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Phasors or Waveforms:

Considerations for Choosing Measurements to Match Your Application

April 2021

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U.S. DEPARTMENT OF ENERGY

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Abstract

As the power system undergoes change, so must its measurement systems. The grid is currently in a state of rapid change with the proliferation of power electronic devices at all levels of the power system: generation, transmission, distribution, and load. A commonality among these devices is their tendency to manipulate voltage and current waveforms and alter their behavior within an electrical cycle. This behavior has already begun to reveal the limitations of today's most advanced wide-area monitoring system based on synchrophasor measurements provided by phasor measurement units (PMUs). Though synchrophasors will continue to be useful in many applications, some emerging use cases require measurements that can more accurately represent underlying voltage and current waveforms.

The objective of this guide is to help readers use their existing measurement systems effectively while navigating the significant changes that the power system is undergoing. To accomplish this objective, the capabilities and limitations of PMUs are described. Where synchrophasors are insufficient, this document describes how point-on-wave (POW) measurements can meet application needs. POW measurements result from the conversion of an analog input signal to digital samples, allowing them to accurately reflect non-sinusoidal signals. This document contains descriptions of PMU and POW technology and the use cases for which each is well-suited. The document also highlights key considerations for expanding a measurement system to enable applications based on POW technology.

Acknowledgments

The work described in this report could not have been completed without the contributions of many people. Sandra Jenkins, of the Office of Energy of the United States Department of Energy, and Dr. Guohui Yuan, of the Department of Energy's Solar Energy Technologies Office, deserve special mention. Their continuing involvement, guidance and support helped us maintain momentum over the evolution of the project. Special thanks to Frank Tuffner, Dan Sabin, Alison Silverstein, and Dani Strickland for feedback and comments on this guide.

Acronyms and Abbreviations

AGC	Automatic generation controller
CIP	Critical Infrastructure Protection (NERC standard)
DDR	Dynamic disturbance recorder
DER	Distributed energy resource
DFR	Digital fault recorder
EERE	Office of Energy Efficiency and Renewable Energy
EMS	Energy management system
EPRI	Electric Power Research Institute
GMLC	Grid Modernization Lab Consortium
GNSS	Global navigation satellite system
GOOSE	Generic Object-Oriented Substation Events
GPS	Global positioning system
IBR	Inverter based resource
IED	Intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent system operator
LAN	Local area network
NASPI	North American Synchrophasor Initiative
NERC	North American Electricity Reliability Corporation
ORNL	Oak Ridge National Laboratory
OE	Office of Electricity
PMU	Phasor measurement unit
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
RMS	Root-mean squared
ROCOF	Rate of change of frequency
SCADA	Supervisory control and data acquisition
SER	Sequence of events recorder
SDN	Software-defined network
STTP	Streaming Telemetry Transport Protocol
THD	Total harmonic distortion

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1.0 Introduction

The power system is undergoing rapid and significant change. Instead of centralized synchronous machines, generation is increasingly distributed and inverter-based. Power electronic devices play a growing role in transmission systems, and energy resources are widely deployed throughout distribution systems. The resistive and motor loads of the past are being replaced with electronic loads, and electric vehicles will change the makeup of load even further. To manage these changes, the measurement systems that support the planning and operation of the grid must be used effectively, but they must also evolve.

The objective of this guide is to help readers use their measurement systems effectively while navigating the significant changes that the power system is undergoing. Two classes of synchronized measurement systems are considered. The first is the synchrophasor system based on phasor measurement units (PMUs), which is widely deployed and utilized in power systems. Though PMU networks constitute a significant advancement beyond Supervisory Control And Data Acquisition (SCADA) systems, they are limited when underlying voltage and current waveforms are non-sinusoidal, a situation that is increasingly common in the modern grid. The second system is currently emerging and is known as point-on-wave (POW) (also referred to as sync-wave[1]). POW measurements result from the conversion of an analog input signal to digital samples, allowing them to accurately reflect non-sinusoidal signals. Continuous point-on-wave (CPOW) refers to POW data that is available, through streaming or storage, on a continual basis. More complete descriptions of these technologies are provided in Chapter 2.

In Chapter 3, six use cases are reviewed to highlight the characteristics of applications for which PMU and POW measurements are each well suited. We consider only a small set of the applications that have been proposed for synchrophasors, many of which are described in reports available at the website of the North American SynchroPhasor Initiative (NASPI)[2]. Similarly, recent additions to the literature propose many novel applications for POW.[1, 3, 4] Rather than compiling an exhaustive list of applications, our objective is to be instructive by discussing why synchrophasor or POW measurements are appropriate in each case. This will enable the reader to make a similar evaluation for any application that they choose to pursue.

Chapter 4 provides a set of considerations for expanding a measurement system to incorporate POW data. Measurements of voltage and current waveforms are already widely used in power systems, but with a relatively limited scope. Time-synchronizing the measurements and making them readily available (through increased deployment, telemetering, continuous collection, etc.) is expected to broaden this scope significantly.[1, 4] Thus, we consider gradual expansion of existing capabilities as well as deployment of purpose-built POW systems.

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[1] W. Xu, Z. Huang, X. Xie and C. Li, "Synchronized Waveforms a Frontier of Data-Based Power System and Apparatus Monitoring, Protection and Control," in IEEE Transactions on Power Delivery.

[2] https://www.naspi.org/reference-documents

[3] Follum, J., E. Ellwein, P. Etingov, X. Fan, H. Kirkham, L. Miller, A. Riepnieks. 2020. “Advanced Power Systems Measurements: A 2020 Literature Review.” PNNL-30757. Richland, WA: Pacific Northwest National Laboratory, 2020

[4] Silverstein, Alison, and Jim Follum. (2020). High-Resolution, Time-Synchronized Grid Monitoring Devices. NASPI. Available online: https://www.naspi.org/node/819

This document is intended for a broad audience of individuals that develop or apply analyses to synchronized measurements for power system applications. This does not exclude those utilizing commercial tools. To the contrary, a solid understanding of the capabilities and limitations of measurement systems will inform proper interpretation of analysis results. This understanding will benefit members of utilities, vendors, and academia as they seek to enhance the reliability and resilience of the power system through the use of advanced measurement systems.

2.0 Strengths of Synchrophasor and POW Technologies

This chapter provides descriptions of PMU, POW, and CPOW technology. These descriptions lay the groundwork to determine whether synchrophasors and POW measurements are well suited to a particular application. Specific examples are provided in Chapter 3. A review of PMU technology is provided first, followed by a discussion of the power system changes driving the need for POW. Descriptions of POW and CPOW systems are then provided.

2.1 PMU Technology

A phasor is a complex number that represents both the magnitude and phase angle of voltage and current waveforms, as shown in Figure 1. The term *synchrophasor* refers to a phasor that is associated with a timestamp using a reference time source, such as the global positioning system (GPS). Synchronizing the measurements to a common time source enables an array of wide-area applications. A device that calculates synchrophasors is called a phasor measurement unit (PMU).

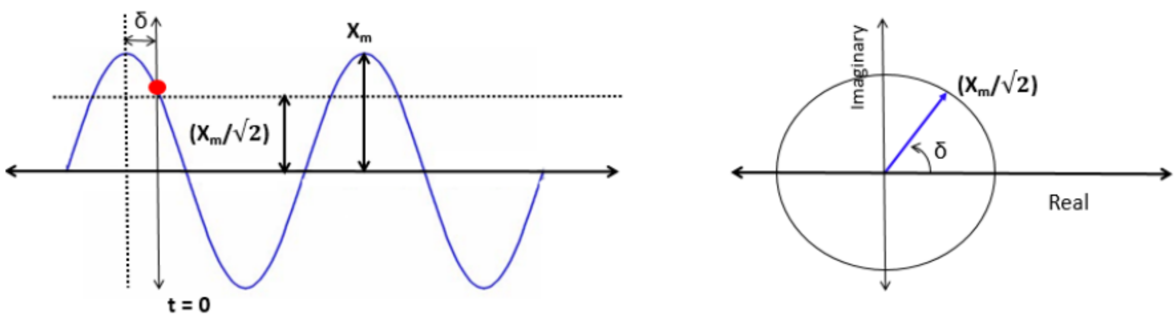

Figure 1: Illustration of a phasor estimate from a continuous waveform

PMUs use analog-to-digital converters (A/D) to collect samples of voltage and current waveforms. The IEEE standard governing PMUs provides an example with 15 samples per cycle, or 900 samples per second.[1] PMUs assume that the input signal, after preprocessing, can be well represented by a sinusoid. The PMU uses the collected samples over a window (the previously referenced example uses two electrical cycles) to estimate the magnitude and phase angle of this hypothetical sinusoid. The magnitude and angle are then reported as the synchrophasor estimate. In a 60 Hz system, PMUs typically report 30 or 60 synchrophasors per second. This is known as the PMU's reporting rate. Though the term *sampling rate* is often used colloquially, the difference is important. For example, the Nyquist-Shannon sampling theorem does not apply to a PMU's reporting rate the way it does to the sampling rate of an A/D. In summary:

- The phasor estimation algorithm is applied to samples of voltage and current waveforms
- Input waveforms are sampled at a much higher rate than synchrophasors are reported

[1] This is for the P-class example in Section C.5 of:
"IEEE Standard for Synchrophasor Measurements for Power Systems," in IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005), vol., no., pp.1-61, 28 Dec. 2011.
This standard provides a much more detailed explanation of the phasor estimation process than the one provided here.

- Phasor estimation assumes that the input signal can be well represented by a sinusoid
- Multiple electrical cycles are used to estimate the synchrophasor

The high reporting rate of PMU systems, along with their time synchronization, makes them well-suited to many applications. For example, Figure 2 shows a comparison between PMU and SCADA measurements, which are typically reported every 4 to 6 seconds, during a power system oscillation. The PMU measurements provide a much clearer picture of the oscillation due to time synchronization and the much higher reporting rate.

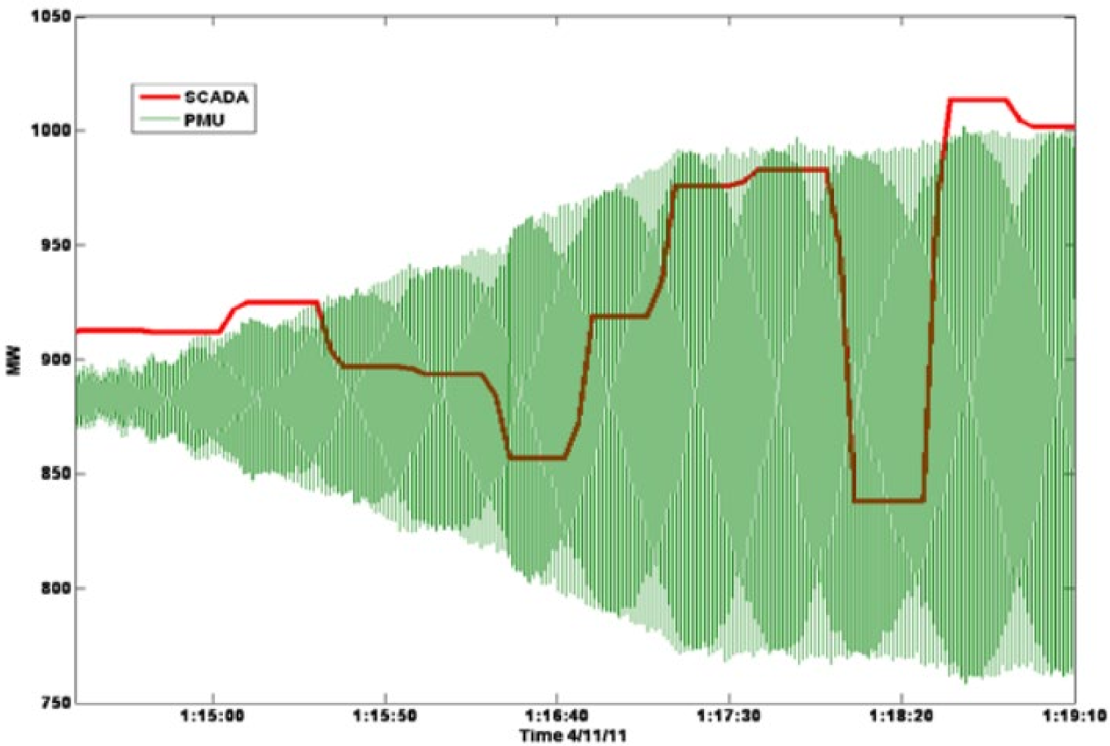

Figure 2: Synchrophasor data provides a much more detailed representation of an oscillation than SCADA data at its much lower time resolution (Source: Dominion)

The advanced capabilities of PMUs have led to their widespread deployment, particularly since the American Recovery and Reinvestment Act (ARRA) of 2009 provided significant funding to support PMU installations. The increase in deployments is apparent in Figure 3. During this time, several software tools became commercially available to use synchrophasors in planning and operations. Now a mature technology, PMU measurement systems will continue to support the electric power industry for years to come.

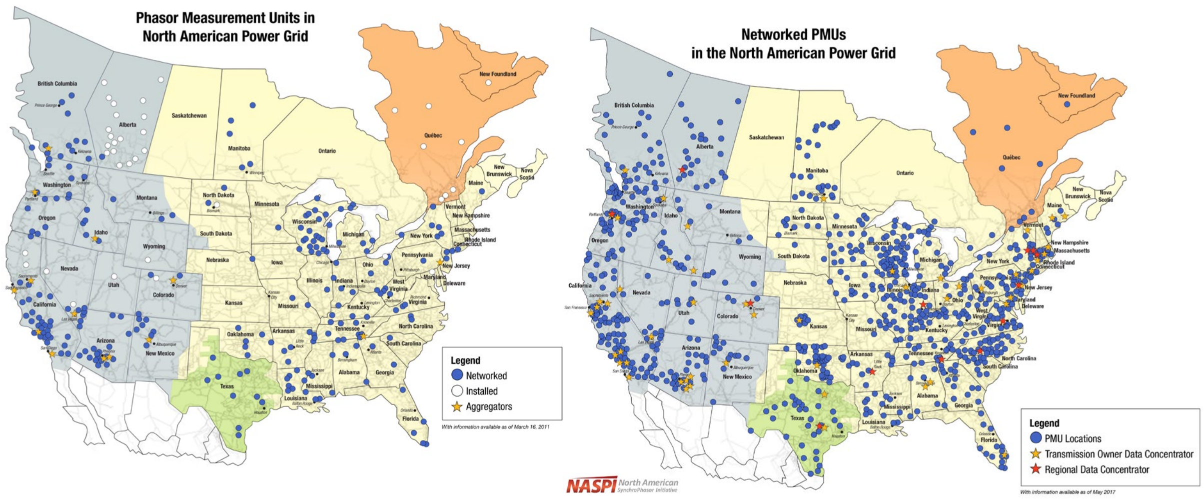

Figure 3. North American Power Grid PMU map 2011 vs. 2017 (Source: NASPI[1])

2.2 Emerging Power System Characteristics and a Need for CPOW

The Blue Cut Fire in 2015 brought to the attention of NERC a situation in which a phase jump, depicted in Figure 4, was incorrectly treated as a large drop in frequency.[2] The effect was to cause 700 MW of generation to trip offline, and subsequent investigation showed that similar generation losses were occurring about every month. Due to the sub-cycle nature of this event, direct measurements of the voltage waveform were required to understand what happened. Estimating the signal's magnitude, phase, and frequency is of little benefit because the underlying waveform is not well-represented by a sinusoid.

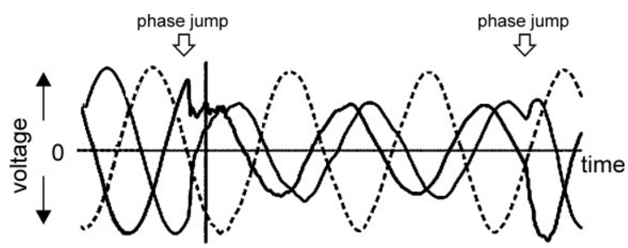

Figure 4: NERC graph based on DFR data, showing phase jumps that were interpreted as a major drop in frequency. Solid lines are the actual data, while the dashed line is a sinusoid shown for reference. (Source: NERC[1])

This consideration is becoming increasingly important due to the proliferation of power electronic devices, which can manipulate waveforms and alter their behavior within an electrical cycle.[3] The widespread deployment of PMUs has greatly increased wide-area situational awareness through time synchronization and reporting rates much higher than SCADA systems. But as useful as PMUs are, they are limited to representing the input signal with magnitude, phase, and frequency terms corresponding to a sinusoidal model. To effectively perform post-event analysis of disturbances where non-sinusoidal behavior plays an important role, as in the Blue Cut Fire, measurements that effectively capture that non-sinusoidal behavior are needed.

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[1] https://www.naspi.org/node/749

[2] NERC. (2017). 1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report. Atlanta: NERC.

[3] NERC Reliability Guideline "Improvements to Interconnections Requirements for BPS-Connected Inverter-Based Resources", Sept. 2019.

A similar consideration is true for model validation and calibration. PMUs were developed during a time when the power system was dominated by large synchronous generators and the use of power electronic devices was limited. In most areas of control, the behavior of generation and load aligned well with the sinusoidal behavior assumed in PMU measurement systems. In 2021, electronic loads are now an important consideration for control, and generating fleets contain high penetrations of inverter-based resources (IBRs). Generation and load models have been modified and created to reflect the new makeup of the power system. To validate and calibrate these models, measurements that capture the high-speed behaviors reflected in these models must be available. POW measurements provide this capability.

2.3 POW Technology

POW measurements are sequential, time-synchronized sampled values of a signal with minimal filtering, typically from 256 samples/second up to a million samples/second.[1] At these high resolutions, POW measurements can represent non-sinusoidal waveforms, as depicted in Figure 5.

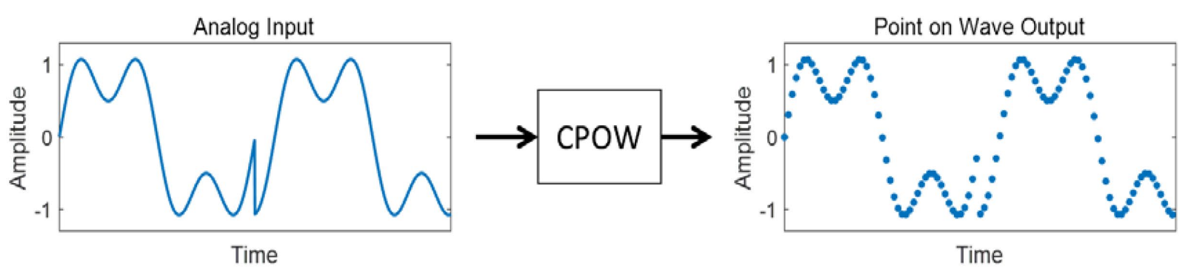

Figure 5: Conversion of an analog input to a point on wave output.[1]

The value of capturing these non-sinusoidal characteristics is illustrated in Figure 6. The top plot shows an analog waveform with a phase jump. In the middle plot, the phase jump is accurately reflected in POW measurements. If the POW measurements are fed into a phasor estimation algorithm (in this case based on a least squares fit), the reported magnitude and phase correspond to the sinusoid in the bottom plot, which is a poor reflection of the analog signal. While PMUs can only represent voltages and currents as sinusoids in terms of magnitude, phase, and frequency terms, POW measurements can provide a more detailed view of the signal.

[1] Silverstein, Alison, and Jim Follum. 2020. “High-Resolution, Time-Synchronized Grid Monitoring Devices.” Available online: https://www.naspi.org/sites/default/files/reference_documents/pnnl_29770_naspi_hires_synch_grid_devices_20200320.pdf

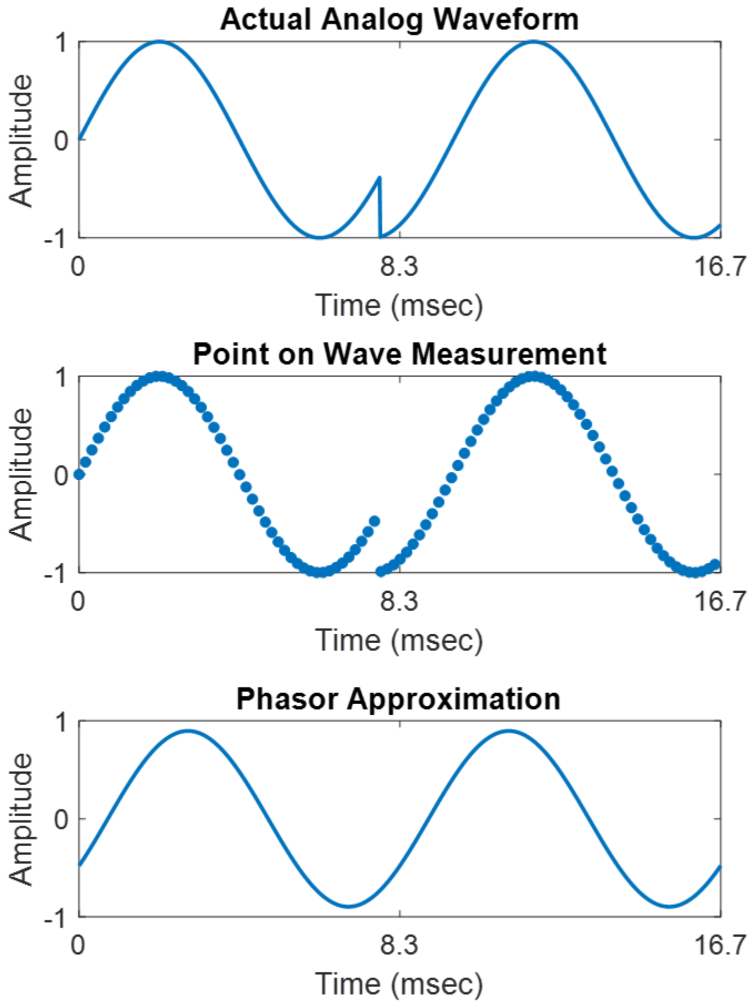

Figure 6. An analog waveform (top), its representation as POW measurements (middle), and its reconstruction from a phasor estimate (bottom).

The underlying technology for POW measurement systems is common in power systems. Many devices sample voltage and current waveforms, essentially making their own POW measurements. For example, digital fault recording (DFR) devices can sample voltage and current waveforms thousands of times per second to record specific events. Digital relays sample grid conditions at up to a million samples/second to detect circuit conditions and activate protection schemes. Though typically built with a specific purpose, such devices may be useful for broader applications if the measurements are time-synchronized and readily accessible.

As digital samples of the input waveform, the Shannon-Nyquist sampling theorem applies to POW measurements. The observable frequency range will extend to frequencies up to half the sampling rate. This frequency range, which extends far beyond the dynamic range of PMUs, makes POW data well-suited to applications such as sub-synchronous resonance (SSR) detection and analysis.

Just like PMU data, time-synchronization entails stamping each measurement based on a common time source. Some of today's POW devices, such as digital fault recorders (DFRs), provide time-synchronized measurements. Older POW devices typically do not include time synchronization capabilities. To achieve the maximum benefit from a POW system, it should be time synchronized to enable applications such as post-event analysis and system protection. As mentioned previously, POW measurements must also be readily accessible to provide a broad set of benefits. This aspect is considered in the following section.

2.4 CPOW Technology

Most POW devices currently deployed in the bulk power system are event triggered and record short-duration, high-resolution waveform data for events that are already recognized. Digital fault recorders are a good example of this type of device. To capture events that are long-lasting, poorly defined, or unexpected, the POW measurements could be recorded continuously. Such a system is referred to as continuous point-on-wave (CPOW).[1]

A CPOW measurement system combines the time-synchronized waveform sampling of a POW measurement system with a system for data availability. Data availability is a broad concept that can refer to the ready access without interruption of data sets, data streams, or both. For example, availability of a data set is high if it can be accessed in moments from any computer with access to the archive that contains the data set, but low if the data set has to be fetched from deep storage overnight. Availability of a data stream refers to how uninterrupted the data stream is as it arrives at its destination.[2]

Synchrophasor measurement streams arriving at data centers tend to have high availability due to being streamed continuously. POW measurements are often not streamed continuously due to their high volume. Data availability for CPOW can be accomplished through several approaches:

- Continuously recording measurements to a local archive and polling by the operations center when there is a system event
- Continuously recording measurements to a local archive and transmitting data onward only during times of low network activity
- Continuously recording measurements and continuously streaming them to an operations center

Merging units[3] are an existing technology that can support a CPOW system. These devices obtain analog voltage and current signals from PTs and CTs, convert the signal to digital, and pass the resulting samples to other devices, such as relays, to perform diverse functions. Devices built to the IEC standard 61850-9-2LE (process bus) publish either 4000 or 4800 samples per second (for 50- and 60-Hz power systems). Devices receiving a merging unit's measurements via process bus could perform local analysis, store measurements continuously, or stream the data to central location. A subset of the applications enabled by this type of system are explored in the following section.

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[1] Silverstein, Alison, and Jim Follum. 2020. "High-Resolution, Time-Synchronized Grid Monitoring Devices." Available online: https://www.naspi.org/sites/default/files/reference_documents/pnnl_29770_naspi_hires_synch_grid_devices_20200320.pdf

[2] Miller, Laurie E., Alison Silverstein, Dhananjay Anand, Allen Goldstein, Yuri Makarov, Frank Tuffner, and Kevin Jones. 2017. "PMU Data Quality: A Framework for the Attributes of PMU Data Quality and a Methodology for Examining Data Quality Impacts to Synchrophasor Applications." Richland, WA.

[3] See IEC 60044-8 for a detailed description of merging units

3.0 Use Cases

This section discusses several use cases for electric power grid measurement systems with an eye to whether the needs are best suited to PMU systems, POW systems, or possibly both.

In a 2010 report, NERC listed existing and future PMU applications that can be grouped into three categories[1]:

- Real-time applications for situational awareness and visualization (wide-area situational awareness, frequency stability monitoring and trending, oscillation monitoring, voltage monitoring and trending, alarming and system operating limits, event detection, renewable resources integration, state estimation, dynamic line rating, system restoration, operations planning)

- Off-line applications for planning and post event analysis (power system performance baselining, event analysis, model validation and calibration, load characterization, special protection schemes design and testing)

- Real-time applications for automated control actions (interarea oscillation damping, voltage control)

There are several recent reports and presentations providing information on synchrophasor technology development and details on the various PMU use cases[2,3]. In the first three use cases, we provide a brief overview of several success stories to highlight the commonalities between applications for which PMUs are well suited.

The latter three use cases included in this section serve to illustrate measurement needs beyond what PMUs can provide alone. There are many other use cases for POW/CPOW data, including subsynchronous resonance, high-frequency resonance, harmonics and power quality, and geomagnetic disturbance detection, among others. In a 2020 report, NASPI listed existing and future POW/CPOW applications.[4]

3.1 Low-Frequency Oscillation Monitoring and Analysis

The application of PMU measurements to oscillation monitoring and analysis is one of the greatest synchrophasor technology success stories. Oscillations are always present in the bulk power system because of the stochastic nature of the load. Inter-area electromechanical modes

[1] NERC, "Real-Time Application of Synchrophasors for Improving Reliability", 2010, Available online: https://www.naspi.org/sites/default/files/reference_documents/rapir_final_20101017.pdf?fileID=519
[2] BPA, "Synchrophasor Technology at BPA: From Wide-Area Monitoring to Wide-Area Control", 2017, Available online: https://www.bpa.gov/Doing%20Business/TechnologyInnovation/Documents/2017/SYNCHROPHASORS%20AT%20BPA%20Nov%202017.pdf
[3] NASPI, "NASPI Synchrophasor starter kit", Draft 2015, Available online: https://www.naspi.org/sites/default/files/reference_documents/4.pdf
[4] Silverstein, Alison, and Jim Follum. 2020. "High-Resolution, Time-Synchronized Grid Monitoring Devices." Available online: https://www.naspi.org/sites/default/files/reference_documents/pnnl_29770_naspi_hires_synch_grid_devices_20200320.pdf

of oscillation are of particular interest because they are related to the system's stability[1]. Such oscillations typically have frequencies in the range of 0.1 – 1 Hz. Local electromechanical oscillations typically occur at frequencies between 1 – 5 Hz. PMUs are particularly well suited to analyzing oscillations in these frequency ranges. Reported 30(60) times per second, synchrophasors can represent content up to 15(30) Hz, though the filters used in the synchrophasor measurement process attenuate frequencies above 5 Hz.[2]

Forced oscillations[3], which occur when a piece of equipment subjects the power system to a periodic disturbance, have been a source of increasing concern in recent years. This concern is centered around the interaction between the forced oscillation and the system's underlying natural oscillatory properties. Once again, PMUs are highly effective in this frequency range.

In contrast, the reporting rate of SCADA systems, typically 2-4 seconds, limits their ability to accurately represent system behaviors in the 0.1 – 5 Hz range. The asynchronous reporting of SCADA measurements further limits their usefulness for this application. Figure 7 shows a comparison of SCADA and PMU measurements during a forced oscillation. The SCADA results omit a good deal of the variability. A NASPI report provides a comprehensive survey of the synchrophasor-based oscillation applications and tools used by various organizations[4].

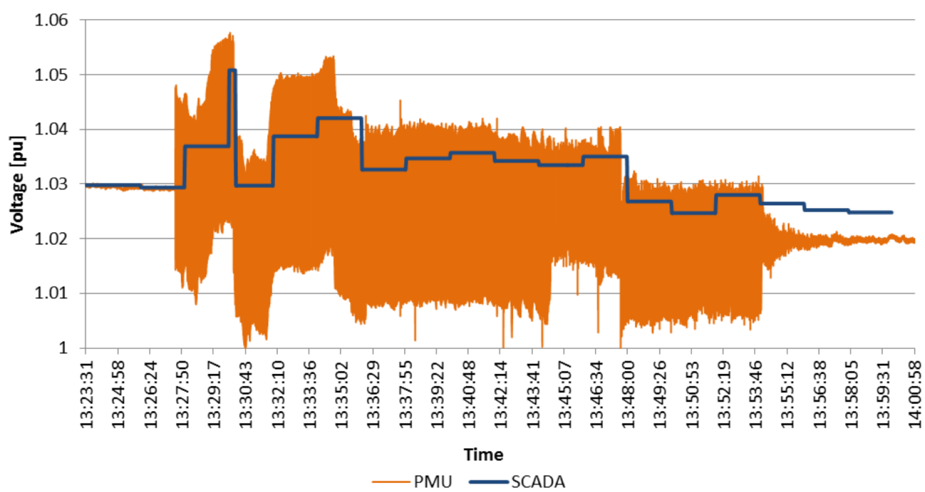

Figure 7. Forced oscillation observed with SCADA and PMU data (source: ATC)

[1] NERC, "Interconnection Oscillation Analysis", 2019, Available online: https://www.nerc.com/comm/PC/SMSResourcesDocuments/Interconnection_Oscillation_Analysis.pdf
[2] As mentioned previously, the Shannon-Nyquist sampling theorem cannot be applied to synchrophasors because the measurements are not digital samples of an analog waveform. Still, transforming synchrophasor measurements to the frequency domain allows representation of frequencies up to half the reporting rate. The frequencies outside of the PMU's dynamic range will be heavily attenuated and may even contain frequency content related to aliasing, so great care must be taken in interpreting results.
[3] NERC, "Forced Oscillation Monitoring & Mitigation", 2017, Available online: https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_-_Forced_Oscillations_-_2017-07-31_-_FINAL.pdf
[4] NASPI, "Using Synchrophasor Data for Oscillation Detection", 2017, Available online: https://www.naspi.org/sites/default/files/reference_documents/crstt_oscillation_detection_20180129_final.pdf

PMUs are well-suited for most low-frequency oscillations. These low frequencies are within the dynamic range of PMUs, and time-synchronization supports a wide-area approach to analysis that is critical given that oscillations can propagate across the system. The variations in voltage and current waveforms that these low-frequency oscillations create are gradual enough that the several electrical cycles within the PMU's analysis window can be represented well by a sinusoid. Thus, the details of the voltage and current waveforms provided by POW measurements are typically unneeded.

3.2 Phase Angle Monitoring

Phase angle differences are strongly correlated to active power transfers and system topology. Greater phase angle differences across the system indicates larger stress in the power grid and therefore can serve as an additional indicator of the system stress[1]. A rapidly changing phase angle difference between two points may indicate a problem in the corresponding area of the grid. SCADA systems report voltage magnitude, but not angle, so they cannot be used to directly monitor phase angle differences. SCADA systems can be used in EMS state estimators, which then provide information on the phase angles, but these estimates are not as reliable as measurements and are not available at high resolution or in real time, as depicted in Figure 8.

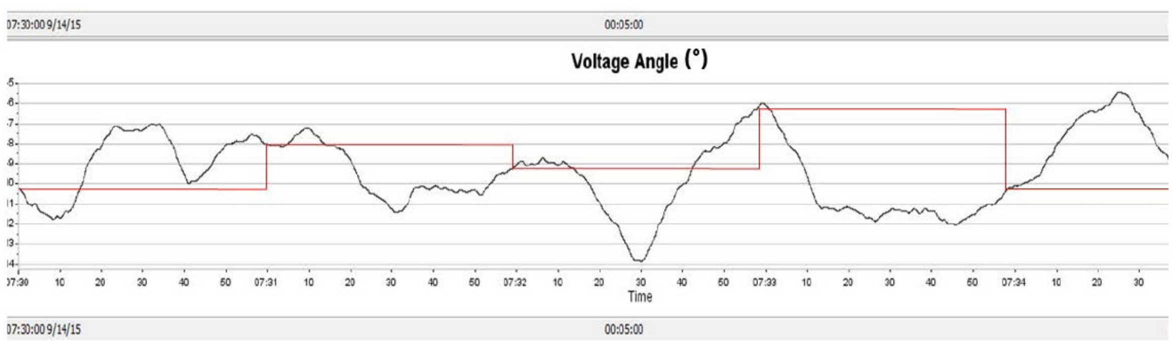

Figure 8. Phase angle from PMU (black) vs. state estimator (red) (source: Peak Reliability)

There are several commercially available tools for phase angle monitoring including: EPG Real-Time Dynamics Monitoring System (RTDMS), GE PhasorPoint, SEL synchroWAVe Central, and V&R Energy Region Of Stability Existence (ROSE)[2]. These applications enable improved situational awareness, providing phase angle difference visualization, analytics, and alarming if monitored phase angle differences exceed limits immediately following a major system event. An example of alarming software is presented in Figure 9.

[1] NERC, "Phase Angle Monitoring: Industry Experience Following the 2011 Pacific Southwest Outage Recommendation 27", 2016, Available online: http://www.nerc.com/comm/PC/Synchronized%20Measurement%20Subcommittee/Phase%20Angle%20Monitoring%20Technical%20Reference%20Document%20-%20FINAL.pdf

[2] NASPI, "Using Synchrophasor Data for Phase Angle Monitoring", 2016, Available online: https://www.naspi.org/sites/default/files/reference_documents/0.pdf

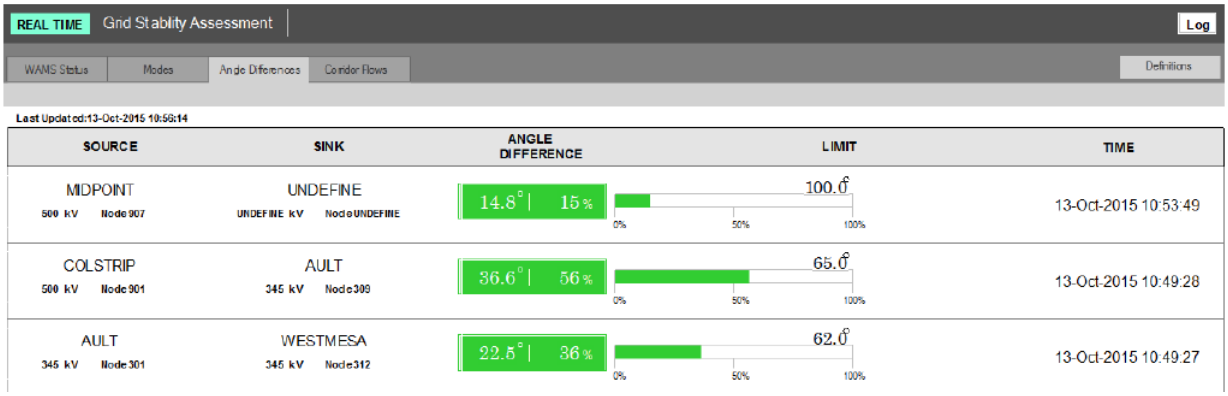

Figure 9. Synchrophasor-based angle alarming (source: Peak Reliability)

Once again, the characteristics of the system behavior of interest make synchrophasors effective for this application. Voltage angles can change suddenly along with topology, but typically the dynamics of these sub-second changes are of less interest than the change between pre- and post-disturbance states. Synchrophasors are fast and accurate enough to enable effective monitoring of these sudden shifts. They can also support monitoring of longer-term trends.

3.3 Conventional Power Plant Model Validation

The power system is designed, planned, and operated using dynamic models that are expected to represent the transient behavior of the system elements (e.g., power plants, transmission grid, distributed energy resources [DERs], and loads). Inaccurate models have contributed to several major North American power outages. A major example was the August 1996 Western Interconnection outage. The frequency response of SCADA measurements makes them of limited use to validate the dynamic models of the power system. Deployment of PMUs and other high-resolution measurement devices has enabled validation and calibration of power system models[1].

The NERC Modeling, Data, and Analysis (MOD) standards enforce requirements for power plant modeling, data, and system analysis. The main goal of these standards is to ensure validation and monitoring of model performance. The MOD standards allow generator owners to perform model validation using disturbance event records.[2] Figure 10 shows the concept of power plant model validation. A PMU or other high-resolution disturbance monitoring device should be installed as close as possible to the power plant point of interconnection. The response of the plant to a disturbance is measured by the PMU and played back into the power plant model using capabilities available in most commercially available simulation software (e.g., PSLF, PSSE, PowerWorld, and TSAT). Simulated and actual responses of the plant are compared to validate the dynamic model. For a high-quality dynamic model, the simulated response should match disturbance records. If there is a large discrepancy between simulation results and PMU measurements, as in the left side of Figure 11, it indicates that the model

[1] NASPI, “Model Validation Using Phasor Measurement Unit Data”, 2015, Available online: https://www.naspi.org/sites/default/files/reference_documents/19.pdf?fileID=1416
[2] NERC, “Reliability Guideline: Power Plant Model Verification and Testing for Synchronous Machines”, 2018, Available online: https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_-_PPMV_for_Synchronous_Machines_-_2018-06-29.pdf

needs to be calibrated. For a previously validated model, a big difference between simulations and measurements can be also an indication of equipment malfunction or abnormal control behavior[1].

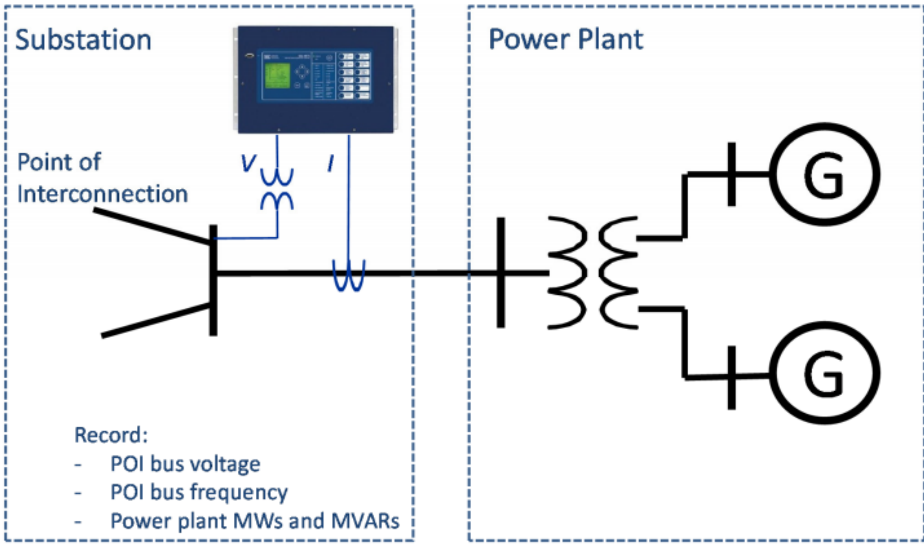

Figure 10. Power plant model validation concept (source: BPA)

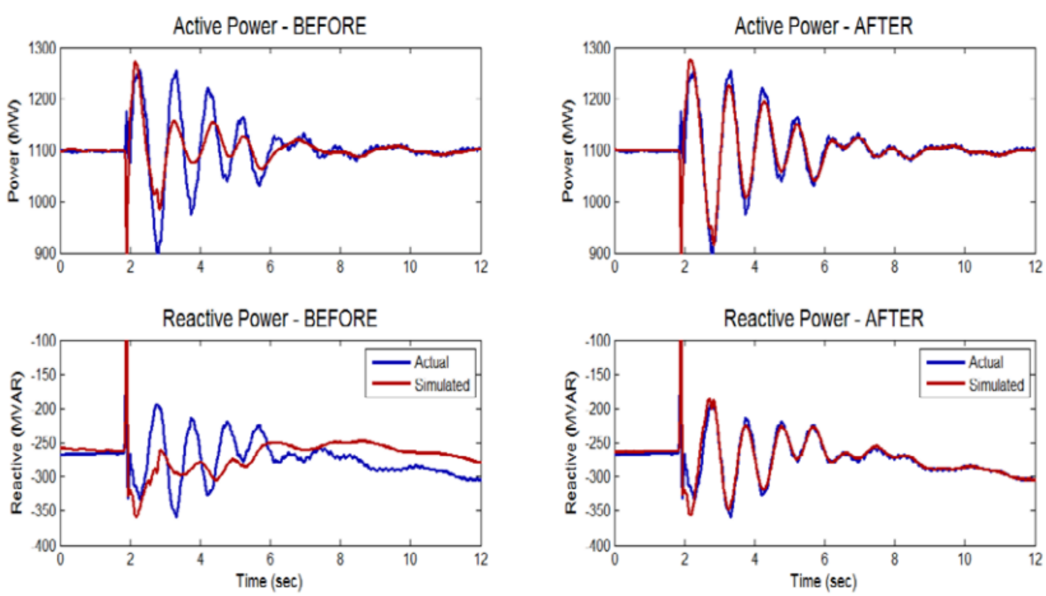

Figure 11. Power plant model validation before and after calibration (source: BPA)

PMU data is effective at validating positive sequence (rms) models that capture the electromechanical properties of the equipment or system. The electromechanical dynamics predominantly manifest at frequencies below 5 Hz, in the range that PMUs are well-suited to

[1] D. Kosterev, "Overview of Synchrophasor Applications", CIGRE tutorial, 2014, Available online: https://www.naspi.org/sites/default/files/2016-09/cigre_tutorial_kosterev_synchrophasor_apps_20141022.pdf

capture. As an intuitive explanation, note in Figure 11 that the fluctuations in real and reactive power occur slowly enough for the PMU to capture several points along the trace. Synchrophasors are much less effective at evaluating electromagnetic models, which characterize much faster behaviors. This topic will be explored next.

3.4 IBR Monitoring and Model Validation

Growing penetration of IBRs, e.g., distributed energy resources, renewable generation, and electronically connected loads, has resulted in new challenges for reliable electrical grid operation, analysis, and control. To successfully solve these issues, it is critical to have accurate models of IBR and accurate measurements with sufficient information to validate these models and to perform post event analysis.

A NERC analysis of recent disturbance events involving IBRs (including the Blue Cut Fire and Canyon 2 Fire) have shown the lack of available disturbance monitoring data adequate to determine the causes and effects of signal behavior during such events[1]. Inadequate data made it challenging, and in some cases impossible, to perform post-mortem event analysis and identify the root causes of large outages. Figure 12 shows a high-speed POW recording of the Blue Cut Fire event after 1,200 MW of PV generation units were disconnected or switched into momentary cessation mode due to inverter control actions[2]. PMUs are not capable of accurately representing this type of distortion because they assume the input signal is sinusoidal. The PMU algorithms try to fit the data to a sinusoidal model, leading to unreliable measurements.

Analysis of these recent events also demonstrated that stability issues during high-penetrations of IBRs are not easily detectable using positive sequence stability simulations due to wrong model parameters and usage of generic IBR models instead of detailed user-defined models. There are also some cases where electromagnetic transient (EMT) modeling of IBRs is needed due to limitations of the positive sequence models (e.g., an IBR connected to a weak system or where there is interaction between the IBR and other power electronics components of the control system). Therefore, advanced EMT-based modeling will play an increasingly important role for stability studies in electrical grid areas with high concentration of IBRs. There is a significant need for improved and validated positive sequence and EMT models and calibrated parameters of these models for proper representation of IBR dynamic behavior in bulk power system (BPS) dynamic studies.

Successful model validation and calibration of IBRs strongly depends on the availability of required measurements, data, and event logs. The key component of the needed dataset is high-resolution POW measurements of the event collected by DFR, power quality (PQ) meters, or other devices. EMT simulations result in voltage and current waveforms, so synchrophasors are not suitable for comparison.

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[1] NERC, "Recommended Disturbance Monitoring for Inverter-Based Resources", 2020, Available online: https://www.nerc.com/comm/PC/SMSResourcesDocuments/White_Paper_IBR_Disturbance_Monitoring.pdf

[2] NERC, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report.", 2017, Available online: https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf

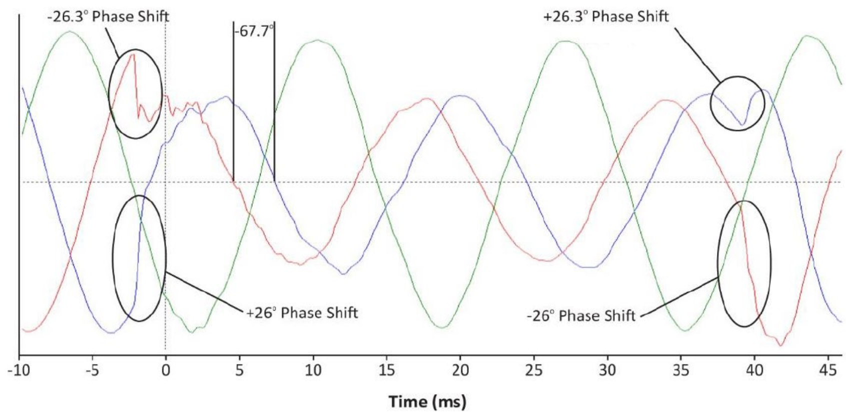


Figure 12. Phase jump at fault location during Blue Cut Fire Disturbance (Source: NERC)

An example of an IBR monitoring system deployed by the HydroOne company (Ontario), which required PQ monitor installation on all renewable generators larger than 250kW, is shown in Figure 13. The more than 1000 PQ monitors that have been installed helped to identify various IBR issues by providing event records for system-wide and local faults, plant-level and individual inverter fault response, abnormal IBR behavior, and equipment malfunction[1].

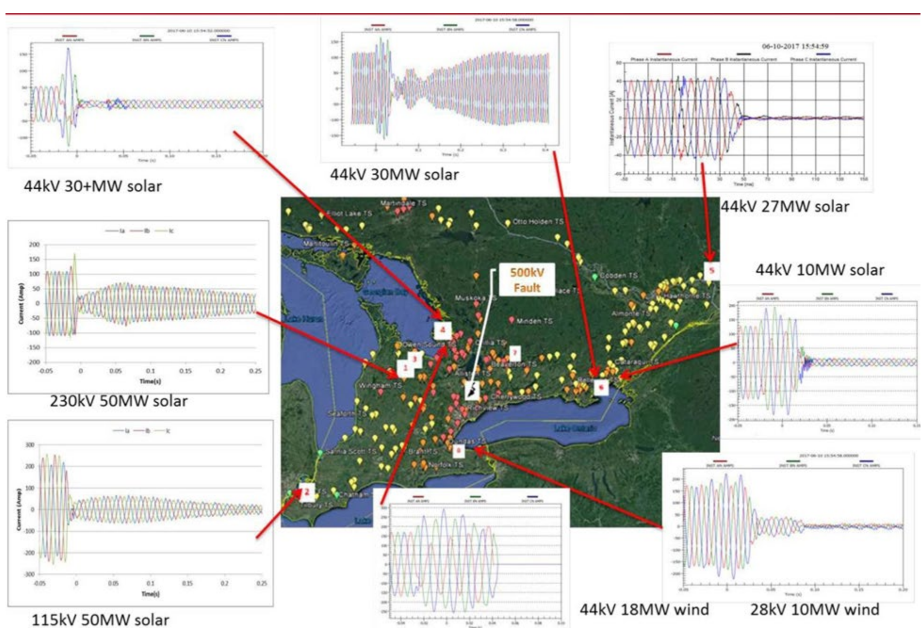


Figure 13. HydroOne renewable monitoring – system wide event (Source: Chester Li[1])

[1] Li, C. (2019). Inverter-Based Resource Monitoring and Event Investigations. Paper presented at the NATF/EPRI/NERC Power System Modeling Conference, Novi, MI. https://www.nerc.com/comm/PC/SAMS%20Agendas%20Highlights%20Minutes/2019_NERC-NATF-EPRI_Power_System_Modeling_Workshop_Presentations.pdf

3.5 Load Monitoring and Characterization

The dynamic characteristics and composition of electric loads have been changing over the past two decades. Increased penetration of electronically-connected load, EV chargers, and DERs resulted in a new problem - such loads respond differently to electric faults and grid events than the resistive loads that previously dominated the grid. Therefore, traditional dynamic load models do not accurately capture the dynamic behavior of the emerging load composition. Under extreme conditions, the stalling of induction motors (e.g., air conditioners) could cause a phenomenon called a fault-induced delayed voltage recovery (FIDVR) event. During this event, the system voltage remains at significantly reduced (inadequate) levels for several seconds after a transmission or distribution fault has been cleared and potentially could cause a cascading outage. Accurate simulation of the loads' dynamic behavior requires dedicated load modeling and parameterization[1].

Availability of field measurements is critical to understand dynamic behavior of emerging loads and to develop proper load models. PMUs and other high-resolution disturbance monitoring equipment have captured transient behavior at the transmission-level; however, limited information has generally been available to study the load response on the distribution level. Due to fast transients and the complex dynamic nature of electronically-connected loads and IBRs, POW measurements (preferably CPOW) are required to monitor and study their behavior.

For example, Southern California Edison (SCE) installed power quality meters (PQM) in a subtransmission network record POW, voltage magnitude, and current magnitude measurements during FIDVR events. [2] The data was used to validate a composite load model. Figure 14 shows measurements collected during a FIDVR event. The meter's voltage magnitude measurements, which are similar to those from a PMU, were able to capture the prolonged voltage recovery. The POW data provides additional detail, particularly for electrical cycles where the voltage is not well-represented by a constant-amplitude sinusoid. Such details are useful in understanding events and validating load models. The study is an excellent example of how PMU and POW data can be used in conjunction.

[1] NERC, Technical Reference Document - Dynamic Load Modeling, 2016, Available online: https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/Dynamic%20Load%20Modeling%20Tech%20Ref%202016-11-14%20-%20FINAL.PDF

[2] R. J. Bravo, R. Yinger, S. Robles and J. H. Eto, "FIDVR in distribution circuits," 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, 2013, pp. 1-5.

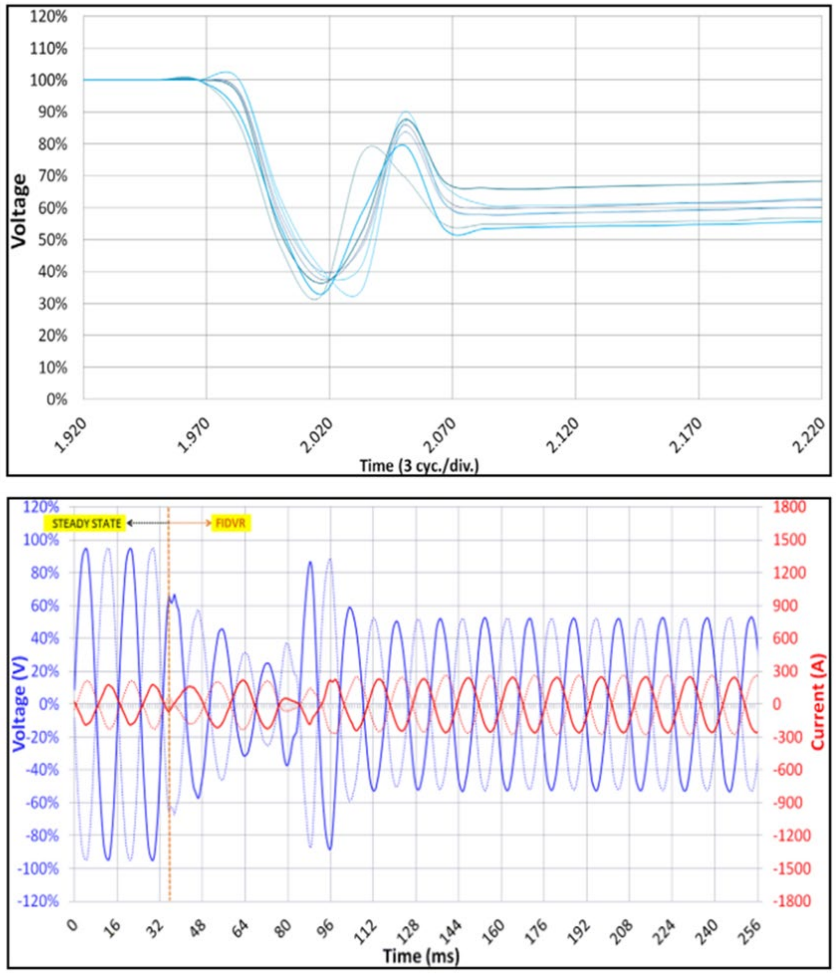


Figure 14. FIDVR event captured in voltage magnitude measurements (top) and POW measurements (bottom) (Source: SCE[1])

CPOW measurements can also be used for non-intrusive load monitoring for identification of load composition and of individual behind-the-meter loads and DER, based on analysis of the aggregated load measured by the main power meter (e.g., PQ meters). There are several approaches used for non-intrusive load monitoring (e.g., active/reactive power analysis, steady state signatures, wave form and harmonics analysis, and artificial intelligence (AI) applications). All electronically-connected loads and IBRs create different harmonics with individual signatures. For example, Figure 15 shows a comparison of POW measurements collected from the Bonneville Power Administration (BPA) headquarters building in 2007 and 2017.[2] According to BPA, increasing penetration of electronically-connected loads between 2007 and 2017 drove the increase in harmonics apparent in the current waveforms. Harmonic signature analysis of the CPOW measurements combined with other sources of information has great potential for non-intrusive load monitoring and characterization. Though PMUs can support some aspects of non-intrusive load monitoring, they are not useful for harmonic signature analysis because these

[1] R. J. Bravo, R. Yinger, S. Robles and J. H. Eto, "FIDVR in distribution circuits," 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, 2013, pp. 1-5.
[2] D. Kosterev and Steve Yang, “Load Composition and Monitoring at BPA”, NERC LMTF meeting, 2017 Available online: https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/2017-10-NERC_LMTF_-_BPA_Load_Survey_and_Monitoring_-_Kosterev.pdf

frequencies are filtered out as part of the measurement process, which is focused on estimating parameters of the fundamental 60 Hz waveform.

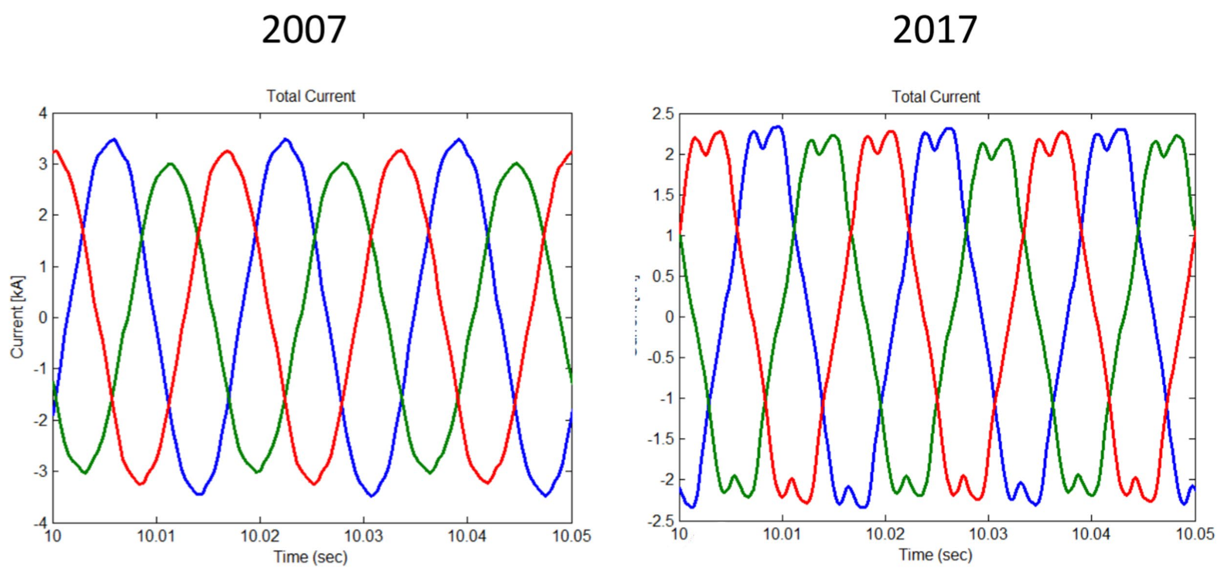


Figure 15. Commercial building POW measurements (Source: BPA[1])

3.6 Asset Condition Monitoring and Management

PMU measurements have been used for asset health monitoring by various electrical utilities and other entities. A comprehensive review of PMU-based applications for equipment health and mis-operations diagnostics is given in the NASPI report, "Diagnosing Equipment Health and Mis-operations with PMU Data." [2] Interestingly, almost all of the reported events resulted in a common symptom: oscillations. As mentioned previously, PMUs are well-suited for detecting and analyzing oscillations. However, many equipment failures will not result in a periodic disturbance leading to an oscillation. Rather, they will create distortions in voltage and current waveforms that cannot be well-represented by synchrophasors.

The recognition that "signatures" in the waveforms can sometimes be used to identify equipment failures has led asset health monitoring to be listed as a potential application of CPOW.[3] In fact, the IEEE PES Working Group on Power Quality Data Analytics recently released a report discussing the topic[4]. The authors introduce the report by stating:

> In recent years, engineers and researchers in the field of power quality, power system protection, and equipment testing have realized that useful information can be extracted

[1] D. Kosterev and Steve Yang, "Load Composition and Monitoring at BPA", NERC LMTF meeting, 2017 Available online: https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/2017-10-NERC_LMTF_-_BPA_Load_Survey_and_Monitoring_-_Kosterev.pdf
[2] NASPI, Diagnosing Equipment Health and Mis-operations with PMU Data, 2015, Available online: https://www.naspi.org/sites/default/files/reference_documents/14.pdf?fileID=1530
[3] Silverstein, Alison, and Jim Follum. (2020). High-Resolution, Time-Synchronized Grid Monitoring Devices. NASPI. Available online: https://www.naspi.org/node/819
[4] IEEE PES Working Group on Power Quality Data Analytics. (2019). Electric Signatures of Power Equipment Failures Technical Report PES-TR73. IEEE Power & Energy Society. Available online: https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TP_TR73_TD_122019.html

from the waveforms for the purpose of equipment condition monitoring. In the field of power quality, for example, power quality monitors routinely collect power disturbance data. Some of the data do not indicate the existence of a power quality problem but they have been used to detect the presence of abnormal equipment operation in the system.

Thus, the power quality community has already begun to address asset health monitoring. The report provides a comprehensive review from a power quality data analytics perspective. The analysis method consists of collecting waveform-type power disturbance data, extracting signature information, and from this information identifying various power equipment failures. For example, Figure 16 shows the waveform signature data from a PQM and its cause: arcing and pitting along the arcing horn of circuit switcher.[1] As another example, Figure 17 illustrates voltage and current waveform data which had initiated transformer maintenance, thereby preventing a catastrophic failure.[2] In each of these examples, the waveforms are highly non-sinusoidal. Their signatures can be clearly observed in POW data, while their appearance in PMU data would be difficult to predict or interpret.

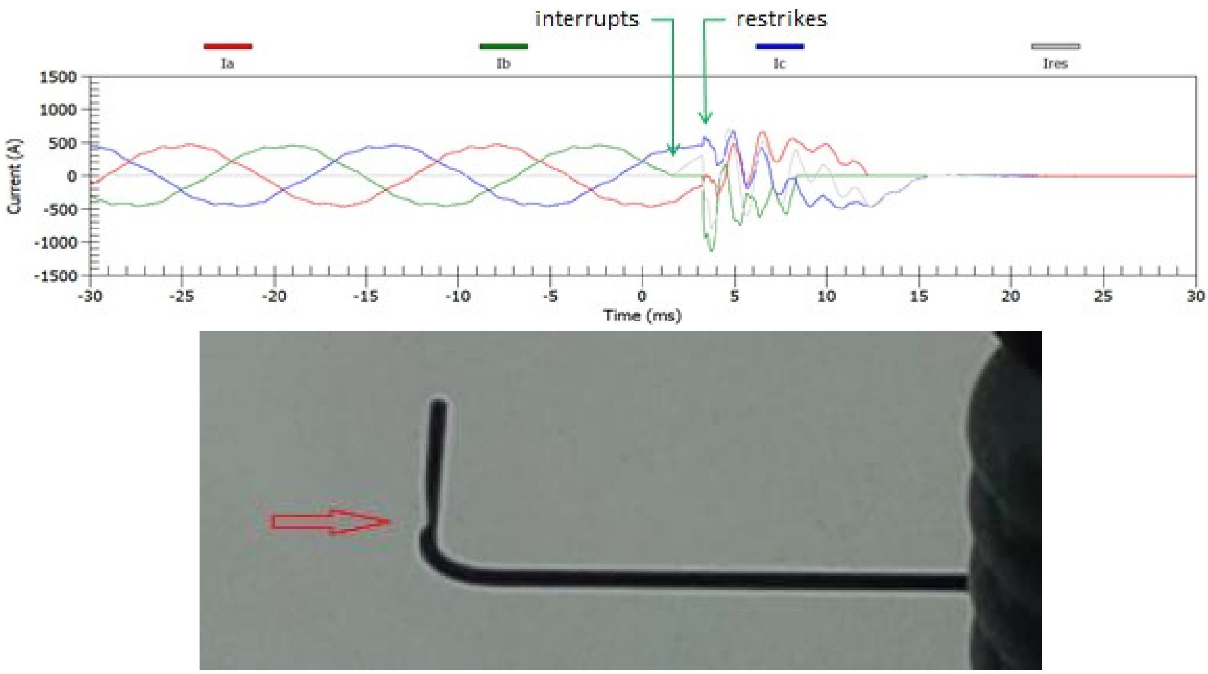


Figure 16. Waveform with restrike of a capacitor bank (upper) and Pitted arcing horn of a capacitor bank (lower)[2]

[1] IEEE PES Working Group on Power Quality Data Analytics. (2019). Electric Signatures of Power Equipment Failures Technical Report PES-TR73. IEEE Power & Energy Society. Available online: https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TP_TR73_TD_122019.html
[2] Irwin, L. A. (2010). "Real experience using power quality data to improve power distribution reliability." Proc. of 14th IEEE PES International Conference on Harmonics and Quality of Power. 1-4.

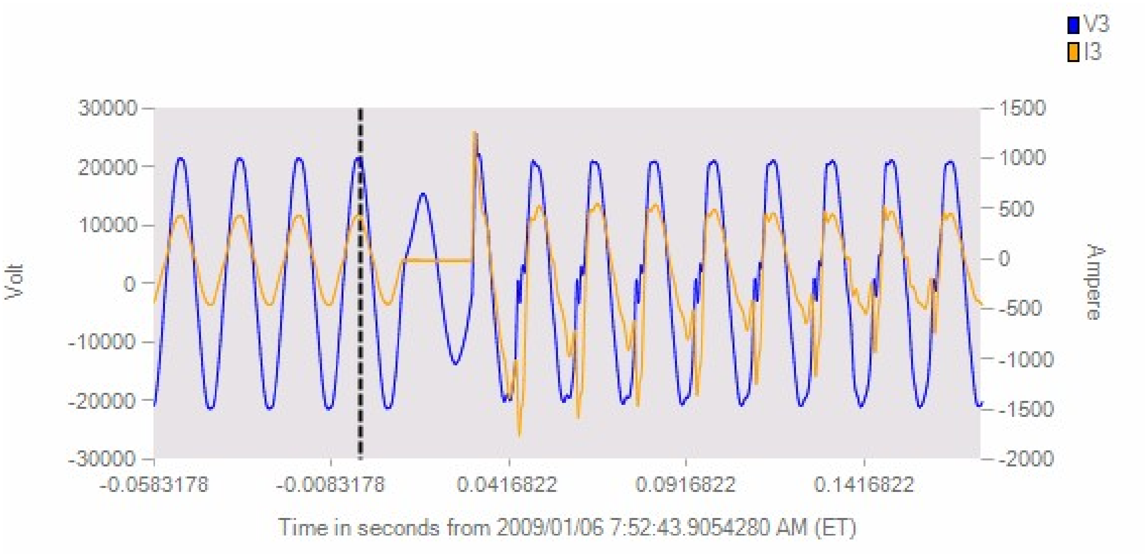


Figure 17. Zero current waveform data during transformer load tap changer failure[1]

Patent US9665843B2, held by ABB Power Grids Switzerland AG, specifies techniques and/or systems for developing a health profile of an industrial asset based upon data pertaining to such an industrial asset, using POW data. [2] There are asset combined monitoring service packages available, such as by ITL Instrument Transformers, which uses CPOW measurement devices and specialized software. [3]

[1] Irwin, L. A. (2010). "Real experience using power quality data to improve power distribution reliability." Proc. of 14th IEEE PES International Conference on Harmonics and Quality of Power. 1-4.
[2] https://patents.google.com/patent/US9665843B2/en
[3] https://itl-uk.com/asset-management-monitoring-challenges/?cn-reloaded=1

4.0 Expansion to POW

Just as measurement technology deployments have been expanding to include PMUs, they will expand to include more CPOW deployments. PMUs and synchrophasor data have existed for decades, and the first of today's modern PMUs entered service around 2010. In 2021, PMU systems are highly sophisticated in some areas but not in others, and we are in the middle stages of deploying PMUs and collecting and analyzing the data.

Once POW measurements are determined to be needed for a particular problem, key elements to a deployment include:

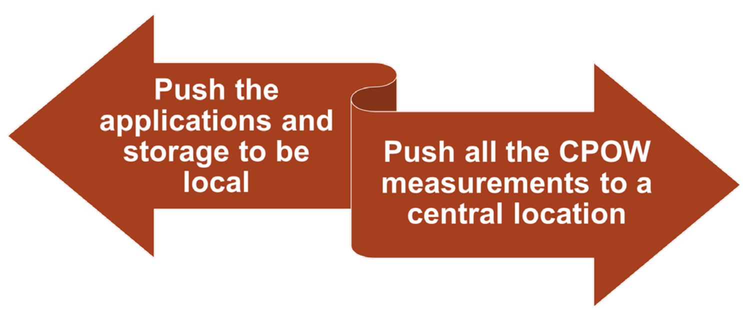
- Potential/current transformers at each point of measurement
- Measurement devices that take the POW measurements
- Some method of transporting that data to where it will be processed or stored
- Storage for the data both for archival purposes and for ready access for applications that perform analysis

It is critical to note that measurement data is of limited use without storage and communications ensuring that the data is available both where and when it is needed. A measurement technology deployment must include sufficient communications and storage infrastructure to function, not just measurement devices alone. Budgeting and planning should include not just equipment, but personnel. One of the lessons learned from PMU deployments is that the quality and availability of measurements is much higher in organizations with personnel assigned to manage the measurement system.

POW measurements can be carried out by many devices already deployed, including digital fault recording (DFR) devices, power quality (PQ) meters, merging units, and digital relays. There are some similarities in the expansion to using POW and CPOW measurements compared to the previous expansion to include synchrophasors. There are some differences as well; short-duration POW devices and data that capture specific events have existed for decades.

Additionally, communications and storage infrastructures, which are fundamental to both PMU and POW measurement systems, already exist for wide-area measurement systems developed for PMUs and can be leveraged for CPOW availability. For both PMU and POW measurement deployments, not every transmission owner and control room will start to use them at the same time or deploy them with the same alacrity.

One aspect of the measurement process that may change is where certain measurements are made. Power quality and synchrophasor calculations are typically carried out by software/firmware located within a remote measurement device, and the resulting measurement results are communicated onward. When the POW sampled values are



communicated onward, power quality, synchrophasor, and other calculations can be performed in multiple places along the data process path.[1]

Alternatively, since many POW uses are local to the digitizer (or merging unit), it is possible to design the data management, storage, and applications platforms to be local to the POW measurement sources instead of in a central location.

What infrastructure is needed should be considered carefully based on the end results needed:

- Local and short duration – needs POW and minimal storage, possibly analytics. Example: Digital disturbance recorders, some protection devices.
- Local and long duration – i.e., observation of changes in grid asset behavior over time: Needs POW and some storage and analytics, but not wide-area availability. Example: Asset condition monitoring.
- Wide area, critical values can be calculated locally or centrally – needs time synchronization and wide-area availability, but modest bandwidth. Example: Synchrophasors.
- Wide area, critical values need to be gathered and calculated centrally at a later time – needs time synchronization and wide-area availability of data with some mechanism for data availability, which may include offline retrieval. Example: Forensic analysis of wide-area system events.
- Wide area or medium area critical values need to be gathered and calculated centrally in real time – needs time synchronization and wide-area availability with high bandwidth. Example: Mitigation of sub-synchronous resonance (SSR) in wind farms[2]

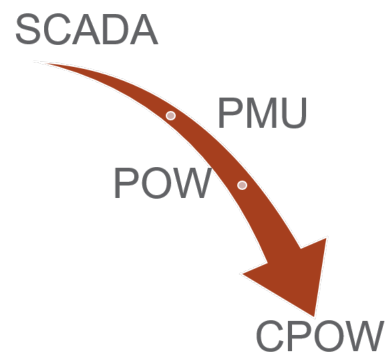
It is worth noting that while there are use cases that require sharing time-synchronized CPOW measurements over a specified area, in many or most cases that area is fairly local. As a result, while the full rollout of PMU-based wide-area monitoring required sharing data among TSOs/RCs in real time, much of the value of using CPOW measurement systems can be achieved without coordinating with outside organizations.

[1] For more on the data process path, as well as on data quality and its relationship to communications networks and storage needs, see:
Miller, Laurie E., Alison Silverstein, Dhananjay Anand, Allen Goldstein, Yuri Makarov, Frank Tuffner, and Kevin Jones. 2017. "PMU Data Quality: A Framework for the Attributes of PMU Data Quality and a Methodology for Examining Data Quality Impacts to Synchrophasor Applications." Richland, WA. https://www.naspi.org/sites/default/files/reference_documents/PARTF_WhitePaper_20170314_Final_PNNL_26313.pdf.

[2] W. Xu, Z. Huang, X. Xie and C. Li, "Synchronized Waveforms a Frontier of Data-Based Power System and Apparatus Monitoring, Protection and Control," in IEEE Transactions on Power Delivery.

The promulgation of POW and CPOW measurement system can be done in stages, gradually expanding the capability to address more and more application and analytics and gradually increasing the ability to create, process, transmit, and store CPOW measurements at higher time resolutions.

The smaller the time gap between measurement reports, the more bandwidth the data stream requires and the greater the storage requirements.



4.1 NERC Recommendations on Data Collection

The industry is recognizing the need for best practices and standardization with respect to data needs for certain problems. Table 1 is redrawn from NERC’s 2020 document, “Recommended Disturbance Monitoring for Inverter-Based Resources” [1]. Table 1 gives recommended data to be collected, time resolution of that data, and length of time that data should be retained. In particular, note the recommendations for DFRs, DDRs (dynamic disturbance recorders), and inverter dynamic recordings. This table is included as an example of how measurement requirements can be specified for a particular application. Organizations seeking to enable a set of applications with POW or CPOW systems should make similar determinations for each application, keeping expansion to future applications in mind.

Table 1: Recommended Measurement Data and Retention[1]

Data Type	**Measurement/Data Points**	**Resolution**	**Retention**	
Plant Control Settings and Static Values	This data includes the settings, set points, and other static information that should be captured about the plant. This information should be captured at a resolution sufficient to identify any changes (i.e., when settings are changed). Data points include: • Active power/frequency control mode of operation • Reactive power (current)/voltage mode of operation Individual inverter mode of operation (e.g., reactive, voltage, or power factor) • Digital control system gains, time constants, limiters, etc.			
Plant SCADA Data	• The plant SCADA system is often a lower resolution repository of information that should include, at a minimum, the following data points:	1-2 seconds	1 year	

[1] NERC, “Recommended Disturbance Monitoring for Inverter-Based Resources”, 2020, Available online: https://www.nerc.com/comm/PC/SMSResourcesDocuments/White_Paper_IBR_Disturbance_Monitoring.pdf

	• All breaker statuses • Shunt (dynamic or static) reactive compensation statuses • Shunt (dynamic or static) reactive power output • Substation transformer status • Substation transformer tap position • Time synchronization (e.g., GPS status word) • Medium voltage collector system statuses • Individual inverter statuses • External control signals from the BA, RTO, RC, etc. • External automatic generation control signals • Active and reactive power commands sent to individual inverters • Active and reactive power output of individual inverters • Overall plant active and reactive power output • Point of Measurement voltage and medium voltage collector system voltages			
SER Data	SER devices should be sized to capture and store hundreds or thousands of event records and logs. SER events records can be triggered for many different reasons but include, at a high level, the following: • Event date/time stamp (synchronized to common reference (e.g., Coordinated Universal Time (UTC)) • Event type (status changes, synchronization status, configuration change, etc.) • Description of action • Sequence number (for potential overwriting)	≤ 1 millisecond	90 days	
DFR Data	This data should be captured for at least the plant-level (e.g., at the Point of Measurement) response to BPS events. It is typically high resolution (kHz) point-on-wave data, and triggered based on configured settings. Data points should include: • Bus voltage phase quantities • Bus frequency (as measured/calculated by the recording device) • Current phase quantities • Calculated active and reactive power output • Dynamic reactive element voltage, frequency, current, and power output	> 960 samples per second, triggered	90 days	

DDR Data	A DDR (e.g., a phasor measurement unit (PMU) or digital relay with this capability) should capture the plant-level response during normal and disturbance events. This data should be captured continuously at the Point of Measurement and can be used for multiple purposes including event analysis and disturbance-based model verification. Data points should include: • Bus voltage phasor (phase quantities and positive sequence) • Bus frequency • Current phasor (phase quantities and positive sequence) • Calculated active and reactive power output	≥ 30 samples per second, continuous	1 year	
Inverter Fault Codes and Dynamic Recordings	The individual inverters are highly complex pieces of equipment, with a vast amount of information continually being calculated and stored within them. The data from inverters are very high resolution. At a high level, for grid BPS faults, the following information should be available from the inverters for analysis by the GO: • All major and minor fault codes • All fault and alarm status words • Change of operating mode • High and low voltage fault ride through • High and low frequency ride through • Momentary cessation (if applicable) • PLL loss of synchronism • DC current and voltage • AC phase currents and voltage • Pulse width modulation index • Control system command values, reference values, and feedback signals	Many kHz	90 days	

4.2 POW Measurements Already Being Collected

POW measurements already exist in a variety of deployed grid devices. PMUs calculate values using POW samples, after which the POW samples may be discarded. However, those samples could be retained for other purposes. Alternatively, PMU measurements can be calculated after the fact from POW data sets as well as on PMU devices themselves.

Additionally, other devices such as merging units, DFRs, power quality meters, and digital relays take POW measurements and thus represent sources of POW data that may already be available and deployed. The POW measurement taken by such devices can be considered for other applications if:

- The data is of sufficient time resolution

- The data meets the application requirements for time synchronization, or the device(s) can be upgraded to meet such requirements
- There is sufficient storage either in the measurement device itself, or sufficient storage and local communications to collect enough data for the application requirements, either as-is or by upgrading local storage and communications
- There is sufficient communications infrastructure for any CPOW streaming requirements for the application

Measurement systems and applications that use POW measurements fall along a spectrum for both sampling/reporting rate and for continuity of sampled/reported data, as shown in Figure 18[1]. POW data samples are fully retained and stored for short durations in event-triggered devices such as digital fault recorders (DFRs), as shown on the left. For devices such as PMUs, the POW data is typically not stored or transmitted, but processed into other metrics which are then continuously reported.

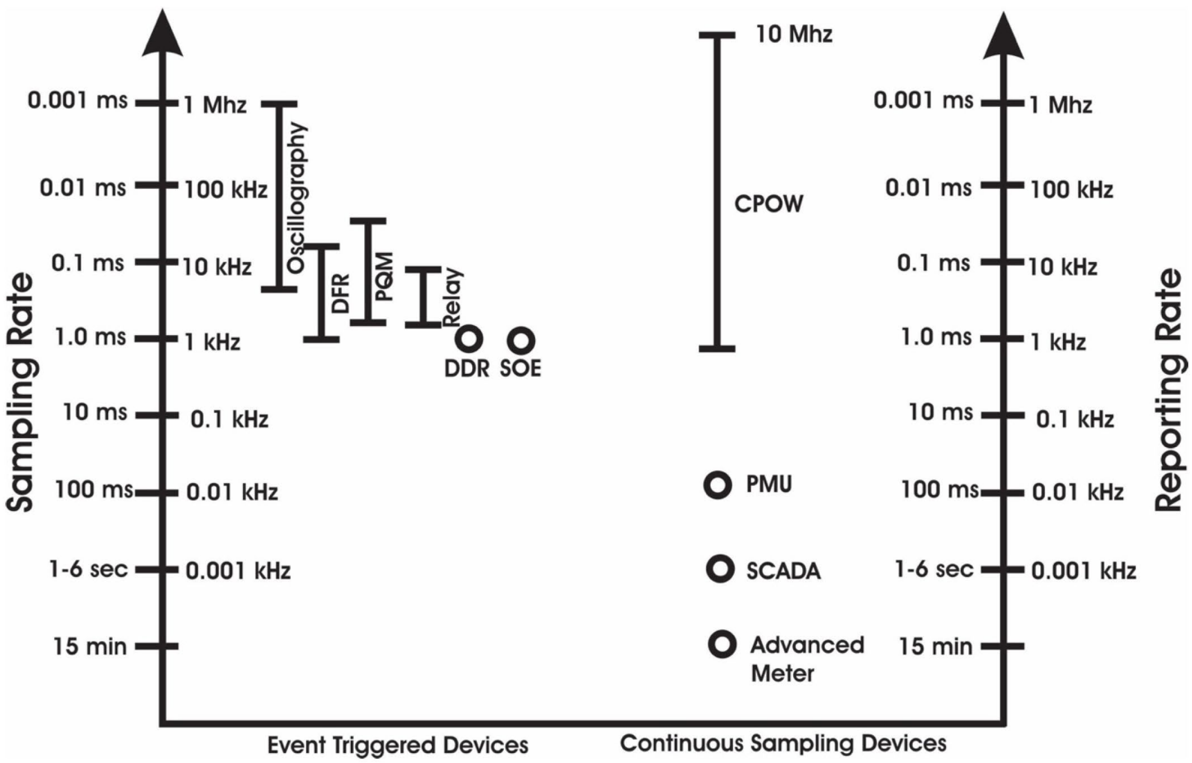


Figure 18: Grid monitoring devices by resolution and data continuity[1].

[1] Silverstein, Alison, and Jim Follum. 2020. "High-Resolution, Time-Synchronized Grid Monitoring Devices." Available online: https://www.naspi.org/sites/default/files/reference_documents/pnnl_29770_naspi_hires_synch_grid_devices_20200320.pdf

4.3 A Complete POW Measurement System

A POW measurement system starts with the equipment needed to take the measurement itself, including the conductor and measurement transformer at the point of measurement and the measurement device itself that takes the sample. The measurement device also contains some amount of storage to retain the values, though this may be limited, requiring that data be off-loaded or discarded as new measurements are taken.

There then must be a complete data process path[1] to deliver the data both to the applications that use the data and to archival storage. Some problems require that POW data be shared over a wider area than one measurement location. That area may be a very small, local area, such as for advance coordinated protection schemes or asset monitoring, or it may cover a very large area. In such cases, infrastructure for communications and storage is needed.

A fully digital substation uses a high-bandwidth process bus (IEC 61850-9-2). In the digital substation, the source of digital measured values is the merging unit that publishes sampled values on the process bus according to the IEC 61869 standard. Merging units are digital devices that are designed to collect multi-channel digital signals as inputs from sensors (current and voltage transformers). From a measurement perspective, this provides a suitable input for virtually any measurement process, from RMS to frequency estimation. It is also not limited to measurements as applications can also consume raw data directly circumventing any data compression.

All of the above components, if already present, can be leveraged for a CPOW deployment, but upgrades may be needed, especially for data storage. Figure 19 shows data storage requirements as they increase for SCADA, synchrophasors, and CPOW measurement systems.

[1] Miller, Laurie E., Alison Silverstein, Dhananjay Anand, Allen Goldstein, Yuri Makarov, Frank Tuffner, and Kevin Jones. 2017. “PMU Data Quality: A Framework for the Attributes of PMU Data Quality and a Methodology for Examining Data Quality Impacts to Synchrophasor Applications.” Richland, WA. Available online: https://www.naspi.org/sites/default/files/reference_documents/PARTF_WhitePaper_20170314_Final_PNNL_26313.pdf.

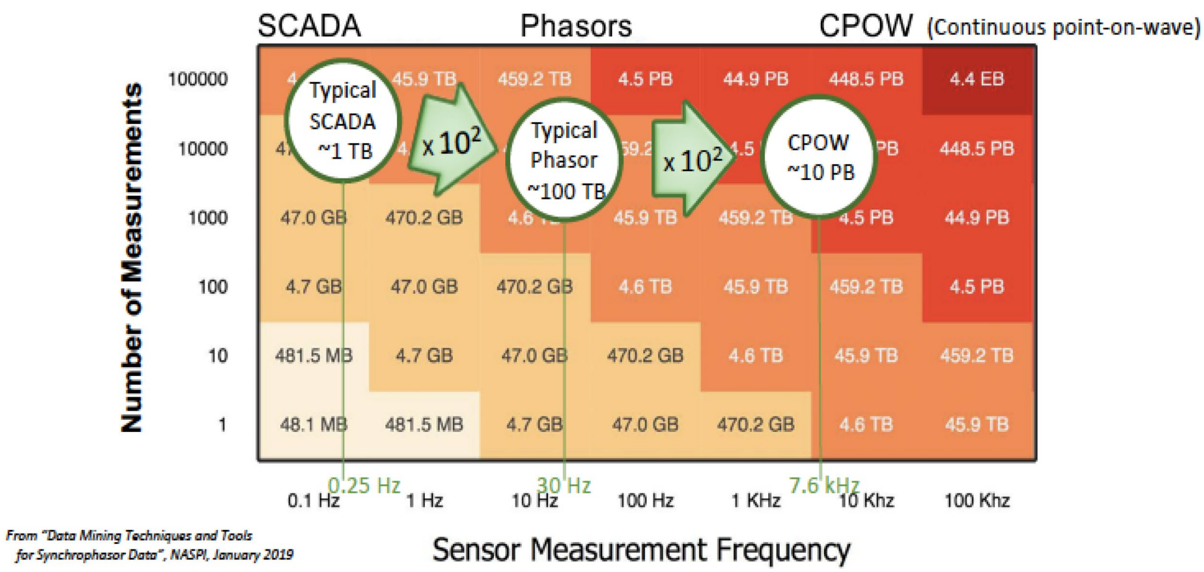


Figure 19: Annual data storage requirements as they increase for SCADA, synchrophasors, and CPOW (Source: NASPI[1])

4.4 Standards

Applicable standards are rapidly evolving and are needed for specifying the capture of data itself, how and how long to store it, and how to transport it securely.

4.4.1 Standards for Snapshot Data

There are two formats specified by IEEE for sharing "snapshot" point-on-waveform measurements: IEEE Std C37.111-2013 COMTRADE and IEEE Std 1159.3-2019.

IEEE Std C37.111, the COMTRADE standard, "…defines a common format for the data files and exchange medium needed for the interchange of various types of fault, test, and simulation data. The rapid evolution and implementation of digital devices for fault and transient data recording and testing in the electric utility industry have generated the need for a standard format for the exchange of time sequence data." [2] It thus specifies a text and binary format for storing point-on-wave samples.

COMTRADE files can use text strings that can be user-defined or pre-defined by the vendor to label quantities that can be used to transmit phasor information. The H8 Working Group of the IEEE Power System Relaying Committee devised a schema for using the COMTRADE format

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[1] The initial version of this figure appears in the NASPI white paper, "Data Mining Techniques and Tools for Synchrophasor Data," which is available online at https://www.naspi.org/node/743. The modified version used here is from the NASPI report, "High-Resolution, Time-Synchronized Grid Monitoring Devices," which is available online at https://www.naspi.org/node/819.

[2] "IEEE/IEC Measuring relays and protection equipment – Part 24: Common format for transient data exchange (COMTRADE) for power systems," in *IEEE Std C37.111-2013 (IEC 60255-24 Edition 2.0 2013-04)* , vol., no., pp.1-73, 30 April 2013, doi: 10.1109/IEEESTD.2013.6512503.

for phasor data by making synchrophasor assignments to the standard COMTRADE parameters.[1]

IEEE Std 1159.3-2019[2], (PQDIF, or Power Quality Data Interchange Format) which is maintained by the IEEE PES Transmission & Distribution Committee, also specifies a standard format for the exchange of POW voltage and current measurements, along with derived power, and energy measurements, with a focus on the power quality domain.[3] Point-on-wave samples, rms values, phasor magnitude/phase angle, and status values can be stored in a PQDIF file. Appendix E of IEEE Std 1159.3-2019[2] is an informative discussion of the relationship of PQDIF to COMTRADE.

IEC 61869-9:2016[4], “Instrument transformers - Part 9: Digital interface for instrument transformers,” defines requirements for digital communications of instrument transformer measurements. This is much broader in scope.

4.4.2 Standards for Communications and a Note on Cybersecurity

Cybersecurity is critical for a measurement system deployment that includes any kind of network access in the data process path.

The wide-area networks and local area networks (LANs) involved in any data process path[5] are at risk unless they are completely isolated intranets. These networks pose the same security risks as any high-bandwidth communications network. Critical data transported over such a network should be encrypted and the network access authenticated. Network access points and the enterprise system should be monitored for intrusion or attack. The electric industry and others are already considering whether and how to use cloud data transport and storage in a secure fashion. Cybersecurity measures for streaming real-time CPOW data will need to be low-latency, so the security and data transport method in combination do not compromise the data’s delivery and usability for intended applications. It is possible to transfer protection data with real-time encryption and authentication over a wide area network using IP/MPLS communications, or IEC 61850-90-5; similar approaches could be used for CPOW data.[6]

IEEE P2664 (the Streaming Telemetry Transport Protocol (STTP) protocol) is a standard under development to define a protocol with built-in security and lossless data compression options for

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[1] Allen, Eric, Scott Anderson, Gabriel Benmouyal, Bui Dac-Phuoc, Bill Dickerson, Jim Hackett, Shane Haveron, et al. 2010. “Schema for Phasor Data Using the COMTRADE File Standard.” https://www.pes-psrc.org/kb/published/reports/Schema_for_Phasor_Data_Using_the_COMTRADE_File_Standard.pdf.
[2]"IEEE Recommended Practice for Power Quality Data Interchange Format (PQDIF)," in IEEE Std 1159.3-2019 (Revision of IEEE Std 1159.3-2003), pp.1-185, 1 May 2019, doi: 10.1109/IEEESTD.2019.8697192. https://ieeexplore.ieee.org/document/8697192
[3] N., Rathina & Marimuthu, N. (2009). ENHANCING POWER QUALITY MONITORING USING WIRELESS APPLICATION PROTOCOL ENABLED MOBILE DEVICES.
[4] “IEC 61869-9:2016 .” 2016. IEC . April 27, 2016. https://webstore.iec.ch/publication/24663.
[5] Miller, Laurie E., Alison Silverstein, Dhananjay Anand, Allen Goldstein, Yuri Makarov, Frank Tuffner, and Kevin Jones. 2017. “PMU Data Quality: A Framework for the Attributes of PMU Data Quality and a Methodology for Examining Data Quality Impacts to Synchrophasor Applications.” Richland, WA. https://www.naspi.org/sites/default/files/reference_documents/PARTF_WhitePaper_20170314_Final_PNNL_26313.pdf.
[6] S. M. Blair et al., "Validating secure and reliable IP/MPLS communications for current differential protection," 13th International Conference on Development in Power System Protection 2016 (DPSP), Edinburgh, 2016

efficient transport of streaming power system data over Internet protocol (IP) communication systems. It specifies data and control channels and uses a publish-subscribe architecture for controlled signal-level data access."[1] [2] STTP supports transferring both real-time and historical time-series data at full or down-sampled resolutions. The Grid Protection Alliance provides a tool called the STTP Connection Tester that validates that a subscription-based connection is working as expected.[3]

4.5 Possible Paths Forward

Paths forward from existing technology deployments to POW/CPOW deployments can vary based on the available infrastructure and devices that are already deployed, the needs of the measurement technology owner, and unfolding standards and best practices.

The trend toward merging units and "digital substations" offers a path towards being able to support a wide variety of existing and future measurement needs, including PMU measurements and POW/CPOW measurements. Local communications and storage at a substation, such as what might already be in place for PMU deployments, may be leveraged for POW/CPOW, either as-is or with upgrades for the greater volume of data. The same holds true for wide-area communications for PMU streaming.

Following a practice to include deployment of POW measurement technology and other measurements and data in the installation all new IBRs provides an opportunity to incrementally add such capabilities throughout a system. Similarly, new substations or major substation upgrades are good opportunities to follow a merging unit / digital substation approach.

Existing merging units, DFRs, power quality meters, and other devices that already take POW measurements represent an opportunity to collect/retain more of that data and expand it to other uses. The existing device deployments and the future application requirements need to be compared to determine what upgrades are needed. Does an existing device take snapshot data or does it record continuously? Does it report that data when triggered, on some regular schedule, or is it streamed continuously? How does this compare to the future application needs? Can existing data concentrators be used to locally store data beyond the limits of the device's storage?

Finally, giving thought to long-term archiving and storage of POW measurements, including the recommendations from NERC detailed in Section 4.1, can allow for the use of existing data for a variety of future applications.

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[1] IEEE P2664. https://standards.ieee.org/project/2664.html

[2] Carroll, J. Ritchie, and Robertson, F. Russell. Fri . "A Comparison of Phasor Communications Protocols". United States. https://doi.org/10.2172/1504742. https://www.osti.gov/servlets/purl/1504742.

[3] https://www.gridprotectionalliance.org/technology.asp#STTP

5.0 Conclusion

The widespread deployment of PMUs has constituted a significant advancement for the modern power system. These devices will continue to provide critical measurements to support reliable power system operation and planning. But they also have limits. In power systems with increasing penetrations of inverter-based generation resources, power electronics in the transmission system, distributed energy resources in distribution systems, electric vehicles, and other electronic loads, measurements that can accurately capture voltage and current waveforms are needed.

Point-on-wave (POW) is a broad class of measurement composed of digital samples of voltage and current waveforms. These measurements are currently available from power quality meters, digital fault recorders, merging units, and other devices. Utilities can begin using these measurements immediately to support emerging applications such as inverter-based resource management and asset health monitoring. Depending on the application, POW measurements can be analyzed and stored locally or telemetered to a central location. The application can also determine whether POW data is collected in snapshots or continuously. Communications and storage infrastructure should be planned and built based on the needs of applications. Including future applications in planning can help ensure the supporting infrastructure will support future needs.

The example uses cases provided in this guide were included to demonstrate the capabilities and limitations of PMU and POW measurements. There are many applications for PMU and POW data already, and the lists will continue to grow. As new applications for synchronized power system measurements are explored, it will benefit the electric power industry to match each application with a suitable measurement system. Our hope is that this document will help guide readers in this decision-making process.

Appendix A: Further Reading on Communications Networks, Storage, and their Impacts on Data Quality for Wide-Area Measurement Systems

As noted in the introduction to this guide, a measurement technology deployment must include sufficient communications and storage infrastructure to function, not just measurement devices alone. The following references may prove useful in understanding the requirements for and impacts of the communications and storage of a power grid measurement system.

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V. C. Gungor et al., "Smart Grid Technologies: Communication Technologies and Standards," in IEEE Transactions on Industrial Informatics, vol. 7, no. 4, pp. 529-539, Nov. 2011, doi: 10.1109/TII.2011.2166794.

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