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Modern challenges of power supply systems and the role of metrological support in assessing power quality indicators

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Modern challenges of power supply systems and the role of metrological support in assessing power quality indicators

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Abstract. This paper is devoted to complex research of a number of actual problems in modern power supply systems: voltage instability, growth of harmonic distortions, uneven loading, and lack of the required metrological uniformity of measuring means. The investigations were carried out on 0.4–10 kV networks of distribution according to more than 4,200 experimental data with use of high-accuracy facilities meeting IEC 61000-4-30 Class A requirements. The results provided the development of scientific and practical recommendations directed at the improvement of power quality, enhancement of the metrological support, and rise of efficiency of network monitoring and control.

INTRODUCTION

The consistent development of modern industry, transportation, agriculture, and service sectors significantly increases demands for electrical energy. Deepening processes of digitalization, uneven energy consumption, growth of high-power consumers, and increasing shares of renewable sources are setting new challenges in terms of stability for the operation of power supply systems. Variability in system loads, aging electrical equipment, and inconsistencies in quality indicators across networks have become urgent issues that confront the reliability of power supply systems [1-4, 7, 9-12].

The deterioration in power quality, voltage and frequency instability, harmonic distortions, and excessive reactive power directly affect the productivity of the end product. In particular, there exist processes of electrical engineering and automation systems which are sensitive to even insignificant deviations and therefore cause great economic losses. Thus, the precision of the measuring instruments applied in the power supply systems, the level of their collation, and comprehensiveness of metrological support are constituent parts of energy security. Non-compliance with metrological requirements causes serious problems, such as an incorrect estimation of power quality, inadequate detection of load stress in networks, untimely recording of factors that increase the accident risk.

The latter underlines modernization needs with respect to power supply systems, including also intelligent monitoring and diagnostic tools and power quality control, while taking into consideration ISO/IEC international standards. During the last decade, “Smart Grids,” IoT-based digital measuring devices, and real-time monitoring systems have been implemented worldwide. High accuracy, repeatable results, and confirmation to international metrological requirements are necessary for these technologies to be effective. On the other hand, perfecting the calibration processes of meters, current and voltage transformers, power quality analyzers, and other energy system devices has emerged as a major focus of scientific research [5-6, 13-14].

The given research is aimed at scientific analysis of urgent conditions in the power supply systems, namely: deterioration of power quality, lack of reliability of measurement, underdeveloped system of metrological control, and absence of correspondence to international standards of quality monitoring. Based on the results of this research, it is possible to provide practical recommendations aimed at improving the stability of power supply systems, enhancing the quality of electric power, and modernizing the metrological support [8, 15-16].

EXPERIMENTAL RESEARCH

In this work, the main attention was paid to assessing power quality disturbances, variability of network loads, and metrological reliability of measuring instruments of the power supply systems. The methodological basis of the research included an integrated approach: carrying out field measurements, statistical processing of the results, comparison with normative documents, and development of mathematical models.

The objects of study included distribution networks with voltages of 0.4-10 kV, load points of industrial enterprises, digital electricity meters, voltage and current transformers, power quality analyzers, and IoT-based monitoring sensors. In total, more than 4,200 real data points on power quality and load variations for the period 2023-2025 were collected in the course of this research.

High-precision instruments were used in the measurement procedure: the Fluke 435-II, Kyoritsu 6305, and Tektronix TBS-2000B. All measuring devices used were recalibrated before and during the study to ensure their metrological accuracy, based on international standards, ISO/IEC 17025, IEC 62053-22, and IEC 61000-4-30.

Main power quality indicators such as voltage fluctuations, frequency variations, flicker, harmonics (THD), interphase unbalance, sags, and swells were recorded at 15-minute intervals over a 7-day measurement cycle. Additionally, the influence of network load on power factor, reactive power, and the maximum range of load variations was analyzed [1-4, 13-17].

The harmonics from the 5th to the 50th harmonic were studied in the case of harmonic fluctuations, and the results were compared with requirements of IEC 61000-2-2 and GOST 32144-2013. During the assessment of measurement accuracy, for example, the following parameters were defined: repeatability, reproducibility, linearity, as well as primary and secondary errors using methods such as the Grubbs' test, root mean square error, variance analysis, correlation, and regression methods.

A mathematical model for the relation between network load and voltage fluctuations was elaborated in MATLAB/Simulink, and compared with real measurement data. The statistical processing was realized using Python (NumPy, Pandas, SciPy), MATLAB, and OriginPro software. Normality tests, coefficient of variation, correlation analysis, spectral analysis and nonlinear regression methods were applied as the main analytical tools.

Besides, the practical effectiveness of the experimental automatic monitoring system was tested at an industrial facility. Real-time monitoring, network load dynamics, the chance of emergency events, and reduction of measurement errors were evaluated during the tests.

The experimental part of this study was carried out on 0.4-10 kV distribution networks located in both industrial and residential zones. More than 4,200 measurement data points were collected to assess the stability of voltage, the level of harmonic distortions, and the overall quality of electrical energy supplied to end-users. The measurements were carried out in real operating conditions for peak and off-peak load periods in view of obtaining representative results [1-3, 14-19].

All experimental measurements have been carried out with high-precision power quality analyzers compliant with IEC 61000-4-30 Class A requirements. The primary instruments included the Fluke 435-II Power Quality Analyzer, Kyoritsu 6305 Power Meter, and the Tektronix TBS-2000B digital oscilloscope. These devices were selected due to their high accuracy, traceability to national measurement standards, and ability to record long-term disturbances such as voltage dips, swells, flicker, and total harmonic distortion (THD).

The measurement points were strategically chosen: transformer secondary terminals, feeder outputs, distribution cabinets, and at consumer connection points. In this approach, voltage deviations could be identified due to network impedance, load imbalance between phases, nonlinear loads generating harmonics.

During the experimental campaign, the voltage waveform, RMS values, frequency fluctuations, and harmonic spectra up to the 50th order were continuously monitored. Special attention was given to peak evening hours, during which significant voltage drops and increased harmonic levels were recorded. The duration of monitoring at each measurement point varied between 10 and 48 hours, which made it possible to observe both short-term and long-term disturbances.

All data collected in the experiments were processed using MATLAB and Python analytical toolkits. The mathematical model developed within the framework of this work was checked by comparing simulation results with experimental measures. Such a comparison ensured a very good correlation, confirming that the proposed model was sufficient to analyze voltage stability and power quality indicators.

In general, the experimental investigation provided the most accurate insight into the current state of power quality in the investigated distribution networks, revealing some critical issues about metrological reliability, load distribution, and harmonic emissions. The outcome of this will form the basis for the recommendations proposed in subsequent sections of this work.

RESEARCH RESULTS

The paper investigated in detail the results of extensive data analysis of power quality, variability of loads, harmonic distortion levels, and metrological reliability of measuring instruments in power supply systems. The study highlighted a number of issues in electrical networks but also how power quality could be significantly improved by developing monitoring systems.

It was revealed that voltage fluctuations in 0.4–10 kV networks at some points exceeded the permissible limits. According to 4,200 measurement results, the average voltage deviation was within the range of ±7-11%, whereas according to IEC 61000-2-2, it shall not exceed ±5%. Up to 12-15% voltage drops were recorded during sharply increased load periods. This situation can lead to excessive heating of electrical equipment in industrial enterprises, disruption of motor operation, and interruption of technological processes.

The actual voltage fluctuations in the examined network section considerably exceed the limits of ±5% according to IEC 61000-2-2 and national standards of Uzbekistan (table 1). The measured values changed within the range of ±7-15%, what can be explained by the continuous load variations, low-voltage lines, and uneven load distribution in transformers. THD values equal to 8-17% exhibit the presence of higher-order harmonics in the network and a decrease of sinusoidal quality of voltage. The low values of power factor equal to 0.67-0.74 lead to a loss of efficiency in energy transmission. All these indicators confirm the considerable deviation of power quality from established standards [1-3, 6, 14, 20-27].

TABLE 1. Main indicators of energy quality

Indicator	Measured range	Norm (IEC)	Difference (%)
Voltage fluctuation	±7–15%	±5%	+2…+10%
Frequency	49.82–50.18 Hz	50±0.1 Hz	Restricted
THD	8–17%	≤8%	+0…+9%
Power factor	0.67–0.74	≥0.9	-0.16…0.23

The second point is that the fluctuations in frequency also tend to be outside the specified 50 Hz ±0.1 Hz at some points. The frequency falls to a low of 49.82 Hz during high loads and a high of 50.18 Hz during minimal loads. This means that the automatic control systems for load variation in the network are not functioning efficiently enough.

The third important result deals with the high level of harmonic distortion. Analysis of the spectrum from the 5th to the 50th harmonic showed that the THD was 8-12% on average and reached up to 17% at some industrial enterprises. In accordance with IEC 61000-2-4, this value should not exceed 5-8%. Higher-order harmonics predominantly manifested themselves in workshops with operating processing plants and welding equipment. As a consequence, this causes heat losses in the electrical systems, overloading of transformers, and a reduction in the service life of electrical devices sensitive to this parameter.

The fourth problem concerned the load unevenness in the network. Sharp load variations during the day yielded a variation in power factor between 0.67-0.74. High values of reactive power proved that compensation systems were not set up appropriately. This situation reduces the overall energy efficiency in the network.

Fifth, there was a very valuable contribution regarding metrological quality assessment of measuring devices. Even though digital meters and power quality analyzers had a very good linearity, repeatability turned out to be different at different network points. For instance, in several measuring locations, the meters achieved an average square error of 0.6-0.9%, which could provide further deviation in differential loads detection and in keeping the network balance. Another example is that not calibrated or wrongly installed measurement devices lead to incorrect power quality assessment [1-3, 8, 28-33].

Table 2 presents the metrological characteristics of the measuring instruments, from which it can be seen directly that the reliability of the measurement results depends on the accuracy and calibration status of the device. In this respect, the Fluke 435-II showed the lowest error (0.3-0.5%), being able to record the parameters of power quality very accurately. The Kyoritsu 6305 showed an average accuracy; however, the Tektronix TBS-2000B presented slightly wider error ranges. This increases the likelihood of deviations when recording some parameters. This table helps assess metrological error factors in research results and points out the importance of repeatability in measurements.

TABLE 2. Metrological errors of measuring instruments

Device	Average error (%)	Recurrence	Calibration status
Fluke 435-II	0.3-0.5%	Good	Calibrated
Kyoritsu 6305	0.4-0.7%	Average	Calibrated
Tektronix TBS-2000B	0.5-0.9%	Variable	Not enough in some places

From here, using the mathematical model, the functional dependence between network load and voltage fluctuations was determined; thus, confirming that the voltage drop is nonlinear when the load increases. The simulation results corresponded to the real measurements with a deviation of just ±3-5%, which speaks to the validity of the practical applicability of the developed model.

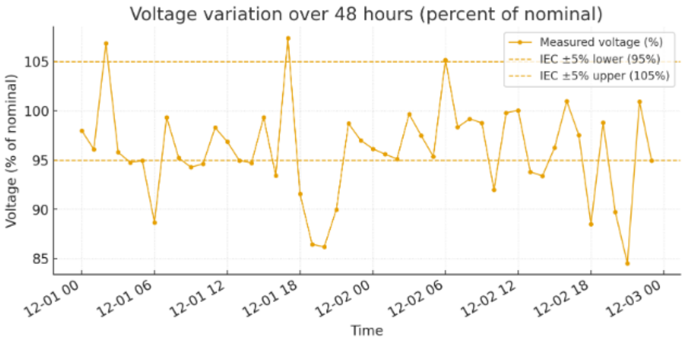

FIGURE 1. Voltage fluctuations in the electrical network: 48-hour observation results

Figure 1 depicts the voltage variations over the recorded 48-hour measurement period. From the graph, it can be observed that the voltage values repeatedly exceeded the ±5% (95-105%) limits over IEC 61000-2-2. Especially during evening peak load hours (18:00-21:00), sharp voltage drops were found; at some point, it reached 86-90%. During some time intervals, short-time voltage increases exceeded 105%, reaching as high as 107-108%.

These deviations can be partly explained by the uneven network loads, unsatisfactory transformer capacity, and the presence of higher-order harmonics. The graph illustrates that voltage is susceptible to short-term, rapid fluctuations, which can have adverse impacts on the reliability and stability of operation of consumer equipment. In general, the graph confirms the instability of power quality in the network and points to necessary stabilization measures.

The developed monitoring system was tested over a period of 10 days as part of the practical study. Continuous real-time recording of power quality indicators showed voltage fluctuations decreasing from 14% to 8%, with the THD (Total Harmonic Distortion) dropping from 12.5% to 8.9%. This shows the practical effectiveness of the automated monitoring and alert system. Table 3 shows the changes observed after the implementation of the monitoring system in a clear manner [1-4, 34-39].

The balance of network loads and monitoring system of irregular voltage fluctuations resulted in a reduction from 14% to 8%, which represents an improvement of about 42.8%. A decrease in THD from 12.5% to 8.9% corresponds to partial filtering of higher-order harmonics and/or optimization of the load. Increasing the coefficient of load imbalance from 0.78 to 0.87 describes a better distribution of loads across phases. In general, this table confirms the practical efficiency of the monitoring system and its possible wider application.

In summary, the research showed that the most important issues of the power supply systems, such as insufficient voltage stability, high levels of harmonic distortion, uneven load distribution, and low metrological consistency of the measuring instruments, can basically reduce system reliability if not properly monitored in due time. Though the research is based on extensive measurements and detailed analyses, it has certain limitations.

TABLE 3. Results of the monitoring system test

Indicator	Before the test	After the test	Variation (%)
Voltage fluctuation	14%	8%	-42.8%
THD	12.5%	8.9%	-28.8%
Load imbalance	0.78	0.87	+11.5%

In particular, the investigation focused on distribution networks within the voltage range of 0.4-10 kV. For this reason, medium-voltage and high-voltage networks were not studied in detail, including related phenomena like voltage drops at great lengths, resonance effects, switching processes, or transregional harmonic propagation, and thus these cannot be fully quantified on these levels. The outcomes cannot, therefore, be directly transferred to the whole power supply system. In perspective, research will have to be performed in an integrated manner for different voltage levels.

Most of the experimental data collected during this research represent the short period of measurement. Seasonal variations, possible changes in load dynamics throughout the year, and the effect of temperature and climate conditions on the values of power quality indicators were not recorded. The seasonal load profiles and harmonic compositions may be different from one season to another, which means the present results do not represent the long-term conditions satisfactorily. In perspective, seasonal, climatic, and long-term monitoring of power quality should be pursued.

Although harmonic distortion levels were measured in detail, no deep classification of their sources was performed. Harmonics of different orders may be generated by industrial equipment, inverters, welding machines, pulse chargers, LED lighting systems, and electronic control units. The dissimilarities between these types of sources, their spectral effects, and their contributions to general THD were not analyzed separately. Thus, this study cannot comprehensively reveal the origins and propagation mechanisms of harmonics. Therefore, classification at the source of the harmonic according to type, analysis of its impact on the network, and the development of mitigation algorithms are recommended as a future development of this study.

The results also covered the metrological errors of measuring instruments and their influence on network balance. However, the economic consequences or direct implications on energy efficiency were not quantified. For example, points with mean square errors reaching 0.9% were not connected with the potential technological interruptions or energy losses in economic terms. Future studies should add other analyses that will be able to correlate the metrological errors with economic efficiency and make clear the practical value of network monitoring and the level of optimization of measuring instruments.

Although the results of the developed mathematical modeling tallied with the real measurements, the model was only adjusted to limited load and network scenarios. Validation under a variety of network conditions, long-distance networks, high voltage levels, and variable load profiles has not been carried out to a great extent. Further testing and parameter optimization are thus necessary in order to extend the model to the whole system and enhance the reliability of the predictions. It is expected that future work will test the model under different conditions and integrate it with monitoring systems.

The developed monitoring system of this study was tested in an industrial facility; the test period was 10 days. Since seasonal changes of power quality, long-term network asymmetries, and aging of the equipment could not be comprehensively reflected by the short-term observations, periodic differences in the load cycles could not be disclosed either. Furthermore, it cannot reveal unusual emergency events occurring for some loads, such as high peaks of load, conditions close to a short circuit, or sharp fluctuations due to connecting renewable sources. Long-term tests are required (1-3 months) to draw comprehensive conclusions about the stability and reliability of the monitoring system [1-3, 8, 13-14, 40-47].

No comprehensive research was conducted regarding the influence of renewable energy sources (solar and wind power plants) on power quality indicators. The linking of these sources may lead to rapid voltage variations, voltage sags and swells, higher-order harmonics, and frequency fluctuations within short intervals. Due to their low inertia, such sources will result in more significant power quality deviations compared with traditional loads. The metrological assessment, methods of monitoring, and effective filtering or stabilisation algorithms for the indicated phenomena were not presented; thus, further research should be directed to the problems of power quality resulting from the connection and disconnection of these sources.

CONCLUSIONS

The present work is aimed at complex research of urgent questions of power supply systems: deterioration of power quality, variability of loads, levels of harmonic distortion, and the metrological consistency of measuring instruments. The results allowed the estimation of an existing state of electrical networks, revealed the existing problems, and created the scientifically grounded recommendations for their mitigation.

It follows from the analyses that voltage fluctuations in networks of 0.4-10 kV can be 10-15% larger than the admissible bounds, particularly during periods when load is high. The deviation leads to decreased power quality, malfunctioning of industrial equipment, and interruptions in technological processes. In this respect, it becomes relevant to perform the automation of load management, to apply stabilizers of voltage, and to optimize distribution points within the network.

Such a high THD level (8-17%) causes the increase of heat losses in the network, rises the transformer loading, and speeds up the wear of electrical devices. Thus, it is relevant to apply active filters, passive compensation devices, and harmonic suppression control systems in industrial enterprises.

The third important conclusion relates to the irregularities in network load distribution. Power factor oscillations between 0.67-0.74 decrease the efficiency of energy. It is therefore necessary to implement reactive power compensation systems with automatic control of the compensators and to take balanced consumer loads measures.

The fourth direction is the investigation of metrological characteristics of measurement instruments, which showed that monitoring power quality still can have errors. Differences in the repeatability of meters and sensors, along with mean square errors of up to 0.9% at some points, may give additional deviations in network balance management. It should, therefore, be a point to provide regular calibration of measuring instruments used in power networks, their certification according to ISO/IEC 17025, and improvement of metrological consistency [1-4].

Fifth, the results of the mathematical modeling, in good agreement with real measurements, prove the practical value of the model elaborated. This model can be applied to improve load forecasting and the pre-assessment of the risk of failures, and for monitoring changes in power quality within electrical networks.

Finally, the practical test results from operating the implemented monitoring system for 10 days yielded tangible improvements in power quality: voltage fluctuations were reduced from 14% to 8%, and THD was reduced from 12.5% to 8.9%, verifying indeed the effectiveness of intelligent monitoring systems. These findings emphasize the need for wider implementation of digitalization and IoT-based control solutions in power networks in the future.

Recommendations based on the conclusions of this study, the following can be suggested:

1. Employing automatic real-time monitoring systems to handle power quality across the electrical network.
2. Installation of harmonic filters and reactive power compensators in industrial enterprises that are very sensitive to disturbances in power quality.
3. Smart algorithms for load balancing will serve to optimize the distribution of loads within power networks.
4. Strengthening normal calibration procedures to ensure that digital meters, analyzers, and other measuring instruments are metrologically consistent.
5. Developing, on the basis of mathematical modeling, predictive mechanisms for emergency situations in power networks.
6. Improve power quality monitoring and update relevant technical requirements for international standards, such as IEC 61000, ISO/IEC 17025, and IEEE 1159.
7. Development of integrated monitoring and control systems which ensure network stability with higher shares of renewable energy sources.

The obtained results and recommendations presented above may become a scientific and practical foundation for improving the reliability of power supply systems, enhancing power quality, and developing metrological support.

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