Center for Alternative Synchronization and Timing

Technical Bulletin # 010: Timing and Synchronization for Modern Power Grids

Summary: Accurate and synchronized timing signals are necessary for effective monitoring, control, coordination, and protection of power grids. This report explores the various services prevalent in power grids, focusing on their critical timing requirements for effective operational functionalities and performance. The importance of precise timing and synchronization across various power grid services is examined, highlighting how timing and synchronization influences the reliability and efficiency of power grids.

Introduction

The modern power grid is increasingly characterized by complexity and interconnectivity, necessitating advanced solutions for improved reliability, efficiency, and sustainability. Modern "smart" grids leverage digital communication, real-time data processing, and automation technologies, transforming traditional electricity delivery and consumption paradigms. Accurate timestamping is fundamental to ensuring reliable system operations and facilitating synchronization among geographically distributed devices. Time synchronization is critical for ensuring accurate event sequencing, precise fault detection and localization, and timely, data-informed operational decisions. It serves as a foundational element for both the security and operational efficiency of modern grid infrastructures. Time synchronization accuracy requirements are application-dependent, spanning a range from seconds to nanoseconds to support the diverse functional demands of grid services. This report outlines key services for power grids and stipulates their timing requirements, critical for maintaining optimal performance and achieving desired operational outcomes.

Power Grid Services and Their Timing Requirements

1. Disturbance Monitoring Equipment (DME)

DME include devices that capture and analyze electrical disturbances in power systems. They record oscillographic data during fault conditions, providing essential insights into system performance and enabling rapid restoration.

- Accuracy requirement: To reach effective disturbance/fault analysis, DME must achieve time-stamping resolution of ±2 milliseconds relative to Coordinated Universal Time (UTC), as specified by NERC PRC-002-2 [1].
- Event Sequence Tracking: The precise timing of events enables utilities to reconstruct the sequence of disturbances and system events. This is essential for root cause analysis,

post-fault diagnostics, optimizing decision-making for system restoration, and regulatory compliance.

2. Power System Protection

Precise time synchronization is essential for reliable power system protection, enabling accurate fault detection, event correlation, and coordinated response across geographically distributed assets such as protection relays. Protection relays rely on synchronized measurements to correctly identify and isolate faults within milliseconds. Discrepancies in timing can result in delayed or incorrect tripping, risking equipment damage and system instability. For example, differential protection schemes compare current measurements at multiple line ends in real-time. Without precise time alignment, protection decisions could be based on inconsistent data, compromising reliability and selectivity. In addition, distance protection measures impedance to a fault and trips based on distance from the relay point. It is less timing-sensitive than differential protection, unless coordinated across long distances such as wide-area protection schemes.

- Accuracy requirement: Accurate operation of differential relays requires synchronization within a few microseconds. IEC 61850-5 [2] outlines that merging units should achieve an accuracy of 4 µs or better.
- Tripping Time: The effective tripping time during fault conditions must be guaranteed with high precision to minimize system disruptions.

3. Traveling Wave Fault Location (TWFL)

TWFL is one of the most precise fault location techniques used in transmission systems, particularly for extra-high voltage (EHV) and ultra-high voltage (UHV) lines. It relies on detecting the arrival times of high-frequency transient waves (in the range of 10 kHz to several MHz) generated by faults. This method provides rapid and accurate fault identification, reducing outage durations.

- Accuracy requirement: The traveling waves move at nearly the speed of light (~300,000 km/s) in transmission lines. Even a 1 µs error in time synchronization translates to a ~300-meter error in locating the fault. Advanced TWFL systems aim for <100 m accuracy, which requires time synchronization precision in the order of tens of nanoseconds. To achieve this high timing accuracy, TWFL systems rely on GPS receivers with nanosecond-level accuracy, IEEE 1588-2008 (PTP) with hardware timestamping (for sub-microsecond sync), or IRIG-B in some legacy systems (microsecond range, less ideal for TWFL).
- High Sampling Rates: TWFL systems demand high sampling rates, enabling the capture of transient signal behavior for accurate fault localization.

4. Synchrophasors

Phasor Measurement Units (PMUs) are critical components in modern power systems, enabling real-time monitoring, control, and protection across wide areas [3]. Their functionality is based on precise time synchronization, which allows phasor data (voltage and current magnitude and phase angle) from geographically distributed locations to be aligned to a common time reference. They are integral in managing system stability and reliability.

- Accuracy requirement: PMUs produce synchronized phasor measurements relative to UTC. To meet IEEE C37.118.1 [4] accuracy class requirements, Total Vector Error (TVE) must be ≤ 1%, which indirectly requires time accuracy better than 1 μs to ensure data integrity and effective grid monitoring (a 1 μs time error translates to a phase angle error of ~0.022° at 60 Hz and ~0.018° at 50 Hz).
- PMUs typically report data at rates ranging from 30 to 60 records per second, or even higher.

5. Supervisory Control and Data Acquisition (SCADA)

SCADA systems are essential for monitoring and controlling power systems, particularly in transmission and distribution networks, ensuring efficient operation of the power grid [5]. Unlike protection and synchrophasor systems, SCADA operates at relatively slower time resolutions and is less demanding in terms of synchronization accuracy.

- Accuracy requirement: SCADA systems typically rely on network time protocol (NTP), which offers millisecond to second-level accuracy, sufficient for most applications.
- Data Reporting Frequency: SCADA systems typically have a reporting rate of every 2-10 seconds, necessitating timely data collection and processing. SCADA systems focus on status monitoring, slow control operations (e.g., breaker status, voltage setpoints), and alarming rather than real-time protection.
- Event Monitoring: High-speed clock synchronization is vital for consistent monitoring of system states, as timely updates can be critical for operational decisions.

6. Advanced Metering Infrastructure (AMI)

AMI is a key component of modern smart grids, enabling two-way communication between utilities and end-user smart meters. AMI systems support billing, outage detection, demand response, and grid analytics—but do not require high-precision timing like the previously mentioned grid services. Data reporting interval is every 15 minutes to 1 hour, sometimes down to 1 minute.

- Accuracy requirement: Time accuracy of a few seconds is sufficient to match outage events or customer usage patterns. However, time synchronization in the order of hundreds of milliseconds is required to ensure efficient frequency and ancillary services demand response functionality and reliability [6].
- Interval Metering: Timing accuracy during data acquisition sessions is essential for maintaining the integrity of metered energy consumption, particularly in dynamic pricing scenarios.

7. Cybersecurity and Grid Resilience

Cybersecurity and grid resilience rely heavily on accurate time synchronization to detect, analyze, and respond to cyber threats and system disturbances in real time. While they are not tied to specific protection functions, these applications depend on consistent and precise timestamps to correlate events across systems, devices, and geographic locations. For example, time-synchronized logging aids in detecting and analyzing cyber intrusions or anomalies by correlating data from different parts of the grid.

- Time Accuracy Matters: Coordinated attack detection (e.g., denial-of-service or data injection) requires matching logs from different systems with a typical timing accuracy of less than 100 milliseconds. In addition, intrusion detection systems (IDS) and Security Information and Event Management (SIEM) platforms rely on timestamp precision to identify patterns and lateral movement within the grid.
- Resilience Operations: Post-event analysis requires precisely aligned logs from IT, OT, SCADA, and protection systems to trace the origin, propagation, and impact of events. Accurate timing enables synchronized restoration and state awareness after major disruptions.

Table Summary

Table 1 shows a summary of the investigated grid services and their timing requirements and commonly used time distribution methods. Table 2 shows the available timing distribution methods and their typical accuracies.

Table 1: Summary of the various grid services and their timing requirements and distribution methods.

Application	Timing Accuracy	Time Synch Method	Notes
Synchrophasors (PMUs)	≤ 1 µs	GPS (most commonly used), PTP (emerging in substation environments), IRIG-B (legacy or backup method)	Enable accurate phase angle alignment across the grid (IEEE C37.118.1).
Differential Protection	≤ 1 ms	GPS, PTP, IRIG-B	Real-time current comparison.
Distance Protection	~1–10 ms	GPS, PTP, IRIG-B	Less sensitive than differential protection.
Wide-Area Protection	≤ 1 µs – 1 ms	GPS, PTP, IRIG-B	Timing accuracy depends on topology.
DME	1–2 ms	GPS, PTP, IRIG-B	Event reconstruction.
TWFL	≤ 1 µs (preferably ≤ 100 ns)	GPS, PTP, IRIG-B	Spatial resolution ~300 m per µs.
SCADA	≤ 200 ms	NTP, GPS (occasionally)	Used for monitoring, control, and logging—not for high-speed protection.

Application	Timing Accuracy	Time Synch Method	Notes
AMI	1-10 seconds (≤ 1 second for tighter demand response or TOU billing)	NTP, Cellular, GPS (indirectly)	Cellular Network Time used by LTE/5G-connected smart meters, while GPS used in head-end or substations for aligning system time, not per-meter accuracy.
Cybersecurity and Grid Resilience	1–100 ms	NTP, PTP, GPS, Secure NTP/PTP	NTP widely used for IT systems and logs, PTP used in OT and critical infrastructure, GPS used for time alignment across substations and PMUs, Secure NTP/PTP needed to defend against time spoofing attacks.

Table 2: Available timing distribution methods and their accuracies.

Time Synch Method	Typical Accuracy	Notes
GPS	~1 µs	Most commonly used.
PTP (IEEE 1588)	<1 µs (with hardware timestamping)	Emerging in substation environments.
IRIG-B	~1 µs (depending on implementation)	Legacy or backup method.
NTP	~1–100 ms	Common for general SCADA and AMI timestamping.
Cellular Network Time	100 ms – 1 s	Used by LTE/5G-connected devices.

Challenges in Timing Precision

Ensuring accurate timing and synchronization in smart grid applications involves several challenges:

- Network Latency: Inherent delays in communication networks can lead to inconsistencies in timing critical for real-time applications, especially in distributed environments.
- Standardization Issues: The absence of uniform timing standards across various devices can complicate integration efforts, hindering data sharing and effective system operation.
- Physical and Technological Constraints: Aging infrastructure may limit the implementation of necessary timing technology enhancements, impacting the operational capabilities of smart grid applications.

Future Directions

To address the challenges and improve timing in smart grids, the following directions are recommended:

- Emerging Synchronization Technologies: Adoption of innovative synchronization technologies, such as internal architected NTP and terrestrial based Precision Time Protocol (PTP), can improve timing accuracy across devices.
- Interoperability Standards: Development and implementation of universal standards are essential for ensuring the effective integration of diverse devices and technologies within smart grids.
- Real-Time Analytics and Adaptive Systems: Increasing reliance on advanced data analytics systems will enhance the ability to dynamically adjust to timing requirements and anomalies in real time.

Conclusion

Smart grids represent a transformative approach to power system management, heavily reliant on precise timing and synchronization across varied applications. This paper has explored critical use cases and their associated timing requirements, highlighting the necessity of accurate synchronization for enhancing operational efficiency, reliability, and responsiveness. By addressing existing challenges and embracing future technologies, stakeholders can further bolster the performance and resilience of smart grid infrastructures.

References

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[6] R. R. Mohassel, et al. "A survey on Advanced Metering Infrastructure." International Journal of Electrical Power & Energy Systems, vol. 63, pp. 473-484, 2014.

The Center for Alternative Synchronization and Timing (CAST) at Oak Ridge National Laboratory (ORNL) performs research, development, testing, evaluation, and technical assistance to enable resilient timing and synchronization for the power grid. Working closely with power utilities, timing hardware and software vendors, network operators, and federal stakeholders, CAST helps develop and validate alternative timing architectures to augment GPS time. CAST also translates and transfers ORNL's research and development (R&D) advances in secure timing and grid communications to power sector applications, and engages across the broader timing community to develop best practices to ensure the resilience of US critical infrastructure. CAST is sponsored by DOE's Office of Electricity. Visit https://cast.ornl.gov for more information.