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ASSESSMENT OF THE IMPACT OF TOTAL VECTOR ERROR AND TIME SYNCHRONIZATION ISSUES ON THE OPERATION OF WIDE-AREA POWER SYSTEM MONITORING SYSTEMS

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In this paper, the total vector error (TVE) of the estimated phasor is assessed across different local area network (LAN) access environments defined in the IEEE C37.118.1-2011 standard, and the critical role of accurate time synchronization for synchrophasor technology is investigated. Phasors synchronized to absolute time constitute the foundation of phasor measurement units (PMUs), which are widely used for power system monitoring. The TVE assessment is performed for three local network models – CSMA/CD, CSMA/AMP, and switched Ethernet – considering standardized network bandwidth (BW) values of 0.1, 1, and 10 Gbit/s in accordance with Standard IEC 61850-9-2:2011, as well as the number of network nodes. A methodology for evaluating the impact of internal and external PMU measurement errors on the performance of critical wide-area monitoring system (WAMS) applications is analyzed, including disturbance localization, oscillation detection, and dynamic line rating (DLR). The analysis results demonstrate that TVE is highly sensitive to the type of local area network and the number of nodes. At the same time, the accuracy of time synchronization remains a significant challenge affecting the reliability of WAMS applications. Ref. 10.

Keywords: phasor, power system, local network, total vector error, time synchronization, PMU, WAMS.

Introduction. The basis of monitoring is information procedures, which are used to obtain quantitative or qualitative information about the monitored object's properties and condition. At the same time, information processing involves the operations of collection, input, recording, transformation, reading, storage, and registration [1, 2]. Phasor measurement technology, which dates back to a mathematical method developed by Proteus Steinmetz in 1916 for the analysis of AC networks, is now critically important for the monitoring and operation of power systems [3]. In 1992, Jay Murphy developed this method to calculate phasors synchronized to absolute time, leading to the creation of the first phasor measurement unit (PMU). Phasor synchronization was standardized in [4], and later codified (i.e., the conversion of physical quantities into a strictly defined digital format) as [5] in 2005, with an updated version in 2012.

The aim of the paper is a comprehensive assessment of the impact of total vector error (TVE) and time synchronization problems on the reliability and accuracy of operation of wide-scale power system monitoring systems (WAMS, Wide Area Monitoring System).

The PMU is a robust tool capable of estimating phasors under both steady-state and transient conditions. However, traditional phasor estimators that rely on the discrete Fourier transform algorithm can introduce significant magnitude and phase errors, which increases the total vector error (TVE). In contrast to the Fourier transform, the Kalman filter is considered a powerful algorithm for estimating phasors under step changes with lower error [6].

Because power systems are large and geographically distributed, energy data acquisition systems require a common time source. PMUs add time stamps to measurements relative to a time source, such as the Global Positioning System (GPS). PMU data is used for situational awareness, event analysis, and system stability monitoring. However, the performance and reliability of WAMS

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end-use applications that use synchrophasors critically depend on the quality of the measurements, which are affected by both PMU and measurement channel errors.

The standard [5] defined a permissible measurement error, called the total vector error (TVE). TVE is the geometric difference between the ideal (reference) vector and the vector measured by the PMU, expressed as a percentage:

$$\mathrm{TVE}=\sqrt{\frac{(X_{r\,meas}-X_{r\,ideal})^2+(X_{i\,meas}-X_{i\,ideal})^2}{X_{r\,ideal}^2+X_{i\,ideal}^2}}\times100\%’ \qquad (1)$$

where $X_{r\,meas}$ and $X_{i\,meas}$ are real and imaginary parts of the measured vector; $X_{r\,ideal}$ and $X_{i\,ideal}$ are the real and imaginary parts of the ideal (reference) vector.

If the amplitude and phase angle errors are known, (1) can be presented in a more visual form:

$$\mathrm{TVE}=\sqrt{2+2\cdot\left(\frac{A_{meas}}{A_{ideal}}\right)\cdot\left[1-\cos\left(\varphi_{meas}-\varphi_{ideal}\right)\right]+\left(\frac{A_{meas}}{A_{ideal}}-1\right)^2}\times100\%, \qquad (2)$$

where φ_{meas} is the measured phase angle; φ_{ideal} is the ideal phase angle.

However, most often for simplified calculations, an approximate formula is used:

$$\mathrm{TVE}\approx\sqrt{\left(\frac{A_{meas}-A_{ideal}}{A_{ideal}}\right)^2+(\Delta\varphi)^2}, \qquad (3)$$

where A_{meas} is the measured amplitude, A_{ideal} is the ideal amplitude, and $\Delta\varphi$ is the phase angle error in radians.

Under steady-state conditions, the maximum allowable TVE for a PMU should be within 1%. The accuracy requirements for a PMU may be relaxed for dynamic input signals such as modulation, rate of change of frequency, and phase shift. For example, for a modulated input signal, the TVE should be within 3%, compared to 1% under steady-state conditions.

TVE expresses uncertainty in the measurement result as the sum of amplitude and phase errors.

Although the standard [5] defined a TVE tolerance, it did not specify the method for estimating the phasors. As an alternative to the Fourier transform, the Kalman filter can be updated using high-throughput, time-critical, measured instantaneous values, SV (Sampled Values), as defined by the communication standard [7]. The Kalman filter is a mathematical method for calculating optimal estimates of the states of a dynamic system [6]. These streaming SV values are transmitted over the substation process bus with a high sampling rate of 80 or 256 samples/period.

The standard [7] defines a process bus and a substation bus, both of which support Ethernet technology. The process bus implements standardized bandwidth values of BW: 0.1, 1, and 10 Gbit/s. The Merging Unit (MU) is responsible for selecting and creating high-throughput SV packets. The MU unit is a device that digitizes analog signals from current- and voltage-measuring transformers and converts them to a digital format for transmission over a communication network.

In its operation, the power system widely uses precise time synchronization as a fundamental tool to ensure effective monitoring of network status, enhance operator situational awareness, coordinate operating modes, and implement relay protection and automation functions. In complex and geographically distributed applications, all means of measurement, control, and data processing must be tightly synchronized relative to a single reference time - Coordinated Universal Time (UTC). Such synchronization is a necessary condition for the correct integration of data from different nodes of the power system and for ensuring the coordinated operation of real-time, decentralized analysis and control algorithms.

Synchrophasor technology requires reliable access to UTC because PMUs have among the most stringent time-accuracy requirements of any power system equipment, given their high-frequency reporting and wide geographic distribution. Phasor Data Concentrators (PDCs) collect, process, and time-align data from multiple PMUs [8].

In most modern devices for synchronized vector measurements used in power systems in Ukraine, the primary time synchronization source remains the GPS signal [9]. At the same time, GPS satellite signals are characterized by low power at the receiving end, making them particularly vulnerable to both anthropogenic and natural factors. Such factors include electromagnetic interference, intentional or unintentional signal jamming, and spoofing (i.e., "substitution" of the satellite signal), which can lead to intentional distortion of time stamps.

Violations of the availability or integrity of the GPS signal can negatively affect the functioning of the synchrophasor infrastructure, including false triggering of monitoring algorithms, the formation of false alarms, and increased operating costs associated with additional checks and personnel intervention. At the same time, under modern conditions, such failures, as a rule, do not lead to large-scale emergencies in the power system but significantly reduce the reliability and trust in measurement results.

Given these vulnerabilities, solutions based solely on GPS for accurate time cannot be considered sufficient to ensure the reliability of critical applications. Until redundant, secure synchronization mechanisms are implemented and the integrity of time stamps and measurement data is ensured, the use of PMUs for automated control and other critical functions should be limited [10]. It should be noted that promising applications of synchrophasor technology impose extremely stringent synchronization accuracy requirements, potentially requiring a time resolution of up to 1 microsecond. The transmission of measured synchrophasor values in real time is a key component of power system monitoring systems. Since synchrophasor technology requires high accuracy, minimal delay, and guaranteed bandwidth, the ability of local area networks (LANs) to ensure stable data transmission without additional distortions is crucial.

The influence of the type of network technology and available bandwidth on the formation of the total vector error TVE when transmitting SV streams is standardized in [7].

SV packets are transmitted at a high sampling rate, which creates a significant network load and requires the LAN to have not only sufficient bandwidth but also stable packet delivery times. Any delays, delay variations, or packet losses directly affect the quality of phasor reconstruction and can increase TVE beyond acceptable limits.

Since SV traffic is time-critical, the IEC 61850 standard defines several network technologies for transmitting these flows. Let's consider the three most common LAN models: CSMA/CD, CSMA/AMP, and switched Ethernet. Each of them has different mechanisms for accessing the medium and, accordingly, a different level of determinism of information transmission.

Carrier Sense Multiple Access with Collision Detection (CSMA/CD) is a multiple-access protocol for a shared medium in a local area network that uses collision detection. When the network medium is occupied by several nodes at the same time, collisions occur, that is, the overlapping of signals, which leads to retransmission and an increase in packet delivery time. In systems where minimal delay is critical, this mechanism becomes a significant source of errors.

Carrier Sense Multiple Access with Arbitration, Monitoring, and Priority (CSMA/AMP) provides priority service for traffic. In the event of a collision, the message with the higher priority is given priority, which partially reduces the randomness in packet delivery times. However, as the number of nodes increases, even this mechanism can cause excessive delays.

Switched Ethernet provides the highest level of determinism, as each node has a separate communication channel with the switch. The absence of collisions and support for full-duplex mode significantly increases the reliability of SV traffic transmission.

The analysis results confirm that maintaining TVE≤1% depends not only on signal processing algorithms but also on the choice of network infrastructure. For the effective functioning of PMU and SV transmission within WAMS, it is necessary to ensure:

- sufficient bandwidth of 1–10 Gbit/s depending on the type of network;
- minimizing collisions and jitters, i.e., unwanted deviation from ideal signal periodicity or synchronism;
- use of switched solutions with high transmission determinism.

PMU measurement errors, caused by both device-level factors (algorithm, synchronization accuracy) and measurement channels (instrumentation transformers, cables), are critical to the reliability of WAMS applications.

To quantify the impact of measurement errors on WAMS applications, results are presented with and without errors [6]. WAMS applications are divided into qualitative (oscillation detection and islanding) and quantitative (fault location and line dynamics). For qualitative outputs, impact is measured by the failure rate, including failed detections and false alarms. For quantitative outputs, the impact is described by the error of the output results.

Localization of power system disturbances. Programs for locating disturbances in the power system promptly detect and spatially localize them, particularly sudden losses of generating capacity or other significant imbalances in the regime. The corresponding algorithms are based on the principle of the propagation of an electromechanical wave along the electrical network, which arises from a disturbance of the established regime and is recorded by phase-measuring devices located at different nodes of the system. Localization of the disturbance source is performed by analyzing the Time Difference of Arrival (TDOA) of the phase angle shifts recorded by different PMUs, thereby allowing determination of the event's coordinates in the network space. TDOA is a method for determining the location of a signal source that calculates the difference in the time of arrival of the same signal at several receivers with known coordinates. In this case, the TDOA parameter serves as a quantitative output of the localization algorithm and directly affects the accuracy of determining the disturbance's location.

Detection of oscillations. The detection of inter-system oscillations in the power system is based on analyzing measurements of relative phase angles between selected network nodes and comparing them with predefined threshold values. However, the effectiveness of such analysis depends directly on the total uncertainty of the measurement channel, which includes the errors of the current/voltage measuring transformers and the PMU devices themselves. Since the measuring transformers can have both positive and negative errors with different signs, the resulting error in the angle difference only increases. This creates a significant static bias in the measurements, which must be considered when calibrating the system, since it can be comparable to the oscillation amplitude.

Phase angle estimation errors, which in dynamic modes can reach values permitted by the standard (in particular, TVE up to 3% for a modulated input signal, corresponding to approximately 1.8° at a nominal frequency of 50 Hz), can significantly affect the reliability of detection algorithms. In particular, for non-oscillatory modes, when random phase angle fluctuations or measurement errors exceed the set threshold values, there is a risk of false triggering and false alarms.

The analysis results confirm that, in the presence of a real intersystem oscillation event, the PMU angular error is highly unlikely to result in a failed detection. However, the false-positive rate increases significantly with increasing phase-angle error.

Islanding detection. Islanding detection, i.e., the isolated operation of a network section with connected distributed generation, is a WAMS qualitative application. Such algorithms are not aimed at an accurate quantitative assessment of the mode parameters, but at timely recognition of islanding to ensure the safety and reliability of the power system. One of the most common approaches to islanding detection is a frequency-based method that uses the instantaneous Frequency Deviation (FD) and the Integral of Frequency Deviation (IOFD) as key diagnostic indicators [6].

Dynamic Line Rating. Dynamic Line Rating (DLR) is a class of quantitative applications of large-scale monitoring systems that determine the maximum permissible current load of a line based on its current thermal state. This approach uses synchronous voltage and current phasor measurements obtained by PMU-synchronized vector measurement devices installed at both ends of the transmission line, allowing estimation of its electrical parameters, particularly the complex resistance. In addition to electrical measurements, meteorological data such as ambient temperature, wind speed, and direction are considered in DLR calculations, which significantly affect the conductor's heat balance.

The presence of errors in PMU measurements inevitably leads to uncertainty in the estimation of line parameters and, consequently, errors in the results of dynamic capacity estimation. In most cases, the focus is on assessing the impact of phase angle error, as it is the dominant factor in determining the accuracy of line resistance and subsequent thermal calculations. Even relatively small angular errors can lead to a significant spread of DLR estimates, especially in regimes close to the limit.

The conducted study of the total vector error TVE in local area networks confirmed that the efficiency and reliability of synchronized vector measurement devices critically depend on both the type of network technology used and the available bandwidth of the communication channel. The results showed that switched Ethernet provides the highest performance and data-transmission determinism, satisfying the requirements for the permissible level of TVE at bandwidths of 1 Gbit/s and 10 Gbit/s. At the same time, the standardized speed of 0.1 Gbit/s proved insufficient to meet the TVE requirements for all types of local area networks considered, limiting its use in time-critical synchrophasor applications.

Conclusions.

1. The reliable operation of synchrophasor technology in large-scale WAMS power system monitoring systems is largely determined by the integrity and availability of accurate time sources. Given the vulnerability of satellite synchronization systems, in particular GPS, to interference, jamming, and spoofing, there are significant risks to the implementation of critical applications, including automated power system control. Until redundant, secure, and highly reliable time distribution mechanisms are implemented, the use of synchrophasor measurements in automated power system control is impossible.
2. The analysis of the sensitivity of WAMS applications to measurement errors showed a clear dependence of their performance on the type of implemented algorithm. In particular, applications with quantitative outputs, such as network fault localization and dynamic estimation of DLR line throughput, are highly sensitive to phase angle errors. Even dynamic PMU errors that remain within the standard's permissible values can lead to significant errors in determining the location of the disturbance or estimating line throughput, thereby reducing the practical value of the results. At the same time, applications with qualitative outputs, in particular algorithms for detecting intersystem oscillations, are less prone to missed events but remain vulnerable to false positives. The frequency of such false alarms increases with increasing phase angle error, especially in the presence of large-amplitude non-oscillatory fluctuations, which negatively affect the system's reliability and operator perception.
3. An effective way to increase the accuracy of results, in particular for the tasks of dynamic assessment of line capacity, is to compensate and calibrate the errors of the measuring channel. Eliminating systematic errors in transformers and connecting elements reduces the accuracy requirements of the synchronized vector measurement devices themselves without degrading the final accuracy of the results, making it a practically feasible and economically justified approach.
4. In general, to ensure the reliable functioning of smart energy networks in the future, significant improvements in precise time distribution systems are necessary, as well as further clarification of the requirements for the accuracy of synchrophasor measurements, taking into account dynamic operating modes and the specifics of the algorithms of specific WAMS applications.

1. Stognii B.S., Sopel M.F. Fundamentals of monitoring process in electroenergy. About the concept of monitoring process. *Tekhnichna Elektrodynamika*. 2013. No 1. Pp. 62–69. (Ukr) URL: https://techned.org.ua/index.php/techned/article/view/1142/1016
2. Kyrylenko O.V., Stognii B.S., Denysiuk S.P., Sopel M.F. Smart-monitoring of electrical power systems. *Tekhnichna Elektrodynamika*. 2024. No 5. Pp. 48–62. (Ukr) DOI: https://doi.org/10.15407/techned2024.05.048
3. Steinmetz C. P., Theory and calculation of alternating current phenomena*, vol. 4: McGraw-Hill Book Company, Inc.*, 1916. https://archive.org/details/theorycalculation00steirich/page/6/mode/2up
4. IEEE 1344-1995 IEEE Standard for Synchrophasors for Power Systems https://ieeexplore.ieee.org/document/8684605/amendments#amendments
5. IEEE C37.118.1-2011 IEEE Standard for Synchrophasor Measurements for Power Systems https://ieeexplore.ieee.org/document/6111219
6. Phadke A. Synchronized phasor measurements in power systems. *IEEE, Computer Applications in Power*, 1993. Vol. 6. Pp. 10–15. https://ieeexplore.ieee.org/document/207465

7. IEC 61850-9-2:2011 Communication networks and systems for power utility automation - Part 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3 https://webstore.iec.ch/en/publication/6023
8. Denysiuk S.P., Sopel M.F., Spodynskyi O.V., Dovhodko Y.M. Synchrophasors in Modern Power Systems: Definition, Measurement, and WAMS Architecture. *Scientific bulletin of Tavria State Agrotechnological University*, 2025. Vol. 15, No. 2 T. 15(2). Pp. 181–187. DOI: https://doi.org/10.32782/2220-8674-2025-15-2-21
9. Bielokha H.S., Denysiuk S.P., Derevianko D.H., Zhuikov V.Y., Sopel M.F., Spodynskyi O.V. SMART Monitoring of the Operational Efficiency of Local Electric Power Systems. Odesa: Galvetika Publishing House, 2025. 280 p.
10. Blinov I.V., Denysiuk S.P., Lezhniuk P.D., Ushchapovskyi K.V., Slobodian R.O., Kozachuk O.I., Miroshnyk V.O., Spodynskyi O.V. Digital Transformation of the Electric Power Industry of Ukraine: Implementation under Martial Law and Post-War Recovery. Odesa: Galvetika Publishing House, 2024. 362 p.

ОЦІНКА ВПЛИВУ СУМАРНОЇ ВЕКТОРНОЇ ПОХИБКИ ТА ПРОБЛЕМ СИНХРОНІЗАЦІЇ ЧАСУ НА ФУНКЦІОНУВАННЯ ШИРОКОМАСШТАБНИХ СИСТЕМ МОНІТОРИНГУ ЕНЕРГОСИСТЕМ

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У статті виконано оцінку сумарної векторної похибки TVE (Total Vector Error) розрахункового фазора в різних середовищах доступу локальних обчислювальних мереж, визначених у стандарті IEEE C37.118.1-2011. Досліджено критичну роль точної синхронізації часу для технології синхрофазорів. Фазори, синхронізовані з абсолютним часом, є основою для блоків вимірювання фазорів PMU (Phasor Measurement Unit), які використовуються для моніторингу енергосистеми. Оцінка TVE була проведена для трьох моделей локальних мереж: CSMA/CD, CSMA/AMP та комутованого Ethernet з урахуванням стандартизованих значень пропускної здатності BW (Bandwidth) *мережі 0,1, 1 та 10 Гбіт/с відповідно до стандарту IEC 61850-9-2:2011, а також кількості вузлів. Проаналізовано вплив похибок вимірювальних каналів і похибок PMU на продуктивність критично важливих застосувань широкомасштабної системи моніторингу WAMS (Wide Area Monitoring System), таких як локалізація порушень, виявлення коливань та динамічна оцінка пропускної здатності ліній DLR (Dynamic Line Rating). Результати аналізу демонструють, що TVE є чутливою до типу локальних обчислювальних мереж та кількості вузлів, а точність синхронізації часу залишається значною проблемою, що впливає на надійність застосувань WAMS.* Бібл. 10.

Ключові слова: фазор, енергосистема, локальна мережа, сумарна векторна похибка, синхронізація часу, PMU, WAMS.

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