Synchro-Waveforms: A Window to the Future of Power Systems Data Analytics

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Background: Waveforms are the most granular and authentic representation of voltage and current in power systems. With the latest advancements in the 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 can be referred to as 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 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.

Accordingly, in this magazine paper, we provide a high-level overview to this 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 vs Phasors: Fig. 1 provides a comparison, based on real-world data, between the conventional phasor measurements that are provided by PMUs versus the raw waveform measurements that are provided by WMUs. The three-phase voltage phasor measurements (magnitude and phase angle) are shown in Fig. 1(a). While phasor measurements can indicate the presence of a major voltage sag event between cycle 25 and cycle 30, the details of this event cannot be understood based on these measurements. However, such details are understood very well by looking at the three-phase voltage waveform measurements in Fig. 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 many other similar examples, raise the following questions: "*Why should we tie up 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 time domain?*"

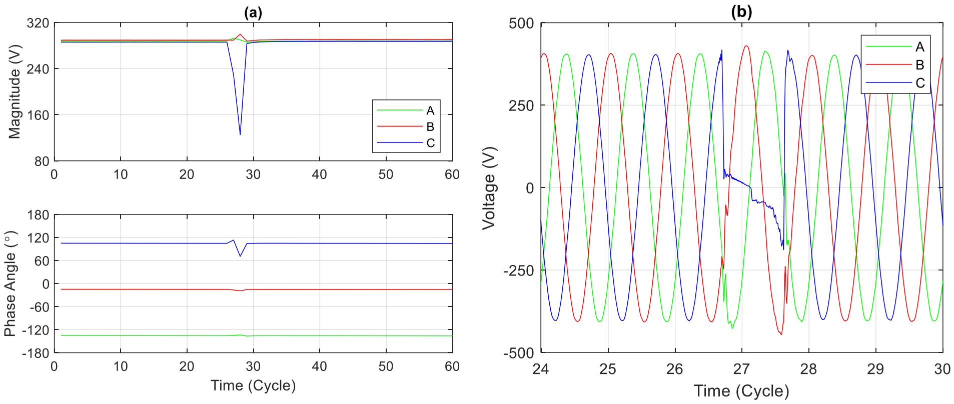

Fig. 1. Comparing raw voltage waveforms with in (a) with phasor representation in (b).

Real-World Technologies: Synchro-waveform measurements can be obtained by a wide range of real-world instruments, which are collectively referred to as WMUs as a generic term. The measurement technology itself can vary, ranging from power quality monitors, digital fault recorders, to general waveform recorders. In fact, the upcoming digital substations will have the synchro-waveform data as default data source. Such data is provided by the Merging Units that digitize CT and PT outputs, tag them using Precision Time Protocols (PTP), and transmit them through substation ethernets for use by various applications. The key in obtaining synchro-waveform data is that the data sampled from different locations must be precisely time-synchronized such as by using an external GPS clock. Fig. 2 shows different examples for real-time installation 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 principal concepts are the same.

Fig. 2. Examples of real-world WMU installations in Riverside, California: (left): 3-phase 12.47 kV installation at a substation; (top-right): 3-phase 480 V installation at a PV inverter; (bottom-right): single-phase 120 V installation at a power outlet.

Real-World Examples: Synchro-waveforms capture the *same* physical phenomenon (i.e., event) as seen by *multiple* WMUs at *different* locations. This is demonstrated in Fig. 2. Three examples are shown here. In all cases, WMU 1 and WMU 2 are located at two nearby power distribution feeders. 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. However, WMU 2 simultaneously captures a more severe signature of a momentary fault on Phase A. The differences between Cases 1 and 2 is due to the different nature and location of the event in these cases. In Case 3, WMU 1 captures a high-frequency resonance on all three phases, which is not seen by WMU 2. This suggest that the resonance is local. Other examples have captured system-wide resonance, i.e., showing resonance on both WMU 1 and WMU 2, which is not shown here.

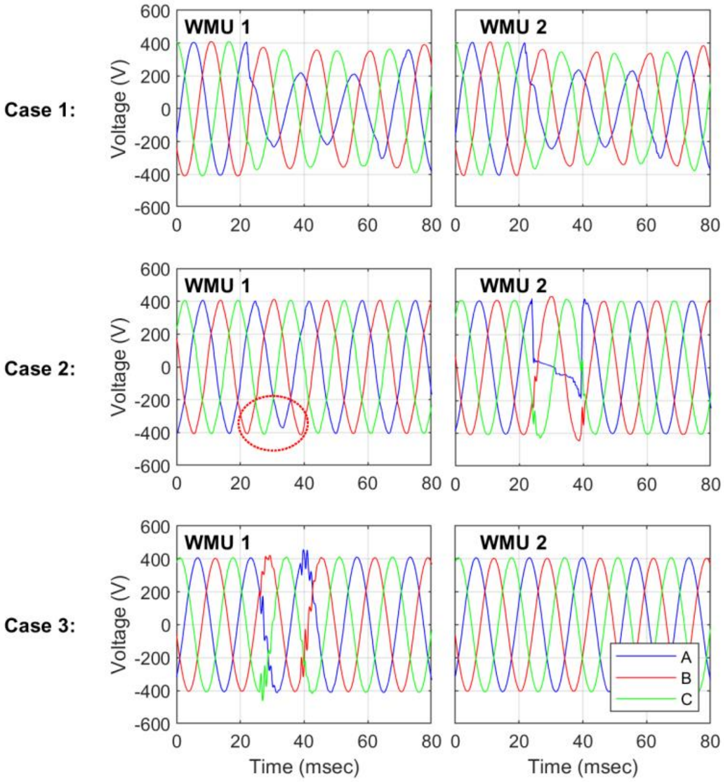

Fig. 3. Examples of voltage synchro-waveforms from two WMUs.

Synchro-Waveform Data Analytics: At a much higher reporting rate than synchro-phasors, synchro-waveforms create a new dimension in Big Data Analytics in power systems, moving beyond the conventional synchro-phasors. Note that, each three-phase WMU reports 3,981,312,000 readings per day (assuming as sampling rate of 256 samples per cycle), which can easily exceed one gigabytes 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. This calls 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. To conduct event-based data analytics, one needs to conduct the following tasks: event detection (using techniques in time-domain, frequency domain, and hybrid wavelet concepts), event classification (by feature extraction, such as transient oscillation modes, impulses, graphical features, number of affected phases, angle, magnitude, and duration of events), and event location identification (using data-driven and model-based methods to pin-point the source location of the event, including sub-cycle and transient events). Many of these techniques may require extracting the event "signal waveform" from the raw waveform, such as by using the concept of differential waveforms. An example is shown in Fig. 4.

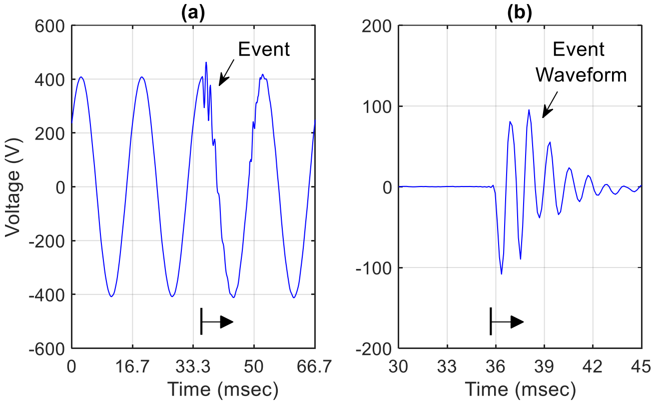

Fig. 4. Real-world voltage waveform during an event, as in (a), and its extracted event waveform, as in b).

Graphical concepts and image processing can also be used, such as by expressing the waveform measurements as Lissajous graph by plotting current waveform versus voltage waveform, as shown in Fig. 5, either in raw for or differential form.

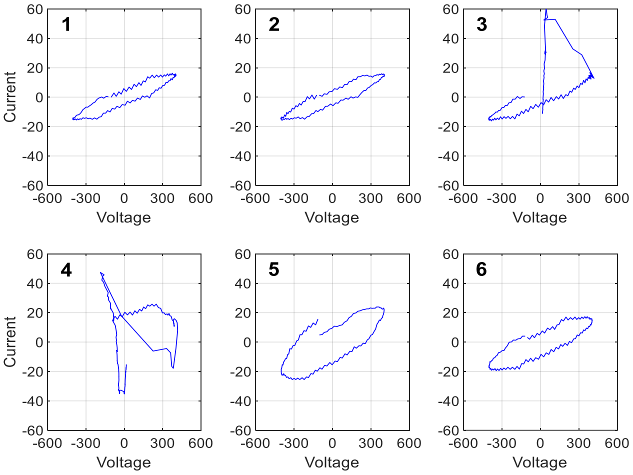

Fig. 5. Per-cycle Lissajous graphs for voltage and current during six cycles. A transient event occurs at cycle 3.

Other data analytics concepts need to be addressed too, such as data compression, data storage, etc. Collectively, the different nature and the much larger size of waveform data compared to both phasor data and the traditional SCADA data, calls for a new vision in big data analytics in this field.

Emerging and Future Applications: Waveform data is not new to power engineers and researchers. What is new about synchro-waveform data is that data from multiple locations can now be analyzed together due to their being able to time-aligned properly. The unique values brought by multilocation data include, for example, to 1) solve location-based problems such as oscillation source detection, 2) characterize multi-port components and subsystems, 3) enhance the accuracy and reliability of information extracted, **4)** asset monitoring and situational awareness with focus on detection and identification of incipient faults (i.e., early stage faults), **5)** analysis of sub-synchronous and super-synchronous oscillations; **6)** analysis of power electronics devices and inverter-based-resources (IBRs), **7)** analysis of direct current (DC) circuits, where phasor data is not applicable; **8)** wildfire monitoring, to characterize the signatures of the events that can lead to ignition; to correlate the outcome of synchro-waveform analytics with external factors, e.g., weather conditions; **9)** differential protection, relay coordination, distributed protection.

These are only a few examples of the potential applications of synchro-waveforms. More applications are likely to be identified as more synchro-waveforms data becomes available for research and in the industry.

Note to EiC: New figures will be added to the full submission of this magazine paper, including real-world examples for sub-synchronous resonance, issues with power electronics devices, and wildfire detection.

- There will be three or four more figures in the full submission to show specific applications.

Further Readings: The paper will be concluded by giving a short list of key references for further reading.