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Review of Applications and Practicalities of Synchronized Waveform Monitoring

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***Abstract*— Synchronized waveform monitoring has the potential to enable advanced, automatic grid operations. Combined with novel processing and analysis techniques, waveform data can unlock several new capabilities – beyond what can be achieved with conventional SCADA- or synchrophasor-based monitoring. This paper serves as a review of these key emerging applications, such as transient monitoring, locating oscillations, and wildfire prevention. Various resources from the literature have been gathered, which represent the state of the art in this field. The paper also analyses several practical aspects which must be addressed to effectively deploy waveform monitoring solutions. In particular, options for the computation and communications infrastructure required for real-time applications are evaluated.**

***Index Terms*—Synchrophasor, PMU, synchronized waveform, waveform measurement units (WMUs), wide-area networks.**

I. Introduction

The definition of a synchrophasor assumes a sinusoidal waveshape, which is an approximation driven by the widespread use of rotating machines to generate power. Grids are moving to include significant converter-interfaced generation and HVDC links to displace conventional rotating machines and AC interconnections. Voltage and current waveforms may contain dynamic transients such as arcing, a fault with a time-varying DC component, phase steps, harmonics, and other forms of distortion which are not fully represented by phasors [1]. The IEEE C37.118.1 synchrophasor standard also requires a tight bandpass filter around the fundamental frequency (50 Hz or 60 Hz) which limits the bandwidth of information which can be extracted from synchrophasors, compared to time-domain samples [2]. Therefore, synchrophasor data does not provide the detailed waveform, harmonic, and frequency dynamic range required to fully detect and analyze all phenomena and events in power systems.

Synchronized waveform-based monitoring, which is sometimes referred to as "point on wave" or “continuous point on wave” (CPOW) monitoring, will be increasingly important for power system monitoring, protection, and control [3], [4], [5]. Waveform data complements phasor measurement units (PMUs) and conventional SCADA measurements by enabling new applications. At present, digital waveform samples are typically used in the following scenarios: internally within conventional protection relays, power quality meters, and PMUs; across local area networks for IEC 61850-enabled protection systems; and for post-event analysis of faults and major system events. As with synchrophasors, accurate time synchronization is important for ensuring that waveform data from multiple locations can be compared [6].

Figure 1 illustrates the value of waveform data compared to PMU data sources. The plots represent the positive sequence voltage magnitude from a PMU (upper plot) and the underlying waveform data (lower plot) for the same simulated event. Clearly waveform data provides richer information about the system, including harmonics and fast-acting transients.

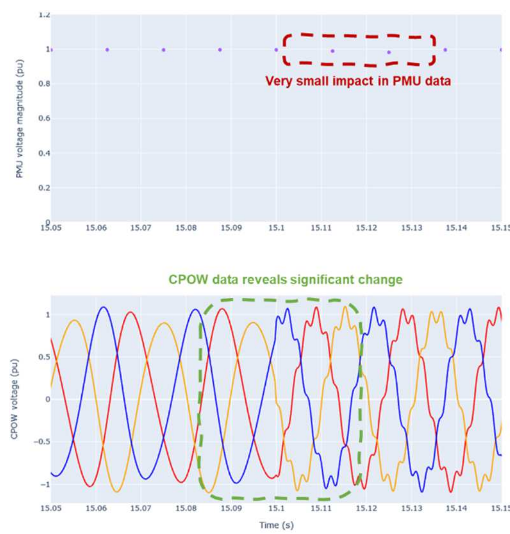

Figure 1 Comparison of PMU and waveform (CPOW) data

This paper will describe the new applications which are enabled through monitoring, transferring, storing, and processing synchronized waveform data. It will also cover practical aspects, technical standards, and other relevant resources.

II. Applications

A. *Transient Event Signatures*

Power system transients typically occur at millisecond or microsecond timescales, which requires high sampling rates to capture the event. As an example, incipient faults are sub-cycle transients that can impact the condition of assets, such as causing gradual insulation degradation which eventually leads to permanent faults in underground cables (Figure 2). Transient signatures can be used to detect, characterize, and locate their occurrence [7]. This can lead to improved strategies for monitoring asset health, to proactively find circuits which are prone to incipient faults before a permanent short-circuit fault occurs, resulting in damage, risk to life, loss of supply, and high cost to repair. The goal is to be able to find early warning signs of interesting or critical events, and use real-time detectors to deliver accurate, timely alarms to system operators.

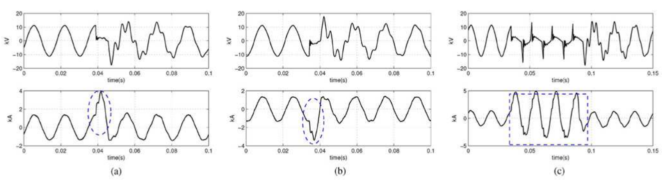

Figure 2 (a) and (b) are cable incipient faults which self-clear, (c) is a permanent fault, two days later (from [7])

Reference [8] provides a method to extract interesting, abnormal data from waveforms. Analysis techniques can build on this to enable deeper classification of events (e.g., for root cause identification for electrical faults) compared to synchrophasor or SCADA methods, by building a history of transients experienced by assets. For example, new techniques in fault classification and fault location exploit waveform data to perform advanced pattern matching [9], [10]. Interestingly, the techniques in [9] provide improved classification results at higher sampling frequencies (76% and 94% accuracy, at 960 Hz and 3840 Hz, respectively). This method can also automatically interpret unseen disturbance waveforms, but without the usual need for a very large set of examples to train classifiers. It leverages the online DoE/EPRI library (see section IV.D) with labelled distribution faults to intelligently classify new events.

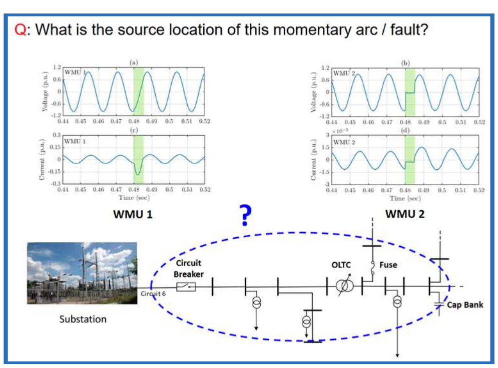

Figure 3 Example of using waveform monitoring to locate transients

Figure 3 illustrates the challenge of how to comprehensively identify and locate transients such as incipient faults in complex distribution networks. Reference [10] achieves this using waveform monitoring at sparse locations, combined with analysis and modelling of the frequency components of these short-duration transients. Increasing the numbers of deployed synchronized waveform monitoring locations can improve the granularity of the results.

Reference [11] proposes using combined frequency- and time-domain features within waveform data to identify and classify events, as illustrated in Figure 4.

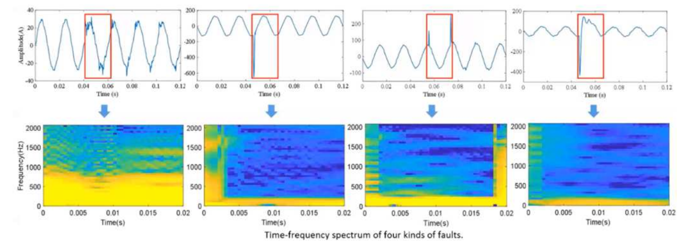

Figure 4 Automated event classification

Other scenarios which can benefit from waveform monitoring, and would be challenging to achieve with conventional PMU data streams include:

- Capacitor switching, involving monitoring for oscillatory transients which can lead to restrikes during capacitor de-energization, due to faulty switch contacts [12].
- Monitoring the per-phase operation time of circuit breakers. For example, one phase operating 1-2 cycles later than the other phases may indicate degradation which requires maintenance.

B. *Harmonics and Power Quality*

Power quality metrics such as harmonics, interharmonics, and total harmonic distortion (THD) can also be computed from waveform data, which is not possible with synchrophasor data based only on the fundamental component.

Figure 5 illustrates an example of the value of waveform data in grid harmonic mitigation [13]. Solar photovoltaic (PV) integration has caused widespread interharmonics to be observed. Initially, this was characterized as an interharmonic at 8 Hz, through analysis of wide-area synchrophasor measurements. However, later investigation with synchronized waveform data revealed that the true frequency was 22 Hz. This mismatch was due to accidental decimation of the synchrophasor data without proper filtering, resulting in frequency aliasing. However, it illustrates how accurate real-time monitoring of metrics such as interharmonics and THD, on a per-cycle basics, at multiple locations, can help to reveal the sources of grid disturbances.

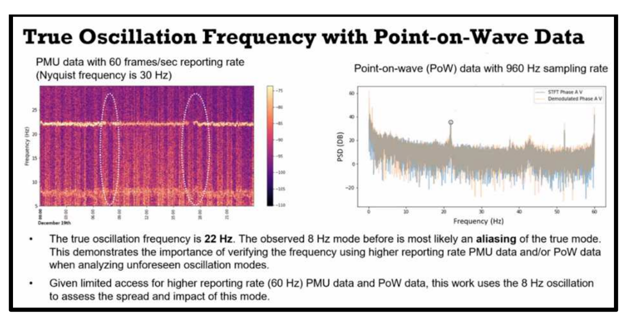

Figure 5 Example of interharmonic investigation with waveform data

Power electronic devices, with relatively high switching frequencies, are therefore a key driver for waveform monitoring with harmonic analysis as they can inject harmonics and interharmonics into the grid. Such devices can also be seriously affected by poor power quality. For example, the Blue Cut fire incident in the USA in 2016 was exacerbated by the response of power electronics during phase step, low voltage, and high-harmonic conditions, resulting from many short-duration faults on HV lines [14].

It should be noted that some power quality standards such as IEC 61000-4-30 assume that power quality meters will adjust the analogue sampling rate based on the measured signal frequency, to optimize Fourier analysis. This approach is not compatible with synchronized waveform data which will generally use a fixed sampling rate. Reference [15] presents a solution using processing of fixed sample rate data from IEC 61850-9-2 Sampled Value streams.

C. *Oscillation Detection*

Electromechanical oscillations which are driven by synchronous generator dynamics have been successfully monitored by PMUs. However, emerging converter-driven dynamics, which are influenced by proprietary control design, mean that the threat of grid instability is rising. This is especially true in relatively small synchronous grids such as Great Britain, compared to mainland Europe or the systems in North America. To fully characterize system oscillation events, it is important to be able to access all frequencies of possible oscillation modes. There are many approaches that use PMUs for oscillation detection and system stability protection, but ultimately waveform data is required to reach the full frequency range without attenuation, to diagnose and locate disturbances.

In general, low system strength can lead to certain voltage control oscillation modes. For example, in the Great Britain grid, oscillations contributed to a major outage in August 2019 which resulted in disconnecting supplies of 1 in 10 customers, in order to secure the wider transmission system [16]. Later offline analysis revealed that there were warning signs visible 10 minutes before the event, including lightly-damped oscillation at 9 Hz, and 7.3 Hz oscillation visible in Scotland (approximately 200 miles away from the origin of the event) which was evidence of power electronic instability. However, real-time systems were not in place to react quickly to this (albeit rare) scenario, and synchrophasor monitoring systems, by design, cannot capture the full frequency range of all possible oscillation modes.

To address these challenges, it is important to be able to detect oscillations in any frequency range in complex, converter-rich networks and provide intelligent and timely alarms for important system events [17]. It may be necessary to identify oscillations at discrete locations, as well as combine information from multiple locations to perform wide-area pattern matching in real time. Such a solution should allow for some remedial action to be taken by the operator to mitigate the event.

Further depth in the applications of waveform data for oscillations is given in [3].

D. *Downed Conductor and Wildfire Detection*

Similar to the techniques described in Section II.A, an important and promising application of synchronized waveforms is the automated detection and prevention of conditions which can lead to wildfires.

Automated techniques should be able to reliably detect precursors to wildfires, such as open conductor conditions due to a broken conductor, and avoid maloperation for similar benign events such as unbalance or single-phase load disconnection. If a trip decision can be made within approximately 1 s, before a broken conductor is likely to fall to the ground, the risk of wildfire ignition from downed conductors can be prevented entirely. A solution involving distributed waveform sensing and multi-zone differential protection is discussed in [18].

There is also value in combining electrical signal analysis with additional context, such as the prevailing weather and circuit loading conditions, to dynamically adjust for scenarios where wildfires are more likely [6].

III. Existing Standards for Waveform Data Encoding and Transfer

A. *Real-Time Data Streaming*

The main existing standard for streaming synchronized waveform data is the IEC 61850-9-2 Sampled Value (SV) Ethernet-based protocol, with some additional conventions for merging units defined in IEC 61869-9. SV is intended for only layer-2 Ethernet transfers within a local area network. IEC 61850-90-5 extended SV for transfer over an IP-based WAN, although has been superseded by secure transmission of data using IEC 61850 Ed 2.1 and the IEC 62351 standards [19]. SV typically requires high data bandwidth for streaming waveform samples, at approximately 5 Mbps for one stream containing four voltages, four currents, and quality information sampled at 4 kHz.

The Streaming Telemetry Transport Protocol (STTP) has been drafted as IEEE standard P2664 [12]. Open source reference implementations are available at [13]. STTP is intended to supersede IEEE C37.118.2 as the future protocol for transferring synchrophasor data, while providing flexibility for other streaming data purposes. STTP supports sending waveform timeseries data, encryption using TLS, and includes an optional lossless data compression feature.

B. *File-Based Waveform Storage*

The PQDIF format (IEEE Std. 1159.3) is designed as a self-contained description of an event involving a power quality issue, fault, or other transient. A PQDIF record typically contains a relatively short burst of waveform data and derived timeseries quantities. It includes a zlib-based compression feature. The COMTRADE format offers a similar capability to PQDIF, but does not group multiple "observation" records together in a single file or provide integrated data compression. Power quality meters typically support standard formats and also provide data in a custom comma-separated values (CSV) format for simple decoding.

IV. Other Practicalities

A. *Data Volume*

Clearly, the use of waveform data has a disadvantage in terms of managing the high density of data, and the communications bandwidth required for streaming or bulk transfer of data between locations. The quantity of raw data which is generated and potentially transferred over a wide-area network (WAN) is much greater than typical synchrophasor or SCADA data streams.

This inherent barrier means that system operators need to manage transmitting data over a WAN and long-term storage, and therefore the benefits from new applications must outweigh the operational burden from deploying infrastructure to support synchronized waveform monitoring.

However, there are promising approaches for lossless, or near-lossless, compression of waveform data for streaming and storage [20], [21], [22], [23], which can greatly reduce the burden on data communications and data archiving. Some compression techniques can operate in real-time and, counter-intuitively, have the benefit of reducing overall latency. This is because there is less data to transfer over the communications network and greatly reduced transfer time, so the computation time for compression and decompression is compensated (or becomes negligible [21]).

B. Processing Architecture – Challenges and Solutions

1) Real-time computation and communications infrastructure

To deliver a variety of real-time applications, suitable infrastructure for robust time synchronization, computation, and communications must be deployed. The infrastructure needs to be scalable in terms of the number of waveform measurement devices supported and the geographical area addressed.

A strategy for avoiding high bandwidth data transfers is to perform initial processing of waveform data streams locally within substations. Data only needs to leave the substation by exception, when local processing has characterized an event. Data compression schemes already exist to significantly reduce data transfers during steady-state conditions, with somewhat increased data bandwidth requirements during system events. Furthermore, processed outputs, such as a frequency spectrum, can be transferred instead of the raw waveform data – so that computation is inherently distributed over multiple substations.

However, some applications, such as robust wildfire prevention, require continuous streaming of waveform data between multiple locations over a wide area. This can be challenging and costly to achieve, particularly for complex distribution networks.

Table I proposes a suitable architecture for various waveform monitoring applications, using the following categories:

- **Local substation**: "edge" processing within the substation can perform the function, perhaps with non-real time reporting to a central location.
- **Wide-area, some substations**: wide-area coordination is required, but sparse deployment of waveform monitoring devices is acceptable.
- **Wide-area, every substation**: full deployment of waveform monitoring at every substation/node is required for optimal results.
- **Grid-wide**: coordination of data over a large synchronous AC region is required.

Table I illustrates that a lot of value can be delivered with local waveform-based computation within substations, involving minimal additional infrastructure. Expanding measurement locations across multiple substations further increases the opportunities, such as for locating transients and oscillations.

2) Offline analysis infrastructure

There are significant opportunities in speculative analysis and visualization of historical data, collected from system-wide sources. However, this requires infrastructure for data warehousing (for long-term storage of data) and computation (such as for training and testing machine learning models) [20]. It also requires expertise in data science and cybersecurity. Depending on the size of the network managed by a system operator, this could be achieved in multiple ways:

- Ad-hoc analysis campaigns with temporary deployment of monitoring equipment, perhaps partnering with third-party specialists for data analysis.
- In-house data centers forming a private cloud, with dedicated teams for data analysis and cybersecurity. This requires maintaining significant resources and specialists.
- Public, commercial cloud infrastructure. This approach does require some caution for securing connections from the utility's systems to the cloud. However, being able to leverage existing, proven patterns and experts from the cloud provider can enable smaller utilities to avoid the need for employing specialist in-house teams to manage cybersecurity. It therefore only requires a low capex commitment and offers flexibility.

TABLE I WAVEFORM MONITORING APPLICATIONS AND ASSOCIATED INFRASTRUCTURE REQUIREMENTS

Application	Local substation	Wide-area, some substations	Wide-area, every substation	Grid-wide
Capacitor switching monitoring	✓			
Circuit breaker condition monitoring	✓			
Cable condition monitoring (e.g. tracking incipient faults)	✓			
Locating transients		✓		
Fault or other event classification	✓	✓ (ideally)		
Wildfire detection/prevention		✓	✓ (ideally)	
Oscillation detection and location	✓ (detection only)	✓	✓ (preferred)	✓ (ideally)
Power quality monitoring	✓ (for some applications)	✓	✓ (ideally)	
Converter dynamics	✓			
Inertia monitoring				✓

C. Data Accuracy

Analysis methods using measurement data need to appropriately handle data quality issues, such as loss of global time synchronization, CT saturation, and missing data. For example, loss and restoration of time sync can lead to drifting and overlapping timestamps. It is recommended that data quality and time synchronization information is preserved within the end-to-end process of acquisition at the sensor to the final long-term data storage solution. Analysis campaigns must also ensure that the data quality information is inspected, so that conclusions from the investigation can be trusted [24].

However, this inevitably adds complexity to the analysis pipeline.

As for protection relays, PMUs, fault recorders, power quality meters, and other devices, waveform measurements are underpinned by the accuracy of CTs and VTs, and how the transducer accuracy may change over time.

D. Resources

Table II summarizes several online resources which provide synchronized waveform data sources and tools.

TABLE II WAVEFORM MONITORING AND ANALYSIS RESOURCES

Originator	Description	Link
DoE/EPRI	Distribution events dataset	http://pqmon.epri.com/disturbance_library/
NI4AI consortium	Assorted waveform datasets	https://ni4ai.org/datasets
ORNL	Grid Event Signature Library (GESL)	https://gesl.ornl.gov/
KIT	Power grid frequency data base	https://osf.io/by5hu/
Grid Protection Alliance	Open source software for various purposes, including waveform analysis and protocol implementations	https://github.com/GridProtectionAlliance
Synaptec	Open source software for compressing synchronized waveform data	https://github.com/synaptecltd/slipstream

V. CONCLUSIONS

While some substation devices such as protection relays and PMUs already process waveform data internally, there are presently many new opportunities for widespread analysis of this data for enhancing grid operations. This paper has reviewed several examples of emerging waveform analysis techniques which enable applications such as incipient fault detection, oscillation location, and advanced power quality analysis.

The paper has proposed an architecture for the practical deployment of several real-time waveform monitoring applications, in terms of the required computation and communications infrastructure. It has also advised on requirements and options for offline analysis applications, such model training.

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