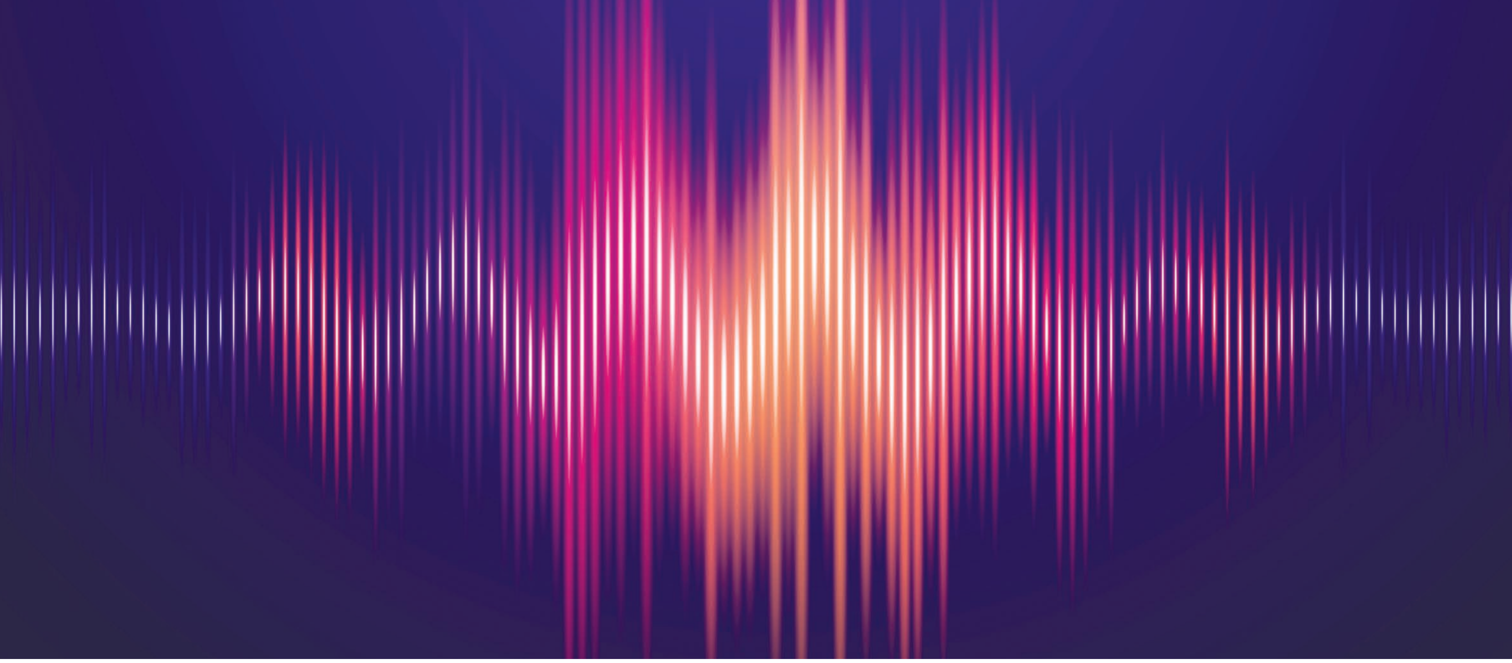



# Synchro-Waveforms in Wide-Area Monitoring, Control, and Protection

## Real-World Examples and Future Opportunities

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THE CONCEPT OF SYNCHRO-WAVEFORMS HAS received increasing attention in recent years in the field of power system monitoring, keeping pace with the changes and the challenges in the power systems and smart grids landscape. The sensor device to record synchro-waveforms may be referred to as a waveform measurement unit (WMU). WMUs record time-synchronized waveform measurements of voltage and current at different locations on a power network.

When synchro-waveforms are compared with synchrophasors, and WMUs are compared with phasor measurement units (PMUs), several similarities and differences

> What can synchro-waveforms offer beyond what is already available with other technologies, such as synchro-phasors?

may be observed. Similar to PMUs, WMUs achieve time synchronization by using the GPS or the Precision Time Protocol. In this regard, WMUs can be seen as an extension of the conventional PMUs. The key difference is that a WMU reports time-synchronized raw samples of voltage and current waveform measurements, whereas a PMU uses these raw samples to calculate phasor representations of the fundamental components of the voltage and current waveforms. WMUs provide the most accurate representation of voltage and current transients in power systems. A brief comparison between PMUs and WMUs is provided in Table 1.

WMUs can report synchro-waveforms as a continuous (gapless) stream of measurement samples, or they can operate on an event-triggered basis, where waveform data are discarded (i.e., not reported) unless specific event detection criteria are met. The latter scenario overlaps with some other existing sensor technologies, such as digital fault recorders and power quality meters. If a digital fault recorder or a power quality meter is capable of time synchronization, these devices too can serve as WMUs to provide synchro-waveforms.

In some literature, synchro-waveforms are also referred to as time-synchronized point-on-wave measurements or time-synchronized sampled values. WMU devices are also sometimes referred to as point-on-wave sensors or synchro-waveform measurement units.

The architecture of a synchro-waveform system is shown in Figure 1. It consists of several WMUs as measurement devices, a mechanism such as a GPS to time-synchronize the waveform measurements, and a platform to process the synchro-waveform data to support various data-driven applications in power systems monitoring, control, and protection.

## Motivation

While the technology and the infrastructure to support synchro-waveform systems are gradually taking shape, we are facing some questions, most notably: What can synchro-waveforms offer beyond what is already available with other technologies, such as synchro-phasors?

In this article, we seek to explore some answers to this question, with a focus on the applications of synchro-waveforms in wide-area monitoring, control, and protection. We will also discuss the implications of the following two key features of synchro-waveforms in these applications: 1) the ability to collect and analyze streaming or triggered raw waveform data instead of phasors or other forms of approximated or processed representations, and 2) the ability to synchronize the waveform measurements from multiple locations on the power network.

Of course, every data-driven power system application may ultimately use some form of filtering and processing of the waveform data. However, having access to raw time-synchronized waveform samples ensures that such filtering and processing is customized for each application.

For instance, with respect to wide-area control and stability (see the section "Synchro-Waveforms in Wide-Area Control and Stability Monitoring"), an analysis based on PMUs can miss the oscillations that are caused by the proliferation of inverter-based resources (IBRs) at frequencies well above and well below the fundamental frequency of the system.

## Features and Characteristics of Synchro-Waveforms and Their Potential to Enhance Wide-Area Monitoring in Power Systems

Synchro-waveforms can support various applications in power system monitoring. The extent of their effectiveness (and necessity) may depend on many factors. In this section, we will discuss some of those factors based on real-world examples of synchro-waveform measurements.

### *Benefits of High Sampling Rates and Time Synchronization*

One of the key advantages of synchro-waveforms is their ability to provide raw waveform measurement samples at high sampling rates. The choice of sampling rate may depend on the specific application, leading to different costs for the technology and the supporting infrastructure. The general expectation is that the sampling rate should be at least at the level of a few kilohertz. Higher sampling rates are also common and often necessary in practice to capture certain transient behavior of interest, such as from tens of or hundreds of kilohertz up to a few megahertz.

**table 1. Brief comparison between a PMU and a WMU.**

| Technology | Reported Measurements | Reporting Rate | Filtering | Synchronization |
|---|---|---|---|---|
| PMU[†] | Fundamental phasors | 10–60 frames (phasors) / second | Meets P and M classes | Yes |
| WMU | Raw waveform samples | 32–512 samples / cycle (or higher) | Meets Nyquist theorem | Yes |

[†]Per IEEE Standard C37.118.1-2011 with Amendment C37.118.1a from June 2015.

Broadly speaking, the sampling rate can determine which physical phenomena can be visible in synchro-waveforms. As an example, consider the voltage waveform measurements in Figure 2(a), which are captured during a fault at a sampling rate of 14.4 kHz. Figure 2(b) zooms into a period of 8 ms (half a cycle) around the beginning of the fault. Figure 2(c) shows the waveform measurements that are captured during the same period and at the same location as those in Figure 2(b), but at a sampling rate of 1 MHz. The waveform signatures in Figure 2(b) and (c) are very different, despite being associated with the same physical phenomena and being from the same window in time. The waveform measurements at the higher sampling rate in Figure 2(c) show the presence of some high-frequency oscillations. These oscillations are more clearly

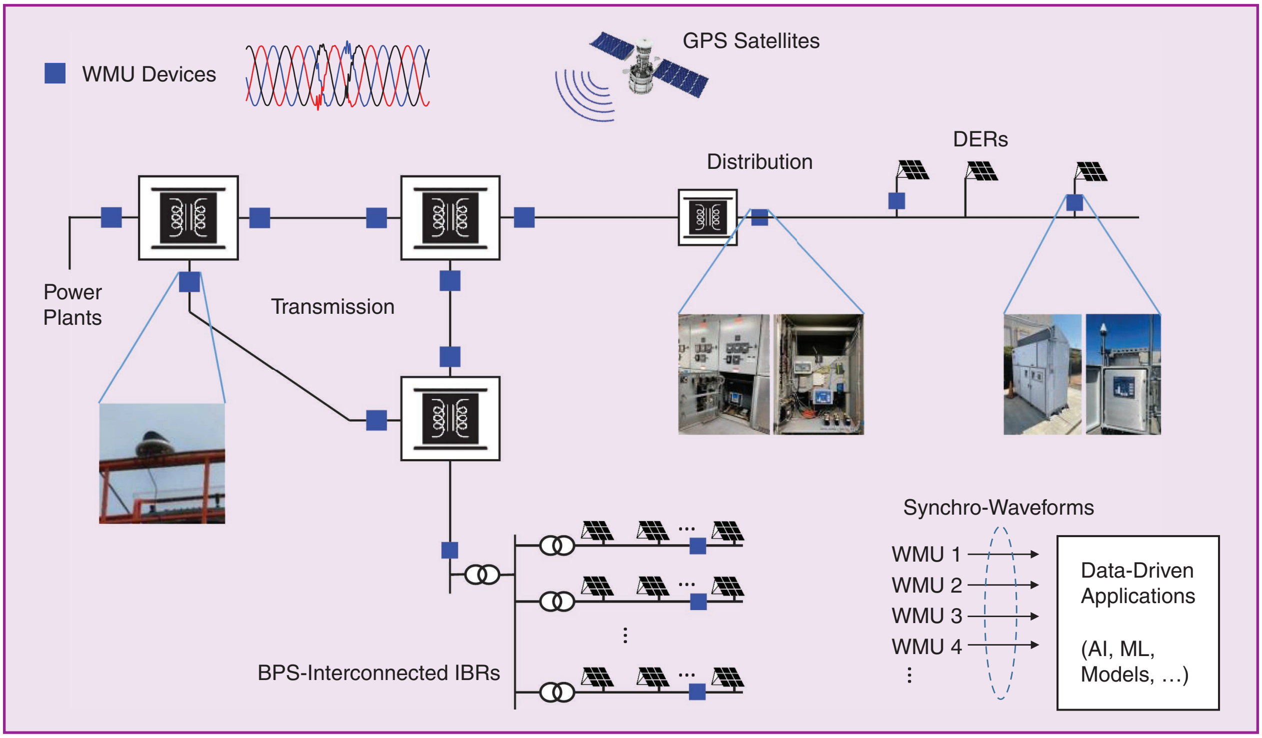


**figure 1.** The high-level architecture of a synchro-waveform system. BPS: bulk power system; DER: distributed energy resource; AI: artificial intelligence; ML: machine learning.

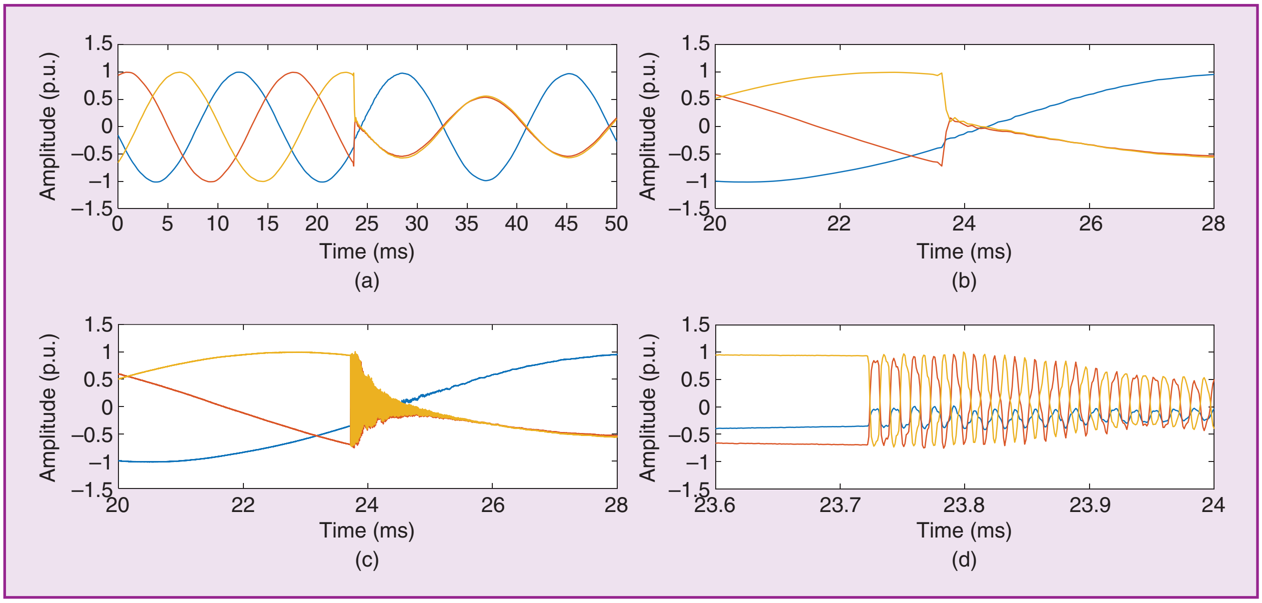


**figure 2.** (a), (b) Voltage waveforms captured during a fault at a 14.4-kHz sampling rate. (c), (d) Voltage waveforms during the same fault and at the same location but captured at a 1-MHz sampling rate.

visible after we further zoom into only 400 $\mu$s of the waveform samples, as in Figure 2(d).

For wide-area monitoring, a sampling rate of tens to hundreds of kilohertz is likely sufficient. However, higher sampling rates can still be beneficial. In particular, when a high sampling rate is combined with precise time synchronization of the waveform samples, it can support a precise sequence of events recording in the power system. The results can be useful in many applications.

An example, with application to fault location, is shown in Figure 3. Figure 3(a) and (b) show the electric field waveform measurements that are taken at the two ends of a high-voltage transmission line during a fault. The length of the line is about 24 km. Once we zoom into the waveform measurements, we can see two different event start times at the sensor locations, as shown in Figure 3(c). The fault is observed within 9 $\mu$s (2.7 km) from one end and within 71 $\mu$s (21.3 km) from the other end. The difference between the two event times is due to the traveling-wave propagation time difference from the location of the fault to each end of the line.

Time synchronization can potentially, but not necessarily, also help to align the time-stamping of the individual samples among multiple WMUs, such as at the two ends of a transmission line. Several protective relaying and fault location applications can benefit from this capability.

Another application of time synchronization is in benchmarking. Here, the idea is to compare the simultaneous waveform responses of a group of components in the power system to the same disturbance. For instance, one can compare how different IBRs (from the same vendor or different vendors) within a certain geographical region may respond to the same disturbances. Such a comparison can lead to early detection of potential IBR malfunctions. It can also be used to fine-tune the control parameters (see the section "Synchro-Waveforms in Wide-Area Control and Stability Monitoring") and the protection system parameters (see the section "Synchro-Waveforms in Wide-Area Protection") of the IBRs by using the desirable responses of the other IBRs in the region as reference points.

WMUs can be installed at high-voltage, medium-voltage, and low-voltage circuits for various purposes. The impact of the same physical phenomenon is likely manifested differently at different locations and different voltage levels, because of the impact of transformers and other elements of the circuit. For example, when a fault occurs at a high-voltage transmission line, it causes a disturbance that can propagate through the 500-kV/220-kV/69-kV/12-kV/480-V transformers to affect an IBR. These transformers (and other factors, such as the electrical distance from the event location) can significantly change the shape of the distortions in the voltage waveforms at the location of measurements. Synchro-waveforms provide the means to allow the understanding and modeling of such changes.

### *Benefits of Continuous Streaming of Synchro-Waveforms*

Currently, the most common approach to report synchro-waveforms is to do so on an event-triggered basis. While each WMU does record the waveforms continuously, it captures and reports them only if it detects an event. Event detection is done using various metrics, such as by checking if the measurements (or the changes in the measurements) exceed certain levels or if the frequency spectrum suggests oscillations. The literature on event detection is diverse, and most WMUs have options to program the criteria and setting the logic and the parameters for event detection.

The analysis of event signatures can be used in a wide range of grid monitoring and situational awareness applications using data-driven methods. For instance, a historical database can be used to train algorithms (using machine intelligence) to detect, predict, and characterize potential issues in various elements of the power system before major system-wide incidents occur.

However, the main challenge in event-triggered waveform capture

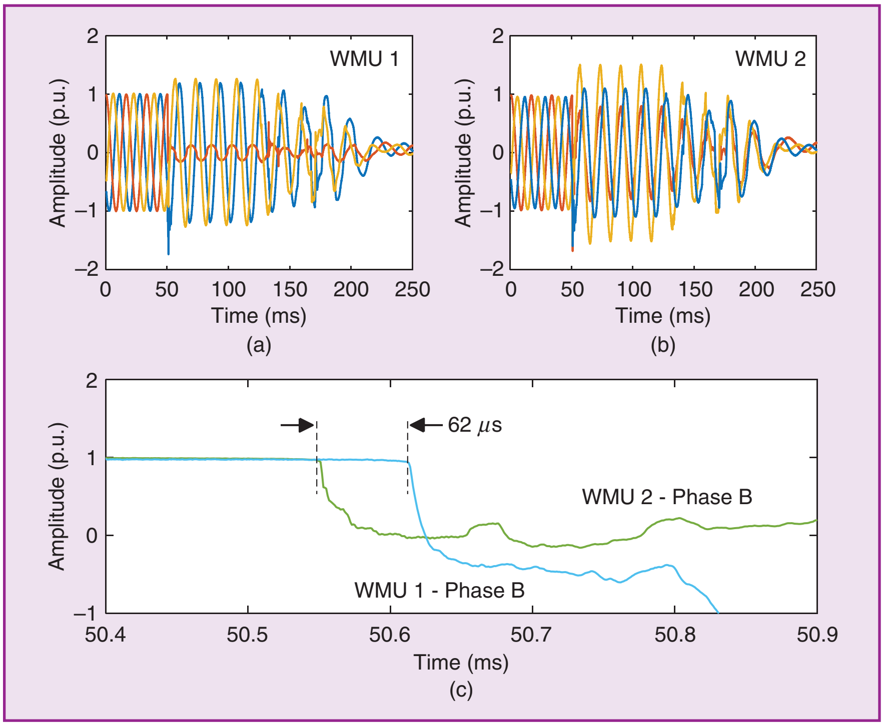


**figure 3.** Precise time synchronization can allow capturing the impact of event propagation time to calculate how the impact of an event (such as a fault) propagates on the network.

Since synchro-waveforms collect data at a much higher reporting rate than synchro-phasors, they create new challenges in big data analytics in power systems.

is that there is no guarantee that all of the informative cycles of the synchro-waveforms are captured at each WMU. This is due to the challenges in properly setting up the event-triggering functions. There are many different types of events with different characteristics; therefore, it can be very difficult to set all of the thresholds correctly. On one hand, a tight event-detection criterion can result in losing important information. On the other hand, a loose event-detection criterion can frequently trigger waveform capture where information of interest is not contained, causing additional overhead in data processing, to the extent that switching to continuous streaming could be more desirable.

Ultimately, the main advantage of event-triggered waveform capture is to cope with the issues regarding the limitations of local data storage and communication. In the future, these issues will likely be addressed through information and communications technology advancements.

### *Challenges With Data Volume and Data Quality*

Since synchro-waveforms collect data at a much higher reporting rate than synchro-phasors, they create new challenges in big data analytics in power systems. Data volume remains an issue irrespective of whether faster communications and larger data storage memories are available. It will be inevitable for the industry to adopt proper data analytics tools using artificial intelligence (AI) and machine learning (ML) to allow full utilization of the benefits from both time synchronization and high sampling rates.

Data quality is another major challenge in this field. Data loss and bad data can occur due to different malfunctions, such as those in the sensor, time synchronization, instrumentation, or communication. In the short term, data quality will also be an issue because of the lack of synchro-waveform standardization; such standardization can help design more accurate systems across the industry.

The high volume of data, particularly under continuous streaming of synchro-waveforms, means that data transport and data storage are major challenges. Effective data compression can help, using tools and techniques in other fields, such as audio and video signal compression. Data transport issues, such as latency and communication bandwidth, also need to be addressed. Needless to say, data transportation is an inherent necessity in synchro-waveforms; the advantages of time synchronization cannot be fully realized unless the data streams are gathered and compared from multiple WMU locations.

Building on the basic concepts we have discussed in this section, in the next section, we will focus on the applications of synchro-waveforms in wide-area control and stability monitoring. We will discuss the applications of synchro-waveforms in wide-area protection in the section "Synchro-Waveforms in Wide-Area Protection."

## Synchro-Waveforms in Wide-Area Control and Stability Monitoring

Traditionally, the dynamic behavior of power systems has been determined by the dynamic performance of synchronous generators and loads. However, with the large-scale integration of power electronics-based systems, such as IBRs for utility-scale solar and wind power generation, the dynamic response of power systems has become faster and more complex.

The time scales related to IBR controls and dynamics may encompass from microseconds to a few milliseconds, and they may not be observed accurately by phasor measurements. Furthermore, the dynamic behavior in voltage and current waveforms is no longer dominated by the fundamental frequency component of the power system. As a result, if we focus solely on the dynamics at the fundamental frequency (i.e., 50 or 60 Hz), which is the current common practice in PMU-based data analytics, we inherently miss the control and stability phenomena in the power system at the frequencies above and below the fundamental frequency of the system.

### *IBR Waveform Dynamics*

The overall dynamic performance of IBRs is dominated by their internal power electronics converter controls that interface the energy source and the electric grid. For example, the dynamic recovery of an IBR after a fault or a major switching event can be oscillatory due to the complex dynamic characteristics of the IBR's phase-locked loop (PLL) control, inner-current control, or high-level control loops. Whether or not any such oscillatory behavior does occur, and the dominant frequency of any such oscillation, will all depend on the IBR's design, its control settings, network configuration, and the characteristics of the disturbance.

Consider the example in Figure 4. This figure shows the voltage and current waveforms at an IBR before, during, and after a minor disturbance occurs in the power system. The disturbance in this example was likely caused by a switching event at a nearby capacitor bank. This disturbance by

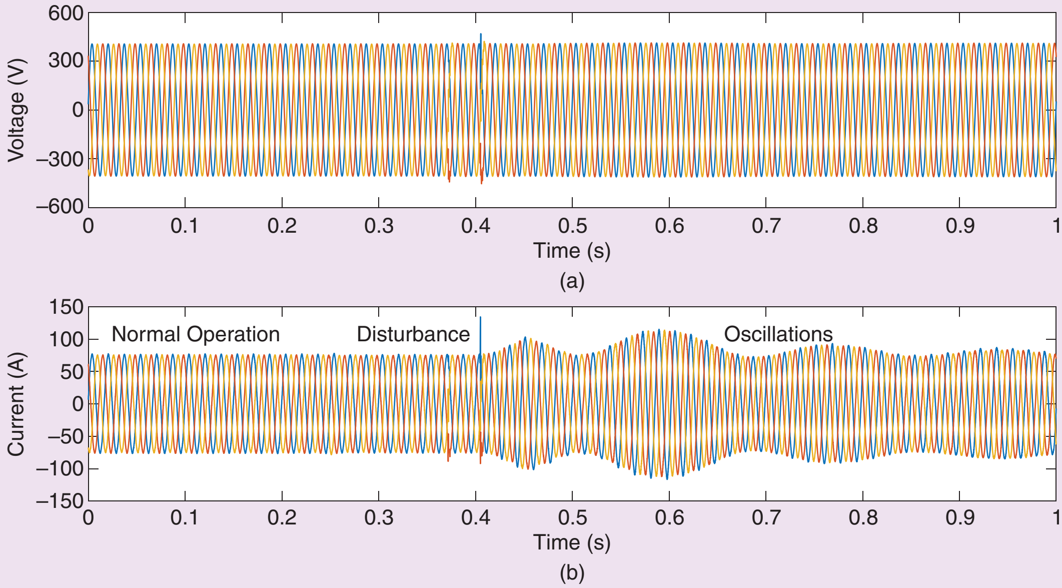


**figure 4.** Subsynchronous oscillations are generated at an IBR shortly after a minor disturbance.

itself is a benign phenomenon. It only resulted in a minor and momentary high-frequency agitation in voltage waveform. However, this minor disturbance triggered an unusual subsequent dynamic oscillatory behavior by the IBR. Specifically, it caused some subsynchronous (with a frequency less than 60 Hz) oscillations in the IBR's injected current. Interestingly, out of more than 100 recorded instances of generally similar disturbances at this location, only four disturbances resulted in this type of clearly visible subsynchronous oscillatory response by the IBR. In the remaining cases, similar disturbances did not trigger any visible subsynchronous oscillations. This attests to the complexity of

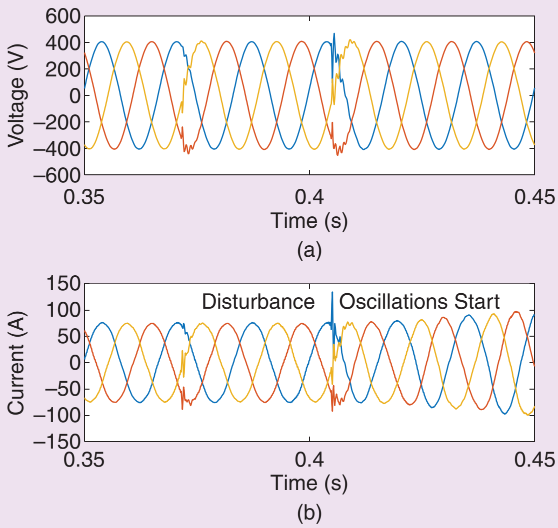


**figure 5.** Zooming in on Figure 4 to see the initial disturbances that triggered the oscillation.

the dynamic behavior of the IBR and the difficulty in modeling such complex dynamics.

In practice, identifying the wide range of possible causes for the oscillations and instabilities associated with IBRs is challenging, partly due to the unavailability of reliable models for various IBRs, including the lack of accurate black box data-driven models, to predict abnormal behavior. The use of high-resolution synchro-waveform measurements can help close this gap.

For instance, further analysis of the waveform measurements in Figure 4 can help reveal additional information about the abnormal dynamics in this figure. First, let us zoom into the voltage and current waveform measurements during the time frame between 0.35 and 0.45 s, as shown in Figure 5. Here, we can better see the waveform distortions that resulted from the initial minor disturbance that happened right before the start of the subsynchronous oscillations at the IBR. Analyzing the waveforms in Figure 5 can help in identifying the kind of disturbances that can trigger the subsequent subsynchronous oscillations at the IBRs that we previously saw in Figure 4.

Next, consider the analysis in Figure 6 that are extracted from the waveform measurements of current in Figure 4. Figure 6(a) shows the IBR's current waveform after we removed the fundamental frequency component and starting from the start of the subsynchronous oscillations. The waveform in this figure is denoted by Δ Current, which is the raw current waveform minus the fundamental current waveform. The extracted waveform in this figure clearly reveals the subsynchronous oscillations at some sideband frequencies that are modulated on the fundamental component. This is evident in the frequency amplitude spectrum in Figure 6(b), which is obtained by applying a fast Fourier transform to Δ Current. The sideband frequency components are at 60 Hz ± $f_{sideband}$, where the fundamental frequency is 60 Hz. Through a trigonometric analysis, it can be shown that the pair of sinusoidal oscillations at 60 Hz ± $f_{sideband}$ result in modulating the amplitude of the fundamental component at modulating frequency $f_{sideband}$, causing the subsynchronous oscillations that we previously saw in the current waveforms in Figure 4. The most dominant sideband frequency in Figure 6(b) is around 4 Hz, where the corresponding sideband oscillations occur at 56 Hz = 60 – 4 and 64 Hz = 60 + 4. Of course, other modulation frequencies (albeit weaker) are also present in this example, as we can see in the frequency spectrum in Figure 6(b). The presence of amplitude modulations at sideband frequencies is known to be due to the dynamics of the PLL and control loops in the dq-frames of the voltage-source converters that are widely used in IBRs.

The previous two analyses are not doable unless we have access to waveform measurements. If PMU data are used instead of WMU data, we may not recognize the high-frequency characteristics (or even the presence) of the disturbance in Figure 5 that triggered the subsequent abnormal oscillations at the IBR. The use of PMU data (instead of WMU data) may also result in misleading conclusions with regard to the frequency of the subsynchronous oscillations, due to frequency aliasing of the sideband frequencies in phasor measurements.

### High IBR Penetration Dynamics and Stability

At high penetration rates of IBRs, their dynamic responses to disturbances may not only affect the individual IBRs but may also cause cascading instability across the power system. In fact, because of the wide timescales related to the controls of IBRs, their dynamics can cross-couple with both the electromechanical dynamics of synchronous generators as well as the electromagnetic transients of the network. Moreover, several inverters nearby may also generate dynamic interactions with each other. Similar interactions can take place between IBRs and other types of power system components with power electronics, such as the controls of high-voltage direct current equipment and flexible ac transmission systems devices. These can lead to unstable power system oscillations over a wide range of frequencies.

By using synchro-waveforms, we can identify the precise time instances and the sequence in time at which the oscillations at each pair of sideband frequencies started at different IBRs. Synchro-waveforms can also assist with identifying the triggering cause of instabilities. For example, some recent case studies have reported detecting subsynchronous oscillations at IBRs without observing any sign of any utility switching, outage, or fault event that could be correlated to the outburst of the oscillations. Access to synchro-waveforms across IBRs and substations can help operators verify or further investigate these unusual cases.

Proper identification of the cause of an IBR-related oscillation can lead to mitigation strategies. For example, if measurements can confirm that the cause of subsynchronous oscillations at a particular interconnection point is resonance with a series compensation capacitor, then increasing the series compensation can reduce the grid impedance and lead to better stability.

Even though some regulatory agencies have investigated the contribution of the large bulk power system (BPS)-interconnected IBRs to harmonic oscillations in recent years, we still have only limited, mostly anecdotal, knowledge about the contribution of (the smaller) distributed energy resources (DERs) in this area. Installing inexpensive WMUs at DERs will allow operators to identify which types of events may trigger oscillations in which types of DERs and to measure the aggregate contribution of the DERs to the oscillations at different frequencies and under different conditions.

Waveform sample measurements can also be used to analyze the strength of the grid at each interconnection point. The strength of the grid in this context refers to the grid's ability to maintain voltage and frequency stability with minimal impact from the injected current by the IBR. If the IBR's injected current affects the voltage magnitude significantly at the interconnection point, then the grid is considered weak; because it is susceptible to IBR's misbehavior. For example, in Figure 4, there was no visible subsynchronous oscillation in the voltage waveforms. However, by repeating the customized analysis in Figure 6, one can reveal the presence of similar subsynchronous oscillations also in voltage, albeit at much lower amplitudes. This line of analysis based on raw waveform measurements can in the future also lead to developing a strategy to predict the

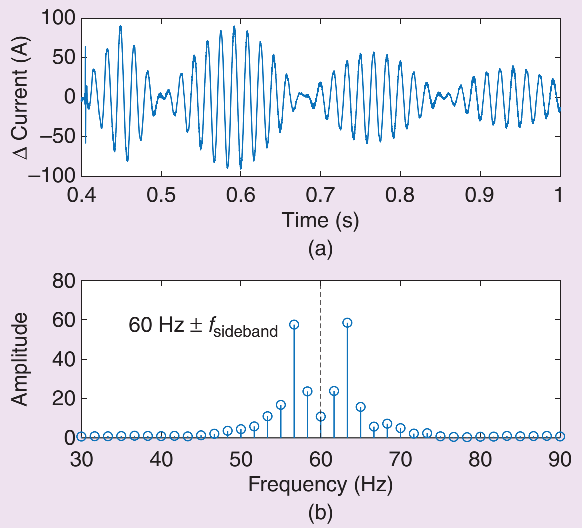


**figure 6.** (a) Current waveform in Figure 5 after removing the fundamental frequency and (b) the resulting frequency amplitude spectrum and the presence of dominant sideband frequencies at 60 Hz ± $f_{sideband}$.

> The momentary impact of the disturbance was misinterpreted as a large deviation in the fundamental frequency, thus incorrectly inducing a high ROCOF.

impact of the IBR-induced subsynchronous oscillations of IBRs of different sizes.

### *Training Data-Driven Models or Validating Physics-Based Models to Support Control and Stability*

A proper model of the IBR controllers and the power system can identify the potential causes of instability and oscillation over a wide range of frequencies and under different operating conditions. In this regard, synchro-waveform measurements can be used in two types of efforts: model development and model validation.

If historical recordings of waveform samples are available, then data-driven models can be developed to predict the behavior of IBRs when connected to the electric grid during normal conditions, contingencies, and under varying factors, such as different grid strengths. One of the advantages of data-driven models is their ability to model the circumstances that may not have been foreseeable during the initial designs or when the interconnection was initially commissioned.

Black box dynamic models can be built in several ways. One approach is to develop models to predict the IBR's injected current waveforms (as an output signal) in response to a given terminal voltage waveforms (as an input signal). This includes impedance spectrum models and transfer functions in the frequency domain or other comparable models in the time domain. Such models can be developed using regression, modal analysis, or ML. They can help identify the circumstances where different types of events may trigger different types of abnormal waveform dynamics at each IBR or each class of IBRs and at each frequency.

Another modeling approach, which is mainly relevant to BPS-interconnected IBRs, is to build models to predict the terminal voltage at each IBR (as an output signal) for a given voltage waveform at the point of interconnection (as an input signal). Such models inherently require time synchronization among the waveform measurements at the locations of the IBRs and the point of interconnection; see Figure 7. Therefore, using synchro-waveforms would be inevitable. This approach is motivated by the recent real-world observations in several solar and wind farms in which the voltage conditions were considerably different during grid disturbances between the individual inverter terminals and the point of interconnection. This condition resulted in unexpected behavior at the plant's terminals. The enhanced plant-level monitoring, control, and protection in Figure 7 can lead to enhanced system-wide monitoring, control, and protection, as previously depicted in Figure 1.

Synchro-waveforms can also help with model validation. They can calibrate the existing physics-based or gray box models to enhance accuracy in identifying instability conditions. The instance of each event that is captured by WMUs may serve as an opportunity to evaluate the accuracy of the existing models in predicting the waveform dynamics of the IBRs. The models can be updated accordingly and integrated into the simulation tools that are used by system operators.

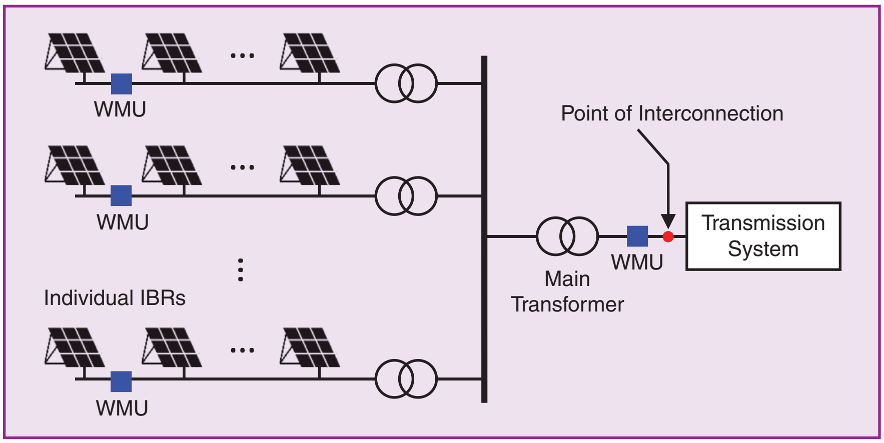


**figure 7.** WMU locations at the point of interconnection and across (a subset of) individual IBRs to collect synchro-waveform data that are needed to build certain data-driven dynamic models.

### *Frequency and Rate of Change of Frequency Estimation*

The presence of events and disturbances can disrupt the estimation of the (fundamental) frequency and the rate of change of (fundamental) frequency (ROCOF). Standard methods based on phasor analysis often fail to make correct estimations during disturbances. An incorrect estimation of frequency and ROCOF can negatively affect control and protection functions. It is necessary to use raw waveform sample measurements to distinguish

> The dynamic behavior in voltage and current waveforms is no longer dominated by the fundamental frequency component of the power system.

transient waveform disturbances from the dynamics at the fundamental frequency components.

In this regard, recent studies have shown that ROCOF estimation is particularly susceptible to sudden phase shifts or amplitude shifts in voltage (or current) waveforms that are caused by disturbances, such as faults, network reconfigurations, and equipment or load switching. In some cases, the momentary impact of the disturbance was misinterpreted as a large deviation in the fundamental frequency, thus incorrectly inducing a high ROCOF.

During disturbances, the voltage waveform can be nonstationary, and the frequency spectrum of the voltage waveform can contain energy across many frequencies in a transient manner. One remedy is to move beyond the traditional use of the Fourier transform as the means to extract phasors from waveform samples. The use of other techniques, such as the Hilbert transform and compressed sensing, has been proposed and tested in recent years.

### *Grid-Following Versus Grid-Forming IBRs*

Finally, in the future, synchro-waveforms can help with analyzing the complex interactions among the emerging grid-forming IBRs, the existing grid-following IBRs, and the synchronous generators, all on the same power system with complex dynamics. This will be a "battlefield" where synchro-waveforms may win over any other legacy monitoring platforms. This issue is still emerging and is not the focus of this article, but it is certainly going to dominate future literature on synchro-waveform systems and WMUs.

## Synchro-Waveforms in Wide-Area Protection

The concept of synchro-waveforms is not new in power systems protection. Both synchro-phasors and synchro-waveforms have been used in differential protection, where time-synchronized measurements from two terminals of a transmission line are compared to detect fault currents along the line. Differential relays usually outperform distance relays in terms of dependability (correctly reacting to faults) and security (correctly not reacting when there is no fault). As another example, time-synchronized multicast messaging has been used in various proposals for protective relay coordination and distributed system-wide protection. However, protection relays typically exchange only status information and processed data, rather than raw waveform samples.

With the increasing penetration of IBRs, there is a need to revisit the traditional protection strategies, to handle power systems that are increasingly supplied by different types of IBRs, including BPS-interconnected IBRs as well as DERs.

For example, IBRs have demonstrated unexpected and complex behavior in response to certain faults, such as tripping in circumstances where they are not expected to trip. The nature of the output of IBRs during a fault and their differences compared to synchronous generators have caused misoperations in the existing grid protection systems.

Another difficulty in this field concerns the interactions between IBRs and unit protection relays at various legacy power apparatuses as well as system-wide protection relays. While these interactions have been studied theoretically and in laboratory settings, very little evidence about the details of these interactions currently exists based on field measurements.

Synchro-waveforms can potentially help in addressing these various challenges in power system protection.

### *System-Wide Fault-Induced Disturbances Caused by High Penetration of IBRs*

The North American Electric Reliability Corporation (NERC) has recently investigated multiple IBR-related disturbances in regions with high penetration of IBRs, such as in California (the Canyon 2 Fire disturbance, Palmdale Roost disturbance, Angeles Forest disturbance, etc.) and in Texas (the Odessa 1 and 2 disturbances). In all cases, loss of generation occurred at several IBRs in response to a fault in the power system, such as a fault in a high-voltage transmission line. This wide-area loss of IBRs happened even though the fault was unrelated to IBRs and it was cleared normally by the protection system within two to three cycles (a few milliseconds). Nevertheless, the subsequent tripping of several IBRs in a large geographical area (such as up to 200 miles away from the location of the initiating event in the case of Odessa disturbances), resulted in system-wide disturbances and frequency excursion.

The causes of wide-area IBR tripping were identified through postmortem analysis, and they were diverse. They included PLL loss of synchronization, momentary cessation, overvoltage at inverter or feeder (for BPS-interconnected resources), dc reverse current in inverter, underfrequency at inverter or feeder, or misoperation in ride-through. Depending on the cause, generation loss can last 5–10 min until an automatic restart after a wait period, or it may require a manual reset (such as in the case of dc reverse current, which causes an IBR fatal error code).

IBRs have demonstrated unexpected and complex behavior in response to certain faults, such as tripping in circumstances where they are not expected to trip.

An example of an IBR tripping (and its subsequent automatic restart) is shown in Figure 8. The IBR in this example is a three-phase solar generation unit in California. The waveform measurements in Figure 8(a) and (b) show the moment when a fault occurred. The fault occurred at an unknown distance upstream of the substation where the IBR was interconnected. The fault caused a momentary voltage distortion and sag at the terminal voltage of the IBR. It lasted only three cycles before the fault was cleared normally by a protection action. Nevertheless, it resulted in losing power production for about 5 min, as seen in the meter-recorded production profile in Figure 8(c). The power production in this example resumed after an automatic restart. Notice that the (minutely) meter-recorded voltage profile in Figure 8(d) cannot reveal the cause of IBR tripping in this case.

Even though the fault itself may last only two to three cycles, the subsequent sudden loss of production can affect the balance of generation and load in the system, which can cause wide-area disruptions and frequency excursions. For instance, during the Canyon 2 Fire disturbance in California, a fault in a transmission line resulted in losing more than 900 MW of solar photovoltaic (PV) generation, which subsequently caused a frequency excursion in the Western Interconnection, as seen in Figure 9. The system frequency reached a nadir of 59.878 Hz at about 3.3 s after the fault. In another example, during the Odessa disturbance in Texas, a fault that occurred on a step-up transformer at a combined-cycle power plant resulted in losing one quarter of all of the PV generation resources in Texas Interconnection. The system frequency reached as low as 59.817 Hz. In both examples, none of the affected IBRs were tripped consequentially by the fault itself.

A key recommendation from NERC in the aftermath of the previous incidents was to equip IBRs with the capability to capture high-speed waveform data, not only from the interconnection point at BPS-interconnected IBRs but also at some of the individual IBRs. This is indeed the same scenario that we discussed in Figure 7 in the section "Training Data-Driven Models or Validating Physics-Based Models to Support Control and Stability" for wide-area control and stability. The reasoning is similar: the voltage conditions during grid disturbances can be vastly different across the grid and between the individual IBR terminals and the point of interconnection.

Having access to synchro-waveforms from multiple locations can explain why each IBR may trip. The results can help improve the relay settings of individual IBR protection systems. The availability of raw synchro-waveforms can also help coordinate the operation of the individual IBR protection relays with that of the protection system

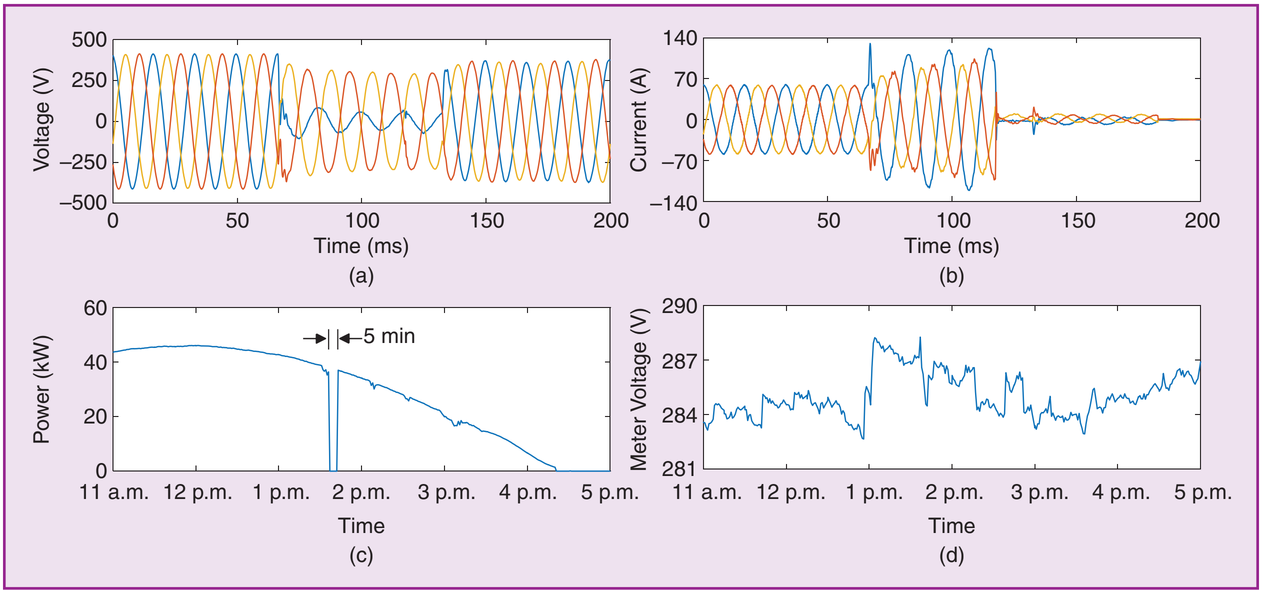


**figure 8.** Fault-induced IBR tripping. (a), (b) Voltage and current waveform sample measurements. (c), (d) Meter-recorded power production and meter-recorded voltage.

at the point of interconnection. If the relay at the point of interconnection deems the disturbance to be caused by an upstream fault for which no plant-level protection action is needed, then it can inform the protection systems at individual IBRs to adjust their actions accordingly, leading to adaptive relaying.

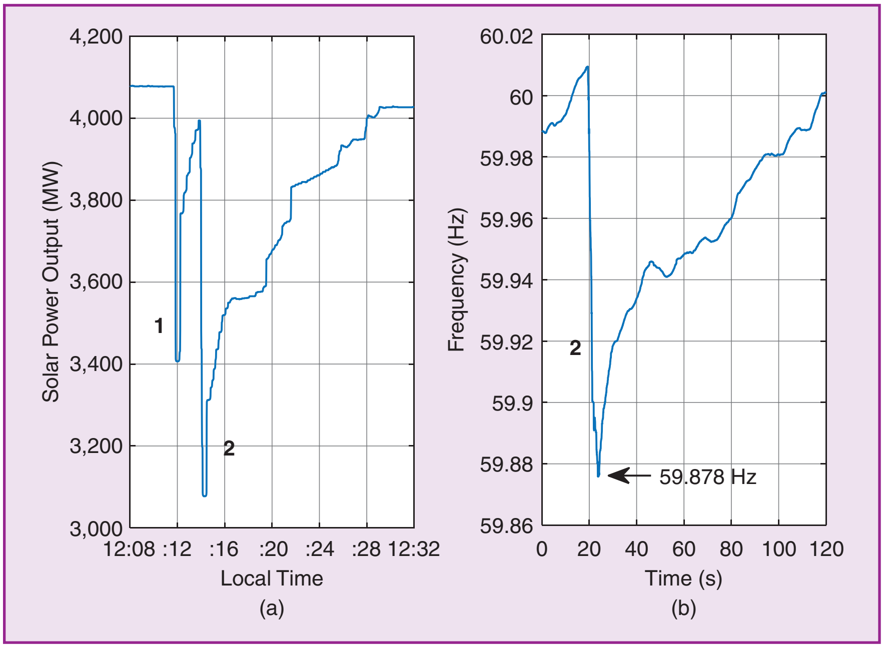


**figure 9.** Two faults (about 2 min apart) on two transmission lines caused the tripping of several PV resources. (a) The loss of solar generation during the two faults. (b) The impact of the second fault on system frequency. (Source: Southern California Edison – Joint NERC and WECC Staff Report.)

Furthermore, synchro-waveforms can precisely identify exactly which part of the distorted voltage waveform during a fault caused the tripping at each IBR. This can be done by time-aligning the waveform signatures across IBR locations versus substation location and protection relay tripping as reference points.

Recent studies have shown that it is common that only a subset of IBRs in a region trip during a wide-area disturbance. Such partial tripping can happen even among the IBRs within the same BPS-interconnected IBR facility. This is true also when it comes to various DERs. Synchro-waveforms can help us understand and possibly model such diverse and complex behavior among IBRs.

An example is shown in Figure 10, where synchro-waveforms are recorded at two IBRs. Both IBRs are DERs, which are interconnected downstream of the same substation

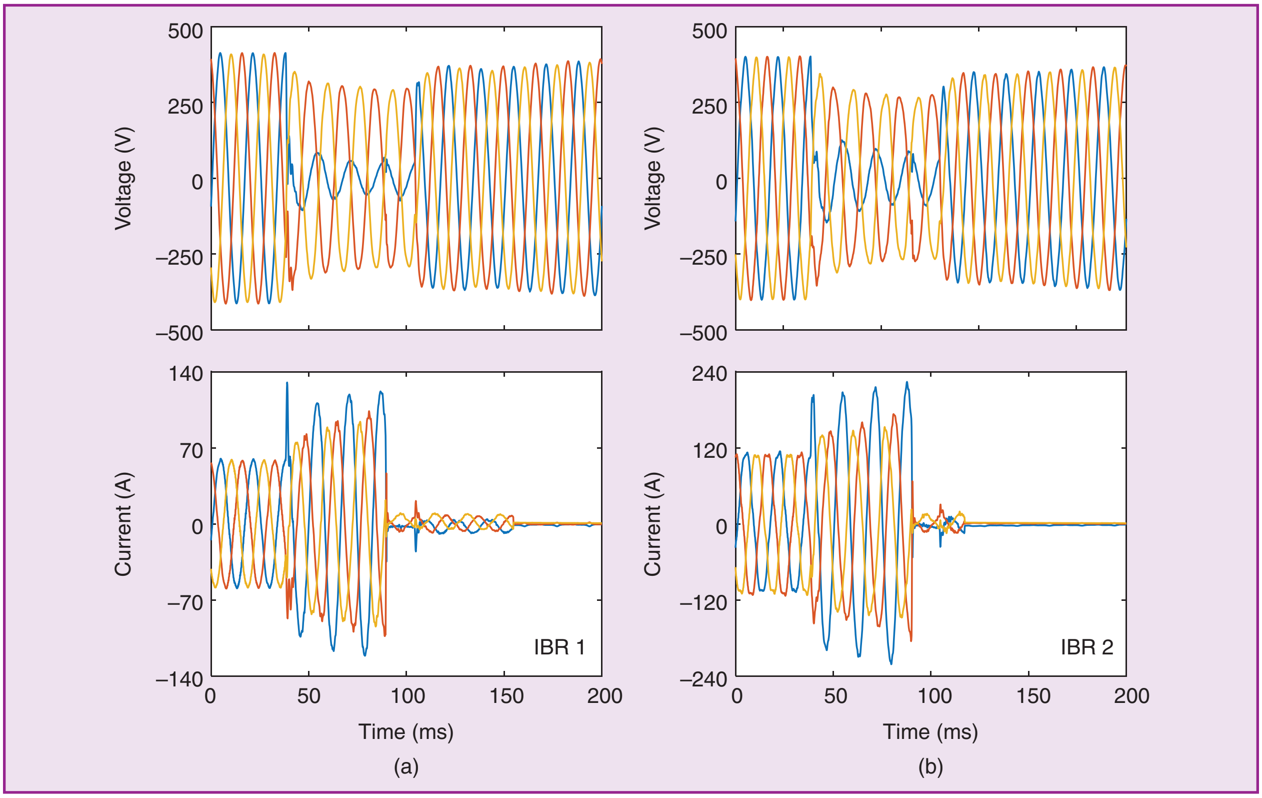


**figure 10.** Comparing the synchro-waveforms at two IBRs during the same upstream fault.

but on two separate feeders. Both IBRs are manufactured by the same vendor, albeit they support two PV systems of different sizes. An upstream disturbance created similar event signatures at the terminal voltages of the IBRs (top subfigures). This caused both IBRs to trip (bottom subfigures). This type of time-synchronized comparison can be extended to several IBRs in a region to study the tripping causes.

### *Impact of IBRs on the Existing Grid Protection Systems*

The complex behavior of IBRs during faults can also cause misoperations in existing grid protection systems. An IBR supplies a much lower short circuit current magnitude because of its current-limiting nature. As an example, during the fault in Figure 10, we can see that neither of the two IBRs supplied a fault current greater than twice the amplitude of the prefault current. On the contrary, a typical synchronous generator may output about six times its rated current. A further complication is that the amount of each IBR's fault current depends on not only its specific design but also on the variable nature of the renewable resource that is behind the inverter device.

Furthermore, IBRs often suppress their output of negative sequence current to maintain a balanced three-phase operation. Although this can vary among IBRs, it can potentially affect the protection relays that monitor the negative sequence current (such as negative sequence overcurrent) to identify unbalanced faults. Changes in the characteristics of negative sequence current can also affect the protective relay's ability to identify the direction of the fault. Correct determination of the fault current direction is critical in many protection systems, such as in distance protection schemes on transmission lines. Sudden phase shifts in voltage may also affect the polarization schemes used in various protective relays.

IBRs also reduce the system inertia, which results in increasing the ROCOF. This further complicates the process of estimating the system frequency that we discussed in the section "Frequency and Rate of Change of Frequency Estimation." This can negatively affect the operation of underfrequency relays in the presence of high penetration of IBRs.

Synchro-waveforms can help predict and mitigate the preceding challenges. Data-driven models can be trained using synchro-waveform data to predict the short circuit current magnitude of each IBR or each class of IBRs under various balanced and unbalanced fault conditions. The results can be used to fine-tune the control settings of the existing grid protection systems. Developing such models can start while the penetration levels of IBRs are still low in the protection zone of interest, and the accuracy of the models can continue to improve as more IBRs are installed. The results can be used in adaptive protection schemes and comprehensive protection studies.

Since legacy protection systems (especially the unit protection relays of power apparatuses) are hard to replace or even redesign, one mitigation option is to modify the IBR control systems to work in harmony with the existing protection principles. Another mitigation option is to develop new protection schemes for system-wide protection relays, based on AI and data-driven training, to detect and properly react to system-wide disturbances while considering the complex behavior of IBRs. Synchro-waveforms can directly assist in achieving these mitigation strategies.

Finally, most existing protection relays are not designed for the presence of the IBR-induced subsynchronous and supersynchronous oscillations that we discussed in the section "Synchro-Waveforms in Wide-Area Control and Stability Monitoring." The use of synchro-waveforms to cope with these oscillations will also help the protection system.

## Conclusions

Synchro-waveform measurements can offer a wide range of new or enhanced capabilities in wide-area monitoring, control, and protection. In the short term, this is particularly true and necessary for power systems with a high penetration of IBRs. Real-world examples and opportunities for further research and development have been discussed in this article.

## For Further Reading


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