak Reliability (formerly part of the Western Electricity Coordinating Council), Western Interconnection Synchrophasor Program, Smart Grid Investment Grant, Final Project Description.

- IPC
- ISO-NE
- MISO
- NYISO

A2.2. OSCILLATION DETECTION & MONITORING

When the electric system is disturbed (i.e., the system experiences the sudden loss of a generator, transmission line, or load), an oscillation occurs. Oscillations also occur due to problems with control systems. Oscillations[74,75] are undesirable pulsations of energy across components of a power grid and are analogous to vibrations in rotating equipment. Inherent in power systems, oscillations manifest as cyclical changes in power system metrics, including voltage, current, frequency, active power, and reactive power.

Understanding oscillations is a key part of planning and operating the electric grid.



Source: Diagnosing Equipment Health and Mis-operations with PMU Data, NASPI Technical Report, March 20, 2015.

Synchrophasor-enabled apps establish the characteristics of system oscillations and help to pinpoint their sources.

Some oscillations are normal and benign while others are harmful and possibly catastrophic for power system equipment. Normally oscillations are damped; they decrease in amplitude over time. Undamped oscillations – constant and persistent, or growing in amplitude – destabilize the power system, and can cause parts of the system to separate from the larger grid, a phenomenon called islanding as described in Section A2.5. A system's ability to damp oscillations is an important indicator of system stability.

Before the deployment of synchrophasor systems, SCADA systems were used to observe the propagation of oscillations across a power grid. The low resolution of SCADA data (typically two to four second scan rates) cannot reliably detect or observe oscillations, as illustrated in the figure on the next page. PMUs provide sufficient data speed to develop a high-definition view of the grid's behavior, including oscillations in power, frequency, and other parameters that were not detectable otherwise.

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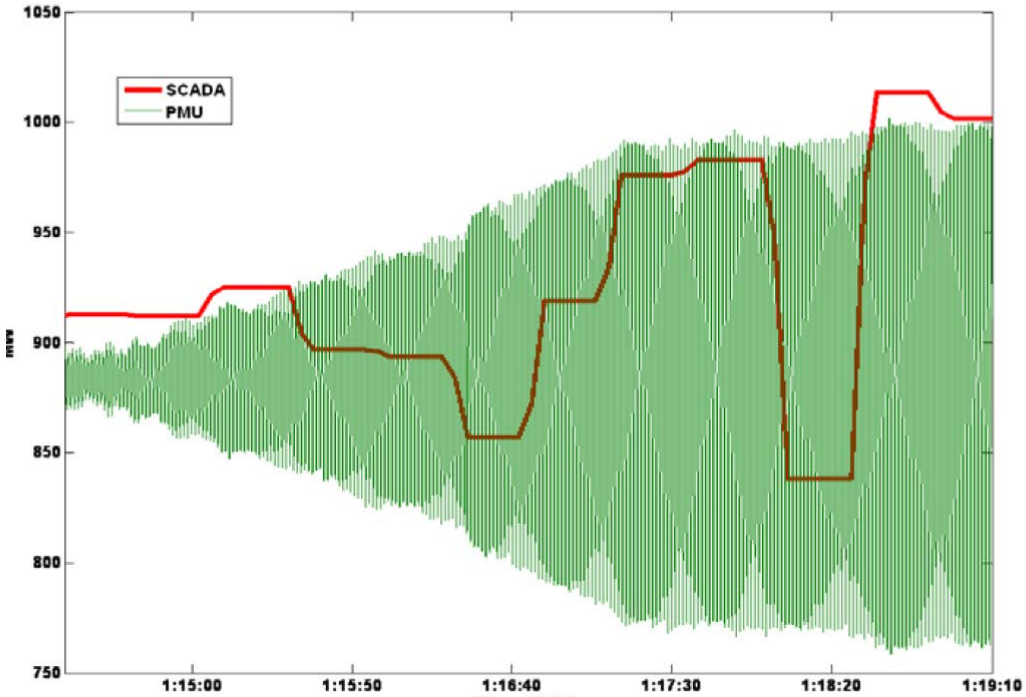
[74] M. Klein, G. J. Rogers and P. Kundar, "A Fundamental Study of Inter-Area Oscillations in Power Systems," IEEE Trans. Power Systems, Vol. 6, No. 3, August 1991.

[75] B. Pai and B. Chaudhuri, "Robust Control of Power Systems," Chapter 2 – Oscillations, ISBN 978-0-387-25949-9, 2005.

ARRA funded PMUs have improved the utility industry's ability to detect and characterize oscillations: detect the presence of oscillations; characterize the oscillation with respect to modes, damping, and energy; determine the extent to which an oscillation poses a threat to the electric grid; and monitor the oscillation to determine if conditions worsen. This allows operators to evaluate the potential impact of the oscillation and perform remedial actions as appropriate.

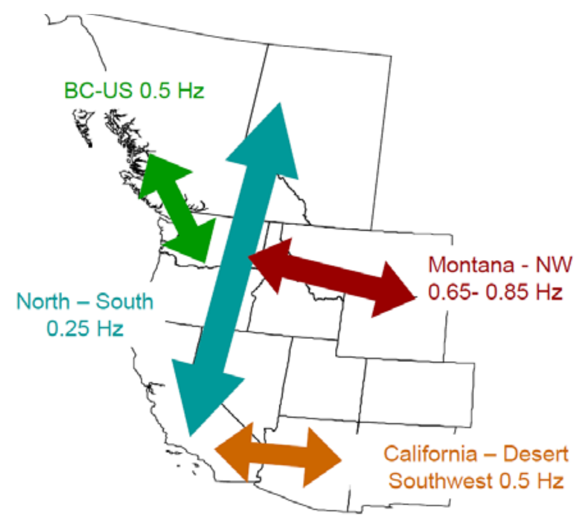


Comparison of SCADA versus PMU recordings of the same grid event – a growing oscillation at a power plant

The availability of PMU monitoring and oscillation applications[76] has resulted in the discovery and analysis of local (within a utility or RTO) and inter-area (between RTOs) oscillations.

Examples of oscillation detection capabilities operationalized by participants include:

- The Western Interconnection is prone to oscillations due to its long transmission corridors and HVDC systems. Some oscillations prevalent within the WECC system are shown to the right. As a result of SGIG funding, WECC implemented oscillation monitoring and analysis applications

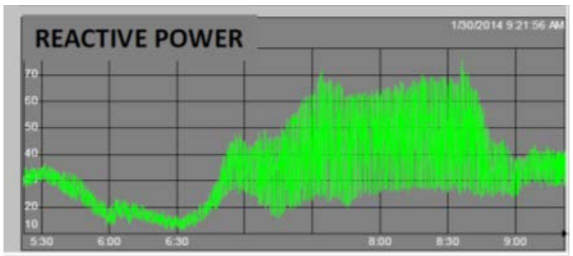


Oscillations in the Western Interconnection

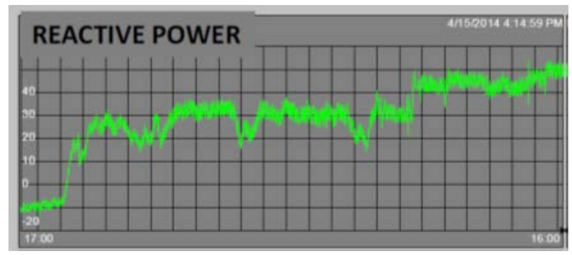
[76] DOE OE funded the development, enhancement, and demonstration of many of the oscillation applications in use by the ARRA-funded projects.

to establish baselines for comparison and determine alarm thresholds for non-routine oscillations.

- In May 2011, WECC member BPA observed oscillations during a period of high wind generation. With the additional PMU coverage provided by SGIG-funded PMUs, BPA determined that these oscillations were potentially harmful and pinpointed their source as a specific wind power plant. BPA notified the plant owner of the problem and the owner upgraded the plant controls, causing the oscillations to decrease significantly. The figure below shows the initial oscillations observed (a) and the improvement after the control upgrade (b).[77]



(a)



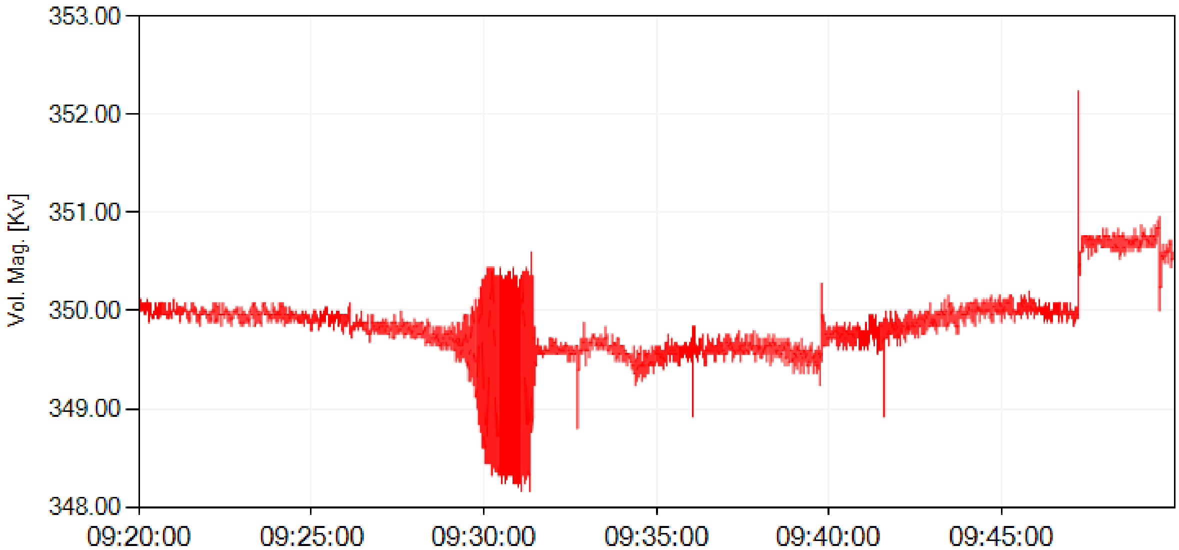
(b)

BPA wind plant oscillations (a) decreased significantly after upgrades to controls (b).

- NYISO also observed oscillations with its synchrophasor system. In May 2013 NYISO observed voltage oscillations (see below).[78] Operators and engineers were able to determine that the oscillation was confined to a small portion of the system by comparing PMU data across the network. The PMUs allowed NYISO to localize the oscillation to a specific generation site and identify the cause as a malfunctioning voltage regulator. Similar oscillations had occurred in the past, but PMU coverage was not extensive enough to identify the source of the problem.

[77] "Diagnosing Equipment Health and Mis-operations with PMU Data," NASPI Technical Report, March 20, 2015, https://www.naspi.org/File.aspx?fileID=1416.

[78] E.B. Cano, "NYSO Case Studies of System Events Analysis using PMU Data," NASPI, March 11, 2014.



Voltage oscillation detected on a 345 kV bus in the NYISO system

- In August 2013, NYISO detected voltage oscillations on its 345 kV transmission lines with SCADA and examined them further with its synchrophasor system. They determined that the oscillations occurred close to a large generator plant in central New York. Generator plant staff found a malfunctioning power system stabilizer (PSS) at one of the units.

Other SGIG participants that use PMUs to monitor and analyze oscillations include:

- ATC
- CCET
- Duke Energy
- Entergy
- IPC
- ISO-NE
- MISO
- PJM

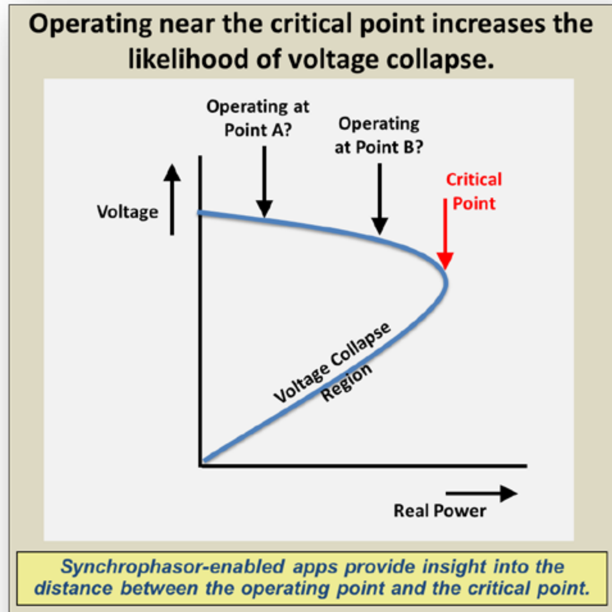
Additional information on using synchrophasors to detect oscillations is available in the presentations from a 2014 NASPI forum on evaluation of commercial oscillation detection applications tested by the ARRA-funded projects.[79]

[79] NASPI Oscillation Detection and Voltage Stability Tools Technical Workshop was held in Houston, Texas, on October 22, 2014.

A2.3. VOLTAGE STABILITY MONITORING

Maintaining the voltage at levels that remain stable is of paramount importance to a power system operator. Voltage stability is the ability of a power system to maintain adequate voltage levels through changes in generation, load, and topology.

Loss of voltage stability almost always results in a voltage collapse: the voltage drops to zero and the load blacks out at that location. Depending on system conditions at the time, a local voltage collapse can propagate to adjacent areas and can ultimately lead to a widespread outage.



Because voltages tend to decline when the electric grid is most stressed, the loss of a generator, transmission line, or other key asset during those times becomes much more significant than losing that same asset at other times. As the bulk electric system is challenged to transport increasing amounts of electric power, the likelihood of voltage collapse increases.

There are various traditional methods for assessing voltage stability.[80] These methods, however, have proven to be more useful in offline planning than in a real-time operating environment. Utility experience with most of these tools is that their efficacy varies with changing grid conditions and that they are least accurate when the system is most stressed.

The ARRA co-funding provided project participants with new PMU-enabled tools to help the system operator detect and diagnose voltage problems and identify actions to remediate problems. The tools included improved voltage stability monitoring (see power versus voltage diagram above), voltage violations/alarms and phase angle monitoring, and visualization and analysis of system voltages. These capabilities better track and quantify the grid's ability to maintain voltages. In addition, models validated using PMU data provide a more accurate estimation of available reactive power during varying grid conditions, enabling more effective management of these resources to maintain voltage levels.

Several of the ARRA-funded projects are testing synchrophasor-based voltage stability tools or using them in real-time. Some information on their experiences is available from presentations from a NASPI

[80] M. Cupelli et al. "Comparison of Line Voltage Stability Indices using Dynamic Real Time Simulation," 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe, Berlin.

forum in 2014 on evaluating the performance of several commercial voltage stability tools.[81] Examples of voltage stability benefits realized by ARRA project participants using synchrophasor data are:

- FPL's PMU data are integrated into their EMS and voltage stability application to identify real-time grid conditions and to enable operators to develop preventative and corrective actions.
- MISO's PMU-based application displays voltage gradients to operators.

Other SGIG participants that use or plan to use PMU data for enhanced voltage stability monitoring include:

- ATC (evaluating)
- CCET
- Duke Energy
- Entergy
- IPC
- ISO-NE
- NYISO

[81] NASPI Oscillation Detection and Voltage Stability Tools Technical Workshop was held in Houston, Texas, on October 22, 2014, https://www.naspi.org/site/Module/Meeting/Forms/General.aspx?m__ID=MEETING&meetingid=347.

A2.4. EVENT DETECTION, MANAGEMENT AND RESTORATION

When an event takes place on the power system, operators must take action to mitigate its effects. The type and extent of the event that occurred are not always obvious to system operators; in some cases, the event is not even discernable to operators. Good event detection, management, and restoration allow system operators to understand the event, minimize its impact, and restore service as quickly as possible.

PMU data provide early indications of grid stress, including abnormal voltages, phase angles, frequencies, and power flows. Before the event occurs, PMU data can provide clues to operators that parts of the system are stressed. With this information operators may have time to take mitigation action before the event worsens. As the event occurs, PMU data provide a view of the system's response to the event in the form of high-resolution graphs of the anomalous power measurement waveforms. This provides insights into the type of event taking place and its extent. The sooner an operator understands the event, the more options are available for mitigating the event.

Synchrophasor technology enhances several aspects of event management:

- Most PMU applications have event playback and drill-down capabilities that help operators and engineers analyze the event to determine how the event occurred, develop mitigation measures and restore the power system to normal operations. Pattern recognition utilizing PMU data has great potential as a decision support tool for diagnosing an emerging event or problem and recommending mitigation measures.
- Some of the ARRA-funded projects are using PMU data for fault location.
- The phase angle and location information provided by synchrophasor data are critical for outage restoration. By knowing phase angles for example, operators can safely close transmission breakers to restore a line to service, avoiding the dispatch of crews to substations for restoration of service or the re-dispatch of generating plants moving the power system operation to a more costly operating point.
- PMUs have provided needed insights into problematic grid conditions and allowed operators to better coordinate remedial actions.

Examples of benefits realized by participants using PMU data for event management include:

- ATC routinely uses synchrophasor data to respond to customer event questions. Now ATC can answer with certainty whether anything was happening on their transmission system at the time that customers were affected. ATC has identified normal and odd behavior on their system. They are working to explain the anomalous PMU data and its cause (i.e., effects of arc furnace loads, generator oscillations, system oscillations after line trips, etc.). Also, ATC has used the PMU data as a quick check on system protection device operation. The PMU data have helped to answer questions such as: Do faults clear in a reasonable amount of time? Do all three phases open at the same time?
- In the Western Interconnection, phase angle data collected and distributed by WECC/Peak is ingested by CAISO and shared with three of WECC's interconnected parties on four major paths. It has already been used to speed the restoration of an important tie line. The PMU data provided the following benefits: (1) rapid restoration of a critical tie line without the need for

generation dispatch, (2) limited service outage of the critical line, and (3) reduction of the power system's vulnerability to a potential subsequent contingency.

Other ARRA SGIG participants that used or plan to use PMU data for enhanced event management and outage restoration are:

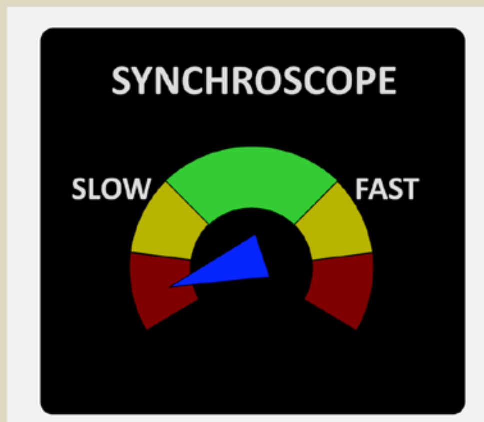
- ISO-NE
- MWE

A2.5. ISLANDING DETECTION, MANAGEMENT AND RESTORATION

Islanding involves the separation of a part of the power system from the larger power grid. Electrical islands occur when relays, circuit breakers, switches, and other topology control equipment operate in such a way as to isolate a part of the grid from the larger interconnection. The isolation could be a disturbance response to protect either the equipment or system. On rare occasions, multiple protection and control actions can create an electrical island.

If there is sufficient generation in the electrical island to supply the load, service may be sustained and operators may not detect the situation for some time. The more probable outcome, however, is that the islanded region blacks out because the balance between generation and load on an island is difficult to sustain.

PMUs identify unsynchronized regions (electrical islands).



PMUs are useful for reconnecting islands to the interconnection.

PMUs monitor frequency, voltages, and phase angles which can be indicators of an island. For example, the frequency in the island can diverge from the rest of the power system and decrease from normal values. The sooner an operator knows that an electrical island has formed, the greater the options available for avoiding a blackout.

As soon as system operators are aware that they are effectively operating two separate electric grids – the islanded region and the rest of their interconnection – they immediately take steps to keep the generation and load in balance. Once the electrical island is stable, operators then adjust the generating units on the island so that voltage magnitudes, frequencies, and phase angles on and off the island match. Now the island can be reconnected to the rest of the interconnection.

The ARRA-funded synchrophasor technology has provided participants with the ability to detect, monitor, and better manage islands if they occur. Synchrophasor technology can quickly identify an island, allowing the operators to synchronize the island to the larger power grid and restore its connection to the rest of the grid. Many of the projects have implemented islanding detection applications, and have rehearsed blackstart processes using synchrophasor tools to manage simulated outage events.

Synchrophasor capability also provides operators with the data to inform them when an island can be successfully reconnected to the rest of the power grid without harming generators, transformers, circuit breakers, or other equipment.

Examples of benefits realized by participants using synchrophasors for island detection and management are:

- ATC used PMU data to analyze in depth an islanding event on their power system. The level of detail provided by the PMUs gave a clear picture of the sequence of events far beyond anything they could have achieved with SCADA data alone. ATC is currently running an islanding detection application in test/study mode to evaluate the performance and integrity of the synchrophasor system. ATC plans to put this application into production sometime in 2015.
- MISO monitors PMU data for islanding conditions and notifies grid operators of real-time conditions that may affect grid stability.

A2.6. EQUIPMENT PROBLEM DETECTION

Detecting equipment problems early can prevent unplanned outages due to equipment failures. Equipment failures can cause customer outages, costly equipment replacement, and can even damage other equipment. Inspections, diagnostic tests, time-based maintenance, condition-based maintenance, repairs, minor overhauls, major overhauls, and even long-term lay-up are planned and scheduled at times that are least costly to the overall grid. Transmission owners strive to anticipate and prevent equipment failures and schedule equipment replacement or upgrades on a well-managed, non-emergency, safe, and cost-effective basis.

Equipment failures pose a risk to reliability and are uneconomical.

Planned Outage	Forced Outage
	• Analyze the event. • Identify the failure. • Develop work plan.
• Develop work plan. • Coordinate with other maintenance activities to minimize outage duration. • Leverage equipment clearances. • Optimize crew deployments. • Optimize cost of replacement power or transmission capacity.	
• Execute work plan.	• Execute work plan

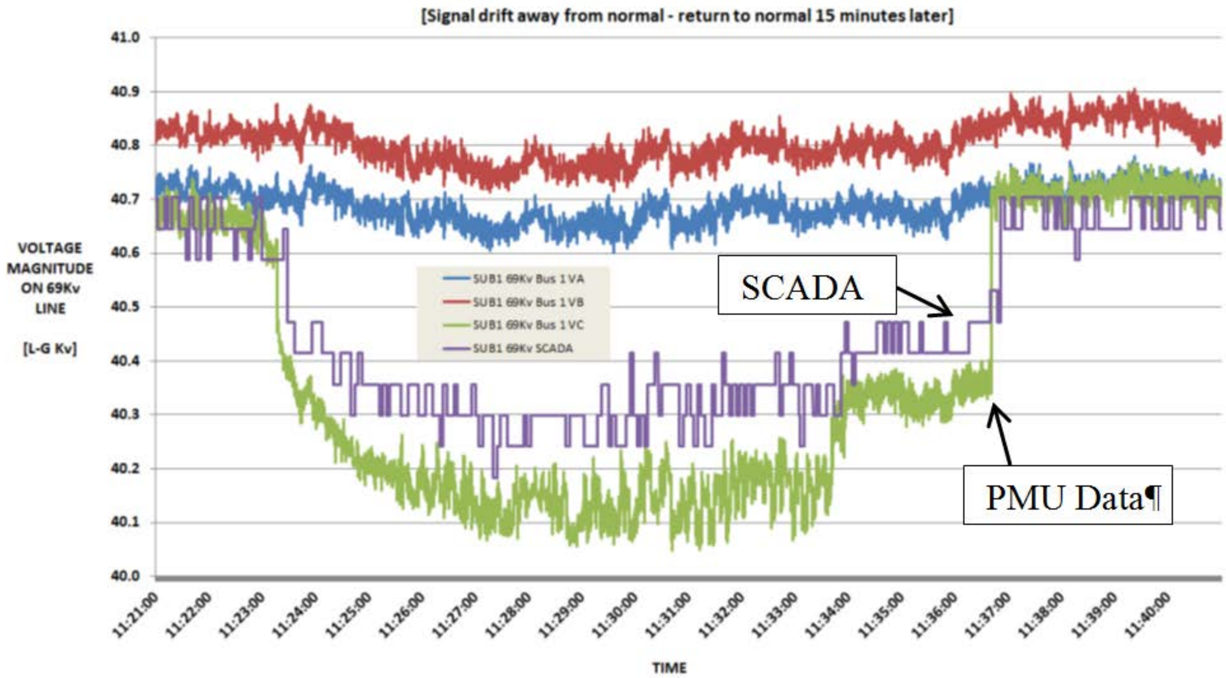
PMU data helps identify incipient equipment failures which helps avoid forced outages.

Synchrophasor technology enhances the capability to detect and diagnose failing and malfunctioning equipment, allowing for replacement during planned outages. Traditional SCADA, monitoring at four second sampling rates, cannot detect many of the data variations that indicate problems. PMUs' faster reporting rates make it possible to observe and analyze grid events and the condition of grid equipment in unprecedented detail.

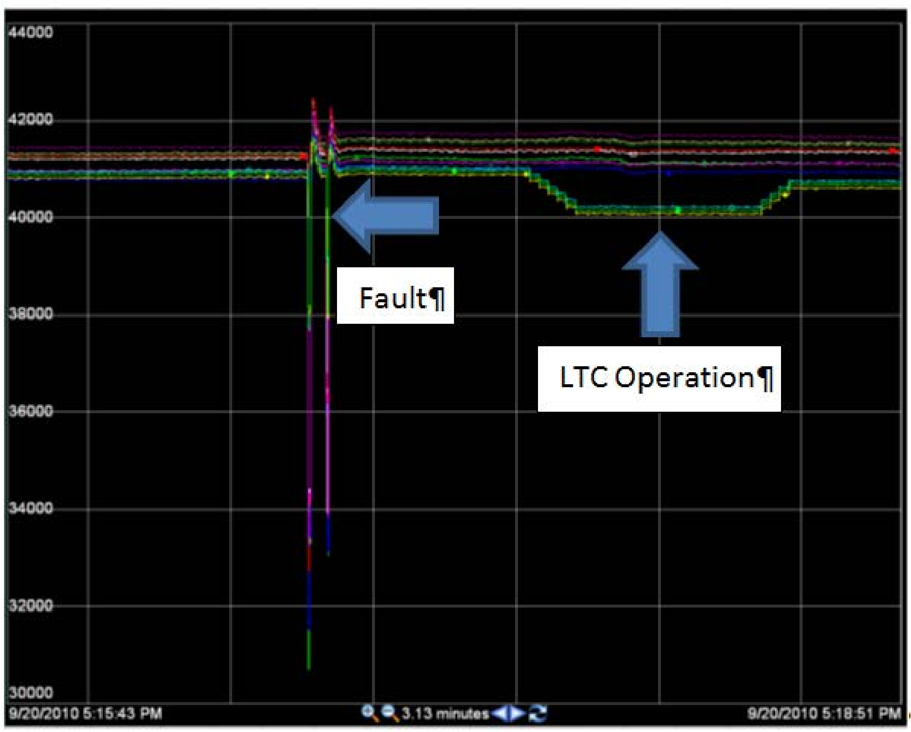
A number of project participants have identified incipient failures using synchrophasor data and been able to schedule orderly replacement of the problem equipment, avoiding or minimizing customer outages.

Some of the examples of ARRA participants benefitting from using PMU data to detect equipment problems are provided below:

- ATC used PMU data to detect a failing potential transformer, auxiliary protection systems functioning improperly (see figure below), an incorrect load-tap-changing transformer (LTC) operation (see second figure below); to detect all of the phase voltages when a shunt capacitor was switched into service; and to verify voltage levels during undesired dual close capacitor operations.



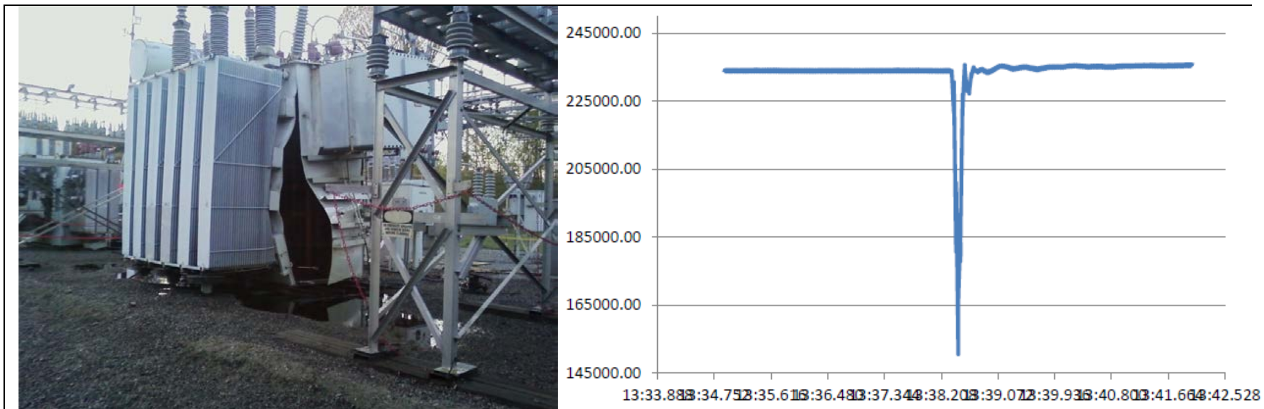
Voltage signature of failing bus PT observed by ATC PMUs[82]



[82] "Diagnosing Equipment Health and Mis-operations with PMU Data," NASPI Technical Report, March 20, 2015.

Incorrect LTC operation on ATC system following a fault on 69 kV system

- Duke Energy's PMUs detected an automatic voltage regulator (AVR) control problem (see figure below). A generating unit's control system AVR had operated incorrectly as a result of a low-voltage transformer fault. The plant operator wanted to know the degree of the voltage dip but was unable see it with SCADA. Using PMUs, Duke determined that the voltage on the 230 kV system dipped momentarily to 150.6 kV, well below the tolerances of the control system. This indicated that the AVR was faulty and needed to be repaired.



Low-voltage transformer fault resulted in mis-operation of AVR on Duke Energy's system[83]

Other SGIG participants that use synchrophasor technology to detect equipment problems are:

- FPL
- MISO

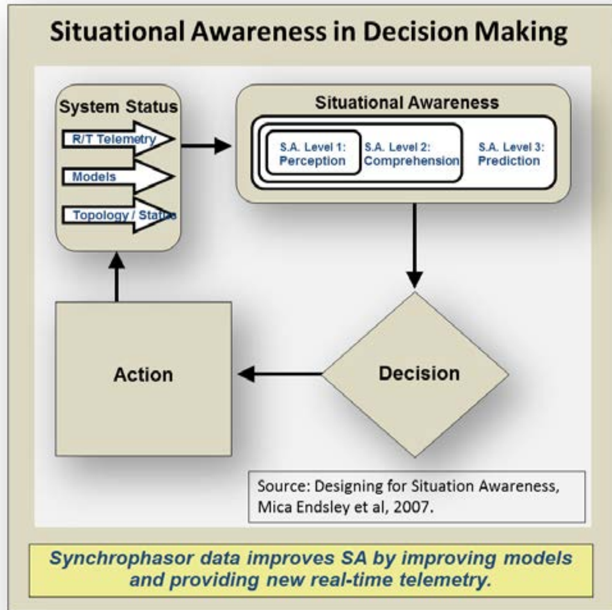
A2.7. WIDE AREA SITUATIONAL AWARENESS

Situational awareness is "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future."[84] In the context of an electric power grid:

[83] Phillips, Evan. "Duke Energy Carolinas Smart Grid Investment Grant Update," NASPI Work Group Meeting, October 22-24, 2013.

[84] Endsley, Mica et al. "Designing for Situation Awareness: An Approach to User-Centered Design, Second Edition," 2011

- Perception refers to the ability of a power system operator to access real-time operating parameters (voltages, currents, topology, and other values calculated from these parameters), contingency analysis results, load forecasts, weather predictions, and the state of the control center's automation and telecommunications systems.
- Comprehension is the ability of a power system operator to recognize the significance of information in the context of the task being performed.
- Projection refers to the ability of a power system operator to anticipate the manner and speed with which the state of the power system is likely to change after some time period or after an event takes place.



This concept is illustrated in the figure above.

Wide area situational awareness enables grid operators to see the bulk electric power system across an entire interconnection, understand grid conditions in real time, and diagnose and react to emerging problems. The electric utility industry's need for improved situational awareness has evolved over the years with the growing complexity of power systems. As systems became increasingly interconnected, the ability for a perturbation to propagate from one system to another increased, and interest in interconnection-wide monitoring increased along with it.

Participants in the North American electric power grid have a collective obligation to operate the bulk electric system within thermal, voltage, and stability limits so that instability, uncontrolled separation, or cascading failures will not occur.[85] Monitoring key parameters over a wide area provides early warning to operators of problems developing on the interconnection and allows them to take prompt action before the problem evolves. Synchrophasor data from PMUs can provide a high-resolution view of power system and asset behaviors under a wide range of conditions across an interconnection. The high-speed sampling rate of PMUs enables system operators to observe and react to behaviors that may not be visible with conventional power system measurement technology.

The ARRA synchrophasor projects built high-speed data networks to deliver PMU data into control rooms across each interconnection. With this network in place, synchrophasor technology improves power system situational awareness by providing better visibility of grid conditions with high-resolution and high-speed data to identify emerging threats such as oscillations and voltage instability and

[85] From definition of "Reliable Operation" in NERC Glossary of Terms, NERC, May 19, 2015.

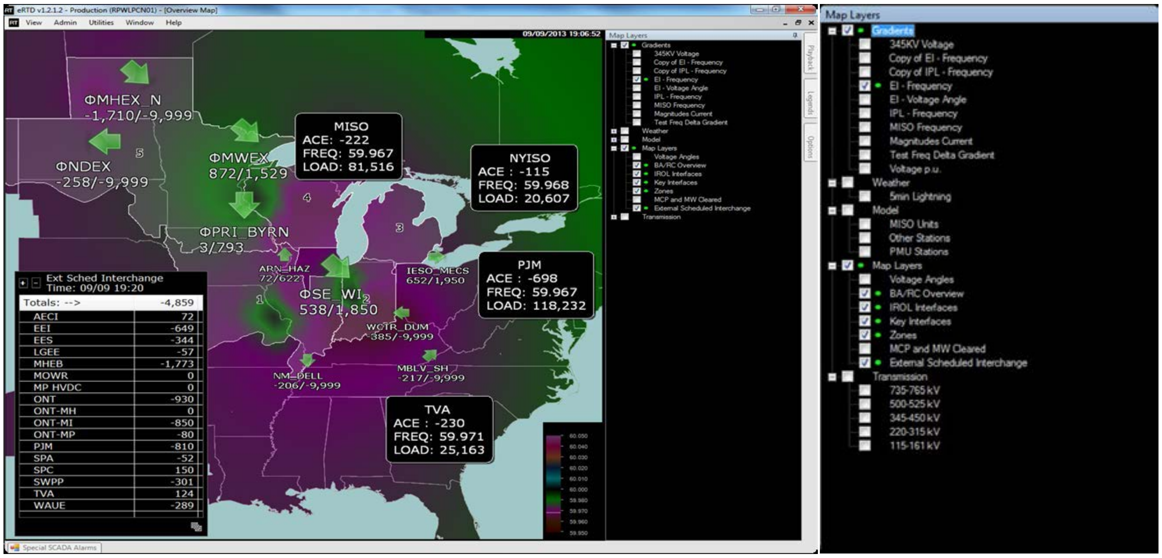
providing common views of grid conditions to control rooms across the interconnection.[86] To this end several ARRA projects deployed, or plan to deploy, PMU-based wide area monitoring and visualization.

Analysis of both SCADA and PMU data are being conducted for the interconnections to baseline their operating conditions. With this information, the ARRA participants are developing and improving insight of power system dynamics and identifying appropriate alerts and application settings for more accurate diagnosis of grid conditions and prediction of grid events. These are leading to recommendations for system operators on how to identify these events and mitigate any possible disturbances. These tools give operators the wide-area situational awareness to observe the propagation of anomalies within their system or interconnection and coordinate necessary actions among themselves and with neighboring operators.

Examples of wide area situational awareness capabilities operationalized by ARRA participants include:

- NYISO displays PMU-based information in its control center. The control room dashboard alarms operators of abnormal conditions including oscillations, voltage magnitudes and phase angles, and frequency. The system also alarms operators of abnormal conditions outside of the New York Control Area.[87]
- MISO displays PMU-based information to system operators in their control center as well as to their transmission owners, thus creating a shared understanding of the evolving state of the Eastern Interconnection. Stability monitoring alerts and other data correlate with their energy management system to provide a unified view, as shown in the figure below.[88]

[86] "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," US-Canada Power System Outage Task Force, April 2004.
[87] Edwin Cano and Jim McNierney, "Visualization and Phasor Enhanced State Estimator", NASPI Working Group Meeting, Houston, TX, October 22-23, 2014.
[88] Kevin Frankeny, "MISO Wide-Area Visualization," NASPI Work Group Meeting, October 22-24, 2014.



MISO wide-area monitoring displays

Other ARRA project participants that use synchrophasor technology for wide area situational awareness are:

- ATC
- CCET[89]
- Duke Energy
- Entergy
- ISO-NE
- PJM[90]

Additional information is available from presentations at a NASPI forum for evaluating and demonstrating various wide area visualization applications.[91] Workshop attendees (including system operators and human factors experts) also provided suggestions on how to improve wide area visualization capabilities using synchrophasors.

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[89] CCET has PMU data displays at the ERCOT control center.

[90] Robinson, Fabian. "Data Visualization, Daily Operations Review and Event Analysis," NASPI Working Group Meeting, Houston, TX, October 2014.

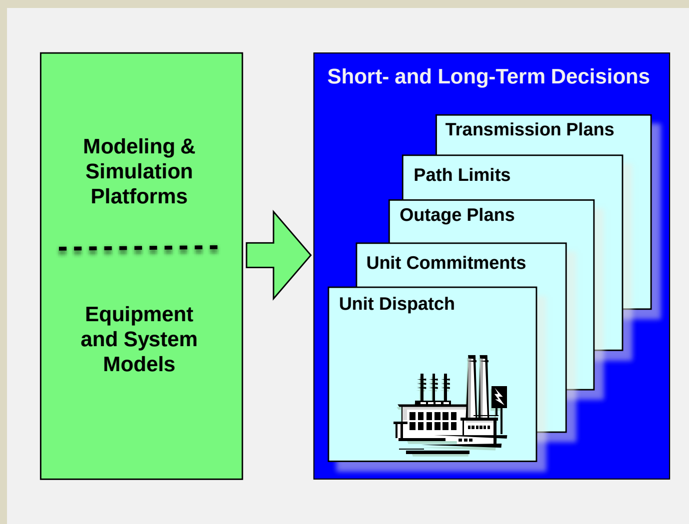
[91] NASPI Phasor Tools Visualization Workshop, Orlando, FL, February 28, 2012; the workshop report is available at https://www.naspi.org/Badger/content/File/FileService.aspx?fileid=5D1FD584EFB4CDD8A525367E7A515252.

A2.8. MODEL VALIDATION & CALIBRATION

Models are used in all aspects of power system planning and operations. Owners and operators of electric power assets use models to predict asset and system behavior under a variety of conditions. These models become more complex as these assets become more complex – the modeling and simulation of the integrated power system is driven by the accuracy of these models. The performance of power system simulations and operating forecasts directly correlates with the accuracy of system models. Improved models also increase the accuracy of dynamic predictions of asset response to events. Thus, the accuracy of these models drives the efficiency and effectiveness of long-term capital investments and real-time system operations. The quality of grid operation is completely dependent on the quality of these models, tools, and input data.

Synchrophasor data provide a high-resolution view of power system and asset behaviors under a wide range of conditions across the interconnection. This capability enables engineers to evaluate and improve their models. PMU data also provide the ability to observe dynamic performance of a generation facility under conditions that may not be achievable under test conditions and to more accurately model its performance or validate the existing model. Truing up generator and system models reduces operational uncertainty, so system operators can better accommodate congestion and other system limitations and reduce the operating margin. With better models, analysis tools provide more accurate insights to decision makers.

Imprecise models drive inaccurate and uneconomical decisions.



Synchrophasor data helps engineers improve system models.

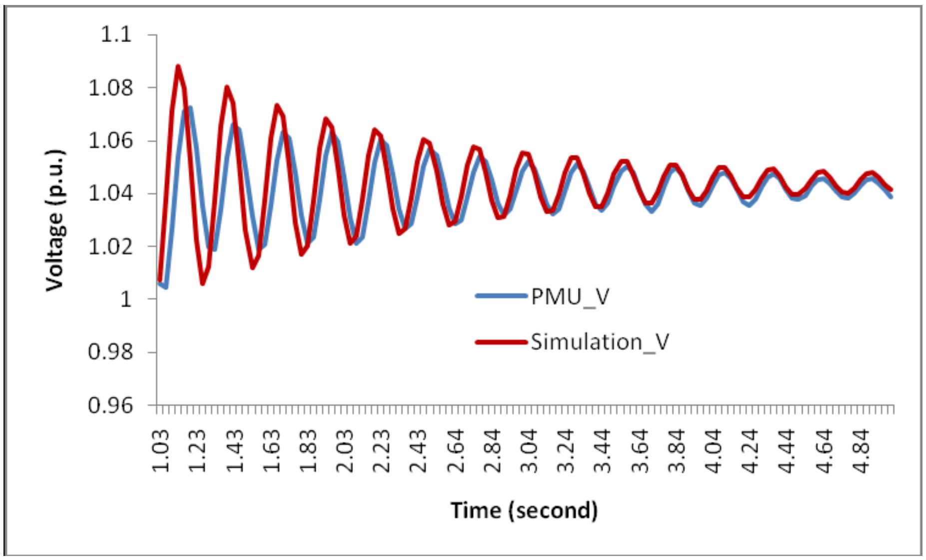
ARRA project participants are using synchrophasor technology to improve models of power plants, systems, and loads. Experience from over a decade of model validation by the electric power industry has proven that more accurate models improve grid reliability. Model validation using synchrophasor technology has shown savings both in labor and analysis costs, producing results in hours rather than weeks and avoiding costs as high as $700,000 in lost revenues, physical testing, and other fees.

By high-speed sampling of dynamic power system conditions, PMUs enable model calibration to better reflect system operations; identify errors in system model data, algorithms, or simulations; and fine-tune the models for simulation applications. Synchrophasor data are also utilized to track dynamic parameters so that models may be adjusted over time to accurately reflect gradual changes in generator parameters or time-sensitive parameters such as transmission line conductor impedance and grid topology.

NASPI provided a forum in 2014 on model validation for asset (e.g., generator) and power system models.[92] The forum shared experiences and benefits of model validation by the industry and showed how PMU data are transforming the practice of model validation, providing dramatic improvements in the accuracy of power plant and power system models.

Examples of model validation and calibration by ARRA participants include:

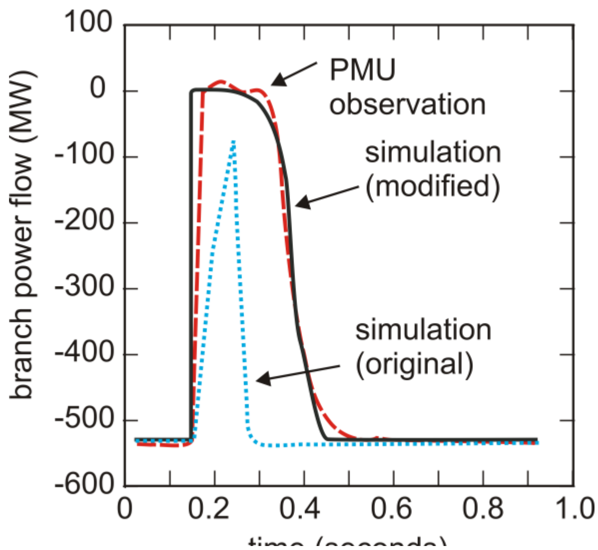
- ERCOT/CCET used PMU data to calibrate a wind turbine model. ERCOT captured oscillations from a wind generator with a PMU and recreated the event using simulation tools. The comparison allowed for the fine tuning of the wind generator model.



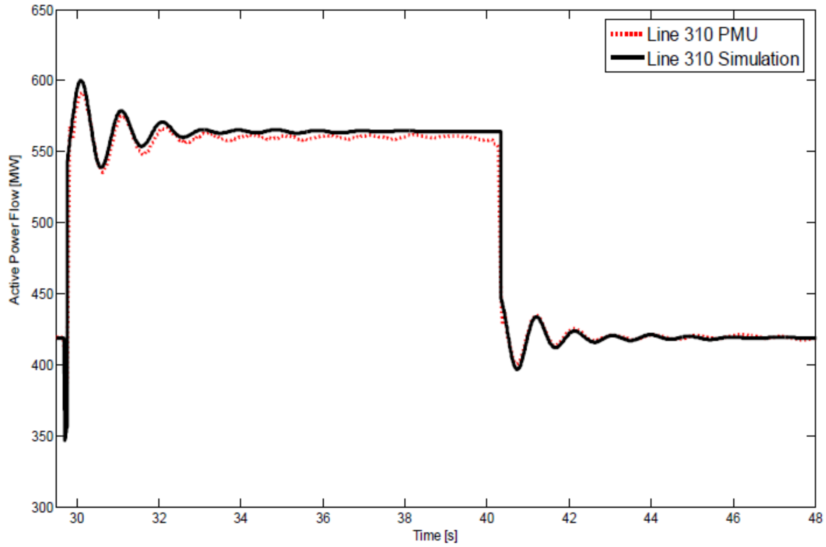
[92] "Model Validation using Synchrophasor Data," NASPI Technical Report, March 20, 2015, https://www.naspi.org/File.aspx?fileID=1416.

PMU versus simulation data for a CCET/ERCOT wind generator model

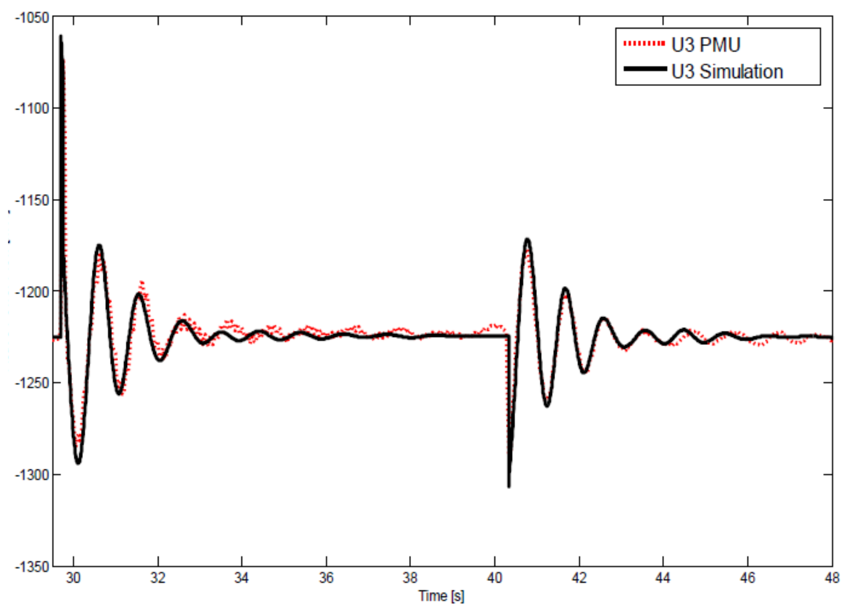
- ISO-NE used PMU data to calibrate two models after system fault events. The figure at right shows ISO-NE's calibration of an HVDC model using PMU data from a single phase-to-ground fault on a transmission line from Sandy Pond Station.
- Synchrophasor data were also used to validate the model of the Millstone Station nuclear plant. A fault occurred on one phase of a transmission line sixteen miles from the station, causing the transmission line to trip out for 10.5 seconds. The figures below compare the PMU data with the simulation



Validation of high voltage direct current (HVDC) model results from the re-validated models of the transmission line and nuclear unit.



Actual and simulated active power flow on the ISO-NE Millstone transmission line



Comparison of PMU and simulated active power output from the ISO-NE Millstone nuclear plant

Other SGIG participants that used or plan to use data from ARRA-funded PMUs for modeling improvements include:

- ATC
- Duke Energy
- Entergy
- IPC
- MISO

- MWE
- NYISO

A2.9. POST-EVENT ANALYSIS

After a system disturbance or blackout, utilities study the sequence of events that led to the problem in order to prevent it from reoccurring. Analyzing system events such as oscillations, islanding, cascading outages, or other unfavorable behaviors is an important component of maintaining power system operational reliability. The insights gained by these analyses allow operators and planners to learn what initiated the system event, how the system responded to the incident, and most importantly, what can be done to prevent another.

Types of data used for post-event analysis

Local Clock

- SCADA event logs
- SCADA analog values:
  - Voltage traces
  - Line flow traces
- Legacy oscillography
- Operator logs
- Interchange schedules
- Load forecasts
- Breaker statuses
- Synchrophasor data

Precision Time-Stamped

- Synchrophasor data
- Modern oscillography

PMU data provides a way to discern the exact sequence of operations – even across operating companies.

To understand how the system responded to the incident, the analysts develop a sequence of events that organizes every action due to the event, such as precise time at which protection equipment (i.e., relays) and circuit breakers involved in the occurrence operated. Using non-time-synchronized technology to determine the sequence of events, as during the analysis of the August 14, 2003 blackout in the United States and Canada, is time consuming and tedious. Significant manual effort was needed to time-align the thousands of various data items from the companies involved in that blackout. It took a large group of engineers over six months to compile the sequence of events because none of the recordings were time-stamped with a common time. As a result, one of the major recommendations of the U.S.-Canada Power System Outage Task Force was to "Require use of time-synchronized data recorders in order to establish time-synchronized disturbance monitoring to help evaluate the performance of the interconnected system under stress…."

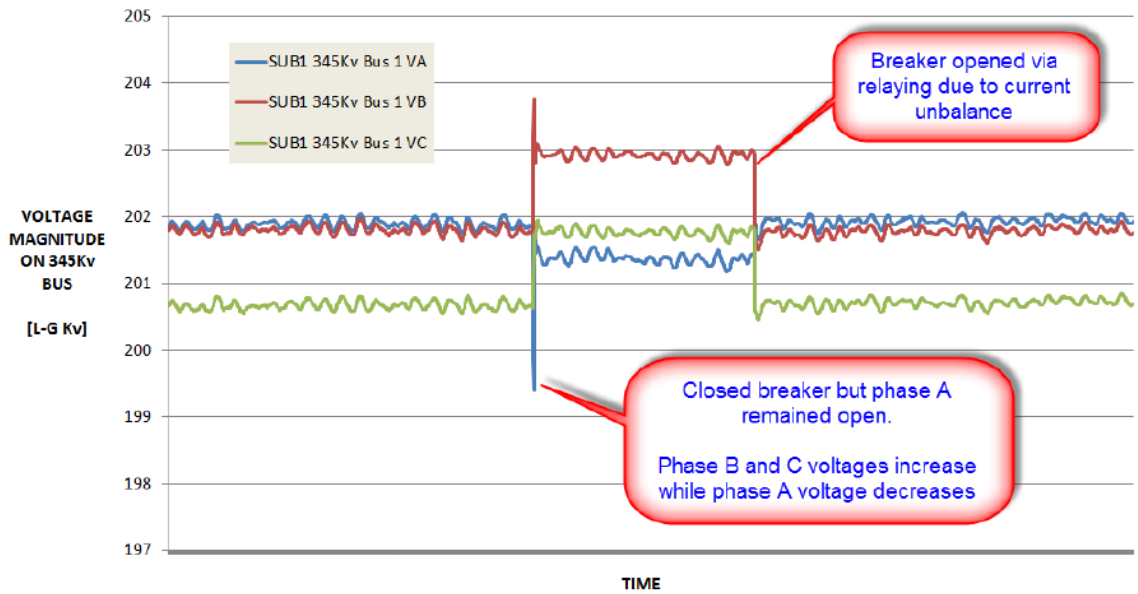
PMUs provide high resolution, time-stamped data so that an accurate aligned record of events can be constructed quickly, often within hours. Such a record of events is needed to be able to perform a root cause analysis of the event. Synchrophasor measurements taken from geographically dispersed parts of the interconnection are time-aligned with precision, and a picture of the dynamic behavior of the entire interconnection can be created quickly along with the determination of the sequence and source of an event.

Synchrophasor technology significantly reduces the labor and cost of post-event analysis. PMU-enabled automated tools have allowed engineers to investigate many events that they previously would not have had time to investigate. The more events that are analyzed, the greater the insights gained by engineers and operators. NERC can now initiate a technical investigation of an event within hours of obtaining the PMU data. PMU data also provide deeper insight into the dynamic behavior of the grid, enabling faster modeling and simulation of a disturbance and faster diagnosis of an event to develop recommendations for corrective and mitigation measures.

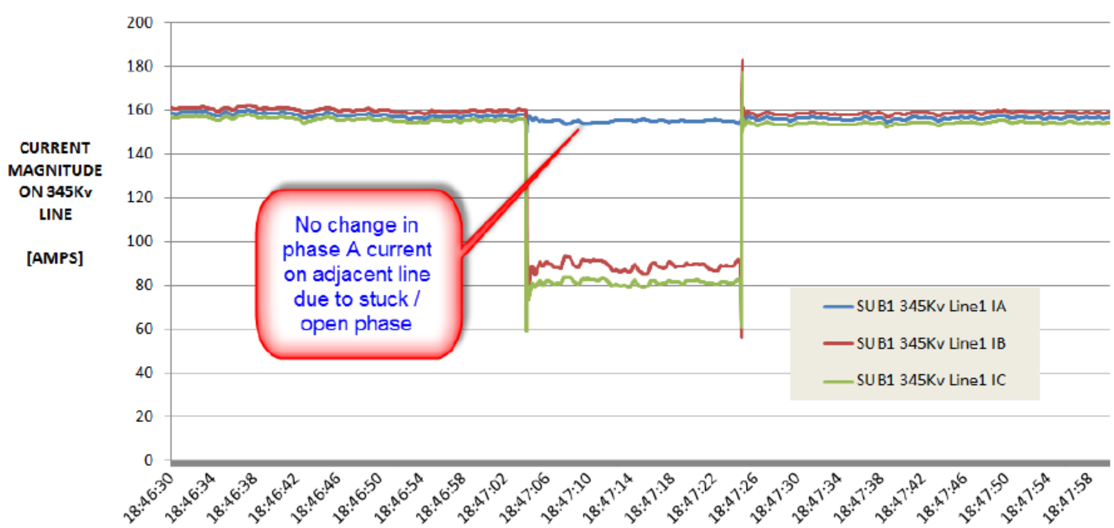
Examples of capabilities realized by ARRA participants using PMU data include:

- ATC developed applications in-house to monitor PMU data and extract data on incidents for post-event analysis. So far, ATC has identified several issues using PMU data, including:
  - widespread effects on the system due to the failure of a surge arrestor,
  - open and unbalanced phases due to improper relay settings or equipment failure,
  - low frequency harmonics injected by equipment recently installed on the system, and
  - improper switching of capacitor banks.

The PMU data enabled engineers to identify the causes and locations of these issues. More information on these events may be found in Section A1.1.

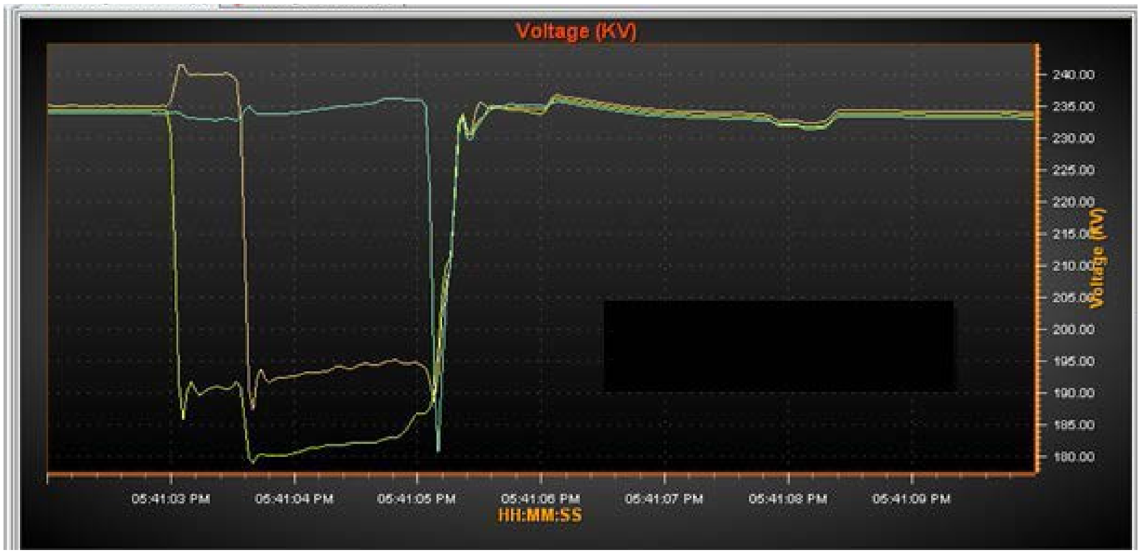


Stuck open phase of 345 kV breaker on close attempt as captured by ATC PMU data



Current readings of another line at substation showing imbalance due to breaker open phase during close attempt as captured by ATC PMU data

- Duke Energy implemented a synchrophasor-based event analysis application used in operations, engineering, planning, protection, and in the control room. A lightning-initiated event was observed where a 100 kV breaker was slow to trip, causing a fault to stay on the system for two seconds. As a result, the 230 to 100 kV transformers at the station tripped by overload and Zone 2 protection was engaged. The magnitude and time duration of the fault (see figure below) were accurately captured by PMU data, making analysis more efficient. Duke is continuing to test the use of PMU data to further reduce the time required for post-event analysis.



PMU data shows voltage dipping from the nominal 230 kV. The problem was attributed to a lightning-initiated fault on the line.

Other ARRA participants that used PMU data for expedited post-event analysis include:

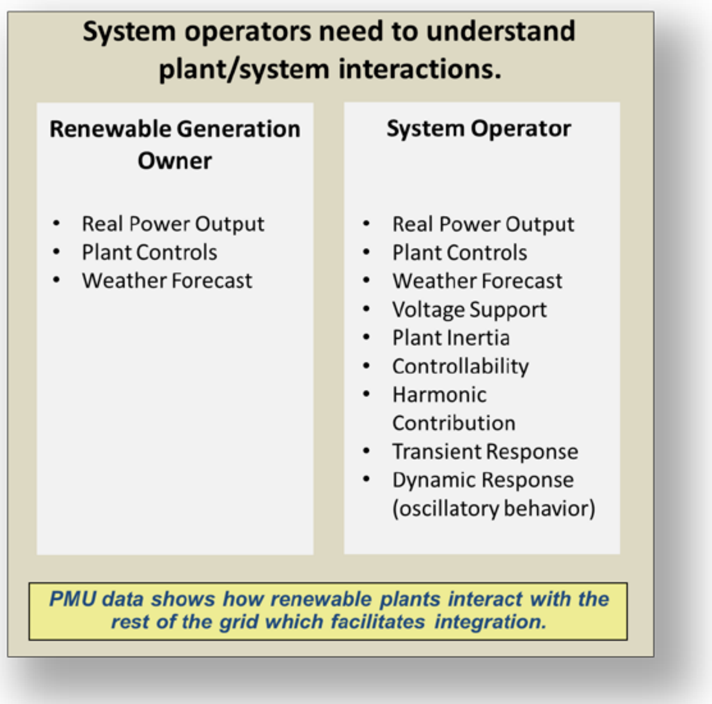
- Entergy
- FPL
- ISO-NE
- LUS
- MISO
- NYISO
- WECC

A2.10. RENEWABLE RESOURCE INTEGRATION

Large-scale renewable generation plants are relatively new to the bulk electric system, so their plant characteristics and control algorithms need to be better understood in the context of the operation of the whole grid. Renewables can be challenging to manage in the grid due to the intermittent nature of their production and the peculiarities of their control systems. This is especially true as they become a greater portion of the generation. Conventional generation is used to balance the variability of wind generation, but is often located far from the wind generation. Synchrophasor systems are particularly useful for monitoring, managing, and integrating distributed generation and renewable energy into the bulk power system. Functionality provided by synchrophasor technology includes:

- PMU data provide better visibility into how renewable generation affects conventional generation, voltages, frequency and oscillations on the power system both locally and across wide areas.
- Dispatchable fossil-fueled generation plants traditionally provide reactive power to the grid. As the amount of renewable energy resources increases, it becomes more difficult for system operators to provide necessary reactive power. PMU-based applications allow operators to more effectively manage reactive power sources to maintain voltage stability with renewable integration present.
- PMU data provide more accurate information for congestion management tools; this can increase capacity for renewable generation that would otherwise be curtailed due to fixed reliability limits.

One of the challenges in integrating renewable energy resources is how to identify and respond to their variability in output. Synchrophasor systems are particularly useful for improved monitoring, managing, and integrating of distributed generation and renewable energy into the bulk power transmission system.

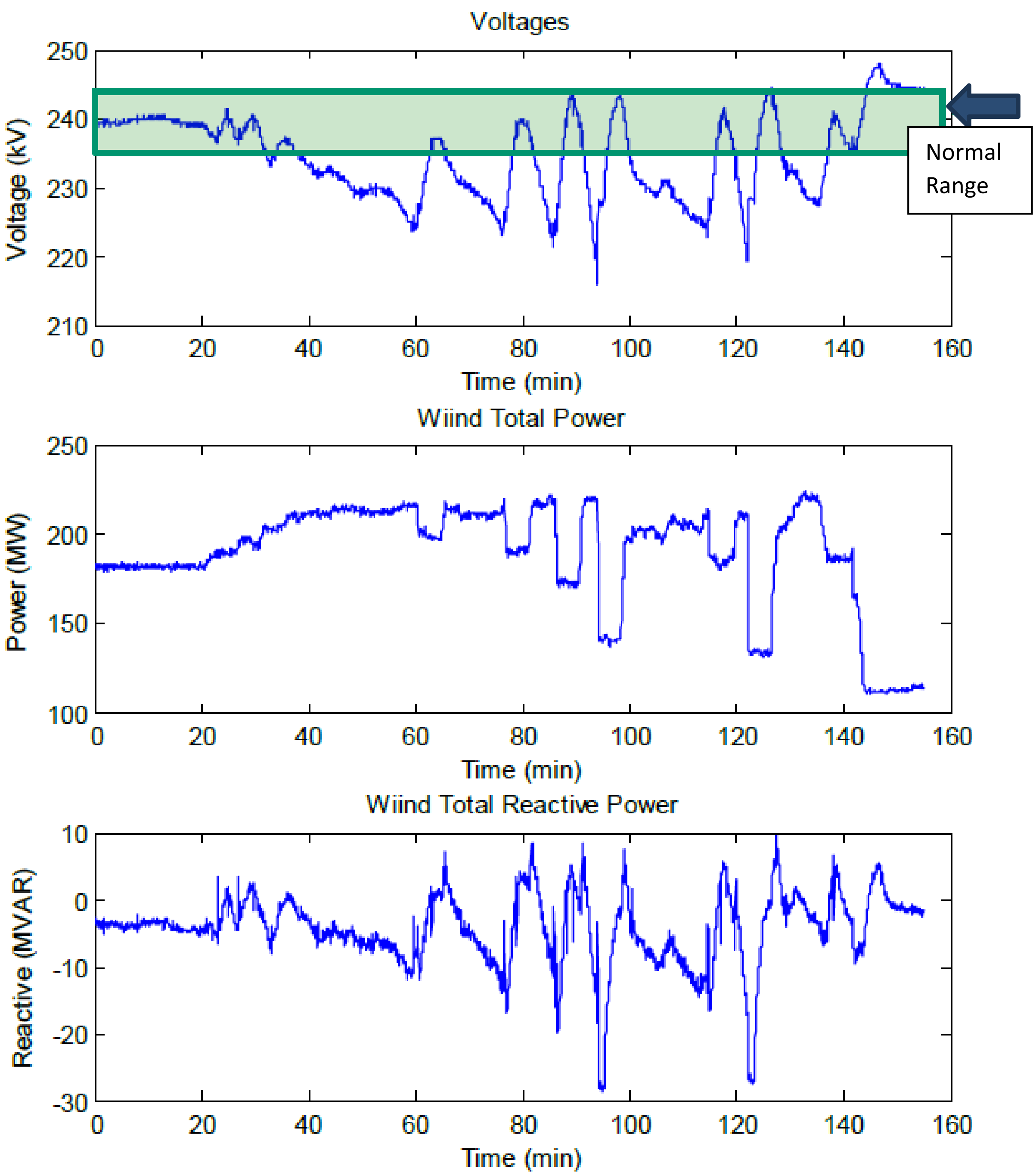


Wind and solar generating facilities can provide voltage support and inertia, and the ability to arrest and stabilize the grid following a disturbance, but the extent to which they are able to do so depends on the specific capabilities of the equipment, controls, and operating procedures implemented. PMUs installed near renewable energy installations provide insights into renewable generation behaviors and control schemes that make it easier to detect operating or grid integration problems early; assess impacts on reserve, protection, and contingency requirements; and initiate control actions if necessary. PMUs located elsewhere on the interconnection provide insight into how the larger grid responds to the new renewable generation plants. These insights inform plans to mitigate the large and sudden changes in generation driven by fluctuations in wind speed/direction and/or solar insolation.

ARRA-funded PMUs have enabled planners to improve models of renewable generation sources, increase their understanding of grid dynamics, and identify needed system enhancements to better integrate these intermittent assets. They also allow system operators to detect abnormal system behaviors driven by the renewable generators and to develop appropriate mitigation plans.

Renewable energy benefits realized by participants using PMU data include:

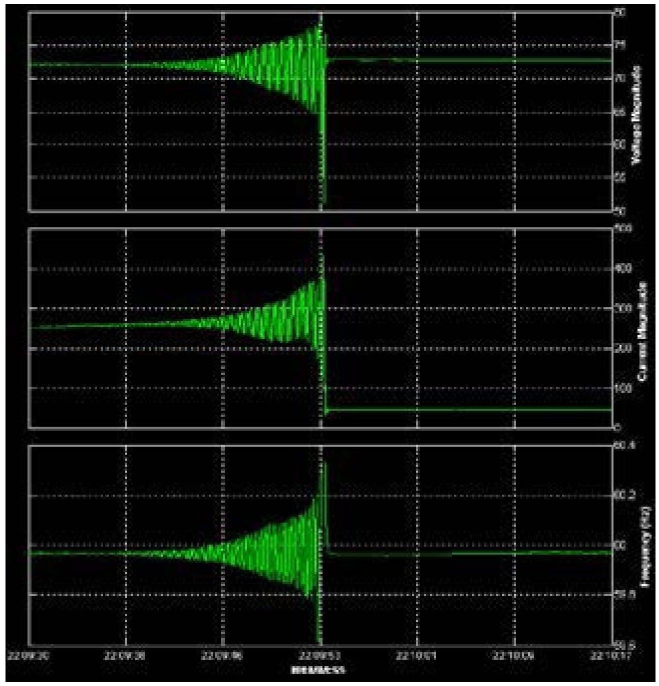
- WECC/Peak has 2,421 MW of renewable generation now monitored by PMUs. The BPA has installed PMUs in at least 15 wind power plants. BPA's wind generators are highly concentrated, with plants clustered into large hubs. Approximately 4,500 MW of this wind generation lacks validated generator models. The utility is working with plant operators to enable voltage control functions, which can increase the amount of wind integration. In one case a wind generation hub that had been limited to 420 MW increased output to 600 MW with dynamic voltage control capabilities. BPA found that PMU measurements can be used for wind hub voltage control and reactive power coordination and has developed an advanced synchrophasor application for voltage control monitoring of wind plants. They also found that PMU measurements provide better situational awareness of voltage stability, especially during fast wind ramps.



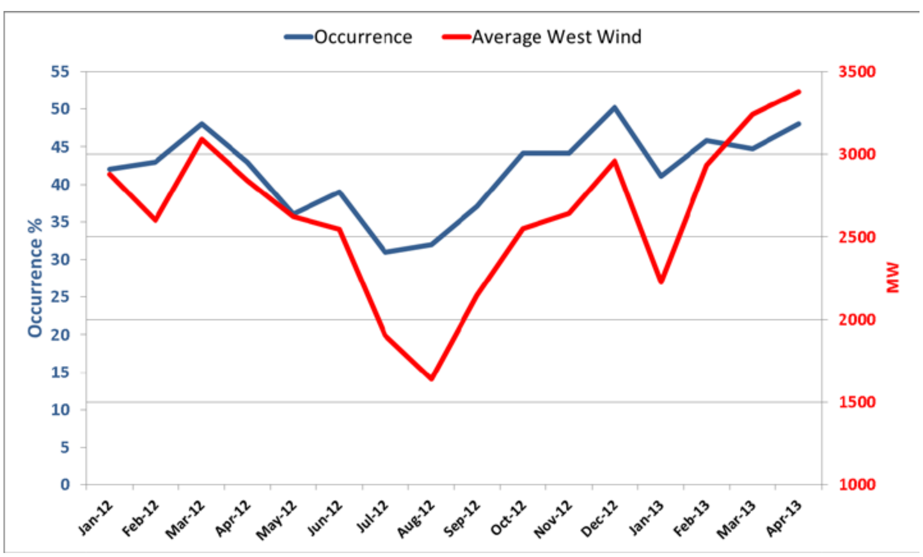
Voltage and power oscillations observed by BPA at a wind hub in the WECC/Peak region, December 2010[93]

[93] "Synchrophasor Technology and Renewables Integration," Report, NASPI Technical Workshop, June 7, 2012.

According to the Energy Information Administration, the State of Texas produced the most wind generated energy in the nation in 2013.[94] The CCET SGDP project was targeted for ARRA support in part to use synchrophasor technology to enhance wind integration. ERCOT built a transmission upgrade to support increased wind production by providing increased and additional transmission capacity so that wind produced electricity can flow to customer loads. ERCOT identified ten previously unknown and unmonitored oscillation modes which were operationally significant. They correlated the occurrence of two of these oscillations with wind data and eight with control systems. ERCOT plans to validate the two oscillations (see figures to the right and below) that they believe to be related to wind generation and then implement changes to mitigate oscillatory modes.[95]



ERCOT-observed voltage event (shows voltage, current and frequency) near wind turbine



Oscillation with 0.9 Hz mode on ERCOT system likely due to wind production

[94] For the year 2013. U.S. EIA Electric Power Monthly. http://www.eia.gov/todayinenergy/detail.cfm?id=15851
[95] Sidharth Rajagopalan et. al, "ERCOT Data Mining For Oscillations from Wind Generators," NASPI Working Group Meeting, San Mateo, CA, March 24, 2015.

Other SGIG participants that used data from ARRA-funded PMUs for renewable energy integration include:

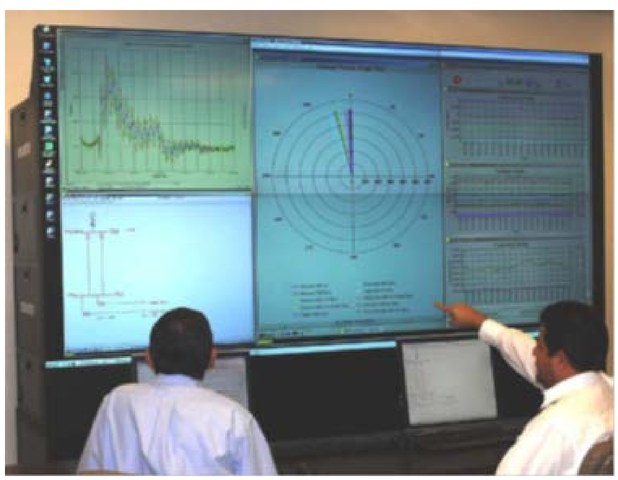
- Duke Energy
- IPC

A2.11. OPERATOR TRAINING

Power system operators and engineers rely on specific procedures for making decisions regarding real-time control of the grid. They need to understand the electric grid's behavior in real time in order to know which procedure to apply and when to apply it. Formal training on procedures is conducted using simulators of power system operation.

All of the ARRA-funded projects incorporated extensive training into their projects. Much of this training has utilized synchrophasor technology by simulating grid behaviors (e.g., oscillations and voltage instabilities) based on event data captured by PMUs. Application-specific training often utilized event playback capabilities of synchrophasor-based tools to understand and respond to various grid events.

Participants also trained their staff on the use and interpretation of new synchrophasor tools such as oscillation monitoring applications, event detection and analysis tools, and model validation tools. PMU data are being incorporated into Dispatcher Training Simulators to provide a realistic operating environment for the training exercises. This is so operators can gain a more fundamental understanding of various dynamic power system phenomena and their effects on the power grid's operation, and also to provide the operators first-hand experience with the new synchrophasor data displays.



Synchrophasor screens at Southern California Edison[96]

Examples of synchrophasor training and procedures implemented by the ARRA participants include:

- CCET/ERCOT provided training on their wide-area monitoring system to both ERCOT and system operators. Training on synchrophasor-based applications has been conducted by their software development vendors. There have been a total of 41 participants, 20 from ERCOT and 21 from

[96] Thomas Botello, "Use of Phasor Data for Real-Time Operations," NASPI Working Group Meeting, June 2009.

TOs, trained on these applications. The hands-on exercises in the training were based on ERCOT use cases.[97] CCET/ERCOT also developed system performance indicators (such as alarm limits from baseline studies) used by operators that utilize synchrophasor data and applications.

- NYISO has provided control room operators with nine hours of formal synchrophasor classroom training. This included incorporation of PMU data in alarming procedures, defining the steps operators must take when an alarm occurs. There are internal control area alarms for oscillation detection, voltage magnitude, and angle and frequency limits, and external region alarms for angle differences across external regions, voltage magnitude, and frequency limits. Also, several control room operators participated in the test and acceptance process for synchrophasor application software products.

Other SGIG participants that have used synchrophasors for operator training and/or trained operators in the use of synchrophasors include:

- Duke Energy
- Entergy
- FPL
- ISO-NE
- MWE
- PJM
- WECC/Peak

[97]Bill Blevins, "CCET Discovery Across Texas Synchrophasor Team Meeting," NASPI Working Group Meeting, October 24, 2013.

APPENDIX 3: CORE METRICS FOR SYNCHROPHASOR PROJECTS

Build Metrics were used to track expenditures and progress as PMU systems were acquired and installed. Project participants were required to report this information quarterly until they had submitted their final invoice to DOE. All quantities were reported by Project (ARRA-funded) and Total System (includes non-ARRA equipment). Costs reported were both for federal funding and for recipient cost share.

Impact Metrics were designed to record the performance of the systems once they were installed and operating. Project participants reported Impact Metrics semi-annually beginning after the system was operational, until the end of the project. Each project participant had different Impact Metrics. Many Impact Metric quantities were impractical to report. DOE, in cooperation with the project participants, developed Core Metrics to better characterize PMU performance and benefits. The Core Metrics were implemented in late 2013, before most projects had significant information to report under Impact Metrics.

Nine project participants voluntarily agreed to use the Core Metrics to report the impacts of their synchrophasor systems. All project participants had the ability to make specific information "Commercially Valuable" if it contained sensitive information that could not be made public for security or for competitive business reasons.

Metric	Metric Qualifier	Unit
PMU Count – Devices	Number of PMUs (devices). Provide both (a) project-total (includes cost share) and (b) system-wide total. A phasor measurement unit (PMU) is any device that produces synchrophasors from voltage/current measurements that are time stamped using a common time source. Count PMUs both deployed and networked. Deployed means the PMU is installed and functional. Networked means the PMU is continuously delivering data. A PMU can be a dedicated device, or the PMU function can be incorporated into a protective relay or other device.	#
PMU Count - Substations	Number of substations where PMUs are deployed. A phasor measurement unit (PMU) is any device that produces synchrophasors from voltage/current measurements that are time stamped using a common time source.	#
PMU Count - Signals	Number of signals (synchrophasors) provided by the PMUs. A phasor measurement unit (PMU) is any device that produces synchrophasors from voltage/current measurements that are time stamped using a common time source.	#

Metric	Metric Qualifier	Unit
PDC Count	Number of PDCs deployed and networked. A phasor data concentrator (PDC) receives/collects, time-aligns, and/or archives the PMU data. Include operational backup PDCs in your count but not those used only for testing or as spares.	#
System Description - from PMU to Applications	Provide a high-level description of the system used to deliver data from PMUs to applications. The description should include the rationale for PMU/PDC placement (where did you place PMUs and why), the communications system, and how the data is managed (how data is aggregated, stored and delivered). If diagrams are available, please upload them via the Project Documents section of the Data Hub. Do not include sensitive information.	Text
System Performance	Describe how the system is performing in terms of delivering data from PMUs to applications (with respect to delivery rates, data quality, data availability and data system recovery). Please provide the performance information and your method used to determine performance. The goal is to show progress as the system performance changes (e.g., improves) over time. If applicable, mark this information as being "commercially valuable" (DOE will only aggregate this information).	Text
Data Sharing - Yes or No?	Are you sharing your data with others? Are you obtaining data from others?	Y/N
Data Sharing - Text Description	Who are you sharing data with? From whom are you obtaining data? What are the intended or realized benefits of your data sharing? Describe purpose of sharing.	Text
Procedures (Operating and/or Planning) - Yes or No?	Have any operating/planning procedures been modified or created due to the availability of synchrophasors? Procedures refer to those documents that are developed and used in operating and planning the bulk power system. For these purposes, procedures are not "standards" or "guidelines".	Y/N
Procedures (Operating and/or Planning) - Count	Number of operating/planning procedures modified or created due to the availability of synchrophasors. Procedures refer to those documents that are developed and used in operating and planning the bulk power system. For these purposes, procedures are not "standards" or "guidelines".	#
Procedures (Operating and/or Planning) - Text Description	Describe operating/planning procedures that have been modified or created due to the availability of synchrophasors. Procedures refer to those documents that are developed and used in operating and planning the bulk power system. For these purposes, procedures are not "standards" or "guidelines".	Text

Metric	Metric Qualifier	Unit
Applications using Synchrophasor Data - Count	Number of applications being developed or deployed for both offline and online analysis.	#
Applications using Synchrophasor Data - Text Description	The description of an application should include its purpose (e.g., state estimation, oscillatory modal analysis, model validation), its status (e.g., under development, in testing, timeline to deployment, in use), how it is being used (e.g., training, studies, operations, planning) and its intended or resulting benefit. For relevant applications, include a discussion of progress to date and plans to achieve system observability. If relevant, estimate % observability (coverage) achieved for a given application.	Text
Control Schemes utilizing Synchrophasor Data - Count	Number of control schemes implemented utilizing synchrophasor data. Include control schemes that were enabled by the project.	#
Control Schemes utilizing Synchrophasor Data - Text Description	Describe control schemes implemented utilizing synchrophasor data. Include control schemes that were enabled by the project.	Text
System Performance Indicators - Count	Number of changed or new system performance indicators using synchrophasor data/applications.	#
System Performance Indicators - Text Descriptions	Describe changes or new system performance indicators using synchrophasor data/applications. Describe the resulting benefit(s).	Text
Applications and Control Schemes	Summarize benefits realized or expected by the use of synchrophasor data in applications and/or control schemes that are related to reliability improvements. If possible provide quantitative measure of the benefits.	Text
Model Validation	Summarize benefits of improved model validation. Provide quantitative value where possible.	Text
System Dynamics	Describe new oscillation modes or other events/phenomena detected by synchrophasor data (and their potential impact). Describe how you will or have addressed them.	Text

Metric	Metric Qualifier	Unit
System Resiliency and Restoration	Describe where and how synchrophasor data has been or will be used to: 1. mitigate or reduce system disruption/outage 2. maintain and restore the system following an outage (e.g., islanding, load restoration). Describe the value provided by synchrophasor data.	Text
Transmission Capacity	Describe where synchrophasor data/application(s) have enabled additional transmission throughput, congestion relief, and/or deferral of capital investments. Provide the economic value where possible.	Text
Organizational Efficiency / Effectiveness	Describe where synchrophasor data/application(s) have improved the effectiveness and efficiency of organizational processes and procedures (e.g., reduction in labor requirements, faster analysis time). Quantify where possible.	Text

APPENDIX 4: GLOSSARY

AC – Alternating current
AGC – Automatic generation control
AMI – Advanced metering infrastructure
ARRA – American Recovery & Reinvestment Act of 2009, which funded the DOE SGIG and SGDP awards for synchrophasor and other electric technology investments
ATC – American Transmission Company
AVR – Automatic voltage regulator

Bandwidth – The maximum data transfer rate of the communications network; it is a measure of how much data can be sent over a specific connection in a given amount of time.
BPA – Bonneville Power Administration
BPS – Bulk power system

CAISO – California Independent System Operator
CCET – Center for Commercialization of Electric Technologies
CCVT – Capacitance-coupled voltage transformer, a transformer used to step down extra high voltage signals and provide a low voltage signal for measurement or to operate a protective relay
CIP – Critical Infrastructure Protection
CO2 – Carbon dioxide
COI – California-Oregon Intertie
Control scheme – A control scheme is a systematic approach for managing the state of power system devices or systems.
CT – Current transformer
CVT – Capacitive voltage transformer

Data quality – Represents the extent to which data are accurate and timely. Accuracy refers to how well the data that represents the physical phenomenon is being measured. Timeliness refers to the data being available in the timeframe required by the capabilities that the data inform.
DC – Direct current
DCRS – Dynamic capability rating system
DCS – Distributed control system
DER – Distributed energy resources
DFR – Digital fault recorder
DOE – Department of Energy

eGRID – Emissions & Generation Resource Integrated Database
EHV – Extra high voltage
EIDSN – Eastern Interconnect Data Sharing Network
EMS – Energy management system
EPG – Electric Power Group
EPRI – Electric Power Research Institute
ERCOT – Electric Reliability Council of Texas

eRTD – Enhanced real-time display
EV – Electric vehicle

FACTS – Flexible Alternating Current Transmission System
FE – Frequency error
FERC - Federal Energy Regulatory Commission
FOA – Funding opportunity announcement
FPL – Florida Power & Light Company
fps – Frames per second, the rate that frames of synchrophasor data are transmitted
Frequency bias – A value, usually expressed in megawatts per 0.1 Hertz (MW/0.1 Hz), associated with a Balancing Authority Area that approximates the Balancing Authority Area's response to Interconnection frequency error.[98]
***F*s** – Frequency of measurement data reporting, in frames per second

Governor – The electronic, digital or mechanical device that implements Primary Frequency Response of generating units/generating facilities or other system elements.[99]
GPS – Global positioning system
Grid – Electric power system network

HVDC – High voltage direct current
Hz – Hertz, such as the U.S. electric power system operates at 60 Hz (or cycles per second)

IEC - International Electrotechnical Commission
IEEE – Institute of Electrical and Electronic Engineers
IEEE/PES – IEEE/Power and Energy Society
Interconnection –Any one of the three major electric power system networks in North America: Eastern, Western, and ERCOT.[100]
IPC – Idaho Power Company
IPP – Independent power producer
Islanding – Islanding involves the separation of a part of the power system from the larger power grid.
ISO – Independent system operator
ISO-NE – Independent System Operator New England

kV – Kilovolt (one thousand volts), a unit of power system voltage
kW – Kilowatt (one thousand watts), a unit of power system real power, which is the portion electricity that supplies energy to the load.[101]
kWh – Kilowatt-hour (one thousand watt-hours), a unit of power system energy

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[98] http://www.nerc.com/files/glossary_of_terms.pdf
[99] http://www.nerc.com/files/glossary_of_terms.pdf
[100] http://www.nerc.com/files/glossary_of_terms.pdf
[101] http://www.nerc.com/files/glossary_of_terms.pdf

kVAr – Kilovar (one thousand vars), a unit of power system reactive power, which is the portion of electricity that establishes and sustains the electric and magnetic fields of alternating- current equipment.[102]
kVA – Kilovolt-ampere (one thousand volt-amperes), a unit of power system complex power, which is the vector sum of real and reactive power.
KPI – Key performance indicator

Latency – The amount of time it takes for data to be transmitted across a communications network.
LTC – Load-tap-changing transformer
LUS – Lafayette Utilities System

MISO – Midcontinent Independent System Operator
MMV – Measurement, monitoring, and verification
ms – Millisecond (one-thousandth of a second)
MVAr – Megavolt ampere reactive (a million vars), a unit of reactive power (see kVAr)
MW – Megawatt (one million watts), a unit of real power (see kW)
MWE – Midwest Energy
MWh – Megawatt-hour (one million watt-hours), a unit of power system energy
MVA – Megavoltampere (one million volt-amperes), a unit of complex power (see kVA)

NASPI – North American SynchroPhasor Initiative
NASPInet – A conceptual architecture (developed by the NASPI community) for a physical communications transport network that could support hundreds of phasor gateways and thousands of PMUs. NASPInet is also used to mean one or more regional or interconnection-wide dedicated communications networks carrying phasor data between PMUs, applications and control centers to support real-time grid operations. Most of the SGIG synchrophasor recipients are implementing NASPInet architecture concepts in their projects. Cybersecurity elements are embedded into the NASPInet design.[103]
NEPA – National Environmental Policy Act
NERC – North American Electric Reliability Corporation
NETL – National Energy Technology Laboratory
NIST – National Institute of Standards and Technology
NREL – National Renewable Energy Laboratory
NYCA – New York Control Area
NYISO – New York Independent System Operator

OE – DOE's Office of Electricity Delivery and Energy Reliability
openPDC – Open phasor data concentrator
ORNL – Oak Ridge National Laboratory

PDC – Phasor data concentrator
PDCI – Pacific Direct Current Intertie

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[102] http://www.nerc.com/files/glossary_of_terms.pdf
[103] from "Synchrophasor Technology Glossary." https://www.naspi.org/documents

Peak – Peak Reliability
PG&E – Pacific Gas & Electric
PGDA – Phasor Grid Dynamics Analyzer
PHEV – Plug-in hybrid electric vehicle
PJM – The PJM Interconnection
PMU – Phasor measurement unit
PSS – Power system stabilizer: The Power System Stabilizer (PSS) is a supplementary excitation controller used to dampen generator electro-mechanical oscillations in order to protect the generator shaft and stabilize the grid.[104]
PT – Potential transformer, designed for use on high voltage equipment to step down system voltage to a level that is safe for monitoring single-phase and three-phase power line voltages or potential.

R&D – Research and development
RAS – Remedial action scheme: An automatic protection system designed to detect predetermined power system conditions, and automatically take corrective actions that may include, but are not limited to, adjusting or tripping generation, tripping load, or reconfiguring a system(s).[105]
RC – Reliability coordinator
Resiliency –The ability of the power system to withstand the loss of generators, transmission lines, loads, or other assets beyond what it was designed to withstand.
ROSE – Region of Stability Existence
RTDMS – Real Time Dynamics Monitoring System
RTO – Regional transmission organization
RTU – Remote terminal unit

SCADA – Supervisory control and data acquisition: a system of remote control and telemetry used to monitor and control the transmission system.[106]
SCE – Southern California Edison
SGDP – Smart Grid Demonstration Program
SGIG – Smart Grid Investment Grant
SIDU – Synchrophasor Infrastructure and Data Utilization
SIEGate – Secure Information Exchange Gateway application
SOPO – Statement of Project Objectives
SPASE - Synchrophasor-assisted state estimator
Stability – The ability of an electric system to maintain a state of equilibrium during normal and abnormal conditions or disturbances.[107]
SubstationSBG – Substation Secure Buffered Gateway
System dynamics – oscillations or other phenomena that result from the system being perturbed.

T&D – Transmission and distribution
TLC – Transfer limit calculator

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[104] http://www.alstom.com/products-services/product-catalogue/power-generation/coal-and-oil-power/automation-and-controls-for-coal-and-oil/power-system-stabilizer/
[105] http://www.nerc.com/files/glossary_of_terms.pdf
[106] http://www.nerc.com/files/glossary_of_terms.pdf
[107] http://www.nerc.com/files/glossary_of_terms.pdf

TO – Transmission owners
TVA – Tennessee Valley Authority

VACAR – Virginia-Carolinas subregion of the SERC Reliability Corporation region.
VAr – Volt ampere reactive (kVAr)

WAMS – Wide area measurement system
WAN – Wide-area network
WECC – Western Electricity Coordinating Council
Wide area situational awareness – Wide area situational awareness enables grid operators to see the bulk electric power system across an entire interconnection, understand grid conditions in real time, and diagnose and react to emerging problems.
WISP – Western Interconnection Synchrophasor Program

APPENDIX 5: FURTHER READING

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