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HIGH-RESOLUTION, TIME-SYNCHRONIZED GRID MONITORING DEVICES

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North American Synchrophasor Initiative
Technical Report

March 20, 2020

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All errors are the authors' alone.

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1.0 Introduction & summary

Over recent decades, as modern power systems have become larger, faster and more complex, system operators and planners have begun asking for the collection of high resolution, time-synchronized data on system conditions and events.

Traditional power systems were built and operated using SCADA systems that report measured grid conditions every 4 to 6 seconds, usually time-stamped to the transmission owner's local time. Those systems now contain digital relays that sample grid conditions at a rate up to a million samples/second to detect breaker conditions and implement system protection schemes, and digital disturbance recording devices (DDRs) sampling at rates up to 24,000 samples/sec. to record and preserve data on specific events. For the past decade, many transmission owners have been installing phasor measurement units (PMUs) that continuously report from 30 to 60 samples/sec., using the UTC-synchronized data for event analysis, model development, and operations support.

As users and analysts become accustomed to interpreting and using PMU data, there is increasing demand for higher-resolution, time-synchronized point-on-wave (POW) data that can reveal more about local and wide-area conditions without the filtering and processing that occurs within a PMU. Synchrophasor measurements are obtained by estimating the magnitude and angle of a sinusoid based on sampled voltage and current waveforms. A POW measurement device reports the sampled waveforms directly, typically at rates of 256 samples/sec. or higher. Such sampling rates are well within the capability of many Intelligent Electronic Devices (IEDs) and monitoring devices, although many such devices cannot record and store long durations of data. With the addition of on-board or local data storage capability and easy data access capability, these IEDs and monitoring devices will enable many new data uses.

POW data differs from PMU data in important ways. Many POW devices sample and report measurements at a higher rate than current PMU devices, from 256 samples/sec. up to a million samples/sec. While PMU data is filtered and processed to yield synchrophasors, POW measurements are sequential, time-stamped scalar measures of a single value (current or voltage) with minimal filtering, offering a highly accurate representation of the waveform measured. Thus, POW data can be used in a variety of applications with use-specific filtering and processing applied as needed – including the calculation of synchrophasors.

This paper advocates the deployment of continuous POW monitors (CPOWs) to complement the fleet of event-triggered, short-duration POW monitors with the PMUs and SCADA already in use. A CPOW should have the following features:

- Time-synchronized POW measurements at a rate of 256 samples/sec. or much faster,
- Continuous rather than event-triggered recording of grid conditions,
- Data retained long enough to support analyses and collection requests following system disturbances, and
- High data availability through connectivity that enables remote polling or real-time streaming of some or all of the data from the CPOW device or its archive.

The availability of higher resolution PMU and DDR data has enabled insights about power system characteristics and behavior, such as inter- and intra-area oscillations that were undiscoverable with only low-resolution SCADA data. But because event-triggered POW devices only record short-duration, high-resolution waveform data for events that are already recognized, those devices do not capture waveform data for all of the events that happen on the grid, particularly for longer events that are not fully recognized and specified for data recording. The lack of high-resolution, longer-duration, archived CPOW data is limiting our ability to understand and diagnose high-speed grid conditions and events.

Most observers anticipate that CPOW monitors will not replace SCADA or synchrophasor monitoring systems, but will complement and augment those systems over the coming decade. Adding CPOW data to current sources and analyses will let the electric industry leverage multiple layers of data to serve multiple functions and analytical purposes, collectively enabling another step-change improvement in power system observability, planning and operation.

The principal steps needed to enable the effective collection and use of CPOW data effectively will entail:

- getting long-duration CPOW measurement devices deployed for the purpose of general analysis, rather than short-burst dedicated local use (as in the case of a digital relay or digital fault recorder (DFR));
- developing new analytical techniques and applications that use POW data to address widespread challenges such as renewables integration, inverter management, and asset health monitoring; and,
- building on evolving information technology and communications capabilities to implement a workable, economical, secure set of methods, protocols and platforms to store, retrieve, share, manage, analyze and apply CPOW data.

1.1 Overview

Power system planners and analysts see growing opportunities in the use of higher-resolution, time-synchronized grid data for a variety of applications. This paper defines high-resolution measurements as those faster than 256 samples/sec.[1], ranging up to a million samples/second (1 MHz). It reviews the types of devices that can make such measurements. It looks at some of the more valuable applications for high-speed, time-synchronized data use and considers where on the grid such applications might be implemented.

The paper also looks at some of the implementation issues associated with these new uses, including:

- development of new measurement technologies
- analytical tools and architecture
- data communications and storage
- time synchronization and delivery methods
- cyber-security
- technical standards
- reliability standards

This review concludes that there is great value to be gained from deploying high-resolution, time-synchronized continuous POW grid monitoring systems that complement SCADA and synchrophasor systems, to enable monitoring, analysis, and controls that cover grid events at multiple time scales.

1.2 Research methodology

This paper is based upon insights gained from interviews with several experts in current and emerging synchrophasor and associated technologies, and in current and emerging synchrophasor applications. Most sections of the paper reflect information offered by more than one expert, and on literature research. Last, the paper reflects the authors' decades of experience working in the electric industry and observations from the primary author's over ten years as project manager of the North American Synchrophasor Initiative, supporting the evolution, adoption and use of synchrophasor technology in domestic and international power systems.

1.3 Terminology used in this paper

<u>Data sampling rate</u> – devices used in power systems sample input current and voltage analog waveforms to support their functionality. This sampling is performed using an analog-to-digital converter (ADC) to yield digital measurements. In this document,

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[1] Few definitions for POW data specify a minimum sampling rate. The value of 256 samples/sec. was selected to ensure that, at a minimum, the power system's AC waveform at 50 or 60 Hz can be captured effectively. Much higher sampling rates are expected to be necessary for most practical applications.

the rate that these samples are collected is termed the *device's data sampling rate*, which is measured in samples per second. Though a misnomer, sampling rates are often referred to in Hz (cycles per second of a periodic, continuous waveform such as electricity or sound) rather than samples per second.

Device reporting rate – a grid monitoring device may sample the electric waveform at a high sampling rate, but report measurements out at a rate set by the user. For instance, a relay may sample at a rate of up to 12kHz (12,000 samples/second) acquisition speed, but report the data out at user-selected rates of 5, 6, 10, 12, 15, 20, 30, or 60 samples per second on a 60 Hz network. The device down-selects from the sampled measurements to execute its directed reporting rate.

PMU reporting rate -- The IEEE technical standard C37.118-1-2011 for PMUs refers to reporting rates in terms of data frames per second; this is done to avoid confusion with the sampling rate of the ADC that samples the voltage and current waveforms. PMU data frames include the magnitude, phase, frequency and rate of change of frequency of the input signal, because these elements characterize the estimated phasor value of a continuous voltage or current; with time synchronization, this becomes a synchrophasor.

Resolution – how many measurements are collected, in samples/second. *Resolution* is used interchangeably with the device reporting rate.

Speed -- the data transport rate, or how quickly data are delivered from one point to another in a communications network.

1.4 Distinguishing characteristics of a continuous point-on-wave measurement system

The concept of point-on-wave (POW) measurements in power systems has developed significantly in recent years. The term *point-on-wave* is quite general, referring to the analog-to-digital conversion of an input signal used in a variety of disciplines. In this document, the term *continuous point-on-wave* (CPOW) refers to a power system measurement system with three characteristics, discussed below.

- Waveform sampling (measure the actual waveform, rather than force-fitting it to a sinusoid waveform)
- High availability (highly available data are accessible when and where they are needed despite system disruptions)
- Time synchronization (each measurement is time-stamped relative to Coordinated Universal Time (UTC)).

Each of these characteristics is discussed below and used to distinguish POW from conventional power system measurements.

Waveform sampling refers to the representation of the actual waveform in measurements, rather than fitting samples to a simplified signal model such as a sinusoid. Waveform sampling is important because it allows the device to capture high-speed grid behaviors that are obscured when a sinusoidal model is assumed.

Data availability matters because data only has value if it can be accessed and analyzed when needed. Synchrophasor measurements tend to have high availability because they are typically streamed continuously for upstream storage and use. Due to the high sampling rate of POW measurements, continuous streaming may not be practical in all systems. Thus, data availability for a CPOW system may be achieved by continuously recording measurements to a local archive and polling when necessary. This architecture is distinct from most existing DFR systems, which only capture short periods of event data and may require manual retrieval.

Time synchronization refers to the use by of a common clock or time source by different devices to stamp measurements. This allows measurements from multiple locations and devices to be aligned for computation (as for synchrophasor calculation) and event analysis. Today, PMUs and some POW devices use time synchronization. However, SCADA and many older POW devices now deployed on the grid are not synchronized to UTC time, but operate on local time without verification or synchronization to an accurate time source.[2] POW applications such as system protection, coordinated inverter management and forensic analysis will require or benefit from centralized analysis of measurements from different parts of the power system, so time synchronization of POW measurements enhances the flexibility and usability of those measurements for many planned and potential future uses and analyses.[3]

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[2] Synchronization has often been accomplished using the GPS system to access Coordinated Universal Time (UTC) time, but a growing number of PMUs and other POW devices can maintain precision time synchronization using other space-based satellite navigation systems, internal clocks, network-delivered time, or terrestrial WWVB radio signals.

[3] Many power system events are analyzed and characterized by the speed and duration of the event (e.g., speed to reclosure or duration of an oscillation). Relays and some other IEDs were initially designed as fixed time delay devices, starting the event time count for recorded samples at the start time (trigger) of the event and calculating time differentials from that point in order to take pre-programmed action at a pre-determined later time. This requires precise time determinations and time-stamping but does not require time synchronization. Observation of dynamic local events compares changes in asset or grid behavior need not be time synchronized as long as the measurement or timing error or bias is consistent over time. Other power system time uses, such as revenue metering and generation dispatch, need not be synchronized to precise UTC time because they are based on long duration time periods (e.g., hour-to-hour or 15-minute metering or five-minute dispatch intervals) that do not require high-resolution timing.

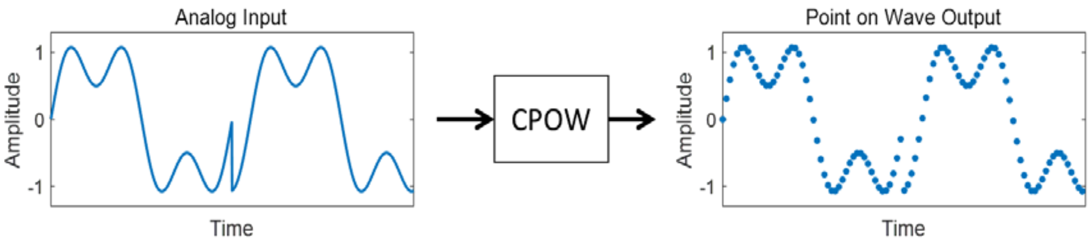
In contrast, time-synchronized, time-stamped measurements can be used for many more purposes than non-synchronized measurements. Time synchronization is necessary to calculate synchrophasors. It enables analysts to correlate grid conditions quickly across a wide region for event reconstruction and analysis; NERC recognizes the need for UTC-based time synchronization of disturbance data to enable, “the time alignment of large volumes of geographically dispersed data records from diverse recording sources.” (NERC PRC-002-2) And time-synchronized data can also be used for all of the grid protection functions that calculate time delays.

1.4.1 Waveform sampling

All of the power system monitoring devices used today collect information about grid conditions by using an analog-to-digital converter (ADC) to sample the input voltage or current waveform. The ADC samples a continuous analog signal such as current or voltage, converting it to a series of discrete digital values representing the amplitude of the analog signal.[4] While the output of an ADC represents points along the input waveform, the term *point-on-wave* is used to refer specifically to the output of a power system measurement device for the remainder of the document.

Figure 1 shows how an ADC samples an analog electrical signal and converts it into a digital signal. The resulting samples directly represent the value of the input as a function of time.

Figure 1 -- Conversion of an analog input signal to a discrete set of point-on-wave measurements



1.4.2 POW measurements

POW systems will collect measurements for a wide array of applications, so the measurements must be highly available[5] and suit multiple uses. Just as digital relays were modified to incorporate PMU functionality, DFRs, power quality meters, relays, and many other devices could be modified to support a POW measurement system – particularly to enable continuous monitoring rather than event-only monitoring.[6]

One benefit of analyzing POW data is that it contains much more of the original, wide-spectrum detail about the waveform (up to the Nyquist frequency of the device sampling rate). POW data can be used for a wide variety of applications because POW

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[4] On the bulk power system, merging units are modern ADC devices that collect analog signals from current and voltage transformers and convert those signals into time-synchronized digital IEC 61850-9-2 values. Optical sensors now in development could acquire and feed signals to PMUs and other devices in lieu of direct connection to a transformer; these may be able to take a million samples per second.

[5] *Availability* covers aspects such as timely data retrieval, streaming, continuous storage, etc.

[6] For devices that already have digital addressability and the capability to perform continuous monitoring, such modification might require turning on the continuous monitoring capability (turning off event-specific triggering with retention time limits and data over-writing) and installing an external storage device to poll the POW data at regular intervals for long-term archiving. That storage device should have connectivity for remote data retrieval or full-time data streaming from critical locations or assets.

measurements apply significantly less filtering to the waveform signal, thereby leaving it true to the original grid waveform. This allows the analyst to examine the raw data for purposes like artificial intelligence-based pattern detection, anomaly detection and model validation, and to apply different data filters appropriate to the specific investigative goals. One observer comments, “The faster you sample, the easier it is to meet every application’s requirement.” POW data can be down-sampled within the sampling multi-function IED or streamed in full to other local or distant IEDs or processing units for additional task-specific filtering, analysis, and action.

1.4.3 PMU processing and filtering

Measurements from SCADA and PMUs use the phasor representation of a sinusoid to describe the input signal, creating a quasi-stationary representation of the power system values. Time-synchronized multi-purpose measurement devices such as digital relays or DFRs sample grid conditions at a very high resolution, but only a small subset of the representation of those samples is reported by the SCADA or PMU device.

In a PMU, the sampled waveform is used to calculate the magnitude and angle that best represents the input as a sinusoid.[7] The PMU performs specific signal processing and filtering on time-synchronized measurements for this purpose. It strips sampled power system signals of the nominal power system frequency component, passes them through a low-pass filter to a Nyquist-limited bandwidth (about 30 Hz for a reporting rate of 60 frames per second) or less; and then calculates and time-stamps the current and voltage phasors. These are sent to a data archive and up through the communications network for use.[8]

Figure 2 illustrates the comparison between an actual waveform, its representation by a PMU that has forced the sampled measurements to fit a sinusoidal model, and the same waveform represented by POW measurements. PMU processing yields data that are valuable for many uses, but it strips out many of the dynamic elements in the data. Additionally, PMU vendors develop proprietary filters that, while compliant with the relevant technical standards, differ in non-transparent ways; these may eliminate key dynamic details or cause delays, or create filtering artifacts that distort the representation relative to the original waveform. One expert commented, “Forget all the lossy compression and synchrophasor calculation – just record the waveforms and convert it into a synchrophasor or RMS later. Don’t do the conversion up front and throw away the raw data….”

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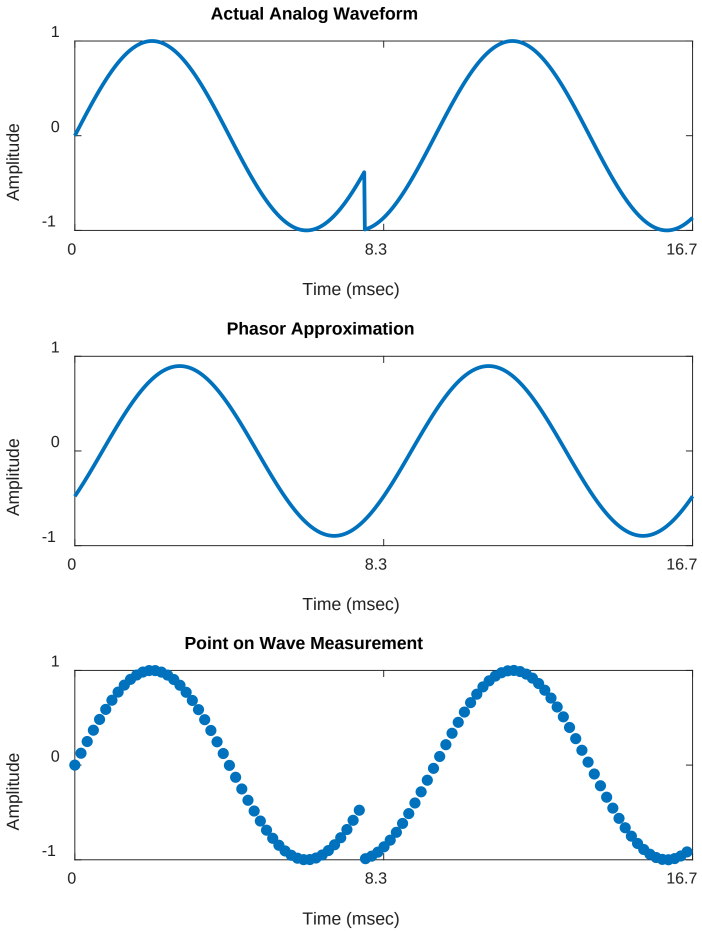
[7] In the case of SCADA, these measurements are not time-synchronized.

[8] This process is covered under IEC/EEE Joint Standard JEC/ IEEE 60255-118-1-2018, “Measuring relays and protection equipment – Part 118-1 – Synchrophasor for power systems – Measurements,” published December 19, 2018.

Figure 2 – Waveform, PMU and POW representation comparison


Actual Analog Waveform

Phasor Approximation

Point on Wave Measurement

As Figure 2 shows, while PMU data offer many operational and analytical benefits, the extensive waveform filtering and data processing that is performed to create synchrophasors distorts and destroys the resulting data relative to the source waveform. To date, the benefits of 30-60 samples/sec. grid monitoring and the many uses for synchrophasors and phase angles have outweighed the drawbacks of waveform distortion. However, emerging grid operational challenges are revealing the shortcomings of PMU data, as discussed below.

1.4.4 PMU performance during faults

PMU processing and filtering has an additional drawback for grid monitoring – synchrophasor measurements do not handle transient or fault events well, because in dynamic events, the waveform is not sinusoidal and changes amplitude, phase angle and frequency over a very short interval.[9] It is long-established that PMU measurement

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[9] M. Balabin, K. Gorner et al., “Evaluation of PMU Performance During Transients,” IEEE International Conference on Power System Technology, October 2010, and K. Narendra, D. Gurusinghe & A.D.

accuracy suffers during faults.[10] Industry experts are working to develop improvements beyond the C37.118.1a-2014 standard, but the phasor representation inherent to PMUs will always limit their ability to represent non-sinusoidal waveforms. Further, a number of users report that PMUs in the field are not merely recording inaccurate data during a fault, but they may flatline after the fault. An example of this is shown in Figure 3, which compares PMU data (top) and POW data (bottom) recorded for the same fault. The POW data is shown at much higher resolution than the PMU data.

The process of generating PMU outputs also has the undesirable effect of exaggerating the impact of phase step events, which may be the result of routine grid switching operations. Phase steps can result in significant perceived frequency deviations, and even greater rate of change of frequency deviations (because these are calculated at the first and second derivatives of phase, respectively). This effect creates the risk that benign events will generate confusing and unimportant data, and it complicates the analysis of and real-time control during genuine abnormal events such as faults.[11]

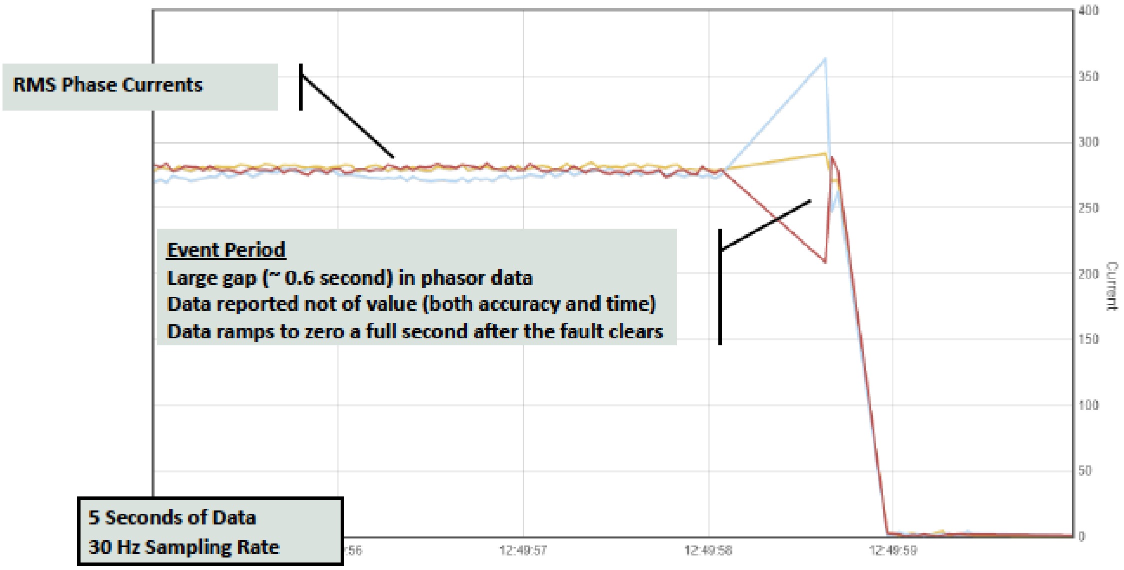
Rajapakse, "Dynamic Performance Evaluation and Testing of Phasor Measurement Unit (PMU) as per IEEE C37.118.1 Standard," IEEE Conference paper, October 2012.

[10] See, for instance, Z. Huang, J. Hauer & K. Martin, "Evaluation of PMU Dynamic Performance in Both Lab Environments and under Field Operating Conditions," Proceedings of 2007 IEEE Power Engineering Society General Meeting; T. Becejac & P. Dehghanian, "PMU Multilevel End-to-End Testing to Assess Synchrophasor Measurements During Faults," IEEE Power & Energy Technology Systems Journal, March 2019; and N. Perera, R. Midence et al., "Applicability of Synchrophasor Based Frequency Data for Protection and Control Applications," IEEE, 72d Conference for Protective Relay Engineers, 2019.

[11] A.J. Roscoe, A. Dyśko, B. Marshall, M. Lee, H. Kirkham, & G. Rietveld, "The case for redefinition of frequency and ROCOF to account for AC power system phase steps", IEEE International Workshop on Applied Measurements for Power Systems (AMPS), Liverpool, UK, 2017.

Figure 3 – Comparison of TVA PMU and DFR data for a fault event
(Source: Russell Robertson, Grid Protection Alliance)

Phasor Data for 12:58.79 Fault



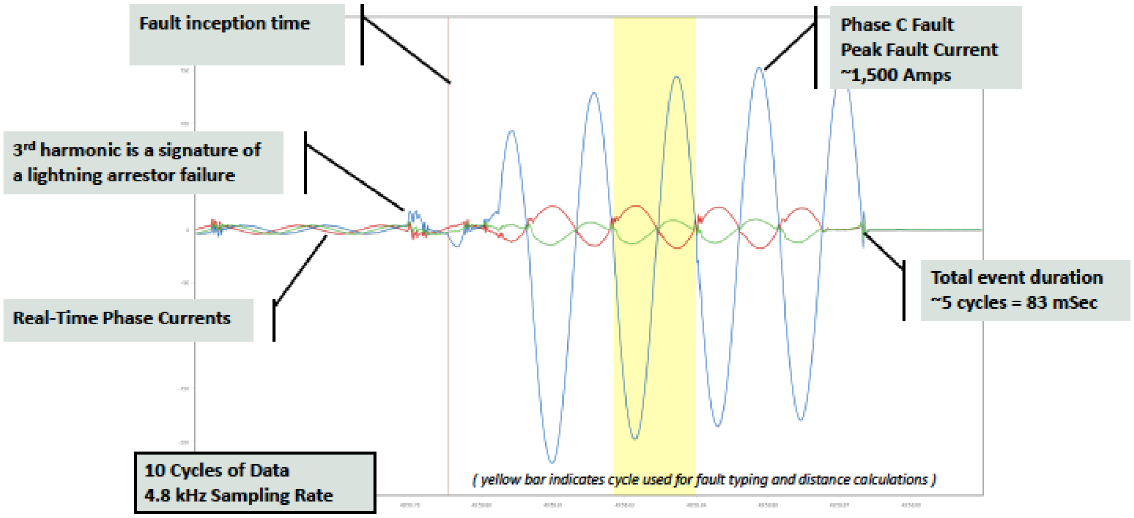
RMS Phase Currents

Event Period
Large gap (~ 0.6 second) in phasor data
Data reported not of value (both accuracy and time)
Data ramps to zero a full second after the fault clears

5 Seconds of Data
30 Hz Sampling Rate

Based on synchrophasor data collected by TVA's openPDC from a PMU

Point-on-Wave Data – L-G Fault @ 12:58.79



Fault inception time

Phase C Fault
Peak Fault Current
~1,500 Amps

3rd harmonic is a signature of
a lightning arrestor failure

Real-Time Phase Currents

Total event duration
~5 cycles = 83 mSec

10 Cycles of Data
4.8 kHz Sampling Rate

(yellow bar indicates cycle used for fault typing and distance calculations)

Based on openXDA's automated analytics using POW data from a TVA DFR [1]

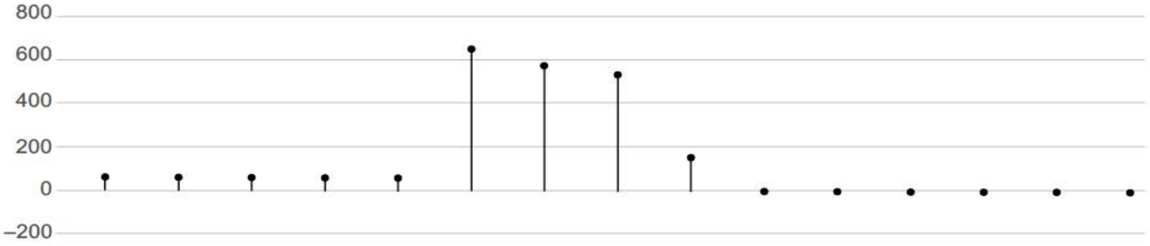
1.5 Measurement resolution and grid event time frames

Figure 4 shows how higher measurement resolution rates reveal greater detail about grid events.

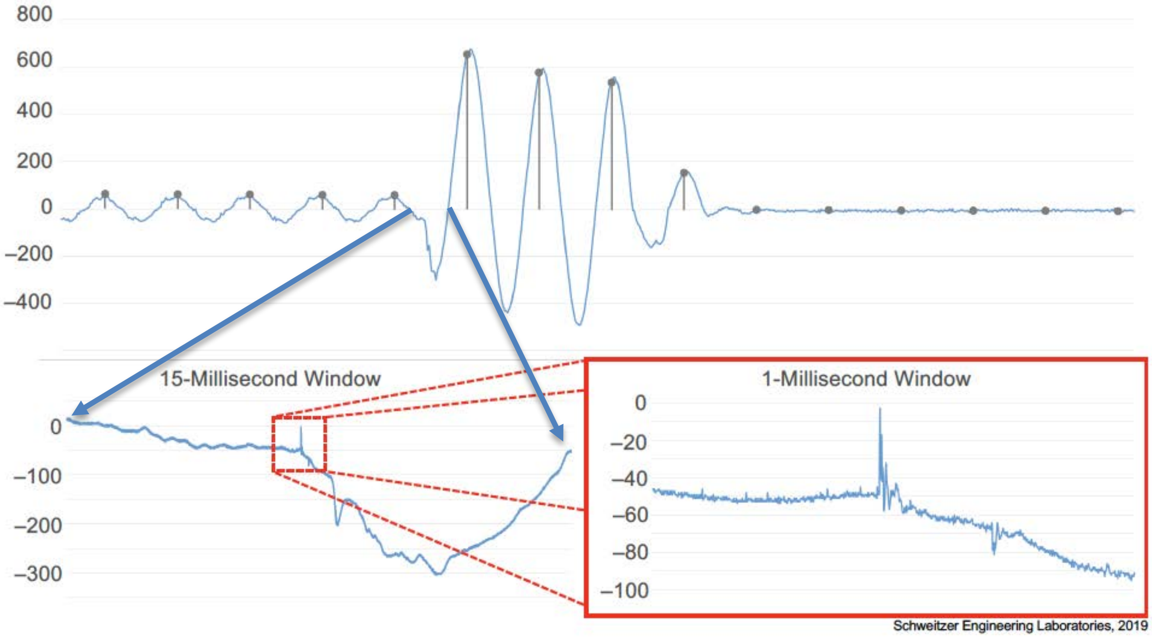
Figure 4 – A waveform sampled by PMUs and higher POW sampling rates

(Source: Greg Zweigle, Schweitzer Engineering Laboratory)

PMU Measurements at 30 samples/second



Same event waveform sampled by higher-resolution POW rates



Schweitzer Engineering Laboratories, 2019

The impact and value of high sampling and reporting resolution matters because power system events occur at a variety of speeds, as shown in Table 1. Although digital relays and DDRs have been able to detect and record fast transient events, they cannot pick up grid events that they have not been set to recognize and record.

Table 1 -- Time frames vary for grid events and applications
(Modified from J. Perez, "A Guide to Digital Fault Recording Event Analysis" [2010])

TIME PERIOD	GRID EVENTS	GRID APPLICATIONS
Nanoseconds	• Arcing faults	
Microseconds	• Lightning strike • Switching of inductive or capacitive loads, transformers	• Breaker restrikes • Harmonics higher than 16th
Milliseconds	• Harmonics • Faults	• Fault-induced delayed voltage recovery of air conditioners • Solar PV inverter trip and recovery • Meter error • Relay operation • Fast frequency response
Seconds	• Load shifts • Load flow changes • Generation dispatch	• Governor, exciter automatic voltage response (electromechanical transient) • Inertial response to frequency loss
Minutes	• System stability	• Power swings • Time of use meters • System peak
Hours	• Load variations	• Generation schedules

It follows from the varying speeds of different grid events that it is useful to have diverse monitoring devices that can capture information about the faster grid events.

1.6 Types of high-resolution grid monitoring devices

This paper defines high-resolution sampling as a rate faster than 256 samples/second. Most current POW measurement devices collect samples at a relatively high rate (typically 256-1024 samples/second or faster)[12], in order to capture the electrical waveform effectively. These rates are much higher than telemetered data sources such as SCADA (1 sample every several seconds) or phasor measurement systems (30-60 samples/sec.).

Digital fault recorders (DFRs) and power quality meters report waveform measurements at high sampling rates, but generally record measurements for short time periods[13] rather than performing continuous long-term sampling and recording.[14] These data event

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[12] This paper describes measurements in terms of a 60Hz electrical system; most electrical devices described herein are easily convertible to monitor a 50 Hz electrical system.

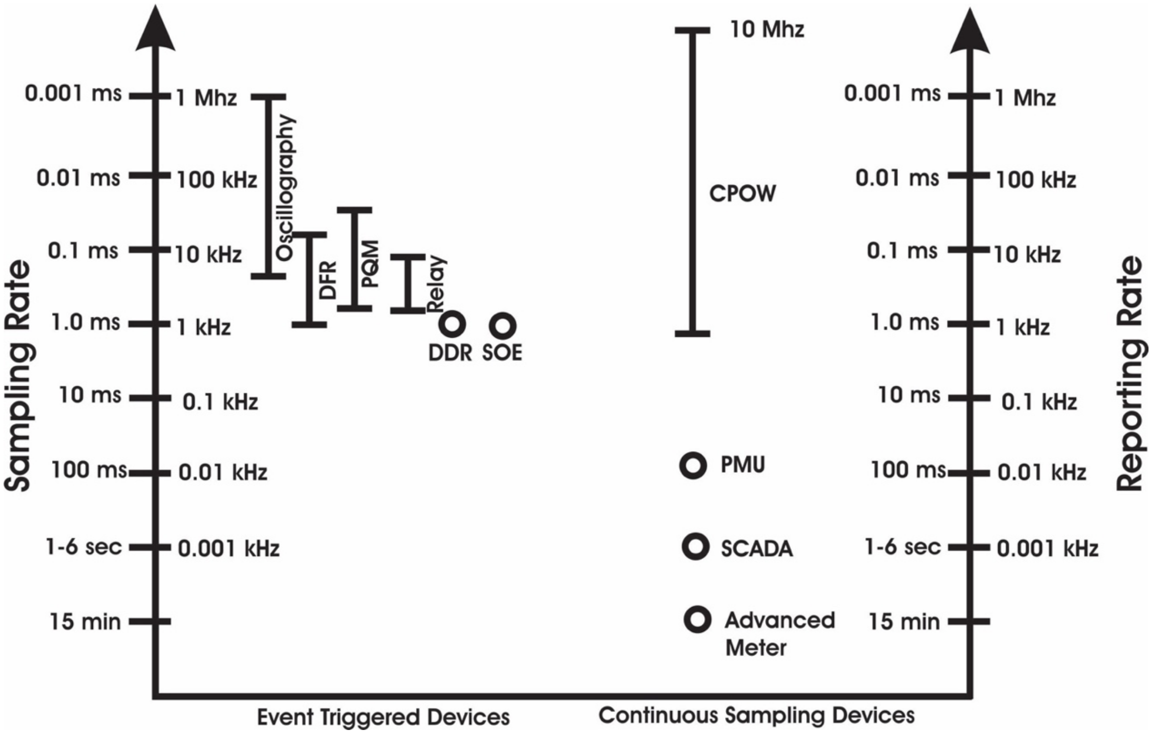
[13] A DDR or DFR has limited storage on-board. The device monitors and samples power system conditions continuously, keeping recent moments' data in a "circular" storage buffer, and deletes and writes over older (leading) data if no event occurs to trigger data retention.

[14] Until recently, dedicated power quality meters offered time-stamped but not time-synchronized measurements; however, with the emergence of multi-function measurement devices and the advent of

windows are valuable for grid operations and event reconstruction, but lack continuity of measurement and consistent availability across the entire grid. Additionally, DFRs will miss events that don't match the situations they were programmed to trigger on.

Figure 5 shows the spectrum of grid monitoring devices along two dimensions – sampling or reporting rate and sampling continuity. As noted above, most current high-resolution POW devices are event-triggered, while PMUs and other continuous monitoring devices sample at slower rates. To date the only commercial CPOW device available is a merging unit.[15] This paper recommends the development of additional commercial Continuous POW monitors (CPOWs) to fill the gap in high-resolution continuous monitors.

Figure 5 – Grid monitoring devices by resolution and data continuity[16]



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precision time delivery mechanisms such as GPS and network-delivered time, more devices are capable of producing UTC-synchronized time-stamped grid measurements.

[15] The merging unit acquires ac current and voltage from CTs and PTs and converts those analog signals into digital values, transmitting them as sampled values under the IEC 61850-9-2 standard.

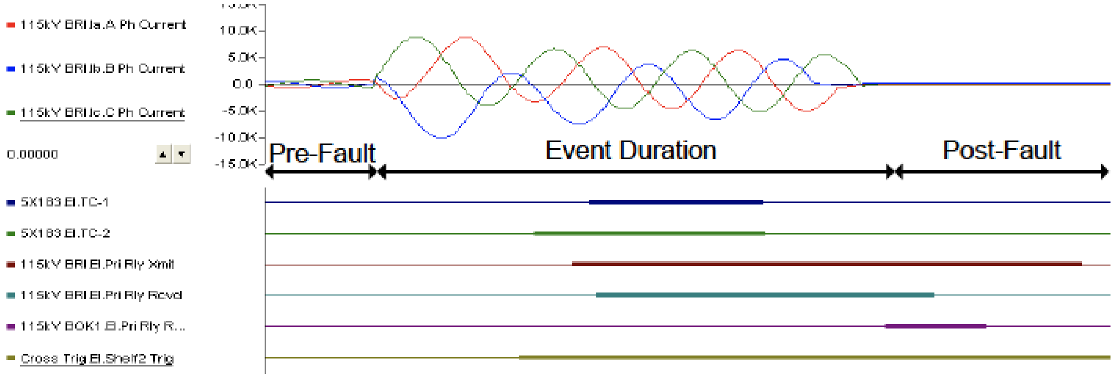
[16] This graphic uses "sampling rate" for event-triggered devices because they don't report; the user pulls the sampled data to analyze it as collected. Continuous sampling devices report out at a user-selected rate which may be slower than its sampling rate.

1.7 Event-triggered versus continuous monitoring

Back when SCADA was the dominant grid monitoring method, NERC adopted reliability standard PRC-002-2, “Disturbance Monitoring and Reporting Requirements,” to require Transmission Owners to capture higher-resolution, event-specific data using sequence of events recording (SER) and fault recording data from key bulk electric system buses. These recordings capture data on grid conditions leading up to, during and after an event, as shown by the sample fault event record in Figure 6, which shows a single event as recorded at multiple locations.

Figure 6 -- An oscillographic record of a grid event shows what occurred before, during and after the event

(Source: J. Perez, “A Guide to Digital Fault Event Analysis,” [2010], p. 4)



The NERC PRC-002-2 standard requires that fault event records contain at least two cycles of data preceding the triggering event, at least three cycles of post-trigger data, and at least 30 cycles of data at that trigger point, at a minimum recording rate of 16 samples per cycle (960 Hz). DDR records must retain at least three minutes of data sampled at an input rate of at least 960 Hz and an output (device recording and calculation) rate of at least 30 samples per second, synchronized to UTC (with a clock accuracy of +/- 2 millisecs of UTC). These time resolution requirements were designed to capture dynamic events including inter-area oscillations, local generator oscillations, HVDC control modes, exciter control modes, and wind and steam turbine torsional modes, with frequencies ranging from 0.1 to 20 Hz.

With the rapid increase of inverter-connected renewable generation and storage devices on the grid, there have been several events where multiple solar photovoltaic plants disconnected in response to faults on the transmission grid,[17] as with the example in Figure 7 below. This is a high-speed recording that shows four instantaneous phase shifts in the voltage waveforms in the area affected by the Blue Cut fire on August 16, 2016 around 11:45am, after 1,200 MW of transmission- and distribution-connected PV units

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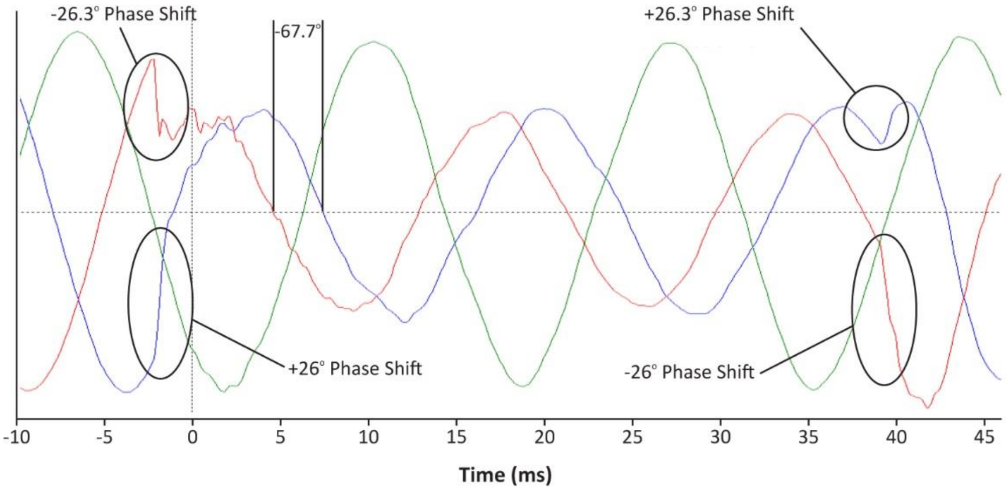
[17] See NERC reports on the Blue Cut fire disturbance (August 16, 2016), the Canyon 2 fire disturbance (October 9, 2017), the Angeles Forest disturbance (April 10, 2018) and the Palmdale Roost disturbance (May 11, 2018).

disconnected or performed momentary cessation due to inverter actions.[18] Figure 7 shows POW data; a PMU would not have revealed the sine wave distortions so clearly.

Figure 7 – Rapid phase-jumps distorting voltage sine waves after Blue Cut Fire PV disconnects

(Source: NERC, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Report," June 2017)



SCE and CAISO were unaware that wildfire-related transmission faults could cause solar PV disconnects, but have since identified 10 more similar occurrences between August 16, 2016 and February 6, 2017.[19] Because no one knew these PV disconnects could occur until the Blue Cut Fire revealed the issue, some POW devices triggered for related faults but did not specifically trigger for and fully record these disconnects.

The NERC-WECC report on the Blue Cut Fire and similar events observes that, "…lack of data visibility and poor data quality continue to be a concern for comprehensive event analysis after large [bulk power system] disturbances…. In many cases, [Generation Owners] were only able to provide SCADA data with resolution on the order of 5-10 minutes (rather than msec)."[20] Even PMUs recording at 30 samples/sec (every 33 msec) could miss momentary cessation events. Event records with resolution of one second or slower, or with poor or inconsistent time-stamps, hinder determination of the causes of inverter tripping. NERC observes that, "point-on-wave recording from the inverters, plant-level controller, and POI [point of interconnection] are the most useful sources of data…," to investigate high-speed inverter-related events.[21]

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[18] NERC, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Report," June 2017, p.7.

[19] Ibid., p.3.

[20] Joint NERC & WECC Staff Report, "April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report: Southern California Events: April 20, 2018 and May 11, 2018," (2019), p. 23.

[21] Ibid.

1.8 Layered measurement data collection and CPOW devices

NERC has issued a reliability guideline with recommended measurement data and performance monitoring techniques to assure that there is sufficient and appropriate data collected for monitoring performance and investigating failures of bulk power system-connected inverter-based resources. This guideline recommends a variety of monitoring methods with specific data resolution and retention, as shown in Table 2; NERC asks that all of this data be time-synchronized to enable faster data alignment and event analysis.[22]

Table 2 – NERC-recommended measurement data & retention for monitoring inverter-based resources

Data type	Resolution	Continuous or triggered	Retention period
Plant SCADA data	1-2 seconds	continuous	1 year
Sequence of Events recording data	<= 1 millisecond	triggered	90 days
Digital Fault Recorder (DFR) data	>960 samples/second	triggered	90 days
Dynamic Disturbance Recorder (DDR) data, including PMU or digital relay	>= 30 samples/second	continuous	1 year
Inverter fault codes and dynamic recordings	Many kHz	continuous	90 days

One of the weaknesses of using DDRs and DFRs that collect data windows, rather than sampling data continuously, is that these windows are triggered by pre-defined event conditions. This identifies event categories that are already known, such as transient faults, oscillations or FIDVR – but as illustrated by the PV disconnects, there may be very rapid local phenomena that have not been recognized absent high-resolution monitoring and are therefore not on the list of pre-specified event triggers. One observer commented, “Trigger-based POW recording never works, because you don’t know what the key events are so you can’t design the right trigger to record them.” Even if recording devices near the disturbance are triggered, those farther away may record nothing, hindering an analyst’s ability to understand the impact of an event on the larger system.

This paper recommends that the above approach to layered grid monitoring data be supplemented by the use of continuous POW (CPOW) devices at key locations across the grid. It is clear that the existing suite of monitoring devices is not capturing all needed data on known fast events, such as inverter-related resource behaviors, even as the share of inverter-connected resources on the U.S. grid nears 10% and is proliferating faster than any other generation source.[23]

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[22] NERC, “Reliability Guideline: BPS-Connected Inverter-Based Resource Performance,” (September 2018), Table 6.1.

[23] Energy Information Administration, “Today in Energy, “EIA forecasts renewables will be fastest growing source of electricity generation,” January 18, 2019; EIA, “EIA expects U.S. electricity generation from renewables to soon surpass nuclear and coal,” January 30, 2020.

As the Blue Cut Fire discussion indicates, there is a monitoring and event recognition gap that can be filled by a CPOW monitoring device. Some such devices are used today at the distribution level (e.g., power quality monitors such as the PQube3) or could be modified from DFRs now used for transmission-level monitoring.

Once CPOW monitoring is in place, the analyst could use a variety of event detection tools to analyze the CPOW data to identify interesting events (beyond those currently triggering DDR or DFR recordings). This could reveal additional events that are not currently recognized, just as PMU data has revealed the extent and character of intra- and inter-regional oscillations.

2.0 High-value uses for high-resolution, time-synchronized power system measurements

There are many needs and opportunities to use high-resolution, time-synchronized power system data, as discussed below. The challenge will be to develop specific applications that accurately deliver new insights and operational value to users, by tailoring analytics and data sampling speed appropriate to the use. At some point in the future, there may be a high-resolution sensor embedded in every grid-connected device (as there are today in photovoltaic-connected inverters), and no need for lossy data analysis or compression – but until then, grid monitoring devices need to be used purposefully.

Table 3 lists a number of applications for high-resolution POW and PMU data. Many of these applications use voltage and current phasors and phase angles, as indicated; several – particularly inverter-based resources integration and load monitoring – may be better analyzed using faster CPOW data than PMU data alone. We conclude that because of the relative shortcomings of PMUs discussed above, several applications (indicated in bold text in the table) can be better served with CPOW data (or CPOW complemented by PMU data) than with PMU data alone:

- Renewables integration, inverter-based resource management
- Subsynchronous resonance
- Harmonics and power quality
- Geomagnetic disturbance & high-altitude electromagnetic pulse (HEMP) detection
- Asset condition monitoring & management
- Load monitoring & characterization.

Table 3 – Grid Application Needs for Time-Synchronized Data

(Source: modified from S. von Meier, "Precision Micro-Synchrophasors for Distribution Systems: A Summary of Applications" (2017))

V: Voltage Waveform
VM: Voltage Magnitude
VA: Voltage Angle
F: Frequency

I: Current Waveform
IP: Current Phasor
VP: Voltage Phasor
DF: Rate-of-Change-of-Frequency (ROCOF)

APPLICATION	DATA TYPE NEEDED	
	POW	PMU
TRANSMISSION & GENERATION		
Frequency monitoring & management	--	F, DF
Oscillation monitoring & management	--	F, VP, IP
Voltage monitoring & management	--	VM
Real-time situational awareness	--	F, DF, VP, IP
State estimation	--	VP, IP
Renewables integration, inverter-based resource management	**V, I**	**F, DF, VP, IP**
Phase identification	--	VA
Geomagnetic disturbance & HEMP detection	**V, I**	--
Event detection & classification	V, I	F, DF, VP, IP
Fault location *	V, I	F, VP, IP
Asset condition monitoring & management	**V, I**	**F, DF, VP, IP**
Model validation	V, I	VP, IP
Island detection	--	F, VA
Black-start restoration	--	F, VP, IP
Automated controls	V	VP
System protection	V, I	VP, IP
Outage management *	--	F, VP, IP
Load monitoring & characterization	**V, I**	**VP, IP**
DISTRIBUTION		
Load characterization	**V, I**	**VP, IP**
PV, DG & storage monitoring & integration	**V, I**	**F, DF, VP, IP**
Microgrid	V, I	
Harmonics	**V, I**	
Power quality	**V, I**	
State estimation	--	VP, IP
Topology detection	--	VP, IP
Outage management *	--	VP, IP
*** POW or PMU data can be used but are not necessary for this application**		

This conclusion is supported by recent analysis from the U.S. Department of Energy. DOE's grid modernization work includes a focus on the sensors and measurement capabilities needed to support and improve power system operation that has more distributed and inverter-based resources and requires more speed and flexibility. That effort produced a technology roadmap that calls for significant improvement in electrical parameter measurements to identify the "most rapid signatures of low-probability, high-consequence events … to enable preventative action that can prevent large-scale failures and minimize impacts," for better grid resiliency.[24] DOE also recommends the use of such data to identify abnormal or unusual behavior to better identify asset performance and failure issues.

While DOE calls for improvements in the dynamic response and accuracy of PMUs and synchrophasor precision,[25] the technology roadmap also seeks measurements at faster rates, higher precision and greater accuracy with lower costs.[26] DOE's Sensor & Measurement Technology Roadmap describes the desired performance metrics for numerous applications; many of the desired performance metrics, which are listed in Table 4, are consistent with CPOW measurement devices.

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[24] D. T. Rizy & P. Ohodnicky, U.S. Department of Energy, Grid Modernization Laboratory Consortium, "Sensing & Measurement Technology Roadmap," February 2019, p. 54.
[25] Ibid., p. 68.
[26] Ibid., p70.

Table 4 – Desired performance metrics for next-generation electric system sensors
(Per U.S. DOE GMLC Sensor & Measurement Technology Roadmap, Feb. 2019 (pp 70-72))

HIGH-GRADE TRANSMISSION LEVEL SENSORS FOR FAULT DETECTION & DYNAMIC SYSTEM PROTECTION	GRID ASSET HEALTH SENSORS	DISTRIBUTED ENERGY RESOURCES & NEXT GENERATION DEVICES
Fault current – 0.01 to 100x nominal rated current • Bandwidth line frequency > 10 MHz • Latency < 1 millisecond Voltage – 0.01x to 5x nominal voltage p.u. • Time resolution < 1 microsecond • Latency < 1 millisecond Frequency measure accuracy < 0.5 milliradians Phase angle accuracy within ± 0.5° times harmonic number Harmonic component • Amplitude accuracy < 5% • Individual harmonic phase angle accuracy < 1% • Sampling rate > 1,000 per 60 Hz cycle • Total harmonic distortion accuracy < 0.5%	Monitor voltage, currents, real & reactive power, phase angle, harmonics, total harmonic distortion Current -- < 3x nominal voltage Voltage – up to 5x nominal voltage • Time resolution < 1 microsecond • Sampling rate > 1,000 per 60 Hz cycle • Latency < 1 millisecond	Monitor current, voltage, current & voltage derivatives, frequency, ROCOF, phase angle, fault currents, pulse width modulation Voltage – up to 5x nominal voltage Current – up to 3x nominal current • Time resolution < 1 microsecond • Sampling rate > 1,000 per 60 Hz cycle • Latency < 1 millisecond Phase angle accuracy within ± 0.5° x harmonic number Bandwidth 1kHz to 1 MHz Accuracy < 0.05 Hz/second Harmonics sampling rate > 100 per 60 Hz cycle Phase balance/imbalance accuracy < 0.5% PWM and balance accuracy < 0.5%

2.1 Renewable and distributed generation monitoring and integration

Most regions of the United States are experiencing the rapid growth of asynchronous utility-scale wind and solar generation and customer-owned solar photovoltaics, along with retirements of aging, slow-moving synchronous thermal generation. These are creating new stability challenges for the bulk power system as the levels of synchronous generation resources fall – transient stability failures can occur within a few cycles in areas dominated by inverter-based power sources. This necessitates a better understanding of system dynamics to identify a transient event as it is happening, and to recognize the conditions that might lead to transient stability failure and fast voltage collapse. It requires more data about both the grid and individual assets, collected at high CPOW time resolution and waveform fidelity to complement PMU data.

Inverter-based renewable resources can cause a number of grid effects, including voltage fluctuations, reverse power flows and low-fault currents, with interactions between the control loops of different inverters. Wind generators have caused oscillations and voltage problems on the grid,[27] and different types and models of renewable generators have had differing dynamic impacts upon the bulk power system. As noted in the review of PMU performance under fault conditions, PMUs are not fast enough or accurate enough to capture useful representations of ac waveforms under fault conditions. Therefore, it will be useful to use high-resolution CPOW measurements with PMU data to capture the performance of utility-scale wind and PV plants and correlate that to substation data, to better understand dynamic interactions and identify potential mitigation measures.

2.1.1 Utility-scale renewable generation

Most utility-scale generators today are monitored using a PMU placed on the high side of the point of common coupling (PCC) to the bulk power system. This collects useful information for the transmission owner on the net behavior of the generation plant, which is usually composed of multiple strings of photovoltaic or wind generators aggregated behind the PCC. The inverters on each PV unit or wind turbine will react to a grid disturbance within milliseconds, and each may react differently, so it would be valuable to have multiple CPOW recorders deployed across generator field assets to understand how they react to field voltage or frequency swings, and identify whether all of the unit control systems are properly coordinated.

2.1.2 Distributed generation disaggregation and monitoring

As discussed above, PMUs and many current POW devices are unable to capture full data on the swift response of distributed photovoltaics to system faults. The number of solar PV systems connected directly to distribution circuits or behind customer meters is growing rapidly across the nation. These units are materially changing the way that distribution systems respond to bulk power events, particularly because inverter-connected resources respond so quickly to local and transmission-level stimuli. High-resolution monitoring is needed to capture these fast distribution events, and continuous POW data is needed to spot phenomena that PMU filtering and sinusoid-fitting may mask.

Work by entities such as the University of California, Berkeley, Hawaii Electric Company, and others have shown that PMU and other monitors enable the analyst to identify PV generation, distinguish PV from masked customer load, correlate feeder voltage changes with DG behavior, and detect reverse power flows.[28] With distribution-

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[27] See for instance studies of wind generation-initiated oscillations, as in Y.-H. Wan, "Synchronized Phasor Data for Analyzing Wind power Plant Dynamic Behavior and Model Validation" [2013] and Center for the Commercialization of Electric Technologies, "Technology Solutions for Wind Integration in ERCOT," (2015).

level PMU and CPOW monitoring and good analytics, it should be possible to identify storage devices and electric vehicles as well. This would allow the system operator to anticipate PV ramps and customer load changes and plan supply and demand-side resources accordingly to protect distribution system reliability.

2.2 Subsynchronous resonance

Subsynchronous resonance (SSR) is coincident oscillation at a natural harmonic frequency lower than the system's normal operating frequency (60 Hz) that occurs between a turbine generator shaft and a transmission system with long radial lines that are series capacitor-compensated system.[29] SSR may cause torsional interaction between a turbine generator's mechanical system and transmission or electrical self-excitation of the generator due to steady-state disturbances, or torque amplification (higher transient torque) on a generator during or after a transient three-phase to ground fault. It can also cause subsynchronous control interactions between the series capacitor-compensated transmission system and the generator's controls.[30] SSR events have occurred in Nevada, South Texas, Sweden and Vietnam. They can have devastating impacts, harming resonating transmission elements, fracturing a generator shaft, and leading to cascading outages.

Transmission systems have become more vulnerable to SSR with the increasing use of series capacitors for voltage support and the increased use of poorly-tuned electronic devices, HVDC lines, and more electronic generator control systems (as with wind and solar generation connected through inverters) attached to the grid. SSR protection involves tripping the generator affected by or causing the SSR, using and placing SSR protective relays on all series capacitors;[31] mitigation methods include SSR studies, generator disconnection, control system upgrades, and other adjustments.[32]

Figure 8 shows two examples of SSR. A transient-induced SSR may decay within seconds of the initiating event, or continue for 30 minutes or up to several hours.[33] DDRs can detect an SSR event, but since a DDR triggers and records for a limited time period, it will record bursts of an event but may not record the entirety of longer sustained SSR oscillations. PMUs have been used to conduct SSR research, but without modification they are not well-suited to the task;[34] typical PMU reporting rates and filters prevent their measurements from accurately reflecting most SSR events. In contrast, CPOW measurements accurately reflect the input waveform at a high reporting rate, making SSR oscillations, and their impacts at different points on the grid, clearly observable. Rather

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[29] Subsynchronous oscillations can also occur between a turbine generator and active system elements such as HVDC equipment controls and static VAR system controls.

[30] ERCOT Board Report, "NPRR Number 562, Subsynchronous Resonance," (2017).

[31] Ibid.

[32] A. Dixit & P. Ramasubbu, "Subsynchronous Oscillations (SSO) and PowerWorld Applications at ERCOT," [2014].

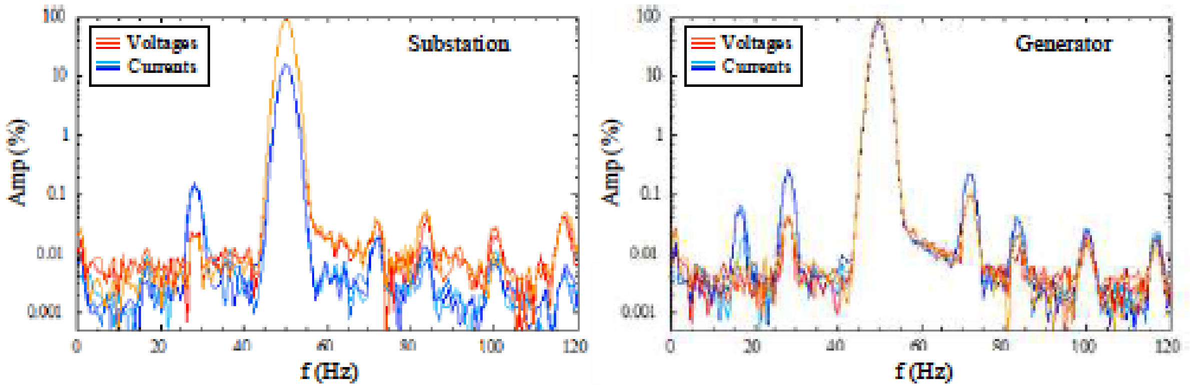
[33] Gajic, Roxenborg et al., "Case Studies and Experience with Sub-Synchronous Resonance Detection Technique," [2016].

[34] G. Antonova, "Combining subsynchronous oscillations detection and synchrophasor measurements to increase power system stability," [2016].

than depending on specialized SSR protection relays, CPOW devices could serve multiple functions including SSR detection to improve return on investment.

Figure 8 – Voltage and current spectra from a 400 kV substation and generator terminals during a prolonged SSR event

(Source: Gajic, Roxenborg et al., “Case Studies and Experience with Sub-Synchronous Resonance Detection Technique” [2016], Figure 5)



High-speed waveform sampling at 200 or 240 Hz can effectively characterize subsynchronous oscillations at relatively high frequencies. These data can be captured and transmitted using the same hardware and IEEE C37.118.2 protocol as for normal synchrophasors and PMUs.[35]

2.3 Power quality and harmonics

Power quality (PQ) issues include voltage sags and swells, voltage surges or under-voltage, voltage unbalance, high-frequency noise, non-zero frequency impedance, power factor, harmonic voltages and currents, inrush currents, and light flicker. Power quality problems can increase energy usage and costs, damage customer equipment, make equipment unstable, and cause costly production failures.

Many PQ issues are related to distortion of the voltage waveform. Thus, PMUs are ill-suited to PQ analysis. Dedicated power quality and harmonic analysis meters already exist as specialized instruments to analyze sampled waveforms. CPOW devices collect all harmonics within the measurement bandwidth of the instrument, and continuous recording would support more thorough investigation of PQ issues.

Deployment of CPOW devices at the transmission level enables these characteristics of the power system to be evaluated on a much larger scale, especially in areas where power quality may not have typically been monitored (e.g., at locations beyond a feeder head or large-scale industrial customer connection). Such insights could provide diagnostic

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[35] See, Warichet, J., D. Wilson & N. Al-Ashawal, “D.25, Recommendations for the future evolution of synchronized measurement technology and deployment in Europe,” MIGRATE-EU, (November 18, 2018).

capabilities on the bulk power system, particularly to examine how large-scale inverter-based generation may be influencing other nearby generation plants or devices.

2.4 Geomagnetic disturbance as seen through harmonics

A geomagnetic disturbance (GMD) occurs when ionized particles from solar wind enter the earth's magnetic field. An intense GMD event can create geomagnetically-induced currents (GICs) that create voltage differentials at different electric transmission ground points, creating harmonics on the power system.[36] GICs could cause "asymmetric saturation of many transformers across a transmission grid, resulting in thermal stress to the transformers, absorption of large amounts of fundamental-frequency reactive power, and the injection of large amounts of even- and odd-order harmonic currents into the transmission grid."[37] Monitoring a site for GICs "involves simultaneously measuring transformer phase and neutral currents for both ac and dc quantities,"[38] to determine whether the transformer is saturating and creating the harmonics because of the GIC, or only passing the harmonics through. Hydro Quebec has found that, "a fine-grained, localized analysis of geomagnetic activity within a three hour time window can be used to predict potential impact at nearby locations on the grid," and can be used to alert operators in advance of large-scale GMD events.[39]

PingThings has found a correlation between PMU MVAR consumption records with GICs on transformers and GMD storm rate of change as measured by U.S.G.S. magnetometers[40] and working with Central Maine Power, between low-level GICs and harmonics, as shown in Figure 9.[41]

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[36] V.D. Albertson, B. Bozoki et al., "Geomagnetic Disturbance Effects on Power Systems," (1993).

[37] R.A. Walling & J. Taylor, "High-Level Harmonic Distortion During Geomagnetic Disturbances: a Hidden Threat to Grid Security," (2014), p.1.

[38] V.D. Albertson, B. Bozoki et al, "Geomagnetic Disturbance Effects on Power Systems" (1993), p. 1211.

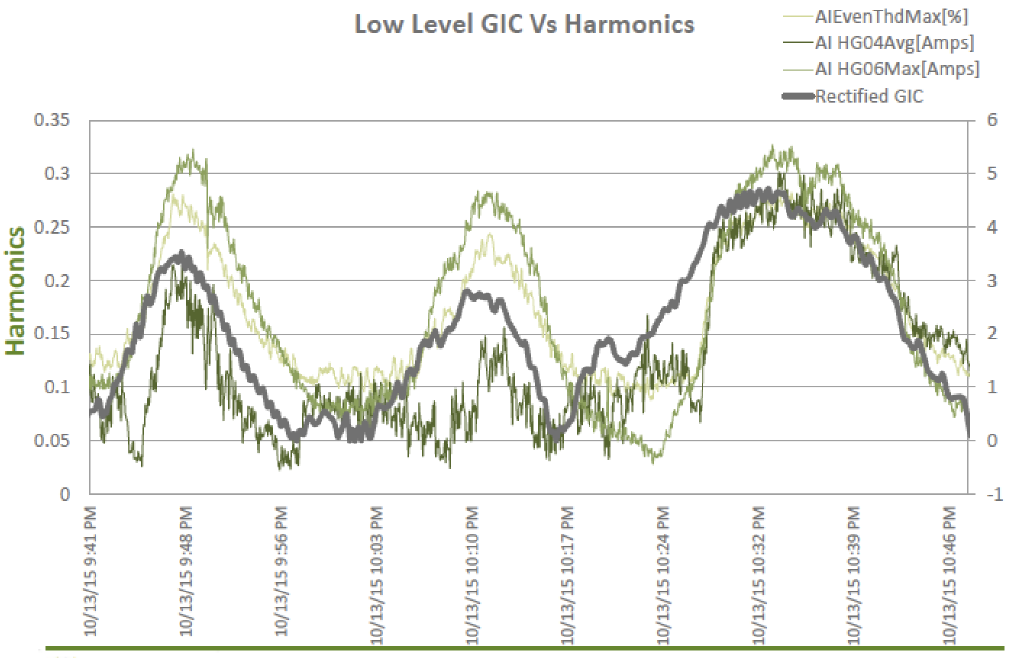
[39] C. Basu, M. Padmanaban et al., "Combining Multiple Sources of Data for Situational Awareness of Geomagnetic Disturbances," IEEE Power & Energy Society General Meeting, 2015, and L. Cauchon, S. Guillon et al., "Discovering Geomagnetic Disturbance Patterns for Synchrophasor-based Event Prediction in Québec: A Knowledge-based approach to Understanding PMU Data," NASPI/ISGAN International Synchrophasor Symposium, March 2016.

[40] PingThings, "GMD/GIC detection explorations via PMUs," NASPI Work Group Meeting, October 23, 2014.

[41] S. Murphy & J. Michlig, "From the Sun to Maine – Investigating GMD's Impact on Operational Transmission Assets," NASPI, March 23, 2016.

Figure 9 – Correlation between low-level GICs and harmonics

(Source: Murphy & Michlig, “From the Sun to Maine – Investigating GMD’s Impact on Operational Transmission Assets,” (2016))



Existence of a correlation with PMU-captured phenomena is useful but not sufficient to develop a good early warning system for the onset of a GMD event. CPOWs could be better detection tools because a sampling rate of at least 256 samples/sec or faster is needed to capture higher-order harmonics, and might also be able to capture the DC offset associated with GICs. Further monitoring and study of the correlation strength between field harmonics, voltage, GICs and GMD strength can determine whether high-resolution CPOW monitors can be used to provide situational awareness and early warnings of growing GICs that could affect grid operations and harm electric and communications equipment.

2.5 Asset monitoring

It is well established that PMU data can be used for transmission and generation asset monitoring, to recognize operational problems and detect equipment failure.[42] Early work by the Berkeley Labs and others indicates that PMU data can be used in a similar fashion as the distribution level, as shown in Figure 10.[43] If PMU data can reveal asset conditions and problems, then it is likely that higher-resolution, unfiltered CPOW data measuring precise waveforms may reveal even more than the PMU data, particularly for asset responses to transient events.

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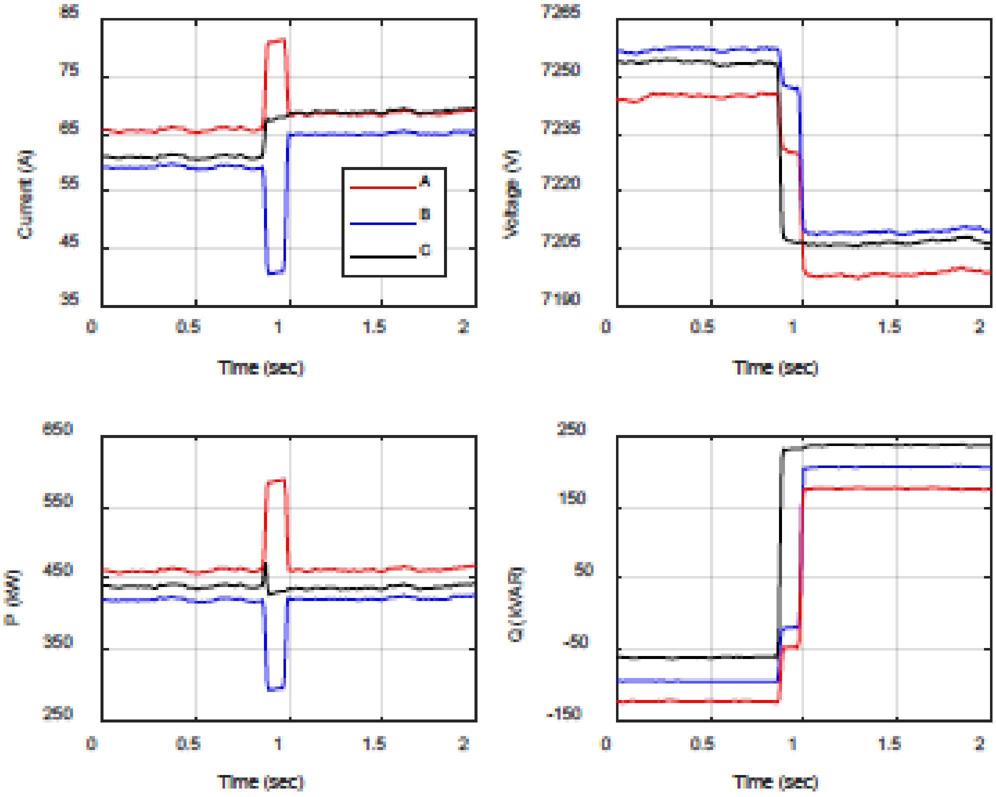
[42] A. Silverstein, “Diagnosing Equipment Mis-operations with PMU Data” [2015].

[43] A. von Meier, E. Stewart et al., “Precision Micro-Synchrophasors for Distribution Systems: A Summary of Applications” [2017].

Figure 10 – Capacitor bank switching problem detected using µPMU data
(Source: H. Mohsenian-Rad, UC Riverside, "Event Location Identification using Distribution Synchrophasors," [2018])



A further motivation for improved asset monitoring is that with higher levels of intermittent assets and faster grid operation, many transmission assets now work more duty cycles each year, often under hotter temperatures causing more equipment stress. The industry does not have much experience on asset performance under these changed use conditions and needs better monitoring to track ongoing asset performance and identify potential asset deterioration and performance impacts before the point of failure.

2.6 Load monitoring and characterization

The character of electric end use loads has been changing over the past two decades, with an increasing proportion of loads becoming electronically coupled (as with batteries, LED lighting, air conditioners, and anything else with an electronic converter that converts AC to DC) or having variable speed drives. (See Table 5). The Department of Energy estimates that 80% of the nation's electricity will flow through power electronic devices by 2030.[44] Such loads respond differently to electric faults and grid events than the resistive loads that previously dominated the grid. Under extreme conditions, the

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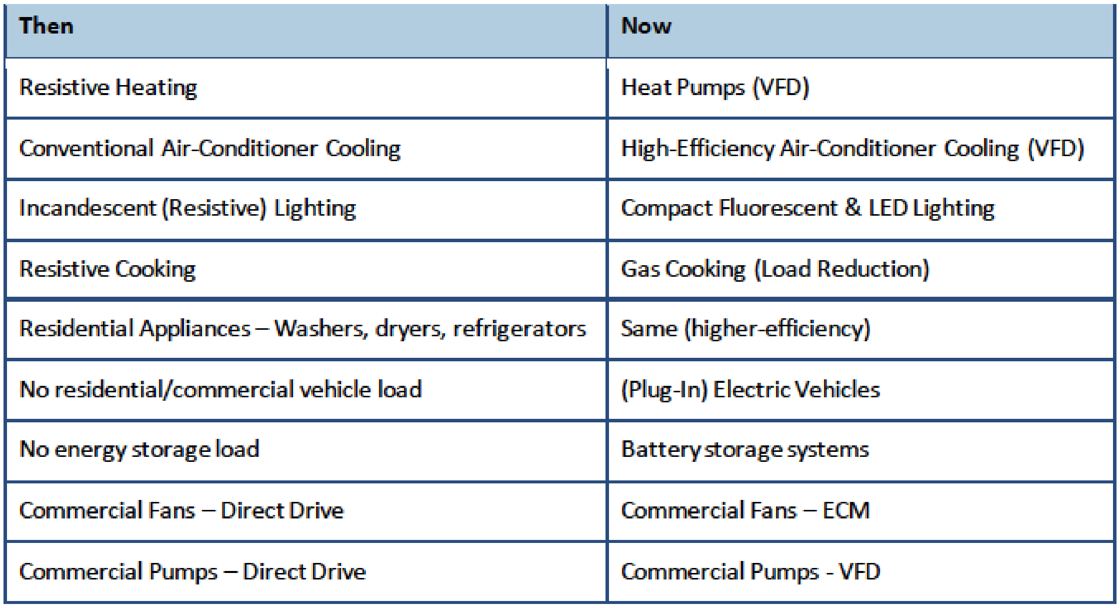
[44] L.M. Tolbert, T.J. King et al., "Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications" [2005], p. I-1.

existence of a high proportion of electronically coupled loads relative to resistive load could cause Fault-Induced Delayed Voltage Response and cascading outages.[45]

Table 5 – Changing character of end-use loads

(Source: NERC, “Dynamic Load Modeling Technical Reference Document” (2015), p.3)



Then	Now
Resistive Heating	Heat Pumps (VFD)
Conventional Air-Conditioner Cooling	High-Efficiency Air-Conditioner Cooling (VFD)
Incandescent (Resistive) Lighting	Compact Fluorescent & LED Lighting
Resistive Cooking	Gas Cooking (Load Reduction)
Residential Appliances – Washers, dryers, refrigerators	Same (higher-efficiency)
No residential/commercial vehicle load	(Plug-In) Electric Vehicles
No energy storage load	Battery storage systems
Commercial Fans – Direct Drive	Commercial Fans – ECM
Commercial Pumps – Direct Drive	Commercial Pumps - VFD

NERC and other analysts recommend the use of high-resolution, long-duration load monitoring (such as CPOW monitors) to capture the character and response of various customer load elements, in aggregate and individually. Such monitoring has been conducted by Southern California Edison at residential feeders using power quality meters[46] and by Bonneville Power Administration doing POW monitoring on its headquarters building, both using PQubes.[47] CPOW-type monitoring is well-suited for this task, since the CPOW data can be used to identify load responses to transient as well as stable conditions, and can be used to calculate phasor measurements as needed. Electric load modelers have recognized that loads must now be represented with multi-dimensional, multi-character models, such as the Composite Load Model now in use in WECC.[48]

2.7 Distribution event monitoring, detection and analysis

Load monitoring with CPOW devices could also be helpful to gain better understanding of electric distribution systems. These are more diverse, fragmented and complex, and less understood than transmission systems, in part because distribution systems have

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[45] See particularly, NERC Load Modeling Task Force, “Dynamic Load Modeling Technical Reference Document,” [2016], and D. Kosterev, “Changes in Load Composition and Its Impact on Power System Reliability” [2018].

[46] R. Bravo, R. Yinger, J. Eto, “FIDVR in Distribution Circuits” (2013).

[47] D. Kosterev & S. Yang, “Load Composition and Monitoring at BPA” (2017).

[48] See, for instance, D. Kosterev, “Composite Load Model Development & Implementation” (2015).

received less dedicated high-speed monitoring and study. Electrical phenomena tend to be slower at the bulk power system level due to grid damping and inertia, but move much faster at the distribution level.

Continuous sampling is needed on the distribution system to better understand everything that is happening at that level, including what happens at very fast speeds inside all of the equipment that makes up or is attached to the distribution system. With the proliferation of behind-the-meter inverter-connected renewable generation and battery storage, demand response, and electronically-connected loads, many more distribution system events are occurring, and those events are having greater impact on customers and have a higher probability of adversely affecting the bulk power system. These concerns have increased the importance of having better visibility into and understanding of distribution system operation and events.

A majority of the customer outage minutes experienced each year arise from events that originated with a problem on the distribution system. The sources of these problems are wide ranging, from weather to operational or equipment failures. As more detailed CPOW data becomes available for distribution feeders, those data can be used to identify distribution event signatures and the precursors that indicate an emerging problem. This will enable distribution managers to anticipate and react to distribution problems with greater speed and effectiveness. It will also help identify weak points and practices that compromise distribution effectiveness, and design new equipment configurations (such as microgrids and time- or equipment-specific demand response actions) and practices to improve system resilience and reliability.

2.8 Opportunities from new data combinations

The Department of Energy recognizes that the modern grid extends to the outer edges of customer energy sources and uses. Thus, it is worthwhile to think about how to use CPOW measurements (and other emerging sensors and measurements) to serve these broader purposes.

The discussion above has addressed time-synchronized data from power system measurement devices. However, there is potentially great value to be gained from combining multiple types of heterogeneous data, despite potential time resolution and time occurrence mismatches. This value may come from combining different types of data using artificial intelligence and big data management techniques to yield new insights in the areas outlined in Table 6, which shows applications that could benefit from combining high-precision time-synchronized grid data with other data.

One interesting issue to explore in future analyses will be the question of how well non-UTC-synchronized data with approximate time labels can be correlated with highly accurate time-stamped CPOW data. CPOW data samples are hundreds or thousands of times faster than other time-labeled power system data sources, from PMUs to SCADA to smart meters, and will be more precisely time-stamped than external data such as local irradiance feeds, customer service calls and tweets, and weather data. But similar data quality, data matching and down-sampling issues are being explored and resolved using technical data in other sectors and problems (e.g., aircraft operation and equipment condition or wind turbine fleet management), so electric industry POW analysts should be able to learn from those efforts.

Table 6 – Reasons to combine time-synchronized power system data with other data

Application	Time-synchronized data
Load forecasting	• Smart meter data • Feeder data • Building energy management systems • Electric vehicle chargers
Customer outage management	• Smart meter data • Customer service center information • Distribution management system • Customer social media activity
Solar PV forecasting	• Weather data • Insolation or irradiance data • Inverter records
Power system situational awareness	• Traffic data • Weather data • Satellite photos • Drone inspection footage • Fire and police activity
Power market analysis	• Market price and locational data (LMPs)
Generation fuel availability	• Gas pipeline activity
Geomagnetic disturbance detection	• Space weather data • Field magnetometer data
Cyber-attack detection	• Communications and IT traffic patterns

3.0 Implementation issues

This section reviews a number of implementation issues relating to how the electric industry might use CPOW data and offers suggestions for how to resolve each issue. Much of this discussion is based on the key assumption discussed in Section 2 on ways to use high-resolution measurements – these advanced measurements should be deployed and used to supplement existing measurement systems.

The CPOW data uses discussed in Section 2 can be sorted into four categories along the dimensions of local data processing and action versus centralized analysis and action, and real-time or fast uses versus slower off-line uses. The factors of how quickly the data analysis is needed and where a responsive grid management action should be initiated offer guidance for where the CPOW analysis should take place, which in turn would affect CPOW data storage, communications and analytics architecture. Table 7 sorts out many of the POW applications from Section 2 along these dimensions.

Table 7 – CPOW applications by location and speed

	LOCATION OF ANALYSIS AND ACTION	
SPEED OF ANALYSIS AND ACTION	**Local (at the edge of the system)**	**Centralized (in the control room)**
Real-time or fast (within a few seconds or minutes)	• Fault location • Detection of imminent asset failure • Geomagnetic disturbance detection • Feeder situational awareness • Harmonics	• Distribution system topology discovery • High-level system situational awareness • Coordinated alarms and alerts
Delayed (a few minutes or hours) or off-line	• Distributed generation characterization and disaggregation • Asset condition monitoring (distribution, generation, transmission, customer) • Power quality analysis	• Data-based model construction • Model validation • Load monitoring and analysis • Load forecasting • DG forecasting • Event analysis

Most of these applications require CPOW measurement devices to be located at the edges of the system, as within distribution feeders, at inverter-connected resource busbars, and between the distribution feeder and the transmission system.

3.1 Availability and development of high-resolution measurement devices

When synchrophasor technology was in its infancy in the late 1990s and 2000s, most PMUs were research-grade and use of the PMU data was constrained by limited communications, data storage and analytical capabilities. In contrast, POW measurement already exists – it is the technological heart of every digital relay and dedicated devices, such as DFRs, merging units, and power quality meters. Since transient events on the grid may peak and decay in microseconds, a meter or sensor will need to sample at a rate of 2 MHz or faster. There are already commercial meters and monitors capable of sampling at rates from 256 and 512 samples/cycle up to 6 MHz (100,000 samples/cycle, or every 166 nanoseconds).

Today, measurement functionality, such as power quality and synchrophasor calculations, is performed internally within the device by low-level software within the hardware, most often in ways that are not upgradeable or replaceable. But in a software-based sensor, those algorithms could be applied to CPOW data locally within the sensor or the use application, or applied centrally; they could be performed immediately upon measurement or long after the waveform data has been measured and stored. On a software-based sensor, the algorithms could be updated and supplemented to serve multiple functions and applications as new uses and techniques evolve. This would also enable wider use of open software and more transparency about the nature and effects of the algorithms being used.

Signal processing is an important element of high-resolution measurement. Other industries – particularly audio and video – are already performing routine signal processing at rates of 44.1 to 96 kHz. One expert expects that at some point in the future, ADC capability will be built directly into every electric transducer, enabling all signal processing to be performed on general purpose computers.[49]

One of the great benefits of software-based CPOW sensors with communications addressability is that the device owner can do remote software updates to update the device's capabilities without being locked into dated vendor firmware. Additionally, it frees the data from becoming frozen by algorithms or reference architectures tied to a specific point in time, and allows data processing anywhere, any time.

3.2 CPOW data storage, analysis and communications architectures

The world outside the power sector has already developed and embraced economical data storage and archiving (remote and in the cloud), fast and reliable data communications architectures and networks (physical and in the cloud), advanced signal processing capabilities, and fast artificial intelligence and other sophisticated real-time and off-line analytical capabilities. The electric industry can use all of these evolving technologies immediately. The use of large volumes of CPOW measurements is limited today by reservations about what are the most pressing ways to use CPOW data, how much data is needed for each application, and how to manage and use all of the collected data effectively.

As with synchrophasors and other smart grid technologies, CPOW device deployments, application placement, data storage and communications, and overall system design should be driven by the goals and uses for the insights and benefits sought. SCADA systems stream field data up to the control room for analysis and action; most PMU systems were initially designed to stream data up to a Phasor Data Concentrator (PDC) and pull data from the PDC to feed into various centralized applications such as wide-area situational awareness and model validation. In contrast, since many CPOW uses are local, it is possible to design data management, storage and applications architectures that use local data locally, then stream it to a central location for analysis and data archive. This would differ from current PMU-type data architectures, which tend to centralize data storage in utility-owned physical hardware, compress data in ways that may compromise data quality, and delete rather than retain older data.

This section reviews some key ideas about the design of CPOW data storage, analysis and communications.

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[49] This is what happened in the audio and video fields, enabling the development of standards-based, off-the-shelf technology tools such as ProTools (audio) and AVID (video), which contain more signal processing capability than will be needed in any electric substation.

3.2.1 Match system design to analytical needs

Many CPOW data applications will perform the calculations and act on their results close to the measurement device at the edge of the power system, as at the feeder or substation. This works for applications such as fault location, equipment monitoring, local protection and controls such as volt-var management, monitoring distributed inverter-based resources, or identifying ground-induced currents. Such applications should perform immediate data analysis,[50] compare the results against pre-determined triggers (e.g., under-voltage condition, fault occurrence, inverter cessation), initiate responsive local action as appropriate, and send at least the derived information and alerts up to a central processing point for further attention and action. Ideally the CPOW data will be streamed to and archived in a central data hub for several years.

Local field applications such as system protection, fault location and voltage management will need to coordinate between multiple devices, so there it will be useful to enable local communications between those devices. When one field IED measures conditions that match a known trigger condition, it should initiate a poll of other nearby devices to determine what they measured. As with existing protection schemes, automated analysis and logic should determine whether and which automated action is an appropriate response and report the conditions and alert to a central authority which may itself initiate remedial action.

Very large CPOW data archives will be required for analysis with statistical or artificial intelligence and machine learning tools, as to identify renewable generation patterns, diagnose asset conditions and anomalies, and identify event precursors. It is already feasible to run such analyses on streaming data in the field, or in the central control room; for the near term, analysts should focus on identifying key data signatures based on deep learning analysis of historical CPOW data, and use those signatures to screen streaming CPOW data in the IED and in the local substation.

3.2.2 Match filtering and processing to analytical needs

CPOW direct empirical measurements can be analyzed instantly and stored at the point of measurement in the field, with processing and analysis tailored to the specific application need. This would allow an analyst to compare original CPOW data in real-time against known alert and anomaly patterns and triggers, use one set of PMU filters and algorithms on the data for damping control, and use another set of filters and algorithms for harmonics analysis. The same CPOW data could be moved into a data archive for later analyses of wide-area grid patterns, asset conditions and load characterization.

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[50] One expert recommends that, "If computation is performed in the IED at the edge of the power system, it should be open and transparent so the users of the data can understand how that data has been transformed."

3.2.3 Don’t throw away CPOW data

The model for SCADA and PMUs is that almost all data collected is streamed to central data hubs[51] and applications to serve centralized bulk power reliability management and wide-area situational awareness. A single SCADA monitor may generate about 21,600 records per day; a PMU will generate 5,184,000 readings in the same period; and a single CPOW device could produce 124 million measurements in a day. This volume of data makes data management and storage a significant challenge for a system that collects and combines SCADA, PMU and other data for analysis and retention. Fortunately, the recent availability of remote field archives, high-speed data communications networks to support batch data retrieval and real-time data streaming, cloud storage of large data archives, and many advanced data handling tools will make it easier, faster and cheaper to store, retrieve and manage very large amounts of CPOW data. It is likely that the question of how and where to place CPOW data storage and analysis at the edge versus central operations will be an evolving balance that changes over time with data storage advances and analytical needs.

Newer POW devices have communications capabilities so they can either be queried as the data are needed to pull the data up for analysis, or can initiate an event-specific notice that sends a reduced dataset of relevant data and field calculations up to a central analytical and action point.[52]

Much of the data collected locally by CPOW devices does not need to be streamed in real-time, so the communications capability and central data storage requirements for CPOW systems may be less daunting than they initially appear. It is likely that early CPOW system plans will collect, compress[53] and store most data at the edge of the system and feed event data up to the cloud for long-term storage and retrieval.[54] Real-time data streaming to the control room could be limited to selected chunks of CPOW data and analysis-derived results that meet pre-defined criteria for reliability problems or anomalies (e.g., voltage stability or imminent asset failure), or are pulled up later on a publish-subscribe basis for a specific event investigation.

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[51] The Phasor Data Concentrator (PDC) was developed to collect and time-align data sent from multiple PMUs, sites and sources up to a single point, and move the resulting aggregate dataset up for analysis and use or into a data archive. PDCs were initially conceived as stand-alone computers and routers; increasingly, PDC functionality is built into network functions and the PDC as a stand-alone device is becoming obsolete.

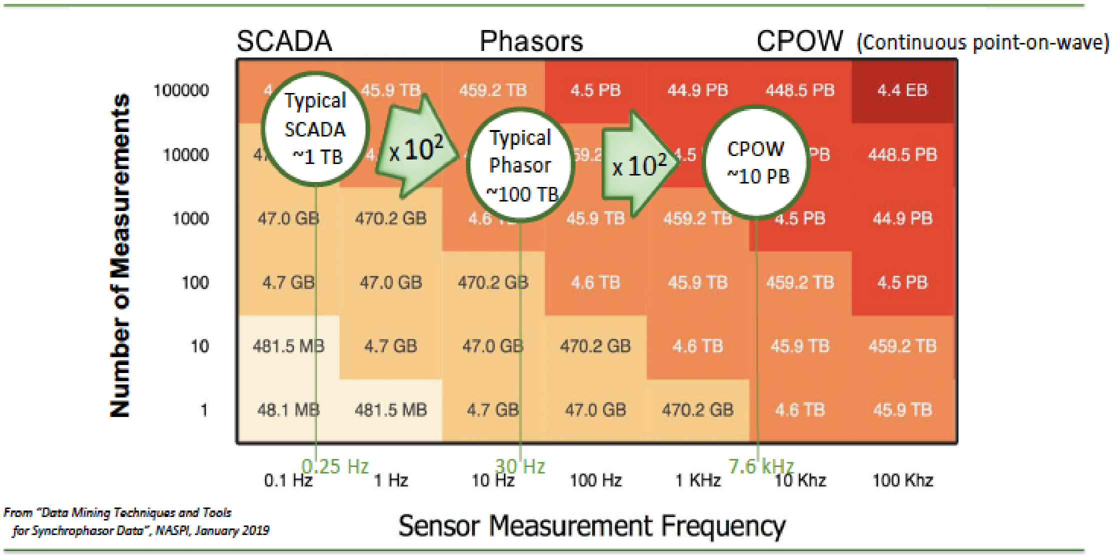
[52] Older POW devices may not have extensive data storage on-board, so data access may require a truck roll to the site for manual data retrieval.

[53] Lossless compression of CPOW data in IEC 61850-9-2 or IEC 61869-9 format is possible, resulting in reduced data rates by approximately a factor of two, depending on the latency required; if low latency is not required (which is likely to be the case for CPOW data), then increasingly improved data compression can be achieved. Counterintuitively, this leads to a significant and beneficial reduction in encoding time (in the merging unit) and decoding time (at the end application), and faster data communications transmission times due to the reduced frame size. However, this approach is not yet standardized. See S.M. Blair, A.J. Roscoe and J. Irvine, "Real-time compression of IEC 61869-9 sampled value data," 2016 IEEE International Workshop on Applied Measurements for Power Systems (AMPS), Aachen, 2016.

[54] One observer commented, “It’s likely that most of the CPOW data collected will never be shipped, only compressed, archived and ignored.”

Analyses of data storage requirements tend to assume that newer data collection devices are deployed in high volumes immediately, and that all grid monitoring data will be pulled up to a central data archive for long-term data storage. Figure 11 exemplifies these assumptions, showing the number of measurements collected annually by different levels of grid monitoring devices and the cumulative annual storage requirement for each. While these data volumes appear daunting, any entity stepping into CPOW data measurement would not grow its fleet of CPOW measurement devices immediately. Additionally, the availability of cloud storage materially reduces the annual cost of data storage.

Figure 11 – Comparison of annual data storage requirements
(Source: R. Robertson, Grid Protection Alliance)



From "Data Mining Techniques and Tools for Synchrophasor Data", NASPI, January 2019

Several recent papers address existing or proposed data management and analysis structures. These include work by the U.C. Berkeley-CIEE team on the ARPA-e µPMU project team,[55] Dominion Virginia Power working with PingThings,[56] Arizona Public Service working with PingThings,[57] a proposal from Schweitzer Engineering Lab,[58] and the NASPInet 2.0 Guidance document.[59] These papers collectively suggest that data management and analysis of high volumes of data should be manageable.

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[55] H. Mohsenian-Rad, E. Stewart & E. Cortez, "Distribution Synchrophasors," [2018] and A. Shahsavari, M. Farajollahi et al., "A Machine Learning Approach to Event Analysis in Distribution Feeders Using Distribution Synchrophasors," (2018).

[56] See for instance, Kevin Jones, "Getting Beyond Base Camp: Scaling Your Synchrophasor Data Mountain," (2018).

[57] M. Rhodes, S. Murphy & J. Schuman, "Real World Experiences and Benefits with a Next Generation Data Platform for Synchrophasors," (2018).

[58] G. Zweigle, "A Wide-Area, Wide-Spectrum Big Data System," (2015).

[59] J. Taft, "NASPInet 2.0 architecture guidance," (2018).

3.2.4 Use existing communications networks to retrieve CPOW data

Most new CPOW devices have on-board or adjacent data storage capabilities that can store multiple days or weeks of continuous measurements. They also have addressable communications capabilities. This enables the user to stream the data continuously or to stream the data in batches, using the same field network that supports substation relay and protection data. Data compression methods may help reduce the amount of bandwidth needed to stream real-time CPOW data or retrieve it in event-specific polls or routine batch uploads to a master data archive. One argument in favor of continuously streaming CPOW data is that if a major grid event happens, that event may destroy the ability of the communications system to deliver the data needed to analyze and resolve that event.

3.2.5 Suitable data archive and database technology already exists

Amazon Web Services and other web-based services already provide data storage services that can handle large volumes of data such as those that will be accumulated by CPOW measurement systems. An extensive set of commercial database management tools exists, developed in concert with the growth of AI/ML applications, that can handle CPOW-scale data. Electricity sector-specific tools available for handling CPOW and CPOW data include the Lawrence Berkeley National Laboratory's toolset (BTrDB -- Berkeley Tree DataBase[60] and plotter), PingThings' PredictiveGrid,[61] Kx Systems' kdb+ time-series database,[62] and the Synaptec Synthesis tool.[63]

3.2.6 Analytical tools

There are already many powerful statistical and deterministic tools available to analyze synchrophasor, SCADA and POW data, and these tools should work with CPOW data as well. Many artificial intelligence and machine learning (AI/ML) tools can be applied to CPOW data in combination with other data sources. While it is possible to develop AI/ML tools that analyze streaming data in real time, that should not be necessary for many field uses of CPOW data. Rather, once off-line analysis has identified solid patterns and markers of key events and concerns within the data, it should be sufficient to perform real-time comparisons of the streaming data against those known patterns to generate alerts and alarms for the control room, or initiate local control actions to protect the grid.

As industry analysts gain more experience and understanding of very fast grid phenomena, they are likely to develop new analytical techniques and tools to systematize and implement those insights. It may be difficult to develop new, novel monitoring, alert or control triggers beyond those already known (e.g., FIDVR or PV inverter cessation) until more long-duration CPOW monitoring and analysis has been completed.

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[60] The Berkeley Lab Power Data Portal uses the BTrDB to handle the POW datasets demonstrated.

[61] See https://www.pingthings.io.

[62] See https://kx.com.

[63] See https://www.synapt.ec.

3.2.7 Use standard protocols and file formats for data communications

The Department of Energy's grid modernization efforts incorporate a strong commitment to the use of standards and protocols to assure consistency, quality and interoperability between equipment and data flows. DOE and the electric industry have committed large amounts of time and money toward this end to improve the quality and usability of diverse IEDs, information and applications – but data format standardization and compatibility is an ongoing challenge.

Current data protocols being used to stream real-time PMU data have been found inadequate to assure reliable, timely high-volume data flows due to data losses (UDP) and latency (TCP). To remedy this, the Department of Energy funded the Grid Protection Alliance to develop a new data protocol, STTP (Streaming Telemetry Transport Protocol), that is specifically designed to transmit high volumes of real-time telemetry, such as PMU or POW data, with CPU-efficient lossless compression.[64] That protocol has been tested and demonstrated extensively with a large set of industry partners, and is now being developed into an IEEE protocol (IEEE 2664). When that standard is approved, STTP can replace current POW transmittal methods.

Merging units are now using IEC 61850-9-2 to send CPOW data as sampled values within a substation.

Time-sensitive networking (TSN, being developed under IEEE 802.1) could be useful for CPOW data communications. TSN addresses time-sensitive, low-latency, high-availability data transmission over Ethernet networks. It is being developed for real-time audio and video streaming and industrial and automotive control networks. Insights from software-defined networking and network virtualization could also help CPOW data architectures and management. The IEC 61850-90-13 Task Force is presently investigating the impact of TSN in power system applications.

3.2.8 Look outside the electric industry for solutions

The electric industry often assumes that its technical problems are unique and can only be addressed using purpose-built technology developed with in-industry resources. But as the electric industry and its customers use more and more automation, software, sensors, information technology and communications to manage its assets, it becomes clear that the electric industry is following in the technical footsteps of other industries (as with the Internet of Things) rather than breaking new ground.

High resolution data sampling is routinely used in other industries, as are ADC and signal processing (e.g., audio and video), high speed data transport (finance), time-sensitive networking (industrial automation), AI/ML (manufacturing, retail, and many more). Simultaneous parallel data sampling and communications at differing data sampling rates

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[64] J.R. Carroll, "A Practical Approach to Streaming Point-on-Wave Data," (2019).

is already occurring in the communications, automotive, and infotainment fields. The electric industry can find and adopt new technologies faster and with lower cost if we leverage experience and insights gained with standardized technologies adapted from other fields, rather than attempting to craft new technologies for narrow purposes.

3.3 Time synchronization and delivery

The time domain is a common framework for organizing data and creating understanding across many human and industrial activities. The electric industry already uses data sampled at different rates for purposes such as forensic event analysis and linear state estimation. This is generally performed using up-sampling and down-sampling from the various input data streams; it is made much easier if the data are UTC-time synchronized rather than merely time-stamped.[65] Beyond the electric industry, other sectors and analysts are successfully using AI/ML techniques to combine multiple data sources that are not time-synchronized and reflect differing sampling rates with time-synchronized data (e.g., weather conditions with shopper information and social media).

Clock or precision time delivery sources for time synchronization need to be accurate up to ± 500 nanoseconds to provide the 1 microsecond time standard needed by a PMU or other synchrophasor device. This accuracy requirement is already achievable from a variety of sources, including on-board cesium clocks, geo-satellite time sources such as GPS and GLONASS, terrestrial sources such as WWVB radio, and network time delivery using the IEEE 1588 PTP protocol.

The time synchronization standards now used in the electric industry work well for measurements at synchrophasor speed. But it may be necessary to reexamine time synchronization standards and practices to determine whether and how they need to improve – particularly with respect to cybersecurity and redundancy -- to serve POW measurements at thousands or a million samples per second. In particular, given cyber-security concerns about both timing sources and measurement devices and networks, it will be necessary to develop methods to verify that POW devices are measuring consistently across a location and retain consistent time synchronization.

3.4 Cybersecurity

Cybersecurity is important for CPOW devices, the communications networks between devices and to a central analysis and data archive hub, and for the applications and archive points. Deployment of many CPOW devices and CPOW-based applications in the field will increase the scope and number of devices (and possibly networks) that require physical and cyber protection. However, CPOW devices are unlikely to create new cyber or physical security complications that differ from the challenges already

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[65] Although we know how to time-synchronize power system measurements, the electric industry has not yet identified a set of best practices for time-stamp correlation, particularly with respect correlating and aligning measurements (as from DFRs and relays) that are not time-synchronized against UTC or its local equivalent.

posed by relays, PMUs, substations and other field devices. In the near term, it is likely that most CPOW data will be archived and processed locally and retrieved in batches as needed for centralized analysis, rather than streamed in real time; this may reduce cyber vulnerabilities.

More broadly, any high-bandwidth communications network poses a security vulnerability for its users. Critical data transported over such a network should be encrypted and the network, its access points, and the enterprise system 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 don't 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.[66]

Although cybersecurity is critical for the success of many electric processes and applications, it is likely that most cybersecurity technologies and solutions will be developed outside the electric industry and applied within the industry as needed.

3.5 Technical and interoperability standards

Several observers recommend that further development of technical standards for CPOW data should be delayed until there is better understanding of how it will be used. They fear that premature standards could hamper further innovation in the measurement technology, IED development and data applications, and facilitate vendor lock-in.

At some future point it will be appropriate to define the appropriate minimum sampling speed for CPOW data and the measurement and data quality necessary to accurately represent dynamic electric waveforms. That will enable refinement of the performance standards and conformance guidelines for CPOW measurement devices, tailored to support high-value early CPOW applications. It will also drive development of new data storage, retrieval and streaming protocols appropriate for the volumes of data that will be collected with high-resolution CPOW devices; these will likely be segmented between edge and central data management. Cybersecurity considerations should be integral to all of the above designs and standards.

Once high-speed CPOW measurement devices are routine, it will be appropriate to develop new technical standards for practices such as the necessary speed and quality of measurement filtering and processing.

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[66] 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.

3.6 Reliability standards

As discussed in section 1.4, NERC has already adopted reliability standards that require high-speed event recording for event capture and modeling purposes. Not all of these standards require that high-speed event data be time-stamped, nor that it be archived permanently for event analysis or combination with other data for later analysis. NERC standards tend to follow, rather than lead, technology development and reliability applications; it is unlikely that reliability standards will drive the adoption of newer CPOW IEDs, CPOW data retention practices, or CPOW data applications in the near future.

3.7 Will CPOW data replace PMU data?

It seems unlikely and unnecessary that CPOW will replace PMU data, at least over the next 10-20 years, just as PMUs did not replace SCADA systems. The electric industry has been managing, planning and analyzing the power system using EMS and SCADA data (neither of which are UTC-synchronized) and event-specific POW data from DFRs for the past 40 years. We have been accessing PMU and synchrophasor data for only 20 years, but the first of today's modern PMUs only entered service around 2010. In 2020 we are in the middle stages of deploying PMUs and collecting and analyzing the data.

But there are DFRs in every substation today and commercial CPOW devices are available for use. It may take another 5 to 10 years to move through the applications conception and development phase for CPOW data, and more time for analysts and early adopters to gain confidence in how to use the data collected and what it means. Just as PMU use has not yet spread to every transmission owner and control room, it will take many years before most industry members see enough application value – beyond monitoring renewable generation and other inverter-based resources -- to justify investing in wide deployment of CPOW devices and the associated storage and communications networks. However, CPOW data will join SCADA and PMU data as another layer in a suite of data sources that offer differing, complementary information and insights and are used in complementary and redundant, rather than competitive, roles to support the operation and planning of the modern grid.[67]

4.0 Conclusions

It seems probable that CPOW measurement systems will complement synchrophasor and SCADA systems over at least the coming decade, and contribute to an improved continuum of measurement across the power system. Although there are many valuable ways to use CPOW data (as reviewed in Section 2), many factors will affect the ease and speed of adoption of sustained POW monitoring and analysis systems (as reviewed in Section 3). It will take some time before industry analysts and users have analyzed

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[67] This highlights the importance of finding ways to access and aggregate multiple data sources and integrate them successfully despite varying data formats, content and quality.

enough CPOW data to gain confidence that they understand what is happening at very high speeds on the power system. The electric industry may use targeted, limited CPOW measurement systems to solve industry pain points such as inverter-based resource monitoring. But many industry members will wait until wider information technology developments have made data communications, storage and analysis so easy and low-cost that CPOW measurement becomes hard to resist.

In the meantime, it will be useful for the Department of Energy and some leading industry members to begin deploying CPOW devices and data collection systems to monitor some key applications, including some utility-scale inverter-based resource (IBR) sites and complex distribution feeders with high penetrations of distributed renewables, storage devices and electric vehicles.[68] These data archives can be used as the foundation for analysis and application development. Since the North American Synchrophasor Initiative (NASPI) collaborative effort was very successful at joint problem-solving to advance the development and quality of synchrophasor technology, and CPOW measurements are the next logical step in the continuum of grid monitoring technology, DOE could expand NASPI's scope and charge to include CPOW exploration and development.

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[68] DOE should also implement a policy that any CPOW deployments it funds must share the data collected for a national archive that can be used for research and analysis purposes, rather than being held privately by individual data owners without shared research access. The lack of PMU data-sharing has significantly delayed the speed and quality of synchrophasor application development and realization of the value of wide-area monitoring and situational awareness.

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