Виконано оцінку ступеня відповідності показників якості електричної енергії нормам за допомогою теорії нечітких множин. Запропоновано інтегральний показник якості електричної енергії для конкретних видів навантаження. Показано конкретний приклад нечіткої оцінки якості електроенергії і представлені інтегральні показники якості електричної енергії для двигунного, освітлювального навантаження і для приладів з мікропроцесорними блоками керування

Ключові слова: якість електричної енергії, вид навантаження, нечіткі множини, інтегральний показник

Выполнена оценка степени соответствия показателей качества электрической энергии нормам с помощью теории нечетких множеств. Предложен интегральный показатель качества электрической энергии для конкретных видов нагрузки. Показан конкретный пример нечеткой оценки качества электроэнергии и представлены интегральные показатели качества электрической энергии для двигательной, осветительной нагрузки и для приборов с микропроцессорными блоками управления

Ключевые слова: качество электрической энергии, вид нагрузки, нечеткие множества, интегральный показатель

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ASSESS ELECTRICITY QUALITY BY MEANS OF FUZZY GENERALIZED INDEX

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1. Introduction

Electric power, supplied by power supplying organizations to consumers under contracts, acts as a special kind of product, characterized by the coincidence in time the processes of production, transportation and consumption, as well as the inability to store it and return. Accordingly, as any type of goods, electricity is applied to the concept of "quality". Deviation of index of electricity quality (IEQ) of the limits set by the standards, conditions worsen as the operation of electrical networks and consumers.

All the indexes of electricity quality are regulated by GOST 13109-97 [1]. The indexes of electricity quality dee viation of the normalized values impairs the conditions of operation of electrical power supply companies and electricity consumers, and could lead to significant losses, both in production and in the domestic sector. Therefore, the correct assessment of indexes of electricity quality is quite acute and pressing problem.

It must be noted that the indexes of electricity quality deviation of the standards does not necessarily lead to a deterioration of the equipment. For example heaters and incandescent lamps, the deviation coefficient of asymmetry and non-sinusoidal from the norm does not entail any negative consequences. But at the same asynchronous motors at the asymmetry coefficient deviation from the norm and non-sinusoidality have additional power losses, deteriorating nominal operating modes, reducing service life. In this connection there is a need to develop a single integrated evaluation criterion IEQ, which would take into account features of different types of loads. Thus to date in assessing the quality of electrical energy used classical deterministic methods that do not take into account the uncertainty of information, all this leads to an incorrect use of the equations, conditions, balance sheet ratios. Therefore, the representation of the IEQ in the form of fuzzy and integral development of the IEQ is an urgent task.

2. Analysis of published data and problem statement

Resolving the problem of uncertainty and the problem of constructing a generalized index of electricity quality in the literature are considered separately. Least developed problem is constructing a generalized indicator of quality. But in spite of that research are also conducted in this area. In particular, [2] had made an attempt to assess the combined effect of the IEQ on the regime of the various power consumers. Also in the work [3] we propose to use the generalized index of electricity quality for the motor load under the influence of negative sequence voltage unbalance and harmonics. Today decided to use a deterministic campaign, in which the output of an electric energy is based on the analysis of measured IEQ, limits are regulated by GOST 13109-97.

On the uncertainty issue of the initial information, in the GOST 13109-97 it is permitted by averaging multiple measurements carried out with the assistance of statistical methods. However, the implementation of the measurement process of the IEQ for the purpose of obtaining reliable input data for making decision not only the measurement result must been available, but the most confident characterize its uncertainty. Uncertainty makes it possible to quantify the quality of the measurements. According to the latest international standards in the field of metrology and standardization of the basic assessment of the quality measurement results is recommended to consider its uncertainty [4]. If the measurement process of the IEQ is characterized by complexity, uncertainty, necessity to make decisions in an uncertain conditions with expert knowledge, it is convenient as mathematical basis of presentation of measurement uncertainty using the theory of fuzzy sets [5, 6]. In [4] the uncertainty of the measurement result of regime parameters is recommended to describe any standard deviation or symmetrical borders. In the first case, apply objective probability assessment of a number of measurements, and the second possible using of subjective knowledge, mathematically formalized using fuzzy sets theory.

In the monograph [7] shows that for decision making in assessing the IEQ it is more expedient to use the theory of fuzzy sets, rather than the classical methods of probability theory as a fuzzy representation gives a simple description of the object and, as a consequence, increase the speed of making decision. If the distribution of measurement results during repeated experiments adopted symmetrical and unimodal, you can use triangular membership function. In the case where the results of direct measurements are used to calculate future indirect measurements, it is mathematically convenient represented as fuzzy numbers with triangular membership function [8].

Calculating indirect uncertainty measurement with the level of confidence 1 and less than 1 in the case of impossibility linearization equation error, you can use the device of fuzzy numbers proposed in [6, 9]. The results are not satisfactory, if the distributions are asymmetric. This occurs when there is a small number of operations. Therefore the authors recommends [6, 9] is to make distributions estimation in important cases.

In this way, if the systems of inherently are imprecise, vague reference and measurement inputs, then for the mathematical description of these parameters, as well as the relationships between them is recommended to use the mathematical apparatus of fuzzy sets. In addition, the application of fuzzy mathematical description allows to use for mathematical models with the results of measurements expertise and assessment, presenting them in the form of fuzzy numbers, membership functions and distribution functions of options.

3. The purpose and objectives of the study

The purpose of this article is to develop a methodology quality rating of electrical energy in the conditions of uncertainty and the construction of a generalized indicator of quality in a fuzzy way.

To achieve this goal it is necessary to solve the task of converting a deterministic dependency fuzzy mind, taking into account characteristics of specific types of network load

4. Methods of determining the quality of electricity in the form of fuzzy

Since the fuzzy approach is a generalization of a deterministic, then we take as a basis the methodology given in [1]. For these IEQ as voltage deviation, voltage non-sinusoidality, voltage unbalance, frequency deviation, etc. measurements are made within 24 hours. During this time numerous ΔIEQ dimension N_D formed. Imagine this set of fuzz y numbers with triangular membership function, as suggested in [6, 8, 9].

$$\mu_{\Delta IEQ} = \max\left\{0, \min\left\{\frac{IEQ - IEQ_{min}}{IEQ_m - IEQ_{min}}, \frac{IEQ_{max} - IEQ}{IEQ_{max} - IEQ_m}\right\}\right\}, \quad (1)$$

where

$$IEQ_{max} = \max_{\Delta IEQ}\left\{IEQ_j\right\}, IEQ_{min} = \min_{\Delta IEQ}\left\{IEQ_j\right\}, \quad (2)$$

$$IEQ_m = \frac{\sum_{j=1}^{N_\Delta} \mu_{IEQ_j} IEQ_j}{\sum_{j=1}^{N_\Delta} \mu_{IEQ_j}},$$

here μ_{IEQj} – membership function (degree of confidence) IEQ_j multiplicity ΔIEQ.

The value m_{IEQj} can be determined informally [1, 0], which is undesirable because subjectivity can distort the real picture. More objectively, these parameters can be obtained by estimating the distribution using the apparatus of mathematical statistics. For example, to obtain a histogram, breaking range $\{IEQ_{min}, IEQ_{max}\}$ for N_d intervals and determine the frequency of IEQ_j contact at appropriate intervals. Data values of frequencies assigned to the maximum value of the frequency can be taken as m_{IEQj}.

5. Methods of determining the standards of electricity quality in the form of fuzzy

Standards of electricity quality (SEQ) [1] are defined as intervals and permissible limit values.

From the point of view of the theory of fuzzy sets, this rule can be represented by a fuzzy set: fuzzy membership function with interval

$$\mu_{SEQ} = \max\left\{0, \min\left\{1, \frac{SEQ - SEQ_{min}}{SEQ_{m1} - SEQ_{min}}, \frac{SEQ_{max} - SEQ}{SEQ_{max} - SEQ_{m2}}\right\}\right\}. \quad (3)$$

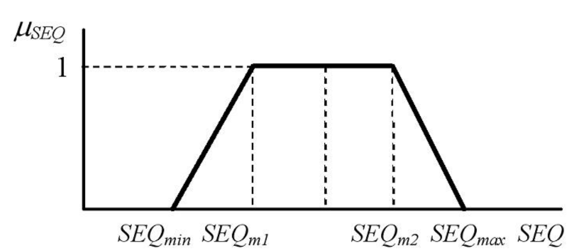

Fig. 1. The functions of fuzzy electricity quality standards

Only maximum fine and maximum permissible limits identified for some SEQ. In this case the expression (3) is simplified (SEQ_{min}=SEQ_{m1}=0).

6. Conformity assessment of indexes of electricity quality standards established in the form of fuzzy

Degree of compliance with fuzzy values IEQ (1) fuzzy SEQ (3) can be estimated from their intersection

$$S = S_{SEQ} \cap S_{IEQ}. \qquad (4)$$

The intersection of fuzzy numbers [4, 5], in general, has a membership function that is different from the triangular and height $h \neq 1$.

Numerically, the intersection of fuzzy numbers can be estimated by the square shape formed by the intersection of the membership function (Fig . 2). In Fig. 2 indexes, rel, l, mv, h, vh – respectively extremely low, low, modal value, high, very high. Then, the membership function of a fuzzy matching IEQ fuzzy rules electricity quality (EQ) can be represented as

$$\mu_{EQ} = S / S_{IEQ} . \qquad (5)$$

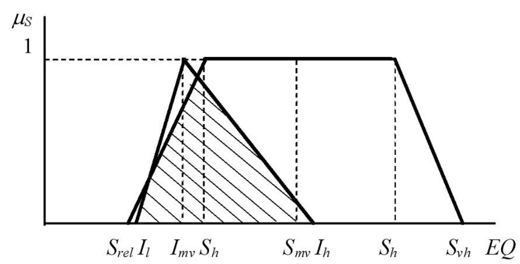

Fig. 2. The intersection of fuzzy numbers and fuzzy intervals

The area of the intersection of the triangle and trapezoid is determined by the known geometric relationships.

7. Construction of the generalized indicator of quality in the form of fuzzy

To characterize the quality of electric energy with generalized index there are the following types of loads: lighting, motors, heating appliances and devices with microprocessor control units. There are figures in Table 1, which shows the types of influence certain aspects of electricity quality to work for power consumers [11].

Table 1

Influence of IEQ on the kind of demand for electroreceivers

IEQ	Type of load		
	motor	lighting	devices with microprocessor control units
steady voltage deviation δU_s	+	+	–
scope voltage changes δU_t	–	+	+
flicker P_t		+	+
coefficient of n harmonic component of voltage $K_{U(n)}$	+	–	+
coefficient of voltage asymmetry by reverse sequence K_{2U}	+	–	–
coefficient of voltage asymmetry by zero sequence K_{0U}	+	+	–
frequency deviation Δf	+	–	–

Given the above, method of determining the fuzzy generalized index of electricity quality for different types of load using (1)–(5) is proposed [12].

All figures in Table. 1 are based on the IEQ measurement method which is given in [1], and processing the measurement results by the method (1)–(3). Note particularly the definitions of some of the IEQ. Because the regulations are not given the amount of change in voltage amplitude measurements dU_t the metering unit, we may consider singleton, like every value flicker has independent significance and can be represented as a singleton. Their membership functions are of the form

$$\mu_{\delta U_t}(\delta U_t) = 1 , \mu_{P_{St}} = 1; \mu_{P_{Lt}} = 1 .$$

Using formulas (4), (5) assesses the extent to which the IEQ standards.

Since operations on fuzzy sets uniquely projected on the operation of their membership functions, then form a single indicator of the fuzzy concept of "electricity quality" can be quite simple.

For example, using the logical operation of crossing a single quality measure it may be represented as follows

$$EQ = \bigcap_{i=1}^{N_{EQ}} EQ_i; \quad \mu_{EQ} = \min_i \left(\mu_{EQi} \right), \qquad (6)$$

where N_{EQ} – the number of considered indicators of quality.

Then μ_{EQ} we can assume a generalized indicator that assesses the quality of power number in the range [0 , 1] .

Using relation (6) and the analysis results listed in Table 1, we obtain the values of integral quality indices of electricity for the three considered types of loads in the form of:

– for the motor load

$$\mu_{EQ} = \min \left(\mu_{\delta U_s}, \mu_{K_U}, \mu_{K_{U(n)}}, \mu_{K_{2U}}, \mu_{K_{0U}}, \mu_{\Delta f}, \mu_{\Delta t_P}, \mu_{rU} \right), \qquad (7)$$

– for lighting load

$$\mu_{EQ} = \min \left(\mu_{\delta U_y}, \mu_{\delta U_t}, \mu_{P_t}, \mu_{K_{0U}}, \mu_{\Delta t_P}, \mu_{U_{imp}} \right), \qquad (8)$$

– for devices with microprocessor control units

$$\mu_{EQ} = \min \left(\mu_{\delta U_t}, \mu_{P_t}, \mu_{K_U}, \mu_{K_{U(n)}} \right) . \qquad (9)$$

In the expressions (7)–(9) generalized indexes of electricity quality can take values from the range [0, 1]. However, if exactly follow the requirements set forth in [6], the values are different from 1 uniquely μ_{EQ} qualified as a lack of required electricity quality – non-compliance with GOST 13109-97. At deeper implementation of fuzzy approach when assessing the quality of electricity can be avoided such a rigid differentiation due to a deterministic approach in [1]. For example, you can enter for each type of load allowable values of fuzzy generalized indicators of quality. However, this provision requires a separate study and can serve as a basis for the revision of the current approach to assessing the quality of electricity.

Consider a specific example of fuzzy electricity quality assessment and obtaining the integral index for different types of loads. We take data measured at the substation 10/0.4 kV.

The estimation of the voltage deviation (Fig. 3, *a–f*).

$\mu_{\Delta U_A} = 0{,}757, \quad \mu_{\Delta U_B} = 0{,}986, \quad \mu_{\Delta U_C} = 0{,}999,$

$\mu_{\Delta U_{AB}} = 0{,}963, \quad \mu_{\Delta U_{BC}} = 0{,}929, \quad \mu_{\Delta U_{CA}} = 0{,}973.$

Evaluation of voltage deviation in a fuzzy form shows that in general, the quality of electricity for this indicator is within acceptable limits, but there is some underutilization of phase A, which should be reflected in the index of voltage asymmetry [11].

The estimation of voltage asymmetry (Fig. 4, *a*, *b*).

$\mu_{\Delta K2U} = 1, \quad \mu_{\Delta K0U} = 0{,}648.$

In this case, the fuzzy evaluation of voltage unbalance of the residual is different from 1, so there is a basis for the analysis of the causes. Fuzzy assessment of index of electricity quality to determine the “weaknesses” of a particular network and advance to schedule work to normalize conditions [10].

To assess the non-sinusoidal voltage ACEM data selected by the first ten harmonics (Fig. 5, *a*–*i*).

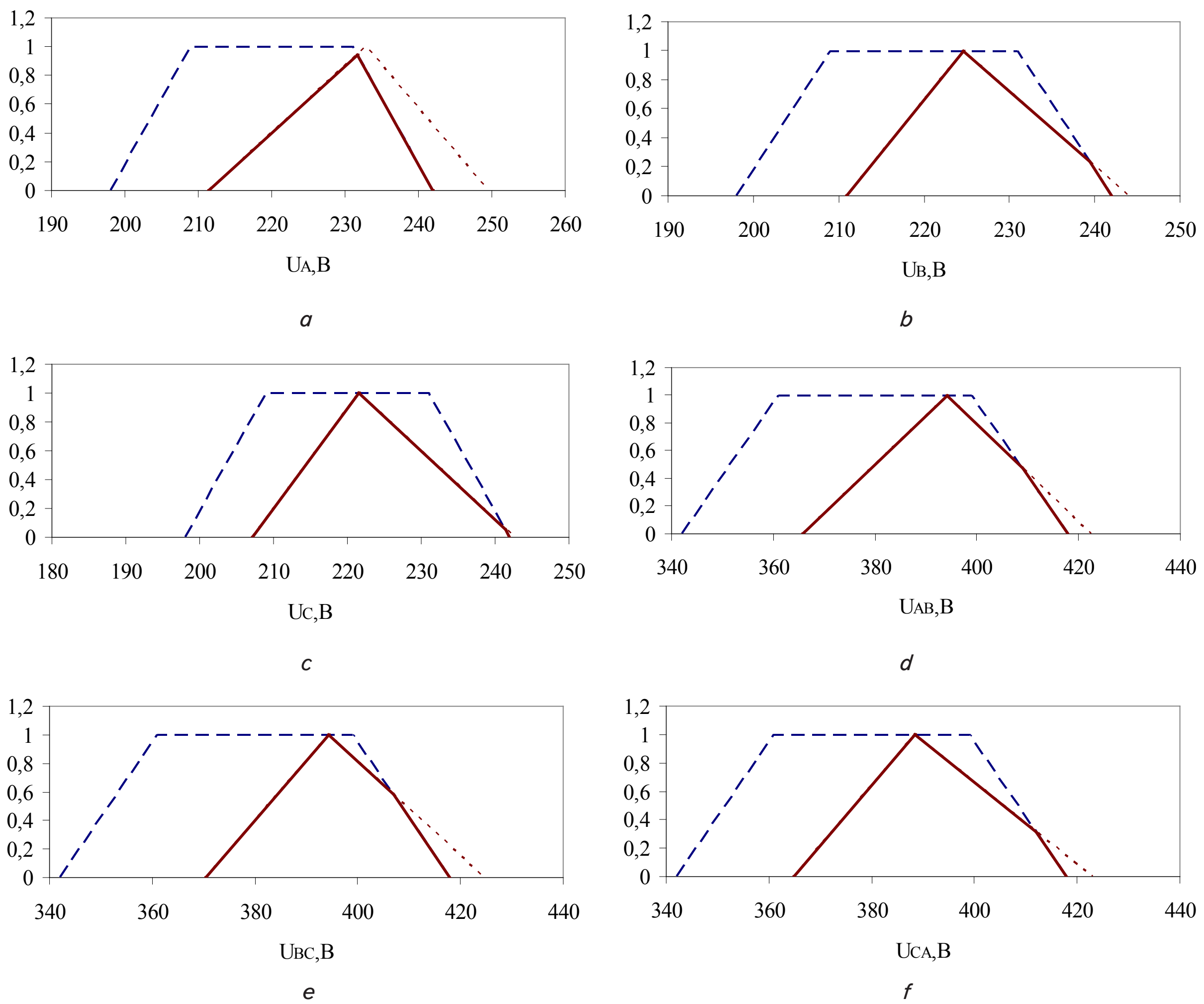

Fig. 3. The result of fuzzy evaluation of voltage deviation: — — — Norm EQ, - - - - - EQ index, ——— intersection ; *a* – line voltage U_A, B, *b* – line voltage U_B, *c* – line voltage U_C, B, *d* – phase voltage U_{AB}, B, *e* – phase voltage U_{BC}, B, *f* – phase voltage U_{CA}, B

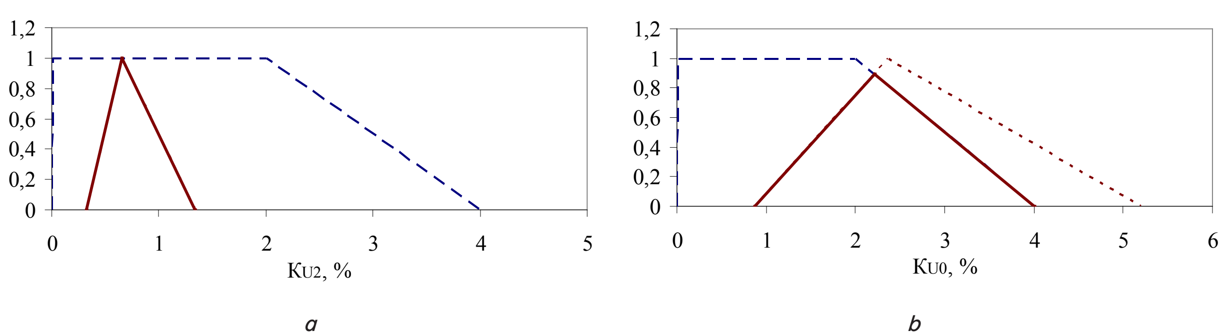

Fig. 4. The result of fuzzy evaluation of voltage unbalance: — — — Norm EQ, - - - - - EQ index, ——— intersection; *a* – the reverse sequence coefficient K_{U2}, %, *b* – coefficient of direct sequence K_{U0}, %

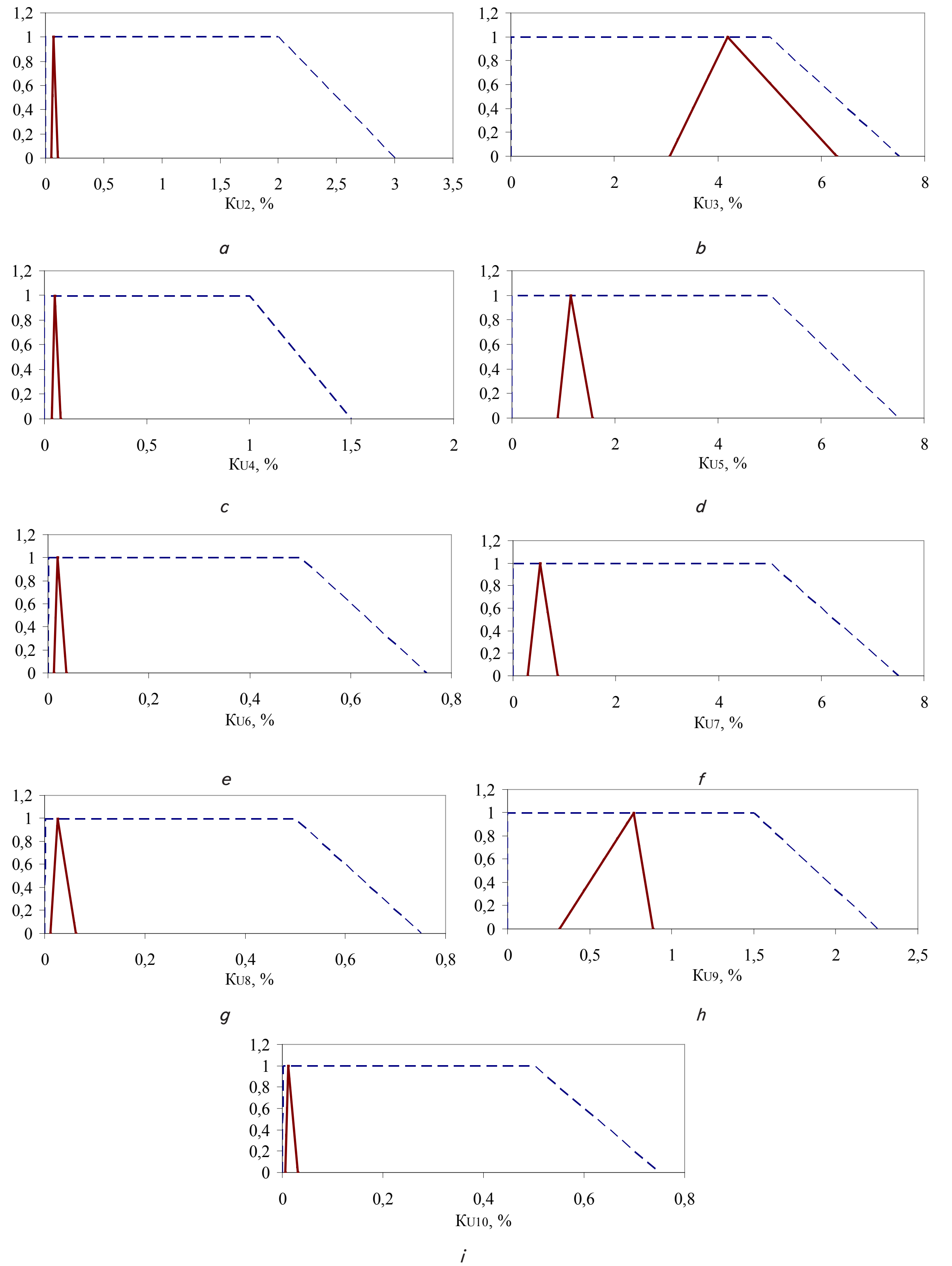

Fig. 5. The result of fuzzy evaluation of non-sinusoidal voltage: Norm EQ, EQ index, intersection; *a* – the coefficient of the *n*-th harmonic component of the voltage K_{U2}, %, *b* – coefficient of the n-th harmonic component of the voltage K_{U3}, %, *c* – the coefficient of the *n*-th harmonic component of the voltage K_{U4}, %, *d* – factor of the *n*-th harmonic component of the voltage K_{U5}, %, *e* – the coefficient of the *n*-th harmonic component of the voltage K_{U6}, %, *f* – the coefficient of the *n*-th harmonic component of the voltage K_{U7}, %, *g* – coefficient of the *n*-th harmonic component of the voltage K_{U8}, %, *h* – coefficient of *n*-th harmonic component of the voltage K_{U9}, %, *i* – coefficient of *n*-th harmonic component of the voltage K_{U10}, %

$$\mu_{KU2}=1,\quad \mu_{KU3}=1,\quad \mu_{KU4}=1,\quad \mu_{KU5}=1,\quad \mu_{KU6}=1,\quad \mu_{KU7}=1\,,$$

$$\mu_{KU8}=1,\quad \mu_{KU9}=1,\quad \mu_{KU10}=1\,.$$

Obviously, fuzzy evaluation of the quality of electricity shows that for at least 10 major harmonics, it complies.

Integral index of electricity quality [10], based on the evaluations of individual conjunction fuzzy indicators is

$$\mu_{EQ}=\min(\mu_{\Delta U_A},\ \mu_{\Delta U_B},\ \mu_{\Delta U_C},\ \mu_{\Delta U_{AB}},\ \mu_{\Delta U_{BC}},\ \mu_{\Delta U_{CA}},$$

$$\mu_{\Delta K2U},\ \mu_{\Delta K0U},\ \mu_{KU2},\ \mu_{KU3},\ \mu_{KU4},\ \mu_{KU5},$$

$$\mu_{KU6},\ \mu_{KU7},\ \mu_{KU8},\ \mu_{KU9},\ \mu_{KU10})=0{,}648.$$

Using the integral index, we can describe the quality of electric power, depending on the type of load – lighting, motor, heating and appliances with a microprocessor control unit. Therefore, if we know the type of load, it is possible to consider only the IEQ, which have a negative effect on the operation of a particular electroreceivers. Taking into account the expressions (7)–(9) we obtain the following values of the generalized IEQ:

– for the motor load

$$\mu_{EQ}=\min\left(\mu_{\delta U_y},\mu_{K_U},\mu_{K_{U(n)}},\mu_{K_{2U}},\mu_{K_{0U}},\mu_{\Delta f},\mu_{\Delta t_P},\mu_{rU}\right)=0{,}648,$$

– for lighting load

$$\mu_{EQ}=\min\left(\mu_{\delta U_y},\mu_{\delta U_t},\mu_{P_t},\mu_{K_{0U}},\mu_{\Delta t_P},\mu_{U_{imp}}\right)=0{,}648,$$

– for devices with microprocessor control units

$$\mu_{EQ}=\min\left(\mu_{\delta U_t},\mu_{P_t},\mu_{K_U},\mu_{K_{U(n)}}\right)=1.$$

In comparison with the deterministic method [1], which is designed to secure the presence of rather poor quality of electricity and determine the measures to normalize EQ into the developed methodology allows you to track changes in the quality of electricity even if the major parameters are within the permissible values, to analyze the dynamics of change and the IEQ identify proactive measures to normalize the EQ.

8. Conclusion

A method for evaluation of quality of electric energy in the form of fuzzy was developed. The proposed method makes it possible to assess the degree of conformity of quality standards, as well as to monitor changes in the quality of electricity even if the major parameters are within the permissible values, to analyze the dynamics of change IEQ and identify proactive measures to normalize the EQ.

The integrated indicator of quality of electric energy for specific load was proposed. Using integral electrical energy quality indicators you can determine the degree of influence of poor electrical energy mode specific groups of consumers, as well as the additional electrical energy losses. If you know the type of load, it is possible to consider only the IEQ, which have a negative impact on the operation of a particular electroreceivers.

Thus, using the generalized indicator of the quality of electrical energy, being aware of the type of load you can determine the degree of influence of poor electrical energy mode of operation, the service life of specific groups of consumers, as well as the additional electrical energy losses.

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