Challenges and Their Potential Solutions in Implementing Synchronized Waveform Applications

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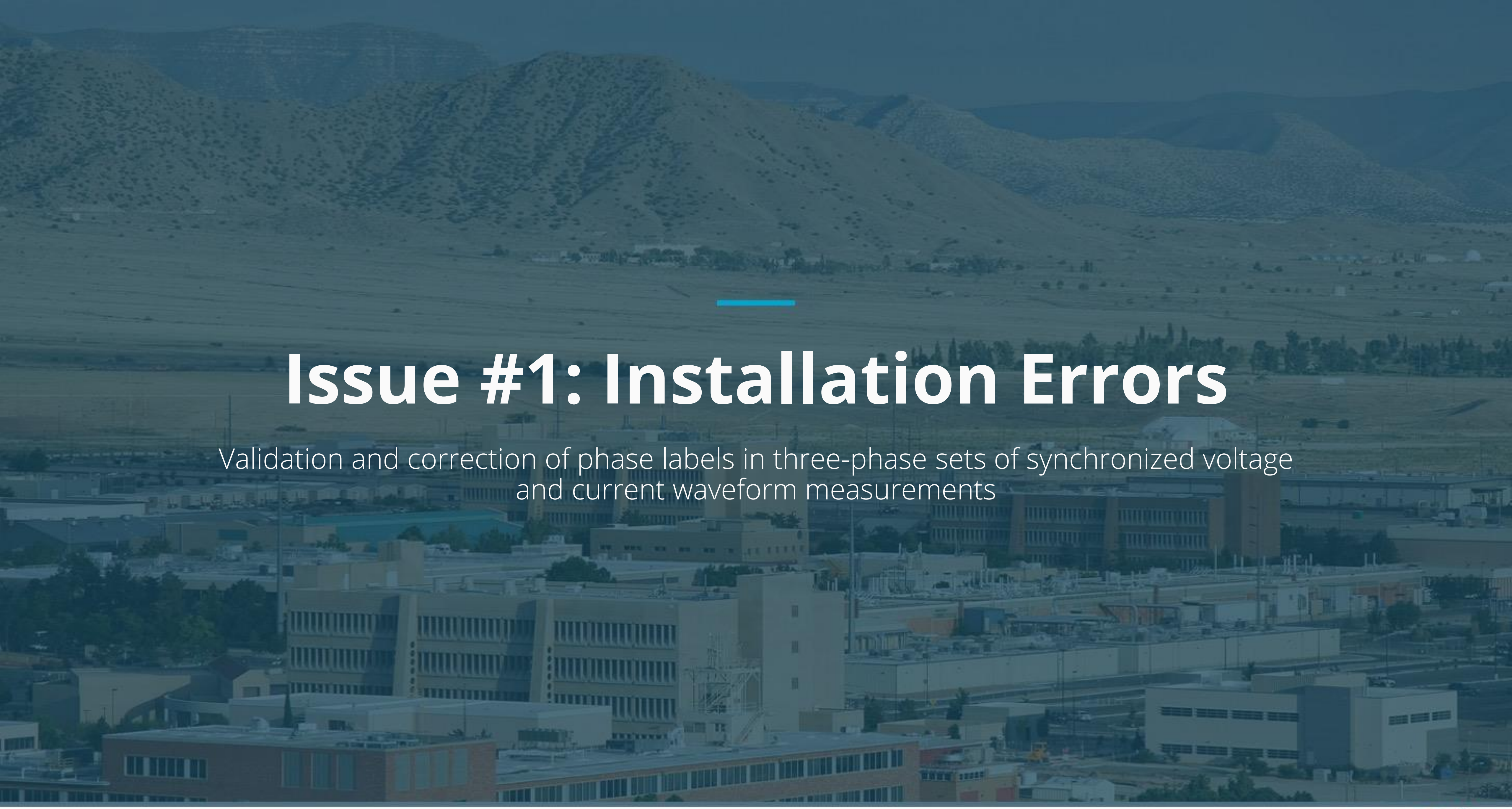
Motivation

Data for Analysis/Control in Power Systems

Challenges on the use of data for analysis and control in power systems:

- Data quality issues
  - Missing or latched data
  - Abnormal range or extreme values
  - Meter resolution and measurement noise
  - Time synchronization
- Improper measurement type
  - E.g.: AMI that provides 15-min *average* voltage values is not suitable for detecting short-duration voltage variations
- Data collection infrastructure incompatible with the desired applications
  - E.g.: AMI initially installed for billing may not be suitable for real-time applications
- Data storage/access
  - E.g.: continuous monitoring creates large amount of data and outdated database structures result in slow data queries
- Communication network constraints
  - E.g.: congested communication networks may not be able to transmit data in a timely manner for real-time applications
- Calibration or installation errors
  - E.g.: the clamp-on current transformer is positioned backwards, resulting in a 180° shift in the current measurements



Issue #1: Installation Errors

Validation and correction of phase labels in three-phase sets of synchronized voltage and current waveform measurements

Validation of Synchronized Waveforms Measurements (I)

- Measurement validation is a safeguard technique and its importance should not be underestimated.
  - Any monitoring device is subject to generate erroneous data due to human configuration or connection error, hardware malfunctions, or errors in algorithms.

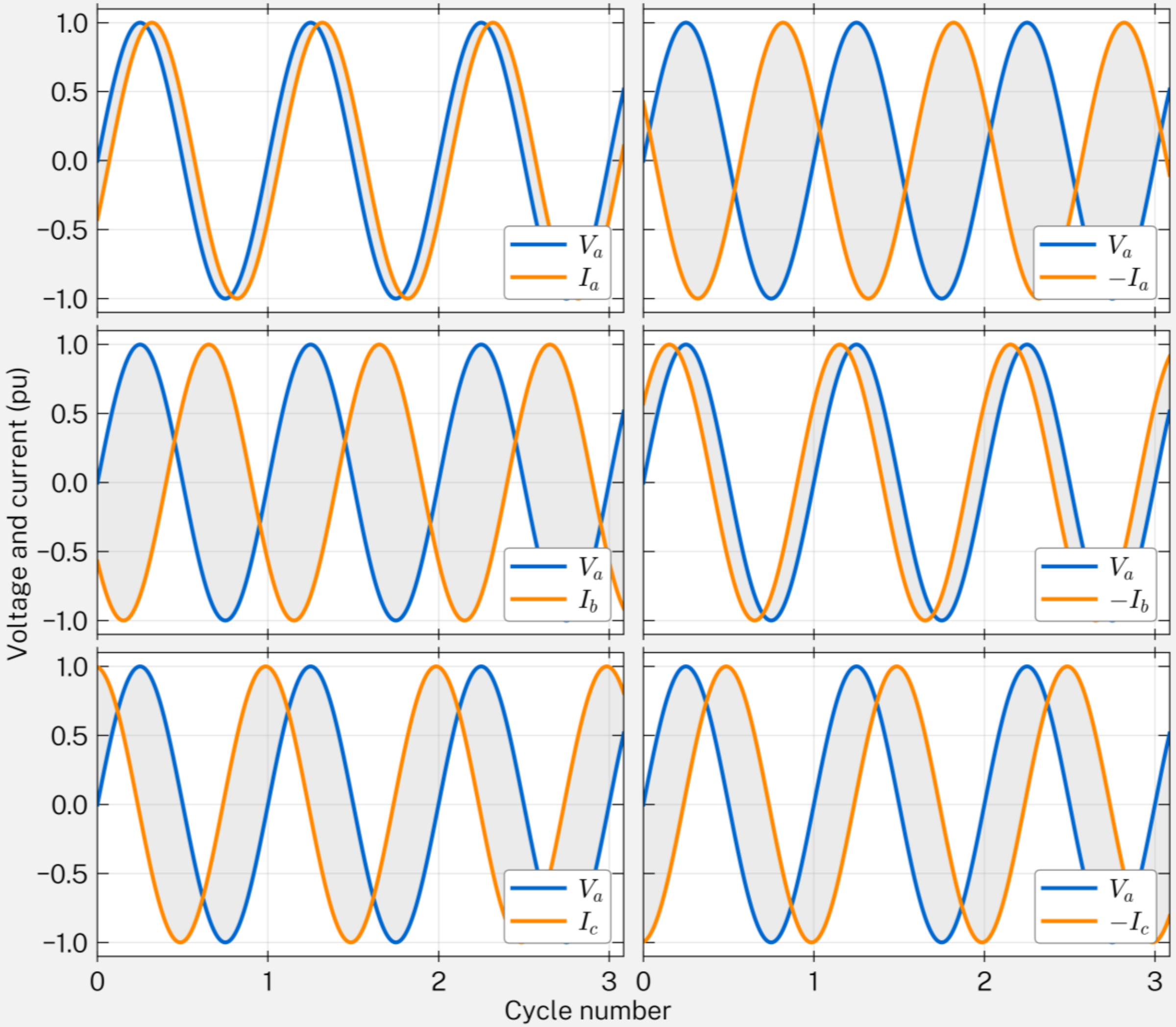
- Worse than not getting data is getting erroneous data and treating it as valid data.

Validation of Synchronized Waveforms Measurements (II)

- AC current measurements in power systems are oftentimes obtained through clamp-on current transformers (CTs).
  - This type of probe is placed unobtrusively around a conductor or bus bar without having to interrupt the circuit.
- It is not uncommon to encounter instances in which CTs' connections are backwards and/or in the wrong phase.
  - Many CT cases have directions for polarity printed or molded into them, but it does not prevent all human errors.
  - CTs with an incorrect connection still provide data, but they are erroneous and possibly have a wrong phase label.

Overview of the Validation of Phase Labels (I)

- **Goal:** given a set of three-phase synchronized voltage and current waveforms, find the correct phase correspondence between them.
- **Approach:** it is assumed that the correct voltage/current phase correspondence results in the lowest displacement angle (i.e., the highest power factor).



Overview of the Validation of Phase Labels (II)

- Let:
  - δ_a: phase angle of voltage in phase A
  - β_a: phase angle of current in phase A
  - $\theta_a = \delta_a - \beta_a$ is the power factor angle for phase A
- Assume the displacement between phases is 120°.
- Assume an *ABC* phase sequence.

Phase angles for each waveform

Phase	Voltage	Current	Backwards current
A	δ_a	β_a	β_a-180°
B	δ_a-120°	β_a-120°	β_a+60°
C	δ_a+120°	β_a+120°	β_a-60°

Overview of the Validation of Phase Labels (III)

Pseudocode:

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1. Expand the set of current measurements to include their corresponding backwards waveforms, i.e., $I_a$, $-I_a$, $I_b$, $-I_b$, $I_c$, and $–I_c$.
2. For each voltage waveform, identify which current waveform (among all 6) results in the highest power factor.
   – Each one of these pairs are the presumed correct correspondence between voltage and current waveforms.
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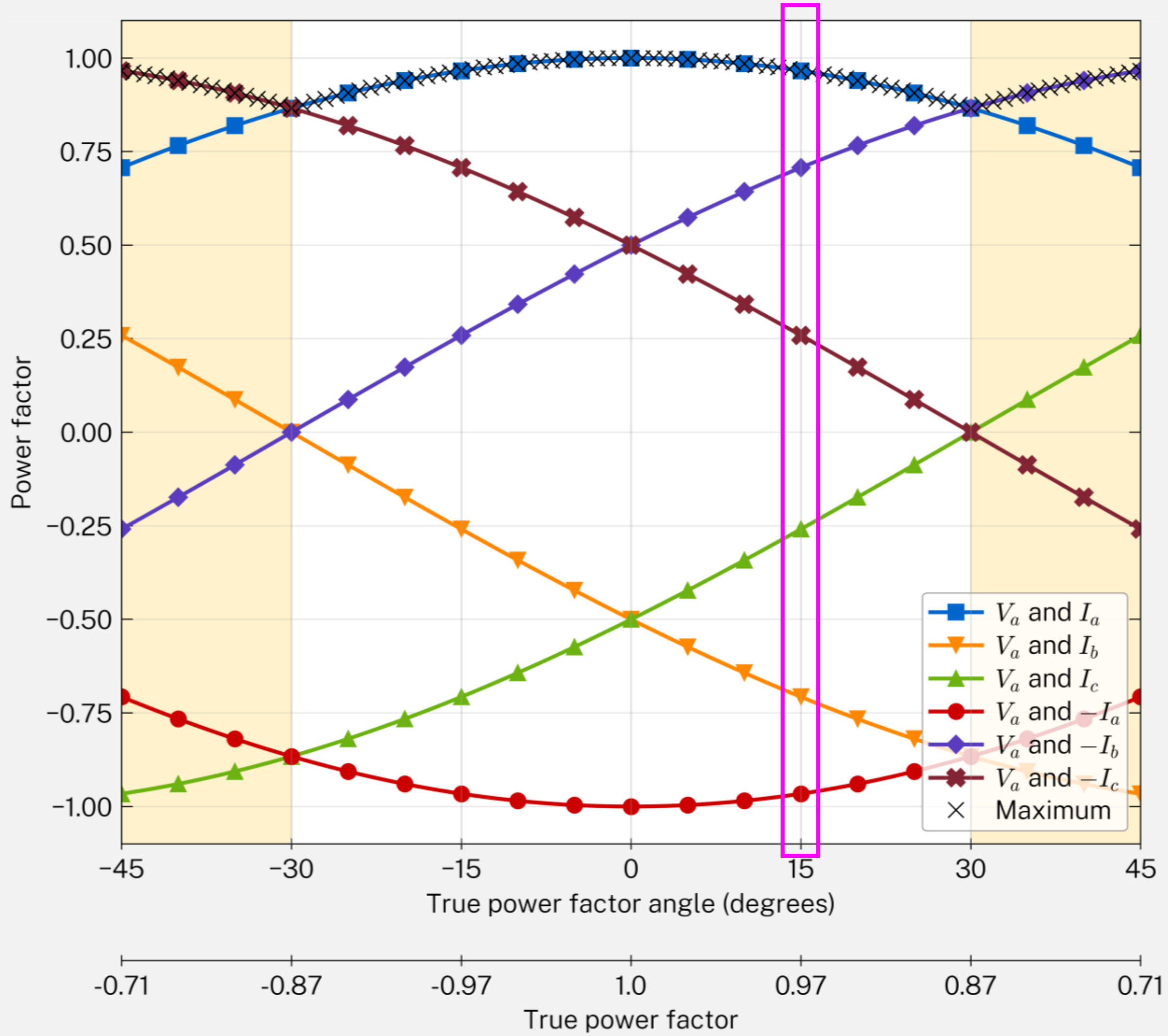
Power factor angle for each combination of voltage and current waveforms

	I_a	I_b	I_c	$-I_a$	$-I_b$	$-I_c$
V_a	θ_a	θ_a+120°	θ_a-120°	θ_a+180°	θ_a-60°	θ_a+60°
V_b	θ_a-120°	θ_a	θ_a+120°	θ_a+60°	θ_a+180°	θ_a-60°
V_c	θ_a+120°	θ_a-120°	θ_a	θ_a-60°	θ_a+60°	θ_a+180°

Overview of the Validation of Phase Labels (IV)

- Power factor curves for voltage waveform in phase *A* and all six possible current waveforms.
  - θ_a (the true power factor angle) varies from -45° to +45°

- The proposed phase labelling algorithm fails whenever the true displacement between the voltage and current waveforms is larger than 30°.



Overview of the Validation of Phase Labels (V)

- From local to geographical widespread waveforms phase labeling:
  - Consider that multiple three-phase sets of synchronized voltage and current waveforms have been labeled using the approach described previously.
  - The next step consists in associating the measurements from different locations, which is based on the difference between voltage phase angles.

Location #1:
- Phase *A*: $\delta_{a,1}$
- Phase *B*: $\delta_{b,1}$
- Phase *C*: $\delta_{c,1}$

Location #2:
- $\delta_{x,2}$, $\delta_{y,2}$, $\delta_{z,2}$
- Unknown phase labels*

Phase *A* at location #2: $\text{argmin}_{x,y,z}\{|\delta_{x,2}-\delta_{a,1}|,\ |\delta_{y,2}-\delta_{a,1}|,\ |\delta_{z,2}-\delta_{a,1}|\}$

Phase *B* at location #2: $\text{argmin}_{x,y,z}\{|\delta_{x,2}-\delta_{b,1}|,\ |\delta_{y,2}-\delta_{b,1}|,\ |\delta_{z,2}-\delta_{b,1}|\}$

Phase *C* at location #2: $\text{argmin}_{x,y,z}\{|\delta_{x,2}-\delta_{c,1}|,\ |\delta_{y,2}-\delta_{c,1}|,\ |\delta_{z,2}-\delta_{c,1}|\}$

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*For location #2, the correspondence between voltage and current waveforms have already been determined previously. The goal in this step is to label the phases at location #2 (*A*, *B*, and *C*) with respect to the labelling at location #1.

Discussion of the Validation of Phase Labels

- The proposed phase labelling algorithm is applicable to cases in which the true displacement between voltage and current waveforms is at most 30°.
  - It should be applicable to most substation measurements*, but it may fail if the measurements are taken at some equipment terminals throughout the feeder.
- Some alternatives under analysis:
  - Correlation between trends in harmonic distortion in the voltage and current measurements.
  - Correlation between voltage and current waveforms during a disturbance event.
- Note: a phase labelling algorithm does not need to run continuously. Instead, it is used to validate the data only when the connection of the monitoring device to the power system is changed.

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*We have successfully applied this algorithm to validate and fix the phase labelling of synchronized three-phase waveform measurements collected at two nearby substations.

Issue #2: Time Synchronization

On the importance of highly accurate time synchronization for synchronized waveforms applications

Use of Time-Synchronized Data in Power Systems

- Time synchronization is an important part of modern electric utility power system design and operation.
  - It is critical to the emerging requirements for smart grid operation.
  - Many utilities already make extensive use of synchrophasor networks for monitoring, control, and post-mortem analysis.
- Synchronized waveforms are only useful when they can be *accurately* correlated in time.
- Although time synchronization is accurate over the long-term, it is subject to short-term instability and lack of availability.

Time Synchronization Requirements

- Time synchronization accuracy requirements depend on the intended applications:
  - Time-of-use billing: sub-second or sub-minute
  - Power quality billing: sub-second
  - Grid power frequency and phase monitoring and controlling: sub-millisecond
  - Sequence-of-event for real time control and fault diagnosis: sub-millisecond
  - Power quality analysis: nanosecond
  - Synchrophasors: the maximum allowable time error in IEEE Std 60255-118-1-2018 is ±26 μs for a 60-Hz system and ±31 μs for a 50-Hz system, leaving no additional error margin for synchrophasor data computation

- For most synchronized waveforms applications, the maximum time error should correspond to less than 1° phase shift between the actual and measured waveforms.
  - In a 60-Hz system, 1° phase shift is equivalent to 46.3 μs.

- Proper consideration must be given to monitoring/control systems that merge data with mixed precision timestamps.

Typical Accuracies in Time-Synchronized Systems

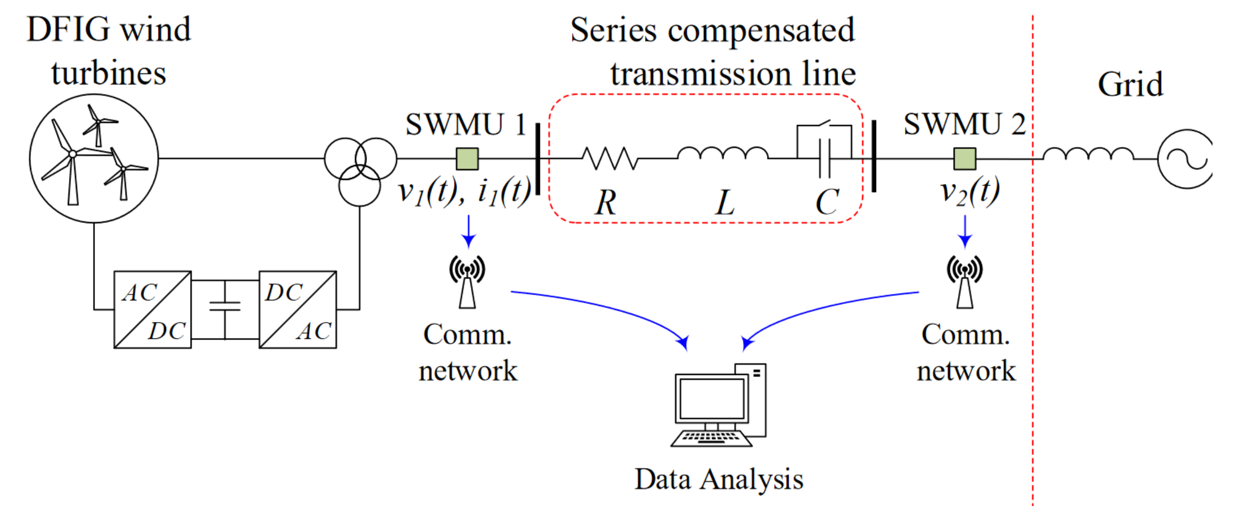
- Time-synchronized systems are composed of a time reference (such as from GPS), one or more time distribution mediums, and one or more monitoring devices.
- Time distribution systems distribute time from the time sources to the monitoring devices.
  - Examples: wired-analog, wired-digital, fiber-optic, wireless-analog, wireless-digital, etc.
  - Each medium has different characteristics and is subject to different impairments (delays, noise, interference, distortion, network traffic, etc.)
- Further, the selected distribution method affects the accuracy of the distributed times.

Distribution Method	Accuracy
1PPS	Better than 10 ns
IRIG-B1yz Modulated	Better than 1 ms
IRIG-B0yz Unmodulated	Better than 100 ns
IRIG-B2yz Manchester	Better than 100 ns
IRIG-J	Better than 1 ms
NTP/SNTP	Between 1 ms and 50 ms
IEEE Std 1588 PTP/PTPv2	Better than 1 μs

Reference: "IEEE Guide for Designing a Time Synchronization System for Power Substations," in *IEEE 2030.101-2018* , vol., no., pp.1-118, 26 July 2018, doi: 10.1109/IEEESTD.2018.8421294.

Case Study: Effects of Time Synchronization Accuracy on SSR Detection (I)

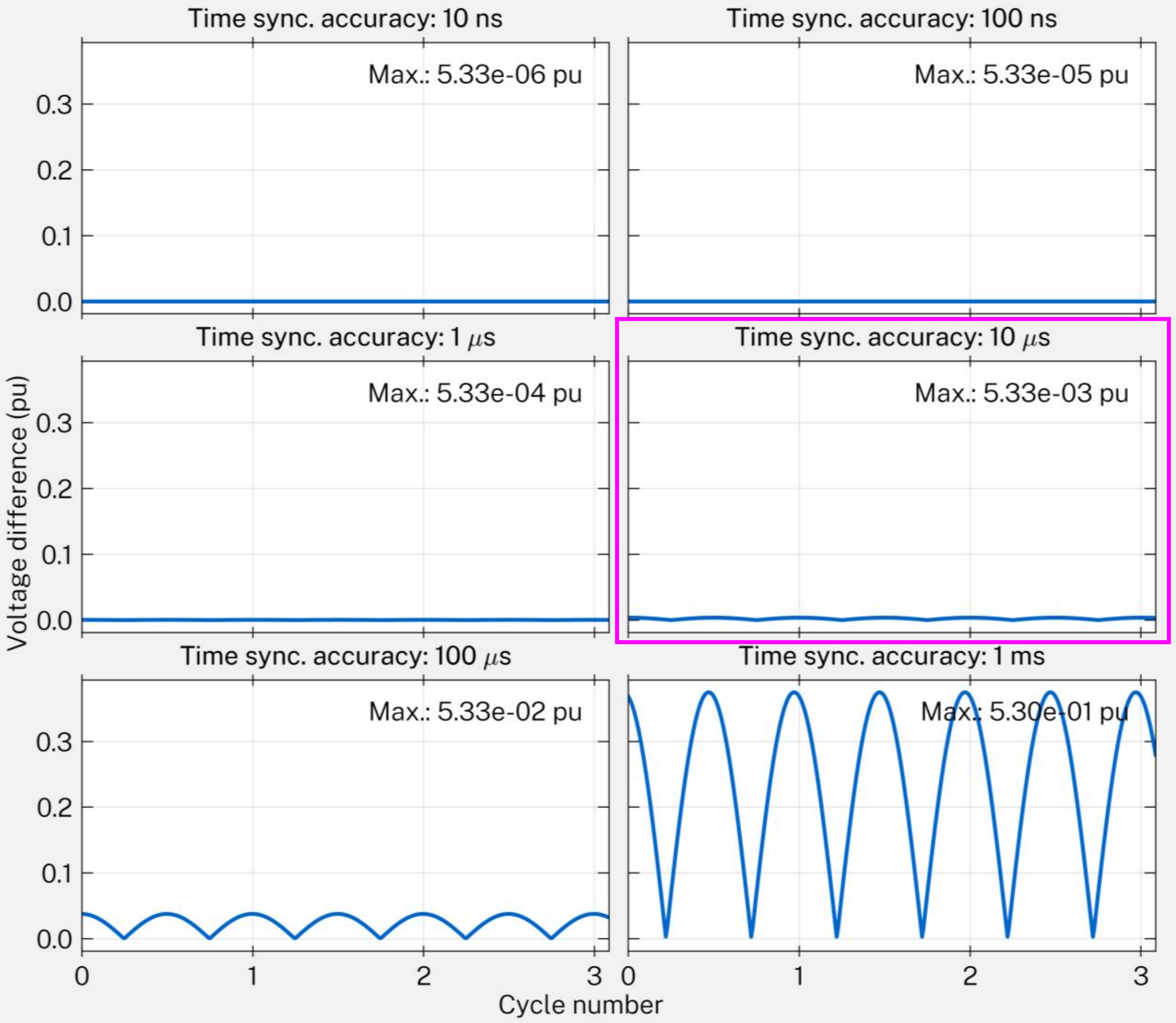
- Subsynchronous resonance (SSR) is a common event in wind farms.
- Potential consequences:
  - Significant loss of generation;
  - Damaging of the generators.
- Early and accurate SSR detection is critical for its effective mitigation.
- A detection algorithm has been proposed based on time-synchronized waveforms on both terminals of series-compensated transmission lines.



Reference: B. Gao, R. Torquato, W. Xu and W. Freitas, "Waveform-Based Method for Fast and Accurate Identification of Subsynchronous Resonance Events," in IEEE Transactions on Power Systems, vol. 34, no. 5, pp. 3626-3636, Sept. 2019, doi: 10.1109/TPWRS.2019.2904914.

Case Study: Effects of Time Synchronization Accuracy on SSR Detection (II)

- The detection algorithm starts with the computation of ΔV_{line}, the voltage difference between the two ends of the transmission line*.
  - This computation is greatly affected by the accuracy of the time synchronization.
- Example of ΔV_{line} during steady-state conditions (i.e., *without* a SSR or any other disturbance) for multiple time synchronization delays.
  - Even a 10 μs delay, which is better than the required accuracy for PMUs, creates relative large ΔV_{line} values (instead of 0).



*Please see full algorithm in the referenced paper.

Discussion of Time Synchronization Issues

- Synchronized waveforms systems should designed, tested, and maintained to ensure that they are able to support the intended applications.
  - Periodical inspection to confirm its proper operation.
  - Development of automated methods for detection of the system's degradation.

- Utilities, researchers, and manufacturers should develop guides with recommendations of the minimum time synchronization accuracy required for different applications.

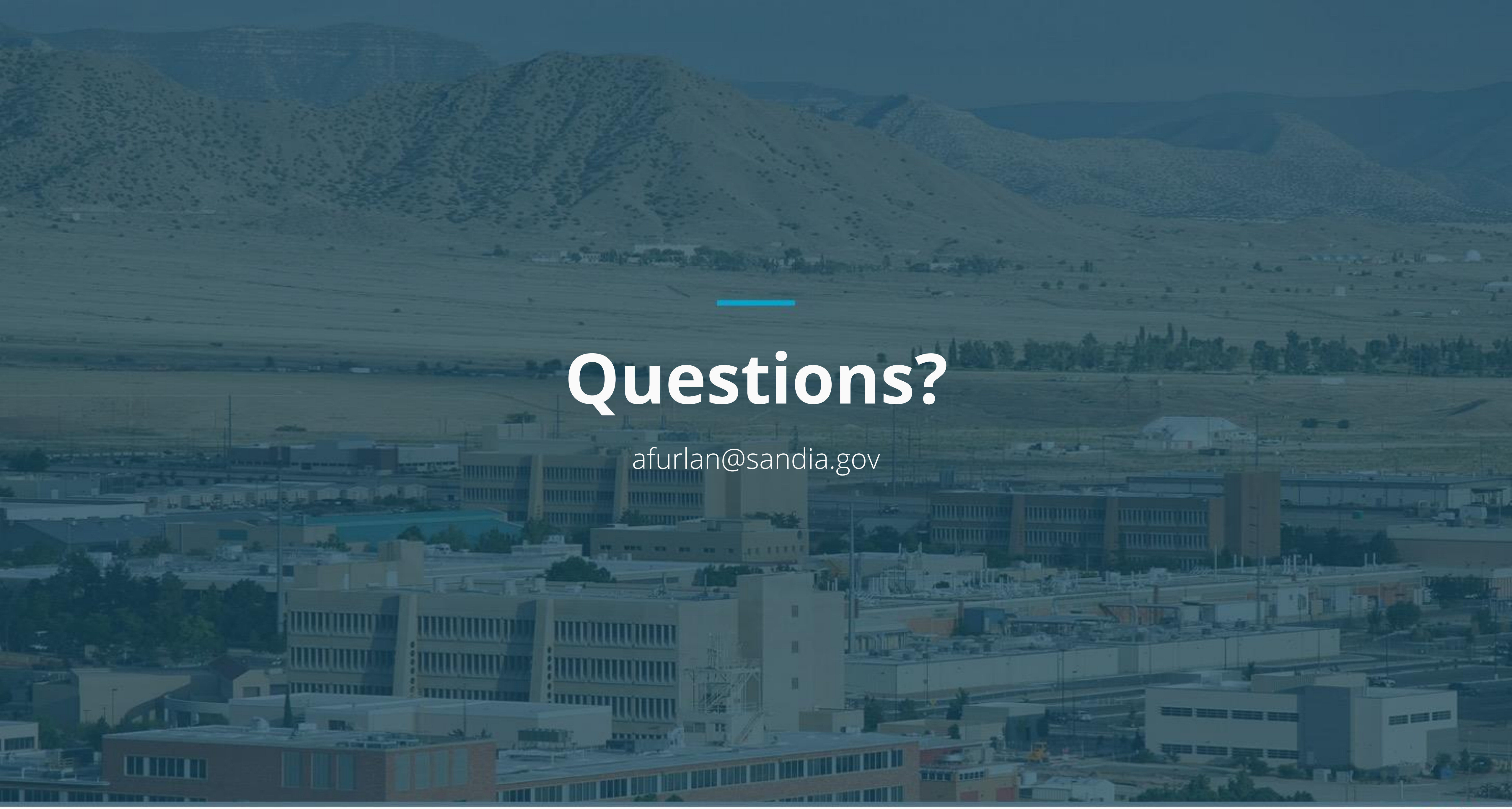
Conclusion

Final Thoughts

- Synchronized waveforms should not be seen as a replacement for AMI and PMU networks; instead, they are a complementary tool for enabling applications that could not be developed with the previous types of data.

- In the case of continuous monitoring, robust algorithms must be used for parsing through large datasets and identifying the segments of interest.
  - A. F. Bastos and S. Santoso, "Universal Waveshape-Based Disturbance Detection in Power Quality Data Using Similarity Metrics," in IEEE Transactions on Power Delivery, vol. 35, no. 4, pp. 1779-1787, Aug. 2020, doi: 10.1109/TPWRD.2019.2954320.
  - B. Li, Y. Jing and W. Xu, "A Generic Waveform Abnormality Detection Method for Utility Equipment Condition Monitoring," in IEEE Transactions on Power Delivery, vol. 32, no. 1, pp. 162-171, Feb. 2017, doi: 10.1109/TPWRD.2016.2580663.

- Large penetration levels of power-electronics-based distributed energy resources (such solar photovoltaics and battery energy storage systems) presents many opportunities for synchronized waveforms applications.



Questions?

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