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Synchronized Waveforms – A Frontier of Data-Based Power System and Apparatus Monitoring, Protection, and Control

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***Abstract*—Voltage and current waveforms contain the most authentic and granular information on the behaviors of power systems. In recent years, it has become possible to synchronize waveform data measured from different locations. Thus large-scale coordinated analyses of multiple waveforms over a wide area are within our reach. This development could unleash a set of new concepts, strategies, and tools for monitoring, protecting, and controlling power systems and apparatuses. This paper presents an in-depth review and analysis of the advancements in synchronized waveform data, including measurement devices, data characteristics, use cases, and comparisons with synchrophasor data. Based on the findings, five strategies are proposed to discover and develop synchronized waveform based applications over multiple application areas. The paper also presents three complementary measurement platforms and two data screening algorithms for application implementation. It further discusses committee activities and standard developments useful to explore the full potential of the data.**

***Index Terms*—Power system monitoring, power system dynamics, power quality, condition monitoring, synchronized waveforms.**

I. Introduction

OUR capability to monitor power systems and apparatuses has been expanding rapidly in recent years due to advances in measurement and communication technologies. Several decades ago, *magnitude* data collected by the SCADA systems were made available. The data became the foundation of Energy Management Systems. Around 1980s, *phasor* data emerged [1]. Applications of phasor measurement units (PMU) started and the Wide Area Monitoring Systems (WAMS) were established [2]. Lately, capturing voltage and current *waveforms* with precision timestamps has become a reality. Since waveforms represent the most authentic and granular data of power system behaviors, one can envision that a set of new concepts, strategies and tools for power system and apparatus monitoring, protection and control will emerge soon.

There are at least three industry trends driving the need for waveform data. Firstly, the increased adoption of power electronic devices such as HVDC links and inverter-based resources has made it essential to add waveform monitoring capability at least for such devices since they work on waveforms [3]. Secondly, modern power systems possess more complex dynamic responses such as inverter-related power oscillations and supersynchronous resonances [4]. These phenomena can only be characterized and understood using waveform data. Thirdly, online condition monitoring of power apparatuses is gaining significant attention [5]. The signs of emergent equipment failures are typically embedded in the waveforms. Therefore, waveform data are essential for the development of reliable condition monitoring tools [6].

Waveform data are often collected from multiple locations of a system. Extracting information from such data requires accurate time alignment of the waveforms. Fortunately, devices that can record waveforms with precision timestamps are becoming widely available. Thus synchronized analysis of multiple waveforms over a wide area is within our reach.

The objective of this is to introduce the developments in this promising direction and to share our ideas on how to develop advanced applications using synchronized waveform data. To facilitate subsequent descriptions, this paper calls such data as "sync-waves", i.e., *synchronized waveforms*.

The article is organized as follows: Section II reviews hardware available for sync-wave measurement and discusses characteristics of the data. Section III illustrates various ways to use the data through six use cases. Section IV compares the sync-wave data with synchrophasor data. Building on the above background sections, three visions are presented: 1) strategies to discover and develop sync-wave-based applications (Section V),

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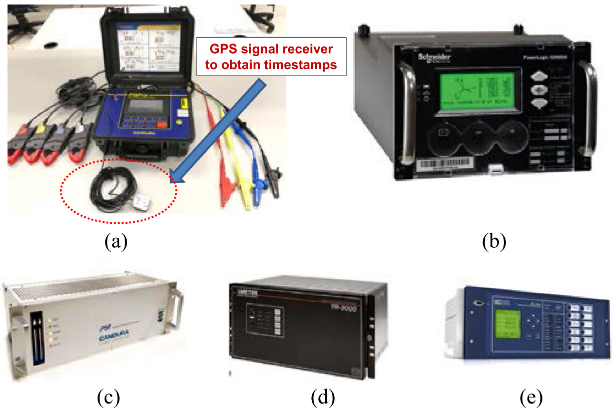

Fig. 1. Sample sync-wave measurement units (SMU) in the market. (a) Portable PQ monitor (b) Stationary PQ monitor. (c) Gapless SMU (d) DFR-based SMU (e) Relay-based SMU.

2) platforms to implement the applications (Section VI), and 3) a proposal for committee activities and standard developments (Section VII).

II. Characteristics of Synchronized Waveforms

A sync-wave is the voltage or current waveform data with (explicit or implicit) precision time information that can be used to align the waveform with those recorded at other locations. The most common timing information is the precision timestamps tagged to some or all of the data samples. The accuracy requirement for the timestamp needs to be established through standardization activities.

Sync-waves may be collected using various sampling rates. Sampling rates ranging from 16 to 1024 samples/cycle (1kHz to 61kHz) are available in commercial products. A sampling rate of 64 samples/cycle (or 3.8 kHz) is generally adequate for many waveform-based applications.

A. Hardware for Sync-Wave Measurement

Devices that can measure waveforms have been available for a long time. In fact, various IEDs in a substation have this capability. What has been changed in recent years is the capability to equip the data with precision time information. Several methods are available to obtain the information. They are (1) Geo-satellite time source such as GPS [7], (2) Precision Time Protocol (PTP) in a substation Ethernet [8], (3) On-board atomic clock [9], (4) Ping-pong testing message method [10], and (5) Disturbance signature-based synchronization [11]. Methods 4 and 5 provide synchronization information without explicit timestamps.

Instruments capable of recording sync-waves with a timing accuracy approaching 1 μSecond (0.02° of 60Hz wave) are already available. To facilitate subsequent presentations, such devices are called collectively as Sync-wave Measurement Units (SMU) in this paper. *The term SMU does not imply a new type of measurement devices but rather refers to devices with sync-wave measurement capability*. Fig. 1a shows a portable SMU originally developed for power quality (PQ) monitoring purposes. The data are stored in a secure digital (SD) card. Fig. 1b is a stationary PQ monitor that uses GPS or Ethernet PTP to get precision timestamps. Fig. 1c shows a generally-purpose stationary SMU that can record three-phase voltage and current waveforms for several months continuously (gapless) at a rate of 256 samples/cycle. Fig. 1d shows a digital fault recorder (DFR) that records GPS-stamped sync-waves. Fig. 1e is a relay that uses sync-wave data to make tripping decisions. Furthermore, the front end of a PMU which samples waveforms and the Merging Units in digital substations are essentially SMUs.

It is worthwhile to note that digitized waveform samples collected by Merging Units and Ethernet-based PTP are essential features of the future IEC 61850-complied digital substations. Thus PTP-timestamped data from the Merging Units could become the most common and widely available source of sync-wave data. GPS-timestamping is useful for portable SMUs and those SMUs located outside the substations such as in the distribution feeders.

An important conclusion drawn from these developments is the following: devices capable of recording sync-waves are becoming widely available. Advances in telecommunication have made it increasingly easier to bring such data together for synchronized analysis. It is, therefore, the time to go beyond the synchrophasor data and to create a new-generation, waveform data based applications. The objective of this paper is to share ideas on how to develop and implement applications assuming SMUs are readily available. As a first step, it is useful to understand the characteristics of sync-wave data and various modes of their transmission and usage.

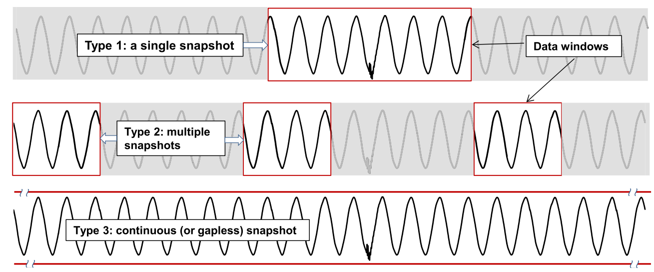

Fig. 2. Three types of sync-wave data.

B. Types of Sync-Wave Data

Waveform data are usually recorded in the form of snapshots. A snapshot is a section of waveforms recorded using a given sampling rate and window length. For example, one snapshot may contain 30 cycles of waveform data or 1920 data points if the sampling rate is 64 samples per cycle. Based on our knowledge and industry practice, there are three types of sync-wave data, and they are illustrated in Fig. 2:

- Type 1 – Single snapshot: This sync-wave consists of one waveform snapshot with limited window length. It is normally used to record a disturbance event. Start and end of recordings are triggered when certain thresholds are exceeded. This data type is analogous to motion detector-triggered video segment recorded by a security camera;
- Type 2 – Multiple snapshots: This sync-wave consists of a series of snapshots taken at equally-spaced time intervals automatically. Every snapshot has the same window length. This type is normally used for long term recording if storage capacity is limited. An example is a set of 12-cycle

snapshots taken every 5 seconds for one week. This type is analogous to a series of short videos taken by a security camera, for example, at the start of each hour;
- Type 3 – Continuous (or gapless) snapshot: This sync-wave is a single snapshot recorded with an extremely long window, such as three months or longer. It is used to capture every behavior of a variable continuously. Gapless means there is no gap between the two sampling windows. This sync-wave can be resampled to produce type 1 and type 2 data. A security camera analogue is a non-stop video recorded over multiple days.

It is important to differentiate three concepts here: (1) data with precision timestamps, (2) synchronized recording of data, and (3) synchronous transmission of real-time data. Concepts 2 and 3 have mixed up the data itself with the means of data collection and transmission. As will be explained in Section II.D, collection and transmission of data are application dependent. On the other hand, the availability of (explicit or implicit) precision timestamps in the data is the fundamental and universal characteristic of sync-waves.

C. Basic and Derived Forms of Sync-Wave Data

Although the original sync-wave data at the measurement locations are in the form of waveforms, the data sent to a central location for eventual synchronized data analysis may take different forms. Examples are:

1) Waveform data: The data are in the form of original waveform samples. This is a time-domain representation;
2) Derived data: The waveform data may be represented in another domain. Examples are frequency, harmonic, and modal domains. Alternatively, the data may take the form of indices, such as power, energy and phase. Note that phasors are one form of derived sync-wave data. The derived data are used to reduce data transmission burden in some applications, i.e., the data are processed first by the SMUs. The results are transmitted to a central location.

Application examples will be provided in Sections III and V to illustrate the use of different data forms. Regardless of the forms of representation, all data shall contain precision timestamp information sufficient for synchronization.

D. Schemes of Data Collection and Transmission

Synchronization means proper alignment of the time axes of two sets of data. As such, a minimum of two SMUs is required to make sync-waves meaningful, and the data collected from various locations must be transmitted to and analyzed together at one location. After a variable is sampled, there are three schemes to handle the data:

- Scheme A: Data are stored in the SMU and are available for download to other locations. This is similar to the methods used by PQ monitors and DFRs;
- Scheme B: Data are transmitted to a central location only if it contains a disturbance (i.e., Type 1 data). This event-driven method is useful to capture transients from various parts of a system using low-cost communication networks;
- Scheme C: Data are transmitted to a central location continuously. For Type 2 (multiple snapshots) data, there may exist idle time between the transmissions of two snapshots. For Type 3 (gapless snapshot) data, the data are streamed continuously in real-time.

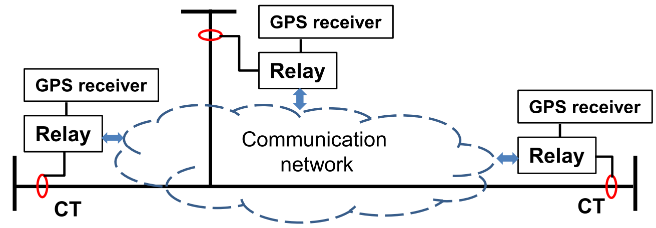

Fig. 3. An example setup of differential protection for a 3-terminal line.

The above description does not specify how fast the data shall be transmitted. As will be shown in the examples later, there are essentially two data transmission modes: (1) real-time and (2) delayed. The first is akin to live streaming of video, and the second is akin to on-demand streaming. The former is needed if an action must be taken in real-time, such as tripping a line. For such applications, even the latency of the communication network must be compensated. There are also many applications that accept delays of several seconds, minutes or even days (see Section III). The delayed data can always be synchronized using the precision timestamps.

It is also important to note that the term "central location" used here does not necessarily mean it is the control center. As will be shown in the next sections, this location is more likely to be a substation or an engineering office. Among the various arrangements, the most advanced and also the most costly version is the real-time streaming of gapless data to the control center from multiple SMUs, as discussed in [12].

III. Developments in Sync-Wave Applications

Sync-wave data have started to attract industry attention recently. Some useful applications have emerged. A few research papers also appeared in anticipation of the arrival of such data. This Section reviews six representative applications based on the classifications in Section II. The findings will facilitate explaining the proposed visions later.

A. Digital Line Current Differential Protection

Differential protection is a very useful protection scheme. However, it is difficult to implement if the two currents to be compared are located far away, as in the case of a transmission line. The advances in communication technologies in recent years have made differential line protection a reality [10].

Fig. 3 shows a commercially available, GPS-enabled setup of differential protection for three-terminal lines. In this arrangement, current sync-waves are transmitted to the two remote terminals through, for example, a synchronous optical network (SONET) over optical fiber and microwave. Each terminal synchronizes the three currents (one from local and two from remotes), adds them up and then makes a trip decision. One commercial relay designed for this application uses a waveform sampling rate of 1 kHz [13]. Data packets consisting of 4 samples are transmitted every 4 msec. Therefore this customized

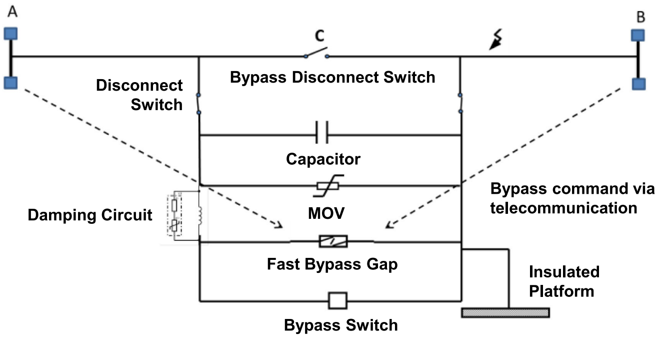

Fig. 4. A series-capacitor installation with telecom-based bypass gap device.

"SMU" (i.e., relay) uses Type 3 (gapless) sync-wave. The data are transmitted using Scheme C (real-time streaming). There are three "central locations" in this case, and all of them are substations.

B. Sync-Wave Based Event Analysis

Sync-waves can be very useful for power grid event analysis. Examples are postmortem investigation, forensic examination, performance/model verification, troubleshooting analysis, and design validation. One such application is illustrated in Fig. 4, where the protection set up for a real-world 500 kV series compensated line is shown. The series capacitor at Station C in the figure is a gapped mid-point installation, providing 50% compensation to the circuit of approximately 300km between Station A and Station B. In protection design for this line, the risk of terminal breaker restrike due to augmented Transient Recovery Voltage (TRV) stress must be mitigated [14]. One practical solution is fast discharging (bypass) of the capacitor before terminal breakers start to interrupt the fault current. The bypassing command is initiated by line protection relay (at the same moment when breaker tripping command is generated) and transmitted to the series capacitor controller via SONET. EMT simulations conclude that TRV risk can be mitigated as long as the series capacitor is bypassed 3ms prior to the line terminal breaker current interruption. This essentially requires the combined time delay from telecommunication, series capacitor controller signal processing and fast bypass gap execution at Station C must be at least 3ms less than the terminal breaker interrupting time at Stations A and B. Since the actions at three locations could be less than a quarter cycle apart, synchronized waveform recordings are necessary to validate the design.

Fig. 5 verifies the timing coordination with a naturally occurred fault on the 500kV line. The faulted phase voltage measured at Station A, the faulted phase current measured at Station A and B, and the series capacitor discharging current measured at Station C are conveniently aligned for sequence-of-events inspection thanks to synchronized waveform recording. The sync-waves suggest that the series capacitor bypass gap was fired prior to line terminal breaker current interrupting, and there was approximately another quarter-cycle safety margin in this tight time coordination. This verification study also provided valuable input to the later breaker replacement specifications. For such

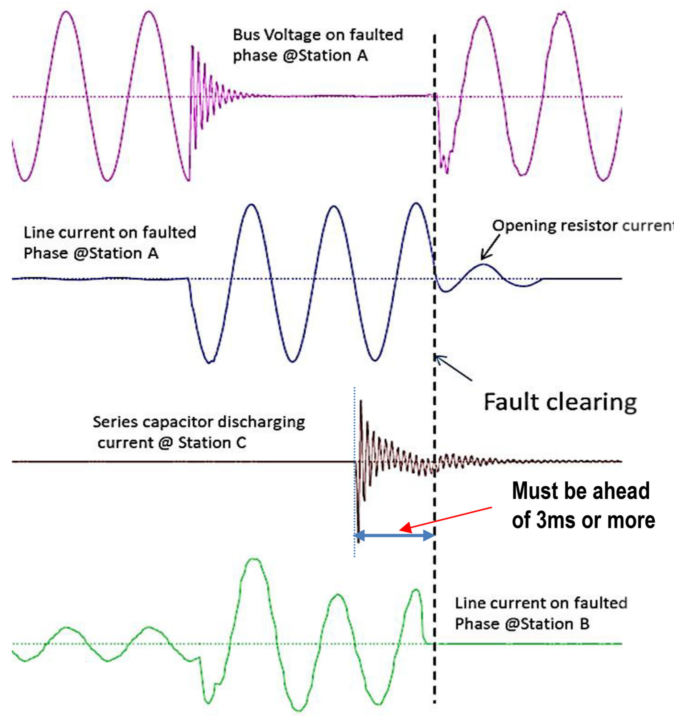

Fig. 5. Fault records with synchronized waveforms from three stations.

offline applications, portable SMUs recording Type 1 (single snapshot) or Type 3 (gapless) sync-wave data can be sufficient. The data are stored in the SMUs and downloaded (Scheme A) for analysis after an event is recorded.

C. Characterization of Harmonic Cancellation Effect

Harmonics are an important power quality concern. Engineers and researchers have been speculating, even to these days, on how the harmonic currents injected from different loads eventually add up at a given location in a power system. Various theories of probabilistic harmonic addition were developed to answer this question [15]. The IEC standard [16] governing the interconnection of new nonlinear loads requires system planners to use the following formula to estimate the allowed level for the h^{th} harmonic.

$$V_{combined}(h) = \sqrt[\beta]{V_{new-load}^{\beta}(h) + V_{background}^{\beta}(h)} < V_{limit}(h) \quad (1)$$

where $V_{background}$ is the background harmonic voltage at the interconnection point before the new load is added. $V_{new\text{-}load}$ is the allowed harmonic voltage that can be produced by the new load. $V_{combined}$ is the estimated total harmonic voltage, and this voltage cannot exceed the IEC harmonic limit V_{limit}. β is a parameter taking into account the harmonic addition and cancellation effect, and its value is harmonic dependent. However, there is a lack of real-world evidence to support the above formula and to determine the proper values of $\beta(h)$.

Eq.(1) was adopted because of lack of information on the phase angles of $V_{background}(h)$ and $V_{new\text{-}load}(h)$. With the help

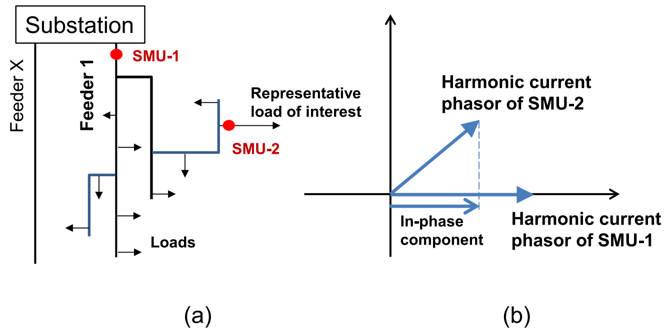

Fig. 6. Measurement of harmonic current addition/cancellation effect.

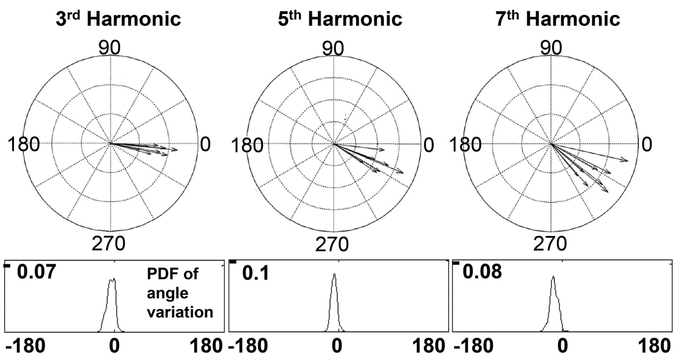

Fig. 7. Distribution of SMU-2 current phasors w.r.t. to SMU-1 phasor.

of sync-waves, the above puzzle can be solved through field measurements and statistical analysis. For this purpose, the authors conducted a field measurement, illustrated in Fig. 6, to determine how harmonic currents produced by a group of residential loads at SMU-2 location add to or cancel out the harmonic currents entering the transmission system through Feeder 1 at the substation (i.e., SMU-1 location). Fig. 6a shows the measurement setup where two portable SMUs are deployed. Fig. 6b shows the h^{th} harmonic current phasors. The in-phase component determines the degree of harmonic addition or cancellation with the feeder current.

Fig. 7 shows the findings based on 24-hour measurement results. It can be seen that the relative phase angles do not vary significantly, invalidating some assumptions used in [15]. Similar measurements can be conducted on different types of loads. Statistical analysis can then be performed to establish an improved estimation formula and parameter for the IEC standard. In this application, Type 2 (multiple snapshots), time-domain data were collected. The data were saved in the portable SMUs (i.e., Scheme A). The results are obtained through offline analysis of the downloaded data.

D. Harmonic Source Detection

In addition to the above application, harmonic current phasors are important data for locating harmonic sources, i.e., to identify which loads are the main contributors to an increased harmonic level at certain locations in a power system. Assuming SMUs are installed at all substations, [17] proposed an independent-component, harmonic phasor based method to determine which substation contains harmonic sources. For this application, the

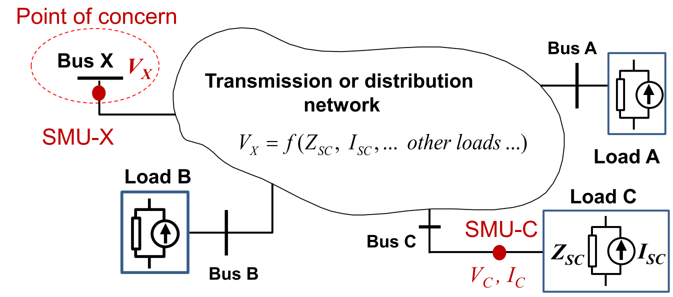

Fig. 8. Determining the harmonic contribution of customer C using SMUs.

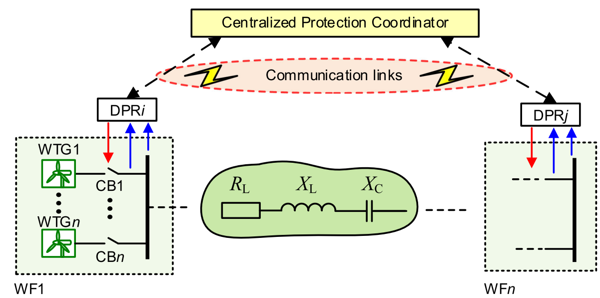

Fig. 9. A sync-wave-based SSR monitoring and mitigation scheme.

paper assumes that Type 2 (multiple snapshots) data in the harmonic domain are available and are transmitted to the control center continuously (i.e., Scheme C). Since harmonic source location is not a time-sensitive task, the analysis can be done in the background while the data are received with possible delays.

In view that it is impossible to have SMUs at all substations, [18] proposed to deploy (portable) SMUs at the site that experiences harmonic problems (Bus X) and at the suspected load (Load C) as shown in Fig. 8. Its authors formulated and proposed a solution to the following problem:

> *Given measured sync-waves of V_X, V_C and I_C, determine the percentage of V_X that is caused by Load C harmonic source I_{SC} at harmonic order h.*

For this application, portable SMUs can be used to record Type 2 (multiple snapshots) or Type 3 (gapless) sync-waves for the desired monitoring period. The monitoring can be done sequentially or simultaneously for other suspected loads such as Loads A and B. Offline analysis of downloaded data then identifies the harmonic impacts of loads A, B and C at bus X.

E. Mitigation of SSR in Wind Farms

SSR (Sub-Synchronous Resonance) associated with wind-farms can be triggered, for example, when inverter controlled doubly-feed induction generators behave as negative resistances at frequencies that resonate with a series-compensated grid [19]. If appropriate measures are not taken, the resulting oscillation can make the system unstable and damage equipment. As an (area) system-wide phenomenon, SSR mitigation requires a system-wide monitoring and protection scheme.

Fig. 9 shows the structure of a sync-wave based SSR mitigation scheme [20]. It consists of distributed protection relays (DPRs) and a centralized protection coordinator (CPC). The

DPRs are SMU-like, customized measuring & computing devices deployed at the windfarm substations. Each DPR collects the voltage and current waveform data at its location. It also processes data to estimate the oscillation frequency, amplitude and impedance of each windfarm as functions of time. The data are timestamped, packaged, and sent to the CPC through communication links. The CPC then computes the aggregated impedance model of the whole area power system and performs the following two tasks:

1) Comparing the measured impedances of the monitored windfarms. A large negative resistance implies that the corresponding windfarm contributes more to worsening the SSR. Thus critical windfarms are identified. Tripping of such windfarms is more effective for stabilizing the system;
2) Determining the amount of negative resistances and the corresponding windfarms that need to be removed according to impedance-based stability criterion. Tripping commands are issued to the DPRs of selected windfarms.

For this application, derived data of Type 3 (gapless) sync-wave is transmitted to the central location using Schemes C (real-time streaming). Alternatively, the system could be designed to transmit derived data only when the onset of SSR is detected. In this case, derived data of Type 1 (single-snapshot) is transmitted to the CPC using Scheme B (event-driven). When there are no signs of SSR, the data transmission activity is idle.

F. Fault Location in Distribution Networks

Finding the locations of short-circuit faults in a distribution network is an essential task of system operation and maintenance. However, it is a difficult one due to lack of sufficient sensors or monitors. As a result, various fault location ideas have been proposed specifically for distribution networks. One interesting idea is to utilize the voltage travelling wave produced by a fault for fault location [21]. This idea is similar to the Time of (signal) Arrival (TOA) method developed to locate cellphones. For application in distribution networks, the travelling waves' arrival times at various monitoring locations are determined using waveform analysis and precision GPS clock. A set of traveling-time equations can be established for the TOAs according to the network topology. The location is solved using an optimization method, as this is an over-determined problem.

It is clear that high-resolution sync-waves are required for this application. Fortunately, information to be extracted from the sync-waves is the TOAs, and as a result, Type 1 (event-triggered single snapshot) sync-waves in the form of a derived index (i.e., TOA) are sufficient for this application. Transmitting TOAs instead of high-resolution waveforms cuts down the telecom bandwidth requirement significantly. According to [21], an SMU just recording voltage waveforms (called Voltage TW Detector) has been designed and tested in the field. The authors propose to integrate these low cost, special-purpose SMUs into field devices such as reclosers and pole-mounted tele-switches. The TOA data are sent to distribution control center, whenever an event is detected, using existing telecom means of the field devices. There is no need for real-time data transmission and equation solving in this case since a few minutes delay in finding the location of a fault is acceptable. Note that it takes a much longer time to dispatch a crew to do the repair work.

TABLE I
CHARACTERISTICS OF SYNC-WAVE DATA AS AFFECTED BY APPLICATIONS

Data Characteristics \ Application types		Offline Analysis	Online Monitoring	Real-time P&C
Data Type	1: Single snapshot	B	F	E
	2: Multi-snapshot	C	D	
	3: Gapless snapshot	B, C		A, E
Data Form	Time-domain	B		A,
	Derived form	C	D, F	E
SMU Type	Stationary	B	D, F	A, E
	Portable	B, C	D	
Transmission Scheme	A: Download	B, C	D	
	B: Event-driven		F	E
	C: Streaming		D	A, E
Trans. Mode	Real-time			A, E
	Relayed		D, F	
Central location	Control center		D, F	E
	Substation			A,
	Engineering office	B, C	D,	

Note: Letters A∼F represents the IDs (i.e., section numbering) of example applications. Some applications can have more than one data option.

G. Summary

Additional examples of sync-wave based applications, such as transmission fault location, open-conductor detection, and parameter estimation can be found in [22]–[24]. Although some of the methods are more academic than practical, they do point to a direction – sync-wave can help to improve the monitoring, protection or control of power systems and apparatuses. The applications can be classified as follows and are summarized in Table I:

1) Offline analysis. Examples are Use Cases B and C. Almost all event analysis and model validation applications are offline type. In fact, NERC requirement for high resolution monitors [3] is intended primarily for offline uses of the waveform data.
2) Online monitoring. Examples are Cases D and F. These applications digest the sync-wave data and deliver high level indices automatically for the purpose of improving operational situation awareness. Others examples include incipient fault detection and compliance monitoring.
3) Real-time protection and control (P&C). Examples are Cases A and E. These applications take either protection or control actions automatically in real time based on measured data. Many protection oriented applications and the combined protection and control of power electronic devices belong to this type.

Table I will help the formulation of application platforms to be covered in Section V. From the table, one can draw the following conclusions: the application potentials of sync-wave data are very broad. There are different ways to handle and use the data, and each has different requirements for communication infrastructures. We should not limit our imagination to the scenarios associated only with a system-wide, synchronous-streaming-type sync-wave monitoring network. In fact, many applications do not need such an expensive setup.

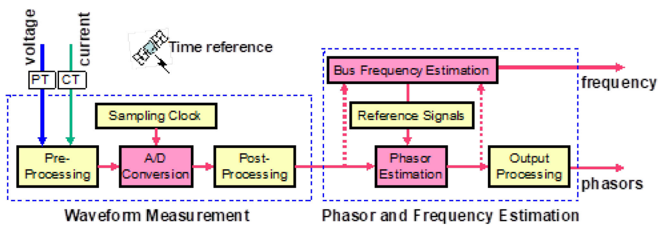

Fig. 10. An illustration of synchrophasor measurement processes.

IV. SYNC-WAVE VERSUS SYNCHROPHASOR

Sync-wave and synchrophasor measurements share a few similar features and implementation mechanisms. The most obvious one is time synchronization using a high-precision time source. And both types of measurements need communication systems for bringing multi-location measurements together to support an application. Another similarity is that they are both based on measuring voltage and current signals using PTs and CTs. Fig. 10 illustrates the measurement processes of synchrophasor [25].

This figure also illustrates the differences between sync-wave and synchrophasor measurements. One major difference is that synchrophasor measurements require the subsequent processing as shown in the 2nd box of Fig. 10 because phasors are not actual physical signals and cannot be directly measured but estimated. Such processing involves various windowing, filtering and estimation algorithms which can lead to inconsistency and inaccuracy of phasor measurements [25], though advancements in IEEE standards and associated testing requirements have mitigated some of these issues.

Synchrophasors have found applications [2]. But there is a persistent issue with the interpretation of measured synchrophasors of non-stationary signals. The definition of phasors is valid only for stationary sinusoidal waveforms [26]. However, real-life power systems always experience dynamic behaviours and frequency drifts. Phasors are, therefore, always an approximation of reality. Especially during transient periods when they would be needed most, phasor measurements may contain errors that render them less useful or lead to undesired outcomes. This includes the subsequently derived quantities such as frequency. For example, let's consider a non-stationary sinewave that has a varying frequency $\omega(t)$ and varying phase angle $\theta(t)$. This waveform has two interpretations:

- It is a constant frequency ($=\omega_o$) sinewave with a changing phase angle $\delta(t)$:

$$V(t) = M\cos[\omega(t)t + \theta(t)] = M\cos[\omega_0 t + \delta(t)] \quad where \quad \delta(t) = [\omega(t) - \omega_0]t + \theta(t)$$

- It is a variable frequency [$=\Omega(t)$] sinewave with a constant phase angle of 0:

$$V(t) = M\cos[\omega(t)t + \theta(t)] = M\cos[\Omega(t)t], \quad \text{where} \quad \Omega(t) = \omega(t) + \theta(t)/t$$

It is impossible to say which one of the above is close to the "truth" since there is no "truth" strictly speaking for such a signal. IEEE Std. C37.118.1 [26] adopts the first interpretation for estimating the phasor while the second interpretation is adopted for estimating the frequency. Therefore, PMU output represents a consensus rather than the actual characteristics of a phenomenon. A recent example of undesired outcomes of such ambiguous interpretation of reality is the loss of 700 MW solar generations during the California Blue Cut Fire event [27]. The 3-phase voltage waveforms during the event are shown in Fig. 11, with two phase jumps indicated. The solar inverters interpreted the first phase jump as instantaneous frequency drop to below 57 Hz and disconnected solar generation per NERC PRC-024-2 standard.

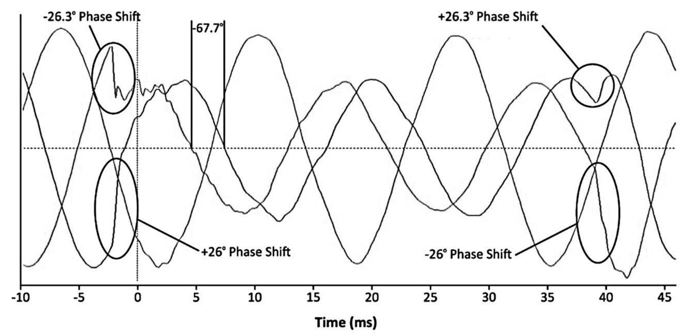

Fig. 11. Voltage waveforms leading to PV generation trip ([27]).

In contrast, waveforms capture actual physical signals, i.e., instantaneous voltage and current, which are well defined and understood. Standards for waveform measurements have been well developed [28]. Having good definitions and standards yields multiple benefits for the measurements: 1) It brings consistency in the measurements; 2) The measurement process does not need the estimation step as shown in Fig. 10, which enables simpler and less costly design and implementation; 3) Testing of SMUs is easier and better defined. The testing instrumentation and setup are less complicated; and 4) the accuracy of SMUs can be defined straightforwardly as the difference of measured and original signals. Thus sync-wave data from IEDs of different vendors can be readily used together most likely. In comparison, the Total Vector Error (TVE) defined in the IEEE phasor standard is a combined error of a phasor's amplitude and angle. This means two PMUs meeting the same 1% TVE requirement does not necessarily have same level of phase accuracy or amplitude accuracy [29].

Fundamentally, sync-waves carry much more information than synchrophasors, analogous to color videos versus black-and-white ones. Therefore, sync-waves can support more applications. This is especially important for emerging power systems with high penetration of inverter-based renewable generation. As shown in Fig. 10, once sync-wave measurements are available, synchrophasors can be derived from them for target applications using the same estimation algorithm. This approach is more reliable than collecting synchrophasor data from multiple PMUs which might be implemented with inconsistent algorithms and assumptions.

In fact, some manufacturers have realized the limitations of phasor measurements, and they are expanding the capability of their PMUs to recording waveforms. These developments coupled with the limitations of phasors also point to the new trend identified earlier, i.e., sync-wave represents a natural advancement in power system measurement and monitoring. It is

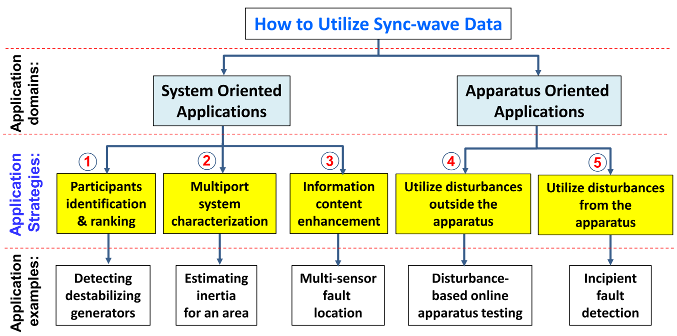

Fig. 12. Strategies to utilize sync-waves for application development.

the time to go beyond the synchrophasor data and to create a new-generation, sync-wave data based applications.

V. Vision 1 - Strategies to Develop Sync-Wave Applications

A common approach to application development as adopted in various publications promoting synchronized data is to cover a list of potential application areas such as stability, DER integration, and power quality. While this approach may help readers appreciate the range of possible applications, it offers few clues to stimulate research ideas. A more helpful approach is to understand the strengths of sync-wave data first. Based on such understanding, we can formulate general strategies for application discovery and development over multiple application areas. This section proposes five strategies conceived based on the second approach.

What makes sync-wave (and synchrophasor) unique is that coordinated quantitative analysis can be performed on data from different locations. As a result, one can derive meaning from the system level instead of the individual monitor level. Sync-waves, therefore, have an edge to solve *problems involving more than one location or one component*.

Another strength of sync-wave data is that it contains authentic transient and dynamic responses of a network. Not only are such events the primary targets of monitoring, but also the data carry more information about the system and apparatus conditions. When made available at multi-locations, this property can significantly expand the events and problems addressable by the sync-wave data, especially those requiring high-frequency phenomena.

Based on the above reasoning and the various examples reviewed in Section III, a pattern of utilizing sync-wave data can be recognized. This finding leads us to propose five application development strategies, three for system-oriented applications and two for apparatus-oriented applications. These strategies, shown conceptually in Fig. 12, intend to help researchers to discover new applications over multiple technical areas. Details on the strategies are presented in the next two subsections, along with examples.

A. System-Oriented Applications

System-oriented applications solve power system-level problems. These problems are often, if not exclusively, related to the interactions of various components in a system triggered by unexpected incidents. Thus, there are significant needs to determine each component's contribution to system-level dynamics, to characterize subsystem behaviors, and to derive reliable information from the complex interactions.

- *Strategy 1 – Participants Identification and Ranking:* Examples of system-level problems are loss of stability, power oscillation, unstable resonance, voltage unbalance, etc. Since there are multiple components involved in such problems, it is critical to identify and quantify the degree of participation, contribution or influence of various components. Such information helps to pinpoint problematic areas and to find appropriate solutions. Sync-wave, due to its multi-location nature, can play a unique role in answering such questions by bringing responses from different components together for coordinated analysis. This observation leads to the first proposed strategy: identifying and ranking participants to a system-wide problem, and initiating protection or control actions based on the impact level of participating components. Application cases C and E are examples of this strategy.
- *Strategy 2 – Multiport System Characterization:* A power system has various components or subsystems with more than one interface with other parts of the system. Such components or subsystems are called multiport systems here. Sync-wave data are capable of capturing the full responses of a multiport system and thus make the investigation of its behavior possible. One example is an external network that has several interfaces with the system under analysis. If SMUs monitor all interfaces, the impact of the external network can be studied much more thoroughly. Thus, we propose the 2nd strategy for utilizing sync-wave data: characterization of multiport systems or components. The term characterization here includes, for example, model validation, impact assessment, response modelling, event-timing determination, statistical feature extraction and so on. Application cases B and C are examples of this strategy.
- *Strategy 3 – Information Contents Enhancement:* Data from more than one location or component can be used for cross-checking, mutual validation, noise reduction, and so on. From this perspective, sync-wave data can be applied to boost information content or clarity associated with a phenomenon. One example is using the voltage travelling waves detected at more than one location to locate faults in a distribution system (Case F). Another is the differential line protection, where the difference between two current waveforms yields a much more definitive conclusion on the occurrence of a fault (Case A). All these examples reveal a pattern; namely, sync-wave data can be harnessed to increase information content and clarity, resulting in more reliable event detection and decision-making. This finding leads to the 3rd proposed strategy.

The above three strategies truly utilize the multi-location nature of the sync-wave data. The disturbance-capture and high-resolution properties of the data significantly expand application ranges of these strategies, i.e., they are no longer limited to the

60/50Hz problems. In the following, examples are presented to illustrate the three strategies.

1) Example of Strategy 1: Ranking of Destabilizing Components: Power system oscillations, such as super- or sub-synchronous resonance, low-frequency oscillations and so on, are a form of instability (small-signal instability) and are an important concern to system operators. With the increased use of inverter-based generators, more oscillation phenomena have been reported, including wide-band oscillations with the frequency ranging from a few Hz to several thousand Hz [4].

A crucial task for power system stability control is to identify which components produce the most destabilizing effects, and thus proper countermeasures can be taken. In offline studies, participation factors derived from eigen-vectors of a linearized system model have been used to achieve this goal [30]. To our knowledge, methods for online real-time identification of destabilizing components have yet to be developed. With the help of sync-wave data, this challenging problem could be solved.

This paper proposes two potential ideas of using sync-wave data to identify and rank destabilizing generators (including inverters) for various types of oscillations. The first idea is based on the understanding that oscillations are driven by excessive energy or power at the oscillation frequency. For example, the voltage and current of a generator participating in oscillation of frequency ω_{mode} can be expressed as follows

$$i(t) = I_0 \cos(\omega_0 t + \theta_0) + I_{\text{mode}} e^{-at} \cos(\omega_{\text{mode}} t + \theta)$$
$$v(t) = V_0 \cos(\omega_0 t + \delta_0) + V_{\text{mode}} e^{-at} \cos(\omega_{\text{mode}} t + \delta)$$

The corresponding instantaneous power can be found as:

$$\begin{aligned} p(t) &= i(t)v(t) \\ &= V_0 I_0 \frac{\cos(2\omega_0 t + \theta_0 + \delta_0) + \boxed{\cos(\theta_0 - \delta_0)}}{2} + \quad \leftarrow \text{Active 60Hz power} \\ &\quad I_0 V_{\text{mode}} e^{-at} \frac{\cos((\omega_0 + \omega_{\text{mode}})t + \theta_0 + \delta) + \cos((\omega_0 - \omega_{\text{mode}})t + \theta_0 - \delta)}{2} + \\ &\quad V_0 I_{\text{mode}} e^{-at} \frac{\cos((\omega_0 + \omega_{\text{mode}})t + \delta_0 + \theta) + \cos((\omega_0 - \omega_{\text{mode}})t + \delta_0 - \theta)}{2} + \\ &\quad V_{\text{mode}} I_{\text{mode}} e^{-2at} \frac{\cos(2\omega_{\text{mode}} t + \theta + \delta) + \boxed{\cos(\theta - \delta)}}{2} \quad \leftarrow \text{Modal power, i.e. destabilizing power} \end{aligned}$$

It can be seen that the fourth term is directly related to the oscillation (ω_{mode}). Its average over a period of modal frequency is called modal or oscillating power. *This is the power that drives and sustains the oscillation*. If a generator injects such a modal power, it could be considered as a contributor to instability. On the other hand, a generator consuming the power is expected to help to damp the oscillation. (The 2^{nd} and 3^{rd} terms represent the interaction between the modal component and the fundamental frequency (ω_o) component. Their average powers are close to zero since all terms are cosine functions of time *t*). Thus, the proposed idea is to use the modal power output of a generator or inverter to identify and rank destabilizing generators. The work of [31] supports this postulation. It shows that at least low-frequency oscillations are associated with energy exchanges. Another support evidence is to view an oscillation phenomenon as the presence of non-stationary interharmonics in the system. The direction of interharmonic power has been proposed to detect SSR-contributing DFIGs [32] and to trace sources causing voltage flicker [33].

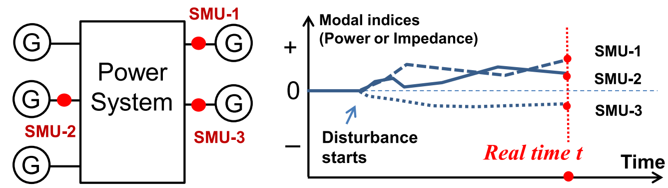

Fig. 13. Synchronized comparison of generators' destabilizing effects.

The second idea is inspired by the work of [20] (i.e., Case E) where windfarms with significant contributions to an SSR event are ranked based on how negative their equivalent resistances are at the SSR frequency. It may be possible to extend this idea to other oscillation phenomena by utilizing the impedance-based stability analysis methods [34], [35]. For implementation, each generator's equivalent impedance at the oscillation frequency (i.e., modal impedance) is estimated and then compared. The results are used to rank the generators for their destabilizing impact. The modal impedance can be estimated in real-time since the system is oscillating at the frequency of interest, and thus there is sufficient excitation for impedance estimation. The generators include traditional synchronous machines and inverters.

SMUs are a natural candidate to implement the above ideas, and they can be deployed at the generators of interest. The units calculate modal power or impedance (i.e., derived indices) and transmit them in real-time to the control center with precision timestamps. The control center then identifies destabilizing generators based on synchronized comparative analysis of the indices as the event unfolds. This scheme is illustrated in Fig. 13. As one can see, the generator monitored by SMU-1 injects most destabilizing power and is, therefore, the best candidate for generator shedding.

Identifying and ranking participants to a problematic situation such as instability, oscillation, and distortion could be a killer application area of sync-wave data. The above ideas can be expanded to determine which generators need to be tripped in order to mitigate the oscillation. It may be possible as well to further expand these ideas to identify which transmission lines are more influential to an oscillation event based on the amount of modal power passing them.

2) Examples of Strategy 2: System Inertia Estimation: Multi-port subsystems are not uncommon in power systems. A regional network is one such example. Sync-wave data are ideal for measuring or estimating the aggregate inertia (or frequency-dependent characteristics) of a regional system such as the Great Britain system [36], [37]. The inertia information is very important nowadays since it can help estimate how fast an area's frequency can change if there is a loss of import/export power, especially when the area contains many low-inertia inverter-based generators [36].

Various methods have been developed to estimate the frequency-dependent characteristics of individual loads. It is, however, not easy to estimate the characteristics of an area since

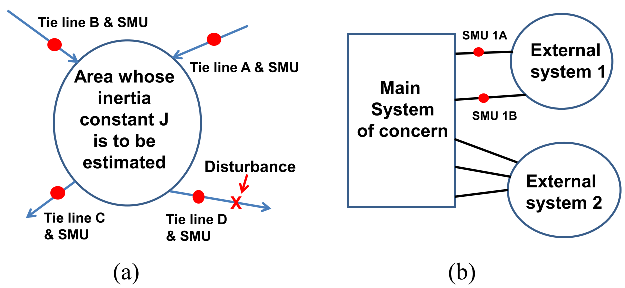

Fig. 14. Two examples based on application strategy 2. (a) Measuring area inertia constant (b) Estimating the impact of external system.

an area often has multiple interfaces with external systems. In addition, the estimation can only be done when there is a sufficient import/export power disturbance ongoing in the area, such as the outage of tie-line D in Fig. 14a. SMUs are the device capable of providing adequate data for this task. Firstly, SMUs can be deployed to measure all tie-line power exchanges of the study area. Secondly, the recorded voltage waveforms are analyzed together to establish an "equivalent" or "representative" frequency for the area. Note that the area is undergoing a dynamic process. *The frequencies can be different at different tie lines, and they all contain transients.* PMU estimated frequencies suffer ambiguity, and they are not directly applicable to this application [37]. This application can be implemented offline after event data are collected.

Another potential application inspired by the 2nd strategy is to monitor the impact of external system on power oscillation. In this case, the total oscillating power injected from the External System 1 can be estimated using sync-wave data collected from its interface points (Fig. 14b). If the external system injects net oscillating (i.e., modal) power into the main system, it can be considered as contributing to oscillation. Otherwise, it has a damping effect. This application can improve the situation awareness for power system operators. As such, it is an online monitoring application where event-triggered indices are transmitted to the control center.

3) Examples of Strategy 3: Information Content Enhancement: This strategy is to use the data collected from different locations and components to enhance the clarity and reliability of information derived. The strategy is applied to develop an incipient fault detection scheme for underground cables. It is illustrated as example 2 of the next section.

B. Apparatus-Oriented Applications

Apparatuses such as generators, transformers, and HVDC links are building blocks of power systems. From the perspective of the utility industry, monitoring apparatus is as important as monitoring power systems. For example, the consequence resulted from power line caused forest fire can be as devastating as that caused by instability related generator/load trips [38]. In fact, apparatus condition monitoring has become a significant R&D activity among equipment manufacturers.

Apparatus monitoring includes condition monitoring, performance monitoring, parameter estimation, protection and so on. Due to page limitation, this section will focus on the application of sync-wave data to apparatus health condition monitoring. The health condition of an apparatus is typically assessed using two means as follows: (1) Offline testing. Here test signals are injected into the apparatus. Its response is measured to derive a conclusion. One example is the measurement of the dissipation factor (tanδ) of a cable. (2) Detection of abnormal behavior when the apparatus is in operation. Examples are monitoring signs of incipient failures of overhead lines due to vegetation encroachment.

Accordingly, this paper presents two strategies (Strategies 4 and 5) to develop sync-wave-based applications to improve apparatus health monitoring:

- Strategy 4 – Utilizing disturbances outside the apparatus:

This strategy proposes to use natural disturbances as "test signals" to evaluate an operating apparatus, i.e., online implementation of offline testing methods through the use of natural disturbances. Example natural disturbances are voltage/current transients caused by faults, energizations, switching's and so on. In addition to avoiding expensive offline test setup, this online strategy can "test" an apparatus frequently due to an abundance of natural disturbances. As a result, the health trend can be tracked over time. It is clear that the "test signals" must be captured authentically as waveforms. It is often that more than one monitoring location is needed. Thus sync-waves become the only candidate to make such online testing possible.

- *Strategy 5 – Utilizing disturbances from the apparatus:* This strategy is to detect abnormal apparatus behavior using multiple monitors. Monitoring one event at multiple locations often yields more useful information. Such an approach was not adopted in the past because synchronized data analysis could not be done. Sync-wave data fill in this crucial gap and have the potential to unleash a new set of monitoring schemes and algorithms.

1) Example of Strategy 4 – Grounding Condition Monitoring: Grounding grid is an essential component of a substation. It not only supports the operation of substation equipment but also serves as a means for personnel safety. Unfortunately, a ground grid can deteriorate over time due to corrosion, ageing, vandalism and other factors. As a result, utility companies need to conduct regular measurements to monitor the grounding grid conditions of their substations.

A common monitoring method is to measure the grounding resistance of a substation according to the fall-of-potential method [39]. This measurement relies on specialist consultants and involves an elaborate setup. If a substation is in a crowded area, there are considerable difficulties in conducting the measurement due to space constraints. In addition the results obtained through occasional measurements are not sufficient to reveal the trend of condition deterioration.

Following Strategy 4, the authors have conceived an online scheme for monitoring the grounding resistance. The proposed scheme is shown in Fig. 15. It utilizes the ground faults in, for example, Feeder 1 as the source to inject a "test" current into the grounding grid. This current, $i(t)$, is measured using a CT placed at the transformer neutral. The corresponding ground potential rise (GPR), denoted as $v(t)$, is measured using a voltage monitor.

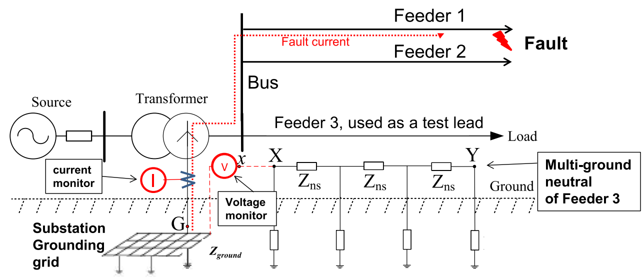

Fig. 15. An online substation grounding impedance monitoring scheme.

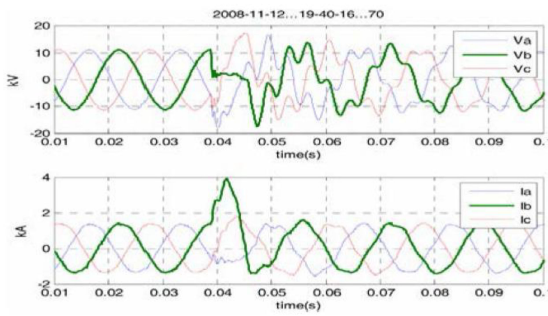

Fig. 16. Waveforms of a self-clearing incipient fault of a cable (©IEEE).

This monitor uses Feeder 3 as a "test lead" to access the zero potential reference point.

Note that the measured current and voltage before the fault are not zero due to unavoidable imbalance in downstream feeders. The test current and voltage that are solely caused by the fault should be obtained by subtracting the pre-fault waveforms from those during the fault. The grounding impedance can thus be estimated as follows:

$$Z_{Ground}(f) = \frac{F\{v_{during\_fault}(t) - v_{pre\_fault}(t')\}}{F\{i_{during\_fault}(t) - i_{pre\_fault}(t')\}}$$

where $F\{*\}$ represent frequency-domain transformation. It is clear that $v(t)$ and $i(t)$ must be synchronized together for calculating Z_{Ground}. Thus sync-wave measurement is an essential requirement for the proposed scheme. For this scheme, single-snapshot (i.e., Type 1) sync-wave data are used. Event triggered data transmission is sufficient. Delays of a few seconds are acceptable. The "central location" in this case is the substation to be monitored. The precision timestamps can be obtained from the substation Ethernet.

Although the above example is about grounding condition monitoring, the concept of pushing offline testing methods online with the help of disturbance-containing sync-waves is equally suitable to other apparatuses. A lot of new research topics can be formulated based on the proposed strategy.

2) Example of Strategy 5 – Incipient Fault Detection: Incipient faults are signs of pending apparatus failures. Examples are self-clearing arcing of cable insulation and temporary contact to a tree branch by an overhead conductor. These faults do not usually result in currents that either are large enough or have sufficient duration to trigger protections. However, they are observable as distorted voltage and current *waveforms,* as shown in Fig. 16. Successful detection of such incipient faults can lead to a new paradigm for power system protection called proactive protection (or fault anticipation), i.e., to take actions before actual permanent failures occur [6].

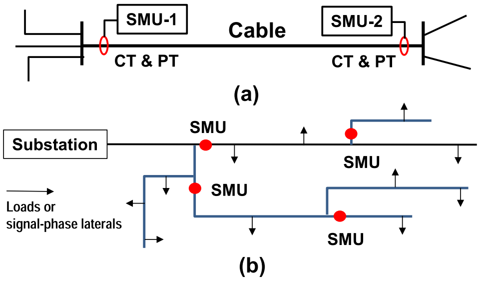

Fig. 17. Two possible schemes for incipient fault detection.

Fig. 17a shows one idea pursued by the authors to monitor incipient faults of *transmission* cables. Before the permanent failure of a cable, there are signs of sporadic insulation arcing events that may last several weeks to months undetectable using traditional relays [6]. The goal of the proposed idea is to identifying such arcing events and *quantifying their severity*. The findings can be used, for example, to justify cable replacement. The proposed scheme uses two SMUs placed at the two ends of the cable. Two SMUs are essential in this case to (1) determine if a disturbance event originates from the cable, (2) find the arcing location and (3) *quantify the arcing severity by estimating the nonlinear arcing resistance.* In this application, the SMUs shall be able to record single-snapshot (i.e., Type 1) sync-waves. The data can be downloaded for offline analysis (Scheme A) or are transmitted to one of the substations for online analysis (Schemes C). There is no need for real-time data since incipient failures are treated as alarms for follow-up actions.

The authors believe that it is possible to use multiple SMUs to "triangulate" the locations or zones of incipient faults in a distribution network (Fig. 17b), based on the *degree of waveform deformation* at the SMU locations. A potential application is the prevention of overhead line-caused forest fires due to vegetation encroachment. In this application, a cellular network can be used to transmit single-snapshot sync-waves (i.e., Type 1) to a central location using event-triggered transmission Scheme B. An application program is run whenever data are received. The central location may be the district office that looks after the distribution network of interest. The app becomes a tool for maintenance personnel.

Although incipient faults are used as examples above, the concept of using multiple SMUs to capture apparatus- generated disturbances and to determine their characteristics (such as location, severity, frequency, etc.) is generalizable. It can be applied, for example, to develop new schemes for reclosing overhead lines or for detecting misoperation of feeder capacitors. Research needed in this direction also includes the optimal deployment of SMUs.

C. Summary

This section has presented strategies and examples of how to utilize sync-wave data to create innovative applications. It should be noted that these strategies are not an exhaustive list of potential paths of application development, but rather a stepping stone to inspire more innovative ideas on the application of sync-wave data.

Once an application is formulated along with solution ideas, the kinds of SMUs to use, types of sync-wave data, schemes of data handling, site of "central" location and other implementation details will fall into place naturally. More information is provided in the next section.

VI. Vision 2 – Platforms for Sync-Wave Applications

Although there are various potential applications of sync-wave data, they can all be classified into three types according to the modes of operations, as explained in Section III:

- Offline analysis;
- Online monitoring (i.e., no automatic control action);
- Real-time protection & control.

Each type of applications has different requirements on data infrastructures, and thus they form the basic considerations to build appropriate application platforms. This section presents our ideas and opinions on three types of potential application platforms, for the purpose of stimulating discussions and innovations.

A. Special-Purpose Sync-Wave Platforms

Applications that lead to real-time protection & control actions are the mission-critical type of applications. Representative examples are the differential line protection (Case A) and generator tripping scheme (Case E) in Section III. There is an exceptionally high reliability expectation for such applications. Utility companies are extremely careful in accepting applications where actions are automatic and have an immediate impact on power systems. Mixing such applications with other applications is even harder to justify. It is our opinion, therefore, that customized, dedicated special-purpose SMU networks are the most suitable platforms for such applications. Both example applications A and E adopted this approach. This is the approach widely practiced in power system protection as well, which is also the reason that both DFRs and relays are used even though relays can record faults. Another example is BPA's synchrophasor based Remedial Action Scheme (RAS). BPA has a WAMS with various applications, but its RAS is based on a fully redundant system [40]. A dedicated network is simpler to speedup, operate and maintain as it only needs to deal with one application. *It is important to note that a dedicated network does not mean dedicated infrastructures*. The communication and sensing systems can be shared with other platforms, just like what has been practiced for different protection schemes. The cost of dedicated SMUs is low.

B. Multi-Use Sync-Wave Platforms

Accordingly, the tasks left for a multi-use SMU network are the offline applications and online monitoring applications. A common characteristic of these applications is that *real-time streaming* of data is not essential. (But a streaming mode that enables timely situation awareness for operators is still desirable). Thus a lot more options become available to construct such a SMU network. This network may be called sync-wave-based wide-area monitoring system (SWAMS). We believe attentions are needed in the following three areas for building a SWAMS:

- On-demand streaming: Sync-waves have many offline applications as shown earlier. These applications need to access the recorded data through download, a form of on-demand streaming. On-demand streaming also includes data retrieving through automatic polling by the control center (for online monitoring applications). Therefore, efficient and seamless on-demand access to data is an important design consideration for a SWAMS;
- Disturbance streaming: Sync-waves are most useful if it contains disturbances or changes. Steady waveforms do not provide new information. As a result, it is beneficial to stream disturbance containing data only (i.e., Scheme B) to reduce the demand and cost on data communication. One model is the per-use data transmission using cellular networks. This model can be used, for example, to monitor incipient faults for forest fire prevention (Section V.B);
- Distributed data storage: Recorders with huge storage capabilities are widely available nowadays. One sensible strategy to build a SWAMS network with heavy on-demand streaming may be to store the sync-wave data locally at each SMU or substation. This is the approach used successfully by the PQ monitoring networks, and DFRs also store data locally.

The development of a SWAMS can learn from the experiences of PQ monitoring networks [41] and WAMS [2]. In fact, A PQ monitoring network may be easily upgraded into a basic SWAMS if the PQ monitors are upgraded with precision timestamps. It may be possible also to upgrade the current WAMS into SWAMS, especially if derived indices are transmitted (more in Section VI.D).

C. Portable SMUs and Mobile Sync-Wave Platforms

A portable SMU is a unique device suitable for various offline applications, such as troubleshooting and model validation. Such tasks only need SMU data occasionally. Portable SMUs have a unique advantage: They can be deployed at almost any locations as needed with little site preparation and infrastructure support, thus significantly expanding the coverage and applications of sync-waves.

In fact, a fleet of portable SMUs could be viewed as a third sync-wave platform - the mobile platform - complementary to special-purpose SMU networks and SWAMS. The SMUs can be moved to different sites to carry out different tasks. Application Cases B and C in Section III present good examples of this practice. Note that portable measurement devices are used in utility companies routinely. Fig. 18 shows the installations of two SMUs (PQ monitor type) for the harmonic cancellation study reported in Case C of Section III.

Portable SMUs are also a very important tool to support university research. Researchers can use them to record sync-waves in labs, homes or other locations to get in touch with real-world power system responses. The data recorded by gapless SMUs can also be used to emulate PMU, leading to a portable PMU device. Lack of portable PMUs and realistic phasor data among university researchers in the early years was one deficiency in PMU-related research activities.

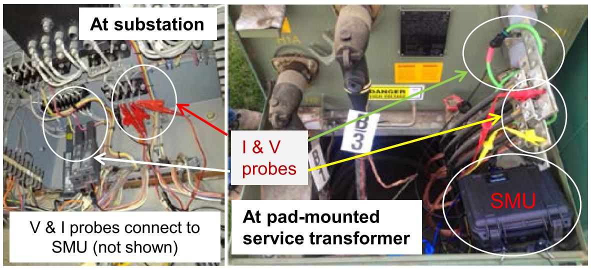

Fig. 18. Installation of two portable SMUs at different sites.

D. General Purpose Algorithms

A few common data analytics algorithms are needed for the above three sync-wave platforms. This is especially true for the multi-use SWAMS and the mobile platform, as almost all applications need them to select the relevant data to work on. The authors have identified two such algorithms.

1) Algorithms to detect abnormal waveforms: As explained earlier, sync-waves that contain changes, transients, oscillations and disturbances are useful data. The waveforms may also contain unknown deviations from regular sinewaves. Such waveforms are collectively referred to as abnormal waveforms here. It is essential to develop algorithms that can detect and extract abnormal waveforms from the massive amount of waveform data. Otherwise, it is impossible to know which segment of a waveform needs to be analyzed. Fortunately, some research works have started in this direction [6],[42];
2) Algorithms of disturbance pattern recognition: Experiences of PQ monitoring have shown that even abnormal waveform data can be overwhelming [6]. Therefore, it is useful to have algorithms to further digest the disturbance-containing data through, for example, pattern recognition and characterization. Note that PQ monitors recognize disturbances from PQ perspectives, such as voltage sags and transients. What is needed here are much more general algorithms that can recognize and group "similar" abnormal waveforms ranging from switching transients, power oscillations to incipient faults and so on. This is a fertile ground for Artificial Intelligence (AI) and big data analytics. The ultimate goal of this line of research is to identify the root-causes of the abnormal waveforms.

In addition, it is worthwhile to research algorithms that calculate derived indices such as modal parameters (modal frequency, power, impedance, damping etc.). Although such indices are application-specific, some of them may form a core set of algorithms to extract advanced information from sync-waves. Note that many applications only need derived data at the central locations. Such an distributed processing and centralized analysis strategy could significantly reduce the communication requirement for sync-wave applications as no waveform data need to be transmitted.

Actual field data play an important role in supporting the research of the above algorithms. There are many types of abnormal waveforms in real life that are way beyond what can be conceived using simulations. Portable SMUs are a great tool for researchers to obtain actual measured data.

E. Other Factors to Consider

The development of a sync-wave measurement network also requires consideration of other factors such as communication media, data protocols, cybersecurity, the impact of 5G networks and so on. These subjects are beyond the scope of this paper. But further investigation by experts on these subjects would be important for SMU network development.

F. Summary

The authors believe that dedicated, special-purpose SMU networks are the best option for individual applications that perform real-time automatic controls. The experiences of power system protection have shown that this is a widely accepted practice for mission-critical functions.

The first generation multi-use sync-wave-based WAMS, SWAMS, is likely for online monitoring applications. Its primary data handling schemes could be on-demand data access, abnormal waveform streaming, and distributed data storage. This proposal is based on the successful experiences of PQ monitoring networks and DFR practices.

A fleet of portable SMUs is essentially a third sync-wave measurement platform. It offers some unique advantages and is an important tool to support application research.

It is very important to develop general-purpose algorithms for the detection and characterization of abnormal waveforms. They are essential tools to identify and extract relevant data for use by various applications.

VII. Vision 3 – Collaborative Activities and Standards

Sync-waves present a great opportunity for innovation. In addition to individual research activities, collective efforts are also needed. Examples are information sharing and standards development.

A. Committee Activities

Since sync-waves have two application domains (system and apparatus), it is natural to have committees focusing on each type of application. However, both types of applications need to access the same resources and data. They also face the same data screening issues, such as abnormal waveform detection and pattern recognition. A lot more can be gained, therefore, if these committees can work together to share their knowledge and perspectives.

There are at least three disciplines to approach apparatus-oriented applications. These are condition monitoring, protection and power quality. A Working Group (WG) called Power Quality Data Analytics was formed a few years ago to explore the use of waveform data (including sync-waves) for apparatus-oriented applications. Although the WG was created under the PQ umbrella, it has been working with researchers from protection and condition monitoring to promote waveform based applications.

For system-oriented applications, the Power System Dynamic Performance Committee has ongoing efforts looking into various aspects of synchronized waveform measurements already: The WG on Power System Dynamics Measurements has a focus on the technologies, requirements, and applications of sync-waves, and the Task Force on Modeling and Simulation of Large Power Systems with High Penetration of Inverter-based Generation are exploring the use of sync-wave measurements for generator model validation.

The committee of Power System Instrumentation and Measurements can also play a role. This committee has helped the development of PMUs and PQ monitors in the past.

B. Measurement Standards

As discussed in Section IV, sync-waves are essentially raw data collected from metering points with little processing. Therefore, it is easier to develop standards for sync-wave measurement from the perspectives of metrology, design, and commissioning of SMUs. As a matter of fact, some of the standards developed for power quality disturbance data recording, compression, and exchange [43]–[45] can be helpful. Standards covering the frequency response and accuracy requirements on monitors, PTs and CTs have already been established from the PQ perspectives [44]. In terms of sync-wave supporting multiple applications, experience from synchrophasor standardization activities can be useful. In particular, the application oriented requirement classification for synchrophasors in [46] would shed light on sync-wave implementation and costs.

One requirement missing in the current PQ measurement standards is the synchronous recording of Type 2 (multiple snapshots) data. It is very useful if all monitors can start recording each snapshot at exactly the same precision time. Standards developed for SMUs should require this capability.

An area for additional sync-wave standard development is communication protocols and networks. The synchrophasor community is currently working on a NASPInet2.0 architecture [47]. Given the potentially higher data rates for some sync-wave applications, efficient communication protocols and networks are important to ensure low latency and high reliability in data transmission.

VIII. Conclusion

Sync-wave data are becoming widely available through a variety of sample data measurement units and digital substations. They provide unique insights into the behaviors of power systems and apparatuses, especially those associated with transient and high-speed phenomena. A new opportunity has, therefore, arrived for researchers to create waveform data-based solutions to system-level as well as apparatus-related problems. The applications may take three forms, ranging from offline analyses, online monitoring, to real-time protection & control. This paper has presented our visions on how to expand the monitoring, protection and control of power systems and apparatuses using sync-wave data. Main conclusions can be summarized as follows:

- Five strategies have been proposed to inspire the development of sync-wave applications. The concept of using sync-waves to identify participants in system-wide dynamic events points to a new direction to advance online stability monitoring and control. The strategy of migrating offline apparatus testing into online with the help of disturbance waveforms is also an innovative concept to expand online apparatus condition monitoring.
- This paper advocates two types of *stationary* sync-wave platforms: special-purpose SMU networks and multi-use SWAMS. This application-driven platform development strategy should make it easier to justify, design and build a SWAMS network at a reasonable cost. A fleet of portable SMUs is essentially a *mobile* platform. This platform offers some unique benefits. Two general-purpose data screening algorithms are needed to support various sync-wave applications.
- There is a need for collaboration between system-oriented and apparatus-oriented application communities. Both communities are affected by at least two common issues: 1) A set of data screening algorithms are needed to identify information-containing sync-wave data; 2) A justifiable sync-wave monitoring network needs to include both application domains.
- Sync-wave measurement standards are easier to develop in terms of metrology. But communication protocols and networks for sync-wave data could pose new challenges. These standards can benefit from the thirty-plus years of experiences gained from standard development activities for power quality measurements and synchrophasors.

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