By Hamed Mohsenian-Rad and Wilsun Xu

Synchro-Waveforms

A Window to the Future of Power Systems Data Analytics

WAVEFORMS ARE THE MOST GRANULAR AND authentic representation of voltage and current in power systems. With the latest advancements in power system measurement technologies, it is now possible to obtain time-synchronized waveform measurements, i.e., synchro-waveforms, from different locations of a power system. The measurement technology to obtain synchro-waveforms is referred to as a waveform measurement unit (WMU). WMUs can capture the most inconspicuous disturbances that are overlooked by other types of time-synchronized sensors, such as phasor measurement units (PMUs). WMUs also monitor system dynamics at much higher frequencies as well as much lower frequencies than the fundamental components of voltage and current that are commonly monitored by PMUs. Thus, synchro-waveforms introduce a *new frontier* to advance power system and equipment monitoring and control, with direct applications in situational awareness, system dynamics tracking, incipient fault detection and identification, condition monitoring, and so on. They also play a critical role in monitoring inverter-based resources (IBR) due to the high-frequency switching characteristics of IBRs.

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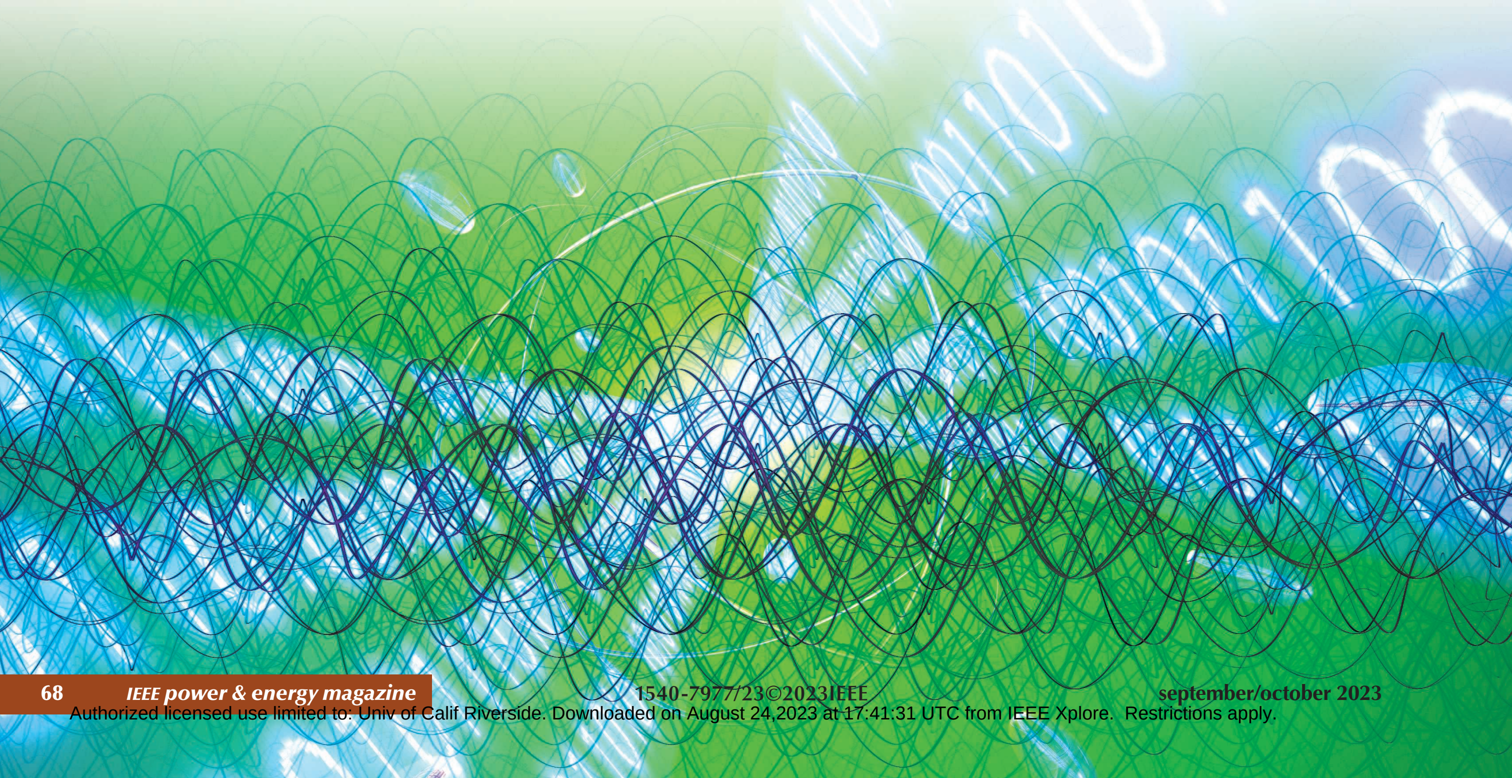

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Accordingly, in this article, we provide a high-level overview of this new and emerging technology and its implications, discussing the latest advancements in the new field of synchro-waveforms, including basic principles, real-world examples, potentials in data analytics, and innovative applications.

Waveforms Versus Phasors

Figure 1 provides a comparison, based on real-world data, between conventional phasor measurements versus raw waveform measurements. The three-phase voltage phasor measurements (magnitude and phase angle) are shown in Figure 1(a). While the phasor measurements can indicate the presence of a major voltage sag between cycle 25 and cycle 30, the details of such an event cannot be understood based on phasor measurements. However, such details can be understood by looking at the raw waveform measurements in Figure 1(b). Here we can see the exact shape of the waveform, not only on Phase C, which is impacted most severely, but also on Phases B and A. This example and other similar examples raise the following questions: *Why should we tie our hands with phasor representation of the voltage and current waveforms, which are "processed" data?* and *Why limit our imagination to one complex number as opposed to looking at the ultimate raw data in the time domain?*

Real-World Synchro-Waveform Measurement Technologies

Although the waveform data can provide much more information, in the past it was very difficult to analyze waveforms recorded from *different locations* in the power system together; because it was practically impossible to time-align the various waveforms properly. However, with the advent of WMUs, waveforms with precision time stamps, i.e., synchro-waveforms, have emerged recently, thus significantly expanding the applications of waveform data. A WMU here refers to various measurement technologies that are capable of measuring and precisely time-stamping waveforms (to the accuracy of, for example, 1 μs). The measurement technology itself can vary, ranging from power quality monitors and digital fault recorders to general waveform recorders. Furthermore, other terms may have been used in the recent literature to refer to WMUs, such as calling them SWMUs or SMUs. The term "synchro-waveform" itself is also sometimes referred to by other names in some literature, such as sync-waves, synchronized waveforms, or synchronized point-on-wave measurements. Regardless of the terminology used, it is anticipated that the upcoming digital substations will have the synchro-waveform data collection capability as a default data source. Such data can be provided by the merging units that digitize current transformer and potential transformer outputs, tag them with precision time stamps, and transmit them through substation communication links for use by various applications. WMUs are anticipated to also be widely deployed outside substations, such as at locations of distributed energy resources, utility assets, loads, as line-mounted sensors, etc. Regardless of the sensor devices used and the locations of sensors, the key in obtaining synchro-waveform data is that the data sampled from different locations are precisely time-stamped, allowing them to be *time-synchronized*, to provide us with a simultaneous view over a broad area to analyze various physical phenomena in power systems. The synchronization is commonly done by using external GPS clocks or by using the Precision Time Protocol. Figure 2 shows different examples of real-world installations of WMUs. These installations include three-phase medium-voltage installations at a substation, three-phase low-voltage installations at grid assets, such as solar inverters, and single-phase low-voltage installations at power outlets. The basic principles are similar.

Basic Examples

Synchro-waveforms can capture the *same* physical phenomenon (i.e., the same event) as it is seen by *multiple* WMUs

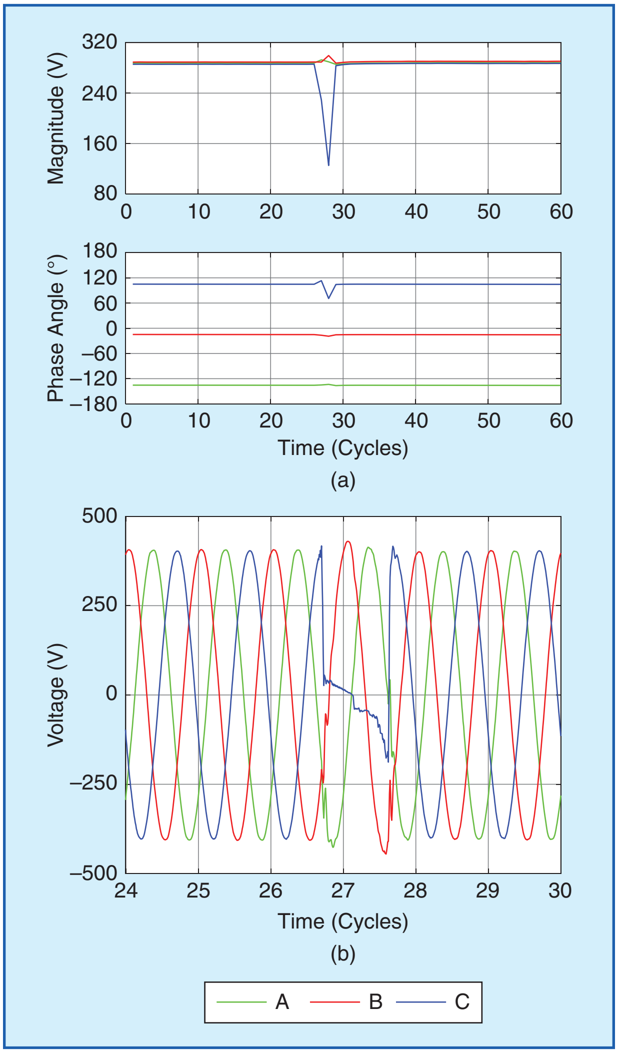

figure 1. Comparing voltage phasors and raw voltage waveforms during a temporary fault: (a) phasor representation in the form of voltage sags and (b) the raw waveforms.

at *different* locations on the power system. This capability is demonstrated in Figure 3. Three examples are shown here. In all cases, WMU 1 and WMU 2 are located at two different but nearby power distribution feeders (the two feeders are near each other). In Case 1, WMU 1 and WMU 2 capture *similar signatures* on all phases. In Case 2, WMU 1 captures a voltage sag on Phase A, as marked inside the dashed red oval. WMU 2 simultaneously captures a much more severe signature of a momentary fault on Phase A. The differences between Cases 1 and 2 are due to the different natures of the two events and the different locations of the events relative to the locations of the WMUs. In Case 3, WMU 1 captures a high-frequency resonance on all three phases, which is not seen by WMU 2. This suggests that the resonance is local. Instances of system-wide resonance, i.e., showing resonance on both WMU 1 and WMU 2, have also been captured but are not shown here.

Synchro-Waveform Data Analytics

Collecting data at a much higher reporting rate than synchrophasors, synchro-waveforms create a new challenge in big data analytics in power systems, moving beyond conventional synchrophasors. Note that, each three-phase WMU reports 3,981,312,000 readings per day (assuming a sampling rate of 256 samples per cycle, and reading only voltage waveforms), which can easily exceed one gigabyte of data. As such, big data analytics become even more crucial—the data must be furnished with useful analytics to translate them into actionable information and practical use cases. Therefore, a need exists for developing new methodologies, tools, and techniques to analyze waveform and synchro-waveform data in power systems.

Data analytics in this field can encompass a wide range of techniques. Waveform data are most useful if they contain disturbances or changes in operating conditions because steady-state waveforms may not provide major new information beyond what is already available. As a result, it is beneficial to do event-based data analytics. To use this strategy, one needs to address the following common tasks that arise in data analytics: *event detection* (using techniques in time-domain, frequency-domain, or hybrid wavelet concepts), *event classification* (by feature extraction from the

(a) (b) (c)

figure 2. Examples of real-world experiments in Riverside, CA, USA, to obtain synchro-waveform measurements. (a) Three-phase 12.47-kV installation at a substation. (b) Three-phase 480-V installation at a solar photovoltaic inverter. (c) Single-phase 120-V measurements at a power outlet. Photography by H. Mohsenian-Rad, P. Khaledian, H. Gomez, and Z.J. Ye.

synchro-waveform data, such as by extracting transient oscillation modes, impulses, graphical features, number of affected phases in the power system, firing angle, magnitude, and duration of the event), and *event location identification* (using data-driven and model-based methods to pinpoint the source location of the event, including subcycle and transient events). Many of these techniques may require extracting the *event waveform* from the raw waveform data, such as by using the concept of *differential waveforms,* which are also sometimes referred to as *cycle-delayed* waveforms. An example is shown in Figure 4. Here, the differential waveform is obtained by *subtracting* the waveform from the power system cycle before the event from the cycle containing the event. The extracted event waveform can much more clearly show the nature of the event. It can be used in various studies, such as in doing *modal analysis* to examine the frequency and the damping rate of the high-frequency oscillations in the system. The frequency of the damping oscillations in Figure 4(b) is about 1 kHz.

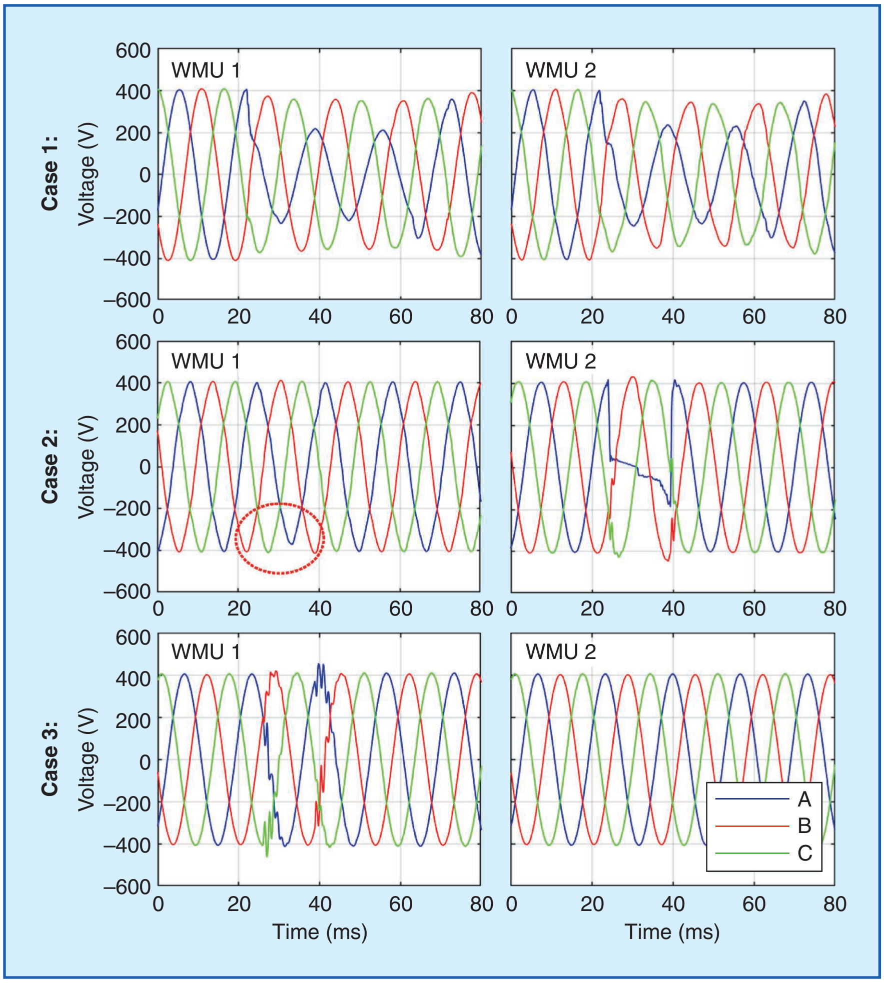

figure 3. Examples of voltage synchro-waveforms from two distribution-level WMUs.

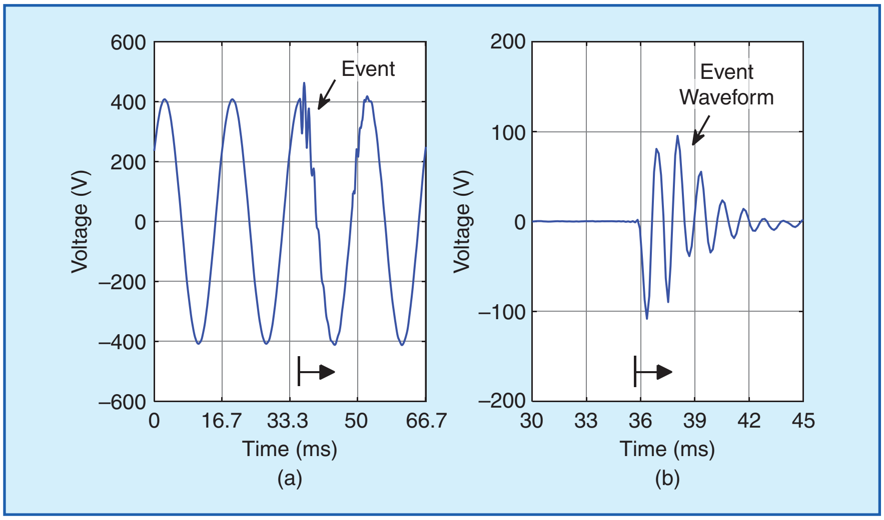

figure 4. (a) Real-world voltage waveform during an event and (b) its extracted event waveform.

Graphical concepts, combined with tools from *image processing*, can also be used, such as by expressing the waveform measurements as a *Lissajous graph*. A Lissajous graph is created by plotting the current waveform versus the voltage waveform, as shown in Figure 5. These graphs can be created using either the raw waveform or the differential waveforms. They can be plotted separately for the waveform measurements from each WMU; thus, providing synchronized screen-shots of the graphical shapes of the waveforms at multiple locations of the power grid; which can be compared to each other. Different features of each Lissajous graph can be analyzed to extract graphical features. For example, the *shape* of the Lissajous graph itself can help identify the *type* of the event. The *rotational angle* of the Lissajous graph can sometimes help identify the location of the event. Further, *similar* events may result in *different* Lissajous graphs that in fact become similar after they are *rotated*. This fact too can be used in identifying the type of an event. The *area* of the Lissajous graph can also be used to detect an event or disturbance.

Synchro-waveforms can also expand our ability to conduct analyses in the *phasor domain*. While PMUs are normally focused on reporting synchrophasors at the fundamental frequency of the power system (such as 60 Hz in North America), synchro-waveforms can also provide synchrophasor *frequencies* or other frequencies. In other words, synchro-waveforms can provide us with *harmonic synchrophasors*. It is noted that, although some existing PMU technologies may support obtaining harmonic phasors on selected harmonics as needed, it is not currently common for most PMUs to provide harmonic synchrophasors as they primarily focus on the fundamental phasors.

An example of obtaining harmonic synchrophasors from synchro-waveforms is shown in Figure 6. The phasor measurements in Figure 6(a), which include the magnitude and phase angle over 800 ms, correspond to the signature of an event as it is captured at the fundamental frequency. Such measurements are those that are commonly provided by PMUs. As for the phasor measurements in Figures 6(b) and (c), they too correspond to the signatures of the *same event* during the *same period*, but they are captured at the third harmonic frequency and at the fifth harmonic frequency, respectively. The additional information that is provided by the harmonic synchrophasors can complement and enhance the analysis that one can do with the synchrophasors in the fundamental frequency. For example, from the graphs in Figures 6(b) and (c), we can see that the event caused an *increase* in the steady-state magnitude of the third harmonic and a *decrease* in the steady-state magnitude of the fifth harmonic. Therefore, even in a frequency-domain analysis, the use of synchro-waveforms can be potentially advantageous because of their ability to provide additional information about the events and their potential root causes. Of course, whether at the fundamental frequency or at harmonic frequencies, synchrophasors are based on applying the Fourier transform to the raw waveform measurements, therefore, they are inherently meant for steady-state analysis. By contrast, synchro-waveforms can capture the raw transient event in the time domain.

Some concepts from power quality analysis can also be used in the analysis of synchro-waveforms, albeit after some modifications. For example, consider the concept of *total harmonic distortion* (THD). In power quality analysis, the THD is often examined over a long period

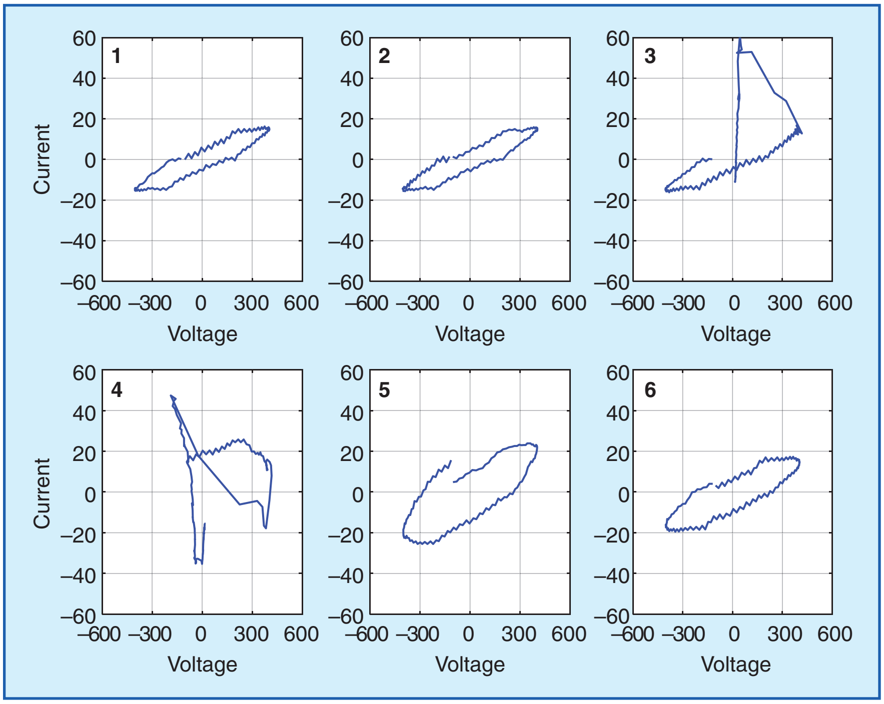

figure 5. Per-cycle Lissajous graphs for voltage waveform (in volt) and current waveform (in amp) during six cycles. A transient event occurs at cycle 3.

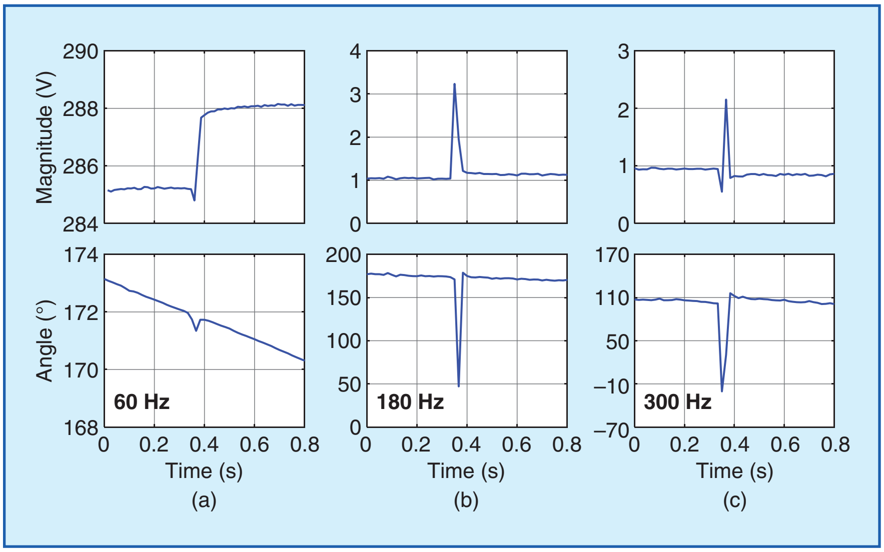

figure 6. Fundamental and harmonic synchrophasor signatures of an event at different frequencies: (a) fundamental frequency, (b) third harmonic, and (c) fifth harmonic.

Synchro-waveforms can be more revealing of bad data, when compared to synchrophasors, because they allow us to directly access the raw waveform measurements.

of time and via statistical metrics. However, in the analysis of synchro-waveforms, we can obtain the THD on a *per-cycle* basis and compare the results across different WMUs in a synchronized fashion. An example is shown in Figure 7. Here, the synchro-waveforms are measured *continuously*, over two hours (120 minutes). Accordingly, 432,000 per-cycle THD values are obtained in this period. The continuous waveform measurements in this example are made by using GridSweep measurement devices at the University of California, Riverside. There are two instances in this figure, corresponding to two cycles, where the per-cycle THD is *unusually higher* than the rest of the cycles. These two instances indicate the occurrence of two separate subcycle events, as marked with arrows. The first subcycle event occurs at a moment when there is also a sudden change in the long-term THD. Notice that the THD suddenly drops when we compare the cycles *before* the first subcycle event in comparison with the cycles *after* that first subcycle event. In fact, the first event is the transitional distortion that happened in the waveform, likely due to a switching action in the power system, which also resulted in a steady-state change in the THD. The second subcycle event appears to be an isolated incident since it does not cause a change in the rest of the per-cycle THD values before and after this subcycle event occurs. By comparing similar graphs from *multiple* WMUs, we can identify the source region of the subcycle events for further investigation.

The previous examples are focused on using data analytics to extract *valuable information* from synchro-waveforms. However, we also need to distinguish and resolve *bad data*. Bad data in synchro-waveforms can be due to different malfunctions in the system, such as in the sensor itself, GPS clock, instrumentation equipment, or the communications systems. Importantly, all such causes of bad data in synchro-waveform measurements also happen in measuring synchrophasors or other types of sensor measurements in power systems. However, the very high sampling rate of synchro-waveforms can make certain bad data more impactful in the analysis using synchro-waveforms. On the other hand, synchro-waveforms can be more revealing of bad data, when compared to synchrophasors, because they allow us to directly access the raw waveform measurements.

Finally, other data analytics concepts need to be addressed too, such as data compression, data storage, choice of sampling rate, etc. Collectively, the different nature and the much larger size of waveform data compared to both phasor data and the traditional supervisory control and data acquisition data, call for a new vision in big data analytics in this field.

Emerging and Future Applications of Synchro-Waveforms

Waveform data are not new to power engineers and researchers. What is new about synchro-waveform data are that waveform data from multiple locations can now be analyzed together because of our ability to time-align them properly. The unique values brought by *multilocation* data include, for example, the capability to do the following: 1) solve location-based problems, such as oscillation source detection; 2) characterize multiport components and subsystems; 3) enhance the accuracy and reliability of information extracted; 4) perform asset monitoring and situational awareness with a focus on detection and identification of incipient faults (i.e., early-stage faults); 5) analyze subsynchronous and supersynchronous oscillations; 6) analyze power electronics devices and IBRs; 7) analyze dc circuits, where phasor data are not applicable; 8) monitor wildfires by characterizing the signatures of the events that can lead to ignition and correlating the outcome of synchro-waveform analytics with external factors, e.g., weather conditions; 9) provide differential protection, relay coordination, and distributed protection; and 10) perform transient state estimation in power systems.

Next, we discuss some of these applications.

Analysis of IBRs

Synchro-waveforms can be used to investigate the behavior of IBRs, such as their *dynamic response* to various system-wide disturbances in a power system. Two examples are shown in Figure 8. Both examples involve the same pair of photovoltaic (PV) inverters. PV inverter 1 and PV inverter

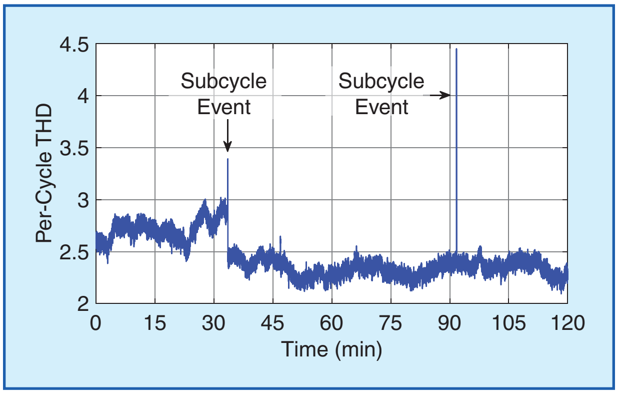

figure 7. The per-cycle THD in a *continuous* stream of synchro-waveforms. Two subcycle events are marked.

2 are on the *same* subtransmission system but on two *different* distribution feeders. They have the same model of three-phase inverters but with different sizes, i.e., different solar power generation capacities. Figure 8(a) and (b) shows the IBR's responses to the same subcycle disturbance. The disturbance causes momentary distortions in voltage waveforms across the subtransmission system, which is visible in the voltage waveforms in Figure 8(a) and (b). The disturbance happens at an unknown location of the power system, and the two inverters are at two different locations on two different feeders under the same substation. Hence, as the disturbance propagates through the power system, it may manifest itself differently in the voltage waveforms at these two different inverter locations. The disturbance results in a dynamic response by each of the IBRs in the form of momentary agitations in their current waveforms. The dynamic responses of the two IBRs are generally similar, with two back-to-back high-frequency oscillations.

Next, consider Figure 8(c) and (d), which shows the two IBRs responding to a fault. The fault causes a severe unbalanced voltage sag on all phases. In response, both IBRs trip and *cease production*, which is evidenced by the severe drop in current in both PV inverter 1 and PV inverter 2, reaching zero current after a few cycles. Notice that, even though the fault itself was cleared after three to four cycles, neither of the two IBRs could *ride through the fault*. It took several minutes for these IBRs to restart and resume production after they tripped (not shown here). Importantly, if a large number of IBRs cease production in response to the same fault, it can suddenly cause a major loss of generation capacity across the power system, which can result in ripple effects, such as an *excursion in frequency*. Such system-wide impacts of faults on IBRs and subsequent frequency excursions have been reported recently in California and Texas. For example, see the report from the North American Electric Reliability Corporation, "900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance," on the event that happened in Southern California on 9 October 2017.

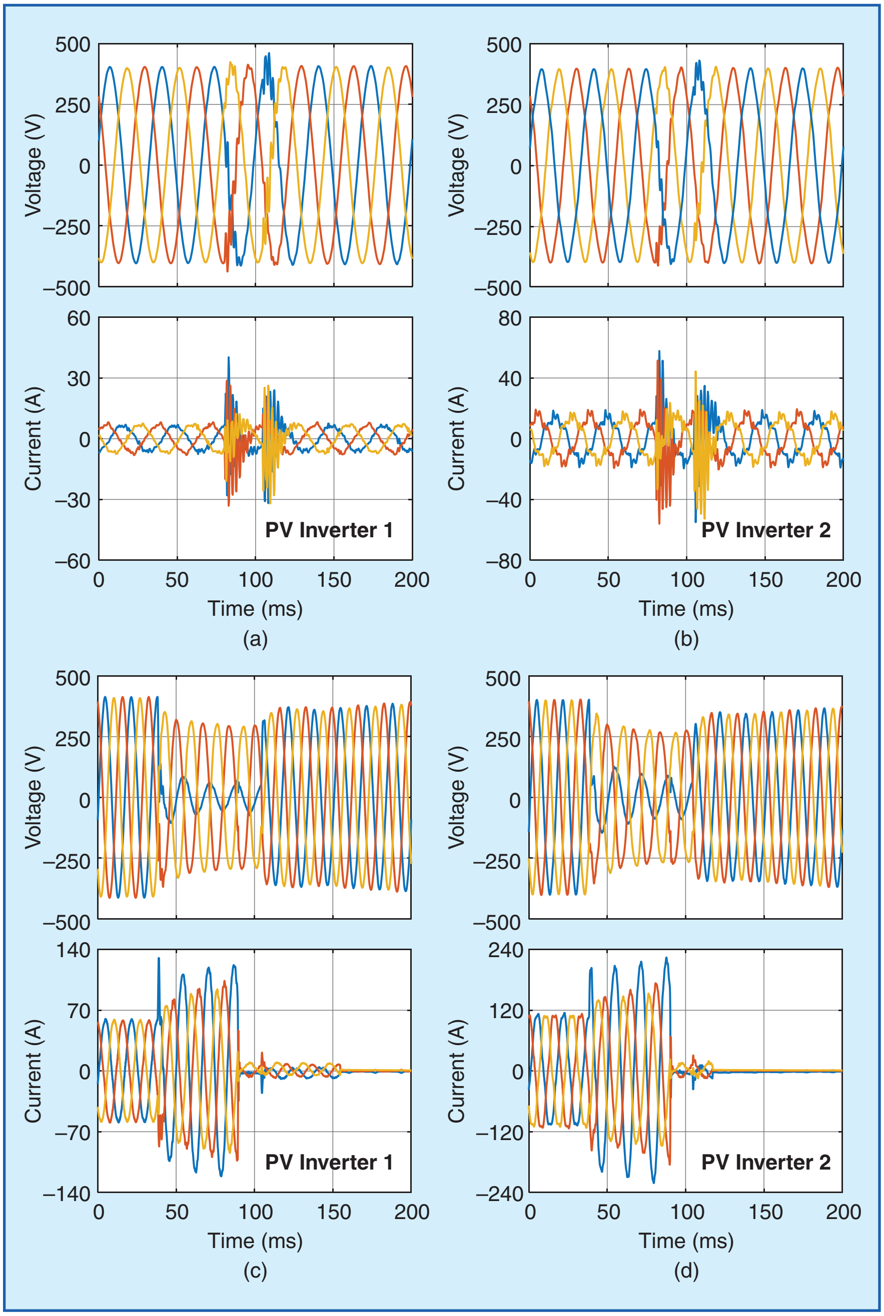

figure 8. Using synchro-waveforms to monitor two distribution-level IBRs. (a) and (b) Simultaneous dynamic waveform response of the two PV units during a system-wide subcycle disturbance. (c) and (d) Simultaneous waveform response of two PV units that cease production when a fault impacting the entire local subtransmission system occurs.

Characterizing Subsystems During Faults and Disturbances

Synchro-waveforms can help analyze the behavior of different subsystems of a power system during various events. An example is shown in Figure 9. The layout of the network is shown in Figure 9(a), which includes a 230-kV substation that serves several 12.47-kV feeders. Four WMUs are installed on this network, one (i.e., WMU 1) at 230 kV and three (i.e., WMUs 2, 3, and 4) at 12.47 kV. A fault occurs downstream of WMU 2. The synchronized voltage and current waveforms are shown in the figure for all four of the WMUs, before, during, and after the fault occurs. We can make several observations based on these synchro-waveforms. *First*, the fault current is *almost entirely* supplied by the 230-kV substation. This conclusion is evident from the huge fault current that is captured by WMU 1 and WMU 2 during the fault. Both WMUs see the fault downstream of their location. We may add that WMU 1 and WMU 2, along with any other WMUs that may exist downstream of WMU 2, can be used for *relay coordination* and adjusting the parameters in distributed protection. *Second*, all four WMUs capture voltage sags. The voltage sag is considerable at the substation, but it is particularly severe at the locations of WMUs 2, 3, and 4. *Third*, the impact of the fault is also severe on the two feeders downstream of WMUs 3 and 4. However, the nature of this impact is very different across these two feeders. For the feeder downstream of WMU 3, the fault causes several loads to trip, which explains the lower current at this feeder even *after* the fault is cleared. Notice that the steady-state current *after* the fault is less than the steady-state current *before* the fault at this feeder. By contrast, for the feeder downstream of WMU 4, the fault causes a dynamic response and a momentary increase in current, shortly *after* the fault is cleared. The higher current gradually wears down, ultimately reaching the pre-fault level (not shown here). The preceding analysis is only one example to demonstrate the advantages of using synchro-waveforms to explain the diverse behavior of different subsystems in a power system during faults and disturbances. Of course, some of the previous observations could also be made (to some extent) by using synchrophasors. Yet, the extent of the additional details that are visible in synchro-waveforms can provide more information about the complex behavior of different subsystems during faults and disturbances.

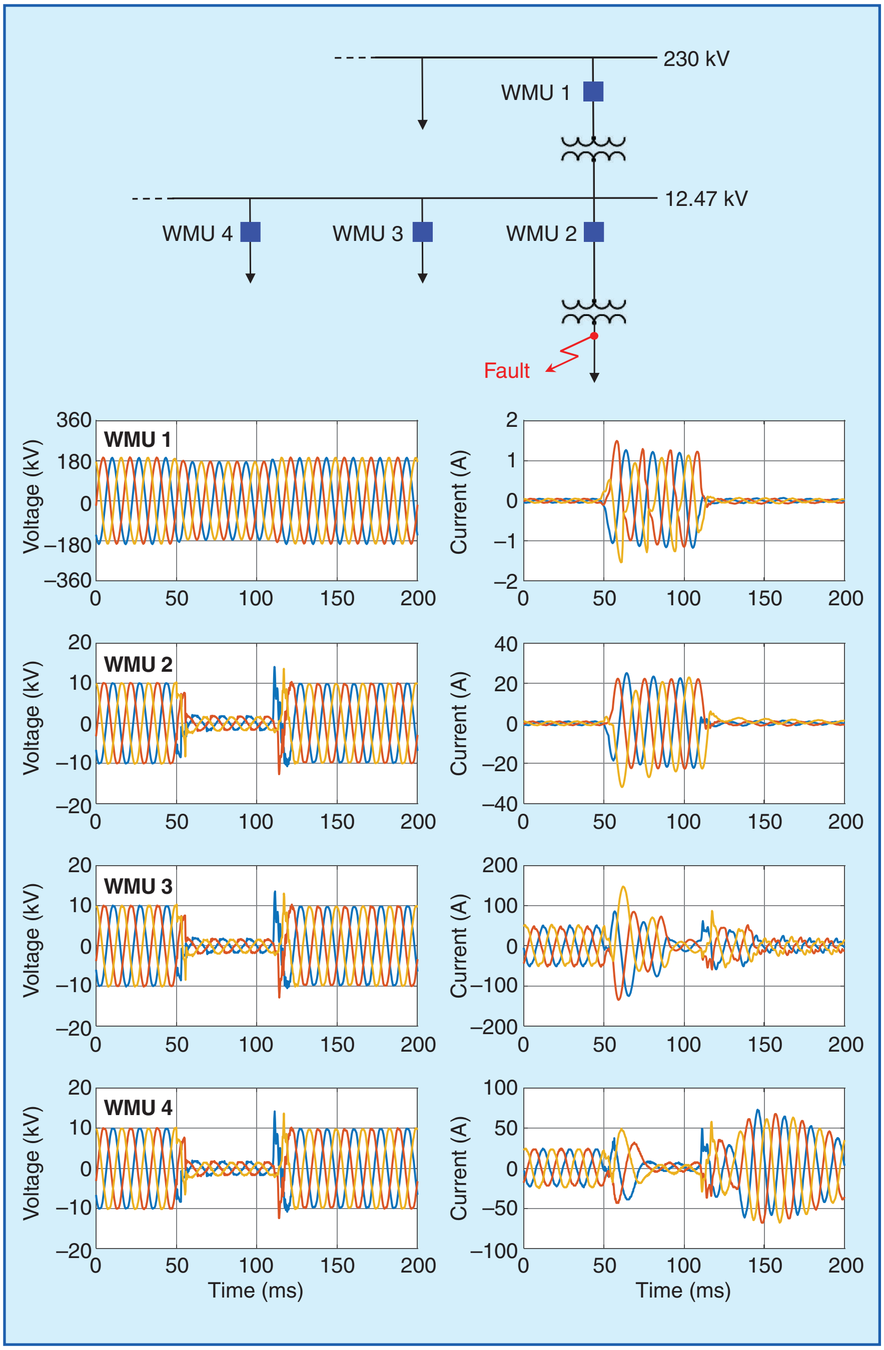

figure 9. Synchro-waveforms for voltage and current that are captured by four WMUs across the 230-kV and 12.47-kV network buses during a fault.

Condition Monitoring and Analysis of Incipient Faults

Waveform measurements are powerful tools for condition monitoring, with the ability to detect incipient faults, i.e., early-stage failures, in power system equipment. Extensive

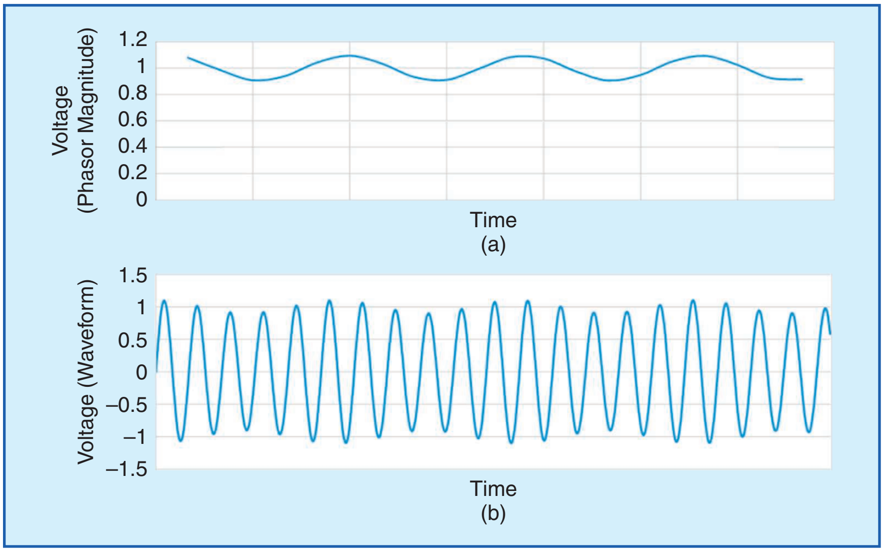

figure 10. Voltage oscillation, as perceived from (a) phasor's perspective and (b) waveform's perspective.

studies have already shown that irregular shapes of voltage waveforms, and particularly of current waveforms, can reveal early signs of failures in underground cables, overhead conductors, transformers, capacitor banks, etc. Such irregularities cannot be easily seen in phasor data. However, traditionally, collecting waveform measurements is considered only after equipment is flagged as potentially having some issues. That is, waveform measurements are traditionally used as a means for *extended inspection* after concerns are raised about the operation of a piece of equipment. This approach has started to change in recent years. With the advancements in sensor technologies and data collection and communication, WMUs can now be deployed in large numbers to *continuously* monitor the conditions of a power system and its components. Nevertheless, it will remain a challenge, so for the foreseeable future we must conduct condition monitoring using the *scarcity in the locations* where WMUs are installed. As a result, we must use the waveform measurements to monitor the power system apparatus not only at the immediate locations of the WMUs, but also at the locations where WMUs are *not* installed. The use of synchro-waveforms, i.e., the capability to synchronize the waveform measurements, can be of great assistance in tackling this challenge. Specifically, by *simultaneously* capturing the same physical phenomenon by two or more WMUs, we can *remotely* detect its occurrence and even extract its characteristics.

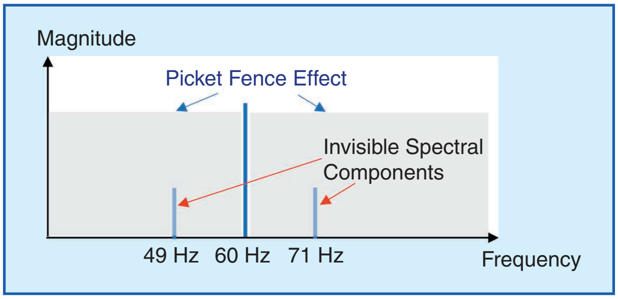

figure 11. Spectral components of voltage oscillation. The components at 49 Hz and 71 Hz can be seen only in synchro-waveforms and not in synchrophasors.

Oscillation Source Identification and Ranking

Power system oscillations, such as *subsynchronous resonance* and low-frequency oscillations, are an important concern to power system operators. With the increased adoption of inverter-based generators, more system oscillation phenomena with higher frequencies than those exhibited in historical behavior have been reported. Power system oscillations are investigated traditionally using phasors, i.e., essentially viewing the oscillation of the 60-Hz voltage. With the help of synchro-waveforms, a new set of techniques could be developed for oscillation monitoring, especially the identification of generators contributing most to an oscillation event. An example is shown in Figure 10. First, consider the fluctuations in the magnitude of the voltage phasors in Figure 10(a). These fluctuations show an 11-Hz voltage oscillation, as perceived from the phasor's perspective in this figure. In reality, the oscillation is the result of the modulation of the $f = 60$ Hz fundamental waveform with a modulation frequency of $f_{\text{modulation}} = 11$ Hz, as shown in Figure 10(b). The voltage waveform in this figure has three frequency components at f, $f + f_{\text{modulation}}$, and $f - f_{\text{modulation}}$. Accordingly, the voltage waveform in Figure 10(b) is the sum of three sinusoidal terms at 60 Hz, 49 Hz (= 60 – 11), and 71 Hz (= 60 + 11). Therefore, if we perform Fourier analysis on the voltage waveform in Figure 10(b), we will see that there are two interharmonic frequency components of 49 Hz and 71 Hz, as shown in Figure 11. These two interharmonic components cause the appearance of an 11-Hz voltage oscillation in the phasor representation. Since accurate energy exchanges can only be assessed in the original waveform in the time domain, the previous waveform perspective provides new insight on how to monitor oscillations. Therefore, if we can monitor the amount and direction of power exchanges among the various generators in the system at these two frequencies, then the main contributors to the oscillation (i.e., the largest interharmonic power producers) can be identified and ranked. Since we need to compare the interharmonic powers of different generators in real time, the powers must be time-aligned properly for comparison, and the synchro-waveform becomes essential data for such an analysis. This concept has been

> By *simultaneously* capturing the same physical phenomenon by two or more WMUs, we can *remotely* detect its occurrence and even extract its characteristics.

demonstrated successfully to identify critical doubly fed induction generators causing subsynchronous resonance in a wind farm. It is key to note that, if we work with the phasors only, the interharmonic components are *not* visible because of the well-known *picket fence effect* of Fourier analysis; i.e., these components are masked because of the lack of spectral resolution (see Figure 11). Therefore, the use of synchro-waveforms is necessary.

Source Location for Transient Subcycle Events

Identifying the source location of disturbances, including the disturbances that are caused by incipient failures, is a critical task in power systems. Over the past two decades, there have been great efforts in developing methods that use synchrophasors to address this task. However, many disturbances, in particular those that are only transient and last for only a fraction of a cycle, i.e., subcycle events, often cannot be properly observed by synchrophasors. Therefore, their source locations also cannot be properly identified by the analysis of synchrophasors. Importantly, recent studies have shown that some of the existing methods used for identification of source location based on synchrophasors can be revised to also work based on synchro-waveforms, albeit after proper modifications. We may also need brand-new methods that directly address the challenges and the opportunities in working with synchro-waveforms.

Standardization and Activities in IEEE Committees

Given the great potential that synchro-waveforms offer to the field of power systems monitoring and situational awareness, there is a growing need to build activities in IEEE across the relevant subcommunities spanning different IEEE Societies. So far, the authors and also others with interests in this new field have initiated several activities across a number of IEEE Power & Energy Society subcommittees, including the Power System Operation, Planning, and Economics Technologies and Innovation Subcommittee, the Power System Instrumentation Measurements Sensors Subcommittee, and the Analytic Methods for Power Systems Big Data Analytics for Power Systems Subcommittee. The activities so far have been in the form of organizing panels and giving presentations on the topic of synchro-waveforms. Similar efforts have been made with relevant IEEE conferences, such as the IEEE International Conference on Smart Grid Synchronized Measurements and Analytics. These efforts need to be expanded, to engage broader involvement from industry and academia, and to ultimately form active working groups and initiate drafts for standardization for the synchro-waveform measurements and analytics.

Conclusions

This article provided a high-level and illustrative overview for the emerging concept of synchro-waveforms for power systems monitoring and situational awareness. The focus was on real-world examples, data analysis, and a wide range of potential use cases. As this new field continues to evolve and grow, it will introduce several new challenges, new opportunities, and new and innovative applications, which are yet to be discovered and addressed. Standardization activities will also be needed to shape and support the growth in this new field and to engage broader involvement from industry and academia.

For Further Reading

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Biographies

Hamed Mohsenian-Rad is with the University of California, Riverside, CA 92521 USA. He is a Fellow of IEEE.

Wilsun Xu is with the University of Alberta, Edmonton, AB T6G 2R3, Canada. He is a Fellow of IEEE.