ACCURATE TIMING SERVICES ARE important for effectively operating power grids. Traditionally, supervisory control and data acquisition (SCADA) systems make use of time stamps to quickly identify and respond to faults in the event of incidents. However, with the increasing penetration of renewable energy sources such as solar and wind, the grid has become more susceptible to even minor disturbances. In response, utilities have begun deploying wide-area monitoring systems (WAMS) to monitor real-time voltage and frequency oscillations, which mainly consist of phasor measurement units (PMUs). These systems require a time stamp at every measurement, with a high level of accuracy, which means that the timing services must guarantee 24/7 availability.

SCADA and WAMS require precise time synchronization for field devices in substations that are spread across different


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KEPCO's Practical Approach

Enhancing Synchrophasor Reliability Through Network-Based Time Synchronization

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Digital Object Identifier 10.1109/MPE.2024.3430888
Date of current version: 3 January 2025

geographical locations. SCADA records event or alarm data with a time accuracy of 1 millisecond, while WAMS further refines this by marking both event data and electric property measurements with an accuracy of 1 microsecond. Despite differing in precision, both systems utilize GPS, part of the global navigation satellite system, as a dependable time source. This reliance on GPS ensures synchronized and consistent timing across SCADA and WAMS systems. The Korea Electric Power Corporation (KEPCO), the largest electric utility in Korea, has employed this technology for several decades.

GPS is generally effective but susceptible to jamming and spoofing. Although these attacks are rare globally due to legal prohibitions, South Korea faces unique challenges. Since 2011, over 7,000 GPS signal disruptions that originated in North Korea have been reported. These disruptions affect not only vehicles such as airplanes and ships but potentially the power grid as well. Traditional SCADA systems, limited to event time stamping, have not reported direct grid impacts yet. However, WAMS, essential for real-time awareness, could suffer from disrupted synchronized phasor measurements, threatening grid stability. Another challenge in Korea is the geographical location of some substations. Seventy percent of the territory is mountainous, causing a “real canyon effect” in some deep valley substations. This geographical feature blocks the direct line of sight to satellites for PMUs, thus resulting in invalid measurements.

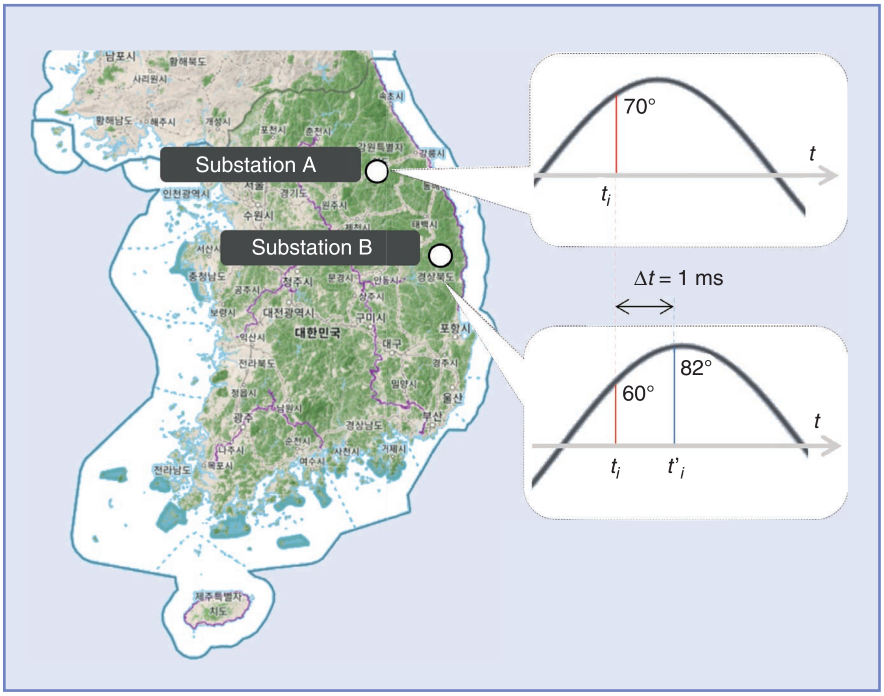

figure 1. The impact of timing mismatches on phase accuracy between two substations. When the timing between substations is perfectly synchronized (red lines on both waves), the phase difference is measured at 10 degrees. However, if there is a 1-millisecond discrepancy in the timing at substation B (blue line on the bottom wave), the measured phase difference would be –12 degrees.

For time synchronization in power systems, it is essential that the time offset among substations remains under one microsecond, and the time quality must stay valid, meaning PMUs should always lock onto a secure and accurate time source. However, challenges such as intentional GPS jamming from North Korea and unintentional geographical signal interference significantly compromise satellite signal reliability in South Korea. These challenges raise a critical question: What could be an alternative to GPS for time synchronization?

To overcome these challenges, KEPCO decided to implement network-based time synchronization without significant investment by leveraging its existing infrastructure. The company installed atomic clocks and synchronized them with the country’s national standard time using its optical cables for distribution automation. The time from these atomic clocks is then distributed to remote substations through network-based time synchronization, using the existing optical communication lines that run over the high-voltage transmission lines. This new synchronization method could ensure the standard accuracy of PMUs and significantly higher availability.

Synchrophasor Measurement and Time Synchronization

According to the IEC/IEEE Standard “Synchrophasor for Power Systems Measurements,” a PMU estimates the phase, magnitude, frequency, and rate of change of frequency (ROCOF) of an electrical wave, attaching a time stamp that represents the time of measurement. The accuracy of these measurements depends heavily on the precision of the PMU’s time clock. As illustrated in Figure 1, a synchrophasor within a PMU captures the phase measurement at a precise moment. These data are then collected in a phasor data concentrator, where they are then arranged in chronological sequence in order to facilitate further analysis.

If there is a 1-millisecond time offset between any two PMUs in a 60-Hz electrical system, it could result in a 22-degree error in the synchrophasor measurements. This error in timing is not only limited to phase measurement discrepancies but also extends to the frequency and ROCOF measurements, which are the first and second derivatives of the phase measurement over time, respectively. Therefore, any timing inaccuracy directly impacts the reliability of

> Challenges such as intentional GPS jamming from North Korea and unintentional geographical signal interference significantly compromise satellite signal reliability in South Korea.

the phase measurement, which, in turn, affects the calculated values of frequency and ROCOF. These three measurements are crucial for maintaining situational awareness of the power system. They enable operators to make informed decisions and implement corrective controls, underscoring the critical importance of timing precision in power system measurements.

Time Synchronization Requirement

Since 2011, KEPCO has deployed 72 PMUs across Korea, with 50 located on the mainland; the remaining 22 are located on Jeju Island, which has the highest penetration of solar power in the country. The primary aim of this deployment is to research how synchrophasors can be utilized in power analysis and applications to securely host the renewable energy. Through long-term verification of data reliability and application feasibility, PMUs are anticipated to be integrated into grid operation via WAMS in a few years.

To ensure the time accuracy of geographically distributed PMUs, what standards should one adhere to? The IEC/IEEE standard advises maintaining time accuracy within a 2.6-microsecond error margin in a 60-Hz power system, aiming for precision at least ten times greater than the values corresponding to a 1% total vector error in phasor measurement; it also requires that the time is recorded with a resolution of 1 microsecond. The North American Synchrophasor Initiative outlines crucial grid timing applications and requirements, stating, “When synchrophasors are used for automatic control actions, it is critical to have accurate, reliable, and secure timing, which necessitates an absolute time accuracy of 1 microsecond.” Since most PMU applications ultimately incorporate control and protection actions, the requirement for 1-microsecond accuracy has become broadly accepted.

Challenges of Time Synchronization in Korea

To achieve the necessary time synchronization of PMUs, the most common method is the use of GPS receivers guaranteeing nanoscale accuracy. However, GPS is known to be susceptible to both intentional interference, such as jamming and spoofing, and unintentional interference, such as obstructions in mountainous areas. South Korea’s unique political and geographical situation makes it especially susceptible to these types of interferences.

After installing PMUs, there have been more than 7,000 reported cases of GPS signal disruptions coming from the North Korea. The attacks from the north extended up to 100 km, potentially affecting a quarter of South Korea. This disruption impacted positioning, navigation, and timing services all at once. Unlike conventional SCADA, which has not reported any direct impact, WAMS could potentially be affected in its operation due to invalid phasor measurements. To mitigate the downstream impact, commercial products equipped with antijamming antennas, advanced signal processing systems, and integration of multiple navigation technologies using satellite systems alongside GPS are available. However, these technologies may not be completely effective against sophisticated signal generators that move freely through the air. This vulnerability stems from the nature of industrial GPS signals, which are broadcasted from high-altitude satellites. Each mitigating technology comes with its own unique costs and implementation challenges related to the technology. In countries with a large number of substations, such as over a thousand, and especially in the United States with 55,000 substations, identifying an affordable and secure method for GPS-based time synchronization presents a significant challenge.

Another challenge for time synchronization is that only 30% of South Korea’s mainland is flat, an area where GPS satellite availability is most consistent, providing 24/7 coverage, as depicted by the light yellow area in Figure 1. This flat area is primarily used for residential and commercial purposes. However, most substations are located in mountainous areas, typically situated in deep valleys in order to accommodate numerous facilities and also provide protection from strong winds. As a result, many are located in GPS shadow areas, which may obstruct the direct line of sight to satellites. This can lead to PMUs in the substations being unable to lock onto GPS signals, resulting in the generation of invalid synchrophasors.

GPS satellites fly in six circular orbits at an altitude of 20,200 km and revisit the same place every sidereal day, which is about 23 h 56 min. From this analysis, it can be inferred that if a PMU is located in a GPS shadow area, time synchronization errors may occur periodically. Data from “PMU no time synchronization” events recorded by the phasor data concentrator at KEPCO headquarters over 10 days, from 21 August to 30 August 2023, were analyzed. This analysis revealed an interesting pattern: PMUs in certain areas periodically experienced “PMU no time synchronization” events, notably in locations situated in deep valleys. A total of 12 PMUs exhibited this suspicious behavior, with four examples presented in Figure 2. Based

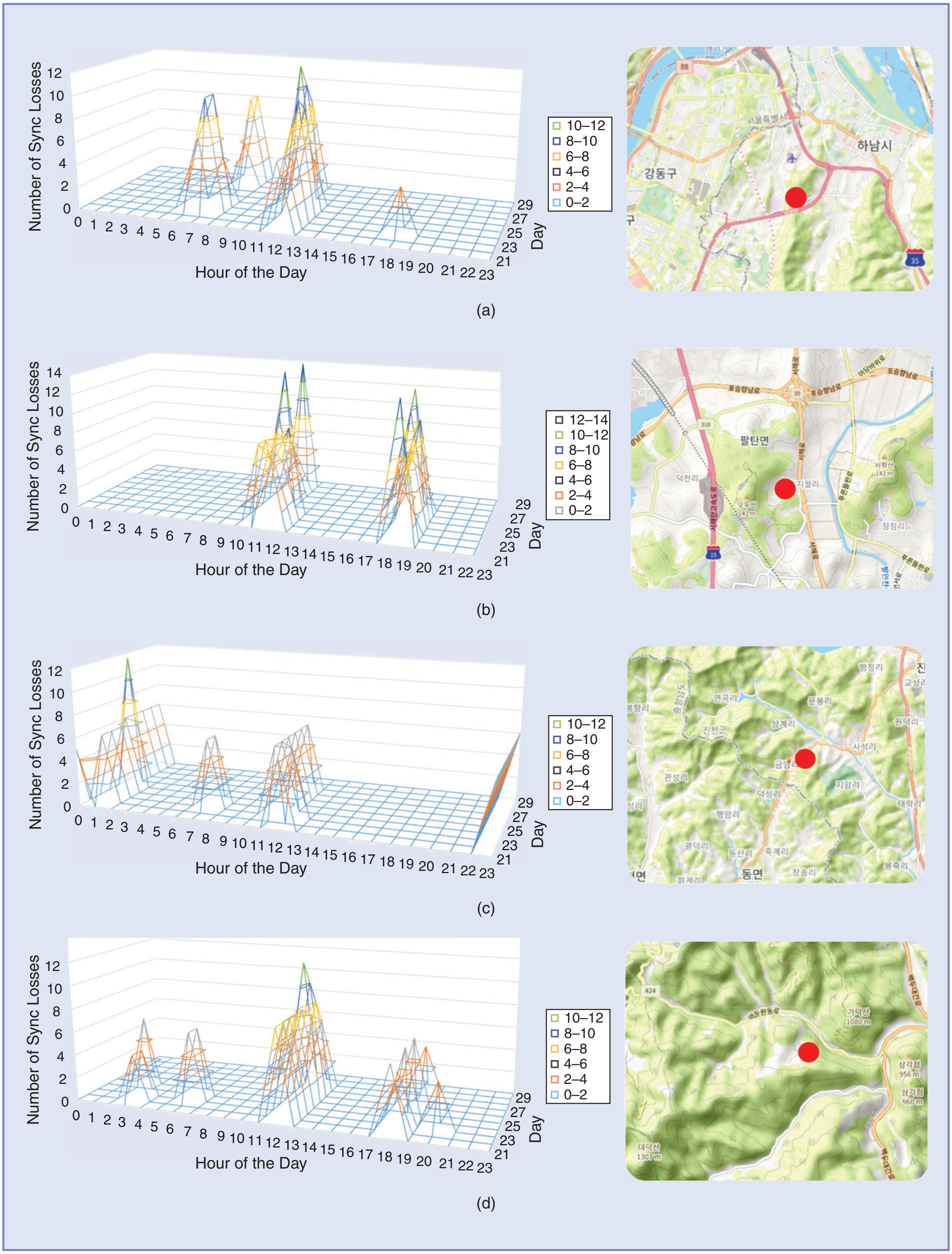

figure 2. An analysis of "PMU no time synchronization" events and the geographical location of a substation in a GPS shadow area. (a) Substation A, (b) substation B, (c) substation C, and (d) substation D. (For security reasons, the names of the substations are anonymous.)

Consequently, KEPCO has decided to establish its own master clocks within the data center, synchronizing their time with KST using the existing optical cables.

on these observations, it was identified that the geographical location of a substation can impact the time synchronization of PMUs with GPS, potentially leading to malfunctions in WAMS. Synchrophasors in a PMU provide not only the time but also a time quality indicator. This confirms whether the PMU time is synchronized with GPS and assesses its reliability. Even a brief interruption in the GPS signal can render the time quality invalid, leading grid applications to disregard the synchrophasor data for analysis.

The two main issues, intentional GPS disruption and PMU locations in GPS shadow areas, hinder the 24/7 availability of satellite-based time synchronization. Therefore, an alternative method to replace GPS is necessary. There are several wireless technologies that could provide time to widely distributed devices, such as radio station call signs or eLoran. However, the accuracy of these ways (ten microseconds at best) is not enough to feed time to PMUs, and their frequency bands (60 kHz to 110 kHz) would not be verified to be valid under the high electrical noise environment of an electrical substation.

Overcoming GPS-Related Challenges

If one cannot solely depend on GPS for the PMU's time synchronization due to special environmental reasons, what alternatives should be prepared? In fact, the GPS system provides two kinds of services for the receiving device:

- ✔ multiple atomic clocks in a GPS satellite that guarantee the accuracy of the time
- ✔ GPS signals that distribute the time exactly to the GPS device in an electrical substation.

To establish an alternative, it is necessary to develop a method for creating an accurate time source and ensuring reliable time distribution.

First, KEPCO needs to establish its own accurate time servers, akin to the atomic clocks in GPS satellites, and synchronize them with a dependable time source other than GPS. Fortunately, the Korea Research Institute of Standards and Science (KRISS), which generates Korea Standard Time (KST), is physically located less than 12 km from the company's data center. Additionally, an optical line for time signal transfer is already installed along the power distribution lines between the two locations. KEPCO operates a distribution automation system that identifies outage locations, dispatches electricians, and swiftly recovers from faults, managing both communication and power lines. Consequently, KEPCO has decided to establish its own master clocks within the data center, synchronizing their time with KST using the existing optical cables.

Next, a reliable method must be ensured for the distribution of accurate time from the master clock to substations equipped with PMUs. A transmission line in KEPCO has an optical fiber composite overhead ground wire (OPGW) that combines the functions of grounding and communications. The outside conductive portion of the cable bonds adjacent towers to the Earth, providing a ground connection and protecting the high-voltage conductors from lightning. The optical fibers inside the cable enable high-speed data transmission, which can be utilized by the electrical utility for protective and control measures of the transmission line. To ensure reliable time distribution, KEPCO employs the Precision Time Protocol (PTP) via OPGW. This protocol is designed to synchronize clocks throughout a communication network and is capable of achieving submicrosecond accuracy, making it well suited for systems that require precise measurement and control.

PTP, a type of network protocol, is also recognized for its vulnerabilities, which include well-known attack methods such as man in the middle, replay, and packet spoofing attacks. However, carrying out an intentional time attack over PTP is almost impossible. This is because an attacker would have difficulty gaining physical access to the device or the optical cables, which are typically located in physically protected substations or electric transmission towers, often around 75 meters in height. To access the OPGW cable at the top of the tower, an attacker would need to successfully circumvent the transmission lines carrying hundreds of kilovolts.

Implementation of Network-Based Time Synchronization

Accurate Time Source

KEPCO collaborates with KRISS to synchronize its master clocks, including two cesium clocks, to KST. An optical fiber, as illustrated in Figure 3, has been laid out spanning a distance of 11.266 km to facilitate this synchronization. Four optical lines are dedicated to this task: two for transmitting time and frequency pulses and two others for data communication. The four lines are physically and permanently routed at the Daeduck substation. Since most of the optical fiber for distribution automation system was already operational, only terminal connections with the clock system at both organizations were required for this task, costing about

US$10,000. The time offset between the clocks is precisely measured and adjusted to guarantee that the time difference remains within 30 ns, 95% of the time, which corresponds to the error level of a GPS receiver.

Figure 4 presents the systematic diagram of the system. One-pulse-per-second signals are gathered from the internal atomic clocks (A), KST time and frequency signals (B), GPS receivers (C), and the output of the master clock (D). These

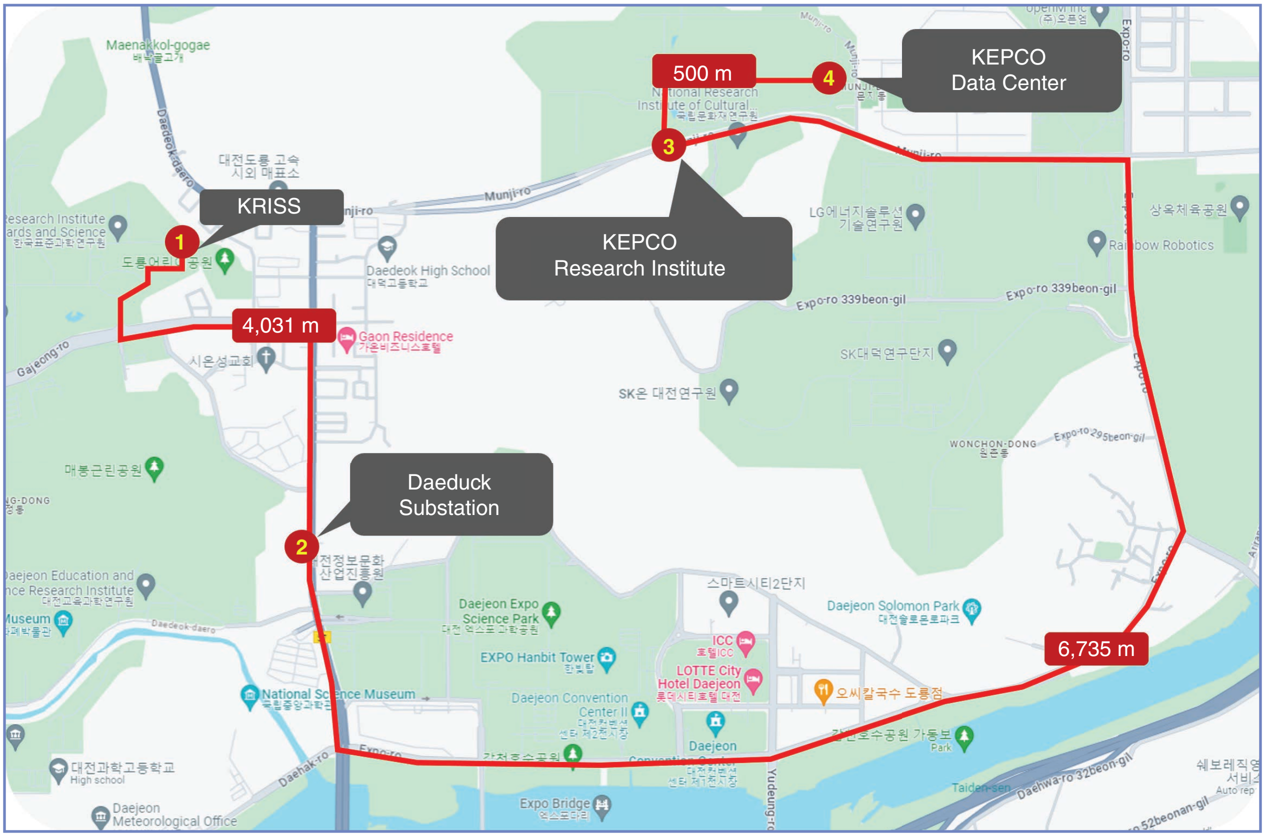

figure 3. The optical cable path between KRISS and KEPCO.

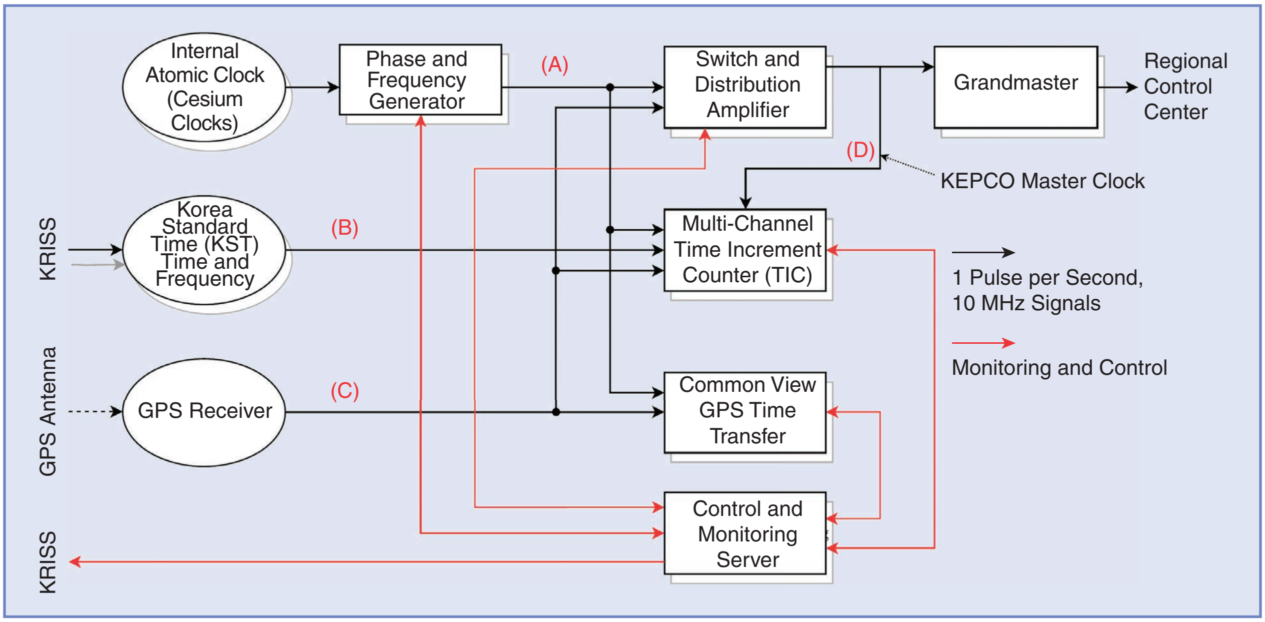

figure 4. A systematic diagram for synchronizing the KEPCO master clock with KST. The time offset between the KEPCO master clock and KST is managed and minimized through the comparison of three clocks (A, B, and D), with the GPS receiver (C) serving as a backup and for long-term tuning.

> The new method for time synchronization, which primarily utilizes network-based solutions with satellite as a secondary support, is expected to significantly enhance the reliability of PMU measurements.

signals are then sent to a multichannel time interval counter, which measures the differences among them. The control and monitoring server aggregates the measured differences and uses a finely tuned algorithm to calculate the required compensation offsets. The server then generates steering controls, which are transmitted to the phase and frequency generator to accurately align the atomic clocks. Except for a GPS receiver, two sets of devices function redundantly, with one serving as the primary set and the other as a backup. Furthermore, the server is responsible for selecting one of the two sets of devices as the master clock based on their performance in terms of accuracy. The signals from the GPS receiver are utilized only if both atomic clocks fail to produce signals of the required quality. Common view GPS time transfer calculates the time offset between the finely tuned atomic clocks and GPS. This offset will be transferred to KRISS and then used to estimate the time difference from KST. This activity assists in the long-term tuning of time synchronization.

Figure 5 displays the time offsets recorded between the KEPCO master clock and KST, whereas Figure 6 illustrates the offsets between the KEPCO master clock and the GPS. Both sets of data were monitored over a six-month period, from 1 May to 31 October 2023. It was found that the master clock's maximum offset stayed under 10 nanoseconds relative to KST and under 20 nanoseconds when compared with GPS. Statistically, the master clock maintained the offset within 8 nanoseconds

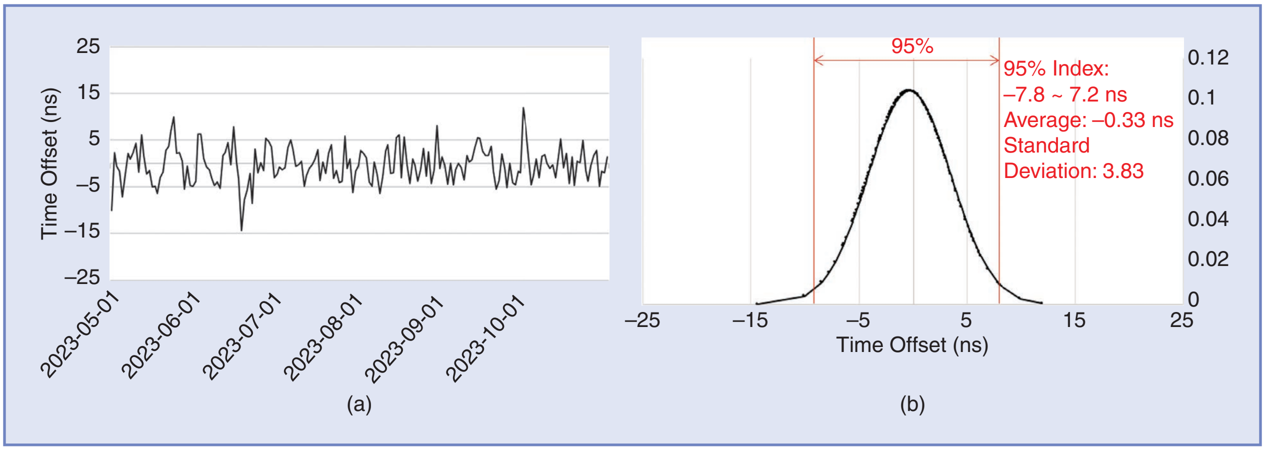

figure 5. (a) The time offset and (b) its normal distribution between the KEPCO master clock and KST.

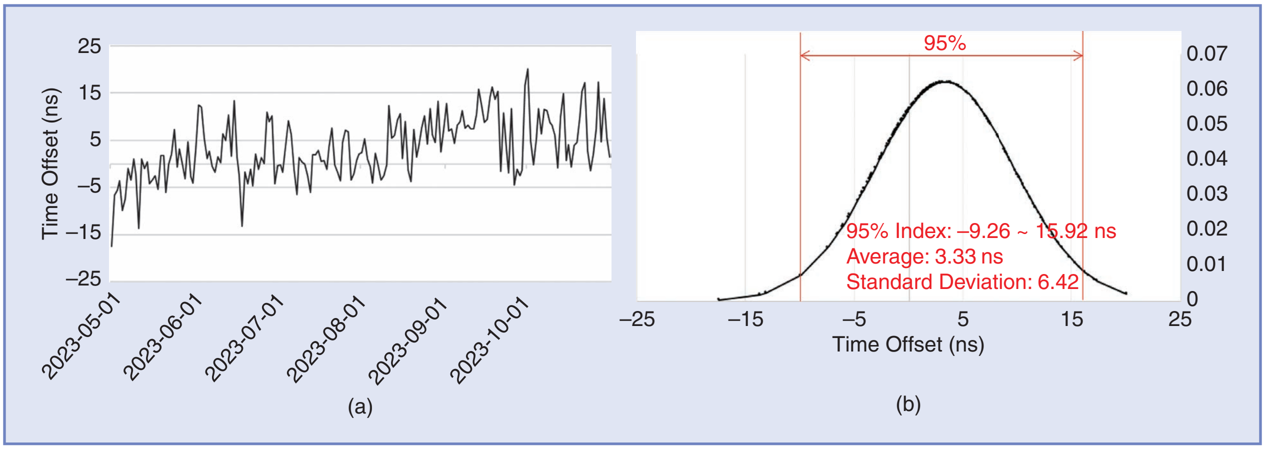

figure 6. (a) The time offset and (b) its normal distribution between the KEPCO master clock and the GPS receiver.

for the KST clock and 16 nanoseconds for the GPS clock, 95% of the time. Consequently, it can be confirmed that the internal master clock achieves higher accuracy than GPS receivers.

Coordinated Universal Time (UTC) is the basis for GPS time and is maintained by several atomic clocks on board satellites. UTC itself is sustained through a collaborative international effort involving highly accurate atomic clocks. The atomic clocks in KRISS contributing to KST are part of the global network of over 450 atomic clocks that collectively establish UTC. Consequently, KST and GPS time have practically the same level of accuracy, and any offset observed is primarily due to the time distribution process.

Secure Time Distribution

Upon synchronizing the master clock with KST, KEPCO implements a two-tiered strategy to distribute time to remote PMUs. Initially, PTP is used to synchronize the clocks at regional control centers (RCCs), located at fifteen different sites, with the master clock. These RCC clocks, designed for redundancy, primarily use PTP and are equipped with GPS receivers for backup. If the OPGW communication link between the master clock and the RCC clocks fails, the system automatically switches from PTP to GPS synchronization. In the next phase, each RCC clock, overseeing multiple substations, is responsible for synchronizing the substation clocks, also using PTP with OPGW. This methodical approach to time distribution is illustrated in Figure 7.

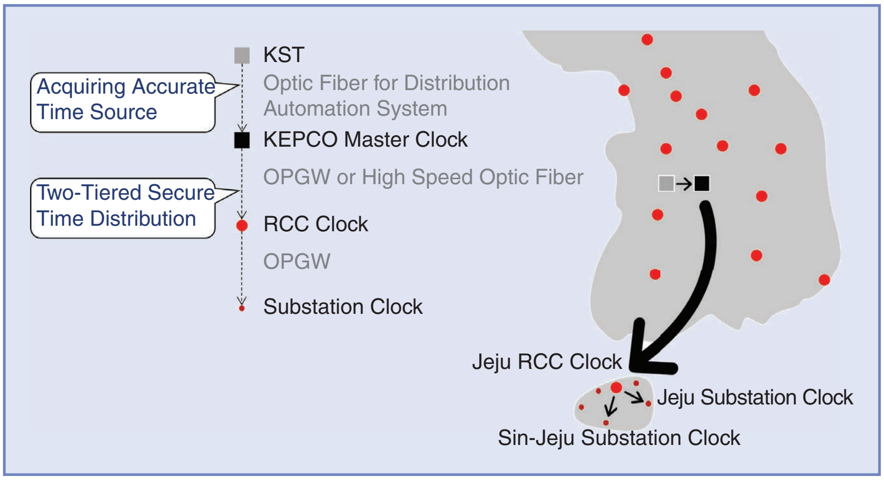

figure 7. The two-tiered time distribution in KEPCO.

To demonstrate the accuracy of the proposed time distribution method, three time servers supporting PTP were installed: one at the Jeju RCC and the others at two substations, Jeju and Sin-Jeju. These locations were selected because they were the farthest from the KEPCO master clock, as shown in Figure 7. To assess the accuracy of the time distribution, it is crucial to measure the time offset between the master clock and the clocks at the substations. Since it is not feasible to directly estimate the master clock's time at a substation, a GPS clock was used as a reference. Figure 8 illustrates the time differences measured by the Calnex Paragon-X device, which analyzes the 1-pps signals to accurately determine the offset between the clocks at the substations and the GPS receiver.

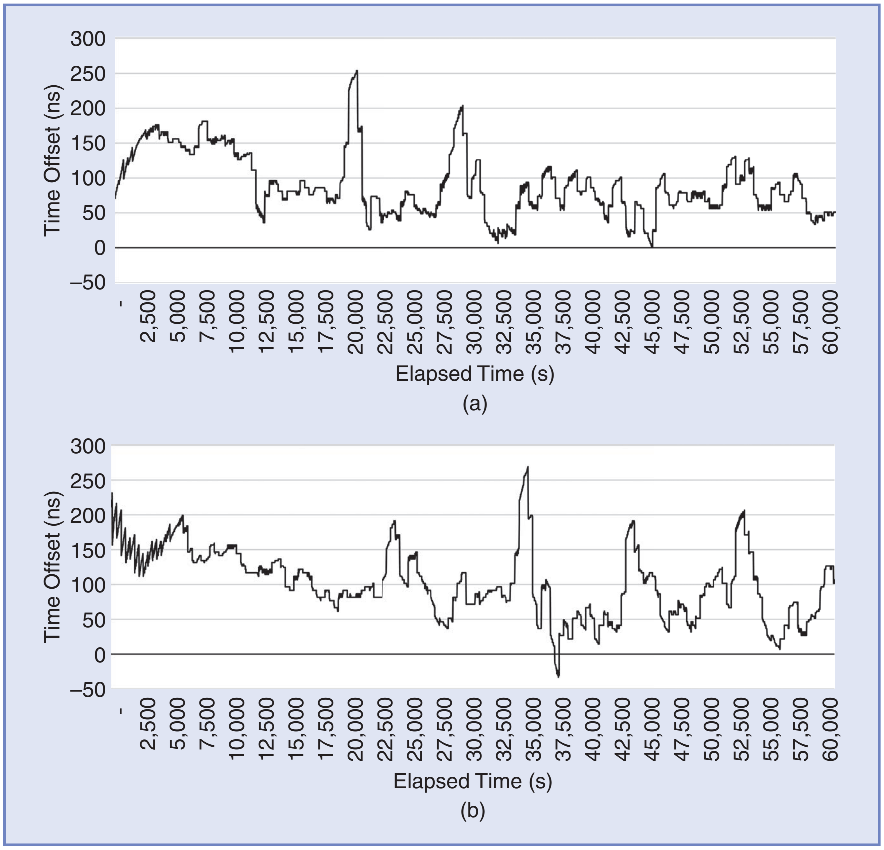

figure 8. The time offset between internal clocks and GPS at two substations: (a) Jeju substation and (b) Sin-Jeju substation.

The clock at the Jeju substation, which synchronizes sequentially with the KEPCO master

KEPCO plans to deploy approximately 200 PMUs over the next four years, including the 72 already installed for research, to enhance the power grid's reliability.

clock and the Jeju RCC clock, maintained its accuracy within 300 nanoseconds of GPS. This was measured over a 17-h period starting at 15:00 on 9 November 2022. Similarly, the clock at the Sin-Jeju substation was synchronized in the same manner and exhibited a comparable time offset over an equivalent period beginning at 11:00 on 10 November 2022. As illustrated in Figure 6, the offset of the KEPCO master clock relative to GPS is less than several tens of nanoseconds. Therefore, it can be reliably distributed over private optical fiber with an accuracy of 300 nanoseconds.

Future Plans

A network-based time synchronization system that meets the accuracy requirements for power systems has been successfully demonstrated. Suitable for applications in WAMS and PMUs, this system provides a reliable alternative in areas where continuous, accurate time availability is compromised by intentional or unintentional GPS disruptions. Our approach offers several advantages over satellite-based synchronization:

- ✔ ensuring time accuracy comparable to satellite-based time synchronization
- ✔ no vulnerability to wireless jamming and spoofing attacks
- ✔ enhanced robustness against cyberattacks targeting PTP, as physical access is challenging
- ✔ no additional construction costs for high-speed communication networks, as many utilities already have these for distribution automation and internal data exchange.

KEPCO plans to deploy approximately 200 PMUs over the next four years, including the 72 already installed for research, to enhance the power grid's reliability. To ensure accurate and secure time synchronization for both new and existing PMUs, the following steps are crucial:

- ✔ upgrading communication devices for PTP support
- ✔ establishing a dedicated network for time synchronization that is separate from synchrophasor data exchange
- ✔ monitoring time accuracy at RCCs and developing GPS fallback mechanisms in cases where PTP is not feasible.

Conclusions

The additional cost could be a major concern when considering an alternative to satellite-based time synchronization. Fortunately, the required physical communication channels for network time synchronization are already in place, thus avoiding significant financial outlays. The costs for additional devices and technologies, such as master clocks and PTP, are considered manageable from KEPCO's perspective for ensuring the reliable operation of WAMS. However, GPS remains indispensable as a backup timing service when the network is unavailable. The new method for time synchronization, which primarily utilizes network-based solutions with satellite as a secondary support, is expected to significantly enhance the reliability of PMU measurements of electrical properties in environments like Korea.

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