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Roadmap for Advanced Power System Measurements

April 2021

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U.S. DEPARTMENT OF ENERGY

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Summary

Conditions in the electric power grid are changing rapidly. Changes are driven, in particular, by the increased penetration of renewable resources in the generation mix. Part of the solution to dealing with the changing conditions is the better use of measurement systems, taking advantage of the better understanding of measurements that was heralded by digital technology. Another part of the solution is the communication of samples of the directly observable voltages and currents by means of continuous point-on-wave values. The increased bandwidth capability of such a system allows more complicated measurement models to be built at the point of use. Additional measurements and analyses can then be performed.

This Roadmap hinges on these two aspects of measuring: improved measurements supported by high-bandwidth (raw data) communications. Following an introduction to the overall subject, the report explores the impact of what can be thought of as the digital revolution in measurement. In essence, that revolution has served to clarify ideas about measurement and is continuing to lead to improved processes.

An extensive survey of the relevant literature was performed[1]. Webinars were held to learn from the wider community of practitioners. Based on this information, a number of gaps were identified whose continued existence would hamper the solution of the challenges now facing measurement and communication in the power grid. The underlying value propositions are interoperability (presently not very satisfactory in many measurements); greater (and less challenging) adoption of distributed energy resources; and improved international competitiveness. Underlying all that, of course, is progress toward a more reliable and resilient power system.

The identified gaps were addressed in four major thrusts: technology deployment and demonstration, education, instrumentation testing and standards, and analytical methods. For each of the thrusts, multiple goals are defined to guide the implementation. The thrusts were designed to close gaps and unlock high-value use cases.

After discussing the literature review, gap analysis, high-value use cases, and research thrusts in chapters 2-5, the report culminates in chapter 6 with a roadmap that links each aspect together to form a unified plan. Developing a research portfolio aligned with this plan will ensure that advanced measurement systems are in place to support reliable operation of the power system as it modernizes.

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

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Finally, the authors would like to express their sincere gratitude to the industry stakeholders that responded to surveys, shared insight during webinars, and provided suggestions during the editing process. This document would not have been possible without their contributions.

Acronyms and Abbreviations

AI/ML	Artificial Intelligence/Machine Learning
ARRA	American Recovery and Reinvestment Act
BIPM	International Bureau of Weights and Measures
CPOW	Continuous Point-on-Wave
DER	Distributed Energy Resources
DFR	Digital Fault Recorder
EMT	ElectroMagnetic Transient
EV	Electric Vehicle
FIDVR	Fault-Induced Delayed Voltage Recovery
GMLC	Grid Modernization Lab Consortium
GOOSE	Generic Object-Oriented Substation Events
GUM	Guide to the expression of Uncertainty in Measurement
HEMP	High-Altitude Electromagnetic Pulse
IBR	Inverter-Based Resource
IEA	International Energy Agency
JPL	Jet Propulsion Laboratory
MTBOOT	Mean Time Between Out Of Tolerance
NASPI	North American SynchroPhasor Initiative
NERC	North American Electric Reliability Corporation
PMU	Phasor Measurement Unit
POW	Point-on-Wave
PTP	Precision Time Protocol
PQ	Power Quality
PQM	Power Quality Meter
RMS	Root Mean Square
SCADA	Supervisory Control And Data Acquisition
SGIG	Smart Grid Investment Grant
TRL	Technology Readiness Level
VIM	Vocabulary of Metrology

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1.0 Introduction

Over the last decades, a combination of factors, including improvements in communications technology, instrumentation, and the availability of inexpensive processing capability, has allowed several significant changes to take place in the electric power grid. Two large-scale "external" changes in particular have overarching implications for the power system, and they are interconnected.

The first of these external factors is the growing concern, in the US and abroad, over sustainability and climate change. In the US, power system response to this factor arguably began with the passing of the Public Utilities Regulator Policy Act in 1978. Section 210 of the Act led to changes that meant there would be retirements of older fossil fuel plants and greater penetrations of distributed (often renewable) sources. The Department of Energy, then a new agency, responded to the changes by funding much appropriate research. Electricity generation from renewable resources is forecasted to increase significantly in the future from 21% in 2020 to 42% by the year 2050[2].

A second external change has been the success of the electric vehicle (EV), arguably due to advances in battery technology. The DOE's predecessor, ERDA, funded basic work on the technologies that are making EVs a significant factor, and perhaps a significant challenge, in transport and energy. NASA's Jet Propulsion Laboratory (JPL) "managed three major programs resulting in complete vehicle systems. The first two, initiated by ERDA in 1976, were run concurrently and investigated the performance potential and economic viability of a near-term electric vehicle amenable to mass production in the 1980s. Recognizing that all-electric vehicles would not be directly competitive with general-purpose conventional vehicles due to range limitations, the Near-Term Hybrid Vehicle [NTHV] Program was initiated in 1978." [3]

According to the International Energy Agency[4] (IEA) in a sustainable development scenario for 2030, the potential of vehicle-to-grid and variable renewable peak capacity is estimated to be 163 GW with 90 GW from electric vehicles connected to the grid. The US EV fleet in March 2019 was 1.18 million[5] vehicles, growing the US vehicle market share to 1.8% from 1.6% in 2018.

The smart grid with sophisticated digitization, communications and analytics can be viewed as bringing these considerations together. We can interpret "smart grid" as meaning a grid with increasing levels of instrumentation and automation, expected to cope with the impact of the distributed resources (including those in the distribution system) and the electric vehicle (which must be considered as a resource as well as a load). This constitutes a grid with much faster dynamics and a much greater need for accurate, high-resolution measurements. Such measurements require better understanding and articulation of what needs to be measured.

This report is aimed at providing DOE with information on the growing needs (and challenges) brought about by the additional control and automation required by the smart grid. As we have

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2 https://www.eia.gov/outlooks/aeo/pdf/00%20AEO2021%20Chart%20Library.pdf

3 The quotation is from D. Kurtz and V. Roan: The JPL Electric and Hybrid Vehicle Systems Research and Development Project, 1977-1984, JPJ D – 1866, Jan 1985, available https://ntrs.nasa.gov/api/citations/19890067893/downloads/19890067893.pdf

4 https://www.iea.org/reports/global-ev-outlook-2020

5 https://www.eei.org/issuesandpolicy/electrictransportation/Documents/FINAL_EV_Sales_Update_April2019.pdf

seen, what the DOE does can have important benefits for the nation. But the Department does not operate in a vacuum. It must know what trends are important and what gaps exist in the many aspects of society that will advance the relevant technology. Identifying such things and presenting them in the form of a roadmap for the Department is the aim of this report.

1.1 The Role of Measurement in Power Systems

The results of measurements are used in the planning and the operation the power system, and in post-event sequence of event reconstructions. Different quantities are useful in these various application areas, and they have different requirements. Table 1 lists the electrical quantities most commonly measured and some of their applications.

Table 1 Commonly Measured Electrical Quantities

Quantity	Application	Most Crucial Uses for Result
Power	Planning, Billing, Operation, State Estimation, Relaying	All
Reactive Power	Planning, Billing, Operation, State Estimation, Relaying	All except Billing
Apparent Power	Planning	
Power Factor	Billing, Relaying	Billing
Voltage	Planning, Operation, State Estimation, Relaying	All: this is a very basic quantity and must be generally known
Current	Planning, Operation, State Estimation, Relaying	All: this is a very basic quantity and must be generally known
Frequency	Operation, Relaying	All
Rate of Change of Frequency	R&D: may find application in operations	

Knowledge of the eight quantities listed in Table 1 is sufficient to plan the development of the power system, operate it, get paid for the product, and ensure reliability of service. It is surprising that the measurement of these quantities suffers from a variety of problems, most of which date back to the early days of the industry.

Table II lists the same quantities and gives a short description of the challenges each is associated with. There is an idealized world in which these quantities are visualized, and there is the real world in which they are measured, and most measurements fail to distinguish the two.

Table 2 Challengers with the Commonly Measured Electrical Quantities

Quantity	Measurement Problem
Power	This measurement has only a relatively minor problem. The determination of when the measurement interval should begin and end in a real system has not been well specified. Adequate solutions exist; better ones may be found.

Reactive Power	There are at least 11 ways to measure reactive power, and the results are not interoperable. State estimators sometimes fail to converge because of this problem.
Apparent Power	This quantity suffers only minor issues because it has few applications.
Power Factor	It has proved impossible to define this quantity such that it can be measured interoperably. This has caused billing disputes. It is impossible to relate single phase power factor results to a three-phase quantity. This causes confusion.
Voltage	Voltage is customarily measured as the rms value. While this method is ancient and well-respected, the limitations on its use are not nowadays well-understood, and the technique is frequently misapplied
Current	Current is customarily measured as the rms value and has the same limitations as rms voltage measurements.
Frequency	Frequency is a term that can only ever be applied approximately to the real world. It is based on an assumption of periodicity—one cycle is identical to the next. The mathematical tools used for the idealized world are not valid if that assumption is invalid. When there is an “event” on the system (loss of a generator, or a fault) the differences are gross, and the word, and its associated implications, does not apply even approximately.
Rate of Change of Frequency	The real-world measurement of amplitude is not challenging, that of phase a little more so. Frequency (as it changes in the real world) is more challenging to measure, and rate-of-change-of-frequency more challenging still.

The situation may be summarized as follows. While it seems reasonable to define a quantity in order to measure it, the definition is (and must be) the definition of an idealized quantity. It is these idealized quantities that allow the user of the results to form an opinion about the meaning of the result—is the frequency low enough that we should add a generator, or trip a load? However, when the real-world does not resemble the idealized world, such judgements can be wrong.

The solution to the definition problem is to switch to a different kind of measurement, one in which the quantity to be measured is constrained by a definition of the method in which it is to be measured. Such a measurement method has been in use in power systems for over a century: the rms value. It has been applied successfully to the measurement of voltage and current, and to some extent power. The work on reactive power has failed to recognize that the method is applied here, too, but with non-interoperable methods.

The approach of defining the method, rather than the measurand, is known as operational and it is part of the theory of measurement, a theory that has advanced considerably over the last half-century. The rms value of a quantity is of this kind. A current or a voltage may be sampled many times per second, and the samples reveal an alternating quantity. It would be convenient to express something about all these sampled values so as to summarize them over the course of (say) a second. This is done by squaring the samples, averaging the squares, and taking the square root. Hence root-mean-square. The reason this is done is that the number obtained gives the same heating value as a dc quantity of the same value. The method was discovered in 1886, using analog instrumentation and a light bulb as the indicator of heating value. It has played an important role in simplifying the calculations of alternating quantities ever since. It is usually defined as applicable over any integral number of cycles of a periodic waveform. It has not been widely recognized that the measurement is what is called operational, requiring that a certain set of operations be carried out in a certain order for the value to be meaningful. The quantity being measured is labeled (voltage, current, etc.) but not defined. The method of measurement is specified.

Any measurement that is based on the rms value of a quantity is automatically also operational. That includes all the quantities in the tables above, except for frequency and ROCOF. As the challenges of making those measurements became more evident in the real world, the measurements became increasingly operational, defined by method. However, it was not recognized.

1.2 The Role of Measurement Theory in Power systems

The technology of measuring electrical quantities has advanced enormously over the years. In the early days of the power industry, a three-phase wattmeter might have looked as in the left side of Figure 1-1, an advertisement from 1910. As electronics got better, instruments got smaller and more robust. In the second half of the 20th century, the pointer was replaced with a digital display. It was not long before the measurement itself was done by electronics. Today, a three-phase wattmeter might look like the one on the right side of Figure 1-1.

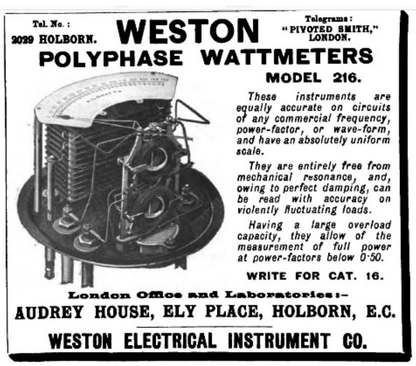

Figure 1-1 Wattmeters; old and new

The new instrument is more flexible, it can be interconnected to other devices, and it boasts a bandwidth of 1 MHz. It can also measure reactive power and power factor, and it displays the results to five significant figures. Its block diagram is shown in Figure 1-2.

But all is not what it seems. While the instrument can make measurements of real and reactive power, and power factor, *they are really no better than those from the hundred-year-old instrument*. In fact, the algorithms executed in the blocks labelled "DSP" and "CPU" are just a digital implementation of the filtering and the so-called "definitions" of a century or more ago.

It will be instructive to consider the measurement of reactive power. Reactive power is defined as $VI \sin \varphi$ where V is the rms voltage, I is the rms current and φ is the phase displacement between the mathematical sinusoids representing the two quantities. The reactive power is an idealized thing, based on the assumed applicability of sinusoidal mathematics. The methods of measurement are not based on a direct implementation of the definition, however, they rely on a convenient relationship in the mathematics.

For any sinusoidal function, sin θ = cos (90°– θ). It is well-known that the power in a circuit is given by VI cos φ. Therefore, by shifting the phase by ninety degrees, a method of measuring power is converted into a method of measuring reactive power. Measuring power is a simple operation this way: after arranging for a ninety-degree phase shift, all one has to do is take the average value of the product of the samples over some number of cycles.

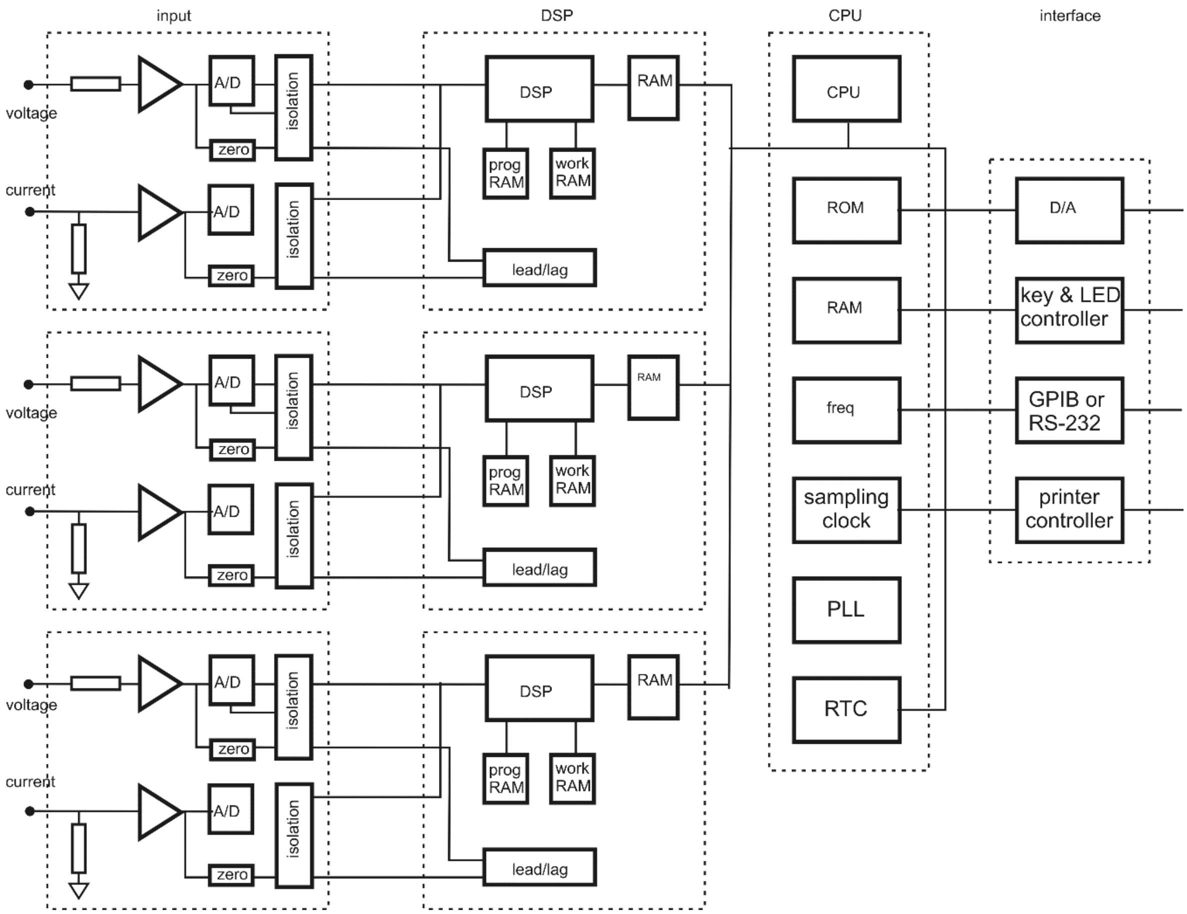

Figure 1-2 Block Diagram of digital wattmeter

However, since the measurement is based on the assumption that sinusoidal mathematics is applicable, there are problems in the real world, where the assumption does not usually hold. The measurement question was investigated in 2011 by NIST, and a report issued. NIST studied eleven different measurement methods for reactive power and demonstrated the inconsistency of results.

Several different (numbered) waveforms were used to compare the results of eleven single-phase measurement methods (called “equations” by NIST)[6]. The currents and voltages were all “normalized” with an rms amplitude of 1. Figure 1-3 shows “waveform 4”, and Figure 1-4 shows “waveform 5,” two waveforms whose effects are examined below. The voltages used with these two current waveforms were sinusoidal.

[6] Nelson, T. 2011. Definitions for calculations of VA, VAh, VAR, and VARh for Poly-Phase Electricity Meters, NEMA C12.24 TR-2011. NEMA.

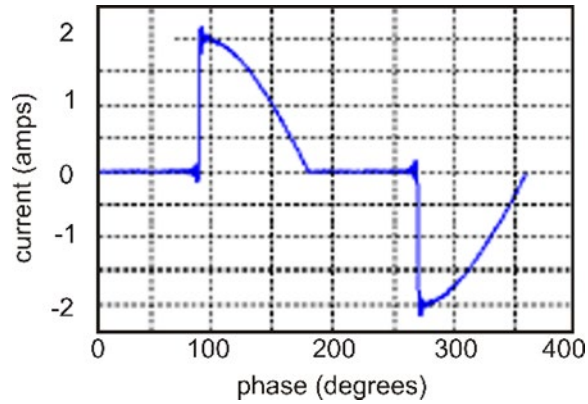

Figure 1-3 “Waveform 4”[6]

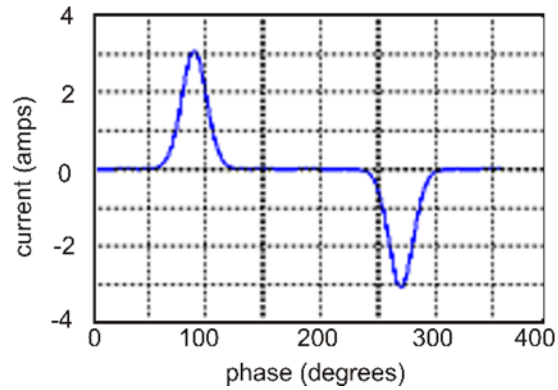

Figure 1-4 “Waveform 5”[6]

Table 3 gives a summary of the results for the waveform in Figure 1-3, representing the current of a phase-cut device.

Table 3 Waveform (Figure 1-4) reported VAr

Equation number (Reactive power measurement model)	1,2 4-6, 11	3	7,9	8	10
VARs reported	0.451	0.376	0.705	0.101	±0.766

A note associated with Equation 8 indicates that the solution requires the square root of a negative number, so that the magnitude of the VAr is imaginary. A note with Equation 9 indicates that the calculated number can flip in sign for very small changes in the phases of the harmonics. The “±” result for Equation 10 is from a manufacturer-specified method.

The results do not show mere *minor* differences: the results are not even close to one another.

Waveform 5 in Figure 1-4, a narrow current pulse, leads to an entirely different set of results, which are summarized in Table 4.

Table 4 Waveform 5 (Figure 1-4) reported VAr

Equation number (Reactive power measurement model)	1-6	7, 9	8	10	11
VARs reported	0	0.766	$j\,0.380$	±0.766	0

Again, the differences are large. The grouping is different, too.

The scatter in the results is not caused by instrumentation errors. The work was done at NIST, and the execution of the measurement algorithms was exactly as it was supposed to be. The results were, in effect, from NIST's "perfect" versions of available instruments.

Reactive power errors matter in the operation and protection of much of the power system. Further, state estimation, a software technique to enable the power system state to be well modeled, sometimes fails to converge[7]. It has to be assisted by "adjustments" to measured reactive power results.

It is important to understand that these measurements have been challenging for many years not because of challenges in instrumentation or hardware. Hardware has improved significantly, and instruments have transitioned into the age of digital technologies. The problems lie with the *measurement process itself*, a process that depends on an intuitively obvious, but actually mistaken, dependence on defining what is to be measured.

In a nutshell, it is fair to say that while there seems to be eleven different ways to measure reactive power, the instruments are actually measuring eleven *different* things. A measurement system reports what it is designed to report. Eleven different things cannot all be called reactive power. These different measurements cannot all be "fit for purpose."

The solution is to choose which measurement *method* makes sense, and then to define the method of measurement rather than to define the thing to be measured. That means that the measurement method is what is called operational because the result depends on the operations performed (See Glossary).

Most of the things that are measured in the electric power system suffer from this sort of issue. It is a theme of this report that an understanding of measurement theory, and especially certain more recent advances, will provide a foundation for solution. As the grid becomes smarter and more automated, it will increasingly depend on measurements. As the amount of inverter-based generation and converter-based loads increases, finding solutions to the measurement challenges will become increasingly relevant.

Another measurement, that of frequency, recently came to prominence as a problem when a faulty measurement was responsible for the abrupt and inappropriate loss of 1200 MW of solar generation at the Blue Cut fire. This is an interesting measurement failure because the problem was at the theoretical level. The instrumentation worked just the way it was designed to. Here's a quick take on the Blue Cut fire:

- In August 2016, there was a fire in the Cajon Pass in Southern California. Smoke triggered several faults on nearby high-voltage power lines.

[7] Hansen, C.W., and A.S. Debs. 1995. "Power system state estimation using three-phase models." IEEE Transactions on Power Systems 10 (2): 818-824

- A 700 MW photovoltaic source abruptly stopped producing. (Other resources also separately relayed out.)
- The trip was viewed as inappropriate because the PV system was not involved in the fault.
- The error was due to an incorrect measurement of frequency.

The details of the fire were documented in a report from the North American Electric Reliability Corporation (NERC)[8]. Our interest here is with the technical details of the faulty measurement. Fortunately, the NERC report included a graphical version of data from a digital fault recorder (DFR) located somewhere close on the system, and we can see from that what the problem was. The DFR results are seen in Figure 1-5.

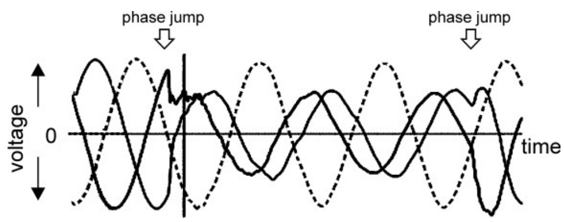

Figure 1-5 NERC graph based on DFR data[8]

The curve shown dotted represents an un-faulted phase. The fault affected only the other two phases. It occurred at the moment of the first evidence of distortion, labeled “phase jump.” On the DFR result, one of the phases can be seen to advance, and the other to retard, so that the two voltages appear closer together. (It may be assumed that at the location of the fault, the voltages would be the same.)

A little over two cycles later, the fault is cleared, and the system voltages return to approximately their pre- fault values. It is reported by NERC that the control system for a 700-MW component of the PV generation measured a frequency of 57 Hz, and tripped instantaneously, because that was what is was programmed to do. In fact, during the fire, even more solar resources were lost, evidently for similar reasons.

This is another example of a measurement that is not “fit for purpose.” *Frequency* is a word that applies only to periodic waveforms, and it is obvious from the figure that the phase jump makes the waveform non-periodic. At the moment of the phase jump, the question “What is the frequency” is entirely meaningless. The signals do not have a “frequency” by any definition of the word, and that means that i*t is not possible to make a meaningful measurement of “frequency.”* This is not an instrumentation issue; it is a measurement issue: the quantity of interest is defined only for signals that do not resemble the signals available near the Blue Cut fire. That measurement choice leads to an instrumentation problem: the designer of the instrument is charged with measuring frequency, something that is not defined for this situation.

The inconsistencies with measuring power factor, reactive power and frequency are failures of *measurement*, not instrumentation. And as the power system moves toward the smart grid, and the amount of automation increases, these inconsistencies will become increasingly important. Underlying measurement issues have potential to make themselves increasingly manifest: there will be more outages of inverter-based resources (IBR), voltage control will become increasingly difficult, disputes over billing will become common, the protection system will become

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

increasingly unreliable, operation of the system will become more challenging, distribution system management will be stressed by the effects of battery-charging for EVs.

All this is despite an increased amount of instrumentation in the system, and at the same time *because* of an increased amount of instrumentation in the system.

The power system is facing this future because, about a century ago, power engineering and measurement science separated, and the two disciplines have been "siloed" for a hundred years. Both fields of study have advanced in terms of theoretical understanding and of technology, yet each has been generally unaware of the advances of the other.

Power engineering has moved to new materials, higher voltages, higher power levels, and constantly increasing levels of renewable resources. System automation is increasing. The advances of measurement have included the recognition of more than one kind of measurement (representational and operational)[9], and recognition that a spectrum exists with these two kinds marking the ends. Most measurements are somewhere along the spectrum.

The term *definitional uncertainty* is probably a new addition to power engineering. It is the result of the distortion always present in the signals representing the voltages and (particularly) the currents, and it dominates power system measurements. It is the reason the converters tripped out at the Blue Cut fire. Given the role that measurements play in grid planning and operation, understanding such matters is of increasing importance. A better link between the two siloed camps can be established.

There is still no generally accepted definition of the term power factor, nor any understanding of how it should be treated in a three-phase circuit. The reason is known in measurement science: power factor is a non-extensive quantity. (See Glossary)

The problems go far beyond just power factor. This Roadmap suggests a path to solving both the underlying problems and their outcomes. One underlying problem can be addressed by education and training. The outcomes are reflected in instrument design and documentary standards. The Roadmap presents a framework for solution.

1.3 The Digital Revolution

This section of the Roadmap Report is included to provide a framework for understanding how digital measurements can help address the measurement challenges in the power system. The advent of digital technology in the late 20th century added considerably to the capability of measurement systems. The measurement of reactive power can now be done using at least eleven different algorithms[10]. The results of these measurements do not, in general, agree with one-another. The differences are caused by distortion in the waveforms: the algorithms all assume undistorted sine waves.

Near the end of the century, the phasor measurement unit (PMU) was invented and commercialized. This was arguably the first instrument of its kind in the power system. It attempted to completely characterize the signal: its result was not just the amplitude of a voltage

[9] See Glossary

[10] Nelson, T. 2011. Definitions for calculations of VA, VAh, VAR, and VARh for Poly-Phase Electricity Meters, NEMA C12.24 TR-2011. NEMA.

or current, but also its frequency and phase offset. The instrument made it clear that there was a considerable loss in information in the results of *other* measurement systems.

For some, the advent of the PMU brought to mind a saying attributed to Einstein: everything should be simplified as much as possible, but no more. All the measurements in the power system could be accused of simplifying too much. The PMU makes *one* simplifying assumption: the signals can be represented by the mathematical function known as a sinusoid. It assumed then that the user might want to know the values of all the parameters that defined the sinusoid.

Sometimes that assumption that a sinusoid is a good representation of the signal is not valid. In fact, it is almost never completely valid. Since the PMU readings are affected, the effect of the signal not being well-represented by a sinusoid is something that is of practical interest. And not just the PMU. Most measurements can now be viewed through the lens of the assumption that signal distortion affects measured results, and the effects can be observed through the digital implementation of the measuring system.

A recent positive trend has been the introduction of measurement devices to sample voltage and current waveforms in the substation environment. Merging units are digital devices that are designed to collect multi-channel digital signals as inputs from sensors (current and voltage transformers). This process is synchronized, and the data is streamed using process bus (IEC 61850-9-2). From a measurement perspective this provides a suitable input for virtually any measurement process, from RMS to frequency estimation. It's also not limited to just measurements. Applications can also consume raw data directly, thereby circumventing any data compression.

Digital technology makes evident the actual process of measurement. This is not a matter of technology. The first part of the digital measuring system is the conversion of an analog signal to digital. There is a transfer from the physical world of the analog signal to the conceptual world where mathematics can be used. The Blue Cut Fire was a stunning reminder that what we do in this conceptual world can have significant impacts on power system resilience. It has also driven interest in using signals as soon as they pass from analog to digital. These direct measurements of voltage and current waveforms are referred to as Point-on-Wave (POW) measurements in this document.

1.4 Roadmap Scope

The findings and proposed research in this Roadmap are relevant to current and voltage POW measurements and all indirect measurements that follow from them, such as those provided by Supervisory Control And Data Acquisition (SCADA) and PMU systems. These measurement technologies were selected because they capture the grid's electrical properties, which most directly reflect changes in system behavior associated with modernization. Principles of measurement theory discussed in this document may, however, be relevant to measurements of temperature, pressure, etc. that are used in power systems. Synchrophasor and waveform measurement systems receive the primary focus in this document because they represent, respectively, an advanced measurement technology reaching maturity and a measurement system that is anticipated to grow rapidly in coming years.

The need for advanced measurement research extends beyond PMU and POW instruments to the broader measurement system. Communication, storage, and analytics must all be addressed to accelerate the adoption and effective use of advanced measurements. As discussed already, the application of measurement theory can guide appropriate use of measurements and the development of better measurement systems. This roadmap is intended to provide several benefits, including (1) ensuring that new measurement solutions are practical for adoption by industry, (2) increasing industry interest, trust, and investment in new measurement systems, and (3) providing a strategy for the national laboratory complex to adhere to. The ultimate objective of this Roadmap is to provide a framework for DOE investment in technology development, standardization, and policy making in advanced power system measurements. A description of the process used to develop this Roadmap is provided in the next section.

1.5 Roadmap Development and Structure

The first step in developing this Roadmap was conducting an extensive literature review. This review established the current state-of-the-art, identified industry needs, and revealed obstacles to meeting these needs. The findings from the literature were supplemented by conducting a set of webinars with stakeholders consisting of utility members, instrumentation vendors, consultants, and researchers. The full set of results from the literature review and webinars were compiled in a standalone document[11]. A discussion of key findings is provided in Chapter 2.

One of the primary objectives of the literature review and webinars was to identify information gaps related to the power industry's advanced measurement systems. Some of these gaps were previously well documented, while others became apparent only after discussion with industry stakeholders. Once information gaps were identified, the sources of these gaps were evaluated. Information gaps may occur for a variety of reasons:

- The necessary technology to retrieve the information has not been developed
- Though feasible, the technology is not commercially available
- A value proposition is unavailable to justify investment
- Company level technology policies necessary for implementation are lacking
- Lack of standardization

For each of the identified information gaps, the underlying technological, standard, or policy (here, company/industry level policies) gaps were explored. The results of this gap analysis are presented in Chapter 3. The literature review also revealed a set of high-value use cases for advanced measurement systems and processes. These use cases are described in Chapter 4. Though valuable, the development of these use cases is currently hindered by the previously mentioned gaps in technology, policy, etc. Thus, the next step in the roadmap development was to formulate a set of activities necessary to close the gaps and unlock the high-value use cases. These activities were organized into a set of four research thrusts, which are described in Chapter 5. The final aspect of this document's development was to assign timelines and milestones to the research thrusts, gap closures, and high-value use cases. This detailed plan is presented in Chapter 6.

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

2.0 Literature Survey and Stakeholder Engagement

The literature was found to be rich with information about existing measurement systems and their applications. An overview of the detailed literature review[12] is provided in this chapter. This chapter also discusses original findings based on the team's interactions with utilities, vendors, researchers, and other stakeholders. Many of these interactions took place during a set of three webinars hosted by the research team. These webinars were designed to help the team gain insights that are valuable but typically unavailable in the published literature. Through the webinars, the team was able to hear directly from over 30 participants. The webinars included presentations by the PNNL team, open discussion, and a live survey where participants submitted answers to specific questions. Notes from the discussions and results from the surveys can be found throughout the following sections. A complete list of the questions posed during the webinars is provided in Appendix F.

2.1 Discussion of Webinar Results

During the webinars, a series of five questions was asked with the intent of finding out what the participants viewed as important in their work on measurements. The first question was *How do you know when you have made a good measurement, one that you can trust?* For many users of measurement results, there are certain aspects of the process that encourage acceptance of the results. The choices that were offered (and the number of votes given by the participants) were

Option	Total votes
The instrument is from a reputable manufacturer	4
The calibration sticker is current	3
The results fit your expectations (pass your sanity check)	14
Other	10

Twenty-one participants responded to the question. The *manufacturer* was regarded as relevant by four, the *calibration sticker* by three, and fourteen respondents put some faith in their *sanity check*. Ten respondents thought there were *other* factors that we had not listed.

It is possible to draw some conclusions from these results, though some must be considered tentative.

- The relatively low importance attached to the manufacturer factor may be a result of the uniformly high quality of most measurement products. Adherence to standards (an example from the *other* category) was mentioned by a participant in the "chat" window as being a factor in assuring good results.
- The question on calibration stickers is a sort of reverse question. An up-to-date sticker may not mean a good result, but an out of date sticker must imply that one can have only low confidence in the result.

In fact, the calibration sticker should be regarded as crucial. The very low score for the calibration sticker choice supports a proposition that a bureaucracy separate from the user community is needed in most companies to enforce the currency of such stickers.

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

Mean time between out of tolerance (MTBOOT) is a statistical guide to setting a calibration interval for the instrument. With the advent of digital instruments, the MTBOOT has generally increased from the days of analog measurements. One may imagine that the digital part of the system either works or does not work, but the analog part of the instrument may be subject to drift (e.g. passive components in the front-end of digital instruments).

The sanity check is viewed as relevant and important. A future problem with reliance on such a check is that it is mostly left to the human part of the measurement chain to apply the check. As the power system evolves toward greater automation, it must surely benefit from a greater amount of automated sanity checking. Another comment from the “chat” window was that this would be a good problem in which to engage the AI community. This poses risks as well. Operator “sanity check” decisions may be vulnerable to latency, biases, and human errors, while automated systems face resiliency problems with dealing with unexpected situations (and measurements).

The next question was *Would it be a help to have a believability metric associated to reported measurement values?* This question required the participant to give their own estimate of value, on a scale from one to ten. The results from the fifteen (approximately half of the audience) respondents are shown:

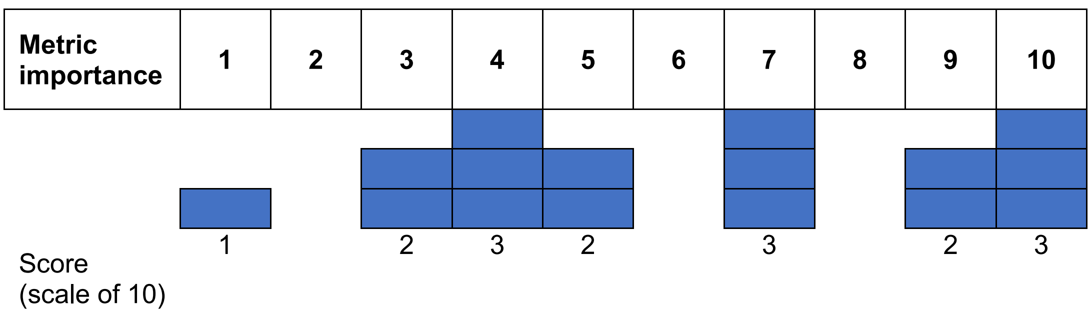

Figure 3-1 Metric importance results

This result suggests that trust metric would be either somewhat needed (could be thought of as optional) for some and required by others. This attitude is unambiguous from the perspective of the International Bureau of Weights and Measures (BIPM), which asserts that a statement of uncertainty is obligatory. Here is what the guide to the expression of uncertainty in measurement (GUM[13]) says in the first paragraph of the Introduction:

> When reporting the result of a measurement of a physical quantity, it is obligatory that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability. Without such an indication, measurement results cannot be compared, either among themselves or with reference values given in a specification or standard. It is therefore necessary that there be a readily implemented, easily understood, and generally accepted procedure for characterizing the quality of a result of a measurement, that is, for evaluating and expressing its uncertainty.

Power engineers in general are accustomed to having no statement of uncertainty in association with the results of measurements in the power system. It seems very likely that the prevailing sentiment is caused by “what you don’t see, you don’t miss.” The lack of such a

[13] https://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

metric is inevitable if the measurement process is purely operational, i.e., the measurement is defined by a set of operations that must be performed. This means that it is not possible to provide such a metric in any conventional way for the measurement of (for example) reactive power.[14]

The third question of the series was How many definitions are you aware of for power factor? The question was answered by 15 participants, as follows:

Power Factor Definitions	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of respondents	1	2			1	1	2	6		2

Figure 3-2 Power factor definitions results

It is strange that there really are multiple definitions for power factor. The question does not require that the participant indicate that he or she knows any of the definitions, it probes the participants' awareness. Nevertheless, one respondent did identify two definitions by name in the "chat" window. It seems that not everyone is aware that there are actually very many definitions, though the majority do seem to know that there is more than one.

The fourth question in the series was *Does reactive power always involve stored energy*? Thirteen respondents thought it did; seven thought it did not. These responses show that while power engineers write a great deal about reactive power[15] and rely on measured results during system operation and planning, there is no general agreement in the power community at large.

This is a problem whose origins are so ancient that it seems fair to describe modern views as fossils. The experts and thought leaders of our profession studied the matter in its early days and failed. There was (and is) no unique answer because the underlying concept is incomplete. The earliest understanding of the problem was indeed founded on stored energy, and it was based in ideas in linear time-invariant circuit theory. If the system is known to be well represented by linear time-invariant modeling, then stored energy is behind reactive power. However, measurements that seem to indicate the presence of reactive power can result from system nonlinearity or time-varying parameters. An early measurement of this kind claimed to find a phase angle even though there was no stored energy. The system was nonlinear and not

[14] The measurement of power is also purely operational, but the calculation involved (the arithmetic average of the sampled values) is not dependent on details of the waveshape of the voltage or current signals provided the samples are simultaneous and the waves are periodic, and the measurement is performed over an interval that is an integral number of the periods of the lowest common period of the two waves. The accuracy of the measurement of power is limited, within the instrument itself, only by the quality of analog parts of the front-end, the A/D converters, and their timing circuitry.
[15] The expression "reactive power" appeared in the metadata of more than 2,200 conference papers and more than 800 journal papers in 2019, the last full year for which IEEEXplore data are available.

time-invariant, and the apparent power was larger than the measured real power. The work was debunked by Steinmetz.[16]

We can now recognize that the incompleteness of concept is the nature of the problem *because now there is an underlying measurement theory* to provide guidance. It is a simple matter to create a system that will produce a measurement of reactive power without stored energy, because the measurement of reactive power is so poorly specified—as was shown in Section 1.2. Many of the reported reactive power values in the NIST report do not correspond to waveforms of systems with stored energy.

Power engineers now have opportunity to leverage measurement theory because it has reached a point that it can illuminate the underlying matter. People who are involved in the fundamentals of measurement have not been greatly concerned with power system measurements.

The final question was *It is taught in school that the power, reactive power and apparent power form a right-angle triangle. How true is that?* The responses for the three choices *never true, sometimes true*, and *always true* were tallied at 0, 17, and 3, respectively. Because the waveforms of the power system are always at least slightly distorted, the right-triangle is never perfectly realized. Perhaps the responses to this question indicate how useful an idealized relationship can be, even if it is never perfectly realized. Still, the power industry must be careful to ensure that these useful simplifications do not create reliability issues.

2.2 Discussion of Literature Review Findings

Our survey has shown that while some details and the theoretical aspects of the process of measurement might be obscured, many new uses for measurement are under consideration. The field is evidently dynamic.

- Significant investments were made under the American Recovery and Reinvestment Act (ARRA) and the Smart Grid Investment Grant (SGIG). Through these efforts more than $7.9B was invested over a 6-year period in smart metering, distribution automation and transmission network projects. During the projects more than 82,000 intelligent/automated devices were deployed in distribution grids and 1,380 PMUs were deployed in transmission grids. One of the conclusions from the SGIG was that further deployment of smart grid technologies, tools and techniques can achieve favorable grid impacts, but they must be accompanied by changes in communications systems, workforce training, and business practices[17]. This approach can be seen through this roadmap as well, addressing communications, workforce training/education, business practices, and use cases.
- Another recent emergence is the “digital substation” that utilizes digital merging units for locally streaming sampled values over Ethernet. In some cases networks are extended over larger areas through LTE, for example, for routed GOOSE applications. This technology, however, utilizes sampled values locally, so there’s potential for extended use of streamed data.

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[16] Steinmetz, C.P. 1892. "Findet eine Phasenverschiebung im Wechselstromlichtbogen statt?" Elektrotechnische Zeitschrift 42: 567-568.

[17] https://www.energy.gov/sites/prod/files/2017/01/f34/Final%20SGIG%20Report%20-%202016-12-20_clean.pdf

- There is support for the development of a more “capable” PMU. Performance limitations, particularly in terms of frequency response, limit the applications of the technology at present. There would seem to be no inherent reason why the performance could not be improved in this regard. It is likely that new algorithms and new documentary standards will be needed if the goal of interoperability is to be achieved.
- Point-on-wave technology would facilitate the development and implementation of schemes aimed at improved operation and protection. Communication systems to support the dataflow that POW requires are available or in development, with latency values that meet the requirements of many applications.
- The power quality field is showing new promise in terms of utilizing the knowledge gained to identify some of the characteristics of these measurement results as signatures of particular interest. From the measurement point of view, this is particularly interesting as a departure from the modeling that has historically characterized power system measurements.
- Another aspect of potential value is the measurement of system parameters. These are normally regarded as fixed quantities. It is known that transmission line parameters are not perfectly constant—the resistance is, for example, temperature dependent. It is likely that both operations and planning would be improved if parameter value estimates could be routinely made.
- The PMU is being considered for application in the distribution system. One might imagine this is a long overdue step. The Westinghouse Electric Utility Engineering Reference Book on distribution systems, first published in 1959 begins with these words:

  > Broadly speaking, an electric power system can be defined to include a generating, a transmission, and a distribution system. The distribution system, on a national average, is roughly equal in capital investment to the generation facilities. The sum of these two generally constitute over 80 per cent of the total system investment. Thus, it is readily seen that the distribution system rates high in economic importance, and represents an investment that makes careful engineering, planning, design, construction, and operation most worthwhile.

  While those words are still likely true, the distribution system has not seen the same level of careful engineering, planning or design that characterizes the other two parts of the utility, and its operation has, for the most part, not been monitored with anything like the details of the transmission system. The addition of PMU technology would represent a big step forward.

These various expansions of measurements will no doubt benefit from a better appreciation of the theoretical aspects of measurement. In this, and other, regards, our survey of the literature has identified gaps as well as possibilities.

In developing our roadmap, we conclude that DOE should be made aware of the gaps as well as the exciting new areas for the application of measurements. The gaps are the subject of the next chapter of this Report.

3.0 Gap Analysis

The surveys of literature and webinar attendees led to the identification of several gaps. These gaps were organized into the following areas:

- Deployment and Demonstration: This area describes identified gaps due to lack of either demonstrated technology readiness level, value, scalability, availability, and other key aspects that encourage technology and method adoption.
- Education: A gap here may refer to incomplete knowledge base or absent measurement theory applications.
- Analytical Methods: Gaps in this area are due to incorrect or missing models (both device simulation models and measurement models), analysis methods, and tools.
- Instrumentation, Testing, and Standards: This area includes limitations in existing instrumentation capabilities, along with the tests applied to instruments and the standards that govern them.

In most cases, identified gaps manifest in complex ways. One example is the absence of high-performance distributed communications infrastructure to support advanced measurement, monitoring, and control techniques. The telecommunications industry has shown that large scale, distributed data transfer is not a technological problem, as many options are available. The gap is rather in the lack of value demonstration and lies in common power company policies. A clear and holistic value demonstration of advanced communications for utilities is a gap to justify the necessary investment. Further, current utility policies tend not to favor communications-centric solutions.

To better articulate the impact of a gap and its relation to other limitations, each gap was assigned one or more categories. These categories are:

- Technology: Limitations that are technological or instrumentational in nature. This category is also applied in cases of low technology readiness level (TRL).
- Knowledge Base: Frequently misunderstood information and gaps associated with limitations in information availability, understanding, and its application.
- Commercial Availability: This category groups challenges regarding availability of matured, reliable, and proven technology, methodology, and applications.
- Value Proposition: Gaps that indicate a need for value demonstration. This usually means the full life-cycle assessments of solutions and evaluation of return-on-investment.
- Policy: Gaps within outdated, incomplete, missing, or needed policy. This term in this document is used to address company-level policies and strategies.
- Standard: Incomplete or insufficiently used standardization or testing.

The literature review also revealed that gaps tend to limit multiple types of applications. Thus, each gap was also associated with a set of the following applications:

- IBR Integration: This indicates potential for risk mitigation when increasing IBR penetration in the grid.
- Asset Health Monitoring: This refers to a specific purpose monitoring with emphasis of estimating and predicting equipment or system failures.

- System Monitoring: Applications in this space are deployed at the system level and include wide area monitoring with impact on situational awareness.
- Control: Controls, particularly of IBRs, including optimized control decisions.
- Protection: This refer to grid asset operations under emergencies for safe and optimal responsive actions.

The table below provides a brief description of each identified gap and lists the categories the gap falls within. It also indicates which applications are affected by the gap to help the reader more readily identify the gap categories that must be addressed to enable a particular application. A discussion of the gaps within the four topic areas follows the table

Table 5 Gap summary table

Gap Description	Categories	Application
Deployment and Demonstration		
Communications Infrastructure Reliable, high bandwidth low latency utility communications infrastructure does not overlap measurement points in the power grid, particularly in distribution systems.	Value Proposition Policy	All
Communications Planning Many utilities do not maintain capabilities to perform forward looking assessments, planning, and implementation of communication solutions.	Knowledge Base Policy	All
Integrated Waveform Measurement There would be significant advantages to making the waveform measurements used by power electronics equipment available for review. Currently, no such devices exist.	Commercial Availability Value Proposition Standard	IBR Integration System Monitoring Asset Health Monitoring
"On-Premises" Data Storage Paradigm On premises centralized solutions are still dominant, but it is a changing landscape. For ultra-large data amounts it is clear that services from specialized providers are a more efficient option. This includes both distributing (instead of centralizing) and outsourcing (instead of hosting) the processing, analyzing, and actioning for high-volume data.	Value Proposition Policy Knowledge Base	All
Education		
Engineer Education and Training Engineers have only a vague idea of measurement as a process. Instruments are accorded unjustified trust. Some common measurements are controversial.	Education	All
Instrumentation, Testing, and Standards		
Measurement Accuracy Accuracy of measurement results depends on the quality of input signals. Industry has indicated the need for a trust metric.	Technology	All
Failure to Capture Unanticipated Events	Policy	IBR Integration

Trigger-based recording of waveform measurements may miss events that were not anticipated. It becomes increasingly difficult to anticipate events in quickly evolving systems.		Protection System Monitoring Asset Health Monitoring
Operationalism Recognition Operational measurements are the subjects of standards that do not recognize their nature. This perpetuates the problems.	Standards	All
IBR-Related Policy and Standards Various standards and policy documents were written for conventional generators and do not consider the changing generating resource mix. These documents need to be revised to promote deployment of the high-resolution measurement devices for IBR monitoring.	Standard Policy	IBR Integration
Standard Waveform Measurement Device Much can be accomplished using existing POW devices such as merging units, power quality meters, and digital fault recorders (DFRs), but a standard measurement device (like the PMU is for phasor measurement) could streamline standardization and implementation.	Commercial Availability Value Proposition	All
Analytical Methods		
IBR Modeling Accurate, validated and openly available IBR models (Positive Sequence (RMS) and electromagnetic transient (EMT)) are needed to properly simulate IBR dynamics in transmission planning and stability studies.	Technology Knowledge Base	IBR Integration
POW Data Silos POW measurements are siloed by application (power quality, protection, disturbance analysis), limiting the use of existing measurement systems.	Commercial Availability Policy Standard Technology	IBR Integration
Waveform Signatures	Knowledge Base	System Monitoring

Signatures of equipment failures, outages, asset performance issues, and power quality phenomena in waveform measurements need to be characterized to enable automation and to make results actionable.	Value Proposition	Asset Health Monitoring
IBR Controller Evaluation There is no standard way to evaluate IBR controller performance. IBR controllers are a black box.	Knowledge Base Policy Standard	IBR Integration Control
IBR Monitoring IBRs are not properly monitored because of lack of high-resolution POW measurements, detailed event logs, data synchronization and retention.	Technology Standard Policy	IBR Integration
Measurement-Based Solutions for IBR Oscillations Several different types of oscillations related to IBRs have been identified. Measurement-based solutions are needed to monitor for these oscillations, address them, and validate model-based studies. Methods for integrating measurements into existing simulation-based approaches need to be tested and made available to industry.	Knowledge Base Value Proposition Commercial Availability	IBR Integration Protection Control System Monitoring
POW Measurement-Based Algorithms/Methods Development of algorithms, methods (including ML/AI-based) and tools based on POW measurements is needed for various power system related applications. Approaches for distributing waveform analytics are also needed.	Knowledge Base	All

3.1 Deployment and Demonstration

In large part, the technology for performing advanced measurements already exists in various levels of maturity. In these cases, the missing part is a convincing demonstration, not only that the technology is operating as advertised, but also that there is provable value across the lifecycle with demonstrated return-on-investment in real-world scenarios.

Point-on-wave measurements are already available in measurement instruments and power equipment as the output of an analog-to-digital converter. The digital representation of the waveform is used within measurement algorithms or to guide operation of electronic equipment. The availability of POW data varies by application, but the technology clearly exists. There would be significant advantages to making the waveform measurements used by power electronics equipment available for review. Another aspect that was identified from industry engagement was the need for trust metric for measurements. Since the foundation for this metric already exists, initial demonstrations are possible in the near term.

Additional aspects that deployments of continuous point-on-wave (CPOW) measurements must address are the retrieval and storage of the data. The literature survey showed that sufficient technology exists, but reliable, high-bandwidth, low-latency utility communications infrastructure does not overlap measurement points in the power grid, particularly in distribution systems. Communications are not the primary business for utilities; therefore, it is understandable that utilities have limited experience and expertise in forward looking assessments, planning, designing, and deploying of communication infrastructure. It is also very expensive. This leads to solutions sold and installed by contractors that are often purpose-built, lowest price, and only address immediate needs. A good example is smart metering infrastructure. The underlying gap here concerns the justification and policy approach to communications related projects. Utilities need to see clear benefit and demonstrated return-on-investment before planning, designing, and deploying high-performance distributed communications. There are also policy gaps to be addressed – even with demonstrated value the policy may prohibit any further action. Without real-time data retrieval many applications lose value and communications are the main enabling system for measurement-based applications and grid services.

The other challenge that needs to be addressed is the storage of data volumes so far unseen by utilities. Multiple ready-to-go solutions exist, but gaps similar to those impacting communications infrastructures are also present. High profile full-lifecycle value demonstration is needed. A directed effort can serve as a base of value proposition for addressing the other policy and knowledge base gaps. On premises centralized solutions are still dominant, but it is a changing landscape.

The final gap category is the insufficient knowledge base in cloud service architectures and designs for utilities and other innovative solutions that could meet the challenges but need value demonstration and change in policies. This includes both distributing (instead of centralizing) and outsourcing (instead of hosting) the processing, analyzing, and reacting for high-volume data.

It is very important to actively coordinate demonstration and deployment plans and activities through all gap areas identified. Demonstration of value of novel methods, models, tools as well as technology deployment directly impacts the feedback loop and provides the necessary motivation for future improvements.

3.2 Education

Early development (meaning low TRL number) of low-cost measuring systems, some of which were discussed in the GMLC Sensing and Measurement Report, may take place in universities. There is almost inevitably no coordinated approach to interoperability of any final product. While it may be that IEEE Standard 1451 has some relevance here (and is discussed later), it seems that this problem is mainly one for the universities to address, rather than DOE. Some oversight of what the systems being developed in academia might offer does seem worthy of consideration, however. Perhaps DOE could be involved via a National Laboratory that could offer guidance on post-processing and reporting of the measurement results, along with possible fast tracking and assistance to market.

Based on the literature review and industry engagement described in Chapter 2, the main approach to understanding whether a measurement is correct appears to be a “sanity check”. Indeed, under certain conditions an instrument may be operating properly, but producing useless results that should at least be removed from decision making processes. Engineers become judges and evaluate information based on their education, training, and experience. Unfortunately, in electrical engineering courses measurement theory and fundamentals have disappeared, leaving a gap. This leads to the unjustified trust in instruments to provide the “ground truth” of the physical quantities. In practice, one gets values for a conceptual model that sometimes has nothing to do with the reality. Instruments in most cases are operating properly as this is a measurement process issue and not instrumentation. Two certified energy meters may not report the same power factor values; frequency measurements may not make sense; reactive power measurements cause problems for state estimation, and still the underlying cause is not addressed.

3.3 Instrumentation, Testing, and Standards

In this topic area, the focus is more on the *how* aspect of instrumentation design, rather than the *what*. The gap exists within the processes and functional properties of instruments, the testing procedures, and standardization. Measurement instruments are designed according to standards and are tested in laboratory conditions, but their primary use is in the field. The accuracy of measurement results depends on the quality of the input signal. When an instrument is designed for laboratory signals the measurement results may be unreliable in the field when off-nominal conditions cause, for example, distorted waveforms. All gaps in the measurement chain are interdependent and have impact in all areas.

- A need for a trust metric has been indicated from the industry. This shows that just having instrument accuracy and measurement uncertainty is not sufficient when input signals are not nominal, such as during power system disturbances. A PV facility tripping due to wrong frequency measurements is an example of the consequences that trusting a bad measurement can bring about.
- There is a need for a tailored approach to instrumentation, testing, and standardization when measurements are operational in nature. If standards do not recognize operationalism, it perpetuates the problems into testing and eventually into instrumentation design. To implement a satisfactory operational measurement, there must be a documentary standard fixing the operations to be performed. In essence, this means fixing many aspects of the design of an instrument. Before such a standard can be finalized, there must be agreement from the community.

Another limitation of existing measurement devices is that they sometimes fail to capture a trigger-based recording of waveform measurements. Though the devices deployed in power systems trigger reliably on anticipated events, the occurrence of missed events is expected to increase as the power system continues to evolve rapidly and fast IBR dynamics become increasingly commonplace. Furthermore, various standards and policy documents were written for conventional generators and do not consider the changing mix of generation resources. These documents need to be revised to promote deployment of high-resolution measurement devices for IBR monitoring.

There is also an opportunity to develop and standardize an instrument for CPOW measurements, much as the PMU is the standard for synchrophasor measurements. Even though there are currently available many power quality (PQ) meters and DFR’s, such a POW measurement device and a standardized approach has potential to streamline implementation and wider deployment.

It is most likely that many measurement standards should be revised to acknowledge the fact that they are, at least to some extent, operational. This is necessitated by the need to achieve interoperable results from systems measuring distorted signals. A controlling documentary standard is required.

There is also a need to revise the standards for the PMU to take into account that they are operational. It is clear that the designer is still allowed enough latitude in implementation that results from PMUs are not always interoperable. There is also an opportunity to create a standard for a distribution PMU.

3.4 Analytical Methods

There are plenty of gaps and shortcoming in the landscape of modelling and analysis methods, especially regarding IBRs. The faster dynamics and black-box elements in the system highlight the need for more information. In this case, advanced measurements are the raw material that can provide that information. Applications that could be enabled and/or improved by having information from POW data include asset health monitoring, system monitoring, IBR integration, modelling, and control.

The first step is to obtain the data. Currently there is a gap in availability for POW measurements. If available, the measurements and databases are siloed by application (power quality, protection, disturbance analysis), limiting the use of existing measurement systems and applications. The next step is to make data actionable. For fast applications, like control, this demands real-time retrieval, analysis, and action. Currently there are limitations in what’s available as signatures of equipment failures, outages, asset performance issues, and power quality phenomena in waveform measurements need to be characterized to enable automation. Automation and data handling gaps also include methods for integrating measurements into existing simulation-based approaches that need to be tested and made available to industry.

Many gaps exist in the rapidly evolving IBR area. Performing trustworthy measurements has a big role in defining and addressing the gaps:

- No standard way to evaluate IBR controller performance. IBR controllers are a black box.
- Need for accurate, validated and openly available IBR models (Positive Sequence (RMS) and electromagnetic transient (EMT)) to properly simulate IBR dynamics in the transmission planning and stability studies.

- Lack of high-resolution POW measurements for detailed event logs, data synchronization and retention that impact IBR monitoring.
- Measurement-based solutions are needed to monitor for these oscillations, address them, and validate model-based studies. Several different types of oscillations related to IBRs have been identified.

An important part of current limitations for analysis and modelling is the need for development of algorithms, methods (including ML/AI-based) and tools based on POW measurements. Such developments would impact many power system applications. Having such tools would enable distributed waveform analytics from large scale distributed data sources and offer wide area situational awareness improvements.

There is a need for collaboration between other gap areas, especially in the area of education with an emphasis on underlying measurement theoretical fundamentals. It is critical to establish a point of trust from where to build the models, methods, and tools. Our industry survey showed that currently there are trust issues for measurements and no transparent and traceable way to adequately propagate uncertainty information through models, simulations, and methods.

4.0 High Value Use Cases

Over the past 15 years, the widespread deployment of PMUs has enabled or enhanced an array of applications. Many of these applications are described in reports available at the website of the North American SynchroPhasor Initiative (NASPI).[18] Now that PMU technology is mature, it is likely that the majority of new applications for advanced power system measurements will be enabled by POW systems. In fact, the literature already contains several proposed applications for POW.[19, 20, 21] In this chapter, three particularly high-value POW use cases are reviewed: IBR model validation and calibration, load monitoring and characterization, and asset condition monitoring. The Roadmap proposed in Chapter 6 includes a timeline for developing and deploying these applications. Once the necessary measurement infrastructure is in place to support these use cases, many more will follow.

4.1 IBR Model Validation and Calibration

The benefits and opportunities with connecting more inverter-based resources (IBR), e.g. distributed energy resources, renewable generation, and electronically connected loads, in the power grid are not without some new challenges as well. Faster dynamics, limited information for analysis and complex controls are some of the challenges. To successfully solve these issues, it is important to have accurate models of IBRs and sufficient measurements to compare them against.

NERC analysis of recent disturbance events involving IBRs (including the Blue Cut Fire and Canyon 2 Fire) have shown the lack of disturbance monitoring data available to adequately determine the causes and effects of their behavior[22]. Inadequate data made it impossible to perform post-mortem event analysis and identify the root causes of large outages. Figure 5-1 shows a high-speed POW recording of the Blue Cut fire event after 1,200 MW of PV generation units were disconnected or switched into momentary cessation mode due to inverter control actions[23]. PMU technology is unable to capture these types of distortions because the waveforms are assumed to be sinusoidal as part of the measurement process.

Analysis of the recent events also showed that stability issues during high-penetration inverter-based resource conditions are difficult to detect using positive sequence stability simulations due to incorrect model parameters and the use of generic IBR models instead of detailed user-

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

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

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

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

defined models. There are also some cases where electromagnetic transient (EMT) modeling of IBRs is needed due to limitations of the positive sequence models, e.g., when IBRs are connected to a weak system or there is interaction with another power electronic control system. Therefore, advanced EMT-based modeling will play an increasingly important role for stability studies in electrical grid areas with high concentration of IBRs. There is a significant need for improved and validated positive sequence and EMT models and calibrated parameters of these models for proper representation of IBR dynamic behavior in bulk power system dynamic studies.

Successful model validation and calibration of IBRs strongly depend on the availability of required measurements, data, and event logs. The key component of the needed dataset is high-resolution POW measurements of the event collected by DFR, power quality (PQ) meters, or other devices.

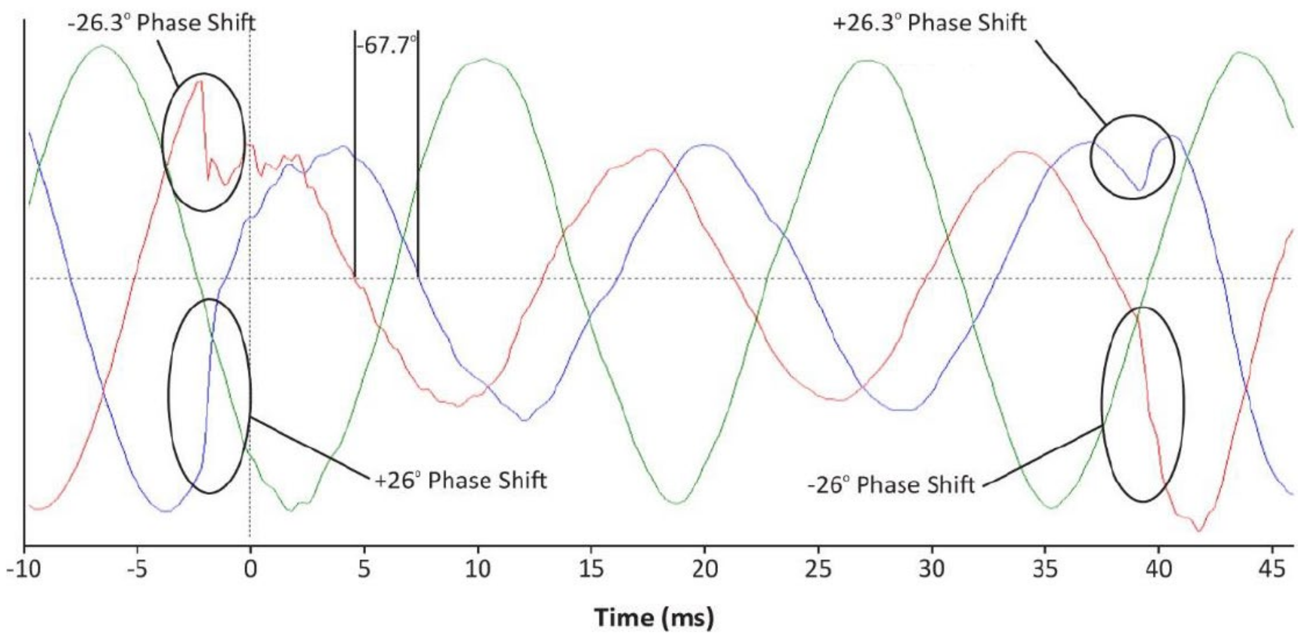

Figure 5-1 Phase Jump at Fault Location during Blue Cut Fire Disturbance[23]

HydroOne, which serves Ontario, Canada, requires PQ monitors to be installed on all renewable generators larger than 250kW. An overview of the system is provided in Figure 5-2. More than 1000 PQ monitors have already been installed, and the system has helped identify various IBR issues providing event records for faults, plant level and individual inverter fault responses, detection of abnormal IBR behavior, and equipment malfunction[24].

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

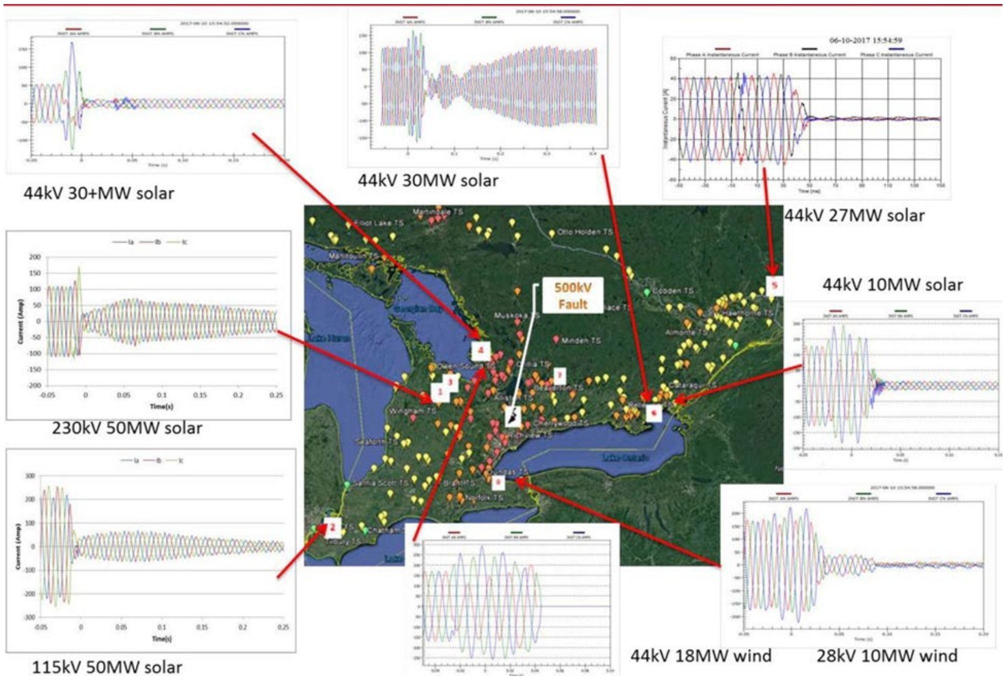

Figure 5-2 HydroOne renewable monitoring – system wide event[24]

4.2 Load Monitoring and Characterization

The dynamic characteristics and composition of electric loads have been changing over the past two decades. Increased penetration of electronically connected load, residential air conditioners, electric vehicle (EV) chargers, and distributed energy resources (DER) resulted in a new problem - such loads respond differently to electric faults and grid events than the resistive loads that previously dominated the grid. Therefore, traditional dynamic load models do not accurately capture the dynamic behavior of the emerging load composition. Under extreme conditions, the high penetration of electronically connected loads could cause a phenomenon called a fault-induced delayed voltage recovery (FIDVR) event. This problem occurs when the system voltage remains at significantly reduced (inadequate) levels for several seconds after a transmission or distribution fault has been cleared and potentially could cause a cascading outage. Accurate simulation of FIDVR events requires dedicated load modeling and parameterization[25]. Availability of field measurements is critical to understand dynamic behavior of emerging loads and to develop proper load models. PMUs and other high-resolution disturbance monitoring equipment have captured transient behavior at the transmission-level; however, limited information has generally been available to study the load response on the distribution level. Due to fast transients and complex dynamic nature of the electronically connected loads and other IBRs to monitor and study their behavior, deployment of high-resolution POW measurements (preferably CPOW) is required.

CPOW monitoring devices were deployed by Southern California Edison (SCE) to study the load characteristics at residential feeders using power quality meters[26]. Similarly, Bonneville

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

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

Power Administration (BPA) monitored their headquarters building using their custom Portable Power System Monitor (PPSM) technology, based on National Instruments hardware and software[27]. Installation of the monitoring systems allowed SCE and BPA to capture multiple events. Figure 5-3 shows POW measurements of line voltages and line currents captured during the initiation of a FIDVR event at the residential customer voltage level. Multiple A/C units stalled in about 1-cycle causing significant increase of the current and reactive power and voltage suppression.

CPOW measurements can also be used for non-intrusive load monitoring for identification of the load composition and individual behind-the-meter loads and DER based on the analysis of the aggregated load measured at the main power meter with, for example, a PQ meter. There are several approaches used for non-intrusive load monitoring (e.g., active/reactive power analysis, steady state signatures, wave form and harmonics analysis, and artificial intelligence (AI) application). All electronically connected loads and IBRs create different harmonics with individual signatures. Figure 5-4 shows a comparison of commercial building POW measurements in 2007 and 2017. It can be clearly seen from the figure that increased penetration of electronically connected loads between 2007 and 2017 created harmonics in the current waveforms. Harmonic signature analysis of the CPOW measurements has great potential for non-intrusive load monitoring and characterization.

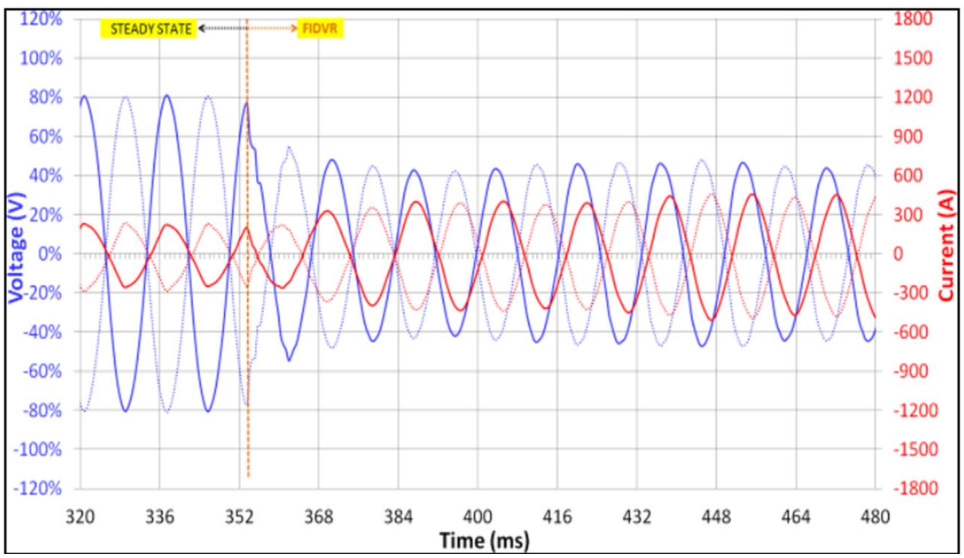

Figure 5-3 FIDVR waveforms at the residential customer voltage level[26]

[27] D. Kosterev and Steve Yang, "Load Composition and Monitoring at BPA", NERC LMTF meeting, 2017 Available online: https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/2017-10-NERC_LMTF_-_BPA_Load_Survey_and_Monitoring_-_Kosterev.pdf

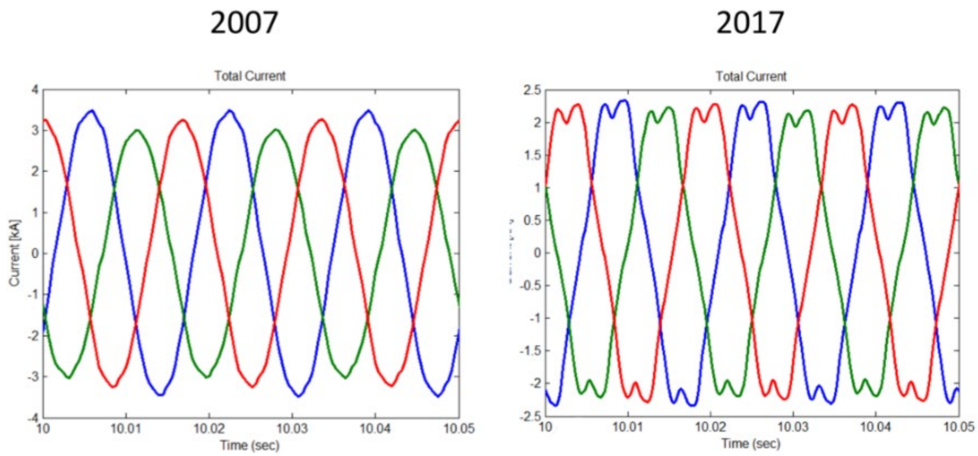

Figure 5-4 Commercial building POW measurements[27]

4.3 Asset Condition Monitoring and Management

PMU measurements have been used for asset health monitoring by various electrical utilities and other entities. A NASPI report contains a comprehensive review of the PMU-based applications for diagnosing equipment health and mis-operations[28]. POW measurements can enhance this capability because they provide observability of electrical waveforms that contain the underlying signatures of equipment failure. The IEEE PES Working Group on Power Quality Data Analytics recently released a report discussing the topic[29]. The authors introduce the report by stating:

> In recent years, engineers and researchers in the field of power quality, power system protection, and equipment testing have realized that useful information can be extracted from the waveforms for the purpose of equipment condition monitoring. In the field of power quality, for example, power quality monitors routinely collect power disturbance data. Some of the data do not indicate the existence of a power quality problem but they have been used to detect the presence of abnormal equipment operation in the system.

Thus, the power quality community has already begun to address asset health monitoring. The report provides a comprehensive review from a Power Quality (PQ) data analytics perspective. The analysis method consists of collecting waveform-type power disturbance data, extracting signature information, and from this information identifying various power equipment failures. For example, Figure 5-5 shows the waveform signature data from a power quality meter (PQM) and its cause: arcing and pitting along the arcing horn of circuit switcher[30]. As another example, Figure 5-6 illustrates voltage and current waveform data which had initiated transformer maintenance, thereby preventing a catastrophic failure[31].

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[28] NASPI, Diagnosing Equipment Health and Mis-operations with PMU Data, 2015, Available online: https://www.naspi.org/sites/default/files/reference_documents/14.pdf?fileID=1530

[29] IEEE PES Working Group on Power Quality Data Analytics. (2019). Electric Signatures of Power Equipment Failures Technical Report PES-TR73. IEEE Power & Energy Society. Available online: https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TP_TR73_TD_122019.html

[30] IEEE PES Working Group on Power Quality Data Analytics. (2019). Electric Signatures of Power Equipment Failures Technical Report PES-TR73. IEEE Power & Energy Society.

[31] Irwin, L. A. (2010). "Real experience using power quality data to improve power distribution reliability." Proc. of 14th IEEE PES International Conference on Harmonics and Quality of Power. 1-4.

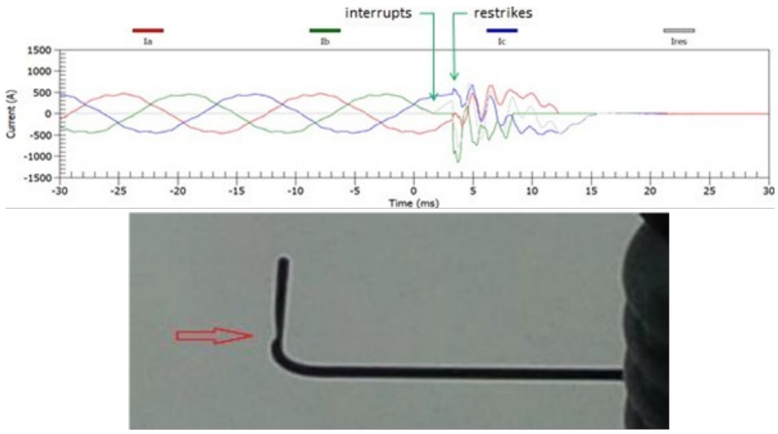

Figure 5-5 Waveform with restrike of a capacitor bank (upper) and Pitted arcing horn of a capacitor bank (lower).[30]

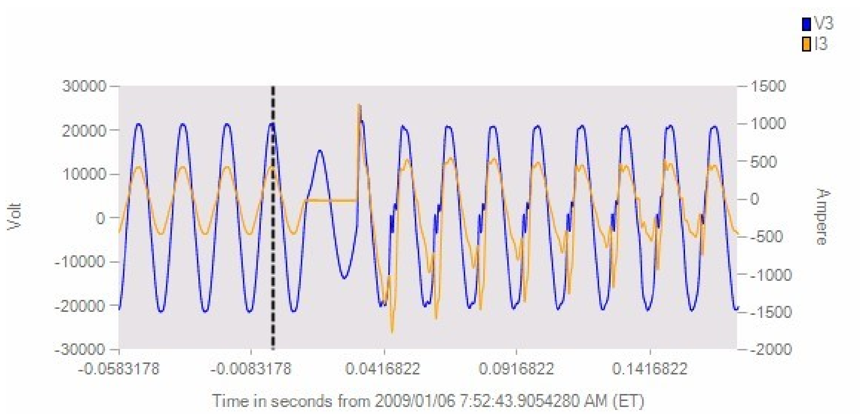

Figure 5-6 Zero current waveform data during transformer load tap changer failure[31]

5.0 Research Thrusts

After identifying the gaps and high-value use cases outlined in Chapters 3 and 4, the research team compiled a list of activities to address the gaps, and consequently unlock the use cases. These activities were organized into four research thrusts corresponding to the gap categories identified previously:

- Deployment and Demonstration
- Education
- Instrumentation, Testing, and Standards
- Analytical Methods

In the following subsections, each of these research thrusts is described. The scope of goals within each thrust are identified, and key metrics for success are listed. These thrusts also serve as the primary structure for the Roadmap detailed in Chapter 6. The Roadmap provides additional details about the connections between thrusts, gaps, and use cases. It also provides a timeline for the activities outlined in this chapter.

Research Thrust I: Deployment and Demonstration

The introduction of new technologies into the electric power system requires that consideration be given to the risk aspects. A process of documenting safety and performance is called for. Formality is appropriate to the rollout of a new measurement system, whether it is predominantly new hardware or new software.

Key goals Encourage non-siloed availability of Continuous Point-On-Wave data. Enable rollout of new measurement ideas and instrumentation by formalizing the process. Enable better integration of CPOW schemes (and more) by establishing a long-term test facility.

Goal I.1: Practical Collection and Analysis of POW Measurements

Non-siloed availability of data is important in the power system and elsewhere. (It is part of a viewpoint that the BIPM calls FAIR: Findable, Accessible, Interoperable and Reusable.) Achieving the FAIR attributes is a goal of this work.

The technology needed to generate CPOW data is currently available. Merging units that are built to the IEC standard 61850-9-2LE publish either 4000 or 4800 samples per second (for 50- and 60-Hz power systems). Harmonics up to about 2kHz should therefore be reasonably represented. While that is more than enough for most "rms" measurements to be made, a higher rate will likely be required for some developments of CPOW applications.

Since the technology for obtaining samples at this rate exists, it is proposed that this part of the thrust area begin with data collection at this rate. The information from the merging unit includes the sampled values, link to Precision Time Protocol (PTP) information and can use networks such as routed-GOOSE (Generic Object-Oriented Substation Events) over Ethernet or LTE carrier to leave the substation yard that houses the merging unit. There are multiple manufacturers building to this standard.

Goal 3 of this thrust area indicates the value of a demonstration capability built for long-term use. That long-term use can build on the merging unit data collection scheme developed under this area. To evaluate the capability and limitations of existing equipment is not expected to be a trivial task, and it is expected to be an ongoing task.

When requirements for higher-rate sampling can be demonstrated, the publishing rate may be revised. A system publishing more rapidly than 4800 S/s may affect the protocols used, and this must be allowed for.

- Findability requires an agreed-to means of advertising the location of data. The press of discovering what is acceptable to all parties may not be simple.
- Accessibility then follows once agreed-to procedures are followed. Cybersecurity is paramount.
- Interoperability of the physical/logical interface is generally handled well by the adoption of the appropriate communication standards, in particular IEC 61850. Nevertheless, instrument systems are not generally plug-and-play. Some while ago, a documentary standard was developed to address exactly this problem (IEEE Std 1451 — a universal transducer protocol standard). The standard solves the challenging question of units (using a method based on the SI system of units) and of such instrumentation-specific things as calibration details. It was developed by the IEEE Instrumentation and Measurement Society, and is supported by NIST, indeed, it was developed with NIST involvement.
- It is recommended that DOE investigate the applicability of Std 1451. At present it seems that there is no link between IEEE 1451 and IEC 61850. If it is found to be appropriate, DOE should steer the community in that direction.
- Reusability depends on storage. Once the sampled value data is received, it would normally be stored, for at least some short time. That capability must also be built in an expandable way. Reusability is shown by access and use by parties other than the original owner of the data. That may require anonymization by some agreed-to method.

It is likely that the analysis of the POW data will concentrate mostly on issues of latency in communications. Very likely, specialized equipment would be needed for that purpose, and some may have to be developed specifically for the job.

Key Metrics: Separate evaluation of Findability, Accessibility, Interoperability and Reusability in various implementations

Attributes: Findable, Accessible, Interoperable Reusable data

Scope: Investigation of present situation, understanding of obstacles to change, generation of best practices documentation

Goal I.2: Formalizing the Deployment and Demonstration Process

Step-by-step, for the demonstration of a new system, the following aspects should be subject to formal documentation:

- The new system should be safe for the power system. That should not be a problem for an instrument—any hazard to the power system would come from how the result of a measurement is applied, not from the instrument itself.

- A new system should be safe for itself. In other words, its ordinary operation should not endanger the accuracy or stability of the measurements. Ensuring that is a normal part of the design process.
- The instrument should be functional. More particularly, it must be possible to demonstrate that it is functional, and that must be provable.
- The question of interoperability has been of importance to DOE for a very long time. The BIPM views that topic as a requirement of data, but it is also a requirement of the instrumentation. Just as data is usually integrated with other data during study, an instrument is always integrated with other equipment during use.
- The formal technology introduction process should likely include reviews. The inclusion of a readiness review should be considered as a prelude to connection to the grid.

Key Metrics: Ease of use; minimization (but not over-reduction) of paperwork

Attributes: Logical progression

Scope: Comparison of procedures with other technology-introduction processes. Investigation of relevant IEEE Standards; Development of new procedures with agreement from all parties

Goal I.3: Demonstration Capability

Implement a program of demonstration, not as a one-time endeavor but as an ongoing aspect of technology development. Two of the more advanced utilities in the US are part of the Department of Energy, and each is located near a major DOE laboratory. Though the infrastructure is limited to transmission, it should certainly be possible to extend influence down to distribution. The Snohomish PUD is one of the most advanced distribution providers in the world, and they are part of the territory of BPA, and close to the offices of PNNL. On the other side of the country, ORNL and TVA have shown over the years that local distribution companies will participate in demonstrations. Other DOE locations with appropriate interests and capabilities (Sandia, INL, etc.) may be found equally suitable.

This facility can be used for demonstrations around multiple use-cases and can be in place long enough to examine seasonal effects (a matter of importance with some renewable resources).

Key Metrics: Access to real-world data as well as simulations

Attributes: Accessible to all sides of the industry and the profession. Low cost participation

Scope: Create a new facility; Make a long-term effort to demonstrate advanced measurement technology at one or more locations. Establish staff of specialists. Begin interoperability test days.

Research Thrust II: Education

In general, engineers and scientists are not taught enough about measurements in university. In the power system, this has led to a significant gap of what the measurement is about, what the results of the measurement mean, and promoted a reliance on over-simplified concepts. A perfectly functioning instrument can give a perfectly useless reading. These are problems that should be addressed without delay because the applicability of the human “sanity check” will fade as the grid gets smarter and more automated.

Key objectives Power subject matter experts educated in measurements, leading to better equipment, better reliability, and improved international competitiveness.

Goal II.1: Continuing Professional Education

While universities should be encouraged to teach measurement, that would not soon solve the problem. For the experienced practicing engineer, on-the-job training, otherwise known as continuing professional education, is the way to reach the individual. Most large companies have programs of continuing education.

DOE should act to ensure that continuing professional education that is relevant to power system measurements is available. It may be that the action required will involve designing such a program, or it may be that some collaboration with the IEEE Instrumentation and Measurement Society and/or EPRI would be advantageous.

To tackle all the various aspects of measurement that should really be understood, multiple topics must be covered:

- Importance of purpose
- Trustworthiness of results
- Different kinds of measurement
- Traceability and infrastructure

The intention is to allow the adult student to have as solid a grounding in measurement as someone emerging from a university. It is not intended to create a generation of instrument designers.

Key Metrics: Ease of setup, cost, ease of access, flexibility, company management requirements

Attributes: On-line accessibility, no cost to individual

Scope: Evaluate available pedagogical materials, assess needs for supplement, enumerate organizational requirements in private sector, liaison with others involved in this kind of education

Goal II.2: Undergraduate/Post-Graduate University Education

The effort at the university level will have increasing importance in new technology development. For the most part, books and papers on measurement eventually reveal themselves to be more (sometimes exclusively) focused on instrumentation. It may be necessary to create courses from scratch. IEEE or some of the big companies in the field may be able to help. A significant problem will be to find room in the already-full syllabus of most courses.

Key Metrics: Cost, time constraints, access to materials and laboratories, flexibility

Attributes: Resiliency, flexibility, security

Scope: Liaison with the National Science Foundation (NSF), identify partner institutions, evaluate available pedagogical materials, assess available teaching talent, assess needs for supplement

Research Thrust III: Instrumentation, Testing, and Standards

The two topics of standards and testing are interconnected. A measurement system for the electric power system will have to deal with voltages and currents that usually have a few percent of harmonic distortion. In the distribution system, the current may have twenty percent distortion, sometimes more. That adds a lot of definitional uncertainty to the results of the measurements, and any given instrument should be required to demonstrate a solution that is satisfactory to the intended application. This sort of demonstration can be done by showing compliance with the appropriate documentary standard.

Key objectives Improvements to existing technology and to development of new devices. Simplified testing. Better standards at the national and international level. Reduced-cost compliance verification.

Goal III.1: Instrumentation Standards and Compliance Testing

Today's measurement standards do not make simple the demonstration of compliance. It can be simplified in many cases because if a measurement is controlled by an operational standard, verification of instrument performance is not required. Verification of compliance with the operational requirements of the standard is sufficient. This has been the process that IEC 60270 followed since it became clear, late in the 20th century, that the processes of measurement of partial discharge had to be specified in detail.

Operational measurements are needed to ensure interoperability when there is much definitional uncertainty in the signal representing the quantity being measured.[32] The measurement of power, reactive power, apparent power, and power factor will soon be governed by an operational standard. Once the appropriate standard is approved, simple and rapid testing can demonstrate compliance, for example that the appropriate filters are used, and the appropriate detector response is present. That same simplification will apply to testing the measurement of many other quantities.

Key Metrics: Impact on existing instrumentation, existing standards, and traceability

Attributes: Testability; Clarity, Unambiguousness

Scope: Evaluate existing standards used for testing various technologies. Identify standards that are partly operational and consider applicability of increasing or decreasing operational

[32] The Phasor Measurement Unit is an example. The performance standard C37.118-1 was written with no particular application in mind. The PMU standard expects to obtain good performance by specifying a very complex suite of tests to demonstrate that a particular PMU is in compliance with its requirements. But it is inevitable that when a signal is presented to a PMU that has not been included in the test suite, the result may differ depending on the details of the PMU. The appropriate way to write the standard is to specify the design of a PMU that will serve some given application, and then test for compliance with those requirements. Such tests are simple and straightforward, and compliance would guarantee that the application would be served, and that all PMUs would give the same result.

level. Establish a recommended set of best practices and standardized solutions for future standards writers

Goal III.2: Trust Metric

It is known to the world outside the power system that the result of a measurement should be accompanied by a statement of the quality of the measurement. It is *not* known outside world of the power system (or inside, for that matter) that in a power system such a quality statement is all-but impossible to obtain. Power system measurements have never used statements of quality and have instead relied on the statement of accuracy in the owner's manual. The problem with that is that it fails completely to account for definitional uncertainty, and that *dominates* in the power system.

Digital measurements, whether located remotely or operating from CPOW signals, have available the information needed to enable the calculation of a trust metric. This can be done in real time (meaning it will not add latency to publishing the result of the measurement)[33]. It has been demonstrated, both in the laboratory at PNNL and in a frequency-measuring system at Sandia National Laboratory, where delay would be problematical. It has also been demonstrated to improve fault location accuracy[34]. The metric applies to a voltage measurement or to a current measurement, and from those the value for other quantities (for example, reactive power) can be found by a process called *propagation*. Propagation of uncertainties is well known in measurements outside the world of electric power. Propagation of a trust metric is a matter for research.

Key Metrics: Impact on existing instrumentation, degree of possible generalization

Attributes: Simplicity of use, ability to be generalized and propagated

Scope: Research in effects of definitional uncertainty on certain specific measurands, and results on residuals; Research on analysis of residuals

Research Thrust IV: Analytical Methods

Measurements are made for a purpose. That purpose may be automation which has minimal human interaction, or it may be operation or planning, with considerable human interaction. In either case, the results of measurement feed into some application software, or (possibly) are displayed on a screen. In almost all these applications, the results become part of a *model*, a mathematical description of a system of interest. It is not difficult to show that not all results can be used in subsequent study, or that not all models are verifiably good representations of the object they are supposed to represent.

Model validation is therefore an important part of many aspects of power system study. Such things come under the broad heading of *analytical methods*. A state estimator is an analytical method, for example.

[33] A. Riepnieks and H. Kirkham, "An Introduction to Goodness of Fit for PMU Parameter Estimation," in *IEEE Transactions on Power Delivery*, vol. 32, no. 5, pp. 2238-2245, Oct. 2017, doi: 10.1109/TPWRD.2016.2616761.

[34] "Incorporating Goodness-of-Fit Metrics to Improve Synchrophasor-Based Fault Location" Matin Rahmatian;Yu Christine Chen;William G. Dunford;Farnoosh Rahmatian, IEEE Transactions on Power Delivery, 2018, Vol 33, Issue: 4

Key objectives Development of analytical methods for POW measurements. Development of analytical methods to make use of a trust metric.

Goal IV.1: IBR Model Validation and Calibration

Continuous point-on-wave technology can be used to make measurements at the point of delivery (of the point-on-wave signals) in exactly the same way that measurements are presently made remotely. CPOW technology also enables some new capabilities. While IBR model validation is indicated, it should be possible to[35]

- facilitate renewables integration (inverter-based resources)
- detect geomagnetic disturbances, and perhaps even high-energy electromagnetic pulses
- monitor asset condition
- improve load characterization
- address concern over power quality

Some of the topics listed have already been the topic of research in the range of TRL 3, laboratory demonstration. However, it is not clear that CPOW has yet been used for these purposes as a continuous capability. In essence, these are measurements that are "non-rms," that is not based on the usual power system quantities that are at the root of most models of the power system. Such measurements will likely be many in number and will enable transient states to be monitored in addition to the steady state conditions that rms values allow. Building a non-rms capability will require further development. That is the goal of this work.

The use of POW data in the study of high-frequency systems, or the high-frequency side-effects of power-frequency systems, is not a completely new topic. However, such functions are not part of routine operation, and the list of applications is broad. Some of the applications listed above require inputs from multiple systems, some require rapid responses. Investigating the overall requirements for a variety of applications should be evaluated.

Key Metrics: Highest frequency represented, dynamic range requirements of digitizers,

Attributes: Broad and deep study

Scope: Create a taxonomy of users (i.e., software) of high-frequency data, organized according to the metrics indicated. Investigate capabilities of existing schemes. Investigate for gaps.

Goal IV.2: Utilization of Trust Metric

Once the digitizer has moved information from the physical world to the conceptual, an indirect measurement can be made, using multiple input quantities. Various algorithms operate on the sampled data to give a result. A new capability that has already been demonstrated in the laboratory (that is, TRL 3) is the use of the signal from a digitizer to generate a trust metric for measured result.

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

To be effective, such a metric must be put to use. Any existing or future measurement can furnish such a metric, but the user-application must know how to deal with it. The list of applications that can use the metric is the set of all measurements, and in particular the ones known as “rms” measurements, the ordinary power system measurements. Uses of the concept are relatively new. A version has been developed at Sandia National Laboratory, where it is used to decide among the outputs of several real-time frequency measurement schemes. It has also been used to select the most credible from a set of fault-location estimates[36].

This use-capability will require development essentially from scratch, as the appropriate result of using it depends on the application. The question to be answered is simple enough: Once you *know* that the measurement results from some particular instrument are not trustworthy, what do you want your control system or analysis system to do? Finding answers is the goal of this work.

Key Metrics: Number and value of applications adapted to use the metric

Attributes: software-updatable to existing algorithms

Scope: Investigate multiple applications for inserting a “metric-evaluator.” Implement some. For those implemented, investigate use of “return point” approach (similar to side-swap) for safety.

[36] “Incorporating Goodness-of-Fit Metrics to Improve Synchrophasor-Based Fault Location” Matin Rahmatian;Yu Christine Chen;William G. Dunford;Farnoosh Rahmatian, IEEE Transactions on Power Delivery, 2018, Vol 33, Issue: 4

6.0 Roadmap

As stated in the introduction, the objective of this Roadmap is to provide a framework for DOE investment in technology development, standardization, and policy making in advanced power system measurements. Chapters 3 and 4 described current gaps in power system measurement and a set of particularly high-value use cases that DOE investment in advanced measurements can enable. These gaps and use cases were identified as part of the literature review summarized in Chapter 2.[37] Next, the research thrusts described in Chapter 5 were developed to close gaps and ultimately enable the high-value use cases. This chapter serves to tie Chapter 3-5 together into a single framework for investment.

At the highest level, this roadmap is organized around the four research thrusts. The goals identified for each thrust in Chapter 5 are repeated here, but instead of long-form descriptions, each goal is summarized by a set of activities describing the work that needs to be done. Each activity description includes a timeline and two sets of milestones, one for gaps and one for use cases. Timelines are specified in terms of quarters and are intended to provide a rough concept of how the work could proceed. Finally, the description of each activity includes a list of related activities to capture the need for coordination and information exchange.

Research Thrust I: Deployment and Demonstration

Key attributes: Non-siloed availability of POW/CPOW, formalized process for new measurement idea and instrumentation rollout, test facility for POW/CPOW scheme integration.

Goal I.1: Practical Collection and Analysis of POW Measurements

Focus on FAIR (Findability, Accessibility, Interoperability, Reusability) as the value attributes and requirements. Key metrics derived for each of attributes.

Activity I.1.A: Collection of a large volume of CPOW measurements

Timeline: Q1 – Q10

Comprehensive collection effort on current POW/CPOW deployments, instrumentation, and data platforms. Including trade-off studies, e.g. cost/benefit, capability/affordability, and value proposition.

Gap milestones:

> *"On-Premises" Data Storage Paradigm* – Q4 – Demonstrate use of distributed and outsourced approaches for processing and analyzing high-volume data.
>
> *Communications Infrastructure* – Q6 – Identify best practices and value propositions (including cost/benefit, cost/performance, and other methods) for deploying reliable, high-bandwidth, low-latency utility communications infrastructure to overlap with key measurement points.

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

Integrated Waveform Measurement – Q10 – Data collection begins from electronics equipment modified to stream waveform measurements.

POW Data Silos – Q6 – Identification of the data silos, classification and evaluation for opportunities and limitations.

Use case milestones:

N/A

Related activities:

Data from this activity supplied to Activity I.1.B for analysis.

Coordinated with Activity IV.1.A

Activity I.1.B: Exploratory analysis of a large volume of CPOW measurements

Timeline: Q3 – Q12

Exploratory analysis of a large volume of synchronized POW measurement for a variety of uses, such as oscillations near IBR sites, real-time operation, transactive energy markets and controls, distributed controls, and other novel applications/uses.

Gap milestones:

“On-Premises” Data Storage Paradigm – Q4 – Demonstrate use of distributed and outsourced approaches for processing and analyzing high-volume data.

Communications Infrastructure – Q6 –Value propositions (including cost/benefit, cost/performance, and other methods) for deploying reliable, high-bandwidth, low-latency utility communications infrastructure to overlap with key measurement points.

Waveform Signatures – Q12 – Waveform signatures of equipment failure, outages, asset performance issues, and power quality phenomena identified, analyzed, and characterized.

Use case milestones:

IBR Model Validation and Calibration – Disturbance recordings at IBR point of interconnection extracted for use in model validation and calibration.

Load Monitoring and Characterization – Disturbance recordings near large electronic loads extracted for use in model validation and calibration.

Asset Condition Monitoring and Management – Asset monitoring methods applied to multi-month dataset of measurements near substation assets.

Related activities:

Data for this activity supplied by Activity I.1.A.

Methods for this activity developed in Activity IV.1.B.

Activity I.1.C: Guide for POW/CPOW implementation

Timeline: Q6 – Q12

Guide for POW/CPOW implementation. Based on analysis findings, user experience and subject matter expert knowledge developed practices, approaches, and guides for utilizing existing systems for POW/CPOW early stage on-premises demonstration.

Gap milestones:

"On-Premises" Data Storage Paradigm – Q4 – Good practices and guide to distributed and outsourced approaches for processing and analyzing high-volume data.

Communications Infrastructure – Q6 – Practices and guide to value demonstrations (including various methods) for deploying reliable, high-bandwidth, low-latency utility communications infrastructure that delivers necessary capability.

Waveform Signatures – Q12 – Practices, methods and guide for waveform signature collection and characterization.

POW Data Silos – Q6 – Guidance on improvements and data silo avoidance. Provided evaluation results.

Use case milestones:

IBR Model Validation and Calibration – Guide and practices for disturbance recordings at IBR point of interconnection extracted for use in model validation and calibration.

Load Monitoring and Characterization – Guide and practices for disturbance recordings near large electronic loads extracted for use in model validation and calibration.

Asset Condition Monitoring and Management – Guide and practices for asset monitoring methods of measurements near substation assets.

Related activities:

Data for this activity supplied by Activity I.1.A.

Analysis results for this activity supplied by Activity I.1.B

Methods for this activity developed in Activity IV.1.B.

Activity I.1.D: Early stage implementation support program

Timeline: Q1 – Q9

Early stage implementation support program. Focusing on utilities and power system measurement stakeholders having an incentive program for early adoption and deployment of POW/CPOW (field trials). An integral part is emphasis on practical uses of the CPOW/POW data.

Gap milestones:

"On-Premises" Data Storage Paradigm – Q4 – If necessary, support early stage deployments of data storage technology (cloud based or outsourced) that enables POW/CPOW adoption and improves processing and analyzing high-volume data.

Communications Infrastructure – Q9 – Support communications systems adequacy for deploying sufficient utility communications infrastructure that delivers necessary capability.

POW Data Silos – Q6 – Support adoption of data sharing and data silo avoidance.

Use case milestones:

IBR Model Validation and Calibration – Support implementation of practices for disturbance recordings at IBR point of interconnection extracted for use in model validation and calibration.

Load Monitoring and Characterization – Support early stage deployment for disturbance recordings near large electronic loads extracted for use in model validation and calibration.

Asset Condition Monitoring and Management – Support early stage deployment for asset monitoring methods of measurements near substation assets.

Related activities:

This activity exchange information and supports Activity I.1.A.

This activity exchange information and supports Activity I.1.B.

Activity I.1.E: Demonstrations of value, affordability, performance, and security

Timeline: Q9 – Q12

Demonstrations of value, affordability, performance, and security. Promote trust and interest in advanced solutions, e.g., IBR model validation/calibration methods and tools.

Gap milestones:

"On-Premises" Data Storage Paradigm – Q10 – Demonstrated feasibility for distributed data storage scenarios, processing and analyzing high-volume data.

Communications Infrastructure – Q12 – Demonstrated value (through cost/performance, utility/affordability etc. analysis) of adequate communications infrastructure that delivers necessary capability for use case support.

Use case milestones:

IBR Model Validation and Calibration – Published results of analysis for disturbances at IBR point of interconnection and their use in model validation and calibration.

Load Monitoring and Characterization – Published results of analysis for disturbances near large electronic loads and their use in model validation and calibration.

Asset Condition Monitoring and Management – Published results of analysis for asset monitoring methods.

Related activities:

This activity exchange information and supports Activity I.1.D.

Data for this activity is supplied by Activity IV.1.B.

Data for this activity supplied by Activities I.1.A, I.1.B, and I.1.D.

Goal I.2: Formalizing the Deployment and Demonstration Process

Aspects for formal documentation include safety (towards power system and measurement system itself), provable function, interoperability, and reviews for formal technology introduction.

Activity I.2.A: Comprehensive analysis

Timeline: Q1 – Q9

A comprehensive analysis that includes stakeholder identification, standards, and regulations investigation as well as development of procedures. Final acceptance from stakeholder perspective is the key criteria.

Gap milestones:

Operationalism Recognition –Q3- Process includes the necessary development and test objectives to address operationalism, where it applies.

Standard Waveform Measurement Device –Q9- Waveform measurement device development and implementation process should follow the formalized deployment and demonstration process

Use case milestones:

NA

Related activities:

This activity exchanges information and supports Activity I.1.E.

Goal I.3: Demonstration Capability

Creation of a new facility for a long-term effort to demonstrate advanced measurement technology at one or more locations. Establishing staff of subject matter experts (SMEs) and launching interoperability test demonstrations.

Activity I.3.A: Stakeholder identification, need/expectation elicitation, and requirement validation

Timeline: Q1 – Q3

Stakeholder identification, need/expectation elicitation, and requirement validation. Team SME identification. Includes concept of operations, scope, preliminary design, and long-term strategy.

Gap milestones:

"On-Premises" Data Storage Paradigm – Q2 – Identified innovative and early-stage designs for distributed data storage scenarios, processing and analyzing high-volume data.

Communications Infrastructure – Q3 – Identified requirements and stakeholders for novel designs, new technology and scenario demonstration of communications infrastructure as part of a successful measurement system.

Measurement Accuracy – Q3 - Identified stakeholders and requirements for novel methods for measurement systems, trust metrics and uncertainty evaluation methods.

Operationalism Recognition – Q3 - Identified stakeholders and requirements for methods and approaches to sufficiently lock and define operations to ensure measurement interoperability.

Integrated Waveform Measurement – Q3 - Identified stakeholders and requirements for waveform measurements capability based on existing measurement systems and electronics equipment.

Use case milestones:

IBR Model Validation and Calibration –Stakeholders and requirements for methods and analysis for IBR model validation and calibration.

Load Monitoring and Characterization –Stakeholders and requirements for methods and analysis for electronic load model validation and calibration.

Asset Condition Monitoring and Management –Stakeholders and requirements for methods and analysis for asset monitoring validation and calibration.

Related activities:

This activity uses information from Activity I.1.C.

This activity informs Activity I.1.D

Activity I.3.B: Establish advanced measurement technology facility

Timeline: Q3 – Q12

Deployment of necessary infrastructure and knowledge base for establishing minimum viable product capability. Value demonstration for interoperability test.

Gap milestones:

"On-Premises" Data Storage Paradigm – Q9 – Deployed capability to demonstrate/showcase innovative and early-stage designs for distributed data storage scenarios, processing and analyzing high-volume data.

Communications Infrastructure – Q9 – Deployed capability to demonstrate/showcase novel designs, new technology and scenarios (through cost/performance, utility/affordability etc. analysis) of communications infrastructure as part of a successful measurement system.

Measurement Accuracy – Q12 – Deployed capability to demonstrate novel methods for measurement systems, trust metrics and uncertainty evaluation methods.

Standard Waveform Device – Q12 – Deployed capability to demonstrate new waveform measurement devices.

Integrated Waveform Measurement – Q12 – Deployed capability to demonstrate (in a consistent manner) waveform measurements capability based on existing measurement systems and electronics equipment.

Use case milestones:

IBR Model Validation and Calibration – Capability to demonstrate methods and analysis for IBR model validation and calibration.

Load Monitoring and Characterization – Capability to demonstrate methods and analysis for electronic load model validation and calibration.

Asset Condition Monitoring and Management – Capability to demonstrate methods and analysis for asset monitoring validation and calibration.

Related activities:

This activity is informed by Activity I.3.A.

This activity exchanges information with and supports Activity I.1.D.

This activity supports Activity I.1.E.

Activity I.3.C: Demonstration capability strategy development

Timeline: Q10 – Q12

Develop a strategy defining the future demonstrations establishing a long-term center for excellence in advanced measurement technology. Includes strategy realization. Expected to be used to help advance technology readiness levels.

Gap milestones:

"On-Premises" Data Storage Paradigm – Q12 – Deployed capability to demonstrate/showcase innovative and early-stage designs for distributed data storage scenarios, processing and analyzing high-volume data.

Communications Infrastructure – Q12 – Deployed capability to demonstrate/showcase novel designs, new technology and scenarios (through cost/performance, utility/affordability etc. analysis) of communications infrastructure as part of a successful measurement system.

Measurement Accuracy – Q12 – Deployed capability to demonstrate novel methods for measurement systems, trust metrics and uncertainty evaluation methods.

Standard Waveform Device – Q12 – Deployed capability to demonstrate new waveform measurement devices.

Integrated Waveform Measurement – Q12 – Deployed capability to demonstrate (in a consistent manner) waveform measurements capability based on existing measurement systems and electronics equipment.

Use case milestones:

IBR Model Validation and Calibration – Capability to demonstrate methods and analysis for IBR model validation and calibration.

Load Monitoring and Characterization – Capability to demonstrate methods and analysis for electronic load model validation and calibration.

Asset Condition Monitoring and Management – Capability to demonstrate methods and analysis for asset monitoring validation and calibration.

Related activities:

This activity is informed by Activity I.3.A.

This activity exchange information and supports Activity I.1.D.

This activity supports Activity I.1.E.

Research Thrust II: Education

Key attributes: Power SMEs educated in measurements, supporting, and enabling development of better measurement systems.

Goal II.1: Continuing Professional Education

Focus on on-the-job training for practicing engineers of various experience levels. Making sure the continuous education program remains relevant to power systems measurements.

Activity II.1.A: Stakeholder identification and need/expectation elicitation

Timeline: Q1 – Q2

Gap milestones:

Engineer Education and Training– Q2 – Identified stakeholders and their needs/expectations. A concept of operations prepared for training program.

Use case milestones:

NA

Related activities:

This activity informs Activity II.1.B.

This activity informs Activity II.1.C.

Activity II.1.B: Material elicitation and overview

Timeline: Q1 – Q4

Gap milestones:

Engineer Education and Training – Q4 – Identified and gathered materials for training program. An overview and review are performed.

Use case milestones:

NA

Related activities:

This activity supports Activity II.1.C.

This activity is informed by Activity II.1.A.

Activity II.1.C: On-line course in measurements in power systems

Timeline: Q3 – Q6

Gap milestones:

Engineer Education and Training – Q6 – Reviewed and deployed continuous education program in utility/industry environment.

Use case milestones:

NA

Related activities:

This activity supports Activity II.1.D.

This activity is supported by Activity II.1.A.

This activity is supported by Activity II.1.B.

Activity II.1.D: Long term impact assessment

Timeline: Q6 – Q6

Gap milestones:

Engineer Education and Training– Q6 – Deployed feedback and success assessment mechanism that ensures program is up-to-date and complies with stakeholder needs/expectations.

Use case milestones:

NA

Related activities:

This activity supports Activity II.1.C.

This activity is supported by Activity II.1.A.

This activity is supported by Activity II.1.C.

Goal II.2: Undergraduate/Post-Graduate University Education

Long-term effort guided towards university level education programs for engineers. Main focus on measurement systems (not specifically instrumentation).

Activity II.2.A: Stakeholder, needs, and detailed gap analysis

Timeline: Q1 – Q3

Gap analysis, including existing courses, programs and identified stakeholders.

Gap milestones:

Engineer Education and Training– Q3 – Identified stakeholders and their needs/expectations. A concept of operations prepared for education program.

Use case milestones:

NA

Related activities:

In long term this activity exchanges information with Activity II.1.C.

This activity supports Activity II.2.B.

This activity is supported by Activity II.2.C.

Activity II.2.B: Measurements in power system program

Timeline: Q3 – Q7

Measurements in power system program. Designed to address gaps as well as serve as foundation for stand-alone academic program development.

Gap milestones:

Engineer Education and Training – Q7 – Reviewed and deployed education program at a university (or similar) environment.

Use case milestones:

NA

Related activities:

In long term this activity exchange information with Activity II.1.C.

This activity supports Activity II.2.C.

This activity is supported by Activity II.2.A.

Activity II.2.C: Collection of long-term impact assessment

Timeline: Q7

Gap milestones:

Engineer Education and Training – Q7 – Deployed feedback and success assessment mechanism that ensures program is up-to-date and complies with stakeholder needs/expectations.

Use case milestones:

NA

Related activities:

This activity is based on Activity II.2.C.

This activity is supported by Activity II.2.A.

Research Thrust III: Instrumentation, Testing, and Standards

Key attributes: improvements in existing technology, development of new devices, simple testing, comprehensive standardization, reduced-cost compliance verification.

Goal III.1: Instrumentation Standards and Compliance Testing

Focus on opportunities for compliance testing simplification, based on operational requirement verification. Operational and partly operational standards can be evaluated with an established recommended set of best practices and standardized solutions. Increased support for work on standards and revisions, including development of IBR standards that reflect those of conventional generation and standards for IBR monitoring. Establish a unified approach for addressing operationalism in standards.

Activity III.1.A: Test procedures

Timeline: Q1 – Q7

Clear and comprehensively defined (representational or operational) device testing procedures to include device performance preparedness for expected field conditions in power system.

Gap milestones:

Failure to Capture Unanticipated Events – Q4 – Test procedures for trigger-based recording of waveform measurements for quickly evolving systems.

Operationalism Recognition – Q6 – Identified operational and semi-operational standards and test procedures.

IBR-Related Policy and Standards – Q7 – Test procedures for high-resolution measurement devices deployable for IBR monitoring.

Standard Waveform Measurement Device – Q7 – Test procedures documented for a new standard measurement device.

Integrated Waveform Measurement – Q4 – Testing procedures that are transferable to existing measurement systems and electronics equipment.

Use case milestones:

NA

Related activities:

This activity is informed by Activity I.1.A and Activity I.1.B

This activity exchange information and supports Activity III.1.B.

This activity supports Activity III.1.D.

Activity III.1.B: New standards and revisions of existing standards

Timeline: Q4 – Q9

New standards and revisions of existing standards. Device testing standards and regulations for CPOW measurement devices. Existing standard revisions to address measurement process throughout the value chain (sensing, processing, reporting, analyzing, decision making). IBR standards (including revisions). National standard and industry regulations for POW/CPOW measurement technology deployments on IBR sites. This includes requirements for data collection and use.

Gap milestones:

Failure to Capture Unanticipated Events – Q7 – Requirements for the data collection and use. Standard identification that can help to address trigger-based waveform measurements for quickly evolving systems.

Operationalism Recognition – Q5 – Identified and addressed operational aspects in operational and semi-operational standards.

IBR-Related Policy and Standards – Q7 – Revised or created relevant documentation, including standards to promote deployment of the high-resolution measurement devices for IBR monitoring.

Standard Waveform Measurement Device – Q7 – Revised, developed documentation (including standards) for a new standard measurement device.

Integrated Waveform Measurement – Q7 – Standards and relevant documentation that covers existing measurement systems and electronics equipment.

Use case milestones:

IBR Model Validation and Calibration – Standardized approaches for data gathering and measurement interoperability for the relevant use case.

Load Monitoring and Characterization – Standardized approaches for data gathering and measurement interoperability for the relevant use case.

Asset Condition Monitoring and Management – Standardized approaches for data gathering and measurement interoperability for the relevant use case.

Related activities:

This activity is informed by Activities III.1.A, I.1.B, and I.2.B.

This activity exchanges information with and supports Activity I.1.E.

This activity supports Activity III.1.D.

Activity III.1.C: Report/Guide

Timeline: Q2 – Q9

Establish a recommended set of best practices and standardized solutions (including coordination and optimization efforts) between national and international standardization efforts for digital power system measurements. Findability, Accessibility, Interoperability and Reusability are goals.

Gap milestones:

Operationalism Recognition – Q4 – Guidance for addressing operational aspects in operational and semi-operational standards.

IBR-Related Policy and Standards – Q9 – Guidance and suggested practices for coordinated effort to revise and/or create relevant documentation for high-resolution measurement systems for IBR monitoring.

Standard Waveform Measurement Device – Q5 – Proof of concept and example for guide.

Integrated Waveform Measurement – Q9 – Guide and best practices for standardization and documenting existing measurement systems and electronics equipment that are POW/CPOW capable.

Use case milestones:

IBR Model Validation and Calibration – Standardized approaches for data gathering and measurement interoperability for the relevant use case.

Load Monitoring and Characterization – Standardized approaches for data gathering and measurement interoperability for the relevant use case.

Asset Condition Monitoring and Management – Standardized approaches for data gathering and measurement interoperability for the relevant use case.

Related activities:

This activity is informed by Activities III.1.A, I.1.B, and I.2.B.

This activity exchanges information and supports Activity I.1.E.

This activity supports Activity III.1.D.

Activity III.1.D: Market for monitoring devices

Timeline: Q2 – Q12

Support establishment of market for monitoring devices. Evaluate common use cases and requirements.

Gap milestones:

IBR-Related Policy and Standards – Q10 – Promoted compliance to relevant standards and testing procedures for high-resolution measurement systems.

Standard Waveform Measurement Device – Q12 – Commercialized device.

Integrated Waveform Measurement – Q12 – Guide and best practices for standardization and documenting existing measurement systems and electronics equipment that are POW/CPOW capable.

Use case milestones:

NA

Related activities:

This activity is informed by Activities III.1.A and III.1.B.

Goal III.2: Trust Metric

Support research and development of measurement trust metrics for usability in existing and new methods and applications. Investigate the aspect of trust propagation throughout models and applications.

Activity III.2.A: Trust metric definition

Timeline: Q1 – Q6

Develop trust metric definitions. A comprehensive study of existing methods and applications and their requirements for expressing trust.

Gap milestones:

Measurement Accuracy – Q5 – Trust metric definition that is compliant to stakeholder needs and expectations.

Standard Waveform Measurement Device – Q6 – Waveform measurement device supports trust metric.

Integrated Waveform Measurement – Q6 – Trust metric can be retro-fitted and applied to existing measurement systems and electronics equipment that are POW/CPOW capable.

Use case milestones:

IBR Model Validation and Calibration – Data quality and trust awareness for disturbance recordings at IBR point of interconnection extracted for use in model validation and calibration.

Load Monitoring and Characterization – Data quality and trust awareness for disturbance recordings near large electronic loads extracted for use in model validation and calibration.

Asset Condition Monitoring and Management – Data quality and trust awareness for asset monitoring methods of measurements near substation assets

Related activities:

This activity is informed by Activities I.1.A, I.1.B, and I.2.B.

This activity exchanges information with Activity II.1.C.

This activity supports Activities III.2.B, III.2.C, and III.2.D.

Activity III.2.B: Trust metric enabled methods, processes, and applications

Timeline: Q6 – Q12

Trust metric enabled methods, processes, and applications. Developed proof of concept for methods, processes, and applications for demonstration.

Gap milestones:

Measurement Accuracy – Q7 – Demonstrated use and value of trust metric enabled methods and applications that is compliant to stakeholder needs and expectations.

Standard Waveform Measurement Device – Q12 – Methods for measurement quality aware waveform measurement device.

Integrated Waveform Measurement – Q12 – Methods for trust metric for implementation in existing measurement systems and electronics equipment that are POW/CPOW capable.

Use case milestones:

IBR Model Validation and Calibration – Data quality and trust awareness for disturbance recordings at IBR point of interconnection extracted for use in model validation and calibration.

Load Monitoring and Characterization – Data quality and trust awareness for disturbance recordings near large electronic loads extracted for use in model validation and calibration.

Asset Condition Monitoring and Management – Data quality and trust awareness for asset monitoring methods of measurements near substation assets.

Related activities:

This activity is informed by Activities I.1.A, I.1.B, and I.2.B.

This activity supports Activities III.2.C and III.2.D.

Activity III.2.C: Study of increased usability

Timeline: Q4 – Q8

Study of increased usability, propagation methodology throughout systems (models and applications).

Gap milestones:

Measurement Accuracy – Q7 – Demonstrated use and value of a trust metric definition, methods, and propagation methodology that is usable at the application and decision-making level. Compliant to stakeholder needs and expectations.

Standard Waveform Measurement Device – Q8 – Demonstrated measurement quality aware waveform measurement device.

Integrated Waveform Measurement – Q8 – Demonstrated trust metric as applied to existing measurement systems and electronics equipment that are POW/CPOW capable.

Use case milestones:

IBR Model Validation and Calibration – Data quality and trust awareness for disturbance recordings at IBR point of interconnection extracted for use in model validation and calibration.

Load Monitoring and Characterization – Data quality and trust awareness for disturbance recordings near large electronic loads extracted for use in model validation and calibration.

Asset Condition Monitoring and Management – Data quality and trust awareness for asset monitoring methods of measurements near substation assets.

Related activities:

This activity is informed by Activities I.1.A, I.1.B, and I.2.B.

This activity supports Activity III.2.D.

Activity III.2.D: Trust aware applications

Timeline: Q8 – Q12

Enhanced and modified applications that utilizes trustworthiness of source data for decision-making.

Gap milestones:

Measurement Accuracy – Q10 – Demonstrated use and value of trust metric applications and value proposition at decision making level. Compliant to stakeholder needs and expectations.

IBR Monitoring – Q11 – Measurement trustworthiness aware application.

Measurement-Based Solutions for IBR Oscillations – Q11 – Measurement trustworthiness aware solutions to monitor oscillations and measurement quality aware methods of incorporating data into simulation-based approaches.

POW Measurement-Based Algorithms/Methods – Q12 – Methods and algorithms that are aware of measurement trustworthiness and adjusts any decision making accordingly.

Use case milestones:

IBR Model Validation and Calibration – Data quality and trust awareness for disturbance recordings at IBR point of interconnection extracted for use in model validation and calibration.

Load Monitoring and Characterization – Data quality and trust awareness for disturbance recordings near large electronic loads extracted for use in model validation and calibration.

Asset Condition Monitoring and Management – Data quality and trust awareness for asset monitoring methods of measurements near substation assets

Related activities:

This activity is informed by Activities I.1.A, I.1.B, and I.2.B.

This activity supports Activities IV.1.B and IV.1.C.

Research Thrust IV: Analytical Methods

Key attributes: analysis and early stage development of the new POW data-based methods. Majority of effort is guided towards IBR model validation and calibration.

Goal IV.1: IBR Model Validation and Calibration

This effort includes well-defined and unknown signal signature aggregation and analysis, controller evaluation, AI/ML software tool developments and integration.

Activity IV.1.A: SME team creation

Timeline: Q1 – Q5

A diverse SME team to analyze and aggregate: known waveform signatures from power quality; protection, and disturbance analysis; high-impact disturbances without well-defined signatures; AI/ML defined model-based signature definition.

Gap milestones:

IBR Modeling – Q3 – Gathering signature POW data usable for IBR modeling.

POW Data Silos – Q4 – Identification of the data silos, classification and evaluation for opportunities and limitations.

Waveform Signatures – Q5 – Signatures of equipment failures, outages, asset performance issues, and power quality phenomena in waveform measurements characterized.

IBR Controller Evaluation – Q4 – Identified signature data that can be useful to evaluate (including requirements perspective) IBR controller performance.

IBR Monitoring – Q3 – Gathered POW measurements, signature information, detailed event logs useful for IBR Monitoring.

Measurement-Based Solutions for IBR Oscillations – Q4 – Identified different types of oscillations related to IBRs.

*POW Measurement-based Algorithms/Method*s – Q5 – Data prepared for potential algorithm, method (including ML/AI-based) development.

Use case milestones:

NA

Related activities:

This activity is coordinated with Activity I.1.A and I.1.B.

Activity IV.1.B: Develop analytical methods

Timeline: Q3 – Q10

Developed analytical methods: IBR model validation/calibration based on PMU and POW measurements; asset health monitoring applications specific to IBRs; POW-based algorithms, methods, and tools; integrating measurements into simulation-based approaches.

Gap milestones:

IBR Modeling – Q8 – Analytical methods used for IBR models to simulate IBR dynamics in transmission planning and stability studies.

IBR Controller Evaluation – Q8 – Methods and algorithms for standard way to evaluate IBR controller performance.

IBR Monitoring – Q6 – Methods and algorithms for IBR monitoring.

Measurement-Based Solutions for IBR Oscillations – Q10 – Methods and algorithms developed for oscillation monitoring, analysis, development of simulation-based approaches made available to industry.

POW Measurement-based Algorithms/Methods – Q10 – Developed algorithms, methods (including ML/AI-based) and tools based on POW. Approaches for distributing waveform analytics.

Use case milestones:

IBR Model Validation and Calibration – Methods and algorithms for IBR model validation and calibration.

Load Monitoring and Characterization – Methods and algorithms for monitoring disturbance near large electronic loads and use in model validation and calibration.

Asset Condition Monitoring and Management – Methods and algorithms for substation asset monitoring.

Related activities:

This activity is informed by Activities I.1.A, I.1.B, and III.2.D.

This activity supports Activity IV.1.C.

Activity IV.1.C: Coordinated holistic exploratory analysis

Timeline: Q8 – Q11

Coordinated holistic exploratory analysis (research) on IBR model validation/calibration and IBR controller evaluation.

Gap milestones:

IBR Modeling – Q11 – Analysis on IBR models and simulated IBR dynamics in transmission planning and stability studies.

IBR Controller Evaluation – Q11 – Proposed standard way to evaluate IBR controller performance.

Measurement-Based Solutions for IBR Oscillations – Q11 – Analysis on different types of oscillations related to IBRs and measurement-based solutions that are needed to monitor for these oscillations, address them, and validate model-based studies. Methods for integrating measurements into existing simulation-based approaches.

POW Measurement-based Algorithms/Methods – Q11 – Algorithms, methods (including ML/AI-based) and tools based on POW measurements evaluated in the analysis.

Use case milestones:

IBR Model Validation and Calibration – Analysis results for IBR model validation and calibration.

Load Monitoring and Characterization – Analysis results for monitoring disturbance near large electronic loads and use in model validation and calibration.

Asset Condition Monitoring and Management – Analysis results for substation asset monitoring.

Related activities:

This activity is informed by Activities I.1.A, I.1.B, III.2.D, IV.1.B, and IV.1.A.

Goal IV.2: Utilization of trust metric

Taxonomy of measurement process stakeholders, with identified requirements, use limitations and potential gaps. Investigate the performance and use cases of methods for automation applications. Research of automation use cases limitations and dependencies on information quality (including synchronization, believability etc.) and quantity (reporting rates, area coverage, asset coverage etc.) to mitigate risks and ensure reliability.

Activity IV.2.A Taxonomy of measurement process stakeholders

Timeline: Q1 – Q4

Includes various stakeholder perspectives, needs, requirements, constraints.

Gap milestones:

POW Data Silos – Q2 – Identification of the data silos, stakeholders, classification and evaluation for opportunities and limitations.

Waveform Signatures – Q3 – Identified stakeholders, expectations, requirements, and limitations.

IBR Monitoring – Q1 – Uses and needs identified in high-resolution POW measurements, detailed event logs, data synchronization and retention for monitoring applications.

Measurement-Based Solutions for IBR Oscillations – Q3 – Identified requirements and limitations for measurement-based solutions validate model-based studies.

POW Measurement-based Algorithms/Methods – Q4 – Identified stakeholders, algorithm requirements, methods (including ML/AI-based) and tools based on POW measurements for various power system related applications. Role in distributing waveform analytics.

Use case milestones:

NA

Related activities:

This activity is informed by Activities III.2.B, III.2.C, and III.2.D.

Activity IV.2.B: Analysis of POW/CPOW automation

Timeline: Q3 – Q7

Analysis of POW/CPOW automation (ML/AI and simplified algorithm-based operations) use case scenarios for stakeholders.

Gap milestones:

IBR Modeling – Q5 – Analysis on IBR models and simulated IBR dynamics in transmission planning and stability studies.

IBR Controller Evaluation – Q6 – Proposed standard way to evaluate IBR controller performance.

Measurement-Based Solutions for IBR Oscillations – Q6 – Analysis on different types of oscillations related to IBRs and measurement-based solutions that are needed to monitor for these oscillations, address them, and validate model-based studies. Methods for integrating measurements into existing simulation-based approaches.

POW Measurement-based Algorithms/Methods – Q7 – Algorithms, methods (including ML/AI-based) and tools based on POW measurements used (evaluated) in the analysis.

Use case milestones:

IBR Model Validation and Calibration – Analysis results for IBR model validation and calibration use case.

Load Monitoring and Characterization – Analysis results for monitoring disturbance near large electronic loads and use in model validation and calibration use case.

Asset Condition Monitoring and Management – Analysis results for substation asset monitoring use case.

Related activities:

This activity is informed by Activities I.1.B, III.2.D, IV.1.B, and IV.1.A.

Appendix A – Glossary

This Glossary is presented with the idea that the reader of this Roadmap would be able to best access the thoughts of the authors if some of the terms are carefully explained. Most of the glossary is based on the International Vocabulary of Metrology (the VIM), from the BIPM. That way, the ideas that the reader might view as "new" can be seen to have a history and acceptance in the wider measurement community.

Quotations from the VIM are used in this Glossary unedited and uncut. (Some of the NOTES are not particularly relevant to our field but are given so that the *whole* view of the definition, as seen by the BIPM working group, is presented.) Other sources are cited where applicable but are not directly quoted. The references for these citations are listed at the end of this Appendix. The abbreviation (*qv*) [Latin *quod vide*, for "which see"] is used to indicate that there is another reference *in this glossary* that should be consulted.

Term	Description	Source	Comment
Calibration	A process by which the relation between the input to a measuring system and its output (the result) is established.		Calibration is an experimental process in which a known quantity (or a known measuring instrument) is used as a reference for comparison. The calibration process allows for adjustments to be made to the system being calibrated, or "correction" data (as in temperature- or altitude-correction) to be obtained. The values of electronic components may change with time, and that can mean recalibration is needed if the part is in some analog stage where its value matters to the result. A time called MTBOOT (mean time between out-of-tolerance) is estimated by the equipment maker and used to set the required recalibration interval.
Cauchy's equation	An equivalent equation is written where the little circle means "combine," used instead of addition since the left side of this equation represents the physical world, rather than the mathematical. For example, the weight of two separately weighed masses are the same as their combined weight.	Hand (2004) Carnap (1966)	The equation applies to the results of measurements. It is used as a test of the usefulness of measurement results. The equation is satisfied if and only if the quantity has the form . In other words, the quantity must be *linear* and have a *natural zero*. That requirement was established for measurements by Maxwell. (Treatise, 1873) If a measurement result does not satisfy Cauchy's equation, it is doubtful that it can be used in subsequent modeling. For example, the common thermometer scales (Celsius and Fahrenheit) do not have a natural zero and are not useful in mathematics.

Definitional uncertainty	component of measurement uncertainty resulting from the finite amount of detail in the definition of a measurand NOTE 1 Definitional uncertainty is the practical minimum measurement uncertainty achievable in any measurement of a given measurand. NOTE 2 Any change in the descriptive detail leads to another definitional uncertainty. NOTE 3 In the GUM:1995, D.3.4, and in IEC 60359, the concept 'definitional uncertainty' is termed "intrinsic uncertainty".	VIM	In the GUM (2008), several kinds of definitional uncertainty are listed. The first three are a) incomplete definition of the measurand. b) imperfect realization of the definition of the measurand. c) nonrepresentative sampling — the sample measured may not represent the defined measurand. In the electric power system, the first of these is generally negligible, but the second is always present, (caused by signal distortion, for example) and can have important effects on results. The third kind of definitional uncertainty corresponds to the sort of signal distortion when there is a fault of the system. It can render results meaningless.
Direct measurement	Measurement of a single (observable) quantity		The measurement of a voltage or a current is a direct measurement. The term is applicable to most of the measurements associated with the measurement of quantities in the SI system of units.
Extensive quantity	A quantity that satisfies Cauchy's equation		An extensive quantity is one that can be physically combined with another such quantity and the result measured as the sum of the two.
Frequency	A term for a parameter in the mathematical representation of a periodic function		The term applies only to periodic functions, and they are the same over the range $-\infty < t < \infty$. That definition rules out anything in the real world, since real things have a finite start time. It is possible to write equations in which the parameter for frequency is made a function of the time, but then commonly used mathematics does not apply. The exponential notation is not applicable, for example. Measurement of changing quantities requires that the rate of change be a parameter of the measurement model (see the GUM). If this is done for frequency, the results for frequency and ROCOF apply only to the measurement window. A value that can be thought of as instantaneous frequency can be obtained by evaluating the measurement model with these parameters, at some instant of time.
Indirect measurement	Measurement in which several quantities are involved.		The quantities involved may be related by a *measurement model* (*qv*). In that case, the measurement is

			representational (*qv*). The model is a representation of the way the various quantities interact. The model is the *definition of the measurand*. If the output quantity cannot be related to the input by a model, the operations that are performed for the measurement must be defined instead. Such a measurement is called *operational*. Most power system measurements are largely operational because their models are based on the (untrue) assumption of signals that are well-represented by mathematical sinusoids. Operational constraints are therefore applied to reduce the effect of definitional uncertainty (*qv*).
Measurand	quantity intended to be measured NOTE 1 The specification of a measurand requires knowledge of the kind of quantity, description of the state of the phenomenon, body, or substance carrying the quantity, including any relevant component, and the chemical entities involved. NOTE 2 In the second edition of the VIM and in IEC 60050-300:2001, the measurand is defined as the "particular quantity subject to measurement". NOTE 3 The measurement, including the measuring system and the conditions under which the measurement is carried out, might change the phenomenon, body, or substance such that the quantity being measured may differ from the measurand as defined. In this case, adequate correction is necessary. EXAMPLE 1 The potential difference between the terminals of a battery may decrease when using a voltmeter with a significant internal conductance to perform the measurement. The open-circuit potential	VIM	The measurand is the thing one hopes to be measuring, OK. But now recall the little humor about "is" in the introduction to this glossary. The VIM definition uses the word "measured." It defines that as simple a matter of assigning numbers to a quantity, but it knows that for an indirect measurement the *definition* of the measurand is all-important, because that definition is a mathematical one, and the process of measuring as an indirect measurement will give parameters of the *definition.* If the definition is not complete, for example, some temperature effect has been overlooked, the result will suffer from inaccuracies attributable to definitional uncertainty (*qv*).

	difference can be calculated from the internal resistances of the battery and the voltmeter. EXAMPLE 2 The length of a steel rod in equilibrium with the ambient Celsius temperature of 23 °C will be different from the length at the specified temperature of 20°C, which is the measurand. In this case, a correction is necessary. NOTE 4 In chemistry, “analyte”, or the name of a substance or compound, are terms sometimes used for ‘measurand’. This usage is erroneous because these terms do not refer to quantities.		
Measurement	process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity NOTE 1 Measurement does not apply to nominal properties. NOTE 2 Measurement implies comparison of quantities or counting of entities. NOTE 3 Measurement presupposes a description of the quantity commensurate with the intended use of a measurement result, a measurement procedure, and a calibrated measuring system operating according to the specified measurement procedure, including the measurement conditions.	VIM	Comment (1) Stevens (1946) wrote a seminal paper about number scales. That has influenced measurement in important ways. He identified four scales, and their properties • Nominal • Ordinal • Interval • Rational A Nominal scale is nothing more than a name: the number of a football player’s jersey, for example. An Ordinal scale puts things in order: the Mohs hardness scale for mineral, for example. But the difference between hardness 3 and 4 bears no knowable relationship to the hardness difference between 4 and 5. An Interval scale solves the problem of *relative* differences. The common temperature scales are Interval scales. A Rational scale is called that because it allows the numbers to be used in taking ratios. A measured quantity that satisfies Cauchy’s equation (*qv*) is on a Rational scale, and the value can be used in downstream modeling. Comment (2) A “measurement” is a process. The word is sometimes used loosely to mean the *result* of a measurement. Such use can be confusing.

Measurement model	mathematical relation among all quantities known to be involved in a measurement NOTE 1 A general form of a measurement model is the equation $h(Y, X_1, \ldots, X_n) = 0$, where Y, the output quantity in the measurement model, is the measurand, the quantity value of which is to be inferred from information about input quantities in the measurement model $X_1, \ldots, X_n$. NOTE 2 In more complex cases where there are two or more output quantities in a measurement model, the measurement model consists of more than one equation.	VIM	
Non-extensive quantity	A quantity that does not satisfy Cauchy's equation		A non-extensive quantity is one that cannot be physically combined with another in a meaningful way. Temperature on the Centigrade scale is an example. Such a quantity is not generally useful in subsequent mathematical modeling.
Operational	An indirect measurement (*qv*) that does not use a measurement model.		The idea of an indirect measurement means that there is more than one quantity involved. The idea of operational means that the way they interact is so complicated that nobody has figured out how to model the interactions. To an engineer or a scientist, that might be the end of the matter, but the world of industry might demand an answer. Hand (2004) says that the word "pragmatic" is sometimes a better description. One of the earliest pragmatic measurements was that of metal hardness, a value that effects the choice of materials in automobile engines Operational measurements are surprisingly common. Examples include gasoline octane, viscosity, permeability (of transformer laminations) and partial discharge. This kind of measurement ensures interoperability by means of a documentary standard.
Quantity	A property that can be expressed as a number times a reference.		The word is in the VIM, but the VIM allocates a large amount of space to it, too much for our needs. By saying it is a property, the VIM is saying that it is not the physical thing but the description that is the essence. Thus

			“length,” a conceptual thing, is a quantity.
Representational	An indirect measurement (*qv*) that is based on an equation called the “measurement model.”		Representational measurements are the “default” for engineers and scientists. Most power system measurements begin as representational measurements, but many operational constraints have to be applied to reduce the effect of definitional uncertainty (*qv*)
Result	The result of a measurement, also called the measurement result, and sometimes shorted to “measurement” is the value obtained by the process of measurement. Except in the case that the measurement is a direct measurement, and the physical quantity sampled for digitization, it is not the same as a “sample.”		A stream of results from an indirect measurement is not the same as a stream of samples. The result of the measurement is a conceptual quantity, not a physical one. While it may be appropriate to apply filtering to a stream of results from a direct measurement, to remove some unwanted effect (the result of a resonant vibration, for example) it is not clear that the same is true for the results of indirect measurements, where value variations may have more than one cause.
Sample	In measurement, a sample is a selection of some physical thing representing a measurand. A sample of blood may be removed from one’s arm. The recording made by a digital fault recorder may be a (not very representative) sample of the system voltage. A sample of voltage may be stored for a short time on a capacitor while the A/D converter works on it. The word is also used sometimes to indicate the digital value that is obtained by the A/D converter.		“Sample” is not another way of saying “measurement result.” In a measurement, the input quantities may be sampled at rates of thousands or millions per second. The measurement that uses those samples may produce results only a few times per second.
Sensor	element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured EXAMPLES Sensing coil of a platinum resistance thermometer, rotor of a turbine flow meter, Bourdon tube of a pressure gauge, float of a level-measuring instrument, photocell of a	VIM	

	spectrometer, thermotropic liquid crystal which changes color as a function of temperature. NOTE In some fields, the term "detector" is used for this concept.		
Type A evaluation	evaluation of a component of measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions NOTE 1 For various types of measurement conditions, see repeatability condition of measurement, intermediate precision condition of measurement, and reproducibility condition of measurement. NOTE 2 For information about statistical analysis, see e.g. the GUM:1995. NOTE 3 See also GUM:1995, 2.3.2, ISO 5725, ISO 13528, ISO/TS 21748, ISO 21749.	VIM	"Uncertainty" (defined below) is a number describing the dispersion of results. Therefore, it is a number that can be obtained only by repeating a measurement, and under controlled conditions. The accuracy with which the uncertainty itself can be estimated is increased by making more measurements, but the process is not linear, and the number of repetitions needed is not generally above about 30. It used to be that with this number of results to analyze, the uncertainty was described as the range of values that have a certain (specified) likelihood of containing the "true value." With the advent of the GUM, the idea of true value is deprecated, and with the use of statistical methods developed by Gosset (1908) the range is now said to be that which has a certain likelihood of containing the means of an infinite number of samples. Above about 6 repetitions, the Gosset range is smaller than the older method.
Type B evaluation	evaluation of a component of measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty EXAMPLES Evaluation based on information — associated with authoritative published quantity values, — associated with the quantity value of a certified reference material, — obtained from a calibration certificate, — about drift, — obtained from the accuracy class of a verified measuring instrument,	VIM	

	— obtained from limits deduced through personal experience. NOTE See also GUM:1995, 2.3.3.		
Uncertainty	non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used NOTE 1 Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated. NOTE 2 The parameter may be, for example, a standard deviation called standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, having a stated coverage probability. NOTE 3 Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information.	VIM	Uncertainty, and ways to evaluate it and express it are the subject of the GUM (2008). The purpose served by expressing the value along with the result of the measurement is to be a guide to whether the result is useable for some given purpose. Uncertainty, in metrology, is a number that combines information from experimental testing and from evaluating the measurement model. The experimental testing is done under conditions in which the measurand is held constant and the definitional uncertainty is carefully made negligibly small. Since that condition does not apply in the real power system, the uncertainty number thereby obtained does not apply to the result of “field” measurement. The uncertainty of a measurement in the field cannot be obtained because a repeated measurement is likely to give a changed result because the measurand value has changed between measurements.

	NOTE 4 In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.		

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Appendix B – The Gap in Measurement

B.1 Introduction

On 20th May 1875, the metric system was adopted by 17 countries (including the USA) with the signing of the *Convention du Mètre* (the Convention of the Meter). The size of the meter and the kilogram were established by agreement, and "prototypes" of these quantities were made and kept for reference in Paris. An enlarged collection of quantities became known as the International System of units (SI) in 1960.

On the 20th May 2019, some fundamental units defined in the SI were redefined, fixed by quantum physical constants. Of particular importance was the change to the definition of the kilogram, which had originally been defined by a physical artifact, the International Prototype of the Kilogram, or "*Le Grand K.*"

The change became effective and was commemorated on the opening day of a meeting of the IEEE Instrumentation and Measurement Society, being held in Auckland, New Zealand. One can be certain that all the delegates to that meeting were aware of the change and its significance.

One can be almost as sure that very few engineers outside of the community of measurements were aware anything had changed.

That difference in awareness is not particularly important *per se*, but it highlights a significant gap, one of many that exist between the measurement community and other branches of science and engineering. There is a gap in education, and that has led to a gap in understanding. That, in turn, has led to an important gap in the way the process of measurement is perceived, and what the result of the process signifies. Because of that, in the community of power engineers, the way we evaluate the quality of a measurement in the field is mostly unfit for purpose. That is not well-known, and not at all good to know, but it is nevertheless an accurate assessment.

The shorthand description is that we all have our own silos.

Most engineers—it would not be an overstatement to say almost all—regard measurement as the simple act of finding a value for some quantity. The physical existence of the measurand is not questioned. One uses a transducer or sensor of some kind to get the quantity of interest into a manageable form, such as an electrical signal, and then simply finds out how much of it there is.

That interpretation of measurement is too simplistic. And it matters. It may not matter that one is unaware of the way a kilogram is defined, but it does matter that one has an appropriate sense of the process we call measurement. Most of us expect the result to be accurate and meaningful, and seem surprised when it is not. And the expectation that the things we measure *must* exist is absolutely wrong.

The very organism that is electrical engineering is not healthy. An important part is not functioning properly.

The general misperception by power engineers of what measurement is has meant that inconsistencies in measured results have gone unresolved for over a century. Concepts that are in fact no more than vaguely expressed ideas abound. Quantities of major importance in the electric power system are affected: the measurement of reactive power, power factor and even apparent power have been argued over, sometimes almost violently, for over a hundred years. And the meaning of these quantities is not agreed to even today. Distortion power, a physical and mathematical impossibility[38], is accepted as real. Our supposedly resilient power system must be regarded as imperiled.

For the most part, the complicated activity of measurement passes unnoticed. As an example, consider the *Sensing and Measurement Technology Roadmap* published by the Grid Modernization Laboratory Consortium in 2019[39]. Recognizing an aim of the Department of Energy to oversee work toward a secure and reliable future electric supply, it outlined a number of areas in sensing and measurement that, it considered, should be on the DOE radar. The emphasis was solidly on sensors.

According to the International Vocabulary of Metrology ("the VIM")[40] a sensor is an "element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured." The VIM provides examples including the sensing coil of a platinum resistance thermometer, and the Bourdon tube of a pressure gauge. The Sensing and Measurement Technology Roadmap considered such things as tilt sensors and temperature sensors, some based on advanced materials. There was interest in aspects such as cost and power consumption.

In the GMLC Roadmap, while the word *measurement* was used many times, it was most often part of the phrase "sensing and measurement." No attention was paid to the activity we call measurement, and no mention made of Measurement Theory: "Many sensing and measurement technologies already exist and are widely deployed across the electric power system." One can interpret that sentence to imply that the authors expect the reader to know that the sensor got the quantity into manageable form, and the measurement was simply done.

Measurement is not instrumentation. Measurement is not sensing. This first major section of this Appendix explores and explains the societal gap in understanding of *measurement*. It begins by demonstrating the problem and concludes by outlining theoretical aspects of the solution that are not likely to be familiar to the reader.

B.2 Measurement: The Problem

Rather than attempt to teach measurement theory as a textbook might, we begin instead by demonstrating the existence of an understanding gap by examining one important symptom. Once that is established, we will examine the various things that constitute the gap, and that allow for the existence of this and many other symptoms.

The example symptom has three aspects that are widely (and incorrectly) believed:

1. Things that we measure in the power system all have physical existence.

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[38] Kirkham, H., A.E. Emanuel, M. Albu, and D. Laverty. 2019. "Resolving the reactive power question." Proc International Instrumentation and Measurement Conference. Auckland, New Zealand.

[39] Rizy, D.T., and P. Ohodnicki. 2019. Sensing and Measurement Technology Roadmap. Washington, DC: US DOE.

[40] Joint Committee for Guides in Metrology 200. 2012. International vocabulary of metrology – Basic and general concepts and associated terms. Paris: BIPM.

2. To be measured these things must be properly defined.
3. Once defined, a quantity can be accurately measured by a good instrument.

Let us examine each of these in turn.

B.2.1 Physical Existence

The VIM provides an immediate negation to the first of these aspects. The VIM defines many words of interest in measurement, one of which is measurement: “process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity.” That seems clear enough.

The VIM also defines quantity. While the meaning of “quantity” might seem obvious, it is not: “property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference.” A quantity is a *property*. It is not an amount of “stuff.”

“Quantity” is described in the VIM text as a *generic concept*. The generic concept of length might apply to the radius of a circle, or the wavelength of the sodium D radiation.

These meanings are not different from the normal use of the terms, but they seem to be. That is because most of us have come to associate “quantity” with “amount of stuff.” Length, weight and so on are, nevertheless conceptual things, things conceived, things you can hold in your mind. Length is one kind of concept, a specific property of interest. One does not need to have a ruler or a piece of paper to visualize measuring the length of a line drawn on that paper. An ordinary table is associated with the properties length, width, height and weight. These can all be measured; in the case of a table they can be measured by very ordinary means.

The result of a measurement is a number, and it applies not to the physical entity involved, but to a *model* of that entity. Sometimes the model is very simple, and sometimes not. To give some solidity to the matter, consider what takes place in a digital voltmeter. Ignoring the details of scaling and filtering at the front-end, we can visualize that the A/D converter operates on a sample of the physical signal that has been “held” for the purpose, by storing it on a capacitor. The A/D converter produces a digital representation, likely in binary form. That binary number is the result of the measurement made by the A/D converter. It is the same as the voltage on the capacitor, only now it is in symbolic form. To be sure, the binary numbers are represented as the states of some transistors, and therefore a physical representation of the binary value exists, but the value is now available to take part in mathematics. The A/D converter makes a *direct* measurement, a measurement of a single observable thing.

Now, suppose the voltmeter is set to read volts dc. To do that, it takes a large number of these direct measurements, and produces an average value. In other words, there is a model of what the measurement is—it is the steady value of the average. We almost always say “The voltage is 400 volts” if that is the average value of our dc supply. But that is a shorthand way of saying what the result really means: “If the signal is well represented by a steady value, its value would be 400 volts.

And that shorthand way of thinking about the result of a measurement has led to the third mistaken idea about measurement. But first, let’s look at the second aspect of our understanding gap: that to be measured something has first to be defined.

B.2.2 A Measurement Needs a Definition

Thinking that something must be defined before it can be measured is a perfectly logical and understandable thing to do. It is almost as if the idea was part of our DNA, it seems so natural. How else would we know if our measurement was any good if we did not know what we were measuring?

Perhaps the most straightforward way to explain is to give a counter example. Suppose you want to measure the hardness of a piece of steel. Hardness is a roughly understood concept, and there must exist a measurable property we could call hardness. There is.

To measure the hardness of the steel sample, you place it in a machine that applies a force to it through a specially shaped diamond probe. It is called an indenter, for reasons we shall see in a moment. At first, a small force is applied, that takes all the slack out of the machinery. Then the force is increased to some specified value and released. You examine the dent and measure its size. Knowing the size of the dent, you can calculate the hardness of the metal. It is a dimensionless number.

At the end of the test, you know the hardness of the metal, but you cannot define the quantity. What you have defined is the method of testing, not the quantity being measured.

Suppose you were interested in reducing the knocking noise that sometimes occurred in the engine of your car. You determine that the noise is due to pre-ignition of the fuel, and you want to find a better fuel. You decide to compare the fuel you have with some other fuel, but you want to standardize the process, so it is repeatable and consistent. You build a special engine, whose operating temperature is monitored, whose oil flow is monitored, and whose speed is carefully controlled. You can even adjust the timing and the compression ratio while the engine is running. For a reference fuel, you decide to use a mixture of heptane (C7H16) which has terrible knocking problems and iso-octane (C8H18) which is much better. You adjust the compression ratio or the timing and listen for the knocking noise when you use your usual fuel. Then, leaving the settings alone, you substitute heptane, and gradually increase the percentage of octane until you get the same level of knocking. That percentage is what you call the octane number for your fuel.

At the end of the test, you know the octane number of your fuel, but you know little about knocking, or what makes a real fuel better or worse. Your definition of the quality of the fuel is based on the method used for comparison with a reference. What you have defined is the method of testing, not the quantity being measured.

Measurements that are based on defining a method (rather than a property) are called *operational* or *pragmatic* methods. The name operational comes from the notion that it is the operations performed in the process of measurement that have to be defined. There are many such methods in use all around us. Blood pressure, food calories, atmospheric temperature, viscosity are just a few examples. In electrical engineering magnetic permeability and partial discharge are examples.

Some measurements are based on a definition, but it is found that, in practice, the definition is inadequate. When this circumstance is recognized, *operational constraints* are added to the measurement process.

When the circumstance is not recognized, endless arguments take place about the "proper" definition of what is being measured. That is what happened to the measurements of reactive power, power factor and apparent power. The arguments continue, though the work of revising the relevant standard (IEEE Std 1459) will improve matters considerably.

B.2.3 A Good Instrument Will Always Give a Good Result

The waveform below was obtained from the output of a dc/dc converter designed to produce 400 V output. The desired output was a flat line at 400 Volts, but there was some instability in the controller.

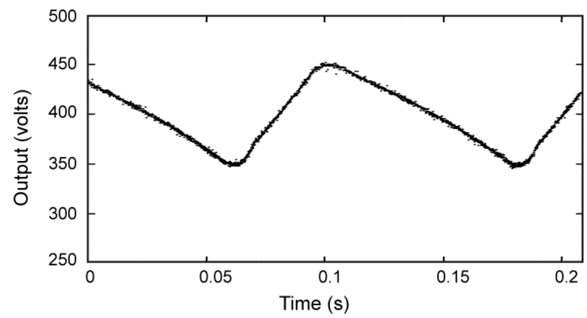

Figure B-1 Output of 400-V dc/dc converter

The waveform was digitized and averaged for a long enough period that the voltmeter was able to say that the voltage was 400.00 volts. The problem was not revealed until an oscilloscope was used.

Whether that 400 Volts result is an "accurate" reading is a matter of opinion. Certainly, the output average was 400 volts. But those numbers would scarcely have told the whole story. Had the voltmeter been set to Volts ac, it might have indicated about 30 volts, assuming that the dc component was blocked from being measured. The rms value was not measured but would likely have been about 430 volts.

These various problems arise because the actual signal does not match the model. That is a routine situation in the power system, because the model is usually that the world is linear, time invariant, and the voltages and currents are well-represented by sinusoids. (The shorthand expression would be that they "are" sinusoids, but the longer version is correct.)

The difference between the model and the reality produces what is known as *definitional uncertainty*. The model is, in fact, a mathematical representation of the quantity to be measured, and if the signal is not well-represented by that, the result can be in error by an amount that depends on the kind of measurement and the amount of the difference.

That leads to consideration of the second aspect of the mistakes commonly made about measurement, that once a thing has been defined, it can be measured or, conversely, that a thing cannot be measured unless it is first defined.

Appendix C – Uncertainty

C.1 Introduction

The quality of a measurement is often expressed by a statement of uncertainty. You may sometimes see a wording like this: “The accuracy is plus/minus 1%.” The impression is sometimes given that the statement is a description of some aspect of the instrument making the measurement. It’s this impression that makes you think you will get a “good” result from a “good” instrument. Now, it may be true that you will rarely get a good result from a bad instrument. But power engineers[41] very often have faith that a good instrument will give a good result. After all, that is implied in the owner’s manual, where it says “Accuracy: 0.5% ±1 digit.”

The International Bureau of Weights and Measures (BIPM) knows that a measurement result that is not accompanied by some indication of how much trust can be placed in the value is not very useful. In 2008, they issued a Guide to help clarify and unify the topic, the Guide to the Expression of Uncertainty in Measurement, a document known as “the GUM.”[42] Here are the opening words of the GUM, in Section 0.1:

> When reporting the result of a measurement of a physical quantity, it is obligatory that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability. Without such an indication, measurement results cannot be compared, either among themselves or with reference values given in a specification or standard.

And, in Section 3.1.2:

> In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate.

How, then, should we calculate the uncertainty of our results in the power system?

C.2 How to Calculate Uncertainty

A small book by a metrologist W.J. (Jack) Youden of the US National Bureau of Standards[43] is an excellent reference for really understanding the fundamentals.[44] Youden shows how repeating a measurement under conditions that are ideally the same nevertheless gives results that exhibit differences. He uses as one example a set of data that were obtained by having a class of 24 students make multiple measurements of the thickness of paper. There are 95 data points (one obvious outlier was rejected). Later in the book, the normal distribution is introduced, and the results of these repeated measurement are used to get an estimate (s) for the value of σ, the standard deviation. He remarks that, “In order to get a really satisfactory estimate of s we

[41] We are not intending to pick on power engineers. But they are our colleagues and our community, the people we know the most about. They are also, of course, the people of most relevance to the present report.
[42] Joint Committee for Guides in Metrology, WG 1. 2008. GUM: Guide to the expression of uncertainty in measurement. BIPM.
[43] Renamed the National Institute of Standards and Technology in 1988.
[44] Youden, W.J. 1984. Experimentation and Measurement, NBS Special Publication 672. Washington, DC: National Burea of Standards.

like to have at least 30 measurements, but there are many experiments in which it is not possible to get this many."

The reader is probably familiar with this kind of work. Often the result is interpreted to mean that if future measurements are made, some given percentage of the results will lie within such-and-such value of the mean of the distribution of the results.

Thirty measurements seemed like too many to William Gosset, working for Guinness brewery at the end of the nineteenth century. His interest was in the crop yields of some of the things needed in the brewery, and an "observation" might require a year to make. Publishing under the pen-name "Student," in 1908 he showed how the required parameters could be estimated with fewer measurements.[45] Youden explains the method. (The reader interested in getting more detail, can find the book as a free download.)

But Student's method changes how the results should be interpreted. The "old" method of estimating uncertainty allowed one to imagine the percentage of future results that should lie about the mean value of the results, within some specified range. The method of Gosset allows one to work out how close the value of the average of the *actual* results from fewer measurements is to the value of the mean of a supposed infinite population of results. This method allows one to regard the result of the estimate as saying things like "based on results from these samples, there is a 95% probability that the infinite-population mean is within the specified range."

What is more, for more than about six measurements, Student's method gives a smaller range than the old method. Using a series of 32 random numbers, which are here labeled "voltage," one may calculate the results for the old method of finding the mean and the distribution, and Gosset's method. The results are given in Figure C-1.

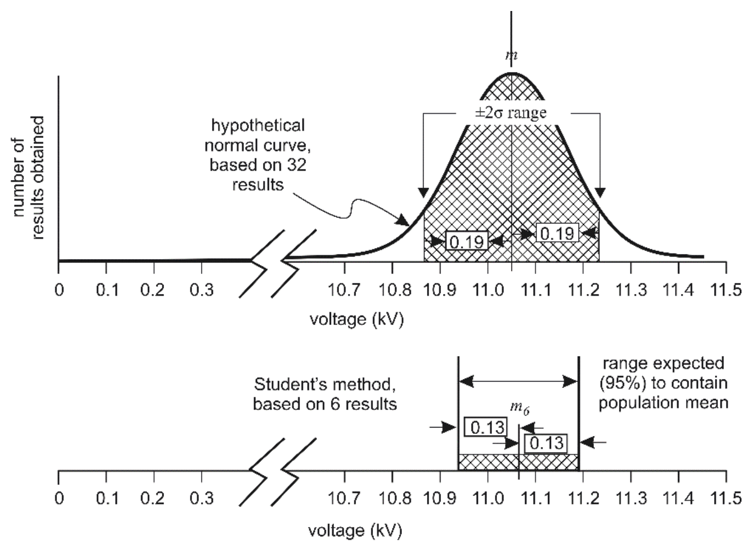

Figure C-1 "Old" method of characterizing data distribution compared to Student's method.

Gosset's method, developed for crop yields, is today routinely applied to the results of technical measurements. When instrumentation was analog, its performance was limited by such irritating

[45] Gosset, W.S."Student". 1908. "The Probable Error of a Mean." Biometrika 6 (1): 1-25. doi:10.1093/biomet/6.1.1.

matters as bearing friction, charge accumulated on the glass of the indicating meter, and dust in the airgap of the magnet. Contact resistance might affect the result, and for some measurements so could small temperature differences between different materials. It used to be routine to make repeated measurements to be sure one was getting a consistent result.

In those days when reading depended on the position of a pointer, even the matter of reading the position of the needle against the scale was somewhat a matter of skill on the part of the individual using the instrument. It was known that taking the average of the results of repeated measurements would have the effect of reducing the impact of various disturbing factors. It was vaguely understood that the reading on an instrument contained a certain amount of seeming randomness, and if these variations in the reading were truly random, their average value should be zero.

It became customary in the laboratory to repeat the measurement enough times that one had confidence that one was seeing some sort of truth. Robert Millikan did this in his famous oil-drop experiments, reported in 1913. Ten years later, he had the Nobel Prize. While his method of “selecting” results has come under criticism, it seems likely that he did no more and no less than we would have done, and threw out results where the oil-drop did not seem to follow the usual behavior pattern. He incorporated 58 data-points from experiments performed between February and April 1912.[46]

So, a culture of repeating measurements and reducing “random errors” arose. Probably most of the people reading this report were taught by people who grew up in this culture, and in that way the culture continues. In 1962, Youden published a paper in which he argued that “repeat measurements cannot reveal the vicissitudes of measurement making unless the operator gives the vicissitudes a chance to occur and exhibit their effects.” He showed ways based on experiment to combine results to reduce the effects of certain kinds of biases in instrumentation.[47] The culture was current in 1962, and still in 1984 when he published his book, it seems.

There is a problem, however, when it comes to the electric power system. The estimate of uncertainty is itself obtained by an operational process. The quantity is not defined *per se*, it is the method of measuring it that is defined. It relies on repeating the measurement. The possibility of repeating a measurement under the conditions required for the result to be useful just does not exist in the power system.

If one measures (say) the frequency for a few cycles, and then repeats the measurement, one expects to get a slightly different result. But one cannot attribute that difference to measurement uncertainty: the speed of the generators in the power system likely changed in response to some change in the load. The same argument applies to any parameter in the power system.

It follows that it is not possible to measure anything in the power system in such a way as to establish the uncertainty.

It is also very obvious that there will be uncertainty in the result of any measurement in the power system as a result of distortion on the signals. The idealized signals are represented by sinusoidal mathematics, but the real signals are distorted. The rms value, used with almost all measurements, will always reflect the presence of harmonics, changing the reading.

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[46] "August, 1913: Robert Millikan Reports His Oil Drop Results." APS News, August/September.
[47] Youden, W.J. 1962. "Realistic Estimates of Errors." Proceedings ISA Preprint 44.5.62: 44.5.62 1-4.

There exists uncertainty in the result of a measurement in the power system, and there is presently no way to know how large that uncertainty is.

Appendix D — Operational Measurements

Measurement results should be regarded as having conditional status: “If the measured quantities are well-represented by the model…”[48]. But sometimes the signals we observe in the power system cannot be treated with the simple models that we use to define our measurands. We must conclude from these considerations that a method of measurement that does not depend on a model must be used. These are the methods of pragmatic or operational measurements. The education gap that exists between the world of measurement and the world of power systems has meant that nobody on the power side of the gap knew that such methods even existed, and nobody on the measurement side knew that the need even existed.

Operational measurements are compared with representational measurements in Table D-1. It should be borne in mind, however, that many representational measurements have some operational aspects, so a “bright line” cannot be drawn between the two kinds of measurement.

Table D-1 Representational and Operational Measurement Compared

Representational	Operational
There is clear conceptual definition of measurand	There may be only a partial and unclear conceptual definition of measurand
Alternative methods nominally give the same result	No alternative method is guaranteed to give the same result. Alternative methods rarely defined
Measurand defined mathematically	Measurand defined by the measurement apparatus. Method frozen in time by standard
Cauchy’s relation applies (linear, natural zero)	Cauchy’s relation does not apply (nonlinear, arbitrary zero)
Measurements are (very nearly) one to one	Measurements usually many-to-one
Measurements applicable in mathematical models	Measurements not applicable in mathematical models
Measurements applicable for multiple purposes	Measurements often designed/suited for single purpose
Concept of true value is useful	There is no single true value
Amenable to uncertainty analysis by GUM methods	Results from all implementations are assumed accurate
Potential for long traceability chains to unit definition	Traceability might be to a standard reference material and a documentary standard

[48] Tal, E. 2016. "How Does Measuring Generate Evidence? The Problem of Observational Grounding." Journal of Physics: Conf. Ser. 772 (012001). doi:10.1088/1742-6596/772/1/012001.

Appendix E — **Distortion Power**

Distortion Power was invented by Constantin Budeanu in Bucharest, Romania in 1927[49]. Budeanu was aware that if the voltage or current wave was distorted, the measured values of apparent power, power and reactive power did not form a right-triangle. It must have seemed that they should, for Budeanu created distortion power to allow a version of the Pythagorean relation to apply. Few people have read his work in the original, and it is often cited as a paper written in Romanian. Perhaps such a paper exists—we have not been able to find it. The citation above is his book, written in French.

There are several problems with distortion power, beginning with the motivation to invent it. (The right- triangle is no more than a coincidence that applies only for sinusoidal waves.) There are two further problems with distortion power: (1) it defies some fundamental laws of physics (it moves power without changing the magnetic or electric fields in the area) , and (2) it uses some invalid mathematics (it reckons that a voltage at one frequency and a current of another can move power).

A recent paper explains all of these problems.[50] We will look at two of the issues briefly in this Appendix. Here is a copy of a paragraph on page 210 of Budeanu's book, including a minor typo (the article with the word for "exchange" is typeset feminine the second time it is used):

> Tandis que la puissance réactive correspond à un échange d'énergie *entre le circuit et le milieu extérieur formé par les champs électrostatiques et électromagnétiques* de sorte que cette énergie a une *valeur moyenne finie*, différente de o, la puissance déformante en phase correspond seulement à une échange d'énergie sur le circuit entre le *générateur* et le *récepteur*, de sorte que cette énergie a une valeur moyenne nulle.

In English, that paragraph could be written as follows:

> Whereas the reactive power corresponds to an exchange of energy *between the circuit and the external environment formed by the electrostatic and electromagnetic fields* so that this energy has a *non-zero finite average value*, distortion power in phase corresponds only to an exchange of energy on the

[49] Budeanu, C.L. 1927. "Puissances reactives et fictives." Instytut Romain de l'Energie (Instytut Romain de l'Energie). Filipski, P. 1989. "Power Components in a System with Sinusoidal and Nonsinusoidal Voltage and/or Currents." IEE

[50] Kirkham, H., A.E. Emanuel, M. Albu, and D. Laverty. 2019. "Resolving the reactive power question." Proc International Instrumentation and Measurement Conference. Auckland, New Zealand.

circuit between the *generator* and the *load*, so that this energy has a zero mean value.

In other words, distortion power has the required property of having a zero-mean value, but it also has the impossible property that it is not associated with an electric or magnetic field. It is an exchange of energy *seulement sur le circuit*—only on the circuit. Such a thing is not possible: it would invalidate the work of Ørsted, Faraday, Hertz, Maxwell, and Poynting at the very least.

Presumably, if distortion power affected, say, the magnetic field, it would have been observable, and since it was *not* observable, it must be operating without affecting the fields. The structure of the sentence—it is a compound sentence, used to establish contrast between the part after the comma and the part before it— signifies that Budeanu knew very well what he was saying.

One might remark that because it breaks the laws of physics, distortion power cannot exist. Perhaps that is a reasonable argument, but it should be borne in mind that measurements are often made of measurands that have no physical existence. Total Harmonic Distortion is such a quantity. The point is rather that the currents and voltages that supposedly enter into the calculation of Distortion Power do not exist. *They* cannot exist because voltages and currents are the fundamental observables of the power system and declaring them unobservable renders the whole concept invalid.

Nevertheless, distortion power has been granted the approval of the IEEE. It is part of standard 1459, which defines power quantities for the purposes of measurement. In the 2010 version of the standard an example is given in which the square of the apparent power on a load that has third, fifth and seventh harmonics in both voltage and current is developed as follows:

$$S^2 = V^2I^2 = (V_1^2 + V_3^2 + V_5^2 + V_7^2)(I_1^2 + I_3^2 + I_5^2 + I_7^2)$$

The definition of apparent power is indeed voltage times current, with both expressed as rms value, that is

$$S^2 = V^2I^2$$

In Standard 1459–2010 this is expanded, harmonic by harmonic.

$$S^2 = V_1^2\left(I_1^2 + I_3^2 + I_5^2 + I_7^2\right) + V_3^2\left(I_1^2 + I_3^2 + I_5^2 + I_7^2\right) + V_5^2\left(I_1^2 + I_3^2 + I_5^2 + I_7^2\right) + V_7^2(I_1^2 + I_3^2 + I_5^2 + I_7^2)$$

Though Standard 1459 takes a slightly different direction, this can be expanded and rearranged as follows,

$$\begin{aligned} S^2 = {} & V_1^2I_1^2 + V_3^2I_3^2 + V_5^2I_5^2 + V_7^2I_7^2 + V_1^2I_3^2 + V_1^2I_5^2 + V_1^2I_7^2 + V_3^2I_1^2 + V_3^2I_5^2 + V_3^2I_7^2 + V_5^2I_1^2 + V_5^2I_3^2 \\ & + V_5^2I_7^2 + V_7^2I_3^2 + V_7^2I_5^2 \end{aligned}$$

Apparent power is a value that assumes periodicity and applies as an average over a period or an integral number of periods. The product of a voltage at one frequency and a current at another is zero if averaged over their common period. In the case of harmonics, the common period is the fundamental.

It therefore follows that all the terms on the last line of the expansion above must vanish when the evaluation is done, leaving only

$$S^2 = S_1^2 + S_3^2 + s_5^2 + S_7^2$$

This means that the cross-products of voltage and current do not affect the value found for the apparent power. However, the standard derives, somewhat unexpectedly, the following:

$$S^2 = S_1^2 + S_3^2 + s_5^2 + S_7^2 + D_1^2 + D_V^2 + D_{37}^2 + D_{53}^2 + D_{57}^2 + D_{73}^2 + D_{75}^2$$

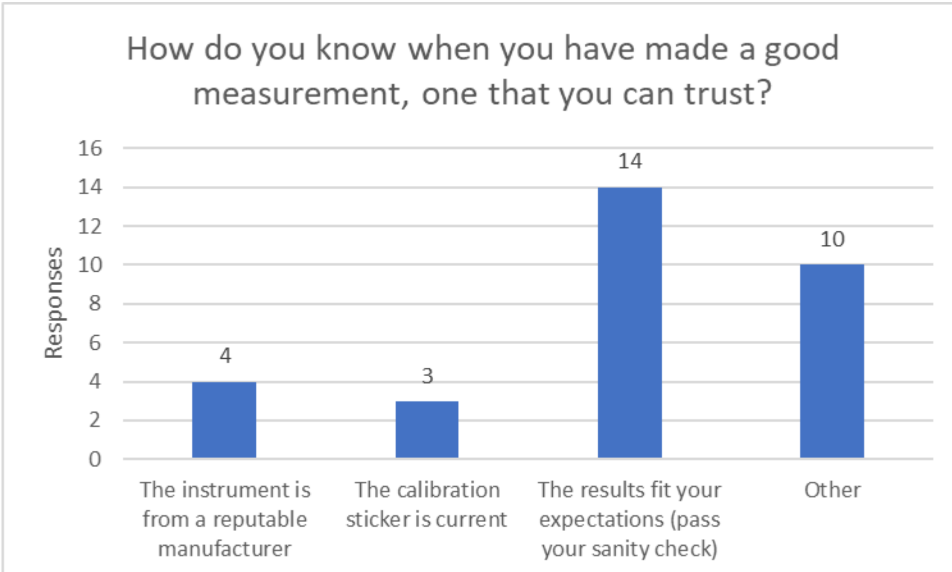
where the terms in D are the distortion powers, with current and voltage harmonics indicated by the subscripts. But the mathematics show that the contribution of Distortion Power disappears when the calculation is done over a period.

Terms involving such “cross-products” have appeared in other Power Theories and have been observed and criticized by other workers. A post-Budeanu example was pointed out as problematical even before the IEEE standard existed. The IEEE working group presently revising Std 1459 (about 40 people from around the world) are agreed that Distortion Power will be removed from the next revision of the standard.

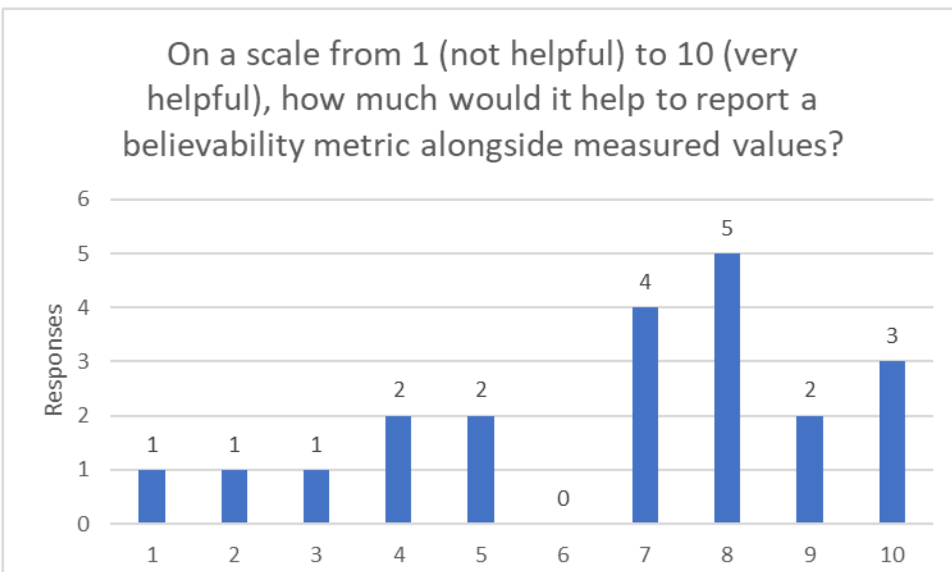
Appendix F — Webinar Questions

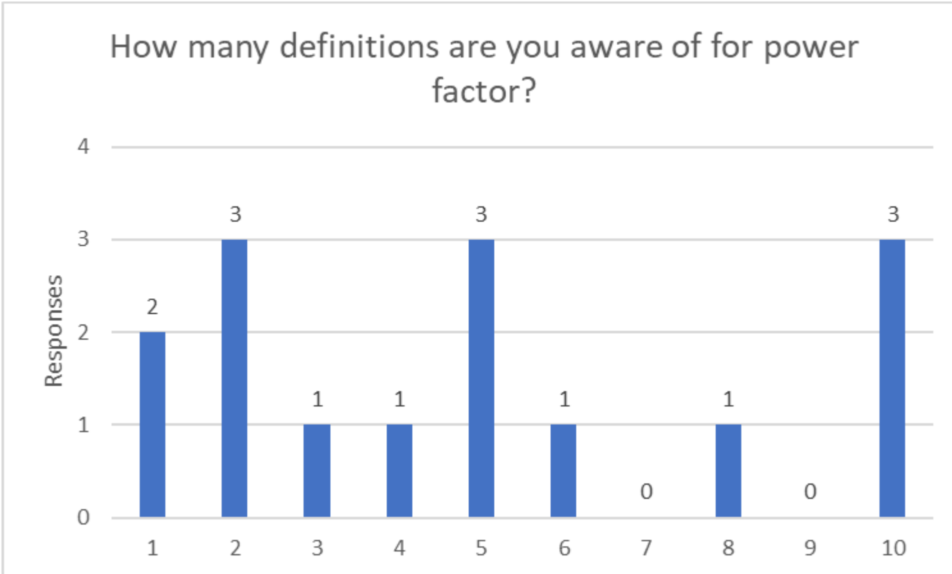
This appendix contains the raw results from the webinars PNNL hosted to receive input from stakeholders. The following subsections correspond to the sections of the webinars.

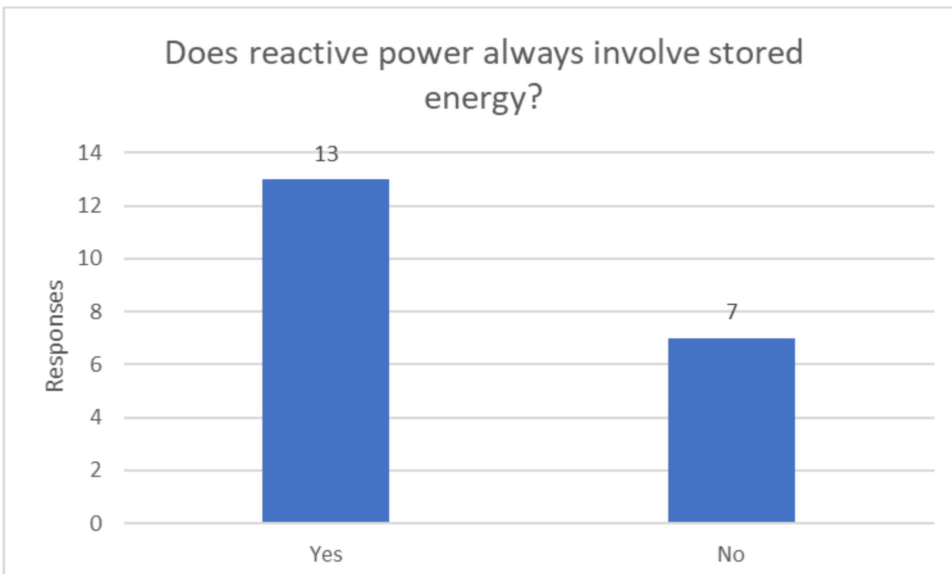
Measurement

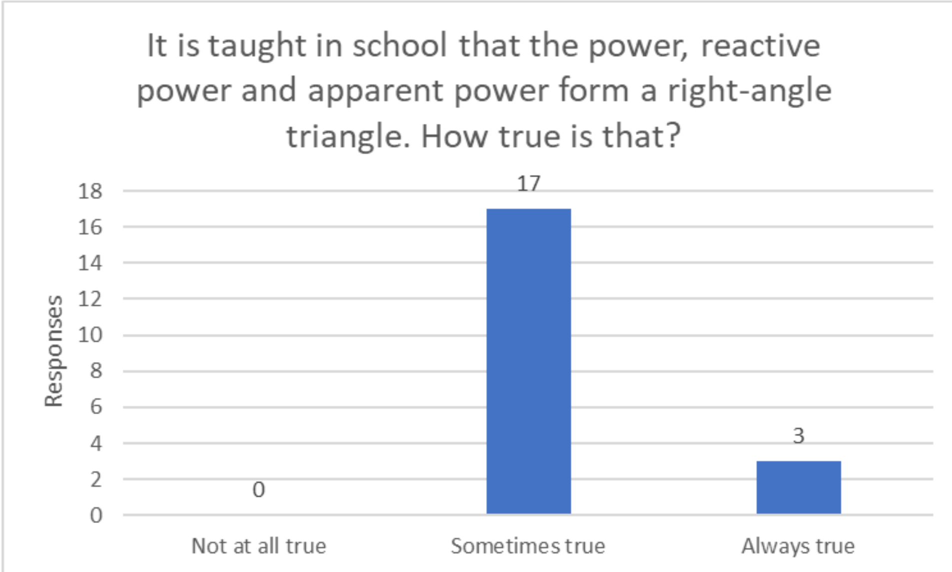


One participant that responded “Other” suggested that the instrument must meet a standard.

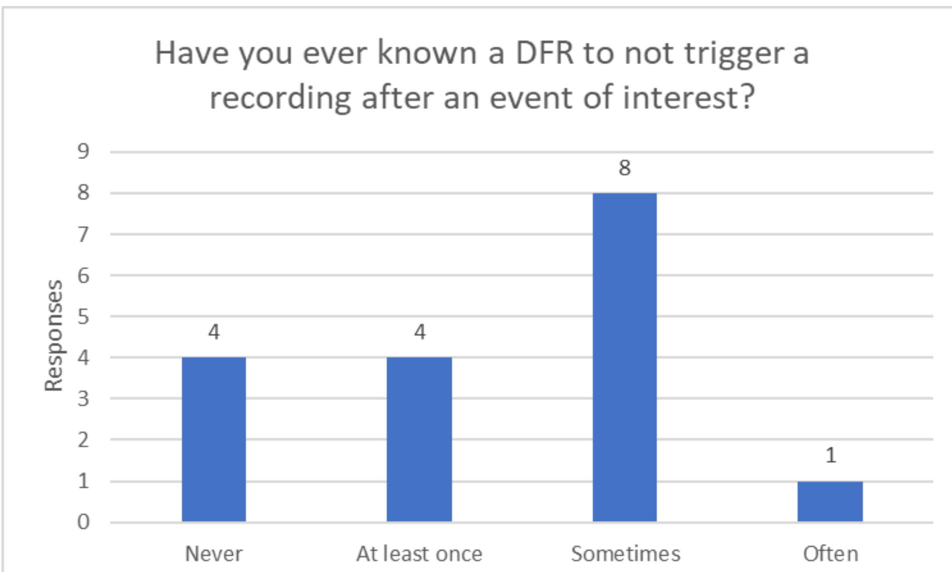


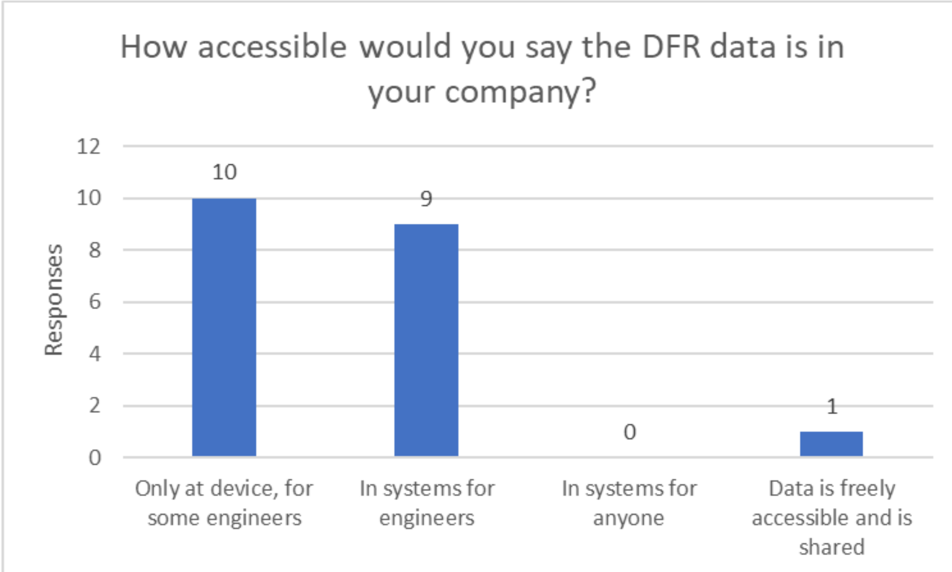

How many definitions are you aware of for power factor?
Responses
4
3
2
1
0
2
3
1
1
3
1
0
1
0
3
1
2
3
4
5
6
7
8
9
10

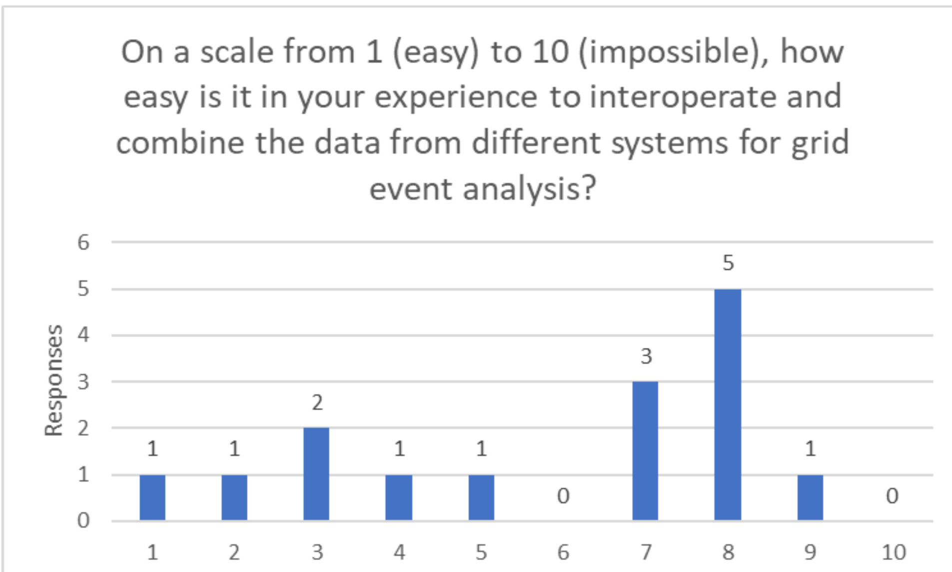

Does reactive power always involve stored energy?
Responses
14
12
10
8
6
4
2
0
13
7
Yes
No



Power Quality, Digital Fault Recorders, and Phasor Measurement Units



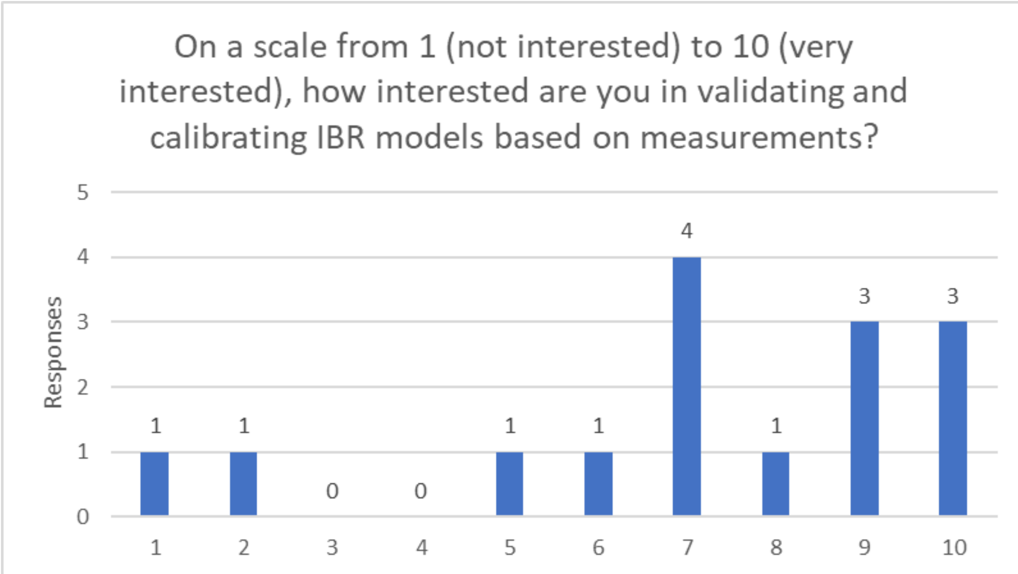


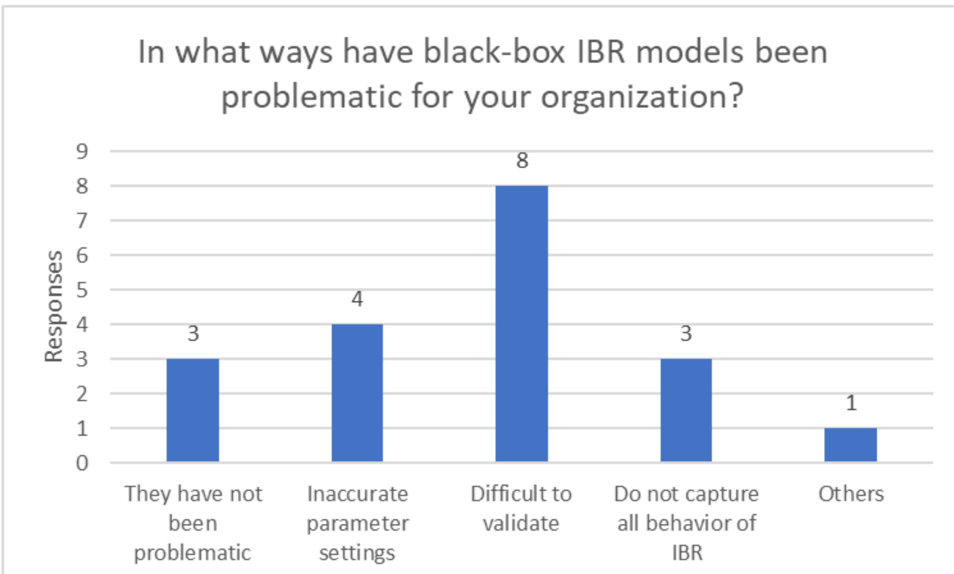


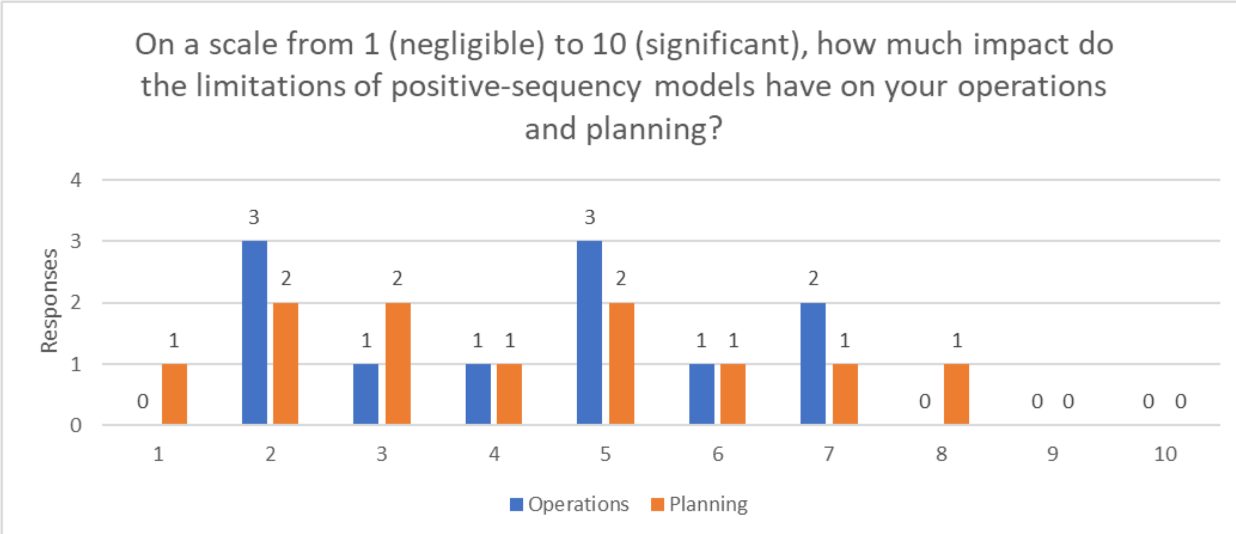
Discussion questions:

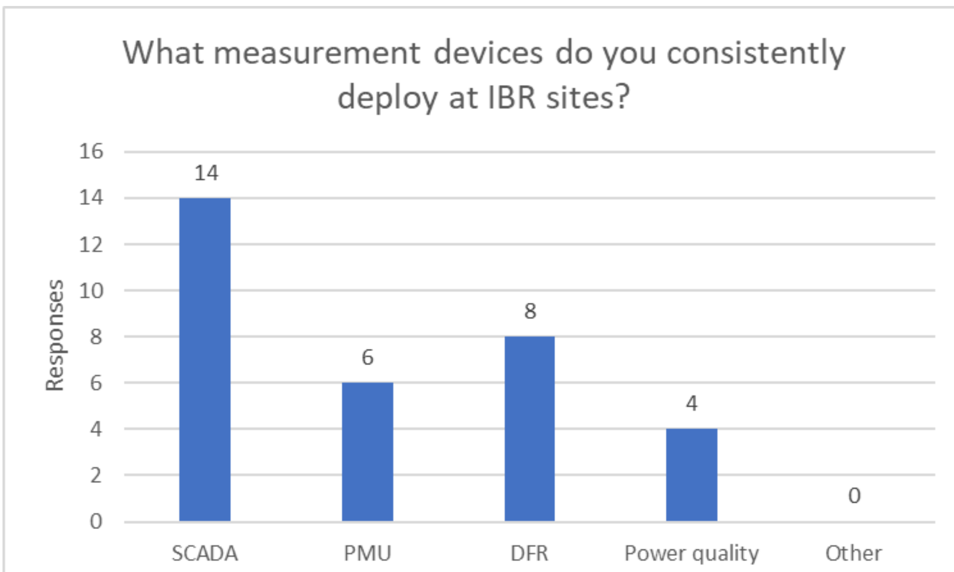
- What are creative ways that your organization has used power quality or digital fault recorder data?
- What are some potential ways that power quality or digital fault recorder data could be used?
- Do you see obstacles that don't allow power quality or digital fault recorder data to be used more extensively and universally?

Inverter-Based Resource Models



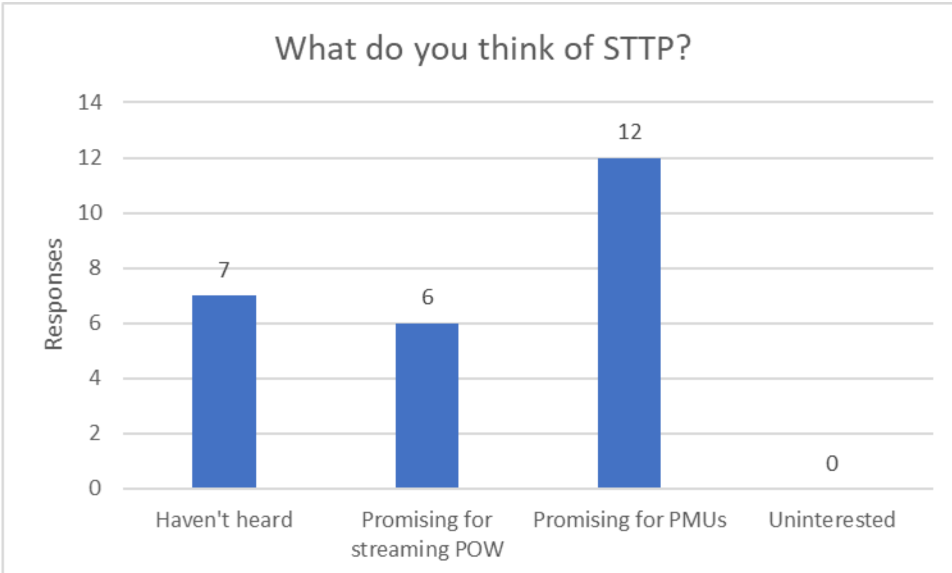


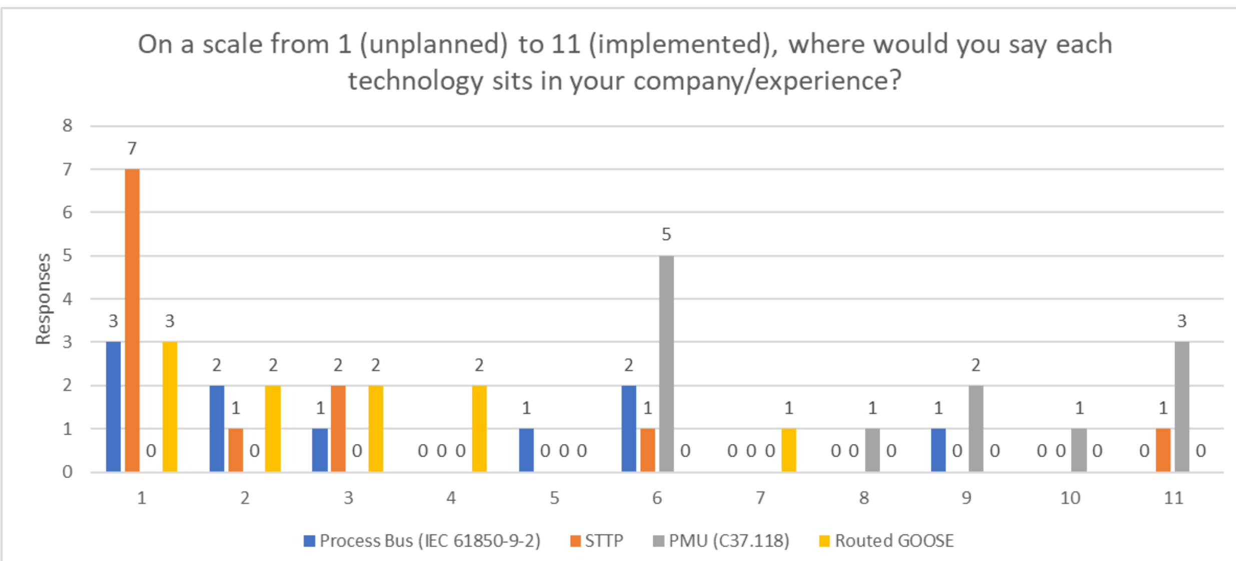


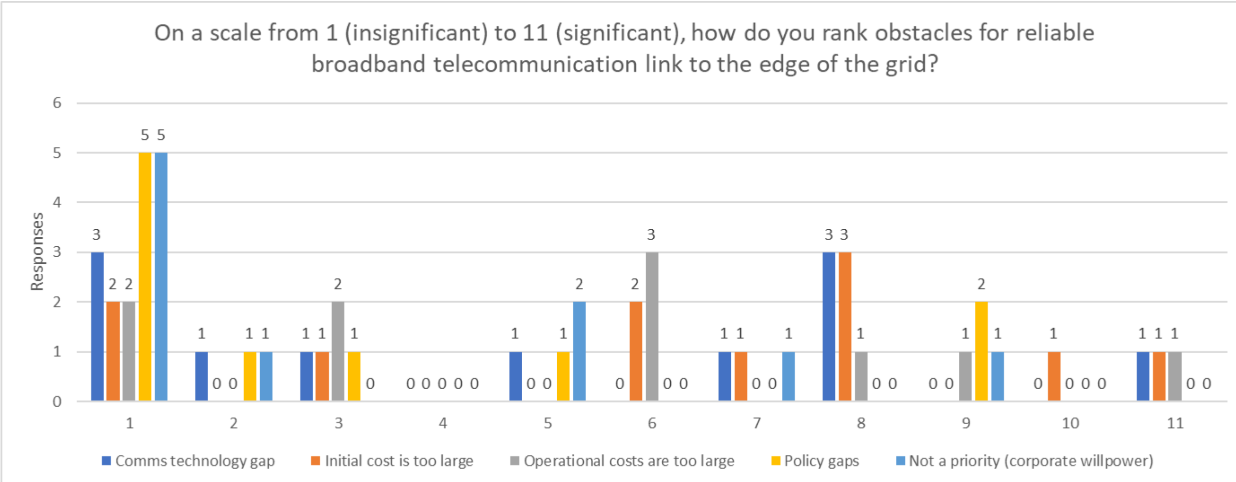


Discussion question: What new regulations, standards, or policies regarding inverter-based resource monitoring would you like to see?

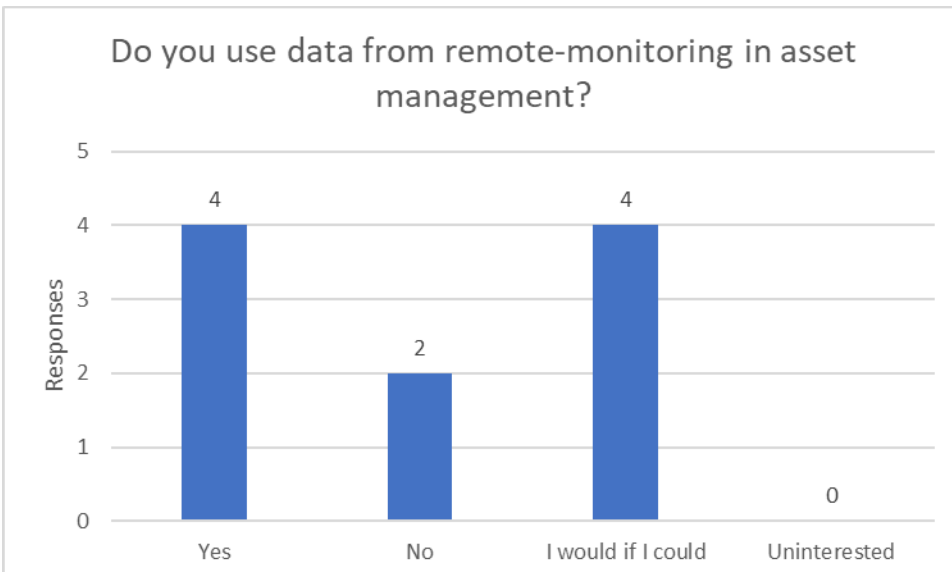
Communications

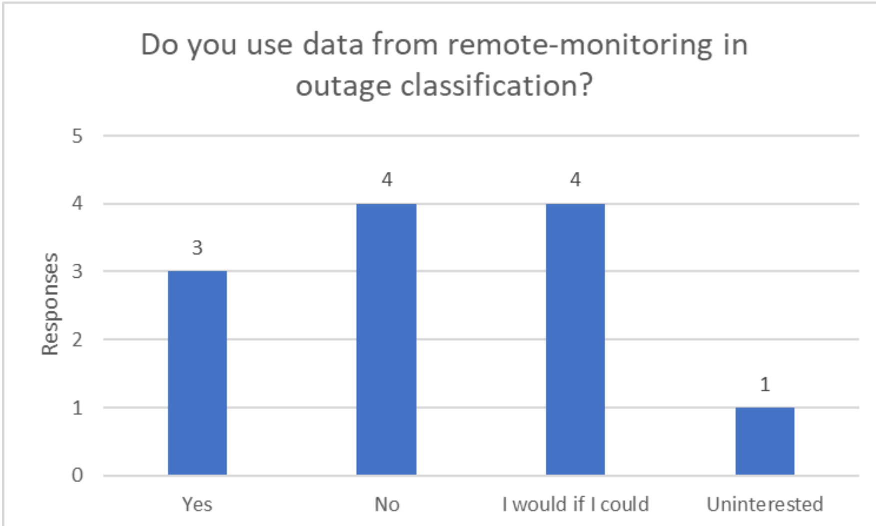


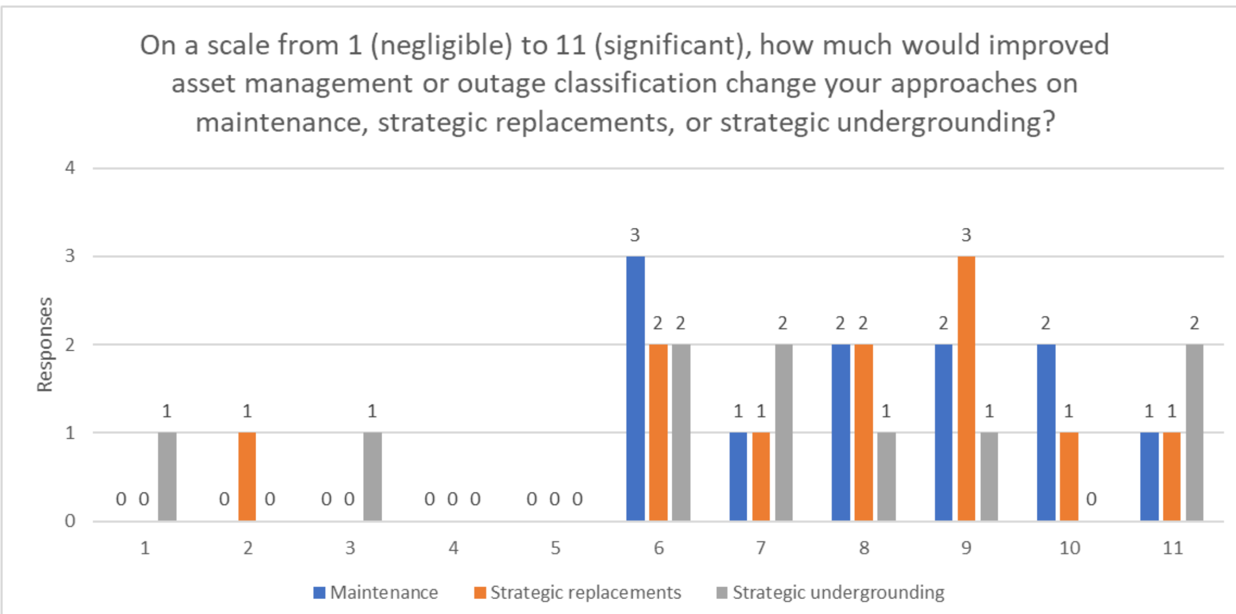




Asset Management and Outage Classification







What types of outages are most vulnerable for being misclassified because of missing/unreliable measurements?

- Common mode and dependent type of outages
- Lightning related
- Tree related
- Fuse failures
- Recloser failures
- Pole-top (distribution) transformer issues
- Intermittent line issues (especially during high-wind or storm conditions)
- Frequency excursions and voltage dips being mistaken as outages

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