ASSESSING AND PREDICTING THE QUALITY OF ELECTRIC POWER SYSTEMS BASED ON AN INTEGRAL CRITERION

A. F. Pashchenko and A. A. Tsvetkov

Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia

✉ a.paschenko@ipu.ru, ✉ tsvetkov-a@ipu.ru

Abstract. This paper considers the problem of assessing and predicting the quality of three-phase electric power systems by introducing an integral criterion. The criterion is based on applied and fundamental research in the field of modern power system management, conducted at the Center of Digital Solutions for Smart Grid, the Trapeznikov Institute of Control Sciences, the Russian Academy of Sciences. The integral assessment criterion is based on several key indicators: frequency deviation, slow voltage changes (in each phase), and the total harmonic distortion (in each phase). Practical results of applying this criterion are presented for the data collected in a real electric power system since 2021. The criterion expands the capabilities of assessing the quality of electric power systems compared to those accepted in the industry.

Keywords: electric power quality, integral assessment criterion, power system management, predictive modeling.

INTRODUCTION

Any modern organization is a power consumer, as it uses lighting, computing equipment, climate control systems, household appliances, etc. In turn, each consumer imposes certain requirements on power supply quality (permissible deviations in voltage and AC frequency, permissible harmonic components, etc.), which affects the reliability and performance of the equipment. Therefore, among the collected data, of key importance are the parameters of an electric power system that can be used to obtain retrospective information about its operation and to build its model. The most promising area of research is the possibility of creating models to predict the future state of a power system based on its current state and historical data; it would enable a shift towards predictive power system management, with the early forecasting and prevention of emergencies or abnormal situations.

Note that when assessing power supply quality, energy retailers and utilities primarily involve the reliability indices of the Institute of Electrical and Electronics Engineers (IEEE). In particular, the following indices are commonly used:

• SAIFI (*System Average Interruption Frequency Index*), representing the ratio of the total number of disconnected customers due to sustained unscheduled outages to the total number of connected customers during a period under consideration; according to the IEEE 1366-2012 [2], this index is calculated by the formula

$$SAIFI = \frac{\sum_{i=1}^{n} N_i}{N_t},$$

where i denotes an interruption event ($i = \overline{1, n}$); N_i is the number of customers affected by interruption event i; and N_t is the total number of customers served in the system.

• SAIDI (*System Average Interruption Duration Index*), representing the ratio of the total duration of sustained unscheduled outages affecting customers to the total number of connected customers during a period under consideration; this index is calculated by the formula

$$SAIDI = \frac{\sum_{i} U_i N_i}{N_T}$$

where N_i is the number of customers affected by interruption event i; U_i is the restoration time or duration of interruption event i; and N_T is the total number of customers served in the system.

In the Russian energy sector, the reliability index is denoted by Π_{SAIFI}; it has been calculated since 2016 in accordance with the methodology established by Order no. 1256 of the Ministry of Energy [3]. However, this methodology considers either instances of power outages (restorations) or differentiates by voltage levels, neglecting important indicators such as, e.g., power system frequency and harmonic components.

A number of international studies have attempted to develop a universal criterion for assessing the quality of power systems. For example, a multifactorial assessment technique using a multicriteria approach based on the VIKOR method was proposed in [4]. For each power system node, this technique yields a comprehensive assessment taking a system of indicators into account: voltage deviation, harmonics, voltage asymmetry, voltage fluctuations and flicker, voltage dips, and frequency deviation. A distinctive feature of the above approach lies in combining weights, which are calculated by an improved technique (gray relational analysis with the method of analytical relations) to consider the interdependence of indicators and expert opinions. The final quality assessment criterion for an entire electric power system (F) is the sum of the products

$$F = \sum_{j} (Q_j D_j),$$

where Q_j is the power supply quality assessment of node j obtained by the VIKOR method; D_j is the degree of influence of node j on the entire power system, calculated based on the theory of complex networks. However, this criterion quantitatively measures how the condition of a particular node degrades power supply quality throughout the entire power system rather than identifies nodes with poor voltage.

A criterion for classifying (recognizing) composite disturbances, i.e., deviations from normal operation, in power supply quality was presented in [5]. Unlike the paper [4], aimed at a comprehensive assessment of the quality level, the problem considered therein is to identify the type of disturbance. The main criterion can be formulated as the accuracy of recognizing the type of a composite disturbance using the transformation of a one-dimensional signal into a two-dimensional image.

The approach described in [6] is similar to that of [4], albeit for a particular object. Indicators are assigned objective weights without taking expert opinions into account. Time intervals are ranked: for each time instant, a single compromise index is calculated to assert, e.g., that slice no. 3 is better than slice no. 5. Moreover, the method proposed therein identifies combinations of factors that duplicate information (e.g., two parameters increase simultaneously and with the same rate) and assigns weights appropriately to avoid the double consideration of the same information.

However, the approaches of the cited studies have not become widespread in practice.

An attempt to standardize power supply quality assessment approaches was undertaken in GOST 32144–2013 [7]; but the quality indicators presented therein are disparate and cannot be used to assess power supply quality at a given time instant comprehensively or compare different electric power systems.

Fluctuations in peak loads caused by climatic factors (winter/summer), the emergence of new categories of consumers (including high-power, energy-intensive data centers), the growing share of electric and hybrid vehicles, the transition to electric heating due to the deterioration of water heating networks and environmental agenda support in disadvantaged regions, the development of energy-intensive data centers for the digital economy, shifts in the balance between active and reactive loads, and other factors make the power system frequency and voltage unstable, increase electricity losses in power systems, and reduce the service life of power systems, particularly cable lines. Changing requirements from consumers of reliability categories I and II regarding power supply quality and the emergence of a new group of consumers (high-tech manufacturing with tougher demands on power supply quality) call for a more comprehensive approach to assessing the quality of electricity supplied to consumers and new metrics for assessing the quality of electric power systems in real time.

The Center of Digital Solutions for Smart Grid (hereinafter referred to as the Center) is a structural unit of the Trapeznikov Institute of Control Sciences, the Russian Academy of Sciences (ICS RAS). Experts of the Center are engaged in the development and research of methods and technologies for the intelligent control of electric power systems. The Center's key objective is to create and improve hardware and software infrastructure for data collection, as well as to develop algorithms and mathematical models for indoor power consumption management and climate control systems.

Since 2021, the Center has organized the acquisition and systematization of the following data (the corresponding sensors are indicated in parentheses):

- power system parameters (Mercury-234 electricity meters installed on the three-phase cables coming from transformer substations);
- microclimate characteristics for the rooms of ICS RAS (multi-sensor systems collecting data on temperature, humidity, illuminance, and carbon dioxide concentration indoors);

• meteorological indicators (a local weather station collecting information on weather conditions).

The architecture of the data acquisition system was presented in detail in [1]; also, see Fig. 1.

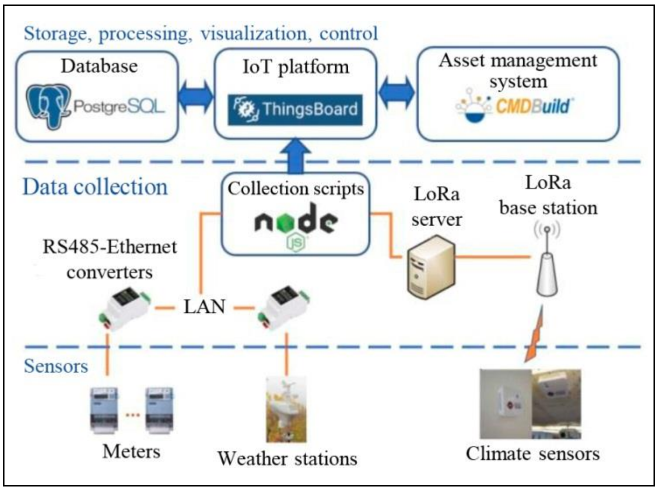

Fig. 1. The architecture of the data acquisition system developed at the Center.

This paper proposes an integral criterion for assessing and predicting the quality of electric power systems, as well as for comparing different electric power systems with one another, based on data collected by systems with a functional architecture similar to the one described in [1].

1. KEY PROVISIONS

According to GOST 32144–2013, the following indicators are used to assess power supply quality:

– frequency deviation,
– voltage deviations,
– voltage fluctuations,
– voltage distortion,
– voltage asymmetry,
– voltage interruptions,
– voltage dips and surges, and
– transient voltages.

The system (Fig. 1) collects tabular information on power system parameters and stores it in a database (Fig. 2). The correspondence between the power supply quality indicators and the attributes of the *Electricity_sensor_readings* entity is given in Table 1.

When forming the integral quality criterion for power systems, the following quality indicators were excluded:

• voltage fluctuations, as they are associated with the presence of harmonics in the supply voltage and are incorporated in the total harmonic distortion;

• voltage asymmetry, since this indicator is calculated, in accordance with GOST 32144–2013, over a sufficiently long period of time (one week) and therefore cannot be used to assess power supply quality in real time;

• voltage interruptions, dips, surges, and transient voltages, since these criteria are associated with rapid and random events in the power system that cannot be tracked within the above data acquisition architecture based on standard hardware.

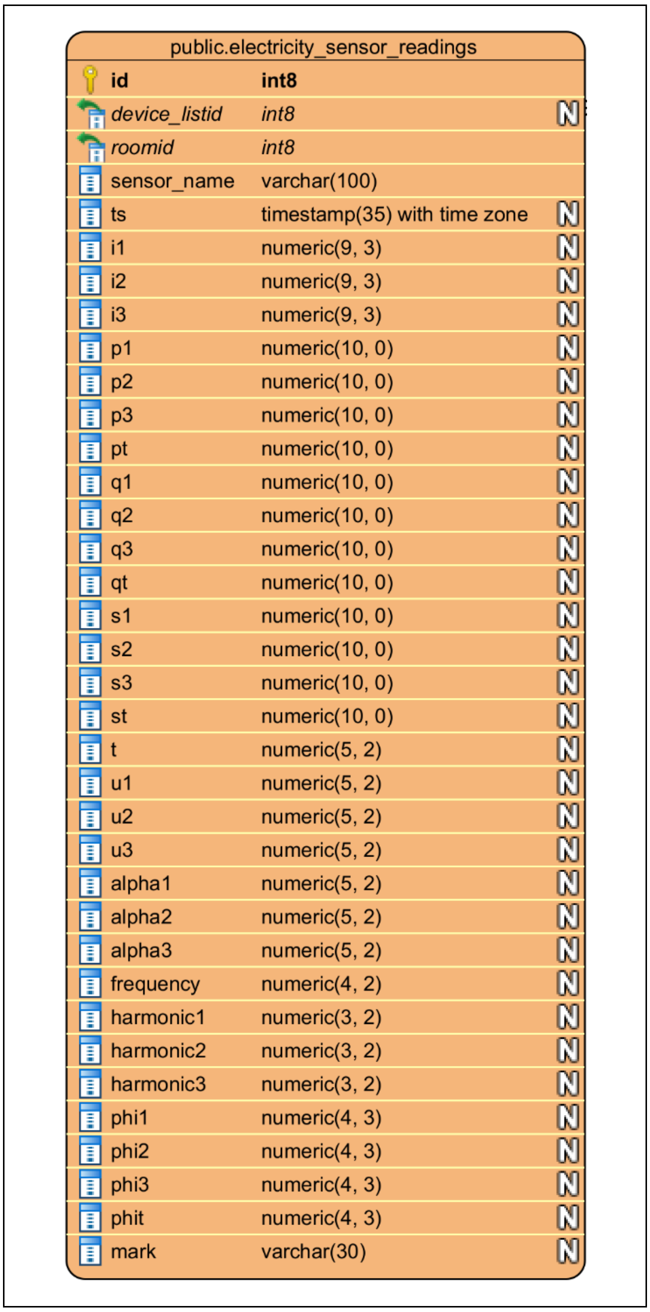

Fig. 2. The database table containing sensor readings (Electricity_sensor_readings).

Table 1

The correspondence between the attributes of Electricity_sensor_readings and power supply quality indicators

Attribute name	Attribute description	Relationship to power supply quality indicator (GOST 32144–2013)
ts	Measurement time, including date, time, and time zone	Not applicable
U_1	Phase 1-to-neutral voltage, measured at a given time instant *ts*, in V	The deviation of the supply voltage at the electrical energy transfer point from the nominal (agreed-upon) value, in %. It is defined as $\begin{cases}\delta U_{(-)} = \left[(U_0 - U_i)/U_0\right]\cdot 100, U_i < U_0,\\ \delta U_{(+)} = \left[(U_i - U_0)/U_0\right]\cdot 100, U_i > U_0,\end{cases}$ where U_0 is the standard nominal voltage (230 V in GOST 32144–2013); U_i is the voltage in the *i*th phase.
U_2	Phase 2-to-neutral voltage, measured at a given time instant *ts*, in V	
U_3	Phase 3-to-neutral voltage, measured at a given time instant *ts*, in V	
frequency	Power system frequency, measured at a given time instant *ts*, in Hz	Frequency deviation, in Hz. It is defined as $\Delta f = f_{\text{freq}} - f_{\text{nom}}$, where f_{nom} is the nominal power supply frequency (50 Hz in GOST 32144–2013).
harmonic 1	Harmonic distortion of the first phase, a dimensionless quantity	Total harmonic distortion K_U, in %
harmonic 2	Harmonic distortion of the second phase, a dimensionless quantity	
harmonic 3	Harmonic distortion of the third phase, a dimensionless quantity	

2. AN INTEGRAL QUALITY CRITERION FOR ELECTRIC POWER SYSTEMS

Within the initial approach to developing an integral quality criterion (IQC) for electric power systems, by assumption, the most significant parameters of three-phase electric power systems are frequency fluctuations, phase voltages, and the total harmonic distortions in the phases. Based on this assumption, the IQC is defined as

$$K_{\Sigma 3} = F\big(\Delta f_{ENet}(t),\ \delta U_1(t),\ \delta U_2(t), \delta U_3(t),\ K1_{\text{THD}}(t),\ K2_{\text{THD}}(t),\ K3_{\text{THD}}(t)\big). \tag{1}$$

Thus, the criterion $K_{\Sigma 3}$ functionally depends on a tuple of the following components:

$\Delta f_{ENet}(t) = f_{\text{freq}} - f_{\text{nom}}$, representing the power frequency deviation as a function of time;

$$\delta U_1(t) = \left|(U_1 - U_0)/U_0\right|, \delta U_2(t) = \left|(U_2 - U_0)/U_0\right|,$$

and $\delta U_3(t) = \left|(U_3 - U_0)/U_0\right|$, representing the deviations of the voltage between the neutral wire and the first, second, and third phases, respectively, as functions of time;

$K1_{\text{THD}}(t)$, $K2_{\text{THD}}(t)$, and $K3_{\text{THD}}(t)$, representing the total harmonic distortions of the voltage in the first, second, and third phases, respectively, as functions of time.

For a fixed time instant *t*, the tuple from (1) can be written as a seven-dimensional (7D) vector (a first-rank tensor), and its absolute value (the Frobenius norm or L_2 norm; for example, see [8]) can be used as $K_{\Sigma 3}$:

$$K_{\Sigma 3} = \Big(\left(\alpha_1 \Delta f_{ENet}\right)^2 + \left(\alpha_2 \delta U_1\right)^2 + \left(\alpha_2 \delta U_2\right)^2 + \left(\alpha_2 \delta U_3\right)^2 + \left(\alpha_3 K1_{\text{THD}}\right)^2 + \left(\alpha_3 K2_{\text{THD}}\right)^2 + \left(\alpha_3 K3_{\text{THD}}\right)^2\Big)^{\frac{1}{2}}, \tag{2}$$

where $\alpha_1 = 2.5\ \text{Hz}^{-1}$, $\alpha_2 = 4.7619 V^{-1}$, and $\alpha_3 = 10$ are the normalizing coefficients for the voltage deviation, frequency deviation, and total harmonic distortion, respectively.

The values of the normalizing coefficients were determined using the least squares method so that the IQC value would fall within the range of 0 to 2 under the maximum permissible values of the electric power system parameters.

3. ANALYSIS OF THE INTEGRAL QUALITY CRITERION

It is impossible to represent the trajectory of the 7D vector $K_{\Sigma 3}$ in the 3D space. Therefore, we analyzed the 3D traces of $K_{\Sigma 3}$ in the coordinate frame $K_{\Sigma 3} = f\left(U_1, U_2\right)$ under fixed values of the other components. Some results are presented below (Figs. 3–7).

According to these figures, if the power system parameters approach their nominal values, the optimum of the IQC vanishes (Fig. 3).

The analysis results for the IQC (2) (its key points) are provided in Table 2.

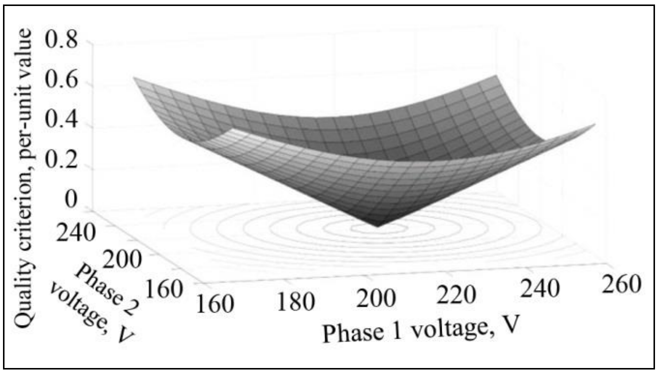

Fig. 3. The 3D trace of the IQC for a three-phase power system with the following fixed values: voltage 220 V in phase 3; frequency 50 Hz; and nominal values of the total harmonic distortions in each phase.

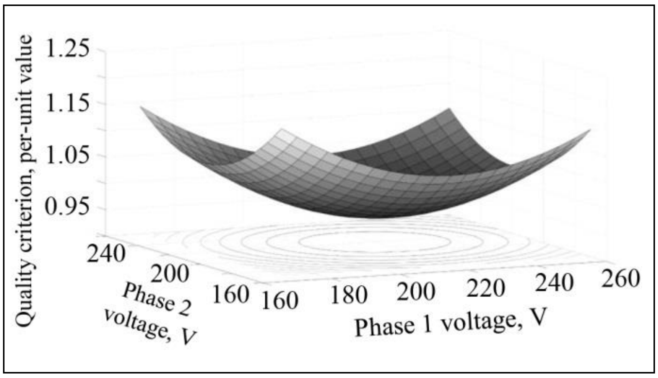

Fig. 4. The 3D trace of the IQC for a three-phase power system with the following fixed values: voltage 220 V in phase 3; nominal values of the total harmonic distortions in phases 1 and 3; frequency 49.2 Hz (minimum permissible value); and the total harmonic distortion in phase 2 is set to 0.3 (failure).

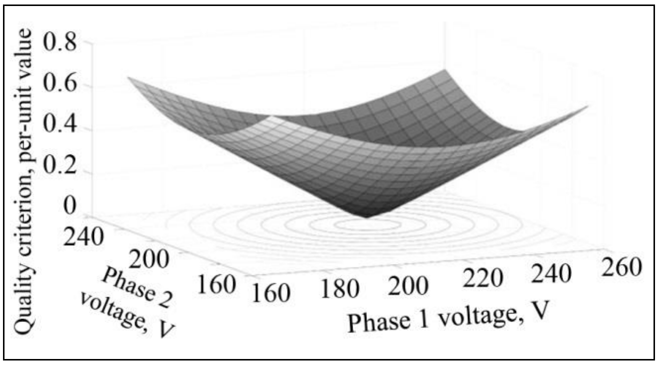

Fig. 5. The 3D trace of the IQC for a three-phase power system with the following fixed values: voltage 220 V in phase 3; nominal values of the total harmonic distortions in phases 1 and 3; frequency 50 Hz (nominal value); and the total harmonic distortion in phase 2 is set to 0.01 (permissible value).

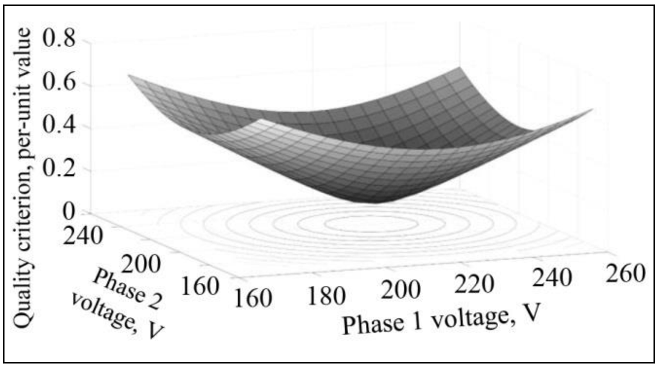

Fig. 6. The 3D trace of the IQC for a three-phase power system with the following fixed values: voltage 230 V in phase 3 (permissible value); frequency 50 Hz; and nominal values of the total harmonic distortions in each phase.

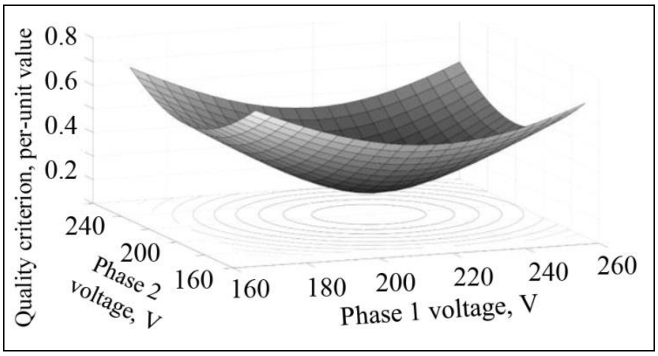

Fig. 7. The 3D trace of the IQC for a three-phase power system with the following fixed values: voltage 240 V in phase 3 (maximum permissible value); frequency 50 Hz; and nominal values of the total harmonic distortions in each phase.

According to the analysis results, for an electric power system meeting the requirements of GOST 32144-2013 at a given time instant (frequency 50 Hz, voltage 220 V in each phase, and zero nonlinear distortion in each phase), the IQC will have a limit value of zero (Fig. 3).

Table 2

Key points for electric power system states

Electric power system state	Key points of $K_{\Sigma 3}$		Comment
	min	max	
Normal state	0	0.218218	All power supply quality parameters are within permissible ranges.
Lower limits for the electric power system parameters	0.218218	0.626783	The power supply quality parameters are below the permissible values, albeit without reaching lower critical thresholds. In other words, the operation of the electric power system is still permissible, but additional measures are required to eliminate the drawbacks.
Upper limits for the electric power system parameters	0.218218	1.520808	The power supply quality parameters are above permissible values, albeit without reaching upper critical thresholds. In other words, the operation of the electric power system is still permissible, but additional measures are required to eliminate the drawbacks.
Lower critical thresholds for the electric power system parameters	0.474386	1.294267	The power supply quality parameters are below the lower critical thresholds. In other words, the operation of the electric power system is prohibited, and additional measures are required to eliminate the drawbacks.
Upper critical thresholds for the electric power system parameters	0.308607	2.035401	The power supply quality parameters are above the upper critical thresholds. In other words, the operation of the electric power system is prohibited, and additional measures are required to eliminate the drawbacks.

4. ASSESSING AND PREDICTING THE QUALITY OF ELECTRIC POWER SYSTEMS

The approaches outlined in Sections 1 and 2 were applied to assess the quality of an electric power system as follows:

1. The data acquisition system for electric power system parameters (Fig. 1) was used.
2. The data acquisition system with a database table describing electric power system states (Fig. 2) was supplemented with a view containing the following attributes from the table:

– references to a particular sensor for data collection;
– time of data collection;
– power system frequency;
– voltage in the first phase;
– voltage in the second phase;
– voltage in the third phase;
– the total harmonic distortion of voltage in the first phase;
– the total harmonic distortion of voltage in the second phase;
– the total harmonic distortion of voltage in the third phase;
– the IQC, the attribute calculated by (2).

3. The IQC value as a function of time was visualized; e.g., see Fig. 8.

For each point on the graph, this user interface also displays the corresponding power system parameters; if the IQC exceeds the permissible limits, the user can determine the parameter violating the requirements of GOST 32144–2013.

The user interface in Fig. 8 allows virtually changing the IQC values for each point on the graph. Therefore, the user can analyze how variations of a parameter (or several parameters) will affect the IQC value. (The modified state is not saved to the database.) This function is intended to simulate various states of an electric power system and consider various scenarios.

Within the above approach, it is possible to predict power supply quality when varying electric power system parameters and, hence, recommend power supply quality improvements and implement timely control measures.

An example of power supply quality prediction is shown in Fig. 9.

According to Fig. 9, at 00:21:40, the IQC value exceeds 2, corresponding to a critically high value for electric power system parameters. After manually changing some power system parameters (highlighted in color in the figure), a second curve appeared on the graph, corresponding to the predicted state. This curve can be used to decide what needs to be changed in the electric power system parameters. (Note that practical recommendations are beyond the scope of this paper.)

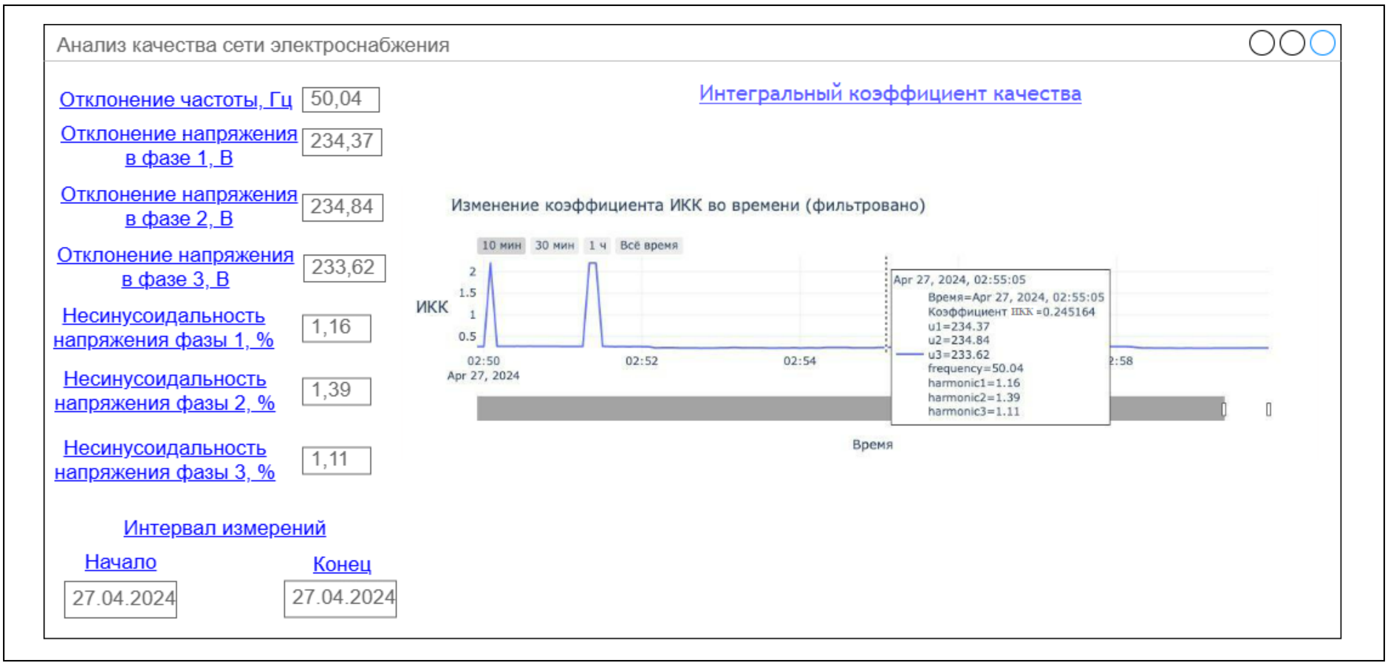

Fig. 8. IQC dynamics visualized. The parameters (left, top-to-bottom) are as follows: frequency deviation, Hz; voltage deviations in phases 1–3, V; voltage distortion in phases 1–3, %.

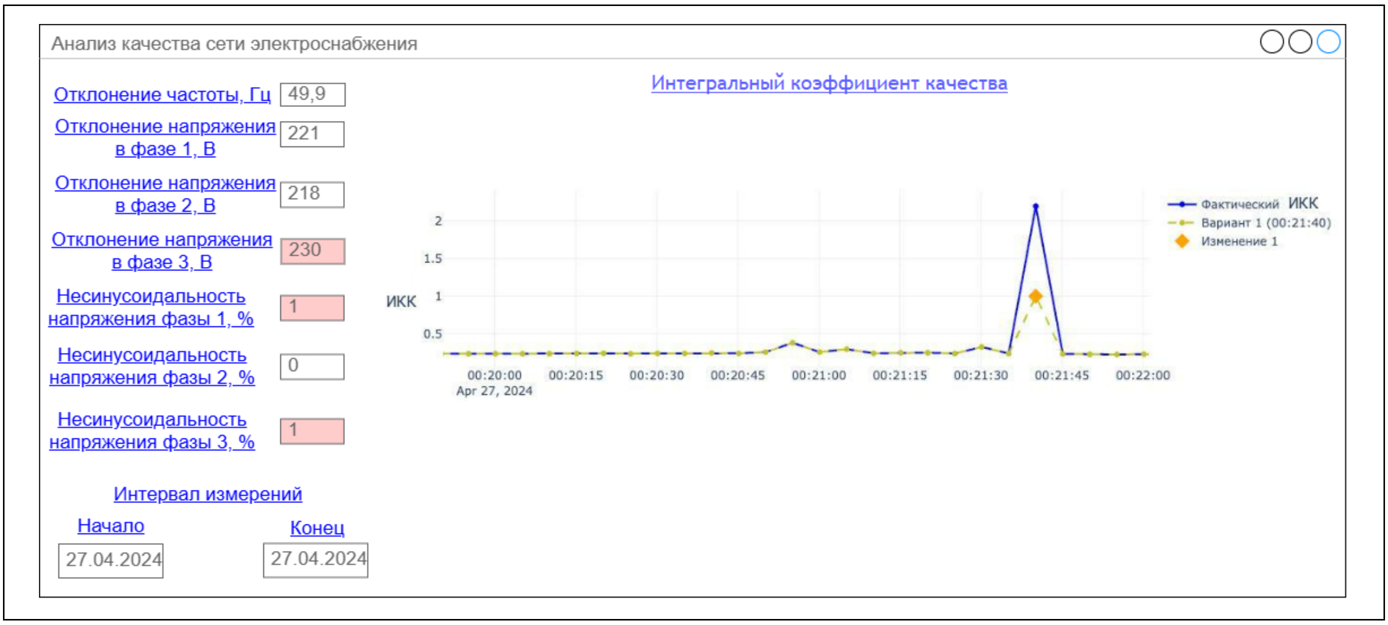

Fig. 9. An example of power supply quality prediction. The parameters (left, top-to-bottom) are as follows: frequency deviation, Hz; voltage deviations in phases 1–3, V; voltage distortion in phases 1–3, %.

CONCLUSIONS

In this study, we have used an integral quality criterion to assess the operation of electric power systems based on data collected within a system similar to [9]. Note that the criterion has been developed at the Center of Digital Solutions for Smart Grid (ICS RAS).

This criterion simultaneously incorporates several electric power system parameters, enabling the scenario-based prediction of power system behavior under virtual (offline) variations to its parameters, such as frequency, voltage in each phase, and the total harmonic distortions in each phase.

The effectiveness of the proposed approach has been verified using real data [10]. Experimental studies of the developed IQC have been conducted using a software prototype that visualizes data collected by sensors in the electric power system of ICS RAS.

The approach can be included in the next edition of GOST 32144–2013 or applied to develop new quality assessment standards for electric power systems.

REFERENCES

1. Bazenkov, N.I., et al., An Office Building Power ConsUmption Dataset for Energy Grid Analysis and Control Algorithms, *IFAC-PapersOnLine*, 2022, vol. 55, no. 9, pp. 111–116.
2. *IEEE 1366-2012 – IEEE Guide for Electric Power Distribution Reliability Indices*, New York: IEEE, 2012. DOI: 10.1109/IEEESTD.2012.6209381
3. Order of the Ministry of Energy of the Russian Federation dated November 29, 2016, no. 1256 (as amended on June 14, 2023) "On Approval of the Methodological Guidelines for Calculating the Level of Reliability and Quality of Supplied Goods and Rendered Services for the Organization Managing the Unified National (All-Russian) Power Grid and Territorial Grid Organizations." (In Russian.)
4. El-Dabah, M.A., Boghdady, T.A., El-Saadawi, M.M., et al., Comprehensive Power Quality Performance Assessment for the Electrical Power System of a Nuclear Research Reactor, *Scientific Reports*, 2023, vol. 13, art. no. 9915.
5. Xiang, Y., Lin, Y., Zhang, Y., et al., A Grid-Wide Comprehensive Evaluation Method of Power Quality Based on Complex Network Theory, *Energies*, 2024, vol. 17, no. 13, art. no. 3193.
6. Liu, Y., Wang, H., Wang, Z., et al., Identification of Composite Power Quality Disturbances Based on Relative Position Matrix, *Frontiers in Energy Research*, 2024, vol. 11, art. no. 1326522.
7. *GOST* (State Standard) *32144-2013*: Electrical Energy. Electromagnetic Compatibility of Technical Equipment. Electrical Energy Quality Standards in General-Purpose Power Supply Systems, Moscow: Standartinform, 2014. (In Russian.)
8. Arushanyan, I.O., *Izbrannye zadachi dlya seminarskikh zanyatii po chislennym metodam: vektornye i matrichnye normy* (Selected Exercises for Seminars on Numerical Methods: Vector and Matrix Norms), Moscow: Moscow State University, 2019. (In Russian.)
9. Pashchenko, A.F., Bazenkov, N.I., Petrov, I., et al., Works and Projects of the Center of Digital Solutions for Smart Grid of ICS RAS, *Sensors and Systems*, 2024, no. 2 (274), pp. 3–11. (In Russian.)
10. *The Center of Digital Solutions for Smart Grid of ICS RAS. Datasets*. URL: https://energy.ipu.ru/datasets/ (Accessed January 19, 2026.)

This paper was recommended for publication by I.B. Yadykin, a member of the Editorial Board.

Received February 2, 2026, and revised April 14, 2026. Accepted May 14, 2026.

Author information

Pashchenko, Aleksandr Fedorovich. Cand. Sci. (Eng.), Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ a.paschenko@ipu.ru
ORCID iD: https://orcid.org/0000-0002-6299-4894

Tsvetkov, Aleksey Anatol'evich. Junior Researcher, Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ tsvetkov-a@ipu.ru
ORCID iD: https://orcid.org/0000-0003-1191-1347

Cite this paper

Pashchenko, A.F., and Tsvetkov, A.A., Assessing and Predicting the Quality of Electric Power Systems Based on an Integral Criterion. *Control Sciences* **4**, 76–83 (2026).

Original Russian Text © Pashchenko, A.F., Tsvetkov, A.A., 2026, published in *Problemy Upravleniya*, 2026, no. 4, pp. 90–98.

This paper is available under the Creative Commons Attribution 4.0 Worldwide License.

Translated into English by *Alexander Yu. Mazurov*,
Cand. Sci. (Phys.–Math.),
Trapeznikov Institute of Control Sciences,
Russian Academy of Sciences, Moscow, Russia
✉ alexander.mazurov08@gmail.com