ANNEX 6

Synchrophasor Applications for Wide Area Monitoring and Control

ISGAN Discussion Paper

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ISGAN Annex 6 Power T&D Systems

Task 1

About ISGAN Discussion Papers

ISGAN discussion papers are developed as input documents to stimulate the global discussion about smart grids. Each is a statement by the author(s) regarding a topic of international interest. They reflect works in progress in the development of smart grids in the different regions of the world. Their aim is not to communicate a final outcome or to advise decision-makers, but rather to lay the groundwork for further research and analysis.

Disclaimer

Acknowledgments

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Executive Summary

This discussion paper describes synchrophasor applications for wide area monitoring and control in North America and Norway. It is the result of a collaboration of representatives from the United States and Norway, enabled through ISGAN's Annex 6.

A synchrophasor is a time-synchronized measurement of a quantity described by a phasor. Like a vector, a phasor is a complex number that represents both the magnitude and phase angle of voltage and current sinusoidal waveforms at a specific point in time. Devices called phasor measurement units (PMU) measure voltage and current, and with these measurements, calculate parameters such as frequency, real power (MW), reactive power (MVAR) and phase angle. Data reporting rates for these parameters are typically 30 to 60 records per second, and may be higher. In contrast, current supervisory control and data acquisition (SCADA) systems typically report data every four to six seconds – over a hundred times slower than PMUs.

Measurements taken by PMUs in different locations on the network are accurately synchronized with each other and can be time-aligned, allowing the relative phase angles between different points in the system to be determined as directly measured quantities. Synchrophasor measurements can thus be combined to provide a precise and comprehensive "view" of an entire interconnection, allowing unprecedented visibility into system conditions.

The number of PMUs installed worldwide, as well as the number and type of grid operations informed by PMU data and applications, have seen notable increases in recent years. The past six years have seen a significant increase in the number of PMUs installed across North America's transmission grid, from fewer than 500 installed in 2009 to nearly 2,000 today. This rapid increase in deployment of PMUs was spurred by the 2009 American Recovery and Reinvestment Act (ARRA), which funded federal Smart Grid Investment Grants (SGIG) and Smart Grid Demonstration Projects (SGDP), with matching private funds. In Norway, responsibility for the deployment of PMUs has recently been assumed by the Transmission System Operator's IT division, meaning that PMUs are becoming an integral part of the grid information infrastructure for system operations.

Applications

Advanced analytical applications are being developed to effectively analyze and utilize the vast amounts of data being generated by PMUs. These applications are being used to improve grid reliability and efficiency and lower operating costs. Phasor data applications can be grouped into two categories – real-time and offline. This document reviews principal applications groups in each of these categories.

Real-time applications support real-time grid operations by providing wide-area visualization and increased state awareness and response-based control applications that use real-time wide area information to effect automated control actions on the power system. Real-time applications can further be divided into the categories of monitoring and analysis (which provide visibility into power system dynamics) and control (which support operator decision tools or automated PMU-triggered control operations).

There is currently a confidence gap in the industry between using synchrophasor tools for off-line applications and a willingness to use synchrophasor tools for mission-critical applications. Acceptance of synchrophasor tools for mission critical-control room uses will require the industry to resolve two challenges that are much larger than the electric sector – how to maintain cyber security of data, communications networks, and applications; and how to assure that multiple points along the time-stamping chain have redundant sources of universal time.

Real-time monitoring and analysis applications covered in this document include wide-area visualization, frequency stability monitoring and trending, voltage monitoring and trending, oscillation detection, monitoring and trending, phase angle monitoring and trending, resource integration, adaptive islanding and black start/restoration, and generator model validation. Control applications covered in this document include adaptive relaying and power system stabilizer/power oscillation damper applications.

Off-line applications improve system planning and analysis using archived data. Analyses can be conducted off-line days or even months after the data has been collected. Phasor measurements should improve the understanding of power system performance and improve system model validation for models used in power system studies. Ultimately, this enhanced understanding should produce better decisions on capital investment and more effective utilization of the transmission system.

Off-line applications covered in this document include post event analysis, system model validation, and state estimation.

Ongoing Challenges

Electronic communication is an important component of synchrophasor implementation and brings associated concerns about cyber security – including new communication links opening the way for cyber-attacks. Given that most of the power system is controlled electronically, a successful cyber-attack could cause great physical and financial damage. Therefore, it is essential that cyber security risks be carefully analyzed and mitigated.

Data management methods which work well for small amounts of data often fail or become too burdensome for large amounts of data. Data management is one of the most time-consuming and difficult challenges for many synchrophasor functions, although some recent technology methodologies are helping to alleviate this problem.

Lessons Learned

The industry has learned important lessons regarding synchrophasor technology implementation as a result of the SGIG and SGDP programs in the areas of synchrophasor deployment, application development, and data quality and sharing:

Synchrophasor Deployment

- Many ARRA deployments have high and consistent levels of device capability and use the same applications; and the North American Synchrophasor Initiative (NASPI) collaboration will make it much easier for late adopters to catch up with industry leaders in the future.
- PMU prices and installation costs have dropped markedly since 2010. Since PMUs and their associated components evolve at much faster rates than traditional transmission equipment, project initiators should consider the pace of development and cost in the planning stages to ensure that vendors are prepared to meet the latest security and data volume requirements.

Applications Development

- There is a considerable learning curve from the installation of synchrophasor systems to user acceptance and use – time is required to develop personnel who are engaged, trained, and committed to utilizing new real-time applications and data outside of the accepted post event analysis framework.
- Moving technology from development to production has been more difficult than expected, particularly in the area of real-time operations. PMU analytics need to be scalable and adaptable as the technology becomes more commonplace.

Data Quality and Sharing

- Sorting through and archiving data to derive the information required presents challenges. Project teams have found that it is increasingly important to test equipment for data accuracy and quality when moving from installation to active use.
- Many data quality problems can only be resolved through improved business practices (such as metrics reporting, accountability, maintenance, contract terms, and hand-offs between organizations).
- There is a need for common vocabulary, definitions, and standardized test/use cases. Data sharing between entities who have installed synchrophasor technologies should also be increased.

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1 Introduction

This discussion paper highlights the deployment of phasor measurement units and advanced applications that have been developed in the United States and Nordic countries. These advanced applications have contributed tangible benefits to power system planning and operations. These benefits can be categorized in three areas:

- *Increased system reliability*: Synchrophasor technology has already prevented outages, detected and diagnosed failing or misoperating equipment, enabled faster reenergizing of out of service transmission lines, and informed system operators of developing problems on the grid.
- *Increased asset utilization and power system efficiency*: Program participants have reduced curtailment of renewable energy sources, been able to increase transmission flows in congested service areas, and validated/updated generator models without having to take the unit off-line.
- *Increased organizational efficiency*: 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.

Synchrophasor Background

A synchrophasor is a time-synchronized measurement of a quantity described by a phasor. Like a vector, a phasor is a complex number that represents both the magnitude and phase angle of voltage and current sinusoidal waveforms at a specific point in time (see Figure 1). Devices called phasor measurement units (PMU) measure voltage and current and with these measurements calculate parameters such as frequency, active power (MW), reactive power (MVAR) and phase angle. Data reporting rates are typically 30 to 60 records per second, and may be higher; in contrast, current supervisory control and data acquisition (SCADA) systems often report data every four to six seconds – over a hundred times slower than PMUs.

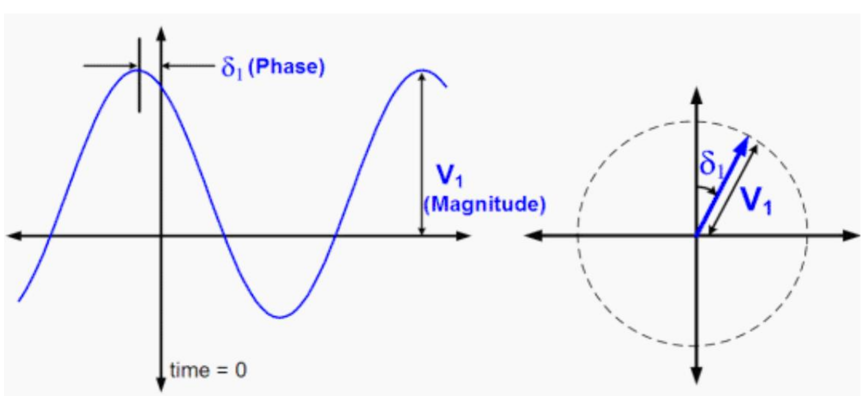

Figure 1. Sinusoidal Waveform and Phasor Representation[1]

[1] Phasor Technology Overview, CERTS (Consortium for Electric Reliability Technology Solutions).

PMU measurements are time-stamped to an accuracy of a microsecond, synchronized using the timing signal available from global positioning system (GPS) satellites or other equivalent time sources. Measurements taken by PMUs in different locations are therefore accurately synchronized with each other and can be time-aligned, allowing the relative phase angles between different points in the system to be determined as directly-measured quantities. Synchrophasor measurements can thus be combined to provide a precise and comprehensive "view" of an entire interconnection.

The accurate time resolution of synchrophasor measurements allows unprecedented visibility into system conditions, including rapid identification of details such as oscillations and voltage instability that cannot be seen from SCADA measurements. Complex data networks and sophisticated data analytics and applications convert PMU field data into high-value operational and planning information.[2]

Current Synchrophasor System Deployment

North America

In 2009, there were fewer than 500 research-grade PMUs installed across North America's transmission grid. Today, there are almost 2,000 commercial-grade PMUs installed. The rapid advances in PMU capability, availability and connectivity were all spurred in 2009 by the American Reinvestment and Recovery Act (ARRA). ARRA funded federal Smart Grid Investment Grants (SGIG) and Smart Grid Demonstration Projects (SGDP) with matching private funds.[3] The projects have collectively installed an extensive set of secure communications networks to deliver PMU data from many electric substations (blue dots in Figure 2) up to transmission owner data concentrators and regional data concentrators (yellow and red stars in Figure 2) across much of the continent.

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[2] Synchrophasor Technology Fact Sheet, NASPI, https://www.naspi.org/File.aspx?fileID=1326.
[3] Phil Overholt, David Ortiz, Alison Silverstein, Synchrophasor Technology and the DOE, IEEE Power & Energy Magazine, Volume13, Number 5, September/October 2015.

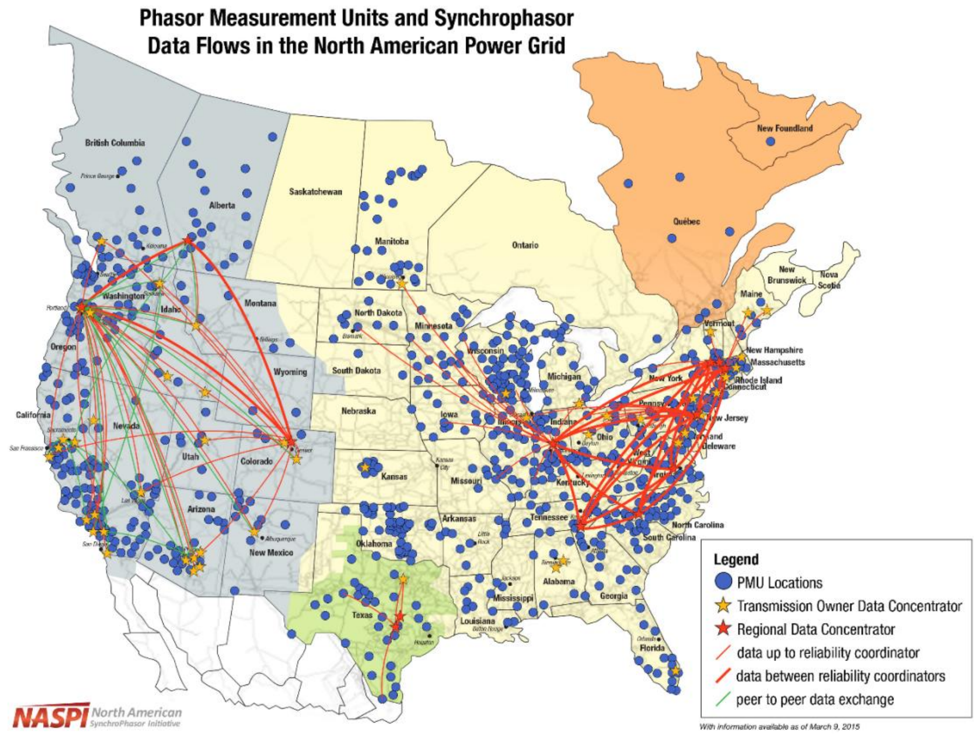

Figure 2. Map of PMUs with synchrophasor data flows in North America

An example of a synchrophasor system is shown in Figure 3. PMUs in the substations collect real-time data, usually from existing potential and current transformers. The PMUs are connected to a high-speed communications system to deliver the data to a phasor data concentrator (PDC). Typically, the local/corporate/regional PDCs performs a number of functions that reject bad data, and package the incoming data into sets based on the time-stamp. The data at the PDC are then relayed on a high-speed wide-area communications network to a higher-capability PDC (i.e. local to corporate or corporate to regional). PDCs typically feed the aggregated data received into a data archive, and to analytical applications such as wide-area visualization tools, state estimators, and alarm processors. The details of these installations can vary greatly, depending on the complexity and scale of the synchrophasor system, and application requirements dictate the rigor of system redundancy, cyber security, and other implementation details. A Synchrophasor Start Kit is being developed by NASPI (North American SynchroPhasor Initiative) to mainstream synchrophasor technology, making it easier for entities to adopt or improve projects.[4]

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[4] Alison Silverstein, Synchrophasor Technology and ERCOT, http://www.texasre.org/Lists/Calendar/Attachments/799/BOD%20Materials%2025AUG2015.pdf.

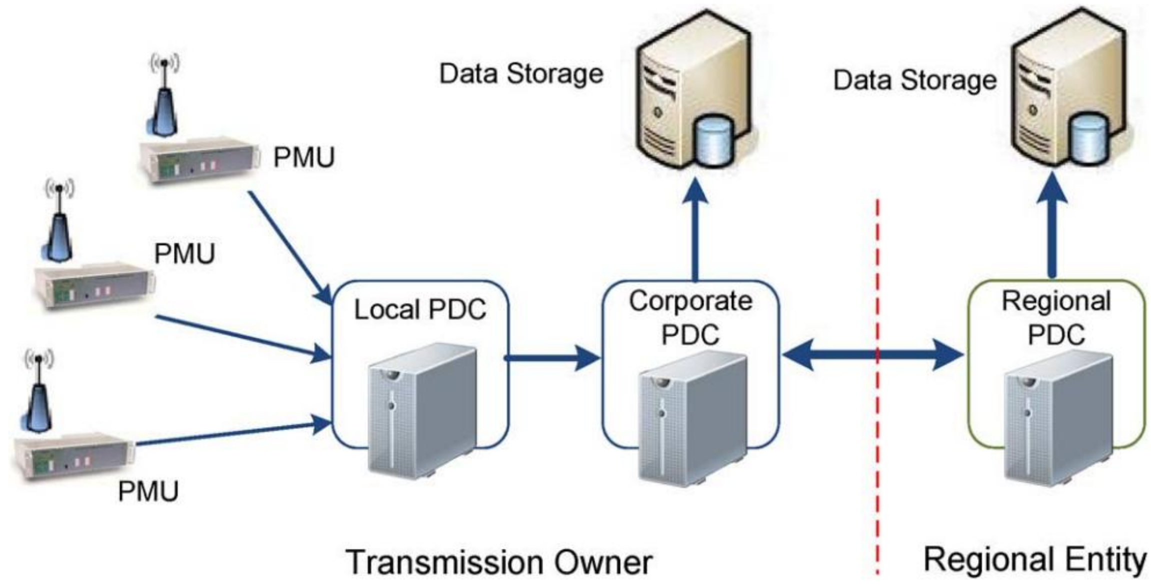

Figure 3. Typical Phasor Measurement System[5]

Today PMUs are deployed primarily in the transmission system, but the industry is beginning to explore the use of PMUs at the distribution level for power quality, demand response, microgrid operation, distributed generation integration, and enhanced distribution system visibility.[6]

Norway

Figure 4 indicates the current and immediately planned deployment of PMUs in the Norwegian transmission grid by Statnett (the Norwegian TSO), now ranging from the Russian border in the north to the southern point with the HVDC interconnections to Denmark.

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[5] Martin, K.E.; Brunello, G.; Adamiak, M.G.; Antonova, G.; Begovic, M.; Benmouyal, G.; Bui, P.D.; Falk, H.; Gharpure, V.; Goldstein, A.; Hu, Y.; Huntley, C.; Kase, T.; Kezunovic, M.; Kulshrestha, A.; Lu, Y.; Midence, R.; Murphy, J.; Patel, M.; Rahmatian, F.; Skendzic, V.; Vandiver, B.; Zahid, A., "An Overview of the IEEE Standard C37.118.2—Synchrophasor Data Transfer for Power Systems," in Smart Grid, IEEE Transactions on , vol.5, no.4, pp.1980-1984, July 2014.

[6] Synchrophasor Technology Fact Sheet, NASPI, https://www.naspi.org/File.aspx?fileID=1326.

Figure 4. Installed (green) and immediately planned (red) PMUs in the Norwegian transmission grid.

Until recently, the deployment and use of PMUs were mainly done and organized through R&D activities. Now, the responsibility for deployment has been taken over by the IT division, meaning that PMUs are becoming part of the grid information infrastructure for system operations. The use of synchrophasor information has gradually increased over the last few years.

The first real use of synchrophasor measurements was by the grid analysis team for model validation purposes, and it is increasingly used for disturbance and fault analysis.

Operators in the control centers have until now been reluctant to accept and apply new application based on synchrophasor information. However, a pilot project is planned in order to introduce sample applications in the control room environment, such as power oscillation and voltage instability monitoring.

R&D activities are carried out in parallel with deployment of PMUs and the related development of communication infrastructure. One example is the real-life testing of a static VAR compensator unit equipped with a power oscillation damper control using synchrophasor measurements (voltage angle difference) as input.[7] On-going research is focusing on development of new applications in monitoring and control. Successful deployment of synchrophasor applications requires a close dialog between researchers/developers and users. Therefore, a main objective in the Nordic R&D project STRONgrid has been to establish a research platform comprised by a power systems emulator (software and hardware labs),[8] PMUs, PDCs and software interfaces allowing easy application development and testing.

Maturity Model for Synchrophasor Deployment

Since synchrophasor technology is still early in its deployment, it is useful to articulate some ideas about what a mature technology deployment would look like as it evolves to support the goals of system operators. A synchrophasor maturity model has been drafted, and is available for review and comment.[9] The purpose of developing and using this maturity model is to help the electric power industry explain synchrophasor technology and articulate a roadmap detailing the steps required to achieve long-term technology maturity.

Applications

When the American Recovery and Reinvestment Act (ARRA) synchrophasor projects began in 2010, most of the synchrophasor analytics and applications available were research-grade and used principally in test mode. Most of the ARRA project funding recipients agreed to work with developers to install and test a few applications appropriate to the needs of each project. There was little expectation that the applications would grow into commercially available, production-grade capability over the grant period. However, between the combination of continued U.S. Department of Energy Research and Development funding, testing by many project partners, and market pull from the growing community of synchrophasor users, several key reliability applications are now operating in trusted roles for engineering support and real-time operations. Phasor data applications can be grouped into two categories: real-time applications and offline applications. This document reviews principal applications groups in each of these two categories. Table 1 shows how the various synchrophasor technology applications map to different types of benefits.

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[7] K. Uhlen, L. Vanfretti, M.M. de Oliveira, A. B. Leirbukt, V. H. Aarstrand, and J.O. Gjerde, "Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network," Invited Paper, Panel Session: "Synchrophasor Measurement Applications in Power Industry to Enhance Power System Reliability", IEEE PES General Meeting 2012.
[8] http://www.nordicenergy.org/wp-content/uploads/2015/11/STRONgrid.pdf

[9] Ryan Quint, Kyle Thomas, Alison Silverstein, Dmitry Kosterev, Synchrophasor Maturity Model. NASPI March 2015.

Table 1. Benefits of synchrophasor technology, by application[10]

	Increased system reliability	Increased Asset Utilization and Power System Efficiency	Increased Organizational Efficiency
Real Time			
Wide area visualization	✓		✓
Frequency stability monitoring and trending	✓		
Voltage monitoring and trending	✓		
Oscillation detection	✓		
Phase angle monitoring and trending	✓	✓	
Resource integration		✓	
Adaptive islanding and black-start capability	✓		
Event detection	✓		✓
Adaptive relaying	✓		
Power system stabilizer/oscillation damper	✓		
Automated protection	✓		
Off-Line			
Post-event analysis	✓		✓
Model validation	✓	✓	✓
State estimation	✓		

[10] Adapted from the Advancement of Synchrophasor Technology in Projects Funded by the American Recovery and Reinvestment Act of 2009, U.S. Department of Energy, Electricity Delivery and Energy Reliability.

2 Real-time Applications

Real-time applications are used to support grid operations by providing wide-area visualization and increased state awareness and response-based control applications that use wide area information to take automated control actions on the power system. Real-time applications require real-time data collection and processing with immediate analysis and visualization or used as control signals for real-time controls applications.[11]

Monitoring and Analysis

Most power system operators today have very little visibility into power system dynamics such as power oscillations, voltage stability indications, and system angular stress. Large-scale integration of renewable resources will present an additional challenge to the system operators, as large and fast power ramps by intermittent generators can dramatically shift generation patterns and operating conditions. Visibility of power system dynamics is becoming even more critical as the power system grows with inclusion of more variable resources with less offsetting machine inertia to stabilize the system.

Wide-Area Visualization

Although SCADA systems have traditionally enabled grid operators to observe conditions within their system limits, a network of PMUs grants visibility to operators, across an entire interconnection. This allows operators to understand grid conditions in real time, and diagnose and react to emerging problems. Analysts believe that synchrophasor-enabled visibility could have prevented the 2003 Northeast and the 1996 Western blackouts. As synchrophasor data quality improves, those data are being integrated into some existing control room visualization tools based on EMS and SCADA data, gaining acceptance for synchrophasor-enhanced wide-area monitoring.[12]

Wide-area monitoring and visualization systems are deployed to enable a more expansive view of the bulk transmission system, while revealing dynamic operating details. Observing the nature of grid disturbances earlier, and more precisely, helps grid operators quickly respond to disturbances and improve service reliability. Enhanced monitoring and diagnostic capabilities provide greater precision in daily operational decision making and improve overall system utilization and efficiency.[13]

RTDMS software, developed initially with funding from the U.S. Department of Energy, is a phasor data-based software platform used by grid operators, reliability coordinators, and planning and operations engineers for real-time wide-area visualization, monitoring and analysis

[11] Real-Time Application of Synchrophasors for Improving Reliability, NERC, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.
[12] Synchrophasor Technology Fact Sheet, NASPI, https://www.naspi.org/File.aspx?fileID=1326.
[13] PMU Deployment in the Carolinas with Communications System Modernization, Duke Energy Carolinas, LLC, https://www.smartgrid.gov/files/Duke-Energy-Carolinas-Project-Description.pdf.

of the power system. RTDMS offers a real-time dashboard with indicators of key grid metrics for situational awareness. The software can be used to identify, monitor and alarm for:

- Grid stress – phase angular separation
- Grid robustness – damping status and trend
- Dangerous oscillations – low damping and high mode energy
- Frequency instability – frequency variation across interconnection
- Voltage instability – low voltage zones and voltage sensitivities
- Reliability margin – “How far are we from the edge?”

RTDMS also archives event data for event and post-disturbance analysis. RTDMS is widely used in North American control rooms, but is not yet viewed as a commercially sustainable, production-grade reliability tool. At present, RTDMS only operates on phasor data and does not include other SCADA information, and it has no linkage to other power system study tools.[14]

Alstom T&D’s e-terravision™ is designed to help operators monitor, predict, anticipate and prevent potential problems that can lead to major power outages. E-terravision™ significantly improves transmission system operations and control by helping to eliminate reactionary decisions being made in control centers today.[15]

PowerWorld Retriever is a real-time visualization and analysis tool used in several control rooms around the USA and a few overseas. PowerWorld Retriever has the ability to simultaneously visualize related quantities such as voltage magnitude, phase angle, and angle differences (along with line flow, breaker status, or any other power system measurement or combination of measurements). Retriever also offers alarm management, animation and contour mapping.[16]

SEL’s *SynchroWave Central* is another real-time visualization tool commercially available.[17]

ABB has introduced PSGuard, a commercially available wide area monitoring system. PSGuard collects, stores, transmits and analyzes critical data from key points across the power networks and over large geographical areas. Its state-of-the-art portfolio of Wide Area Monitoring applications is designed to detect abnormal system conditions and evaluate large area disturbances in order to preserve system integrity and maintain acceptable power system performance.[18]

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[14] For more information, see RTDMS Tutorial, NASPI Training Package, available at https://www.naspi.org/File.aspx?fileID=623.

[15] For more information, see AREVA Activities related to SynchroPhasor Measurements, available at https://www.naspi.org/Badger/content/File/FileService.aspx?fileID=777.

[16] For more information, visit http://www.powerworld.com/products/retriever/synchrophasor-visualization.

[17] For more information, visit https://www.selinc.com/SEL-5078-2/

[18] PSGuard 2.1. Release Note, http://new.abb.com/substation-automation/systems/wide-area-monitoring-system/releases-updates/psguard-2-1-release-note, accessed 11/24/2015

Frequency Stability Monitoring and Trending

System frequency is the key indicator of the load-resource balance. The size of the frequency deviation is well correlated with the size of generation loss — Figure 5 shows an example of frequency response to a generation outage. System frequency is also a good indicator of integrity of an interconnection during system events involving separation or islanding — if a bus frequency in one part of the system stays at 60.5 Hz while frequency in another part of the system holds at 59.5 Hz for several minutes, it is a sure indication of the system separation. Looking at the bus frequencies across the entire interconnection lets the operator identify the islands and system separation points.

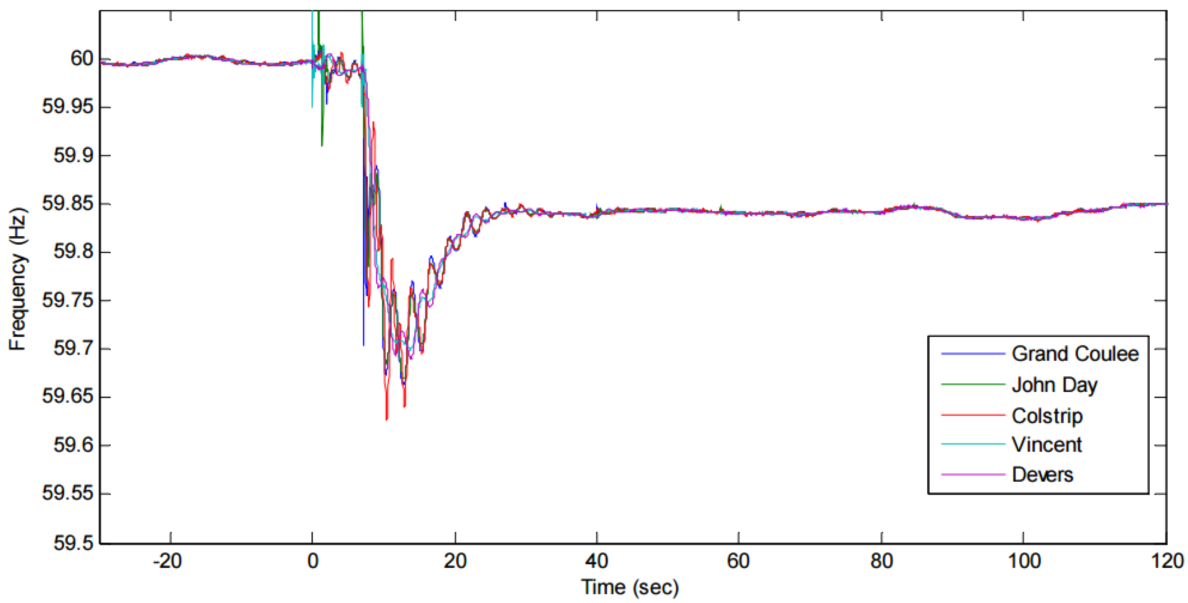

Figure 5. Western system frequency during a large generation outage on July 17, 2002

PMU frequency plots provide a good indication of the lost generation — as an example, a frequency drop of 0.1 Hz is typical in the WECC for 800 MW generation loss. Also, the propagation of the frequency drop can be used to identify where the generation drop occurred.

The Frequency Monitoring Network (FNET) is a wide-area frequency monitoring system currently maintained and operated by the Power IT Laboratory at the University of Tennessee. The system makes use of measurements taken by frequency disturbance recorders (FDRs) deployed across all three North American interconnections. Each FDR itself is actually a single-phase PMU in the sense that it measures the voltage phase angle, amplitude, and frequency from a single-phase voltage source. Frequency can provide information about generation electromechanical transients, generation demand dynamics, and system operations, such as load shedding, break reclosing, and capacitor bank switching. This allows frequency monitoring using FNET to be as informative at the distribution level as it is at the transmission level. Figure 6 illustrates the key components of the FNET system. Phasor measurements from the North

American power grids are collected by widely installed sensors, known as FDRs, and are transmitted via the Internet to a local client or remote data center. In most of the cases, FDR data are transmitted to the FNET data center for processing and long-term storage. FDRs differ from PMUs in that they are connected to the distribution network, typically on low voltage residential and commercial feeders.

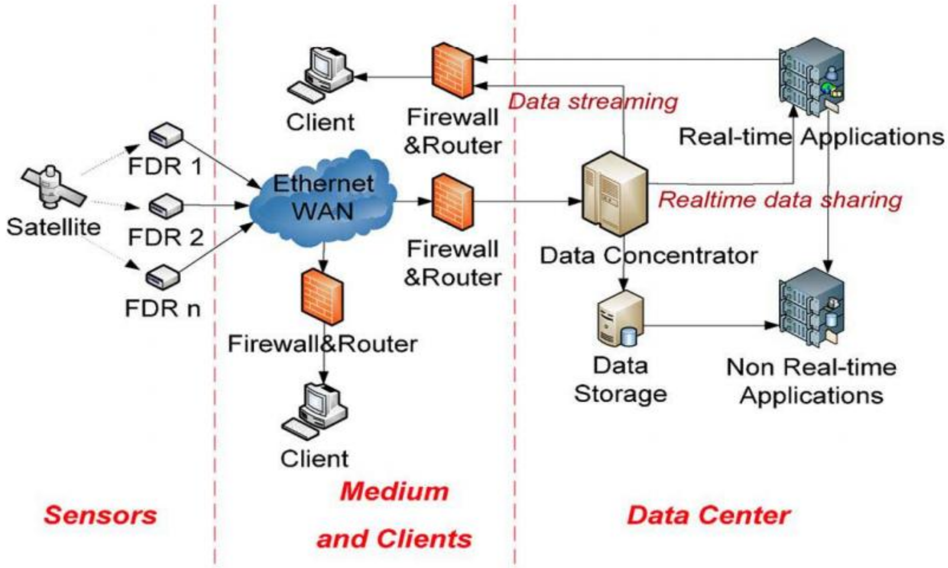

Figure 6. FNET System Structure[19]

Wide-area frequency trending is also one of the most straightforward applications, and has been implemented by many platforms, including BPA Stream Reader, SCE SMART®, and RTDMS. The Tennessee Valley Authority (TVA) and Electric Power Research Institute (EPRI) have been developing a tool called the Synchronous Frequency Measurement System (SFMS) to use synchrophasor data for wide-area visualization and disturbance location.[20]

State Estimation

Synchrophasor data are being used to improve state estimator algorithms for better understanding of real-time grid conditions. Where PMUs provide full coverage of the grid, direct measurement of the voltage magnitudes and phase angles provide what is termed a linear state estimator.

Snapshots of data from PMUs can be integrated into an orthogonal state estimator by feeding PMU measurements (e.g., voltage and current) directly into the state estimator measurement vector and the Jacobian matrix it uses to solve the network. Alternatively, a state estimator can use derived PMU measurements of voltage angle differences and branch factor angle

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[19] Y. Zhang, P.N. Markham, T. Xia, et al., Wide-Area Frequency Monitoring Network (FNET) Architecture and Applications, IEEE Transactions on Smart Grid, vol.1, no.2, pp.159-167, Sept. 2010.
[20] G. Zhang , Wide-Area Frequency Visualization Using Smart Client Technology, No. 1016207, Technical Update, Dec. 2007.

measurements, thus eliminating the requirement for synchronizing state estimator and PMU angle references. This approach enables the state estimator to calculate the network solution based on both PMU and conventional measurements simultaneously, with the advantage that the phasor data offer redundant system condition measurements and enable better solution accuracy. Synchrophasor technologies enable advances in state estimation both algorithmic and architectural. A comparison of different state estimation solutions is shown in Table 2.

Table 2. State Estimation Technology Summary[21]

SE	Uses PMU Data	Accuracy	Solution Speed	Technology Readiness Level
Traditional		Single phase, positive sequence models, time skewness	Iterative Solution	Commercial products
Linear		Phase angle measurements, time-tagged	Direct Solution	Ongoing demos
Hybrid		Limited, if any, improvements	Iterative Solution	Commercial products
Three-Phase		Captures system imbalances & asymmetries	Increases problem size	Few demos
Distributed		Facilitates use of detailed models	Reduces problem size	Few demos
Dynamic		Captures system dynamics – Numerically sensitive to model accuracy	Computationally challenging – increases problem size	Few demos, still in R&D level

Conventional state estimator inputs include MW, MVAR, kV and Amps; phasor data fed into a state estimator include voltage angles at buses and current angles at branches. All phasor data fed into the state estimator are obtained for a single point in time (e.g., one dataset is extracted from the PDC's phasor data flow every five minutes, since the state estimator solves at a far slower rate than PMUs sample). Multiple snapshots of PMU data taken at different times, representing different system loading and topology conditions, may be needed to fully test a PMU-integrated state estimator.[22]

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[21] Evangelos Farantatos, State Estimation Advancements Enabled by Synchrophasor Technology, NASPI.
[22] Real-Time Application of Synchrophasors for Improving Reliability, NERC, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.

Voltage Monitoring and Trending

Phasor systems can be used to monitor, predict and manage voltage on the bulk power system. One of the most promising near-term synchrophasor applications is for trending system voltages at key load center and bulk transmission busses.

Voltage trending and voltage instability prediction are highly desirable uses for synchrophasor systems and a high priority for phasor data applications. Many transmission systems are voltage stability-limited, and voltage collapse can happen very quickly if stability limits are reached. Voltage instability occurs when either: (a) the system has inadequate reactive reserves, or (b) the transmission system cannot deliver reactive power from the source to where it is needed. Monitoring bus voltages across the system using phasor measurements of voltage profile, voltage sensitivities, and MVAR margins allows operators to watch voltage levels in real-time, while a trending application would provide an early indication of voltage instability vulnerability.

Voltage trending visualization should remain “green” or stable as long as voltages stay within appropriate limits, but alert or alarm when voltage moves outside the limits. While long-term voltage trend duration (already provided by SCADA) is one hour, phasor measurements could be used to create short-term voltage trending (about one minute duration). A voltage display should have an intelligent pre-processor to recognize data drop-outs and prevent zero-voltage reports (as from a missing PMU) from causing false alarms.

Reactive reserve monitoring is a closely related tool. Low voltages are indicators of low reactive support. Synchronous generators (operating in voltage control mode), shunt capacitors and static Var compensators provide primary reactive power reserves in the system. Studies can determine the amount of reactive reserves needed in various parts of the system, and be used to set appropriate alarms when the reactive reserves are low. Corrective actions are needed to address reactive needs, such as deploying condensers, adding shunt capacitors, requesting additional reactive support from the generation fleet and reducing flows on transfer paths.

Reactive reserves measurement and operation are becoming more important with the growing penetration of intermittent generation. Additional synchrophasor measurements at wind farms are necessary to ensure that system operators know how much of reactive reserve is primary and how much is secondary, as well as deliverability of the reserves during a disturbance. The above methods should also be reviewed and applied in major load centers.[23]

Oscillation Detection

Synchronous power generators produce electric power at a fixed frequency. The frequency can be raised or lowered by a small amount depending on the variations in the connected load. If a sudden increase in load occurs, the turbine controller may not be able to respond fast enough and increase the turbine power. In this case, some energy is taken from the kinetic energy of the

[23] Real-Time Application of Synchrophasors for Improving Reliability, NERC, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.

generator-turbine system and is converted into power. This will reduce the rotational speed and consequently the electric frequency.[24] When groups of generators are operated together (synchronously) in a large power system, the response of each of them to load changes will not be the same. Some may slow down more than others. This causes groups of generators to oscillate against one another or for some generators to oscillate against the rest of the system. These small oscillations, if undamped or under-damped, can cause a loss of synchronization of several machines that can lead to a blackout of the power system.

Detection of power system oscillations and ambient grid damping are among the premier applications that require the high-speed data that PMUs provide and conventional SCADA does not. Low-frequency oscillations occur when an individual or group of generators swing against other generators operating synchronously in the same system, caused by power transfers and high-speed, automatic turbine controls attempting to maintain an exact frequency. Low frequency oscillations are common in most power systems due to either power swings or faults; undamped oscillations can swing out of control and cause a blackout (such as the Western Interconnection event on August 10, 1996). Small-signal oscillations appear to have been increasing in the Eastern and Western interconnections, causing an urgent need to better understand the problem, detect when oscillations are occurring, and find ways to improve oscillation damping and implement system protections against collapse.

Synchrophasor data (bus frequency, angles, line loading and voltage) are critical to detect potential and actual oscillations within the bulk power system. Inter-area oscillations can be seen by examining bus voltages and frequencies, so most methods of oscillation detection are applied to the path or flowgate. Oscillation detection methods calculate the damping of a ringdown during a system disturbance. The energy of power oscillations indicates whether an oscillation is growing or dissipating. A build-up in energy signals growing oscillatory activity, and can alert an operator to check other indicators.

There are two distinct tools for identifying power oscillations:

- Oscillation detection — tools that calculate damping after a disturbance occurred. This is done in several seconds when oscillations are large in magnitude.
- Mode meters — tools that estimate damping from ambient noise data. These methods extract intelligence from small-signal oscillations from minutes of ambient noise. Mode meters are particularly useful for operations since they can provide early detection of damping issues in the system.

Montana Tech, University of Wyoming, and Pacific Northwest National Laboratory have worked closely with BPA and DOE to develop “Mode Meter” algorithms based on wide-area PMU measurements. Mode meter is a powerful method for monitoring the small signal stability properties of a power system in real-time, giving operators essential information regarding the

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[24] Rogers, G. Introduction, in, Power System Oscillations, Springer Science + Business Media LLC, New York, 2006 pp. 2-4.

health of the power system and allowing them to take preventive actions when needed. The developed algorithms have been evaluated with simulation data and validated with field measurement data. It has been demonstrated that the mode meter can identify the oscillation modes that caused the breakup in the Western Interconnection in the United States in 1996 (see Figure 7 below) and could have issued an early warning on the lightly damped mode. Current efforts have been focused on model and data validation and performance evaluation to reduce false alarms and missing alarms. It is worth noting that the best performing signals for oscillation damping estimation are relative frequencies on both sides of an oscillatory mode, which requires synchronized wide-area measurements.[25]

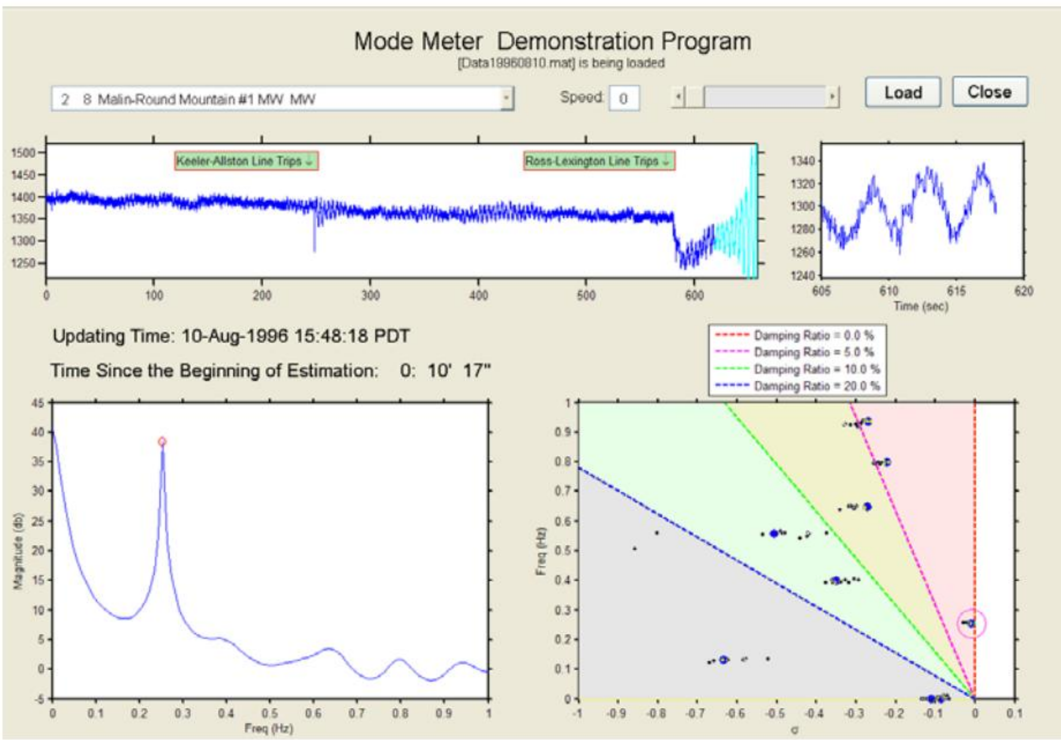

Figure 7. A prototype screen of a mode meter: top left — time plot of a critical signal; bottom left — spectral energy; bottom right — oscillation frequencies and damping, alarm lines included

Phase Angle Monitoring and Trending

Studies of disturbances have shown that relative phase angles in the West strongly correlate with overall system stress and the system susceptibility to inter-area oscillations. Analyses in both east and west indicate that the rate of change of the phase angle difference is an important indicator of growing system stress; fast phase angle rate of change was a precursor for the United States 2003 Northeast blackout and the 2008 Florida blackout, so this can be used as the basis for

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[25] Real-Time Application of Synchrophasors for Improving Reliability, NERC, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.

operator alarms. One goal for a phasor data situational awareness and trending tool is to have it trend phase angles against phase angle limits, to warn operators when system stress is increasing. Such a tool should offer operator intelligence, so that when phase angles exceed critical limits, operators are given options such as increasing or activating reactive power reserves, inserting series capacitors, or modifying path flows.

Almost every ARRA synchrophasor project is using phase angle monitoring as part of its applications:

- FP&L uses PMUs to monitor phase angles directly when switching transmission lines, with operators seeing the angles via enhanced graphical and dynamic displays. Traditionally, FP&L calculated these system phase angles using their state estimator, producing lower accuracy and time resolution.
- WECC uses PMU data to monitor phase angle differences between the ends of four major transmission paths. The data are compared with the 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 restoration needed. BPA has an operating procedure based on this application.
- PMU-based phase angle monitoring enabled WECC to accelerate the reclosing of an important tie line between the Desert Southwest and Southern California.[26] Because significant standing angle separation with this line open has been an issue in the past, standard operating procedures included confirmation of the relative phase angles of the two 500 kV buses and an option to increase generation output in the Imperial Valley area to reduce the angle difference between them and avoid potential equipment damage. In this instance, the CAISO used data from Arizona Public Service's PMU at North Gila and San Diego Gas and Electric's PMU at Imperial Valley (the two ends of the tie-line). These measurements indicated that phase angle separation was well within the limit for successful reclosing, so operators reclosed the line successfully without any delay or unnecessary generation dispatch.

Resource Integration

Phasor measurement systems with real-time data are expected to be particularly useful for better monitoring, managing and integrating power plants into the bulk power system. Integration challenges include how to identify and respond to the variability of renewable and distributed generation. The ARRA projects undertaken by WECC, ERCOT, MISO and PJM have targeted resource integration as a particular technical goal.

Because many renewable technologies are intermittent and highly variable, real-time PMU-based monitoring can improve regulation and load-following using dispatchable conventional generation, storage and demand-side resources. PMUs installed at wind generation collector

[26] Peak Reliability (formerly part of the Western Electricity Coordinating Council), Western Interconnection Synchrophasor Program, Smart Grid Investment Grant, Final Project Description.

points can provide instantaneous data to the system operator. This can help in acquiring generation resources that can be ramped up or down, to meet the energy balance requirements, taking into consideration the wind variability. The California ISO and ERCOT plan to use phasor data for better monitoring of variable generation in real-time and integrate renewable resources economically while maintaining bulk power system reliability. This application is still in a conceptual stage and will require R&D efforts.

Intermittent generation such as wind and solar generally reduce the overall inertia of the interconnected system. This degrades the governing frequency response and alters the modal frequency behavior of the interconnected system, and could adversely impact the grid's transient stability performance. High-speed PMU-based monitoring provides operators better situational awareness and visualization of actual variable output and its effects (along with all other resources) on the bulk power system, and thus allows better grid management and responsiveness. Over time, phasor data could be used for automated control of physical system actions, including generator balancing energy and reactive power production, demand response and storage, and for intelligent protection and operations and maintenance decision support to effectively manage and maintain generation-load balance.

One key to renewables integration is improving prediction of intermittent generation and understanding how individual plants and fleets of generators perform. Phasor data offer better location- and time-specific datasets on technology and plant performance over time, and thus can be used to improve generation prediction and turbine and plant performance models, as well as to improve modelers' understanding of how these resources affect the interconnected grid.[27]

Adaptive Islanding and Black-Start Restoration

PMU data can be used to monitor and manage system islanding and black-start restoration. The islanding of the electric power system in a controlled manner instead of the spontaneous islanding that usually occurs during a wide area disturbance has significant advantages due to the fact that it allows the creation of an island where it is possible to balance the available generation with the important loads. In the best case scenario it should be possible to balance the generation and the loads by properly selecting the locations in the system where the islanding should be executed. The synchrophasor data from multiple locations in the electric power system can be used to calculate the overall load/generation balance in different possible islands in the system.[28]

PMU measurements of the system are also useful in the black-start restoration. Starting generation units without using power from the bulk grid is called a black-start. A black-start plan normally involves energizing the system from a few generators at strategic positions in the grid,

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[27] Real-Time Application of Synchrophasors for Improving Reliability, NERC, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.

[28] Use Of Synchrophasor Measurements In Protective Relaying Applications, Power System Relaying Committee, Report of Working Group C-14 of the System Protection Subcommittee.

then re-energizing the network islands around the generators and finally reconnecting the islands.[29]

There are several ways in which synchrophasor data can provide value during islanding events and black-start restoration:

- Detecting System Islanding Events – real-time synchrophasor data may be used to identify conditions where frequency and voltage angle changes are not in synchronism across the system indicating that an islanding event may have occurred.
- Analyzing Cause and Resulting System Conditions – since synchrophasor data are time-stamped, synchronized and sampled at a much higher rate than SCADA data, it can be used quickly to determine the sequence of events and identify possible causes. This highly precise, time-specific information can prove extremely useful during restoration events and, depending on the nature and severity of the event, may allow the operator to isolate failed Facilities and return the system to a reliable state more quickly than might be possible using SCADA data alone.
- Returning the System within Acceptable Parameters – following a major Disturbance, operations personnel must assess the status of generation and transmission facilities that remain energized to determine if unacceptable operating conditions exist. Failing to stabilize portions of the system that remain operational may result in significant equipment damage and widespread outages. Synchrophasor data can be used to quickly assess post-event conditions and determine risk. Specifically, this data may be used to detect and address power system oscillations and voltage instability.
- Determining Restoration Activities – when a reliability coordinator and transmission operators implement their respective restoration plans, they must ensure their activities to restore shut down areas to service and parallel electrical islands to the main grid are coordinated and do not jeopardize the overall objective of returning the system to a reliable state. Synchrophasor data can be used to more accurately assess the impact such actions may have to system voltage and frequency. The use of this data to detect power system oscillations and potential voltage stability issues resulting from restoration activities may also prove useful.[30]

Salt River Project (SRP) used synchrophasors not only to provide system visualization over traditional SCADA during black-start testing, but also as a synchroscope to connect the SRP and WECC systems.

For the purposes of the black-start testing, SRP islanded from WECC at a 230 kV bus. SRP had two black-start goals: synchronize the thermal and hydro units and synchronize the SRP and WECC systems. During synchronization of the thermal and hydro units, SRP used synchrophasors to monitor frequency and slip differences between the systems to verify when to

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[29] Savu C. Savulescu, Real-Time Stability in Power Systems, 2nd Edition.
[30] Using Synchrophasor Data During System Islanding events and blackstart Restoration, NASPI, June 2015.

connect them. With both the hydro and thermal units online, the synchrophasor visualization software monitored the phase-angle difference. They used the synchrophasor data to verify that the systems were connected and within phase-angle-difference tolerances. With both systems connected, they observed improved frequency stability. Before connecting the hydro and thermal units, SRP observed about 150 mHz of frequency deviation. After connecting the hydro and thermal units, they observed only about 50 mHz of deviation.

The next test was to synchronize their system with the WECC system. During this test, the automatic synchronizer was not operational. The operator used synchrophasor visualization software to view the angle separation and slip between the two systems and manually close the tie breaker. SRP's synchrophasor relays provide two distinct advantages over their previous system: multiple measurement sources and higher update rates.

By installing a Phasor Data Concentrator (PDC), the synchronization process can be completely automated. Further, relays with synchrophasor capabilities throughout the power system, coupled to the PDC, can allow synchronization at any point in the system without additional, stand-alone synchronization devices.[31]

Control

Wide-area synchronized measurements enable unprecedented opportunities for wide-area stability control applications. Wide-area measurements provide much greater observability of the system state, thereby leading to better and faster decisions. Since PMU measurements are instantaneous and have high resolution, phasor data can be used to activate local or centralized control of corrective measures for angular stability, voltage stability, low-frequency oscillations and thermal constraints. Synchrophasor technology can also help in moving from a localized control concept to a coordinated, centralized, wide-area control concept.[32]

Currently there is an industry confidence gap between using synchrophasor tools for specific off-line applications such as model validation and event analysis, which entail some degree of hands-on user involvement, and willingness to use synchrophasor tools for mission-critical applications such as real-time operator decision support tools or automated, PMU-triggered controls operations. Industry members will not be ready to trust these applications until appropriate hurdles such as user testing and experience, cyber security and rock-solid applications performance and data quality have been assured.

Before synchrophasor tools can be accepted for mission-critical control room uses, industry will have to resolve two challenges that are much larger than the electric sector:

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[31] Peak Reliability (formerly part of the Western Electricity Coordinating Council), Western Interconnection Synchrophasor Program, Smart Grid Investment Grant, Final Project Description.
[32] Real-Time Application of Synchrophasors for Improving Reliability, NERC, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.

- how to maintain the cyber security of synchrophasor data, communications networks and applications
- how to assure that multiple points along the synchrophasor time-stamping chain have redundant sources for universal time, so they don't need to rely only upon the satellite GPS system and local antennas for accurate, synchronized timing.

Adaptive Relaying

Conventional protective systems respond to faults or abnormal events in a fixed, predetermined manner. Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection function settings automatically, in order to make them more attuned to prevailing power system conditions. Using synchronized phasor measurements, certain relays and protection schemes could be made to adapt to changing system conditions, thereby enhancing their performance.

The application of PMU measurements for adaptive protection has been researched and investigated, such as out-of-step relays, line relays, better balance between security and dependability depending on system conditions, and reclosing. A promising application of using PMUs is in accurate measurement of line impedance for fault-locating applications. The line impedance is a key input for accurate fault location. PMUs could be used for direct fault calculation using data from both ends of the transmission line. Inaccurate fault location can lengthen the diagnosis and restoration process.[33]

Out-of-step relays are designed to detect electromechanical transients and also make tripping and blocking decisions. Traditional out-of-step relays often fail to determine whether an evolving electromechanical swing is stable or not, because the conditions and topologies assumed when the relay characteristics are determined become out-of-date rather quickly, and in reality the electromechanical swings that do occur are quite different from those studied when the relays are set. On the other hand, wide-area measurements of positive sequence voltages at networks (and hence swing angles) provide a direct path to determining stability using real-time data instead of using pre-calculated relay settings. A related approach was developed for a field trial at the Florida–Georgia interface model.[34,35,36] In order to take appropriate control action it is essential that a reliable prediction algorithm is developed which provides the stable–unstable classification of an evolving swing in a reasonable time. It has been found that in a majority of cases the prediction can be accomplished in about 250 ms after the start of the event, which is a similar time-frame as observed in the Florida–Georgia interface problem.

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[33] Benefits of PMU Technology for Various Applications, 7th symposium on Power System Management, International Council on Large Electric Systems – Cigre Croatian National Committee.
[34] V. Centeno, A. G. Phadke, A. Edris, J. Benton, M. Gaudi, and G. Michel, "An adaptive out-of-step relay [for power system protection],"IEEE Trans. Power Del., vol. 12, no. 1, pp. 61–71, Jan. 1997.
[35] V. Centeno, A. G. Phadke, and A. Edris, "Adaptive out-of-step relay with phasor measurement," in Proc. 6th Int. Conf. Developments in Power Syst. Protection, Mar. 25–27, 1997, pp. 210–213, Conf. Publ. No. 434.
[36] V. Centeno, A. G. Phadke, A. Edris, J. Benton, and G. Michel, "An adaptive out-of-step relay," IEEE Power Eng. Rev., vol. 17, no. 1, pp. 39–40, Jan. 1997.

The existing protection systems with their multiple zones of protection and redundant systems are biased toward dependability over security, i.e., a fault is always cleared by some relay. The result is a system that virtually always clears the fault but as a consequence permits larger numbers of false trips. An attractive solution is to “adapt” the security—dependability balance in response to changing system conditions as determined by real-time phasor measurements. With three primary digital protection systems it is possible to implement an adaptive security–dependability scheme by using voting logic (see Figure 8). A more secure decision would be made by requiring that two of the three relays see a fault before the trip signal is sent to the breaker. The advantage of the adaptive voting scheme is that the actual relays are not modified but only the tripping logic responds to system conditions.[37]

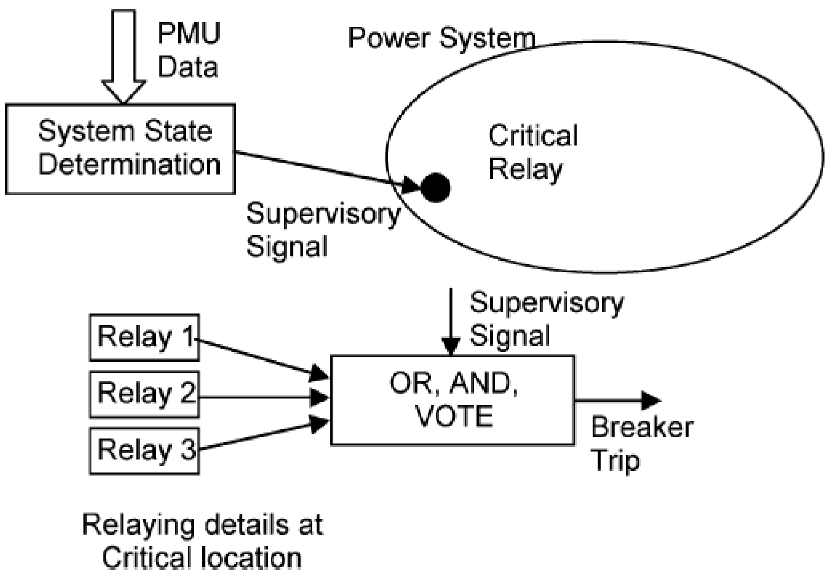

Figure 8. Adjustment of dependability–security balance under stressed system conditions

Power System Stabilizer/ Power Oscillation Damper

With the increased loading of long transmission lines, transient and dynamic stability after a major fault are increasingly important, and they can become a transmission power-limiting factor. Stressed operating conditions can increase the possibility of inter-area oscillations between different control areas and even breakup the system. Power system oscillation damping has always been a major concern for the reliable operation of power systems. To increase damping, several approaches have been proposed; the most common ones being excitation control through Power System Stabilizers (PSS) and/or supplementary damping control of HVDC, SVCs and other FACTS devices. PSSs augment the power system stability limit and

[37] Jaime De La Ree, Virgilio Centeno, James S. Thorp,A. G. Phadke, Synchronized Phasor Measurement Applications in Power Systems, IEEE Transactions On Smart Grid, VOL. 1, NO. 1, June 2010.

extend the power-transfer capability by enhancing the system damping of low-frequency oscillations associated with the electromechanical modes.[38]

PSS with local inputs can damp the system oscillations but may not be very efficient due to the lack of observability in local measurements of certain inter-area modes. The synchronized phasors over wide area, which have implication to the stability, can be measured by using PMUs. The inclusion of PMU as additional and remote inputs in feedback control loop for PSS, allows a global vision of the network, thus better dynamic performance for wide-areas can be achieved. In the area of large-scale power systems, inter-area response (i.e., power flowing between distant points, energy-balance at distant generators) may be more effectively damped through the use of wide-area measurements.[39]

The most important open question is if the current design methods can properly deal with new signals available from PMUs and how to adequately implement those signals in closed-loop feedback. PSSs should be designed to cover damping over a wide range of modes with high robustness and, in addition, the effect of time delays needs to be taken into account. Because time delays bring about a phase lag which can affect the control performance and interactions among system dynamics, it must be considered in the model design process. In WAMS, the important delay period is between the measurement and the controller input signal arrival, which is around 0.5-1.0 s.[40] The total time delay in the control loop in China Southern Power Grid (CSG)'s wide-area damping control system (WADC) is about 110 ms, of which 40 ms is from the PMU's data processing.[41] Adaptive wide area control system (WACS) designed to include transmission delays from 0 to 1.4 s is also studied.[42,43]

Due to the frequent and long-distance power transfers in Northern Europe, the Nordic grid is at times limited by stability constraints related to poor damping of inter-area oscillations particularly during high power exports from Norway and Finland into Sweden. Statnett SF, the Norwegian transmission system operator, has worked since 2005 in the development, implementation and deployment of an integrated Wide-Area Monitoring System (WAMS), which can be used to continuously monitor power oscillations and alarm operators when they reach undesirable levels. To further improve system damping, and thereby increase power transfer capabilities, Statnett has made efforts in the design, the implementation and testing of

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[38] H. Ping, Y. W. Kewen, T. Chitong, B. Xiaoyan, Studies of the improvement of probabilistic PSSs by using the single neuron model, Electrical Power and Energy Systems, Vol. 29, 2007, pp. 217-221.
[39] Chandrasekar Samudi, Kusumakumari.P, Power System Stabilizer Design Using Local and Global signals.
[40] B. Chaudhuri, R. Majumder, and B. Pal, "Wide-Area Measurement-based stabilizing control of power system considering signal transmission delay," IEEE Trans. Power Syst., vol. 19, no. 4, pp. 1971–1979, November 2004.
[41] L. Peng, W. Xiaochen, L. Chao, S. Jinghai, H. Jiong, H. Jingbo, Z. Yong, and X. Aidong, "Implementation of CSG's wide-area damping control system: Overview and experience," IEEE/PES Power Systems Conference and Exposition, 2009.
[42] N. Chaudhuri, S. Ray, R. Majumder, and B. Chaudhuri, "A new approach to continuous latency compensation with adaptive phasor Power Oscillation Damping controller (POD)," IEEE Trans. Power Syst., vol. 25, no. 2, pp. 939–946, May 2010.
[43] J. W. Stahlhut, T. J. Browne, G. T. Heydt, and V. Vittal, "Latency viewed as a stochastic process and its impact on wide area power system control signals," IEEE Trans. Power Syst., vol. 23, no. 1, pp. 84–91, February 2008.

Wide-Area Control Systems (WACS) for Wide-Area Power Oscillation Damping. The test results show that potential flexibility of the Wide-Area Power Oscillation Damper (WAPOD) to choose, among the different PMU signals, those that have the good observability of inter-area modes can be an advantage to the use of local feedback signals for damping control, as it is current practice today.[44]

Automated Protection

More advanced applications use PMU data as an input to Special Protection Systems (SPS) or Remedial Action Schemes (RAS) and can trigger automated equipment controls. Some SPS may also be called Remedial Action Schemes although RAS tend to address less drastic emergency conditions.

The current applications of wide-area measurement (not necessarily synchrophasors) for load shedding exist as System Integrity Protection Schemes (SIPS) used synonymously with Remedial Action Schemes (RAS) and Special Protection Schemes (SPS). According to the NERC Glossary of Terms Used in Reliability Standards, such schemes are "designed to detect abnormal system conditions and take pre-planned, corrective action (other than the isolation of faulted elements) to provide acceptable system performance".[45] This definition specifically excludes the performance of protective systems to detect faults or remove faulted elements. It is system oriented both in its inception and in its corrective action. Such action includes, among others, changes in demand (e.g. load shedding), changes in generation or system configuration to maintain system stability or integrity, and specific actions to maintain or restore acceptable voltage levels.

Such schemes involve measurements over a large part of the system, typically of relay operations, voltage magnitudes, and power flows. These inputs are used to identify crucial outages of a transmission and/or generation component. Such outages are pre-identified based on contingency analysis. The scheme then takes pre-determined actions like generation rejection, load shedding, switching on/off reactive support and other actions. Around 11% of these schemes employ load shedding as a mitigating measure.[46]

Bonneville Power Administration (BPA), in collaboration with Washington State University, is in the process of implementing a Wide Area Stability and Voltage Control System (WACS) that employs sensors that react to the response of the power system to arbitrary disturbances.[47] Voltage magnitudes from several 500 kV stations and the reactive power output from several generators are measured at strategic locations, and the inbuilt algorithms provide commands for

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[44] K. Uhlen, A. B. Leirbukt, Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network, IEEE Power and Energy Society General Meeting, 2012.
[45] NERC Glossary of Terms Used in Reliability Standards, April 20, 2009.
[46] Wide Area Protection and Emergency Control" Power System Relaying Committee Working Group C6 Report, http://www.pespsrc.org/Reports/Wide%20Area%20Protection%20and%20Emergency%20Control_2002.zip.
[47] C.W. Taylor, D.C. Erickson, K.E. Martin, R.E. Wilson, and V. Venkatasubramanian, WACS Wide-area stability and voltage control system: R&D and online demonstration, Proceedings of the IEEE, Vol.93, No.5, pp. 892-906, May 2005.

remedial actions that are similar to those of SPS (including load shedding), but not predetermined.[48]

[48] Use Of Synchrophasor Measurements In Protective Relaying Applications, Power System Relaying Committee, Report of Working Group C-14 of the System Protection Subcommittee.

3 Off-line Applications

Reliability starts with good planning. Offline applications are to improve system planning and analysis, including power system performance baselining, event analysis and model validation. Offline applications use archived data and may be conducted off-line days or months after the data were collected. Availability and analysis of synchronized phasor measurements should improve understanding of power system performance and improve models used in power system studies. Ultimately these should produce better decisions on capital investment and more effective utilization of the transmission system.

Post Event Analysis

Post event analysis enables power system engineers and grid operators to analyze disturbances and large-scale system events, providing better understanding of their causes. This information also supports continual improvements to system models and operations.

Phasor data are invaluable for post-event analysis of disturbances and blackouts. Since synchrophasor data are time-stamped, it can be used to quickly determine the sequence of events in a grid disturbance, and facilitate better model analysis and reconstruction of the disturbance. These enable a faster and deeper understanding of the disturbance causes and inform development of ways to avert such events in the future.[49]

Synchronized wide-area data are essential for disturbance analysis, as evidenced by the August 14, 2003 blackout investigation in the Eastern Interconnection in the United States. Data synchronization is critical for the sequence of event reconstruction, particularly for complex events where many switchings occur in short time frame. The data required for event analysis includes:

- bus voltages, angles and frequencies at key transmission substation
- power flow on key transmission paths and flowgates
- active and reactive power output, voltage and frequency of major power plants
- active and reactive power output, voltage and frequency of major controlled elements, such as HVDC systems and SVCs
- active and reactive power, voltage and frequency of several loads in a major load center
- status of circuit breakers.

[49] Synchrophasor Technology Fact Sheet, NASPI, https://www.naspi.org/File.aspx?fileID=1326.

The infrastructure being deployed by the various SGIG (Smart Grid Investment Grant) projects will greatly enhance event analysis capabilities for future disturbances.[50]

Model Validation

Good dynamic models allow a better understanding of how power systems respond to grid disturbances; better prediction enables better system planning with better grid and financial asset utilization. Synchrophasor data are particularly useful for validating and calibrating models of power plants, FACTS devices and other grid equipment, letting generators and grid operators comply with North American modeling standards with better results at lower cost. These data are also being used to improve system models, calibrating state estimators and dynamic system models and simulations. The Western Interconnection of North America has been a leader in using synchrophasor data for planning applications.[51]

With the widespread deployment of PMUs, the data they produce can be used to improve and validate power system models. Model validation represents the process of comparing model predictions to a trusted source, such as PMU measurements of actual system events, and comparing the results. If the difference between the two responses is within acceptable margins, then the model is deemed valid and it can be used for the appropriate application. But if the difference is outside some acceptable range, then the model is deemed inaccurate and it must be corrected. Once a model is validated, it may require periodic calibration to fine-tune the parameters within the model to reduce error. Calibration uses a known reference to adjust the model's parameters to accurately predict known outcomes in response to actual operating conditions and disturbances.

The primary benefits of using PMU data for model validation and calibration include the following:

- PMU data contain real operating ranges and operational relationships among grid assets more accurately than stand-alone testing of individual physical assets. This produces better models of grid assets and their interactions, which improve overall system reliability.
- Models validated and calibrated using PMU data improve asset and system efficiency by setting more accurate operating limits for grid assets, which may enhance asset utilization.
- Once a good model is developed, engineers can use PMU data with the model to detect equipment mis-operations and predict failures, enabling better asset maintenance. This may prevent more substantial equipment damage and could potentially have safety benefits.

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[50] Real-Time Application of Synchrophasors for Improving Reliability, NERC, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf.
[51] Synchrophasor Technology Fact Sheet, NASPI, https://www.naspi.org/File.aspx?fileID=1326.

- Synchrophasor-based model validation and calibration methods are more economical, timely, and accurate than validation methods that take a generator offline for performance testing. Validation and calibration using PMU data enable the asset owner to continue operating the plant and realizing revenue without stopping operations to conduct testing for model validation purposes. Success stories of using disturbance data to complement the baseline model development and calibration have been documented.[52, 53]
- Synchrophasor-based model validation and calibration are an accepted and cost-effective way to satisfy the requirements of NERC Reliability Standards MOD-26, MOD-27, MOD-32, and MOD-33 to verify generator active and reactive power capability and control systems, and to assure their appropriate responses during system disturbances.[54]
- At the resource planning timescale, accurate models help transmission owners and system planners identify and invest in the correct amounts and types of grid and generation equipment.

The benefits of synchrophasor-based model validation listed above provide power system asset owners and operators many advantages over traditional offline generator testing. These include the ability to meet the NERC Standards, and potentially to operate the grid in a more reliable and efficient manner. Already, several grid operators mandate PMU placement at generator interconnections so that data can be used to validate generator and system models.

PMUs at or near a power plant perform continuous high-speed monitoring that records the plant's response to actual transmission-level grid disturbances, such as generator losses, faults, or breaker operations. The PMU data capture a much wider range of plant responses than would be examined in formal physical plant testing. Furthermore, while physical testing is costly and may only be conducted every 5 years, an owner with access to PMU data can review asset performance and recalibrate the model—or spot mis-operations or erroneous settings—much more frequently. PMU disturbance recordings and automated model validation tools enable continuous, ongoing model validation and recalibration after every grid disturbance.[55]

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[52] Overholt, P., et al. 2014. Improving Reliability Through Better Models. IEEE Power & Energy Magazine, 2014 (May/June).
[53] Huitt, C., D. Kosterev, and J. Undrill. Dynamic Monitoring is Cost Effective for TransAlta, BPA. Electric Light and Power, 82-07 (November/December): p. 52.
[54] FERC. 2014. Generator Verification Reliability Standards, 18 CFR Part 40 [Docket No. RM13-16-000, Order No. 796]. Federal Energy Regulatory Commission: Washington, D.C. Available at http://www.ferc.gov/whats-new/comm-meet/2014/032014/E-4.pdf.
[55] Model Validation Using Phasor Measurement Unit Data, NASPI Technical Report, March 20, 2015.

4 Timing Sources, Communications, and Cyber Security

Synchrophasors use a high-precision common time source that provides 100-nanosecond accuracy at each measurement location. This allows the measurement of power system quantities at different locations across a wide-area system at the same instant in time. Since these data are measured contemporaneously with a common time reference, the measurements can be compared directly, without the need for complex algorithms. The system state is measured, allowing for better-informed decisions regarding how to operate the electric power system.

Electronic communication is an important component of almost all synchrophasor implementations and brings associated concerns about cyber security. Common concerns include new communications links opening the way for cyber-attacks on existing systems or on the new synchrophasor system itself. Because most of the power system is monitored and controlled electronically, a successful cyber-attack could cause great physical and financial damage. Therefore, it is essential that cyber security risks are carefully analyzed and mitigated.[56]

Timing Sources

Synchrophasor measurements require a precise, absolute time reference. The IEEE C37.118-2005 synchrophasor standard mandates a clock accuracy better than one microsecond. This is to ensure that the Total Vector Error (TVE) measured by a phasor measurement unit (PMU) is less than one percent. A figure of merit has been considered in assessing the performances of the synchronization source technologies: accuracy, integrity, availability, continuity and coverage.[57] The main synchronization sources adopted for timing reference include satellite (i.e. GPS, GLONASS, GALILEO, etc.) and terrestrial (i.e. LORAN, Network Timing Protocol) based technologies.[58]

The employment of satellite based timing signals enables the realization of accurate PMU synchronization without requiring the deployment of primary time and time dissemination systems. It assures, at the same time, a set of intrinsic advantages such as wide area coverage, easy access to remote sites and adaptable to changing network patterns. The GPS is a U.S. Department of Defense satellite based radio-navigation system. The Russian GLONASS (Global Navigation Satellite System) provides similar capabilities to GPS. The European Space Agency (ESA) GALILEO system is the third global satellite time and navigation system to come on line. China also developed its own GNS system, called Beidou.

Synchronizing signals may also be generated from terrestrial systems, such as radio broadcasts, microwave, and fiber-optic transmission systems, enabling communication over long distances.

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[56] John Stewart, Thomas Maufer, Rhett Smith, Chris Anderson, and Eren Ersonmez, Synchrophasor Security Practices. 14th Annual Georgia Tech Fault and Disturbance Analysis Conference Atlanta, Georgia May 9–10, 2011.

[57] R. Lilley, G. Church, M. Harrison. White Paper GPS Backup For Position, Navigation and Timing Transition Strategy for Navigation and Surveillance, Aug 22, 2006. Available online at www.loran.org/news/GPS-Backup-Released.pdf.

[58] Guidelines for Synchronization Techniques Accuracy and Availability, North American SynchroPhasor Initiative.

LORAN (LOng RAnge Navigation) is a terrestrial radio navigation system based on low frequency radio transmitters. LORAN uses ground based transmitters that only cover certain regions. The Network Time Protocol (NTP) is a robust and mature technology for synchronizing a set of network clocks using a set of distributed clients and servers over packet-switched, variable-latency data networks.[59]

Communications

Communications between one PMU and one PDC form the simplest part of the phasor network in a smart grid. However, one PDC's aggregated real-time measured data come from different PMUs located in vital substations. First, the correctness of data is investigated though Cyclic Redundancy Check (CRC) and kept in internal memory. All the restored data are accessible and synchronized by a UTC clock. Finally, by comparing the time-stamped data, the measured data would be rearranged and aligned based on their UTC time similarities.[60] Different software, e.g., RTDMS, are implemented through the personal computer at the output port of each PDC to calculate and show the local measured values such as voltage, current, frequency, MW and MVAR for operators. The higher layer includes a Super PDC, which is responsible for an interconnection-wide snapshot based on received data from the PDCs.[61]

Today, the most dominant protocol for communicating synchrophasor data is IEEE C37.118, which includes requirements for synchrophasor measurements as well as a data communications protocol for exchanging synchrophasor in real time. IEEE C37.118 defines a binary messaging format, but it does not require any specific medium or transport mechanism for communicating these frames. The C37.118 Standard describes four message types related to the configuration and transfer of real-time data from a PMU or PDC. These are data, configuration, header, and command messages.

Introduced by IEC Technical Committee 57 (TC57), the IEC 61850 standard signifies the communication protocol over the serial and modern computer type of technology which uses the TCP/IP model and Ethernet-shared media access encapsulation methods of PMU substations. IEC 61850 covers the entire communication requirements of substation automation systems which are not dependent on the manufacturer of instruments. It maps the data model in a group of protocols being able to run over Ethernet-shared media access, such as Manufacturing Message Specification (MMS), Generic Object-Oriented Substation Events (GOOSE), and Sampled Measured Values (SMV). Thus, 4 ms of response time is guaranteed based on the gigabit transmission bandwidth of Ethernet.

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[59] Mills, D.L., Network Time Protocol Version 4 Reference and Implementation Guide, Electrical and Computer Engineering Technical Report 06-06-1, University of Delaware, June 2006, 83 pp.

[60] Smart Grid Communications and Networking, Yi Deng, Hua Lin, Arun G. Phadke, Sandeep Shukla, James S. Thorp, Cambridge University Press, 2012, Print ISBN: 9781107014138.

[61] Consortium for Electric Reliability Technology Solutions (CERT). Phasor Technology. Available at: http://www.phasorrtdms.com/phaserconcepts/phasor_adv_faq.html#Question2 [Accessed 30 May 2014].

Figure 9 shows the skeletal network model and composition of the smart grid in a wide geographic location such as the United States map.

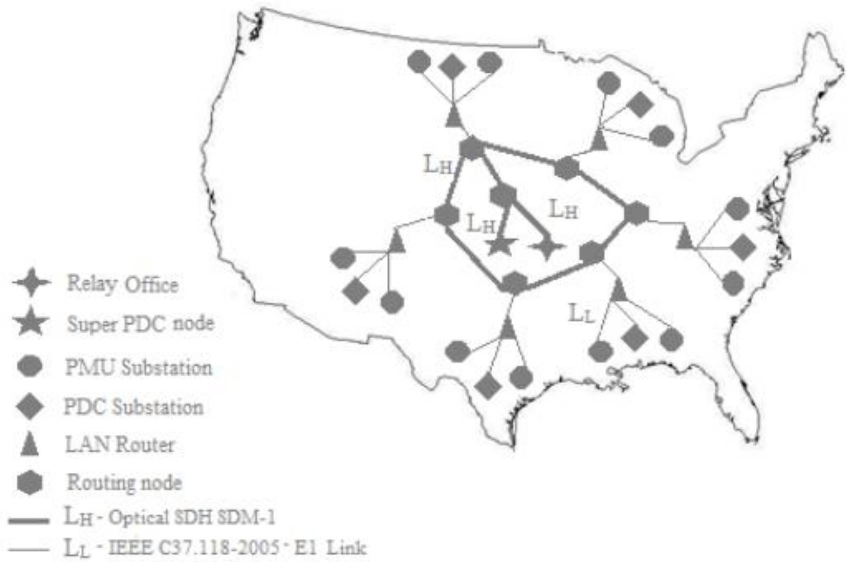

Figure 9. Skeletal network model of the smart grid in the map of the United States[62]

Harris Trusted Enterprise Network (HTEN) is a nationwide managed services network that enables the WECC to move mission critical synchrophasor and other data across a secure and private, high capacity terrestrial communications network. HTEN services, defense-in-depth security approach, which aligned with Peak Reliability (PEAK)'s security needs, began with leveraging the existing private optical infrastructure used by the FAA Telecommunications Infrastructure (FTI) to allocate a portion of the optical transport for the PEAK WISP purpose-built WAN. To ensure the highest level of security this is the only part of the system that is shared. With a dedicated PEAK WISP WAN routing domain, private MPLS PEAK core routers were used for PEAK WISP services. All synchrophasor data flowing through the PEAK WISP system is encrypted. A closed network management system, including a security operations center (SOC) and network operations center (NOC), guards the PEAK WISP WAN infrastructure with 24x7 monitoring, alerting, and incident response. The closed system does not transport other customers or the Internet. A nationwide field force that has completed a national agency background check is dispatched and works within four hours of a ticket being submitted for ticket resolution, with automatic ticket creation, updates, and alerts. At the top of the stack, two-factor authentication permits PEAK portal access to the Service Level Agreement (SLA) Manager, Ticket System, and Sharepoint access. Additional controls have been implemented

[62] Security Analysis of Phasor Measurement Units in Smart Grid Communication Infrastructures, University of Nebraska – Lincoln.

using NERC CIP and NISTIR 7628 as guidance, leveraging the experience implementing and operating FTI in compliance with NIST 800-53 controls.[63]

Cyber Security

Cyber security is one of the main obstacles to widespread deployment of PMUs. There are three security aspects of synchrophasor data: confidentiality, availability and integrity. Availability and Confidentiality attacks are secondary, while integrity attacks are most critical.[64] It can initiate inappropriate generator scheduling, and result in voltage collapse, and subsequent cascading failures. These three security aspects of synchrophasor data must be enforced end to end, starting from the PMUs, through the substation network, through the wide-area networks (WANs), all the way to the end-user application. Common attacks in the PMU network include Denial of Service (DOS), reconnaissance attack, Man-in-the-middle attack, packet injection attack (sniffing), malicious code injection, and data spoofing.[65,66]

Physical and cyber security requirements for synchrophasor systems will depend, for the foreseeable future, on how the NERC Critical Infrastructure Protection standards are written, the degree to which the asset owner recognizes its use of synchrophasor data to be for mission critical purposes, and whether the synchrophasor system's elements are co-located with other critical assets (such as a substation, control room or communications network). Although there are no clear rules or cyber security guidance today, NASPI and NERC recommend that synchrophasor projects be designed to accommodate the expectation that higher security requirements will be imposed in the future. The Department of Energy's Smart Grid Investment Grant awards imposed extensive cyber security requirements on the winning projects, and may raise the bar for all phasor technology implementations going forward.

There are two clear security strategy trends: mission-critical PMU system and mission-support PMU system. In either case, systems were designed, built, and operated in accordance with the NERC Critical Infrastructure Protection (CIP) requirements appropriate to their intended use. From the inception of these projects, DOE required the SGIG/SGDP synchrophasor grant recipients to develop and implement cyber security plans to protect the integrity of their synchrophasor systems and data produced by these systems. Each recipient's progress towards achieving the goals in its cyber security plans was monitored by DOE throughout the duration of the projects. These cyber security plans developed by each recipient included compliance with the requirements of the NERC CIP standards.[67] Phasornetwork Cyber Security Standards include:

- IEC 62351- suggested security standards and protocols through communication media

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[63] Harris Corporation.
[64] http://cnls.lanl.gov/~chertkov/SmarterGrids/Talks/Giani.pdf.
[65] T. H. Morris, S. Pan, U. Adhikari, Cyber Security Recommendations for Wide Area Monitoring, Protection, and Control Systems, Power and Energy Society General Meeting, 2012 IEEE.
[66] Christopher Beasley, Electric Power Synchrophasor Network Cyber Security Vulnerabilities, Clemson University.
[67] Factors Affecting PMU Installation Costs, U.S. Department of Energy, Electricity Delivery & Energy Reliability.

- NERC CIP 002-009 - provided cyber security standards
- IEEE 1686-2007 – investigated the security of measurements with respect to the IEEE 1686-2007, security measures over IEDs (intelligent electronic devices)
- IEEE C37.118 - communications protocol of PMU measurements and communications; previously discussed in this chapter.
- NIST Special Publication (SP) 800-53 -guidelines for federal information systems
- • FIPS 199 and FIPS 200 - basis of system classifications.

There's an ongoing project partnered on using physical measurements from micro-PMUs to detect cyber-attacks against the distribution, partnered by Lawrence Berkeley National Laboratory (LBNL), Arizona State University (ASU), EnerNex, Electric Power Research Institute (EPRI), Power Standards Laboratory (PSL), OSIsoft and Riverside Public Utilities (RPU). The approach is as following:

- Collect real-time measured data from micro phasor measurement units (μPMUs) that reflect the physical condition of the system.
- Collect SCADA network traffic to and from points in the distribution grid.
- Using models of distribution grid state, analyze distribution grid for unsafe operation.
- When anomalies are found, compare deviations from μPMUs with SCADA traffic to determine if cyber event is at cause.

To date they have identified substation cyber-attack scenarios suitable for detection using their methodology and enumerate specific data signatures used for attack detection.

5 Data Management

Data management refers to all aspects of collecting, analyzing, storing, and providing data to users and applications, including the issues of data identification, validation, accuracy, updating, time-tagging, consistency across databases, etc. Data management methods which work well for small amounts of data often fail or become too burdensome for large amounts of data—and distribution automation and customer information generate lots of data.[68] Data management is probably the most time-consuming and difficult in many of the functions, although some recent technology methodologies are helping to alleviate this problem.

Dell, Intel, National Instruments and OSIsoft have developed an end-to-end, smart grid synchrophasor data management solution designed to improve electric transmission and distribution (T&D) system efficiency. The solution, illustrated in Figure 10, combines sensors measuring voltage and current on power lines; PMUs processing the incoming measurements; Phasor Data Concentrators (PDCs) consolidating the data; and a data management system producing visual and actionable data. Now, utilities can cost-effectively deploy information technology to precisely manage T&D systems based on a steady stream of data from hundreds to millions of endpoint measurements.

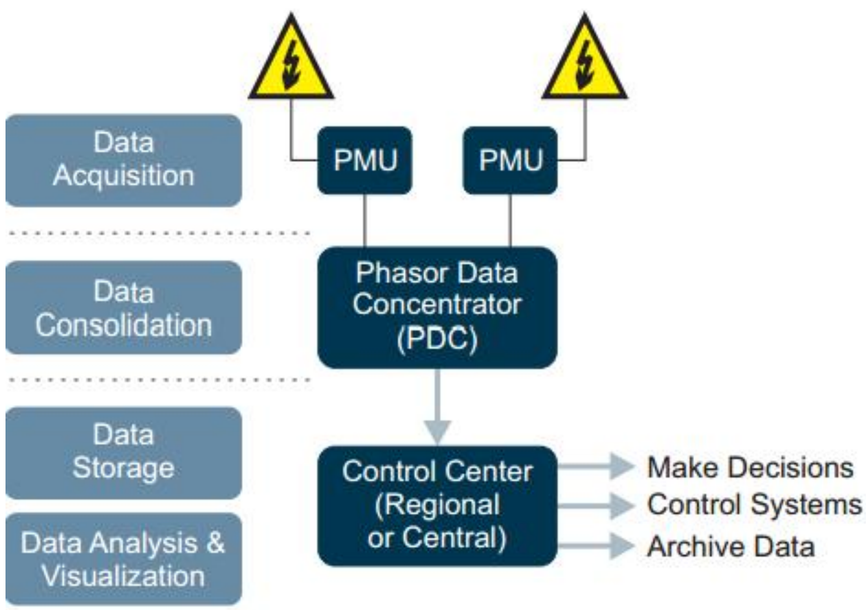

Figure 10. End-to-End, Smart Grid Synchrophasor Data Management Solution[69]

The synchrophasor data management solution employs high volume, standard computing systems used across many industries in order to reduce deployment cost and complexity. For

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[68] Smart Grid for Distribution Systems: The Benefits and Challenges of Distribution Automation (Draft Version 2) White Paper for NIST.
[69] Smart Grid Data Management Solution Enables Utility Companies to Improve Overall System Operation. http://www.intel.com/content/dam/www/public/us/en/documents/solution-briefs/energy-smart-grid-solution-blueprint.pdf.

instance, the data acquisition device from National Instruments is a highly configurable system used for data acquisition in not only the power and electricity industry, but also in oil and gas, manufacturing, transportation and others. Likewise, the Dell servers, storage hardware, networking gear and client workstations are standard products used across all industries. Intel® processors are designed into the solution, from end-to-end, including the PMU, the servers delivering the high-performance computing and storage, and the operator devices providing reports and visualization. The use of Intel processors simplifies the integration, connectivity, security and manageability of the solution. Additionally, the high volume production of these devices delivers a tremendous cost advantage to the solution.

6 Lessons Learned

Because of the SGIG and SGDP synchrophasor projects and the participants' willingness to share their insights, the industry has learned a number of important lessons about synchrophasor technology and technology advancement.

Synchrophasor Deployment

Not all PMUs are created equal. The older, research-grade PMUs are not the performance equals of those that meet the newer, post-SGIG project specifications and standards. And different types of PMUs may each meet technical performance standards and yet produce slightly different measurement or calculation outcomes. Many of the synchrophasor deployments funded by the ARRA are at a relatively high and consistent levels of device capability and are using many of the same applications. This consistency and collective advancement is due in large part to the generosity and willingness of the synchrophasor awardees to work together through NASPI to share information and solve problems together. This cooperation and common effort lifted the quality and capabilities of the entire industry. It will make it much easier for late adopters to catch up with the industry synchrophasor leaders in the future.

PMU prices and installation costs have dropped markedly since 2010. Even small transmission system owners can use best practices and procedures to install PMUs quickly and easily. Off-the-shelf hardware should be used whenever possible to improve system integration capability and improve cost efficiency. Integration with existing systems and streamline ongoing maintenance and support are needed. PMUs and their associated intelligent components evolve at much faster rates than more traditional transmission equipment. Project should consider this pace during the planning phase. Additional time and cost should be factored in when in the planning stages to ensure vendors are or can be prepared to meet security requirements and handle exceptionally high data volume requirements.

Applications Development

There is a long path from the installation of synchrophasor systems (PMUs, PDCs, networks and applications) to user acceptance and use. To fully capitalize on the infrastructure investment system, operations personnel must be sufficiently engaged, trained, and committed to working with the new applications and data outside of the post event analysis framework. The project team must communicate a clear value proposition for embracing the new technology at the operational level.[70]

Moving the technology from development to production has been more difficult than expected. The post-mortem data analysis has been beneficial, but finding must-have applications for real-time operations has been challenging.[71] Although early expectations were that wide-area

[70] PMU Deployment in the Carolinas with Communications System Modernization, Duke Energy Carolinas, LLC. https://www.smartgrid.gov/files/Duke-Energy-Carolinas-Project-Description.pdf.
[71] American Transmission Company LLC (II), Phasor Measurement Unit Project, U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability.

situational awareness would be the "killer app" for synchrophasor technology, in fact much of the immediate reliability and cost-saving benefits of PMUs have come from off-line, engineering uses such as generator model validation, equipment mis-operations diagnosis, and event analysis. Applications of oscillatory/signal theory in real-world utility systems are novel and complex. While the ability to examine PMU data and results in real time is a big step forward from earlier technologies, complete understanding of risks and trends requires statistical tools that provide longitudinal analysis of the data. PMU analytics need to be scalable and adaptable as the technology becomes more commonplace.[72]

Data Quality and Sharing

Configuring synchrophasor data flow is relatively easy. The challenges are sorting through and archiving the massive influx of data to derive the information that supports operations, planning, and system protection personnel. Data quality plays a defining role in the effectiveness of synchrophasor technology. As the project moved from the installation phase to active use of PMU data in applications, it became increasingly important to test equipment to ensure that measurements were accurate and that time stamps were being placed appropriately.

The high bandwidth, high frequency, and sheer volume of PMU data entail special requirements when implementing analytics, visualizations, storage, and retrieval of information. Even after the hardware and software elements of the system have been installed, many data quality problems must be resolved before the system can yield the consistently high-quality, high-availability data needed for many real-time synchrophasor reliability applications. Simulating real-world synchrophasor data network loading is extremely difficult. Many data quality problems can only be resolved by making dogged improvements in business practices such as metrics reporting, accountability and ownership, maintenance commitments, communications contract terms, and careful hand-offs across and between organizations.

There is a need for common vocabulary, definitions, and standardized test/use cases. All entities should use standard, currently adopted and supported communications protocols whenever possible to improve. A comprehensive standard for PDCs should be developed. The original NASPInet (North American SynchroPhasor Initiative Network) design needs to be modernized. Project teams should also schedule adequate time for partnership agreements. Executing comprehensive data sharing agreements was harder to accomplish and longer in duration than expected.[73] Due to concerns about the potential use of PMU data for investigating and enforcing market or reliability violations, or the potential for PMU data to reveal power system security vulnerabilities, only the WECC project has been able to persuade all of its members to share their PMU data. In the East, many entities are still not sharing PMU data with neighboring

[72] Entergy Services, Inc. Deployment and Integration of Synchrophasor Technology, U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability.
[73] Peak Reliability (formerly part of the Western Electricity Coordinating Council) Western Interconnection Synchrophasor Program, U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability.

transmission owners or reliability coordinators or with researchers (who would use it to develop and test new software or devices).