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Limitations in Advanced Measurement Systems: An Overview for Power Systems

March 2023

Artis Riepnieks
Jim Follum
Kaveri Mahapatra
Kaustav Chatterjee

U.S. DEPARTMENT OF ENERGY

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Pacific Northwest National Laboratory
Richland, Washington 99354

Abstract

Measurements have been an essential part of managing the electric power system from the beginning. Surprisingly, today's measurements are not always particularly trustworthy. Countless factors can influence measurement in real-world conditions.

In this report, we look at the measurement system as a comprehensive information acquisition system with complicated interdependencies setting the limiting factors and affecting system performance. The first chapter provides an overview of the whole system and introduces the key elements of the limitations checklist. The second part of the document is a component checklist for measurement system limitations that concisely describes effects, common remedies, and underlying factors.

1.0 Introduction

The main purpose for any measurement is decision making – the need to understand the situation and inform the decision maker. Power systems are operated through countless decisions that need to be made, some from a split-second timeframe (protection), others over many years (planning). This large timespan drives the different sets of requirements for measurement systems.

Several considerations affect whether a measurement is fit for purpose. If it is not, the information provided by the measurement system is sub-optimal, and the decisions cannot be intentionally optimal. This document is meant to serve as a checklist for evaluating measurement system fitness for purpose. We consider the topic from the viewpoint of the instrument maker and the instrument user. We encourage systematic critique of the measurement process, results, and uses.

Overview of the Measurement Process

In order to identify measurement limitations and potential gaps in the measurement systems, we look at the entire measurement process. Any limiting factors and hidden assumptions can “propagate” through the process without the user realizing it, so interactions throughout the measurement process are considered as well. We focus on digital measurement devices because the advances in digital technology have made digital measurement affordable, and they have become the prevalent choice in the industry [1] [2].

Figure 1 depicts a generic digital measurement system with the measurement process shown at the center.

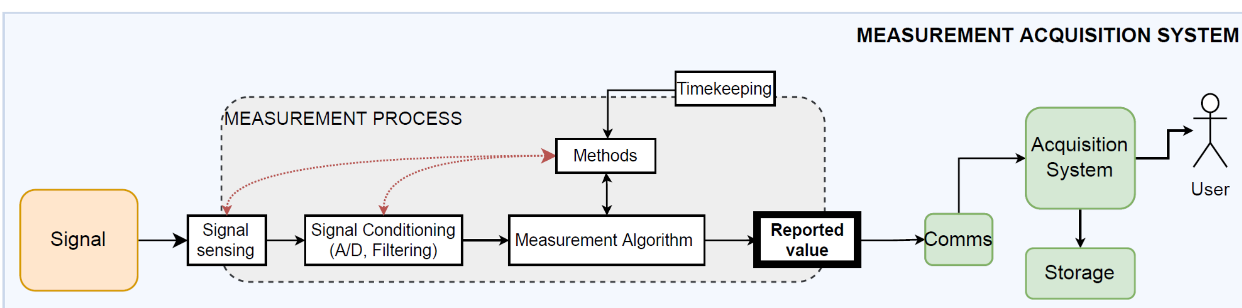

Figure 1. Measurement process block diagram

Each of the blocks identified in Figure 1 can impact the measurement directly and indirectly through assumptions made during the measurand[1] definition and the device design/installation process.

Measurement process breakdown:

- **Signal sensing:** The word “sensor” is applied to the part of a measuring system that is in contact with or exposed to the physical quantity being measured. Usually there are only two electrical observables within any power system: voltage and current. Voltage and current signals are usually isolated from the user by voltage/potential transformers (VTs or PTs) and

[1] Measurand — the quantity to be measured [10]

current transformers (CTs). Rogowski coils[1] are widely used as well. In the instrument itself only low-level signals are observed.

- **Signal conditioning:** The instrument converts the analog signal to a symbolic, digital form (a series of discrete values). This is the exact boundary between real-world (physical) signals and conceptual representation. After the analog-to-digital converter (A/D), measurement deals only with symbolic data[2].

- **Measurement algorithm:** The measurement algorithm may implement a measurement based in the mathematical representation of the voltage or current as a function of time. Usually, for sinusoidal signals, the sine function $X_A sin(\omega t + \varphi)$ is used. A measurement system such as a phasor measurement unit will report the values of the amplitude X_A, the frequency ω, and the phase offset φ (the value of the phase at time-zero). This measurand definition is called *representational* because it is based on *representing* the measurand. That is also a limitation, as the measurement system cannot report anything except the measurement model. For example, if the signals are not sinusoidal, the three values reported will not be a good representation of the signal.

  Other algorithms do not represent the observable signals; they merely operate on the signal is a predetermined way. The calculation of rms is an example. Such a measurement is called operational. Generally, operational measurements involve the loss of more information than representation, and it is practically impossible to have a physical interpretation of the result.

- **Methods:** In most cases, it is not enough to describe the measurement algorithm mathematically, and additional requirements must be defined to provide consistency for measurements. These may be regarded as operational overlays on the main measurement. As an example, it is important to define the period of the measurement window for most power system measurements.

The measurement acquisition system from Figure 1 is depicted as a simplified block diagram. The *signal* block represents the observable reality, and the *user* represents those making decisions based on the information. All the elements shown in Figure 1 are interdependent and should be considered as part of a system that is unique for each kind of measurement type and measurement device.

The measurement system depends on multiple other systems involved to deliver information to the user. Each system has its constraints that affect its usability. The most relevant are:

- The observed signal must be within the device parameter range in terms of amplitude and frequency in order to be meaningfully processed by the measurement system.

- The communication system must be capable of delivering all required information (bandwidth) without too much delay (latency).

- The data validation and presentation processes must process the measurements by performing meaningful operations (mathematically correct and physically sound). If the

[1] Unlike CTs, Rogowski coils do not provide secondary current proportional to applied current; instead a differential voltage is supplied.

[2] Note: mathematics is the processing of symbols, and it is simpler to implement in digital hardware than analog. It is important to keep separate in the mind the conceptual signal and the physical one. Further, any filtering (analog or digital) that is applied during the process is a one-directional operation that involves loss of information and introduction of operational limitations.

measurement is representational, the measurement model must be a validated one. For a variety of reasons, very few measurements in power systems have models that are validated except for sinusoidal representations. The data also must be presented in a contextually correct manner for it to have any meaning to the user.

- On most occasions, storage requires data compression, and that involves a tradeoff between storage space and information loss.
- In essence, the user applies measurement data to explicitly conceptual models. The signals from the field gain *meaning* only through these models. For example, a current *amplitude* value does not hold any particular meaning outside the power system model where it was measured for a specific purpose, say, use in a protection algorithm.

2.0 Measurement Limitation Evaluation Process

The checklist below is provided to help identify common sources of uncertainty, error, and assumptions that might occur in a digital measurement process. It is divided into major measurement-process blocks that are decomposed into specific topics and issues.

A user of the checklist can select the topic of interest and verify that the major concerns are addressed either by the measurement system developer or the system user. Throughout the table, a set of labels are used to indicate the effects of a consideration/limitation:

Frequency content: Directly affects how high-frequency content in the signal is processed and represented in the measurement system

Accuracy: Directly affects the accuracy of a measurement device

Measurement trust: Affects the trustworthiness of a measurement system's output by increasing uncertainty

High-speed reporting: Affects how fast the measurement can be made (measurement window length)

Availability: Affects the potential availability of measured data

End-to-end latency: Affects the full end-to-end responsiveness, including measurement system and communications system

End-to-end bandwidth: Affects the full end-to-end bandwidth, including measurement system and communications system

Device failure: Can cause critical measurement system malfunction or complete failure.

In addition to the checklist, which looks at more advanced issues, there are also a lot of generally applicable and sensible guidance practices that are valid for most digital measurement systems:

- ✓ Instruments should be verified for accuracy in laboratory conditions (check for any certificates from certification laboratories)
- ✓ Instruments should be calibrated (check last calibration date)
- ✓ Instruments should be selected by the necessary accuracy class (better performance than nameplate is unlikely)
- ✓ The instrument operating conditions/environment should be ensured to comply with the particular specification (nameplate parameters are valid only within operational and environmental limits for the specific device, e.g., temperature, humidity, input signal range, EMC environment, etc.)
- ✓ Damaged instruments must not be operated (check for signs of damage or failure)
- ✓ User errors are always possible and probable and should be avoided. Try to exclude human errors from measurement system processes through operating standards, process, and procedures, e.g., device installation, setting input, manual measurement reading, etc.
- ✓ Measurement settings within the device should account for likely operating conditions and reduce potential risks when possible. For example, correct filter settings should be used to avoid overloading the device or unintentionally removing valuable information from the signal.

3.0 Limitations Checklist

Table 1. Signal sensing/instrument transformers: general

Type	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
Environmental limitations Availability Device failure	For installations above 1000 m altitude, adjusted specifications and/or designs are needed.	Insulation failures, transformers may overheat	Inform the instrument maker to adjust the design and reduce the rating by 0.3% for every 100 meters above 1km	Rarified air has less cooling ability and reduced dielectric properties	[3]
Availability Device failure Accuracy	Temperature should be above -30C outdoors and -5C indoors (average 30C or 55C)	The manufacturer indicated accuracy is not usable. With high temperatures transformers overheat, and insulation degrades rapidly (both in too hot and too cold temperatures)	Transformer temperature control aspects in installation guides	With insufficient cooling or heating, instrument transformer falls out of specified accuracy range. Insulation may change its structure and lose dielectric properties.	[3]
Design limitations Accuracy Frequency content	Accuracy class and requirements are different for protection and metering instrument transformers	Measurement device connected to protection instrument transformer will have larger measurement uncertainty and can be outside its accuracy class operations	Use parallel metering current transformers for measurement purposes (with overcurrent protection)	Protection relays need to operate and sense extremely high currents; therefore, the range of a transformer is more important than accuracy at nominal conditions.	[3]
Frequency content	Individual frequency response correction curves are essential for accurate high-frequency (harmonic) measurements	Signal frequency content gets transformed differently for each frequency, with high amplification or attenuation at certain frequencies	Obtain instrument transformer frequency and impulse response curves to correct for the effects. Install high-frequency transformers with flat response for the range of interest.	Transformer windings resonate at some frequencies and amplify or attenuate certain resonance frequencies. The material and its dimensions determine the frequency response.	[4] [5]

Type	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
Operating limitations Accuracy	The instrument burden must be within the designated range	Adding another measurement device to pre-installed instrument transformers changes the measured values	Make sure the burden (transformers and all devices) does not exceed design limits. Changes should be made in device configurations to accommodate additional devices. Use correction curves for actual instrument burden on the circuit	Changing the electrical circuit by adding or removing devices changes its electrical parameters and directly affects secondary signals measured by measurement devices.	[6]
Accuracy	Instrument transformer characteristics are not perfectly linear	Measurements in a specific part of the range are significantly less accurate (measurements at the bottom of the range are usually less accurate)	Implement correction curves that are verified over a number of points within the range.	Transformers with magnetic cores can reach saturation or don't have enough signal strength to excite windings.	[6]
Accuracy	Transformer installed on a bent piece of conductor	Transformer's secondary signal is always offset	Install the instrument transformer on a straight portion of a conductor	A nearby electromagnetic field (like in an elbow bend of the conductor) induces currents within transformer windings affecting the output signal.	[6]
Accuracy	Routine accuracy checks are not implemented in the field	Transformer unknowingly falls out of the accuracy class	Perform routine accuracy checks e.g., as per standard IEEE C5713-2016	While instrument trans-formers are very stable in their operation, unexpected things may happen, e.g., damage (physical or electrical) that causes transformer to deteriorate.	[3]
Accuracy	Operation outside the nominal range increases measurement uncertainty	Large uncertainty for low- or high-level signals results in big measurement variance	Make sure the expected measurement range coincides with the instrument transformer range	Instrument transformers may not pick up very low signals (lower threshold) and saturate with high signals. Such measurements are unusable.	[4]

Table 2. Signal sensing/instrument transformers: CTs and VTs

Current transformers	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
Accuracy	Demagnetize core after switching operations	Residual "measurement" offset for all measurements	Demagnetize the instrument transformer core or identify and adjust it within the measurement device software.	Switching operations and large electromagnetic transient processes cause instrument transformer magnetization that increases the output signal	[6]
Device failure	Open circuits while in operation can damage the transformer	Permanent damage to the current transformer	Open current transformer circuits while not in operation (de-energized)	Open circuit causes a voltage spike that can damage the transformer	[6]
Accuracy	Rogowski coil designs are not measuring low-level current accurately	Low-level current levels are unmeasurable or have a large variance	Use an integrator coil to boost the signal or conventional current transformers for low-level current measurements.	Low-level currents can't induce enough potential difference in the coil.	[4]
Voltage transformers	***Limitation description***	***Effects***	***Common solutions***	***Underlying factors***	***Ref.***
Device failure	Short circuits while in operation can damage the transformer	Permanent damage to the voltage transformer	De-energize the system while handling voltage transformers	Short-circuiting voltage transformer leads cause short-circuit currents that can damage the transformer permanently	[6]
Device failure	CCVTs can interfere with protection during fast transients (including fast-acting IBRs)	Fast transients can cause unexpected measured values that can trigger protection mechanisms.	Tuned transformer circuit with linear frequency response around nominal frequency, outlier frequency filtering.	Interference usually is caused from artifacts of non-linear frequency and impulse responses in CCVT.	[6]
Accuracy Frequency content	CCVTs have a nonlinear frequency response	Higher and/or lower frequency signal content can be amplified or attenuated	Adjust the "tuning network" within the transformer circuit to get a flatter frequency	CCVTs by design contain capacitors and inductors, components that have non-flat frequency response.	[6]

		based on the frequency response	response around nominal frequency. Use of optical sensors may be considered.		
Accuracy **Frequency content**	Higher frequency signal content affected by transformer resonance (frequency and impulse response)	The higher the rated primary voltage, the lower the first resonance frequency	Use specific flat (or known) frequency response instrument transformer. Use frequency response plots to adjust for attenuation.	Resonant frequencies are determined by transformer geometry. 10kV transformer's first resonance is expected to be below 2kHz.	[4]

Table 3. Signal conditioning

Type	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
Design limitations Accuracy Frequency content Measurement trust	"Ringing" in filters	Impulses on measured power/voltage/current curves show as ringing on measurement system output	Better anti-alias filter	A fast-rise spike on the input signal effectively acts like an impulse and is not sufficiently attenuated by an anti-alias filter.	[7]
Frequency content	Filtering is not fit for installation. Not enough filtering.	Unexpected measurement results	Evaluate and validate filter properties against desired measurement applications	(*see definitional uncertainty limitation in the Measurement Algorithm table*)	[6]
Frequency content	Filtering is not fit for application. Too much filtering.	Unrepresentative measurement results. Unintentional loss of information from the signal.	Evaluate and validate filter properties against desired measurement applications. Consider signal transfer functions through all elements of the measurement system.	(*see definitional uncertainty limitation in the measurement Algorithm table*)	[6]
***note on measurement theory aspects** Frequency content Measurement trust	A/D conversion marks the boundary between the physical signal and the conceptual domain. It is not a perfect conversion and the link to reality may be limited.	Models do not represent reality well. The result is definitional uncertainty.	Proactive awareness of measurement systems and their limitations for measurement acquisition and output usability for various applications.	Engineers perform mathematical operations on conceptual domain signals and measurements as if it was reality. However, it is an imperfect representation of reality. Furthermore, with each sequential use of measured values, uncertainty is propagated.	

Table 4. Measurement algorithm: Operational measurements[1]

Type	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
Measurement trust	Measurement consistency issues	Instruments from different vendors give different results for the same observed signal.	Install measurement devices of the same device manufacturer.	Different designs will process a signal differently.	[8] [9]
Availability	Triggering criteria	Failures to trigger point-on-wave recording during system events	Fine-tune trigger levels or use continuous signal recording with sufficient buffer for accessing sampled data *pre-* and *post-factum*.	Triggers are measurements internal to the device and may not be perfectly suited to some applications.	

[1] Almost all measurements in the power system are of operational type. (The phasor measurement unit may be the only exception.) These measurements are based on performing a prescribed set of operations. Unfortunately, the operations have not been uniquely specified. For example, there are seven ways to measure power factor, and ten ways to measure reactive power [22]. These generally give incommensurate results if there is *any* distortion on the signals. Revised IEEE Standard 1459 aims to provide uniquely specified operations.

Table 5. Measurement algorithm: Representational measurements[1]

Type	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
Representational measurement limitations Measurement trust Accuracy	Definitional uncertainty[2]	Unexpected and even completely wrong measurement results, not representative of real happenings in the system	Address the sources of definition uncertainty: incomplete definition of measurand, imperfect realization of the definition, and nonrepresentative sample.[3]	Incomplete definition of measurand, imperfect realization of the definition, and nonrepresentative sampling	[10], [11]
	• Incomplete definition of the measurand[4]	*Not a common problem in power system work*	Awareness of what is the defined measurement model that the given measurement system measures.	Measurand defined mathematically with representation of sinewave	[10]
	• Imperfect realization of the definition of the measurand.	Measurements experience more variance and large uncertainty for measured values	Apply strict signal filtering or employ a trust or similar metric for indication of the condition	When signals representing voltage and current are extremely distorted, the measurement model is no longer a representation of	[10]

[1] The phasor measurement unit may be the only representational measurement instrument in the power system. It is based on a sinusoidal representation of the power system signals. This mathematical representation is the *measurement model.*

[2] In a representational measurement, the measurement model is the definition of what *will be* measured. In other words, the parameters of the model are the results of the measurement. Some aspects of the *actual signal* may not be included in the model. The result of that omission is *uncertainty* in the result. This uncertainty may arise because the definition is incomplete, or because the signal has unexpected properties. In the event of a fault on the power system, this uncertainty is large enough to render the result quite useless. Evaluation of the uncertainty of the measurement result (BIPM GUM [10]) is required for all representational measurements.

[3] "Sample" in this context does not refer to the sampling at the A/D converter, but to the particular stretch of signal being examined.

[4] The physical quantity, or property intended to be measured.

Type	Limitation description	Effects	Common solutions	Underlying factors	Ref.
				reality. Mismatch creates definitional uncertainty for the measured values	
	•Nonrepresentative sampling[1]	Measurements are completely wrong and shouldn't be trusted. IBR equipment wrongly measures low frequency and disconnects from the grid	Ride-through requirements when applicable and useful, or no-trust flagging operation (or similar).	During significant events (faults etc.) in power system, the voltage/current signals cannot be represented by sinewave (phase jumps, spikes, gaps etc.) and measurement model is useless.	[10], [12]
Measurement trust	Measurand definition limitations	Measured values do not represent reality.	Ensure that the intended measurand is included in the measurement model or it can be obtained indirectly (through valid mathematical operations)	Any measurement system is limited by its measurement model. If the parameter of interest is not included in the measurement model, measurement system cannot report it.	[10]
Measurement trust	Measurement consistency issues	Different vendor, same purpose devices for the same observed signal measures different values	Install measurement devices of the same device manufacturer. Utilize operationally defined standards, that standardize operations.	In presence of definitional uncertainty all operations performed throughout the measurement process directly affects	[13]

[1] "Sample" signifies the piece of the measurand selected for measurement

Type	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
				measurement outcome. Two filter designs will process a signal very differently in the presence of harmonics, DC, and other distortions.	
Availability	Triggering criteria	Failures to trigger point-on-wave recording during system events	Fine-tune trigger levels or use continuous signal recording with sufficient buffer, for accessing sampled data *post-factum*.	Triggers are internal measurements to the device and suspect to definitional uncertainty and measurement errors.	[14]

Table 5. Supporting systems dependencies

Type	*Limitation description*	*Effects*	*Common solutions*	*Underlying factors*	*Ref.*
Timekeeping systems Accuracy Availability High-speed reporting	Precision/accuracy and usability of the data	Measurement usability decreases with low synchronization precision and accuracy in measurement systems	Continuously verify time synchronization, use highly precise systems, such as GPS, for synchronization	Device component parameter drift, failures, software errors. Synchronization signal propagation issues, malicious actions from an adversary	[15] [16]
Availability	Availability	Synchronized measurement systems lose synchronism, measurements lack time-stamps	Back-up clock instrumentation to keep local time for time-stamping measurements	A common and precise time source is required from a system perspective to ensure synchronization. Loss of time reference or imprecisions cause loss of synchronism or knowledge of measurement time altogether.	[17]
Availability Device failure	Modes of failure	Malicious actors may influence grid applications through measurement systems	Multiple time sources, or countermeasures at system level	GPS time synchronization can be spoofed or otherwise maliciously impacted	[18]
Communications limitations End-to-end latency High-speed reporting	Latency	Information may arrive too late for it to be useful for an application	Troubleshooting communication networks for bottlenecks and upgrading communication systems.	It always takes time to transport information, depending on the specific technology (e.g., 5G, fiber optic or power line carrier), protocol (DNP-3, IEEE 2030.5 or OpenFMB), and device/network parameters.	[19]
End-to-end bandwidth High-speed reporting	Bandwidth	It is not possible to retrieve enough information from the source	Measurement system prioritization for communication system service.	Each communication system has its capacity for bandwidth, with low power radio or power line carrier	[19]

Type	Limitation description	Effects	Common solutions	Underlying factors	Ref.
			Troubleshooting communication networks for bottlenecks. Upgrading communication systems	being more limited. Ethernet and optical fiber technologies most often are enough for any number of measurements in power grid.	
High-speed reporting	Protocol	Protocols limit interoperability, information exchange speed (latency and bandwidth requirements)	Carefully choose a communications protocol that is fit for the purpose. For example IEEE 2030.5 has a large frame length and significant overhead that requires more bandwidth. PMU standard allows short frames with short UDP transport for lower bandwidth requirements and less strain on network latency and bandwidth.	Protocols are often developed with a specific purpose in mind and with interoperability with specific higher/lower layer protocols that affect the overall performance.	[20] [21]
Storage limitations Frequency content Availability	Compression	Part of the information contained in measurements is lost during data compression, e.g. high, frequency variance content that can get approximated or filtered out	Perform analysis on raw data, if possible, or take into account potential loss of information.	Different compression algorithms process information differently. One of the simplest compression approaches is to discard constant values in a time series. The definition of "constant" will determine the amount of lost information.	[14]
Frequency content Measurement trust	Semantic noise	Data coming from specific measurement systems can contain a specific variance or	Perform statistical analysis on data and make sure that	Different signal processing methods, measurement algorithms can cause the	[14]

Type	Limitation description	Effects	Common solutions	Underlying factors	Ref.
		noise signature in measured data	measurement systems are operating correctly within technical specifications	combined effects to result in “signature” (semantic noise) within the data.	
Availability	Data formats	Data is not interoperable outside the dataset or not accessible to some use cases	Use standardized data formats that keep as much information about the measurement system as possible.	Different data formats can be either manufacturer or software developer specific and limit use. Some data formats truncate values, affecting the information content or don’t keep any information about the measurement system making the data not comparable.	[14]
Availability **Measurement trust**	Data quality	Data set has various sources of data with e.g. different accuracy classes, processing methods and compression algorithms. Missing/incomplete metadata. No methods for synchronization among datasets.	Document all actions performed on the data/signal (preferably beginning from instrument transformer) to create a traceable chain of processes that can be re-created to evaluate data quality and improve data usability	Usually data gets treated as fully trustworthy and fully interoperable agnostic to different measurement algorithms, data processing algorithms etc. This can cause unsystematic approach in creating and handling dataset, that can lead to making dataset useless for certain applications.	[14]

4.0 Bibliography

[1] H. Kirkham, "The digital revolution in measurements," in *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)*, 2013.

[2] Minh, Q.N.; Nguyen, V.-H.; Quy, V.K.; Ngoc, L.A.; Chehri, A.; Jeon, G., "Edge Computing for IoT-Enabled SmartGrid: The Future of Energy," https://www.mdpi.com/1996-1073/15/17/6140/pdf, 2022.

[3] IEEE Power System Relaying Committee, *IEEE Std C57.13-2016: Standard Requirements for Instrument Transformers,* 2016.

[4] J. Meyer, R. Stiegler, S. Konzelmann and J. Kilter, "Practical Aspects of Accurate Harmonic Voltage Measurements in Transmission Systems," in *2022 20th International Conference on Harmonics & Quality of Power (ICHQP)*, Naples, Italy, 2022.

[5] A. J. Wilson, B. R. J. Warmack, R. A. Kerekes and P. D. Brukiewa, "Comparison of Power System Current Sensors via Playback of Electrical Disturbances," in *2022 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, New Orleans, LA, USA, 2022.

[6] IEEE Power System Instrumentation and Measurement Committee, *IEEE Master Test Guide for Electrical Measurements in Power Circuits: P120,* IEEE.

[7] L M Steele, H Kirkham, "LED Lamp Electrical Study," PNNL, Richland, 2014.

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

[9] Kirkham, H.; White, D.R., "The Nature of the Measurement of Partial Discharge," in *Proc I2MTC, International Instrumentation and Measurement Conference*, Auckland, New Zealand, 2019.

[10] Joint Committee for Guides in Metrology, "Evaluation of measurement data - Guide to the expression of uncertainty in measurement," The International Bureau of Weights and Measures, 2010.

[11] Kirkham, H; White, D.R.; Albu, M., "Dealing with Definitional Uncertainty--Better measurements in Power Systems," in *Proc 10th Int Wkshp on Applied Measureemtns for Power Systems (AMPS)*, Aachen, Germany, 2019.

[12] NERC, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report," NERC, Atlanta, 2017.

[13] IEEE Power System Instrumentation and Measurements, *IEEE P1459 "Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions",* IEEE, Under Revision.

[14] Jim Follum, Emily Ellwein, Pavel Etigonov, Xiaoyuan Fan, Harold Kirkham, Laurie Miller, Artis Riepnieks, "Advanced Power Systems Measurements: A Literature Review," PNNL, Richland, 2020.

[15] I. S. C37.238-2017, "IEEE Standard Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications," 2017.

[16] R. S. Singh, H. Hooshyar, L. Vanfretti, "Assessment of time synchronization requirements for Phasor Measurement Units," in *IEEE Eindhoven PowerTech*, Eindhoven, 2015.

[17] P. Castello, C. Muscas, P. A. Pegoraro and S. Sulis, "Trustworthiness of PMU data in the presence of synchronization issues," in *IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Houston, TX, 2018.

[18] X. Fan, S. Pal, D. Duan, L. Du, "Closed-Form Solution for Synchrophasor Data Correction under GPS Spoofing Attack," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*, Portland, 2018.

[19] Admin Conprove, "Analyzing the limits of data transmission in the process bus," CIGRE Sessions 2020, 2020. [Online]. Available: https://www.linkedin.com/pulse/analyzing-limits-data-transmission-process-bus-admin-conprove/. [Accessed March 2023].

[20] I. S. 2030.5-2018, "IEEE Standard for Smart Energy Profile Application Protocol," IEEE, 2018.

[21] I. PC37.118.2/D3.25, "IEEE Draft Standard for Synchrophasor Data Transfer for Power Systems," IEEE, 2023.

[22] H. Kirkham, A. Riepnieks, "A Future Standard for Reactive Power Measurement," in *IEEE Power & Energy Society General Meeting (PESGM)*, Montreal, QC, Canada, 2020.

Pacific Northwest National Laboratory

902 Battelle Boulevard
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