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Synchro-Waveform Measurements: A Survey of Industry Readiness, Deployment Trends, and State of Practice

Prepared by the Synchro-Waveform State-of-Practice Task Force

November 2026

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Abstract

Novel Applications for Synchronized Power Instrumentation (NASPI)[1], in collaboration with the IEEE Power & Energy Society (PES), established the Synchro-Waveform State-of-Practice Task Force to conduct an industry survey of utilities, independent system operators (ISOs), and technology vendors and document the current state of practice for high-resolution waveform measurements. The survey was motivated by growing interest in high-resolution, time-synchronized waveform measurements for monitoring increasingly fast power system dynamics associated with inverter-based resources and large data center loads. These developments have prompted the need to better understand how these measurements are currently acquired, managed, and used across the industry. The task force therefore sought to assess existing deployment practices, commercially available capabilities, application priorities, supporting infrastructure, and potential barriers to broader adoption. The survey was organized around six priority areas: waveform acquisition; time synchronization; communication and data retrieval; storage and data management; applications, analytics, and use; and deployment maturity. Questions were structured separately for utilities/ISOs and technology vendors to compare current end-user practices with available vendor capabilities.

The survey responses indicate that high-resolution waveform measurement capability is already broadly established among participating organizations, with both event-triggered and continuous recording in use and time synchronization widely implemented. At the same time, notable variation exists in data retrieval, communication protocols, storage practices, data formats, compression, and integration of analytics into operational workflows. The results also indicate growing interest in extending waveform use beyond traditional disturbance recording toward applications such as oscillation monitoring and model validation. This report presents the survey results as an industry-informed baseline for the current state of synchro-waveform technology deployment and identifies areas where continued work on interoperability, scalable data management, automation, application-specific requirements, and operational integration could support broader adoption and use.

[1] NASPI is a joint initiative of the U.S. Department of Energy Office of Electricity and the Electric Power Research Institute (EPRI).

Summary

The increasing penetration of inverter-based resources and data center loads is introducing faster and more complex dynamics into power systems. High-resolution waveform measurements provide the temporal and spectral detail needed to characterize these phenomena beyond what is typically available from supervisory control and data acquisition (SCADA) and synchrophasor measurements. The need for improved high-resolution monitoring has also been reflected in recent NERC requirements and guidance, IEEE standards, and broader industry efforts on waveform-based monitoring. In response to this growing need, NASPI and the IEEE Power & Energy Society (PES) established the Synchro-Waveform State-of-Practice Task Force to assess how synchro-waveform technologies are currently deployed and used across the industry. The task force conducted a survey to examine existing measurement practices, commercially available capabilities, supporting data infrastructure, application priorities, and deployment maturity across utilities, independent system operators (ISOs), and technology vendors.

The survey adopted a technology-agnostic view of synchro-waveform capability. The survey was organized around six priority areas: waveform acquisition; time synchronization; communication and data retrieval; storage and data management; applications, analytics, and use; and deployment maturity. Rather than associating synchro-waveform measurements with a specific sensor class, the assessment considered the broader measurement and data-handling capabilities available through digital fault recorders, power-quality meters, protection relays, PMUs with waveform-recording capability, and other dedicated waveform sensors. Questions were structured to capture both end-user and technology-provider perspectives. Utility and ISO questions focused on current deployment and operational practices, while vendor questions addressed available sensing, communication, storage, streaming, compression, and analytics capabilities. A subset of questions was common to both groups to support comparison between current industry practice and available technology.

The survey received 30 responses, comprising 16 utility participants, 3 ISO participants, and 11 vendor participants. The responses provide a cross-sectional view of industry perspectives on the deployment, use, and development of waveform and synchro-waveform technologies. The results indicate that high-resolution waveform measurement capability is already broadly established among the participating organizations. Utilities and ISOs reported active use of waveform measurements through multiple device classes, with both event-triggered and continuous recording widely used. Vendor responses showed corresponding support for both recording modes, indicating substantial alignment between current utility practice and available commercial capability. Time-synchronization also appears to be a relatively mature element of the measurement chain. All utility/ISO and vendor respondents answering the relevant questions reported GPS-based time-synchronization. These findings suggest that many of the foundational capabilities required to acquire and time-align high-resolution waveform measurements are already in place.

The survey further indicates that waveform applications are expanding beyond traditional disturbance recording toward dynamic performance assessment and advanced analytics. Current utility and ISO use remains concentrated in event and incipient-fault analysis, fault recording, power-quality monitoring, and protection. Utility and ISO participants also identified several applications as priorities for future use, with particularly strong emphasis on oscillation monitoring and model validation. These responses indicate growing interest in using waveform measurements to characterize dynamic system behavior and evaluate model performance.

Vendor capabilities align closely with these priorities. Reported vendor-developed synchro-waveform analytics include oscillation monitoring, power-quality monitoring, event and incipient-fault analysis, and model validation. This alignment suggests that commercial capabilities already exist for several of the applications that utilities and ISOs identified as priorities for future use.

Overall, the survey indicates that technology availability is progressing ahead of full operational integration. Vendors reported products spanning much of the measurement-to-application chain, including sensing, communications and streaming, storage and data management, and analytics. However, the availability of these individual capabilities does not by itself translate into fully integrated operational workflows within utilities and ISOs. Broader adoption will depend increasingly on improved interoperability and standardization, scalable data management and automation, operational integration of applications identified as future priorities by utilities and ISOs, and clearer application-specific requirements for sampling, time synchronization, data availability, compression, and retention. Continued industry benchmarking will also be important for tracking progress as these capabilities transition from available technologies to routine operational practice.

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Large language model (LLM)-based artificial intelligence tools were used for limited editorial support, including language refinement and presentation. All content was reviewed and verified by the authors, who retain full responsibility for the accuracy, interpretation, and conclusions presented in this report.

Acronyms and Abbreviations

AMI	Advanced Metering Infrastructure
COMTRADE	Common Format for Transient Data Exchange
CSV	Comma Separated Values
CWS	Continuous Wave Stream
DER	Distributed Energy Resources
DFR	Digital Fault Recorder
DOCSIS	Data Over Cable Service Interface Specification
FTDV	Fast Time Domain Values
FTP	File Transfer Protocol
GPS	Global Positioning System
HTTPS	Hypertext Transfer Protocol Secure
IBR	Inverter-Based Resources
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operator
NASPI	Novel Applications for Synchronized Power Instrumentation
NERC	North American Electric Reliability Corporation
PMU	Phasor Measurement Unit
POW	Point on Wave
PQ	Power Quality
PQDIF	Power Quality Data Interchange Format
SCADA	Supervisory Control and Data Acquisition
SFTP	Secure File Transfer Protocol
STTP	Streaming Telemetry Transport Protocol
TiDL	Time Domain Link
UTC	Coordinated Universal Time

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1.0 Introduction

The electric power system is undergoing rapid change with the large-scale integration of power electronic-based generation and load resources. Inverter-based generation resources can exhibit fast control and protection responses over sub-cycle to multi-cycle time scales, particularly during disturbance events (Gu and Green 2023). Similarly, large computational loads, including data centers, can produce rapid power ramps, abrupt load changes, and sustained oscillatory behavior over a broad frequency range (NERC 2025a). Capturing and characterizing these phenomena requires high-resolution measurements with sufficient temporal resolution and bandwidth to resolve the underlying system dynamics (Silverstein and Follum 2020, Chatterjee, et al. 2026).

Existing grid monitoring systems, such as supervisory control and data acquisition (SCADA) systems and phasor measurement units (PMUs), provide critical operational visibility but have limitations for monitoring fast-acting grid dynamics. SCADA measurements generally lack the temporal resolution required to characterize transient behavior. PMUs provide substantially higher reporting rates and precise time synchronization; however, their reported quantities are obtained through phasor estimation algorithms designed primarily around the fundamental-frequency component (IEC/IEEE 2018). Their effective measurement bandwidth is therefore constrained by reporting rate and low-pass filtering, which can attenuate or misrepresent higher-frequency components (Chatterjee, et al. 2026). Accordingly, high-resolution waveform measurements are increasingly being considered for applications that require greater temporal and spectral fidelity. Point-on-wave (POW) measurements retain discrete samples of the instantaneous voltage or current waveform, preserving the underlying time-domain signal and a broader range of its frequency content. This enables direct observation of fast dynamics that may not be adequately represented in SCADA and PMU measurements (Mohsenian-Rad and Xu 2023, Silverstein and Follum 2020, Xu, et al. 2022).

The need for high-speed measurements has been evident in several recent grid events. Investigations by the North American Electric Reliability Corporation (NERC) into the Blue Cut Fire, Canyon 2 Fire, and Odessa disturbances identified the lack of high-resolution disturbance monitoring data as a limitation in evaluating the response of inverter-based resources (IBRs) (NERC 2021, NERC 2018). NERC subsequently recommended plant-level and, where feasible, inverter-level high-resolution oscillography to support event reconstruction, performance assessment, and model validation (NERC 2018, NERC 2025b). Measurement limitations have also been observed in the analysis of IBR-driven oscillations. At Dominion Energy, oscillations injected by solar plants were initially observed at 8 Hz in 30-frame/s PMU reports but were subsequently shown to be an aliased representation of an actual 22 Hz oscillation identified from higher-resolution POW measurements (Wang, et al. 2021). Similar concerns regarding measurement adequacy are now emerging on the load side. For example, in ERCOT, an event associated with a crypto-mining load appeared in 30-frame/s PMU data as a 25 MW oscillation at approximately 7.5 Hz, whereas higher-resolution waveform measurements later confirmed it to be a 23 Hz oscillation with a magnitude of approximately 50 MW (Gravois 2025). These examples demonstrate that measurement resolution and bandwidth can materially affect the observed frequency and magnitude of fast grid phenomena and, consequently, their interpretation.

These observations are increasingly reflected in industry requirements and guidance. NERC Reliability Standard PRC-028-1, *Disturbance Monitoring and Reporting Requirements for Inverter-Based Resources*, was developed to ensure that adequate disturbance data are

available for evaluating IBR performance (NERC 2025b). In this context, NERC PRC-028-1 specifies event-triggered POW recording at a minimum of 64 samples per cycle to support disturbance analysis. IEEE Std 2800-2022 establishes complementary and, in several areas, more stringent monitoring requirements for transmission-connected IBRs (IEEE 2022). These include plant-level digital fault recording at a minimum of 128 samples per cycle and time synchronization of monitoring devices to Coordinated Universal Time (UTC). Collectively, these requirements reflect the increasing importance of high-resolution, time-synchronized waveform measurements for performance monitoring, event analysis, and model validation.

The monitoring need is also extending beyond generation resources. The NERC *Level 2 Alert* on large-load interconnection recommended the installation of high-resolution disturbance recording capabilities for large loads, particularly in areas susceptible to oscillatory interactions, with sufficient sampling rate, storage, and bandwidth to adequately characterize load behavior (NERC 2025c). This need was reinforced in NERC's *Level 3 Computational Load Alert*, where Essential Action 6 calls for dynamic fault recording capability to capture and share computational load performance during grid disturbances, including continuous lower-resolution recording and higher-resolution triggered fault recording for event and root-cause analysis (NERC 2026). These developments point to a broader shift in disturbance monitoring as both generation and load behavior become faster and increasingly power electronics-based. Measurement systems must provide sufficient temporal resolution, bandwidth, time-synchronization, and data accessibility to characterize the system response.

Interest in time-synchronized waveform measurements has consequently increased across the power system community. The IEEE Power & Energy Society (PES) Task Force on Big Data Analytics for Synchro-Waveform Measurements summarized the technology, infrastructure, applications, and remaining technical challenges in its 2024 report, *Synchro-Waveform Measurements and Data Analytics in Power Systems* (Mohsenian-Rad, Joo, et al. 2024). Drawing on contributions from both industry and the research community, the report identified a range of grid applications that could benefit from high-resolution, time-synchronized waveform measurements. It also highlighted important deployment challenges associated with data volume, communication bandwidth, continuous data streaming, storage and retention, data processing, and interoperability. These challenges become increasingly significant as sampling rates, recording durations, and the number of monitored locations increase. Broader deployment therefore depends not only on the availability of waveform capable devices, but also on the readiness of utility communication, storage, data management, and analytics infrastructure to support the resulting measurement volumes and operational workflows (Follum, et al. 2023).

Against this backdrop, broader adoption of waveform measurements requires a clear understanding of industry needs, current practices, application priorities, and deployment barriers. NASPI is well-positioned to facilitate such an assessment by bringing together utilities, independent system operators, technology vendors, researchers, and other stakeholders involved in power-system measurement and monitoring. NASPI has long provided a forum for advancing synchronized measurement technologies and supporting their transition into power-system monitoring and operations, including industry engagement on synchrophasor applications, data quality, communications, and data management (Dagle 2025). Building on this experience and the growing interest in high-resolution waveform measurements, NASPI and IEEE PES jointly established the Synchro-Waveform State-of-Practice Task Force in 2025. The task force initiated an industry survey of utilities, independent system operators (ISOs), and technology vendors to assess current waveform measurement practices and deployments, commercially available capabilities, application priorities, infrastructure readiness, and barriers

to broader adoption. The survey responses were compiled and analyzed across the different stakeholder groups to provide a cross-sectional assessment of current industry practices and priorities. This report presents the findings from the survey to establish an industry-informed baseline for the current state of waveform and synchro-waveform deployment and use, and to identify areas that may require further industry engagement, technology development, or standardization.

The remainder of this report is organized as follows. Section 2 defines the scope of the survey, Section 3 summarizes the participating organizations, and Section 4 describes the survey questions and respondent groups. Section 5 presents the survey responses from utilities, ISOs, and vendors. Section 6 discusses the principal findings and their implications for the current state of practice, and Section 7 outlines areas for future work.

2.0 Scope of the Survey

The survey examines the current state of practice for high-resolution waveform measurements across utilities, independent system operators (ISOs), and technology vendors. For the purposes of this survey, a *waveform measurement* refers to a sampled time-domain representation of instantaneous voltage and/or current that preserves the underlying waveform at a resolution sufficient to characterize the phenomena of interest. Waveform measurements obtained from different devices or locations may or may not be time-aligned. In this report, a *synchro-waveform* refers to a waveform measurement referenced to a common time base such that waveform records obtained at different locations can be accurately aligned in time (Mohsenian-Rad and Xu 2023, Mohsenian-Rad, Joo, et al. 2024).

The survey takes a technology-agnostic view of waveform acquisition. Synchro-waveform capability may be provided by power quality meters, digital fault recorders, protection relays, PMUs with waveform recording capability, or newer dedicated waveform sensors, depending on the device and application. The emphasis is therefore not on a specific sensor class, but on the measurement and data handling capabilities available across the industry, including how waveform data are acquired, time-synchronized, communicated, stored, retrieved, and ultimately used in operational and engineering applications. This broader definition recognizes that utilities may already possess substantial waveform measurement capability through existing monitoring infrastructure, even where that capability is not explicitly identified as a synchro-waveform system. The survey therefore focuses on the capabilities that determine the practical use of these measurements across the complete measurement data pathway.

The survey was structured around the following priorities:

1. ***Waveform acquisition**:* Document whether utilities and ISOs actively collect and use waveform measurements, whether acquisition is event-triggered, continuous, or both, and the sampling rates associated with each approach. For event-triggered systems, the survey also examines the basis for triggering and the types of devices used for waveform capture.

2. ***Time synchronization**:* Assess whether waveform records are referenced to a common time base and identify the synchronization approaches currently used.

3. ***Communication and data retrieval**:* Characterize how waveform data are transferred from field devices, including manual versus automated retrieval, continuous versus intermittent data transfer, and the communication technologies and protocols employed. The survey considers both current utility/ISO practices and capabilities offered by vendors.

4. ***Storage and data management**:* Determine where waveform records are stored, how long they are retained, which file formats are used, and whether data compression is supported. These considerations become increasingly important as sampling rates, recording durations, and the number of monitored locations increase.

5. ***Applications and use**:* Identify applications in which waveform measurements and synchro-waveform analytics are currently used, as well as applications that utilities, ISOs, and vendors expect could benefit from broader use in the future. These include event and fault analysis, power quality monitoring, oscillation monitoring, protection, asset monitoring, DER monitoring, and model validation.

6. ***Deployment maturity**:* Assess the extent to which waveform and synchro-waveform capabilities have progressed from available technology to operational deployment, including vendor solutions, deployed analytics, and use across transmission and distribution environments.

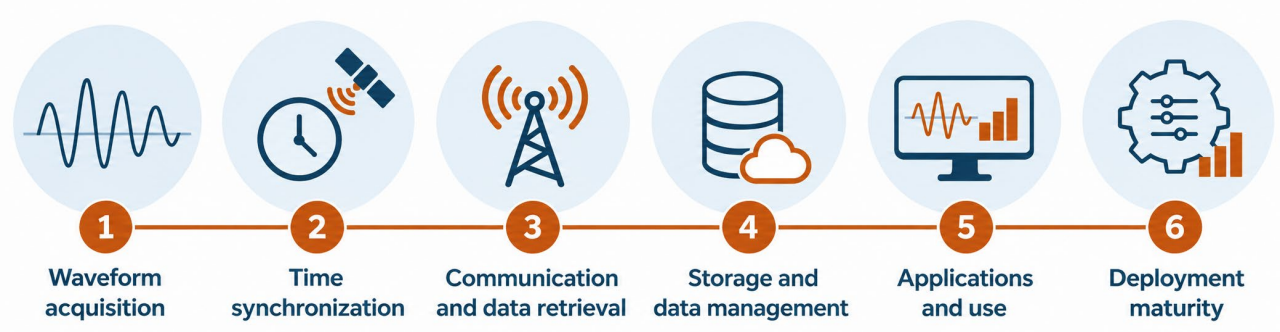


Figure 1. Scope and priority areas of the synchro-waveform state-of-practice survey.

To capture both user and technology-provider perspectives, the questionnaire included utility/ISO-specific questions, vendor-specific questions, and questions common to both respondent groups. Utility and ISO questions focused on deployed measurement practices, data retrieval and retention, and current and anticipated applications. Vendor questions examined available sensing, communication, storage, compression, streaming, and analytics capabilities, as well as the deployment maturity of those technologies. Common questions addressed recording mode, sampling rate, time synchronization, file format, and storage location.

Taken together, the survey provides a structured assessment of how waveform data are currently acquired, synchronized, communicated, stored, and analyzed; which applications are driving their use; and where gaps remain between available technology and present industry practice. These findings provide a basis for assessing current industry priorities and readiness for broader deployment and use of synchro-waveform measurements.

3.0 Overview of the Survey Participants

The survey received 30 participant responses from organizations engaged in the deployment, use, or development of synchro-waveform measurement and analytics technologies. The respondent pool included participants from utilities, ISOs, and vendors. Utility participants formed the largest group, with 16 responses, representing 53.3% of the responses. Vendors accounted for 11 responses, or 36.7%, while ISOs accounted for 3 responses, or 10.0% (see Figure 2).

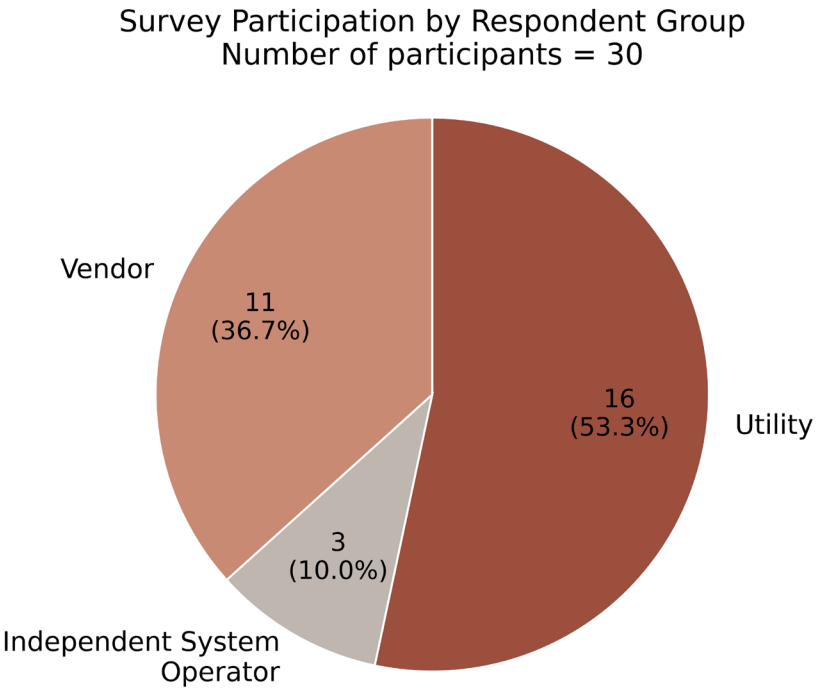


Figure 2. Survey participation by different respondent groups. Grouping is based on participant's type of organization.

Of the 30 responses received, 27 were complete and 3 were incomplete, corresponding to an overall completion rate of 90.0%. Completion rates by respondent group are presented in Table 1. The 27 completed responses included 14 utility respondents, 11 vendor respondents, and 2 ISO respondents.

Incomplete responses refer to cases in which a participant answered a subset of the questions and did not complete the full survey. These partially completed responses were retained because they provided useful information for the questions that were answered. Accordingly, the response rate is reported separately for each survey question later in the report.

Table 1. Survey completion rate by respondent groups.

Participant Type	Total Responses	Completed Responses	Incomplete Responses	Completion Rate
Utility	16	14	02	87.5%
ISO	03	02	01	66.7%
Vendor	11	11	00	100.0%
All Participants	**30**	**27**	**03**	**90.0%**

Most survey participants represented organizations based in the United States (U.S.). All vendor respondents were either U.S. entities or organizations with a significant business presence in the U.S. Among the utility and ISO respondents, three participants represented organizations outside the U.S. The respondent pool therefore reflects predominantly U.S. industry experience, with limited international representation.

4.0 Survey Questions and Respondent Groups

The survey was structured to account for the distinct roles of end users and technology providers in the synchro-waveform measurement ecosystem. Accordingly, the questionnaire was organized into two respondent-specific sections: one for the utilities and ISOs and another for vendors.

- Utilities and ISOs were asked questions focused on operational practices, including the use of waveform measurements, waveform recording devices, data retrieval methods, event-triggered capture, record retention, and present and future application areas. These questions were intended to characterize the current state of synchro-waveform adoption from the perspective of organizations that acquire, manage, and use waveform measurements in power system operations and analysis.

- Vendors were asked a separate set of questions focused on product capabilities and technology offerings. These questions addressed waveform measurement solutions, communication technologies and protocols, product suitability for transmission or distribution applications, data compression, deployed analytics products, and application areas supported by deployed synchro-waveform technologies. The vendor respondent group included organizations offering one or more types of synchro-waveform-related solutions, including sensing and measurement technologies, data analytics and software tools, data streaming and communication services, and data storage and data management services.

- A subset of questions was common to both respondent groups to support comparison across end-user practices and vendor capabilities. These common questions addressed waveform capture options, continuous and event-triggered sampling rates, GPS time synchronization, file formats, and storage of recorded waveform measurements. Although these questions addressed the same underlying topic, their wording was tailored to the role of each respondent group.[1]

Table 2 summarizes the survey structure. Check marks indicate the respondent-group to which each question was presented. Several questions allowed multiple selections, while others required a single response, numerical entry, or ranking. The complete survey questionnaire, including the response options for each question, is provided in Appendix A.

Table 2. Survey questions by respondent group.

#	Survey Questions	Utilities/ISOs	Vendors
1.	Do you actively gather and use waveform measurements?	✓	
2.	What type of device do you use for waveform recording?	✓	

[1] For example, utilities and ISOs were asked about practices they currently use, whereas vendors were asked about capabilities their products or solutions offer or support.

#	Survey Questions	Utilities/ISOs	Vendors
3.	What option(s) do you use/support for waveform capture?	✓	✓
4.	What solutions do you offer for waveform measurements?		✓
5.	What is your maximum sample rate (in samples/cycle) for continuous waveform capture?	✓	✓
6.	What is your maximum sample rate (in samples/cycle) for event-triggered waveform capture?	✓	✓
7.	What is the basis of your event-triggered waveform capture?	✓	
8.	What file format(s) do you use/support for storing waveform records?	✓	✓
9.	Where do you store the recorded waveform measurements? (For vendors: What option(s) do you offer for storing and/or streaming the waveform measurements?)	✓	✓
10.	How do you retrieve waveform measurements?	✓	
11.	How long do you retain waveform records?	✓	
12.	Is your waveform record time-synchronized to GPS?	✓	✓
13.	What other method(s) do you use for time-synchronization?	✓	✓
14.	What communication technologies do you support for waveform data collection?		✓

#	Survey Questions	Utilities/ISOs	Vendors
15.	What communication protocols do you support for waveform data collection?		✓
16.	Where is your product most suited -- Transmission or Distribution?		✓
17.	Do you support waveform data compression?		✓
18.	What is your lossless data compression ratio?		✓
19.	What is your lossy data compression ratio?		✓
20.	Do you currently have a product for synchro-waveform analytics that you have deployed?		✓
21.	Where have you deployed your synchro-waveform analytics technology?		✓
22.	Which of the following synchro-waveform applications have you deployed?		✓
23.	In which applications do you currently use waveform measurements?	✓	
24.	In which applications do you envision using waveform measurements in the future?	✓	
25.	Which applications do you think can benefit most from synchro-waveform technology?		✓

5.0 Survey Responses

This section summarizes the responses received for each survey question, organized by respondent group. The survey responses are presented in two subsections: responses to utility- and ISO-specific questions, and responses to vendor-specific questions.

Unless otherwise noted, percentages are calculated relative to the number of respondents who answered each question. For questions allowing multiple selections, response counts may exceed the number of respondents because each respondent could select more than one option. Nonresponses are reported separately where applicable.

5.1 Responses to Utility- and ISO-Specific Questions

The respondent group for this subsection includes 16 utility participants and 3 ISO participants, for a total of 19. These questions focus on current practices for acquiring, storing, retrieving, and applying waveform measurements in operational and planning contexts.

5.1.1 Do you actively gather and use waveform measurements?

Among the 19 utility and ISO participants, 18 (94.7%) responded to this question. Of these respondents, 17 indicated that they actively gather and use waveform measurements, while 1 respondent indicated that they do not (see Figure 3).

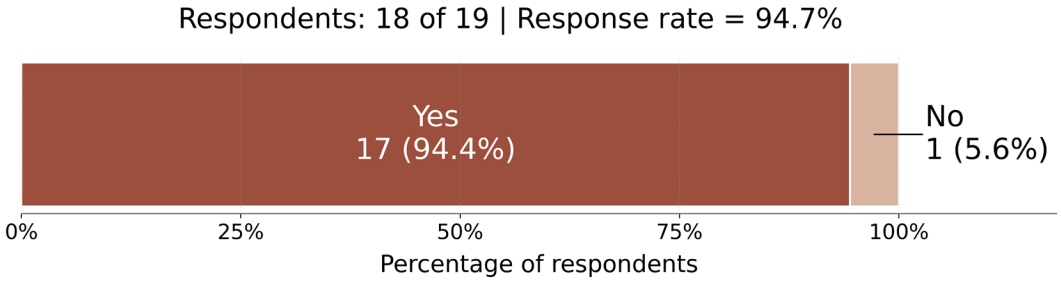


Figure 3. Survey response: Do you actively gather waveform measurements?

Overall, the results indicate that waveform measurement collection and use are already established among most utility and ISO respondents, with 94.4% of respondents reporting active use.

5.1.2 What type of device do you use for waveform recording?

The utility and ISO respondents who reported active use of waveform measurements in Question 5.1.1 were asked to identify the devices used for waveform recording. All 17 respondents from Question 5.1.1 answered this follow-up question.

This question allowed multiple selections; therefore, the total number of selected device types exceeds the number of respondents. All respondents reported using digital fault recorders (DFRs) for waveform recording. PMUs and power quality (PQ) meters with waveform recording capability were also commonly reported, with 12 respondents selecting PMUs and 11 respondents selecting PQ meters (see Figure 4). Smart meters with waveform-recording capability were less commonly reported, selected by 2 respondents.

Respondents selecting “Other” identified additional waveform-recording sources beyond the listed categories, including specialized measurement units, fault detection sensors, protective relays, and portable custom power system monitors.

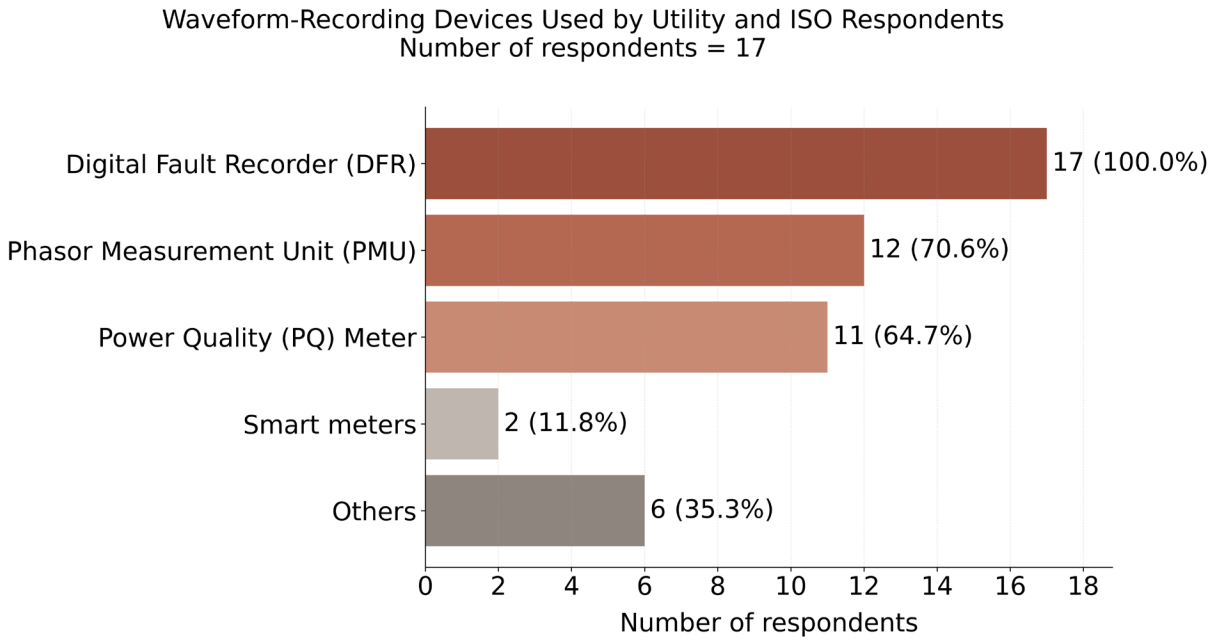


Figure 4. Survey response: What type of device do you use for waveform recording?

5.1.3 What option(s) do you use for waveform capture?

The 17 utility and ISO respondents who reported active use of waveform measurements in Question 5.1.1 were asked what options they use for waveform capture. All 17 respondents answered this follow-up question, corresponding to a response rate of 100.0%.

The respondents were asked to choose from event-triggered and continuous recording options. The question was presented as a multiple-selection question, i.e., the respondent could select one or both options.

- Among these 17 respondents, event-triggered recording was selected by 15 respondents (88.2%), while continuous recording was selected by 13 respondents (76.5%).
- At the respondent level, 11 respondents reported using both continuous and event-triggered recording. Two respondents reported using only continuous recording, while four respondents reported using only event-triggered recording.

These responses (see Figure 5) indicate that both waveform-capture approaches are widely used among the utility and ISO respondents that actively gather waveform measurements. Event-triggered recording was reported slightly more frequently than continuous recording, although most respondents reported using both capture approaches.

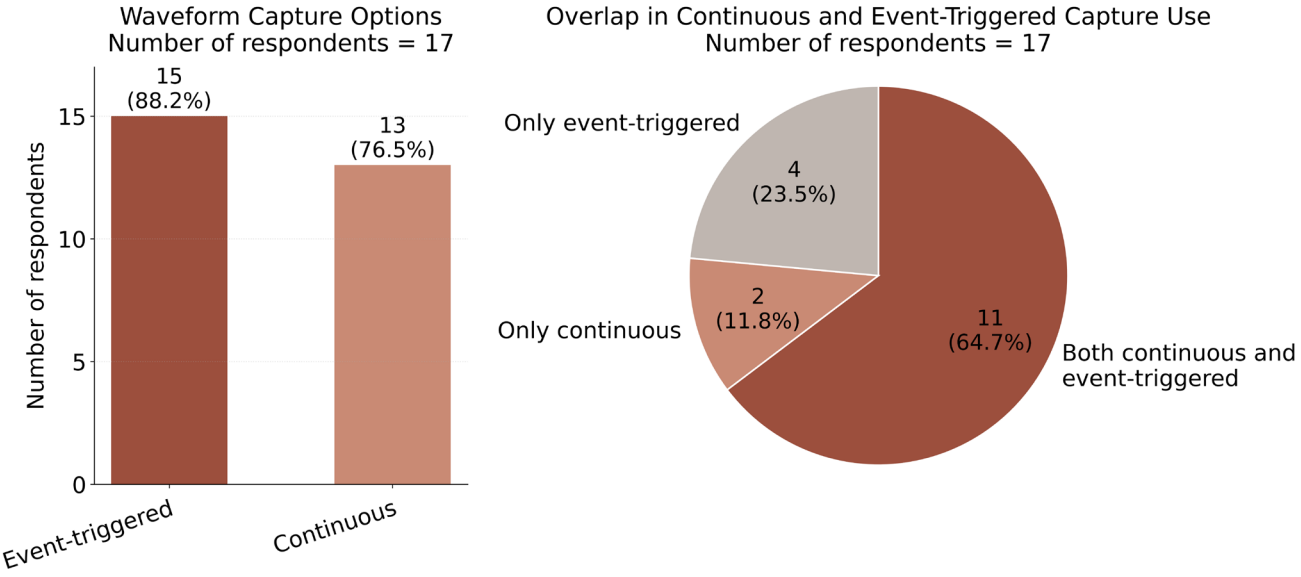


Figure 5. Survey response: What option(s) do you use for waveform capture?

5.1.4 What is your highest sample rate (in samples/cycle) for continuous waveform capture?

The utility and ISO respondents who reported continuous waveform capture provided responses with substantial variation. In many cases, the respondents confused the response with phasors and event-triggered reporting capabilities. The valid responses indicate that reported continuous waveform sample rates ranged from approximately 16 samples/cycle to 512 samples/cycle.

5.1.5 What is your highest sample rate (in samples/cycle) for event-triggered waveform capture?

For event-triggered waveform capture, the utility and ISO responses also showed broad variation, but the reported values are more directly aligned with the purpose of the question. The reported event-triggered waveform sample rates ranged from approximately 16 samples/cycle to 1024 samples/cycle. Several responses were concentrated in the 128–512 samples/cycle range. Some respondents reported device-specific rates in kHz rather than samples/cycle, including values such as 2 kHz, 8 kHz, and 24 kHz, corresponding approximately to 33, 133, and 400 samples/cycle, respectively, at 60 Hz.

5.1.6 What is the basis of your event-triggered waveform capture?

The 15 utility and ISO respondents who reported using event-triggered waveform recording were asked to identify the basis of their event-triggered waveform capture. Of these respondents, 13 answered the question, corresponding to a response rate of 86.7%. The question was presented as a multiple-selection question.

Among the 13 respondents who answered, current was selected by all 13 respondents (100.0%, see Figure 6), while voltage was selected by 11 respondents (84.6%). Four respondents selected “Other” (30.8%) and identified additional triggering bases, including breaker opening, capacitor closing, relay fault/trip indications, harmonic distortion and flicker, and frequency.

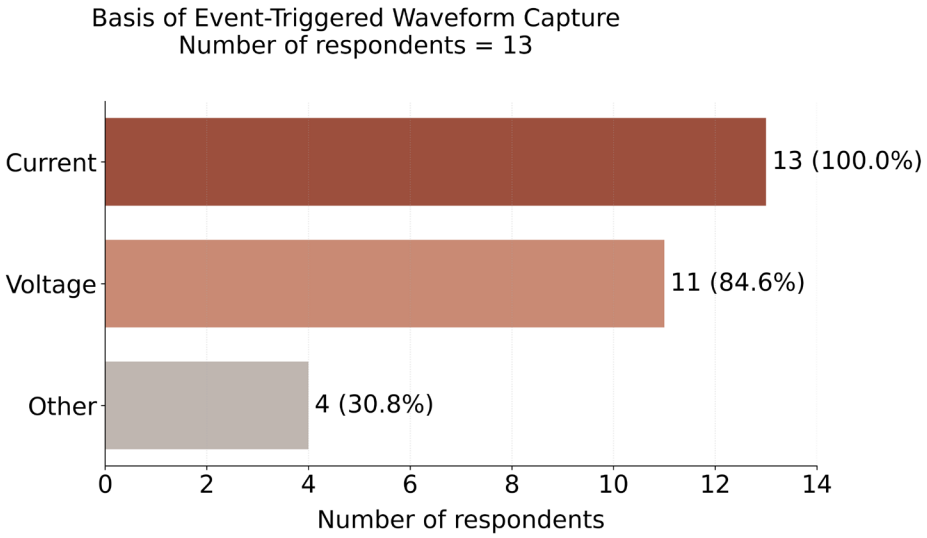


Figure 6. Survey response: What is the basis of your event-triggered waveform capture?

These responses indicate that event-triggered waveform capture among utility and ISO respondents is primarily based on current and voltage quantities. Current was reported by every respondent who answered the question, while voltage was also widely used. The “Other” responses show that some organizations also use equipment operations, relay indications, power-quality conditions, or frequency-based criteria as additional triggering bases.

5.1.7 How do you retrieve waveform measurements?

The 17 utility and ISO respondents who reported active use of waveform measurements in Question 5.1.1 were also asked how they retrieve their waveform records. Of these respondents, 15 answered the question, corresponding to a response rate of 88.2%.

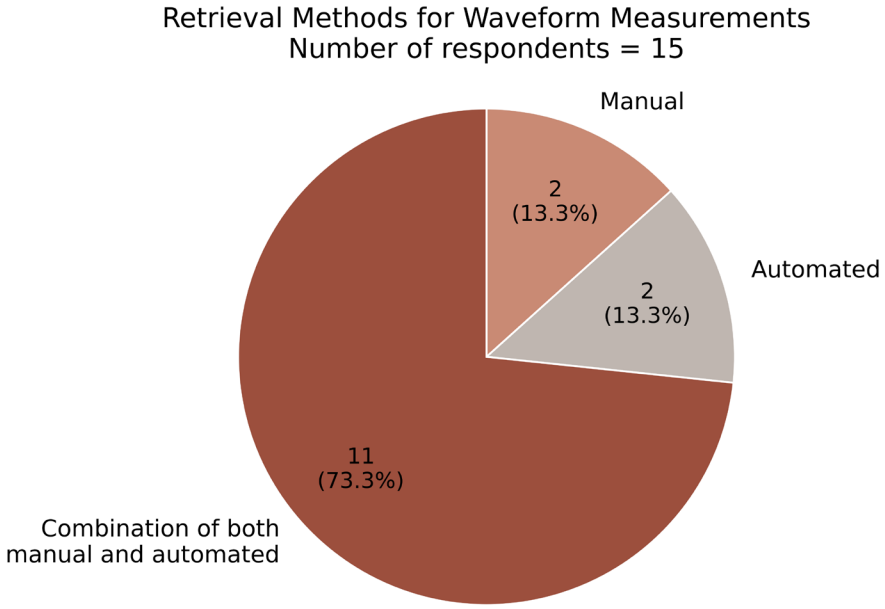


Figure 7. Survey response: How do you retrieve waveform measurements?

The most common response was a combination of manual and automated retrieval, reported by 11 respondents, or 73.3% of those who answered (see Figure 7). Fully automated retrieval and fully manual retrieval were each reported by 2 respondents, corresponding to 13.3% of respondents in each category.

These responses suggest that waveform data retrieval among utility and ISO respondents is commonly implemented as a hybrid process. While automated retrieval is present, the results indicate that many organizations still retain some manual polling in their waveform data retrieval workflows.

5.1.8 Do you time-synchronize your waveform records using GPS?

Of the 17 utility and ISO respondents, 15 answered this question, corresponding to a response rate of 88.23%. All 15 respondents who answered reported that their waveform records are time-synchronized to GPS.

5.1.9 What other method(s) do you use for time-synchronization?

The survey did not capture any responses to this question. No time-synchronization methods beyond GPS were reported.

5.1.10 What file format(s) do you use for storing waveform records?

The 17 utility and ISO respondents who reported active use of waveform measurements in Question 5.1.1 were asked what file formats they use for storing waveform records. Of these, 15 answered the question, corresponding to a response rate of 88.2%.

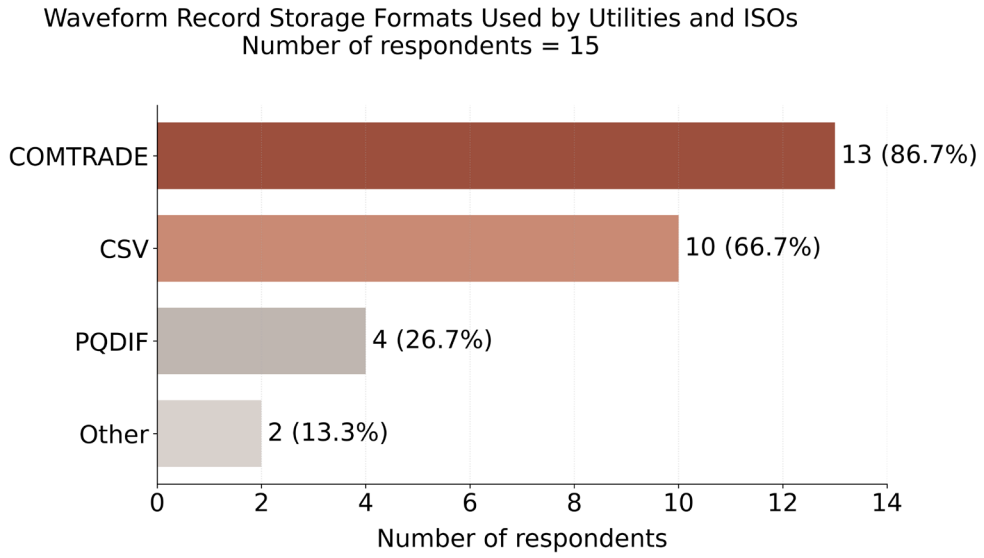


Figure 8. Survey response: What file format(s) do you use for storing waveform records?

The question was presented as a multiple-selection question. Among the 15 respondents, COMTRADE (Common Format for Transient Data Exchange) was the most commonly reported waveform-record storage format, selected by 13 respondents (86.7%), see Figure 8. CSV (Comma Separated Values) was selected by 10 respondents (66.7%), while PQDIF (Power

Quality Data Interchange Format) was selected by 4 respondents (26.7%). Two respondents selected “Other” (13.3%) and identified Parquet and MATLAB file formats.

5.1.11 How long do you retain waveform records?

The same 17 utility and ISO respondents were also asked how long they retain their waveform records. Of these respondents, 14 answered the question, corresponding to a response rate of 82.4%.

The most common retention period was 5 years or longer, reported by 6 respondents, or 42.9% of those who answered (see Figure 9). Retention periods of 90 days to less than 1 year and 1 year to less than 5 years were each reported by 3 respondents, corresponding to 21.4% in each category. A shorter retention period of less than 90 days was reported by 2 respondents, or 14.3% of respondents.

These responses indicate that waveform record retention practices vary across utility and ISO respondents. However, the largest share of respondents reported retaining waveform records for 5 years or longer, suggesting that long-term retention is common among organizations that actively use waveform measurements.

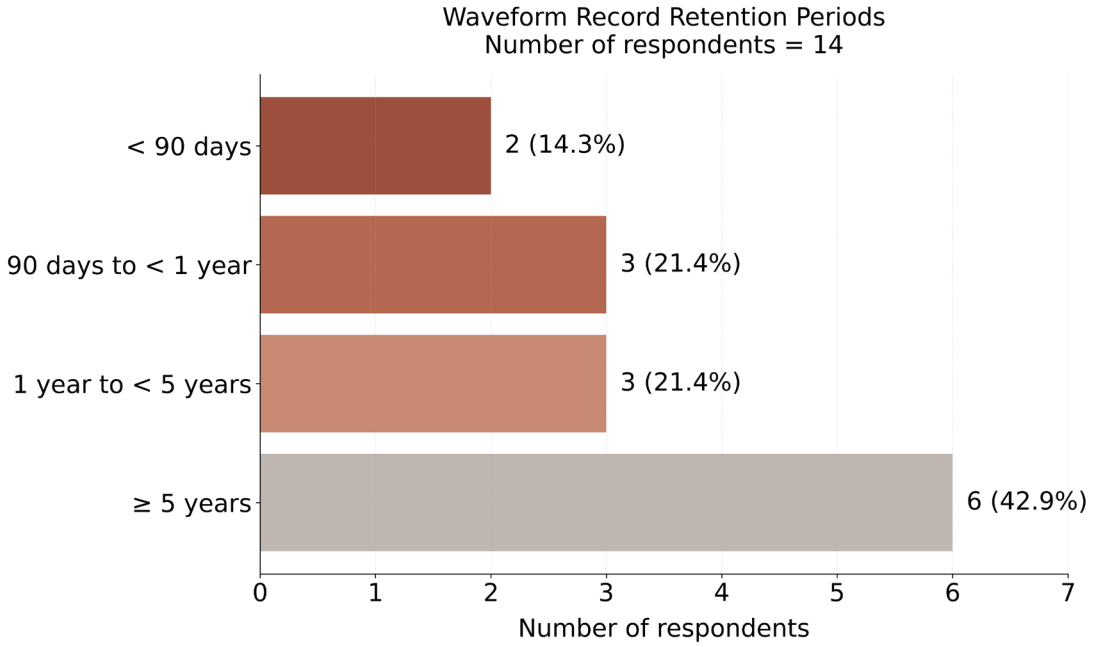


Figure 9. Survey response: How long do you retain waveform records?

5.1.12 Where do you store your recorded waveform measurements?

The utility and ISO respondents who reported active use of waveform measurements were asked where they store recorded waveform measurements. The question was presented as a multiple-selection question, so respondents could report more than one storage location. The response options represent three levels of waveform-record storage: meter-level storage, substation-level storage, and streaming to an external storage, including Cloud.

Among the 15 respondents who answered this question, 13 respondents reported streaming waveform measurements to an external storage (86.7%, see Figure 10), 9 respondents reported recording and storing waveform measurements locally at a meter (60.0%), and 8 respondents reported storing waveform measurements locally at a substation (53.3%).

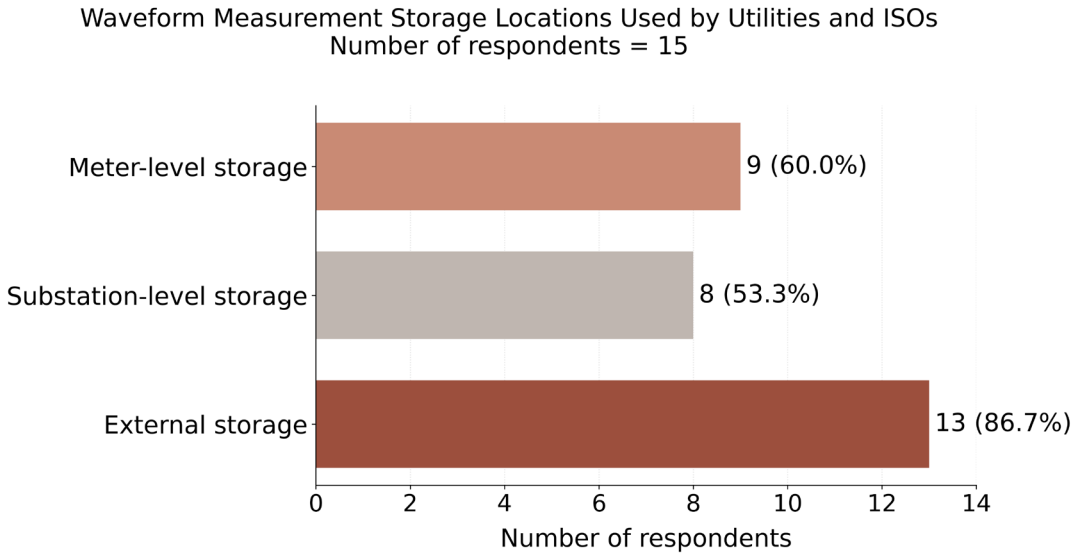


Figure 10. Survey response: Where do you store your waveform measurements?

5.1.13 In which applications do you currently use waveform measurements?

The 17 respondents who reported active use of waveform measurements in Question 5.1.1 were asked to identify the applications in which they currently use waveform measurements. Of these respondents, 15 answered the question, corresponding to a response rate of 88.2%. The respondents could select more than one application for this question.

The most common applications were: (1) event and/or incipient fault analysis and (2) fault recording, each selected by 14 respondents (93.3% of the respondents, see Figure 11). Power quality monitoring was also widely reported, selected by 11 respondents (73.3%). Protection applications were selected by 9 respondents (60.0%), followed by asset monitoring with 7 respondents (46.7%). A smaller but notable share of respondents reported using waveform measurements for model validation and oscillation monitoring, each selected by 6 respondents (40.0%). DER monitoring was selected by 5 respondents (33.3%). Three respondents selected Other (20.0%) pointing to additional uses such as incorporating down-sampled waveform-derived measurements into state-estimation workflows, supporting post-event diagnosis, and other applications.

Overall, the responses indicate that current use of waveform measurements is concentrated in established operational applications, particularly fault-related analysis, fault recording, and power quality monitoring. At the same time, the responses show that utilities and ISOs are already applying waveform measurements to broader analytical functions, including model validation, oscillation monitoring, DER monitoring, asset monitoring, and post-event analysis.

These current-use responses provide a baseline for understanding how waveform measurements are being applied today. The next question asked respondents to identify where

they envision using waveform measurements in the future, providing insight into how the role of waveform data may expand beyond present operational practices.

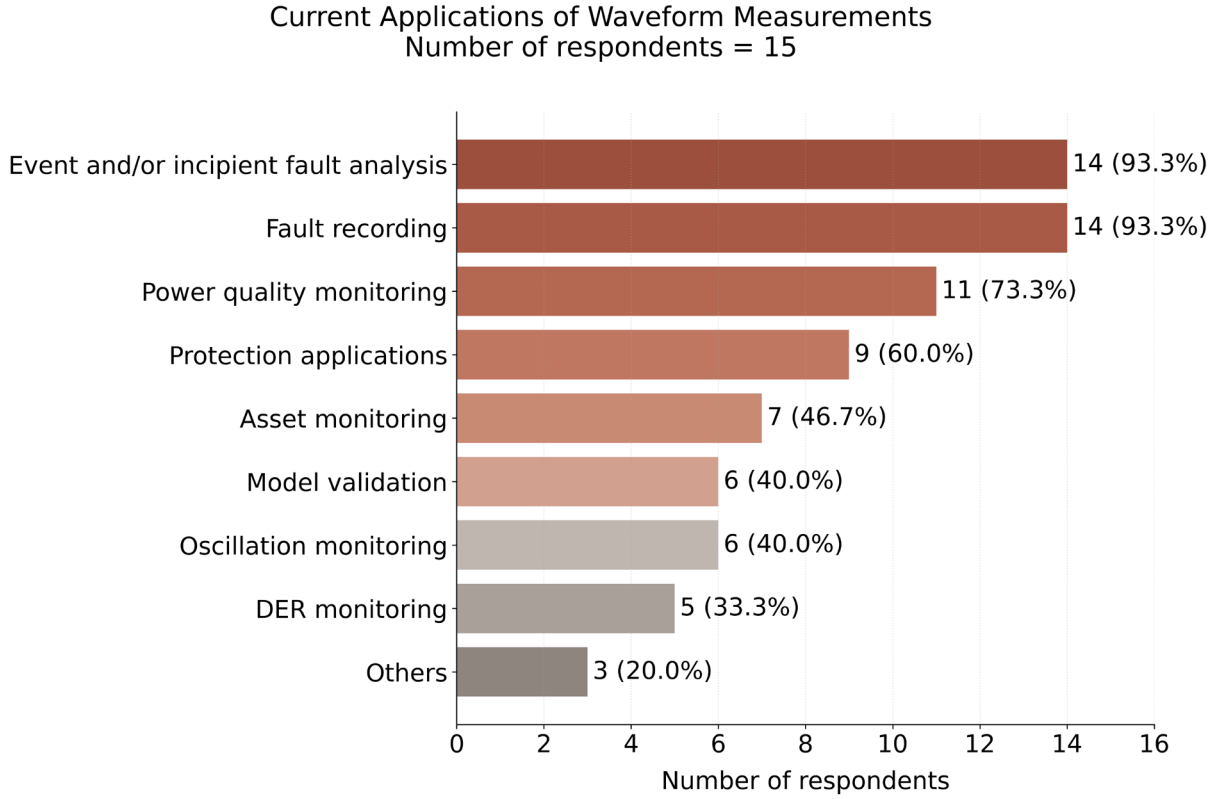


Figure 11. Survey response: In which applications do you currently use waveform measurements?

5.1.14 In which applications do you envision using waveform measurements in the future?

All 19 utility and ISO participants were asked to identify the applications in which they envision would use or benefit from waveform measurements in the future. Of these participants, 15 answered the question, corresponding to a response rate of 78.9%.

The applications most widely identified for future use were model validation and oscillation monitoring, each selected by 14 respondents (93.3% of respondents; see Figure 12). Event and/or incipient fault analysis was selected by 12 respondents (80.0%), while power quality monitoring was selected by 11 respondents (73.3%).

Several other applications were also identified by a substantial share of respondents. DER monitoring and fault recording were each selected by 10 respondents (66.7%). Protection applications were selected by 8 respondents (53.3%), and asset monitoring was selected by 6 respondents (40.0%).

Compared with the current-use responses in Question 5.1.13, the future-use responses indicate increased interest in using waveform measurements for advanced monitoring and performance evaluation. While current use is concentrated primarily in established operational functions such

as fault-related analysis, fault recording, and power quality monitoring, the future-use responses suggest that utilities and ISOs also see value in using waveform data to evaluate model accuracy and identify or characterize oscillatory behavior. This points to a potential expansion of waveform measurement use from event documentation and post-event diagnosis toward more detailed analysis of system behavior.

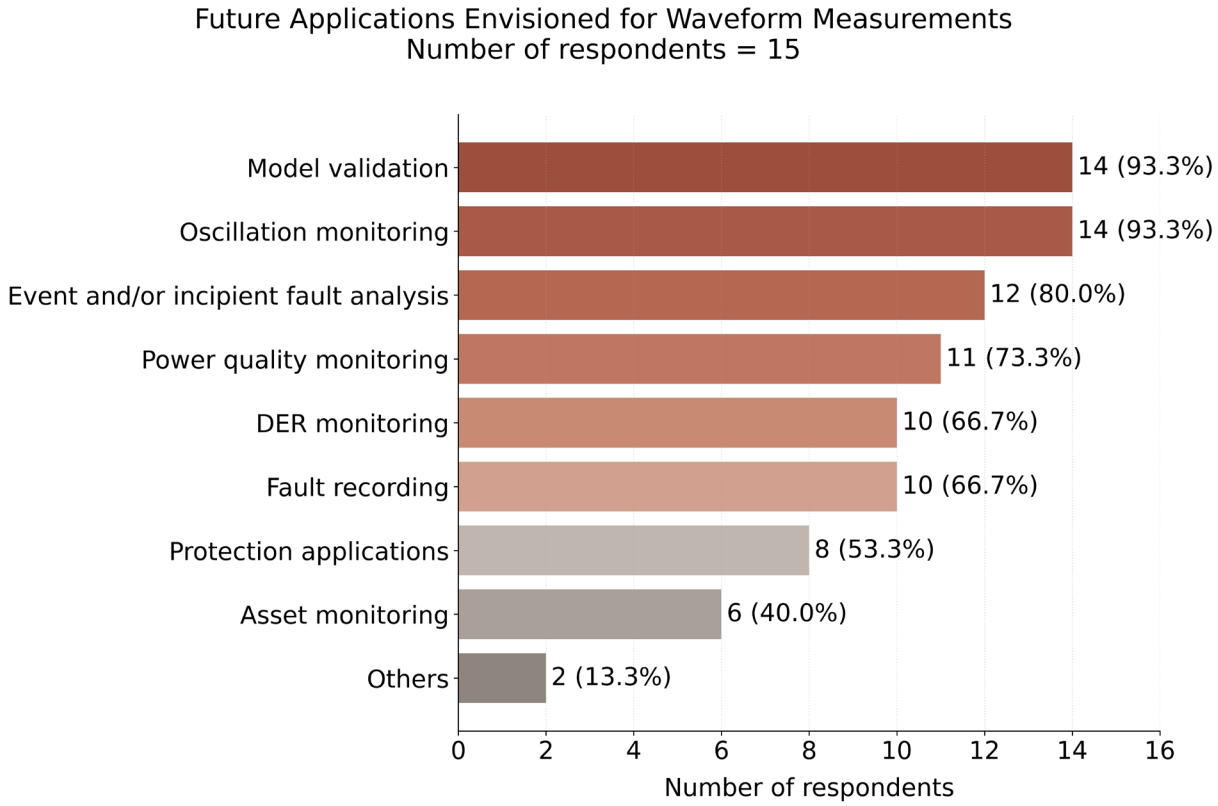


Figure 12. Survey response: In which applications do you envision using waveform measurements in the future?

5.2 Responses to Vendor-Specific Questions

This subsection summarizes responses to the survey questions presented to the vendors. These questions focus on capabilities related to synchro-waveform measurement solutions, communication technologies and protocols, deployment areas, compression capabilities, analytics products, and application areas supported by deployed synchro-waveform technologies.

The respondent group for this subsection included 11 vendors offering one or more types of synchro-waveform-related solutions.

5.2.1 What solutions do you offer for waveform measurements?

The vendor respondents were asked to identify the types of solutions they offer for waveform measurements. The question allowed vendors to select one or more of the following solution types: sensing and measurement technologies, data analytics and software tools, data streaming and communication services, and data storage and data management services (see Figure 13). All 11 vendors answered this question, corresponding to a response rate of 100.0%.

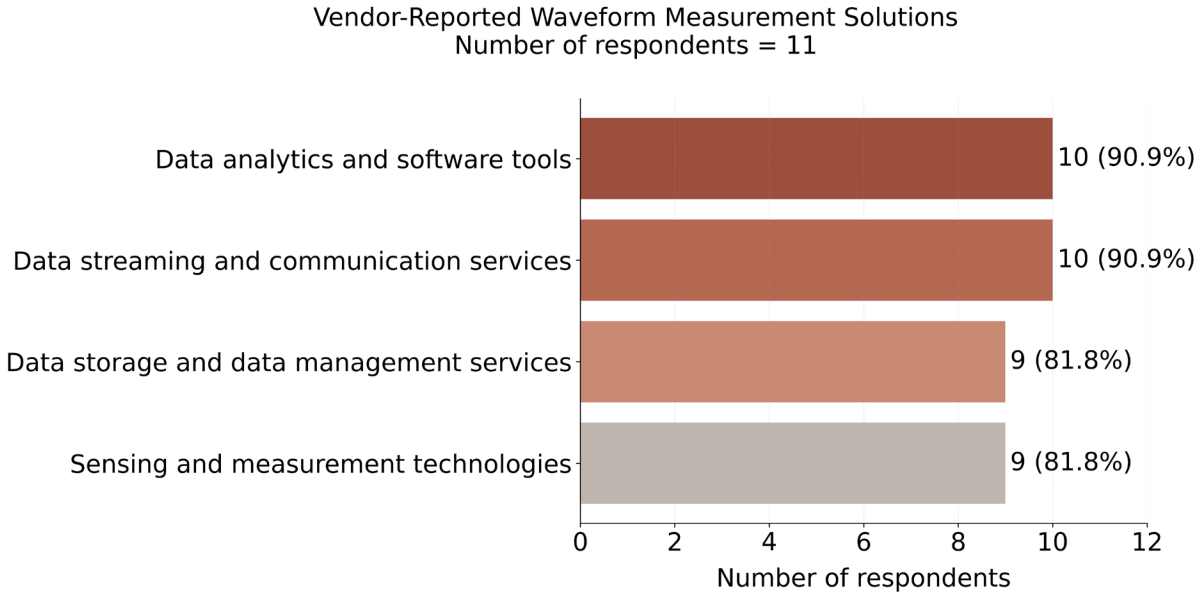


Figure 13. Survey response: What solutions do you offer for waveform measurements?

The most commonly reported solution types were data analytics and software tools and data streaming and communication services, each selected by 10 vendors (90.9% of respondents). Data storage and data management services were selected by 9 vendors (81.8%), as were sensing and measurement technologies (81.8%).

These responses indicate that most vendor respondents offer capabilities across multiple parts of the synchro-waveform technology chain. The results also suggest that the vendor landscape represented in the survey is not limited to measurement hardware, but includes software, analytics, communication, and data-management functions that support the broader use of waveform measurements.

5.2.2 Where is your product most suited?

The vendor respondents were asked to identify where their product is most suited. All 11 vendor respondents answered this question, corresponding to a response rate of 100.0%. The question was presented as a multiple-selection question.

All 11 vendors selected distribution, representing 100.0% of respondents. Transmission was selected by 10 vendors, representing 90.9% of respondents (see Figure 14). At the respondent level, 10 vendors selected both transmission and distribution, while 1 vendor selected distribution only.

These responses indicate that vendor-reported synchro-waveform products are broadly suited for distribution applications, with nearly all respondents also identifying transmission suitability. The responses also suggest that most vendor products represented in the survey are intended to support use across both transmission and distribution system domains.

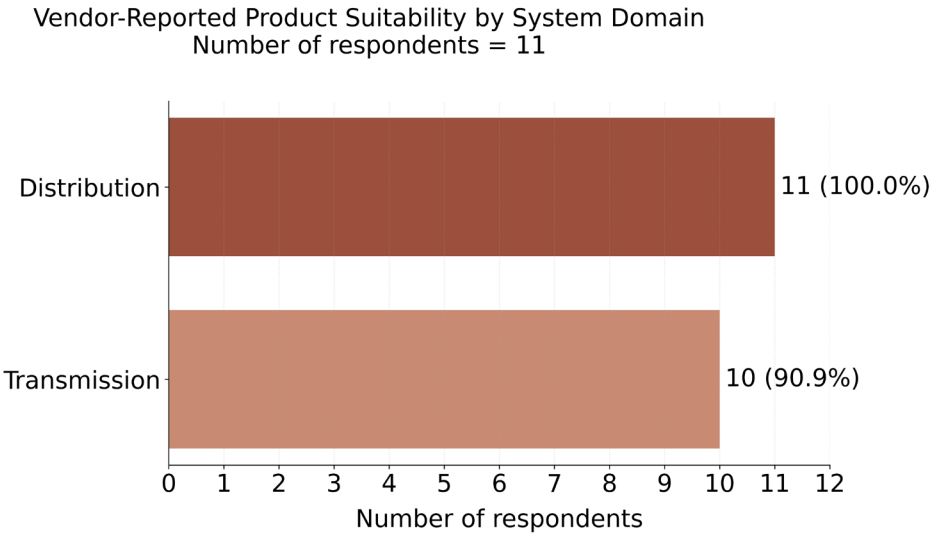


Figure 14. Survey response: Where is the product most suited?

5.2.3 What option(s) do you support for waveform capture?

The vendor respondents were asked what options they offer for waveform capture. All 11 vendor respondents answered this question, corresponding to a response rate of 100.0%. The question was presented as a multiple-selection question.

Among the 11 vendor respondents (see Figure 15), continuous recording was selected by 10 vendors (90.9%), while event-triggered recording was selected by 9 vendors (81.8%). At the respondent level, 8 vendors reported offering both continuous and event-triggered recording. Two vendors reported offering only continuous recording, while one vendor reported offering only event-triggered recording. These responses indicate that vendor offerings generally support both waveform-capture approaches.

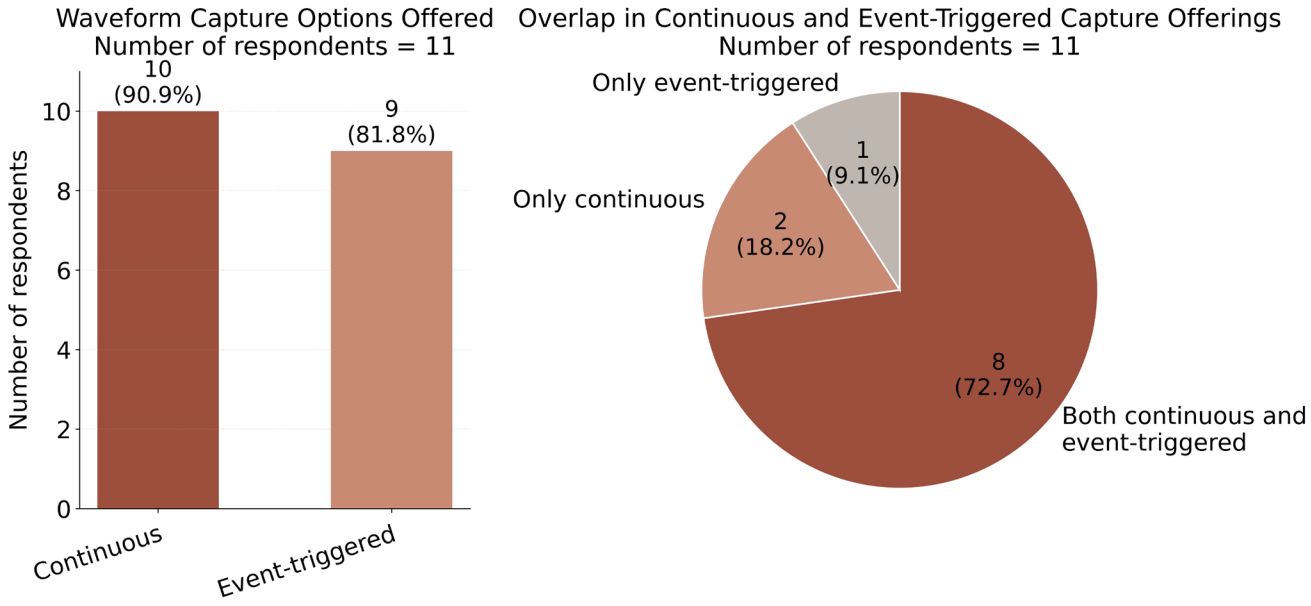


Figure 15. Survey response: What option(s) do you offer for waveform capture?

5.2.4 What is your maximum sample rate (in samples/cycle) for continuous waveform capture?

Among vendors that provide waveform measurement hardware or sensing technologies, the reported continuous waveform capture capabilities varied widely. Reported values ranged from conventional high-resolution waveform rates on the order of hundreds of samples/cycle to very high-speed sampling capabilities on the order of thousands to tens of thousands of samples/cycle. Most vendors reported capabilities around 240-1024 samples/cycle. One vendor reported a much higher capability of 16,667 samples/cycle, i.e., approximately 1 MHz at 60 Hz.

For software and analytics vendors, the reported values appear to represent the sample rates of waveform data that their platforms can ingest, process, or support. These responses included support for incoming waveform streams at hundreds to more than 1000 samples/cycle.

5.2.5 What is the highest sample rate (in samples/cycle) that you use for event-triggered waveform capture?

Vendor responses for event-triggered waveform capture also show a distinction between measurement-technology vendors and software/data-platform vendors. In both categories, most vendors reported similar sample capabilities for event-triggered waveform capture as with continuous capture.

5.2.6 Do your waveform measurement solutions support GPS-based time synchronization?

All 11 vendor respondents answered this question, corresponding to a response rate of 100.0%. All 11 vendors reported that their waveform records are time-synchronized to GPS.

5.2.7 What other method(s) do you use for time-synchronization?

The survey did not capture any responses to this question. No time-synchronization methods beyond GPS were reported.

5.2.8 What communication technologies do you support for waveform data collection?

The vendor respondents were asked to identify the communication technologies used for waveform data collection. All 11 vendors answered this question, corresponding to a response rate of 100.0%. The question was presented as a multiple-selection question.

Ethernet was the most commonly reported communication technology, selected by 9 vendors (81.8% of respondents; see Figure 16). Cellular and/or other wireless technologies and fiber optics were each selected by 6 vendors (54.5%). Two vendors also selected “Other” (18.2%) and identified Advanced Metering Infrastructure (AMI) networks and DOCSIS® (Data Over Cable Service Interface Specification) cable modem as additional communication technologies.

These responses indicate that Ethernet is the dominant communication technology among the vendor respondents, while wireless technologies and fiber optics are also commonly supported.

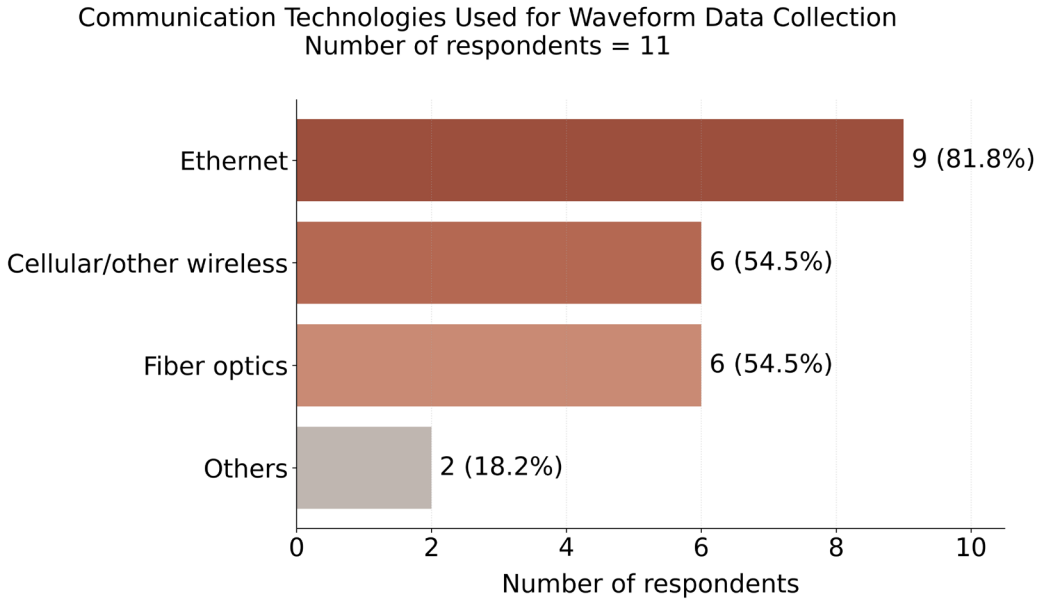


Figure 16. Survey response: What communication technologies do you use for waveform data collection?

5.2.9 What communication protocols do you support for waveform data collection?

The vendor respondents were asked to identify the communication protocols used for waveform data collection. Of the 11 vendor respondents, 9 answered this question, corresponding to a response rate of 81.8%. The question was presented as a multiple-selection question.

At the respondent level, 7 vendors reported using proprietary protocols in some form, corresponding to 77.8% of the respondents who answered this question. Examples of proprietary protocols listed by respondents included WaveServer, Continuous Wave Stream (CWS), Time-Domain Link (TiDL), Fast Time-Domain Values (FTDV), and other vendor-specific protocols.

Standard protocols were also reported by vendors -- 6 vendors reported using at least one standard protocol, corresponding to 66.7% of respondents. The standard protocols identified in the responses included STTP/IEEE 2664-2024 (Streaming Telemetry Transport Protocol), IEC 61869-9, IEC 61850-9-2, C37.118.2, FTP (File Transfer Protocol), SFTP (Secure File Transfer Protocol), and HTTPS (Hypertext Transfer Protocol Secure).

The responses also show overlap between protocol categories. Of the 9 vendors who answered this question, 3 vendors reported only proprietary protocols, 2 vendors reported only standard protocols, and 4 vendors reported using both standard and proprietary protocols, as shown in Figure 8. These responses indicate that waveform data collection in the industry currently relies on a combination of proprietary and standard communication protocols.

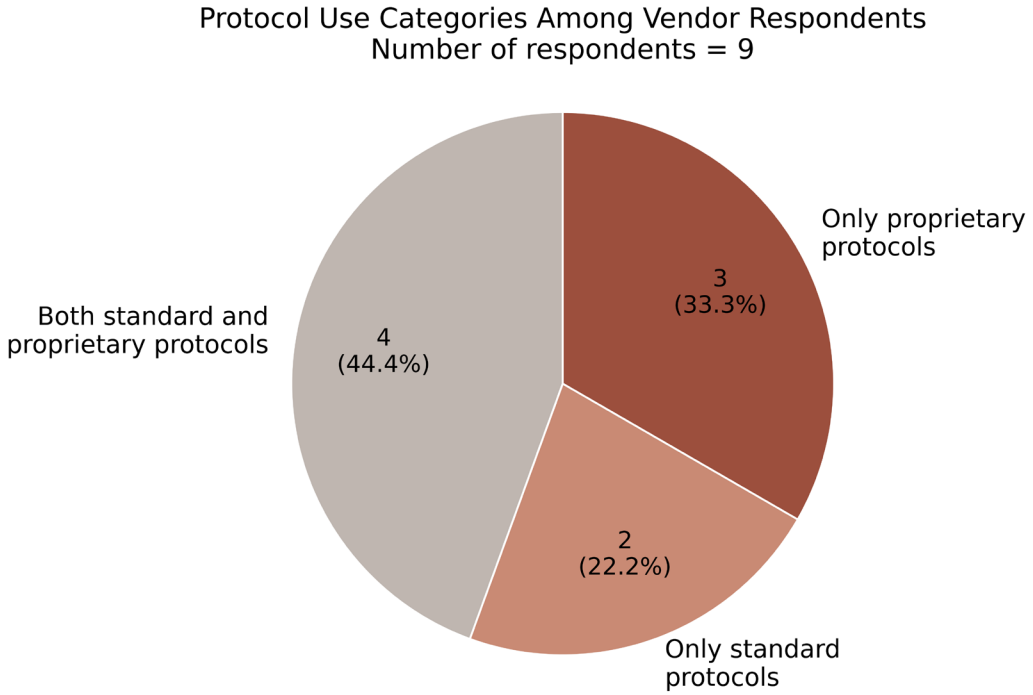


Figure 17. Survey response: What communication protocols do you support for waveform data collection?

5.2.10 What file format(s) do you support for storing waveform records?

The vendor respondents were asked what file formats their solutions support for storing waveform records. Of the 11 vendor respondents, 10 answered this question, corresponding to a response rate of 90.9%. The question was presented as a multiple-selection question.

Among the 10 respondents, CSV was the most commonly reported format, selected by 8 vendors (80.0%), closely followed by COMTRADE, which was selected by 7 vendors (70.0%).

The PQDIF format was selected by 2 vendors (20.0%). Six vendors selected “Other” (60.0%) indicating use of proprietary file formats.

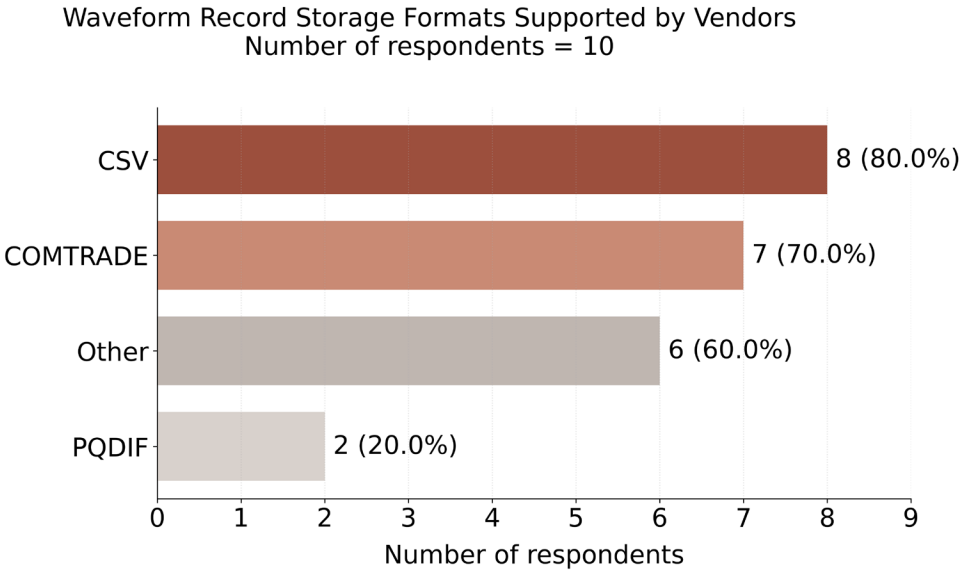


Figure 18. Survey response: What file format(s) do you use for storing waveform records?

5.2.11 What option(s) do you offer for storing and/or streaming the waveform measurements?

The 11 vendor respondents were asked where their solutions store recorded waveform measurements. The question was presented as a multiple-selection question. For the survey, the responses were grouped into two broader storage-capability categories: local storage and streaming to a data concentrator. Local storage includes responses indicating storage at either the meter/device level or the substation level.

All 11 vendors answered this question. Among these respondents, 9 vendors reported capability for streaming waveform records to a data concentrator, while 7 vendors reported support for local waveform-record storage (see Figure 16). Because this was a multiple-selection question, these categories are not mutually exclusive. At the respondent level, 5 vendors reported support for both local storage and streaming, 4 vendors reported support for streaming only, and 2 vendors reported support for local storage only.

These responses indicate that streaming to a data concentrator is the most widely supported vendor storage capability, while local waveform-record storage is also supported by a majority of vendor respondents.

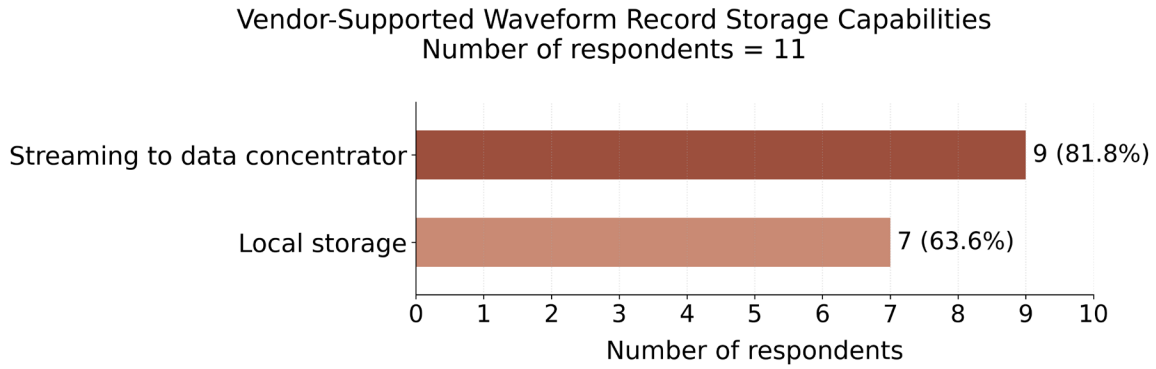


Figure 19. Survey response: What option(s) do you offer for storing and/or streaming the waveform measurements?

5.2.12 Do you support waveform data compression?

The vendor respondents were asked whether their products or solutions support waveform data compression. Of the 11 vendor respondents, 9 answered this question, corresponding to a response rate of 81.8%.

Among the 9 vendors who answered, 5 vendors reported that they do not support waveform data compression, corresponding to 55.6% of respondents. Three vendors reported support for lossless compression (33.3%), while one vendor reported support for lossy compression (11.1%), as shown in Figure 9.

These responses indicate that waveform data compression is not uniformly supported among the vendor respondents. While a subset of vendors reported support for either lossless or lossy compression, the largest share of respondents reported no compression support. This suggests that compression capability varies across the vendor solutions represented in the survey.

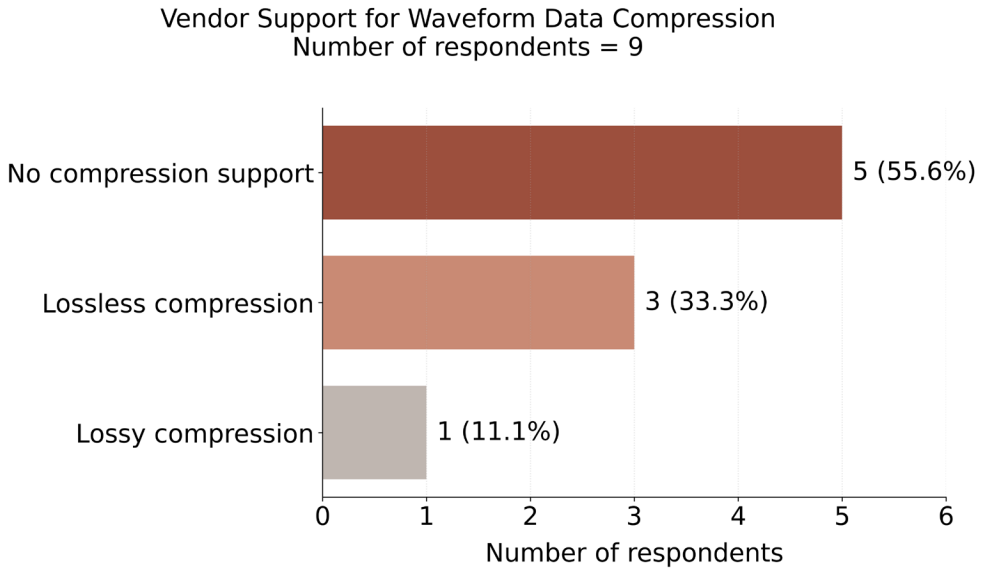


Figure 20. Survey response: Do you support waveform compression?

5.2.13 What is your lossless data compression ratio?

Vendors that reported support for lossless waveform data compression were asked to provide their lossless data compression ratio. No response was recorded for this question.

5.2.14 What is your lossy data compression ratio?

Vendors that reported support for lossy waveform data compression were asked to provide their lossy data compression ratio. No response was recorded for this question.

Together, the responses to Questions 5.2.4 through 5.2.6 show that some vendors reported support for waveform data compression, but no quantitative compression-ratio information was provided. As a result, the survey can characterize whether compression is supported, but it cannot assess the magnitude of compression achieved by the reported vendor solutions.

5.2.15 Do you currently have a product for synchro-waveform analytics that you have deployed?

The vendor respondents that reported offering data analytics and software tools in Question 5.2.1 were asked whether they currently have a deployed product for synchro-waveform analytics. Of the 10 vendors in this respondent group, all 10 answered this question, corresponding to a response rate of 100.0%.

Among the 10 respondents, 7 reported having a deployed synchro-waveform analytics product, representing 70.0% of respondents. The remaining 3 vendors reported that they do not currently have a deployed synchro-waveform analytics product, representing 30.0% of respondents, as shown in Figure 10.

These responses indicate that deployed synchro-waveform analytics products are already present among a majority of the vendors that reported offering data analytics and software tools. At the same time, the responses show that not all analytics-oriented vendors have deployed synchro-waveform analytics products, suggesting variation in the maturity or deployment status of vendor analytics offerings represented in the survey.

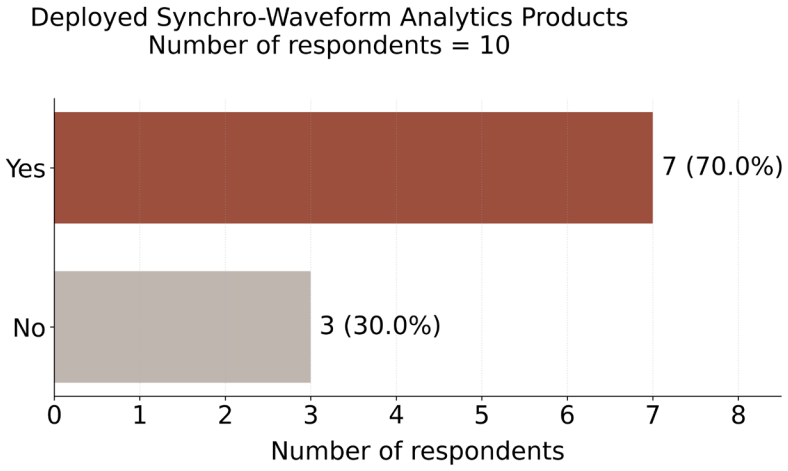


Figure 21. Survey response: Do you currently have a product for synchro-waveform analytics that you have deployed?

5.2.16 Where have you deployed your synchro-waveform analytics technology?

Vendors that reported having a deployed synchro-waveform analytics product, in Question 5.2.7, were asked where their technology has been deployed. All 7 vendors in this respondent group answered the question, corresponding to a response rate of 100.0%.

Among these respondents, 6 vendors reported deployments in both transmission and distribution systems, representing 85.7% of respondents. One vendor reported deployment in transmission systems only, representing 14.3% of respondents. No vendor reported deployment only in distribution systems, as shown in Figure 22.

These responses indicate that deployed synchro-waveform analytics technologies reported in the survey are primarily deployed across both transmission and distribution systems. Only one respondent reported deployment limited to transmission systems.

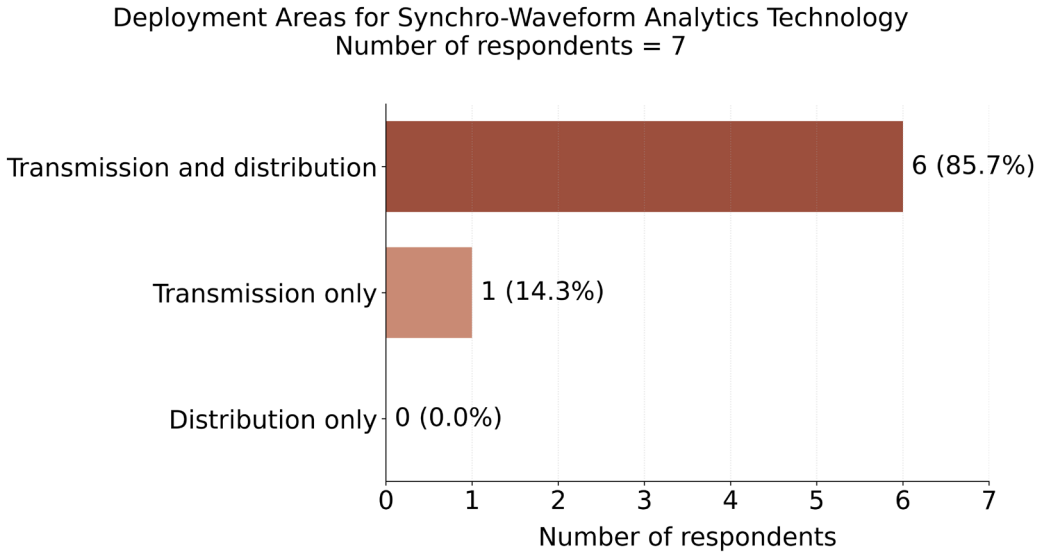


Figure 22. Survey response: Where have you deployed your synchro-waveform analytics technology?

5.2.17 Which of the following synchro-waveform applications have you deployed?

Vendors that reported having a deployed synchro-waveform analytics product were asked to identify the synchro-waveform applications they have deployed. The question was presented as a multiple-selection question.

Among the 7 respondents, oscillation monitoring and power quality monitoring were each selected by 7 vendors (100.0%, see Figure 13). Event and/or incipient fault analysis and model validation were each selected by 5 vendors (71.4%). Asset monitoring, DER monitoring, and fault recording were each selected by 4 vendors (57.1%). Protection applications were selected by 1 vendor (14.3%). Two vendors selected “Other” (28.6%), identifying inertia measurement and system strength measurement as their deployed applications.

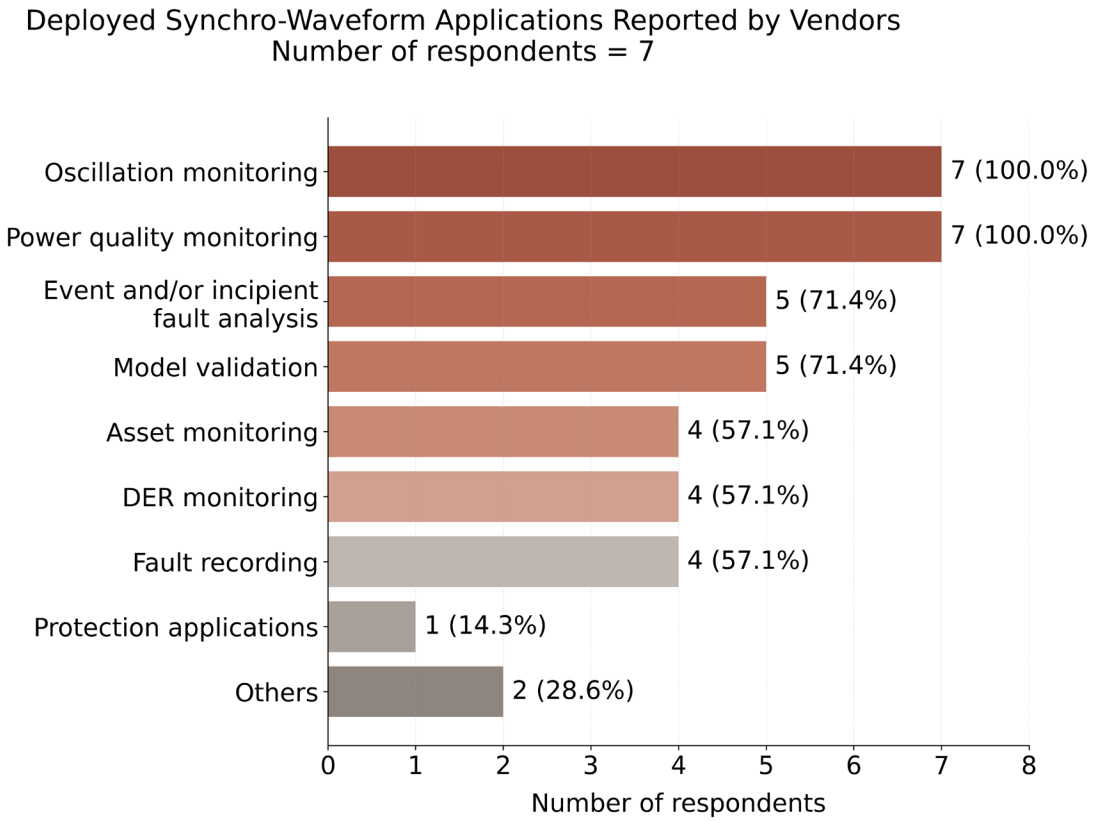


Figure 23. Survey response: Which of the following applications have you deployed?

5.2.18 Which applications do you think can benefit most from synchro-waveform technology?

Vendors were asked to rank the applications they believe can benefit most from synchro-waveform technology. The respondents were given eight high-value applications and were asked to rank their top three choices. All 11 vendor respondents answered this question, corresponding to a response rate of 100.0%.

The applications most frequently ranked within the top three were (1) event and/or incipient fault analysis, selected by 10 vendors (90.9% of respondents), and (2) oscillation monitoring, selected by 9 vendors (81.8%). Next, (3) power quality monitoring was ranked within the top three by 5 vendors (45.5%), followed by (4) model validation, which was ranked within the top three by 4 vendors (36.4%).

Other listed applications, such as (5) fault recording and (6) DER monitoring were each ranked within the top three by 2 vendors (18.2%), while (7) asset monitoring was ranked within the top three by 1 vendor (9.1%). Interestingly, (8) protection applications were not ranked within the top three by any respondent. One respondent provided situational awareness as an “Other” application, but it was not ranked within the top three.

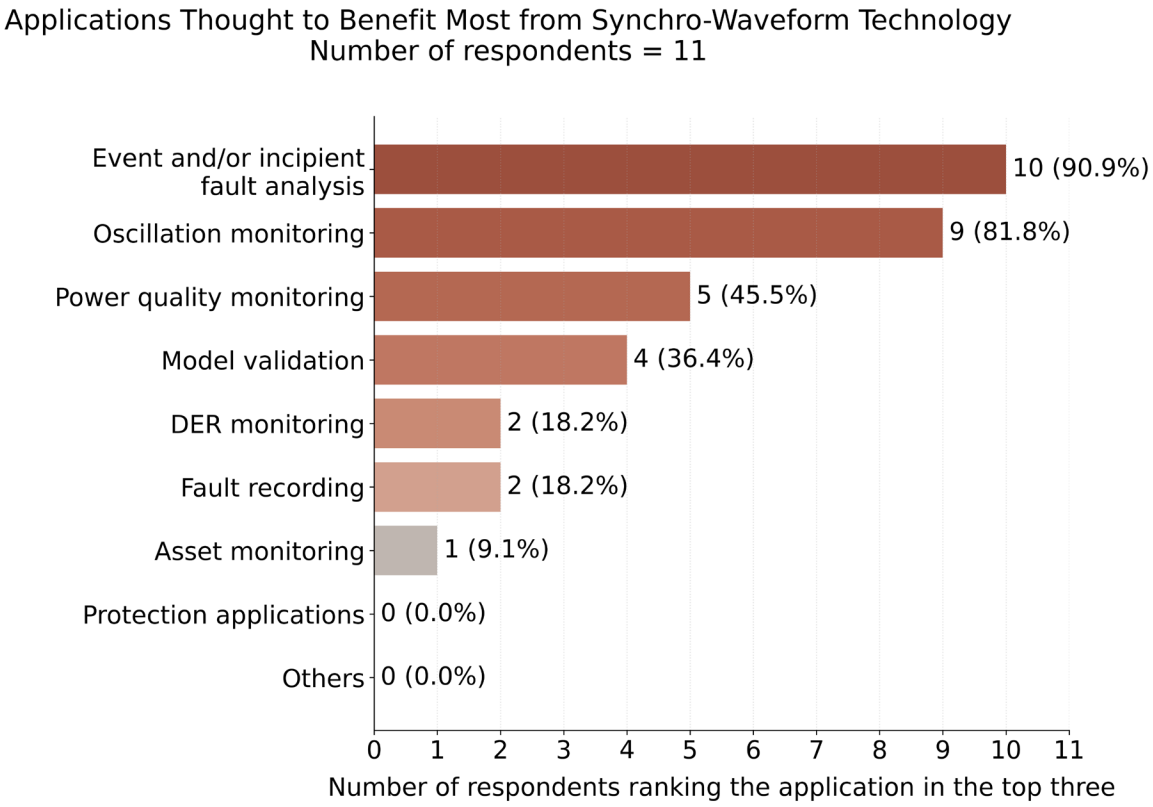


Figure 24. Survey response: Which applications do you think can benefit most from synchro-waveform technology?

6.0 Conclusions and Main Findings

The survey results provide a cross-sectional view of the current state of practice for waveform and synchro-waveform technologies across utilities, ISOs, and technology vendors. Considered together, the responses indicate that the industry has already established many of the foundational measurement capabilities required for high-resolution waveform monitoring, while the principal challenges are increasingly associated with data access, interoperability, scalable data management, and operational integration. The major findings from the survey are as follows.

1. **High-resolution waveform measurement capability and use are already broadly established in practice.**

   Utilities and ISOs reported active use of waveform measurements through multiple device classes, including digital fault recorders, PMUs, power quality meters, protective relays, and specialized waveform sensors. Vendors likewise reported capabilities spanning sensing, communications, storage, streaming, and analytics. There is also strong correspondence between utility practice and vendor capability with respect to recording mode. Both event-triggered and continuous waveform recording are widely used and supported. Event-triggered recording remains important for disturbance and fault analysis, while continuous recording provides access to dynamic behaviors that may not satisfy predefined triggers. Event-triggering practices remain closely tied to traditional electrical quantities, particularly current and voltage, with some respondents additionally using equipment operations, protection indications, frequency, and power-quality criteria.

2. **Time-synchronization of waveform recordings is relatively common.**

   Time-synchronization appears to be one of the more consistently implemented elements of the synchro-waveform measurement chain. All utilities/ISOs and vendors responding to the relevant questions reported GPS-based time synchronization, indicating strong alignment between current utility practice and commercially available capability. The survey, however, assessed the presence and method of synchronization rather than its performance. It did not examine synchronization accuracy, timestamp uncertainty, holdover capability, resilience to loss of the timing source, or the timing precision required for different applications. These factors remain important when evaluating whether synchronized waveform records can support wide-area applications.

3. **Data management and interoperability are emerging as the main technical gaps.**

   The capability to transfer and store waveform data is broadly available, but the responses indicate greater heterogeneity in how those data are communicated, accessed, and managed. Vendors reported support for Ethernet, fiber, wireless communications, and multiple communication protocols. However, standardized and proprietary protocols continue to coexist. A similar pattern is evident in waveform-data formats. COMTRADE and CSV are commonly supported by both utilities/ISOs and vendors, while vendors also reported proprietary formats. The coexistence of multiple protocols and formats may complicate integration across heterogeneous devices, software platforms, and vendor ecosystems.

   Data retrieval and retention practices are also varied. Utilities and ISOs most commonly reported using a combination of manual and automated retrieval rather than fully automated

workflows, suggesting that waveform acquisition is generally more mature than end-to-end data access. Retention periods also vary substantially across organizations, and vendor support for waveform-data compression is not uniform. Together, these findings indicate that scalable data management and interoperability are becoming increasingly important as waveform sampling rates, recording durations, and deployment scales increase.

4. **Applications are expanding from traditional event recording toward advanced analytics for dynamic performance assessment.**

   Current utility and ISO use remains concentrated in established applications such as event and incipient-fault analysis, fault recording, power-quality monitoring, and protection. The future-use responses indicate an important shift in emphasis. Utilities and ISOs expressed particularly strong interest in oscillation monitoring and model validation, suggesting that waveform data are increasingly viewed not only as a record of disturbances, but also as a source of information for characterizing dynamic system behavior and evaluating model performance.

   Vendor responses align closely with this direction. Vendor-supported analytics include oscillation monitoring, power-quality monitoring, event and incipient-fault analysis, and model validation. The alignment between utility priorities and vendor capabilities is therefore particularly strong for broader near-term adoption.

5. **Technology availability is ahead of full operational integration.**

   Vendor responses indicate that many of the individual technology components required for broader synchro-waveform deployment are commercially available today. These products span much of the measurement-to-application chain, including sensing and measurement, communications and streaming, storage and data management, and analytics. Utility responses, however, indicate that the availability of these individual components does not necessarily translate into a fully integrated operational workflow. Broader adoption will increasingly depend on interoperability, automated data access, scalable storage and communications, and integration of waveform analytics into existing utility systems and operational processes.

Overall, the survey indicates that the industry has moved beyond the question of whether high-resolution waveform measurements can be acquired. The more significant challenge is increasingly how these measurements can be managed, integrated, and used at scale. Strong alignment between utility priorities and vendor capabilities provides a foundation for broader adoption, while interoperability, automated data access, scalable data management, and operational integration of analytics remain key areas for continued industry development.

7.0 Discussion and Future Work

The survey establishes an industry-informed baseline for the current state of waveform and synchro-waveform deployment. The responses indicate substantial commonality in several core capabilities, including event-triggered and continuous waveform recording, and GPS-based time synchronization. At the same time, implementation practices remain heterogeneous across device types, data-retrieval methods, communication protocols, storage approaches, and analytics. This suggests that the industry is converging on some fundamental measurement capabilities, while the supporting data and operational architectures remain less standardized.

A broader implication is that future progress will depend increasingly on how effectively these individual capabilities are integrated across the measurement chain. The operational value of high-resolution waveform data depends not only on acquiring the measurements, but also on reliably synchronizing, communicating, storing, retrieving, processing, and interpreting them within engineering and operational workflows. As waveform deployment expands in scale and application scope, integration across these functions will become an increasingly important consideration in system design and implementation.

The survey also has several limitations that should be considered when interpreting the results. First, the respondent population represents a cross-section of participating organizations rather than a statistically representative sample of the entire industry. In addition, partially completed responses were retained where they provided useful information, and response counts therefore vary across questions. A second limitation is that the waveform-measurement chain often spans several functional groups within a large utility or ISO. Expertise in measurement devices, protection, communications, information technology, data management, and analytics may reside with different individuals in different departments. Consequently, a single respondent may not have complete visibility across the entire measurement pipeline and datasets within an organization. Wherever possible, responses were obtained from multiple individuals within the same organization. However, this was not possible for all participating organizations. Future assessments would benefit from coordinated organization-level responses involving multiple functional groups to provide a more complete representation of practices and capabilities across the measurement chain.

The survey also focused primarily on the presence and use of capabilities rather than their detailed performance characteristics and requirements. For example, it identified whether time synchronization, communications, storage, streaming, compression, and analytics were supported, but did not systematically assess synchronization accuracy, communication latency, data availability, storage volume, processing requirements, cybersecurity, implementation cost, or analytical performance. The survey questions were also not fully symmetric between utilities/ISOs and vendors; consequently, direct comparison between utility requirements and vendor capabilities was possible for some topics but not for all.

These limitations also identify priorities for subsequent industry assessment. The present survey establishes a baseline of current capabilities, practices, and emerging areas of interest; future efforts can examine more closely performance requirements, deployment scale, and the practical requirements for integrating these capabilities into operational environments. Based on the survey findings, the following areas merit continued attention:

1. *Interoperability and standardization*: Advance common approaches, including communication protocols and file formats, for exchanging, storing, retrieving, and processing waveform data across heterogeneous devices and vendor platforms.

2. *Scalable data management and automation*: Advance automation in data retrieval and access through scalable approaches for communication, streaming, storage, retention, compression, and processing of continuous high-resolution waveform measurements.

3. *Operational integration of advanced applications*: Expand deployment and operational integration of applications identified by utilities and ISOs as priorities for future waveform use, particularly oscillation monitoring and model validation. Vendor responses indicate that capabilities supporting several of these applications are already available.

4. *Application-specific measurement and data requirements*: Define application-specific requirements for sampling rate, time-synchronization performance, data availability, compression, and retention to support priority synchro-waveform applications.

5. *Continued industry benchmarking*: Periodically reassess the state of practice to track changes in technology adoption, infrastructure capability, interoperability, analytics deployment, and operational use. Future surveys could also use coordinated responses from multiple functional groups within an organization to provide a more complete view of the measurement-to-application chain.

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Appendix A

The following questionnaire was used for the synchro-waveform state-of-practice survey. The questionnaire was structured for two respondent groups: utilities and ISOs, and technology vendors. Each question below is preceded by labels identifying the respondent group to which the question was presented and, where applicable, the required response format.

The labels should be interpreted as follows:

- [Utility/ISO] – Question presented to utility and ISO participants.
- [Vendor] – Question presented to technology-vendor participants.
- [Utility/ISO] [Vendor] – The same underlying topic was presented to both respondent groups. The wording was adapted where necessary to distinguish between practices used by utilities/ISOs and capabilities offered or supported by vendors.
- [Multiple Selection] – Respondents could select more than one response option.
- [Numeric Entry] – Respondents were asked to provide a numerical value.
- [Text Entry] – Respondents were asked to provide a text value.
- [Rank] – Respondents were asked to rank the listed response options according to the instructions provided in the survey.

Unless otherwise indicated, questions without a response-format label required selection of a single response.

Survey Questions:

1. [Utility/ISO] Do you actively gather and use waveform measurements?
    i. Yes
    ii. No
2. [Utility/ISO] [Multiple Selection] What type of device do you use for waveform recording?
    i. DFRs
    ii. PMUs with waveform recording capability
    iii. PQ meters with waveform recording capability
    iv. Smart meters with waveform recording capability
    v. Others (specify)

3. [Utility/ISO] [Vendor] [Multiple Selection] What option(s) do you use/support for waveform capture?
    i. Event-triggered
    ii. Continuous
4. [Vendor] [Multiple Selection] What solutions do you offer for waveform measurements?
    i. Sensing and measurement technologies
    ii. Data analytics and software tools
    iii. Data streaming and communication
    iv. Data storage and management
5. [Utility/ISO] [Vendor] [Numeric Entry] What is your maximum sample rate (in samples/cycle) for continuous waveform capture?
6. [Utility/ISO] [Vendor] [Numeric Entry] What is your maximum sample rate (in samples/cycle) for event-triggered waveform capture?
7. [Utility/ISO] [Multiple Selection] What is the basis of your event-triggered waveform capture?
    i. Current
    ii. Voltage
    iii. Others (specify)
8. [Utility/ISO] [Vendor] [Multiple Selection] What file format(s) do you use/support for storing waveform records?
    i. COMTRADE
    ii. CSV
    iii. PQDIF
    iv. Others (specify)
9. [Utility/ISO] [Multiple Selection] Where do you store the recorded waveform measurements?
    i. Meter-level storage
    ii. Substation-level storage
    iii. External storage/cloud

    [Vendor] [Multiple Selection] What option(s) do you offer for storing and/or streaming the waveform measurements?

i. Streaming to data concentrator

ii. Local storage

10. [Utility/ISO] How do you retrieve waveform measurements?

    i. Manual retrieval

    ii. Automated retrieval

    iii. Combination of manual and automated retrievals

11. [Utility/ISO] How long do you retain waveform records?

    i. Less than 90 days

    ii. 90 days to 1 year

    iii. 1 year to 5 years

    iv. More than 5 years

12. [Utility/ISO] [Vendor] Is your waveform record time-synchronized to GPS?

    i. Yes

    ii. No

13. [Utility/ISO] [Vendor] [Text Entry] What other method(s) do you use for time synchronization?

14. [Vendor] [Multiple Selection] What communication technologies do you support for waveform data collection?

    i. Ethernet

    ii. Cellular/Wireless

    iii. Fiber optics

    iv. Others (specify)

15. [Vendor] [Multiple Selection] What communication protocols do you support for waveform data collection?

    i. Standard protocols (specify)

    ii. Proprietary protocols (specify)

16. [Vendor] [Multiple Selection] Where is your product most suited?

    i. Transmission

ii. Distribution

17. [Vendor] Do you support waveform data compression?
    i. No compression
    ii. Lossy compression
    iii. Lossless compression
18. [Vendor] [Numeric Entry] What is your lossless data compression ratio?
19. [Vendor] [Numeric Entry] What is your lossy data compression ratio?
20. [Vendor] Do you currently have a product for synchro-waveform analytics that you have deployed?
    i. Yes
    ii. No
21. [Vendor] Where have you deployed your synchro-waveform analytics technology?
    i. Transmission and distribution
    ii. Transmission only
    iii. Distribution only
22. [Vendor] [Multiple Selection] Which of the following synchro-waveform applications have you deployed?
    i. Event/fault analysis
    ii. Event/fault recording
    iii. Oscillation analysis
    iv. Asset monitoring
    v. Model validation
    vi. DER monitoring
    vii. Power quality monitoring
    viii. Protection
    ix. Others (specify)
23. [Utility/ISO] [Multiple Selection] In which applications do you currently use waveform measurements?

i. Event/fault analysis
ii. Event/fault recording
iii. Oscillation analysis
iv. Asset monitoring
v. Model validation
vi. DER monitoring
vii. Power quality monitoring
viii. Protection
ix. Others (specify)

24. [Utility/ISO] [Multiple Selection] In which applications do you envision using waveform measurements in the future?

i. Event/fault analysis
ii. Event/fault recording
iii. Oscillation analysis
iv. Asset monitoring
v. Model validation
vi. DER monitoring
vii. Power quality monitoring
viii. Protection
ix. Others (specify)

25. [Vendor] [Rank] Which applications do you think can benefit most from synchro-waveform technology?

i. Event/fault analysis
ii. Event/fault recording
iii. Oscillation analysis
iv. Asset monitoring
v. Model validation

vi. DER monitoring

vii. Power quality monitoring

viii. Protection

ix. Others (specify)



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