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IMPROVING THE RESILIENCE OF SYNCHROINFORMATION SYSTEMS OF SMART POWER GRIDS AND MOBILE COMMUNICATIONS NETWORKS UNDER WARTIME CONDITIONS

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The use of synchrophasors (μPMUs) for performing synchronized vector measurements in distribution electric power systems integrated with renewable energy networks is analyzed. This approach enables real-time monitoring and feedback on operational parameters, thereby allowing for timely detection of islanded networks, improved reliability, and enhanced energy efficiency. We propose an intelligent computer-integrated system that provides continuous multichannel monitoring of synchronization parameters in real-time and generation of synchronization signals for synchrophasors in intelligent electrical systems and mobile communication means with increased reliability. To generate synchronization signals with increased resilience in war conditions, it is recommended to use special GNSS radio receivers, which should be developed with a focus on resilience, to unintentional failures and targeted attacks, as well as technologies of hybrid synthesis of synchronization signals and additional methods of synchronization signal sources' reservation. The current publication addresses the issues of measuring, monitoring and digital data processing, redundancy of reference synchronization sources, and diversifying the processes of providing synchroni-zation signals for smart grids and mobile communications networks. The created automated computer-integrated system for multi-channel monitoring of synchronization signals aggregates digital data obtained from the software and hardware tools of various manufacturers and ensures prompt and reliable diagnostics of a status of the synchronization network both in normal operation mode and in emergency situations. The placement of synchronization devices will be planned taking into consideration geographical aspects, regional features, possible replacement of satellite radionavigation systems, and the use of a greater number of primary synchronization sources. The publication presents an analysis of the results of the procedure for switching over to backup source (alternative priority) in case of emergencies. Reference 28, fig. 2.

Keywords: *intelligent electrical grid, renewable energy networks, mobile communications, signal synchronization, measurement, multichannel monitoring, computer-integrated system, resilience, war.*

ПІДВИЩЕННЯ ВІДМОВОСТІЙКОСТІ СИНХРОІНФОРМАЦІЙНИХ СИСТЕМ ІНТЕЛЕКТУАЛЬНИХ ЕНЕРГЕТИЧНИХ МЕРЕЖ ТА МЕРЕЖ МОБІЛЬНОГО ЗВ'ЯЗКУ В УМОВАХ ВІЙСЬКОВОГО ЧАСУ

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Проаналізовано використання синхрофазорів (μPMU) для виконання синхронізованих векторних вимірювань у розподільчих електроенергетичних системах, інтегрованих *з мережами відновлюваної енергії. Такий підхід дозволяє здійснювати моніторинг у режимі реального часу та зворотний зв`язок щодо робочих параметрів, що дозволяє своєчасно виявляти ізольовані мережі, підвищувати надійність та енергоефективність. Пропонується інтелектуальна комп`ютерно-інтегрована система, яка забезпечує безперервний багатоканальний моніторинг параметрів синхронізації в режимі реального часу та генерацію сигналів синхронізації для синхрофазорів в інтелектуальних електричних системах та засобах мобільного зв`язку з підвищеною надійністю. Для генерації сигналів синхронізації з підвищеною відмовостійкістю у воєнних умовах рекомендується використовувати спеціальні радіоприймачі GNSS, які повинні розроблятися з акцентом на стійкість до ненавмисних збоїв та цілеспрямованих атак, а також технології гібридного синтезу сигналів синхронізації та додаткові методи резервування джерел сигналів синхронізації. У цій публікації розглядаються питання вимірювання, моніторингу та цифрової обробки даних, резервування опорних джерел синхронізації та диверсифікації процесів забезпечення сигналів синхронізації для інтелектуальних мереж та мереж мобільного зв`язку. Створена автоматизована комп`ютерно-інтегрована система багатоканального моніторингу сигналів синхронізації агрегує цифрові дані, отримані від програмно-апаратних засобів різних виробників, і забезпечує оперативну та надійну діагностику стану мережі синхронізації як у нормальному режимі роботи, так і в аварійних ситуаціях. Розміщення пристроїв синхронізації планується з урахуванням географічних аспектів, регіональних особливостей, можливої заміни супутникових радіонавігаційних систем та використання більшої кількості первинних джерел синхронізації. У публікації представлено аналіз результатів процедури перемикання на резервне джерело (альтернативний пріоритет) у разі виникнення аварійних ситуацій. Посилань 28, рис. 2.*

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Ключові слова: *інтелектуальна електрична мережа, мережі відновлюваної енергії, мобільний зв’язок, синхронізація сигналів, вимірювання, багатоканальний моніторинг, комп'ютерно-інтегрована система, відмовостійкість, війна.*

1. Problems of improving the reliability of synchroinformation systems of critical infrastructure in emergencies

The operation of trunk, interstate, and distribution power grids, both in normal operation mode and in emergencies, is carried out by using an automated process control system (substations) based on the measurement results of operating parameters [1] performed by synchrophasors (PMU - Phasor Measurement Unit). The digital data received from the PMU measuring equipment installed at power grid substations is processed in real-time mode by a system of continuous measurement of the parameters and their recording – WAMS (Wide Area Monitoring System), which makes it possible to virtually display the key indicators in the form of vector diagrams of increased accuracy [2]. The use of the WAMS system increases the observability of the electric power grid, contributing to a clear detection of instability and disturbances [3].

The examples of practical implementation of the results of innovative research and the first applications of the solutions that served to transform power grids into very reliable and safe systems are given in a collective monograph (edited by Stuart Borlase) [4]. These solutions are based on improving grid controllability by creating a synchronized PMU infrastructure (NASPI or NASPInet). The monograph [4] states: “NASPI’s mission is to improve power system reliability and visibility by creating a robust, widely available and secure synchronized data measurement infrastructure for the interconnected North American electric power system with associated analysis and monitoring tools for better planning and operation, and improved reliability”.

In distribution power grids, the use of the technology of synchronous vector measurements by PMU is complicated due to a large number of nodes, short distances, small differences in amplitudes and angles between the nodes, faster dynamics, and a lack of standard documentation. These difficulties have led to the development of new high-precision measurement systems, the so-called microphasor measurement units (µPMU) or distribution-level PMUs (D-PMUs) [5]. These devices can measure synchronized voltage and current vectors (both amplitude and phase) in real time with higher resolution and accuracy. The high accuracy and sampling rate of µPMU measurements make it possible to use them to detect MicroGrid islands and improve grid stability by using the proposed intelligent algorithms [6]. The use of microPMU devices in distribution networks is considered by scientists from the Faculty of Electrical Engineering at Sonsil University (Seoul, Korea) [7]. In particular, it is noted that taking into account the price indicators of PMU equipment, they were used mainly on trunk networks. Attention is focused on the use of μPMU devices in distribution networks with renewable energy sources, which ensures increased reliability and resilience of networks, cost savings, and environmental and political benefits. The authors of the article [7] conclude that the use of μPMU is important in power distribution systems integrating networks with renewable energy sources.

The results of a comprehensive study of modern μPMU technology [8] confirmed its effectiveness. The authors of the article [8] note that with the increasing penetration of renewable energy sources, which are controversial in nature, it is necessary to have the hardware and software that can monitor and provide real-time feedback on the operating parameters of electricity grids. These parameters can maintain the stability of electricity production and that of the grid. In the article [8], scientists from India conclude that it is necessary to create a relevant unit that would not only increase the efficiency of the practice of using μPMU technologies but also raise the automation of all aspects of electricity generation, transmission, and distribution to a new level [8].

In Ukraine, in 2021-2022, the National Energy Company Ukrenergo deployed the WAMS system with 24 PMUs at 20 substations, one NPP, and four substations of European operators and piloted the Inertia Monitoring Application [3]. The presentation [3], delivered at the RSA 2024 conference (RSA Conference is a state-owned company, one of the largest system operators in Europe), also notes that it was planned to install additional PMUs at 25 Ukrenergo substations and connect generating capacities in the future. Implementing the WAMS system with PMU measuring equipment is one of the key elements of reaching the dispatch control level that would meet European standards and synchronizing the Ukrainian Power System with the European ENTSO-E [2].

The analysis of the conducted studies makes it possible to assert a tendency to expand the use of synchronous vector measurement technology at various power facilities and increase the number of PMU equipment, along with putting stricter requirements to the same [3-8]. To meet the requirements for generating discrete time instants at which synchronized measurements of voltage and current phasors are performed, dedicated synchronization devices, synchronization networks, and computer-integrated systems are used. It is crucial to carry out simultaneous, specified at the corresponding discrete time instants, i.e. synchronized, vector measurements in PMU equipment that is geographically distributed across power facilities. The problem of determining discrete time instants at each site where the PMU equipment was installed, is solved by using synchronization signals, which essentially make it possible to resolve time uncertainties [1, 4, 9-15]. The international standards IEEE C37.118.1-2011, IEEE C37.118.2-2011 define an accuracy of ±1 microsecond for synchronization signals in synchronized vector measurements with PMU equipment. If the time parameters of synchronization signals deteriorate, the technical performance of both control systems and, accordingly, the intelligent electric power grids they control will be degraded. This dependence affects the energy supply and energy efficiency, which necessitates the use of modern time synchronization devices along with high-quality tools for monitoring the parameters of the synchronization signals they generate [9-15].

The problem of high-quality and reliable provision of PMU equipment with time synchronization signals for measuring voltage values and shapes of the signals in real time has been studied by foreign and domestic experts. For example, the results of the Synchrophasor technology research, which was conducted by NASPI (North American Synchrophasor Initiative) members and is based on the use of time synchronization signals generated from the data of the global positioning system (GPS) in PMU equipment, are presented in publications [12, 13]. The approaches to using Synchrophasor technology in power supply systems using time synchronization signals to synchronize geographically distributed elements of power supply systems are proposed, and the basic requirements for synchronization processes are formulated. Practical recommendations have been developed within the framework of Synchrophasor technology to ensure the required measurement accuracy, stability, and reliability of the measuring instruments, overall safety in the use of power supply systems, compliance with existing standards, cost optimization, nomenclature of software products for the implementation of this technology [12, 13].

It is important that the common method of using Global Navigation Satellite Systems (GNSS) radio receivers as the sources of positioning, navigation and time (PNT) information to generate time synchronization signals, which solves the accuracy problem for many critical infrastructure tasks, cannot always provide the required reliability. This method of generating time synchronization signals has a significant drawback that is a significant dependence on the characteristics of the open radio signal propagation environment. The analysis of the studies confirms the presence of this dependence and determines its impact on the synchronization systems of critical infrastructure [16-19].

An assessment of the dependencies of critical infrastructure's synchronization systems in the financial and telecommunications industries of the United States in case of a GPS failure is presented in [17]. The emphasis is placed on the dependence of critical infrastructure systems, which often cannot function properly without accurate time signals, and timing system failures can have serious consequences with potential threats, including economic losses, reduced security, and loss of human life.

The publication [14] discusses the results that the IEEE P1952 working group used to develop “voluntary” standards based on the use of GPS and other global navigation satellite systems (GNSS) for the widespread implementation of positioning, navigation, and timing (PNT) services at critical infrastructure facilities in many high-tech sectors of the economy, including power grids and telecommunications infrastructure. The comprehensive, cybersecurity-based approach to PNT resilience proposed in the publication, without providing specific implementation examples, is intended to ensure the widespread application of the Resilient PNT Conformance Framework, which is focused on achieving the final result. This approach should, in the long run, reduce the vulnerability of PNT user devices (UEs) that were not designed with a focus on resilience to unintentional failures and targeted attacks [14].

In Ukraine, the issues of highly reliable provision of synchroinformation signals to the generating capacities of intelligent electric power grids, as well as to consumers in other sectors of the economy, were considered through the creation of a unified national synchroinformation system [16]. In today's conditions, the practical implementation of the full-scale unified national system, both within the country's borders and in the areas of use, is complicated. Analysis of the domestic publications suggests that it is problematic to create even a separate synchronization complex based on a network of NTP and PTP servers with master servers synchronized with UTC(UA), the national time standard of Ukraine, which was supposed to be an alternative to the GPS synchronization. This situation occurred even though the National Research Center “Institute of Metrology” formulated “requirements for serious reorganization and organizational measures” in order to create a synchronization complex “as an alternative to GPS synchronization - the best way to develop the Time and Frequency Service” [20]. Instead, the results of the development and trial operation of a “subsystem for providing uniform time to military consumers, which is based on the national standard of time and frequency units, the original standard of time and frequency units of the Armed Force of Ukraine with the use of precision time servers and fiber-optic technologies for the transmission of time synchronization signals via PTP and NTP protocols over the packet data networks - Ethernet” confirmed the possibility of transmitting the reference time and frequency synchronization signals [21].

Significant and effective results have been obtained by domestic specialists in solving the problems of providing synchronization information for cellular communication means [10, 22]. The 2G/GSM, 3G and 4G/LTE mobile communication technologies introduced in Ukraine are provided with synchronization information transmitted by appropriate signals. Highly stable generators, synchronization devices, telecommunication channels, and special control and measuring equipment are used to generate synchronization signals [10, 22]. A set of elements and links between them form an integral structure, i.e. synchronization system, which, thanks to synchronization information, provides a solution to temporal uncertainty in geographically distributed devices. To ensure the possibility of generating synchronization signals with unified indicators and provision of quality mobile communication services in war conditions, the measures to back up the synchronization network have been taken [10, 22]. Thus, domestic specialists, in war conditions, and in other emergency and abnormal situations, have accumulated practical experience in the design and operation of synchronous systems of cellular communication.

The positive experience gained in the creation of synchroinformation systems of various telecommunication means in Ukraine [9-11, 16, 22] is recommended to be used in the process of developing the measures to improve the stability and reliability of intelligent electric power grids. It should be taken into account that after the transition and further synchronous operation of the IPS of Ukraine with ENTSO-E, the functioning of intelligent electric power grids is directly related to the quality indicators of time synchronization signals (accuracy, stability) and reliability of the information transmitted by them [3, 9-11, 16]. According to the NPC standard 20.261:2021 “Technical Policy of NPC Ukrenergo in the Development and Operation of Trunk and Interstate Power Grids”, time synchronization should be implemented both at substations with outdated equipment and at new substations [23]. Also, a similar time synchronization should be performed in the automated process control systems of 220-750 kV substations of the IPS of Ukraine.

Taking into account the fact that in war conditions, and other emergency and abnormal situations, the likelihood of impact on time synchronization signals increases significantly, additional organizational and technical measures are needed. One of such measures may be the use of special GNSS radio receivers proposed by the developers of “voluntary” standards, which should be designed with a focus on resilience and may be more resistant to unintentional failures and targeted attacks [14].

In order to increase resilience of the synchronous information system for intelligent electric power grid, which is very important in war conditions, it is proposed to use a device for multichannel monitoring of synchronous information, a smart system for collecting and processing monitoring data, and a device for hybrid synthesis of synchronous signals in the system structure (Fig. 1). The proposed structure of the synchroinformation system will make it possible to diversify synchronous information support and create an intelligent computer-integrated system for multichannel monitoring of synchronization signal parameters. The intelligent computer-integrated system will provide simultaneous monitoring of several such signals, viewing of measurement data, their recording on storage devices and generation of information to support decision-making in order to increase the reliability of synchronization information of the intelligent electric power grid.

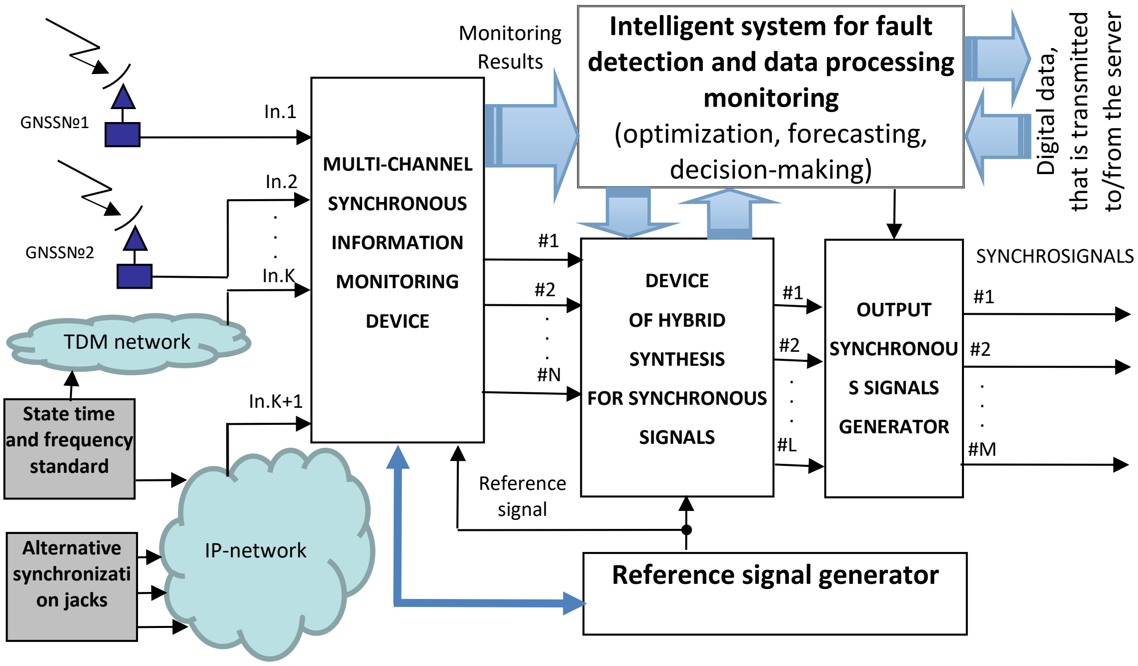

Fig. 1. Structure of the synchroinformation system for intelligent electric power grid

2. Results of the development and implementation of measures to improve the reliability of synchronization system in the cellular network in war conditions

The next stage in mobile communication development, which is 4G/LTE Advance and 5G technologies, requires synchronization of signals with increased accuracy (up to one nanosecond instead of one microsecond) and requires a reduction in network delays (up to microseconds instead of milliseconds) with an increase in the number of synchronization units in the network [22].

The most advanced synchronization networks today are those that provide a reference frequency and accurate time to 2G/3G/LTE mobile base stations. Frequency synchronization (synchronization, i.e. frequency or clock synchronization) is a remote comparison of clocks using the PTP (Precision Time Protocol) protocol in a packet network in combination with differentiation of time errors [22, 24-26].

Asynchronous data transmission methods and technology protocols have led to the introduction of new stability parameters of synchronization signals that enable the evaluation of stability quality in a packet environment. Measurements in the packet environment are based on the data calculation required not only to evaluate the accuracy of time verification and frequency stability, but also to evaluate such network parameters as two-way and one-way packet delay, as well as PDV (Packet Delay Variation) [22, 24].

With the move to IP/MPLS packet networks, synchronization methods have also changed radically, with new types of reference signal transport, new protocols, new types of synchronization equipment, and even new stability parameters for evaluating reference signals and synchronization equipment.

In the development process of synchronization network based on the PTP protocol, the following factors that ensure the quality and reliability of this network were identified: planning the placement of top-level PTP servers that is primary clocks (GrandMaster); ensuring the necessary reservation (both on the hardware level of the PTP server and in the network); as well as conducting monitoring measurements of stability parameters. To organize the planning of PTP synchronization network, it is necessary to consider the requirements of ITU-T G.8261.1 Recommendation [27] in terms of the number of retransmissions. The maximum number of retransmissions can be up to five or up to ten, depending on the selected switching principle on IP/MPLS routers [22, 24]. The second limiting factor is the number of base stations served (actually PTP clients or "ordinary clocks") by one PTP server. As a rule, available PTP servers can provide the proper quality for up to 1,000 PTP clients (depending on the manufacturer) [22]. However, a PTP server should never be loaded to its maximum capacity, as in this case network redundancy becomes more difficult to implement. Network redundancy refers to the capability of servicing the PTP clients of one PTP server by neighboring ones in case of an emergency [16, 22, 24]. Thus, a rational solution assumes planning of PTP servers to operate at 50% load (usually up to 500 base stations/PTP clients per PTP server). The experience of PTP technology implementation shows that for small neighboring regions of Ukraine one PTP server is sufficient, for larger regions – two, and for the largest ones (including a city with over one million inhabitants) – four. This allows for providing backup sources from neighboring regions. It should also be noted that PTP servers themselves must have hardware-level redundancy: two power supplies, two high-stab-ility oscillators (Rb or OCXO), two GNSS receivers (GPS/GLONSS/Galileo/BeiDou) or one GNSS receiver plus an external input of 2MHz/1E1 synchronization reference signal from a classic TDM synchronization network (with cesium primary reference sources and GNSS backup) [15]. This will ensure high-quality reference signals for quite a long time.

Planning and redundancy considerations for a PTP synchronization network to support 4G/LTE and 5G mobile communication are generally similar to the previously developed principles. However, there are several significant differences. According to ITU-T G.8275.1/ G.8275.2 Recommendations [28], phase synchronization and microsecond accuracy must be ensured at each base station. To achieve this, the required accuracy must be delivered directly to the base station. This is possible when using an additional equipment known as "boundary clock" (BC). BCs are placed between PTP servers and PTP clients. Each region will require from two to five BCs (depending on the number of base stations in the region). Also, 4G/LTE and 5G technologies will require updating a software of the existing PTP servers and improving of their primary accuracy. This will be achieved by installing a new PRTC (Primary Reference Time Clock) – a version of PRC for IP network and phase synchronization, as specified in ITU-T G.8272.1 Recommendation. The projected number of PRTCs for Ukrainian networks is between three and five units per operator, located in different regions. Furthermore, when planning a PTP synchronization network, it is necessary to take into account both the unicast (G.8275.2) [28] and multicast (G.8275.1) operation modes of the phase synchronization equipment.

The indicated functioning dependence of the complex of high-tech facilities on synchronous information necessitates the development and implementation of modern means for measuring the quality of synchronization signals, as well as the creation of an automated computer-integrated system with machine intelligence (computational, artificial), which will ensure the possibility of effective implementation of the multichannel monitoring technology of synchronization devices geographically distributed over the network objects [15, 16].

To ensure uninterrupted operation of synchroinformation systems in war conditions, the planning of synchronization network must take into account certain criteria, must include the redundancy for reference sources of synchronization signals and the appropriate switching over to the redundancy in case of an emergency and network overload due to the traffic. This mode of network operation is classified as an intensive operation mode. It is also necessary to continuously monitor (measure) stability parameters of synchronization signals in the network in intensive operation mode for a timely assessment of the performance of the network and synchronization equipment, and for adequate response to emergencies . In addition, it is necessary to have backup sources of synchronization reference signals in case of prolonged absence of signals from GNSS radio navigation systems [15]. For GNSS backup, precessionary cesium oscillators are the most appropriate. For multicast mode, in this case, a long-term phase storage functionality is required. Such devices are already available from vendors. The technology of multi-channel monitoring is not an alternative to the existing synchronization measuring tools, which may be from different manufacturers and of different generations; on the contrary, it performs an integration function, at least in the information and analytical sense. It is recommended to use the measurement functions of the synchronization devices operating on the network through the existing control systems of these devices. Given the above, an automated computer-integrated system for multi-channel monitoring of synchronization signals is hardware and software that combines the measurement capabilities of equipment from different manufacturers in a single user interface. The software must perform the functions of collecting, storing and subsequently processing the measurement results of synchronization signal parameters. Such a monitoring system is used, for example, in the "Kyivstar" network.

The software receives current measurement data from the existing synchronization devices and from the multi-channel control units. The server part of the software must be deployed on a dedicated server. Operators have access to the server part (each under their own account) and can process and compare the measurement results with other similar results by using the user's software. Therefore, the software must include: a "Server part", a "User part", a "Database". The delay deviation parameters of PDV (Packet Delay Variation) and TIE (Time Interval Error) are measured directly at the sites where synchronization devices are installed (the measurement intervals and the presence or absence of both parameters among the received data depend on the equipment settings). Based on the measurement results, it is possible to calculate the following stability parameters of the synchronization equipment: MTIE (Maximum Time Interval Error), TDEV (Time Deviation) – derived from TIE and MAFE (Maximum Average Frequency Error) – derived from PDV (it is possible to expand this list by adding other stability parameters as additional ones).

It is necessary to provide the server parameters needed for installing the "Server Component" software. The server must run Windows OS (a UNIX-like OS is acceptable if a part of the user's software can run under Windows OS). The interaction between the server component and the equipment of the multi-channel monitoring system occurs via IP within the limits determined by the available information about this equipment, with no restrictions for the developer based on data exchange and management protocols. It is important that the "Server Component" software must not be able to interact with the public Internet for information security reasons.

The "Database" software provides the capability to store the results of continuous measurements of TIE and PDV parameters and the results of MTIE, TDEV, MAFE calculations in a digital data format. The data is stored as separate files in graphical or text format. The database can be integrated with the "Server Component" software.

The structure of the automated computer-integrated system of multichannel monitoring of synchronization signals is shown in Fig. 2.

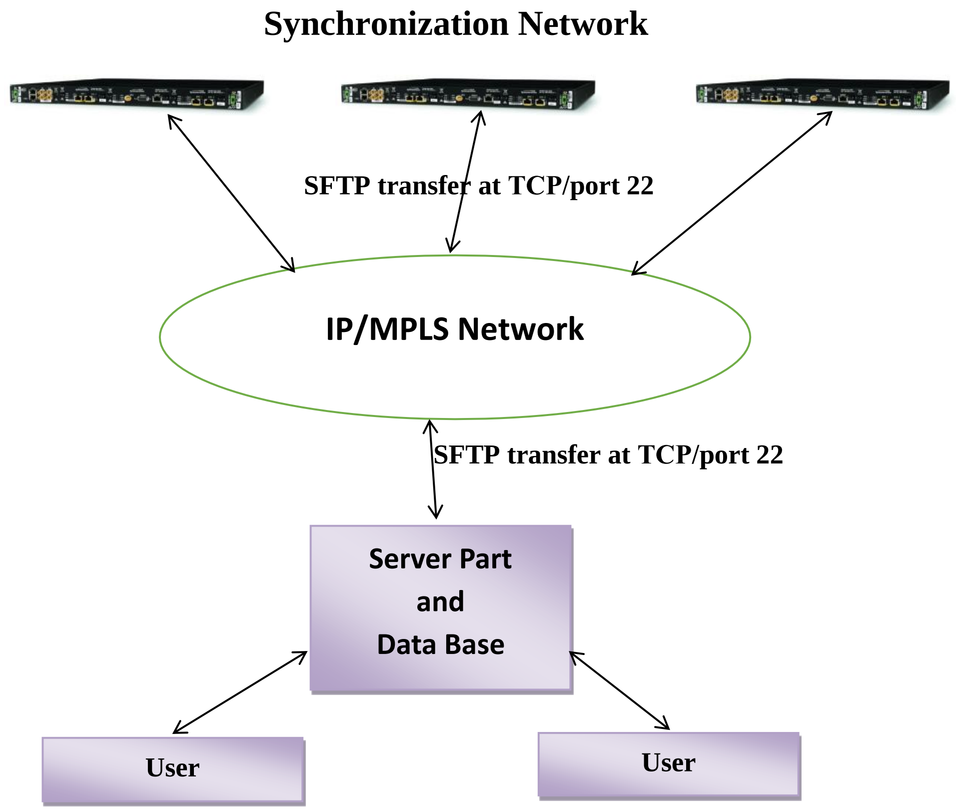

Fig. 2. Structure of the automated computer-integrated system of multichannel monitoring of synchronization signals

3. Conclusions

Smart power grids integrating networks with renewable energy sources, as well as mobile communication systems, which, under wartime conditions, cannot function properly without precise time signals, require the use of additional methods and technical means. Under such conditions, the quality of time signals can be improved by increasing the resilience of synchronization systems that generate them.

The analysis of the operation of signal synchronization systems in smart power grids has confirmed the trend of expanding the use of PMU-based synchronized phasor measurement technology of in transmission, interconnection and distribution power grids integrating renewable energy sources, which necessitates the implementation of organizational and technical changes to meet the requirements for generating time synchronization signals.

It is proposed to use GNSS radio receivers (designed with priority on resilience), synchronization networks, and synchroinformation systems in the structure of a smart power grid integrating networks with renewable energy sources to address the resilience problem in time synchronization signals, taking into account not only current conditions but also the post-war state.

The publication presents the structure of synchroinformation system for a smart power grid, the purpose of which is to generate time synchronization signals with enhanced fault tolerance. The system includes external sources of synchroinformation, as well as equipment installed at power facilities (devices for multichannel monitoring and hybrid synthesis of synchronization signals, generators of reference output synchronization signals, intelligent systems for monitoring data collection and processing).

It is proposed to use additional methods for redundancy of time synchronization signal sources. Based on the results of research and operational experience in the digital network of a telecommunications operator, these methods have demonstrated their effectiveness, ensuring improved resilience of mobile communications under wartime conditions.

Using mobile communications as an example, the principles of synchronization network redundancy are presented. The key stability parameters that need to be measured and monitored in case of emergencies are identified. Requirements have been developed for the software, and a description is provided of an intelligent computer-integrated system that ensures continuous multichannel real-time monitoring of synchronization signal parameters and the generation of synchronization signals with enhanced stability.It is proposed to carry out a scheduled distribution of synchronization devices taking into account geographical aspects, regional characteristics, possible replacement of satellite radio navigation systems, and the use of a larger number of primary synchronization sources.

It is worth emphasizing that the developed and implemented automated computer-integrated multi-channel system for monitoring of synchronization signals, mentioned in the current publication, has improved the reliability of the mobile communications network of one mobile operator both in normal operation mode and in wartime. Therefore, the proposed organizational and technical measures to increase resilience ensure the generation of synchronous signals with improved quality parameters. They can be recommended for continuous monitoring of synchronous information parameters in real time at facilities across various sectors of the national economy as well as for improving the defense capability and security of the state.

The work was carried out under the budgetary theme "Scientific and technical principles of restoration and controllability of the power system of Ukraine in the post-war period under synchronous operation with the European Network of Transmission System Operators for Electricity (ENTSO-E)» (КПКВК 6541030).

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