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POWER COMPONENTS OF ELECTRIC ENERGY FOR TECHNICAL AND COMMERCIAL ELECTRICITY METERING

Purpose. Determination of power components of electric energy in the circuits with polyharmonic current and voltage.

Methodology. Using the modern equipment for measuring the amount of electricity consumption and estimating its quality, an experimental study of the mode indicators of the electric power network node of a small enterprise with a synchronous average-size generator, with a nonlinear and non-symmetric load is performed. Based on well-known publications, the concept of determination of active and reactive power with the use of scalar and vector products of instantaneous currents and voltages is analyzed.

Findings. As a result of analyzing the obtained indicators, power quality defects were recorded. It was noted that measuring the amount is based on the well-known concepts of the active and reactive powers while the quality of the latter is determined indirectly from the current and voltage. For single-phase circuits with polyharmonic currents and voltages according to known methods of Fourier analysis in a trigonometric form the calculation of the instantaneous power was performed and its components were determined. Components of power, which are caused by different frequency components of the current and voltage, were considered as a separate group. It was noted that these components, their combinations, or their effective values can be used to estimate the quantity and quality of electric energy.

Originality. It has been established that measuring the amount of the electricity consumption and estimating its quality indicators by the level of voltage do not allow taking into account the poor quality of energy consumption or energy supplying properly and, consequently, differentiating the amount of low-quality and hi-quality product (energy).

Practical value. The procedure for determining the components of power for estimating the flow of energy at the metering point was proposed with presenting currents and voltages as polyharmonic periodic functions, which is a common technique in electrical engineering.

Keywords: *power of electric energy, amount and quality of electric energy*

Introduction. Electric energy, depending on the sphere of human activity is considered as a philosophical concept, technical term, subject of economic activity or commodity. Also this is a physical term – the energy that has or carries the electromagnetic field. The term “electricity” is used more often as that meaning a certain quantity of energy supplied by the power plant to the electricity grid or received from the network by the consumer. In a market economy, electricity is seen as a product of generation, transmission, distribution and consumption of electric energy.

In this case there is a market of electric energy, which includes certain participants: owners of generating equipment; suppliers of electric energy; electricity buyers, among which there are energy sales companies,

large consumers, guarantee suppliers, organization of export-import operations; infrastructure organizations [1, 2]. The features of the structure and mechanism of the interaction of market elements make the subject of research by researchers of the financial and economic sectors [2–4]. Quantitative indicators of electric energy are considered as parameters characterizing the volume of production. However, regardless of the spheres of use, electric energy is characterized by certain indicators, one of which is the power [5, 6]. This one depends on the parameters of the mode and parameters of the elements of the electric circuit in which it exists, and these parameters actually describe the quantity of electric energy that crosses a certain metering point of the circuit per unit of time.

Analysis of the recent research. According to the work of scientists [7, 8], the analysis of electric power as

a signal can provide information not only about the amount of electric energy flow, but also about some features of this process. Suffice it to recall the definition of the total apparent power of electric energy in circuits with sinusoidal current and voltage, with linear loads, and the elementary division of the apparent power into active and reactive [9, 10]. It allows us to quantify the flow of electric energy, which accompanies the process of execution of work and which has been transferred by the transport system, but has not performed the work itself. If we talk about the accounting of electric energy, as an integral component, which accompanies the settlement relationship, then, unlike accounting for the electric energy of active power, the calculation of reactive power energy is not always carried out.

Like any product, electrical energy has certain indicators that characterize its quality. These indicators and their normative values are regulated by the relevant standards [11, 12]. Some indicators of quality of electric energy are recommended for entering into contracts concerning electricity connection and delivery between the network organization and the consumer as legal entities. But these standards do not include any parameters that are measured as electrical energy or power. That is, the quality of electric energy is considered and evaluated by the level of a certain number of parameters indirectly, using the indicators which are calculated by the voltage at the node of the electrical network. The question arises why, speaking about the requirements for the quality of electric energy, the standards operate with single component which is involved in the formation of the flow of electric energy — voltage, not taking into account the other component, which definitely influences the first one and depends on it — the current. The solution of this issue has led scientists to the need to determine the power of electric energy and determine the components of this power, which qualitatively and quantitatively reflect the level of deviation from the desired mode for single-phase or three-phase circuits or power lines [13].

Formulation of the problem. The technical equipment for the metering of electric energy has quickly passed the path from the first induction counters invented in 1888 to the intelligent metering and information systems for control and accounting the electric energy. These systems are hardware-software complexes with electrical and electronic devices that provide measurement for the processes of generation, transmission, distribution and consumption of electric energy and displaying the data of the flow of electric energy at the metering point or points, with the possibility to take into account the electricity pricing and the quality indicators [14, 15]. The universality, multi-functionality and structure of this complex provide high speed and precision of the data mining. The availability of such complexes and the undeniable effect of their use have made them a tool for monitoring, accounting and optimizing the use of electrical energy at enterprises. At the same time algorithmic support in the part of determination of electric energy indices does not correspond to modern ideas about the components of power in the places of connection of measuring equipment [15]. Thus, the high intel-

lectual potential of measuring and information systems for monitoring and accounting of electric energy is offset by the algorithm for determining the components of power and the corresponding assessment of the quality of electric energy consumption [8].

The objectives of the article. Determination of power components of electric energy in the circuits with polyharmonic current and voltage for electricity metering taking into consideration its quality.

Presentation of the main research and explanation of scientific results. Increasing the number of autonomous electricity producing installations as a result of the implementation of energy saving technologies complicates the system of supply and consumption of electric energy and puts a lot of tasks for the scientists concerning the rational use of these electricity producing installations, including integrated control and management. In fact, the connection of the generating installations affects both the parameters of the circuit of the electrical system and the parameters of the mode. The scheme with a complex asymmetric nonlinear load (which in the initial version of the electricity supply consumes electric energy with a polyharmonic current, loads in a certain way the electrical network by components of power, affects the quality of electric energy) receives an additional mesh of the electric energy flow. In the updated scheme, taking into account the parameters of its equivalent circuit including the parameters of generate elements and their mode, the distribution of components of the power of electric energy is different, conceivably significantly from the original version.

As an example, let us consider some of the regime parameters obtained by measuring at a certain time intervals on the low voltage busbars of the step-down transformer substation of a small industrial plant. The simplified electrical circuit of a worksite of this plant is shown in Fig. 1.

The measurement was performed by the Qualistar CA 8334B analyzer under the mode when the worksite was supplied from the external network through the step-down transformer (TC-1600/10-U3) while the cogeneration unit synchronous generator (GHS 2-800F-10 UHL4) was connected to the mentioned low voltage busbars of the sep-down transformer substation.

The analyzer Qualistar C.A 8334B has a large number of measurement options in comparison to the standard electricity meters which is usually used by enterprises.

The root-mean-square (RMS) value of the current (Fig. 2, *a*), the RMS value of the voltage (Fig. 2, *b*), total

Fig. 1. Simplified circuit diagram of an electrical system to study the parallel operation of a generator with an electric network

Fig. 2. The time diagrams of the electric energy transmission mode through the metering point:

a – the RMS value of the current; b – the RMS value of the voltage; c – the THD coefficient of the current; d – the third harmonic of current; e – the voltage and current unbalance; f – active power

harmonic distortion (THD) of the current (Fig. 2, *c*), the level of the third current harmonic (Fig. 2, *d*), unbalance of the current (Fig. 2, *e*) and active power (Fig. 2, *f*) were measured for the analysis of the processes of electric energy flow.

As a result of the measurement analysis, the level of power and volumes of electricity consumption into the metering point (Fig. 2, *f*) were determined and the increase in the RMS voltage value (Fig. 2, *b*) was noticed. This confirms the energy exchange with the external network. The reactive power analysis was also carried out, but the results are not given in this paper in the absence of useful information. On the interval when energy is flowing from the consumer to the external network, the current decrease in the three phases of the metering point and a significant current increase in the neutral wire (Fig. 2, *a*) were noted. To find out the reasons for increasing the current of the neutral wire, an analysis of the level of current harmonics (Fig. 2, *c*) and the level of the third harmonic relative to the main one (Fig. 2, *d*) was performed, taking into account the unbalance (Fig. 2, *e*).

On the basis of the obtained data, the conclusion was formulated about significant non-sinusoidal nature of the load current. It caused the redistribution between two kinds of power of electric energy: the power which was transmitted by the fundamental components — to the synchronous generator; the power which prevents the transmission of electric energy — to external network through the transformer with delta-connected primary winding, that let it partially act as a filter for zero-sequence components.

Summarizing the executed research a certain insufficiency of the obtained information should be noted. It is impossible to determine the following: the nature of the power of electric energy in the examined mode which is transmitting through the metering point and how much of this energy is transmitted by distortions; the distribution of these powers between the external network, the generator and the load. The information concerning distortions in this case reveals the nature of the process very poorly.

Thus, the use of the applied instrumentation and measurement methods provides the operator with important and useful information, but does not allow estimating the level of power that prevents transmission and distribution in the supply system, estimating the volumes of this energy, to determine the loads that determine the corresponding power and their contribution, using certain technical and organizational measures to reduce this power. In this case, it is first necessary to determine the mathematical apparatus and the procedure for the formation of the relevant criteria, the introduction of the said apparatus into the modern information-measuring complexes and systems, or providing recommendations for their modernization.

As noted in [5, 9, 14], it is necessary to revise the traditional comprehension concerning the power components and the energy that gain new meaning and often become (with time because of some inertia) basic in

the analysis of power components. There were used models for analyzing the interaction between currents (*i*) and voltages (*u*) in the metering point by representing RMS values (*U, I*) as vectors in space or on a plane by vector algebra equations

$$U^2 I^2 = (UI \cos \varphi)^2 + (UI \sin \varphi)^2 = (u, i)^2 + [u \times i]^2, \quad (1)$$

where $\varphi = \arccos[(u, i)/UI]$ is the angle between vectors of voltage and current; this parameter gives a certain geometric interpretation of the energy process.

Such way of representing functions by vectors gives a certain geometric interpretation of vector diagrams. The ratio (1) establishes the decomposition of the vector of current (voltage) by the vector of voltage (current) into the mutual orthogonal components, placing the basis for voltage (current) appropriately, as follows

$$\begin{cases} I_{\parallel} = I \cos \varphi = \|i_{\parallel}\|, & i_{\parallel} = \frac{(u, i)}{U^2} u; \\ I_{\perp} = I \sin \varphi = \|i_{\perp}\|, & i_{\perp} = i - i_{\parallel} \end{cases} \quad (2)$$

$$\begin{cases} U_{\parallel} = U \cos \varphi = \|u_{\parallel}\|, & u_{\parallel} = \frac{(u, i)}{I^2} i; \\ U_{\perp} = U \sin \varphi = \|u_{\perp}\|, & u_{\perp} = u - u_{\parallel} \end{cases} \quad (3)$$

with decomposing any power into two orthogonal components, with the representation of one of them in the form of scalar product, and the other in the form of vector multiplication for corresponding vectors. But we should note the important property of vector multiplication

$$u \times i = -i \times u,$$

which as a scalar product loses any meaning. In most sources from the theory of electrical engineering it is adopted that the projection of current vector are placed on the voltage vector [7]. Then, considering expression (1), one should use the terms active ($i_a = i_{\parallel}$) and reactive ($i_r = i_{\perp}$) currents. Let us show the instantaneous power in the form

$$p = u_i = u(i_a + i_r) = ui_a + ui_r.$$

It was accepted that the reactive power is considered as a measure for the last component

$$Q = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} (ui_r)^2 dt} = u \times i = \|u\| \|i_r\| = UI \sin \varphi. \quad (4)$$

The active power is considered as a measure for the first component

$$P = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} (ui_a)^2 dt} = (u, i) = \|u\| \|i_a\| = UI \cos \varphi. \quad (5)$$

Suitably the root of the sum of squares of these measures — apparent power

$$S = \sqrt{P^2 + Q^2} = \sqrt{U^2 I^2}. \quad (6)$$

For the case of monoharmonic currents and voltages, the active power is

$$P = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} (u_i)^2 dt} = \frac{1}{T} \int_{t_0}^{t_0+T} u_i dt = (u, i). \quad (7)$$

These indicators are the basis for calculations of energy flow distributions in the networks, in particular, between the active and reactive powers, and, in fact, are fundamental in determining the volumes of electricity consumption with polyharmonic currents and voltages. In this case, for sameness (6) they introduce the residual value which reflects the power of electric energy transmitted by distortions. For single-phase metering points this is the distortion power [5, 7]

$$D = \sqrt{\sum_{k \neq l} U_k^2 I_l^2 + U_l^2 I_k^2 - U_k I_k U_l I_l \cos(\varphi_k - \varphi_l)}.$$

For three-phase metering points they introduce additionally the pulsed power, which reflects an asymmetry and has two components due to the action of the voltages and currents of the forward and reverse sequences

$$T = \sqrt{S^2 - P^2 - Q^2 - D^2}.$$

But all these components are intended to transform (in suitable cases) the square of the RMS values product of the currents and voltages (norms) (6), that is, the square of apparent power, to the sum of the squares of the active (4) and reactive (5) powers. Thus, the parameter of apparent power determines all subsequent actions connected with the decomposition of the power components and the identification of their appropriate partial contributions into the total power flow, which is characterized by the apparent power.

In fact, all calculations of the power of electric energy are generalized by the integral expression, known from the functional analysis and derived from the Cauchy-Budyanovsky-Schwartz inequality [6]

$$\left(\int_{t_0}^{t_0+T} u_i dt \right)^2 = \int_{t_0}^{t_0+T} u^2 dt \int_{t_0}^{t_0+T} i^2 dt - \frac{1}{2} \int_{t_0}^{t_0+T} \int_{t_0}^{t_0+T} (u(\tau)i(t) - u(t)i(\tau))^2 d\tau dt,$$

which corresponds to the equation

$$P^2 = S^2 - Q^2,$$

and if in the case of harmonic functions (currents, voltages) they understand the Q as the reactive power, then in the cases of polyharmonic functions the question of the expediency of the semantic load and content of the parameters S and Q actually arises. And if the active power is in any case determined by scalar product

$$P = (u, i) = \frac{1}{T} \int_{t_0}^{t_0+T} u_i dt = \sum_k U_k I_k \cos \varphi_k,$$

and determines the energy transmitted through the metering point to perform useful work, then the total power is manifested by multiplying the norms

$$S = \|u\| \|i\|,$$

and from the point of view of electricity metering cannot be used [14]. Accordingly, the question arises about the rationality of electricity metering for the power Q and the components which will reflect the nature of the flow of electric energy except the active power.

In the theory of electrical engineering for calculating the modes of circuits with nonlinear elements, the methods of harmonic analysis are used, in the power engineering these methods are used for calculations of the quality of electric energy. Flow distribution, thus, is calculated by the powers P and Q for the corresponding harmonics.

In [7], they consider the simplest case of the function of electric power at the input of a two-terminal circuit with a given polygonal voltage function

$$u = \sum_k u_k = \sum_k \sqrt{2} U_k \sin(k\omega t + \psi_{uk}). \quad (8)$$

Then the current i at the input is

$$i = \sum_n i_n = \sum_n \sqrt{2} I_n \sin(n\omega t + \psi_{in}), \quad (9)$$

where the order-numbers of harmonics are defined by the set $V = \{1, 2, \dots, k, n, \dots, v\}$. The angle of shift between harmonics of voltage and current of one order is $\varphi_k = \psi_{uk} - \psi_{ik}$. In this case, instantaneous power is

$$p = ui = \sum_k u_k \sum_n i_n = \sum_{k,n} u_k i_n.$$

Taking into account expressions (8, 9), the instantaneous power function is represented in the form

$$p = \sum_{k,n} 2U_k I_n \sin(k\omega t + \psi_{uk}) \sin(n\omega t + \psi_{in}),$$

or

$$p = \sum_{k,n} U_k I_n \cos[(k-n)\omega t + \psi_{uk} - \psi_{in}] - \sum_{k,n} U_k I_n \cos[(k+n)\omega t + \psi_{uk} + \psi_{in}]. \quad (10)$$

From expression (10) it follows that the spectrum of the instantaneous power function contains harmonics with the order (s) that is determined as the difference ($k-n$) as well as the sum ($k+n$) of the orders of the voltage and current harmonics, i. e. ($s = k \pm n$). So, instantaneous power is

$$p = \sum_s p_s = p_0 + p_1 + \dots + p_{k-n} + \dots + p_{k+n} + \dots + p_z, \quad (11)$$

where the order-numbers of harmonics are defined by a set $Z = \{0, 1, 2, \dots, s, \dots, z\}$, the minimum element value in the set is 0 and the maximum one is $2v$. Harmonic spectrum of instantaneous power depends on which harmonics ordered-numbers are represented in the voltage and current spectrums.

It is necessary to take into account the fact that different, but certain combinations of voltage and current harmonics create same-order power harmonics (for example, if $k = n + 1$, then the difference $s = k - n$ is equal to 1 at any numbers $s = k$ and $s = n$), therefore the actual number of harmonics of power may be less than the maximum value, but not less than double number of voltage and current harmonics ($z = 2v$).

As pointed in [5, 6], the harmonics spectrum of the instantaneous power gives a general characteristic of power fluctuations and can be used to determine a number of coefficients that characterize the form of oscillation.

Instantaneous power, which is determined by a double sum (10), is written in the form

$$p = \sum_k U_k I_k \left[\cos \varphi_k + \cos(2k\omega t + \psi_{uk} + \psi_{ik}) \right] + \sum_{k \neq n} U_k I_n \cos \left[(k-n)\omega t + \psi_{uk} - \psi_{in} \right] - \sum_{k \neq n} U_k I_n \cos \left[(k+n)\omega t + \psi_{uk} + \psi_{in} \right].$$

The first part of this equation is formed by the components formed by the same-order voltage and current harmonics and is called the harmonic power

$$p_{kk} = \sum_k \left[U_k I_k \cos \varphi_k + U_k I_k \cos(2k\omega t + \psi_{uk} + \psi_{ik}) \right],$$

and the second one is formed by the different-order voltage and current harmonics and therefore is called the interharmonic power

$$p_{kn} = \sum_{k \neq n} U_k I_n \cos \left[(k-n)\omega t + \psi_{uk} - \psi_{in} \right] - \sum_{k \neq n} U_k I_n \cos \left[(k+n)\omega t + \psi_{uk} + \psi_{in} \right].$$

Harmonic power p_{kk} contains the members with dual frequency harmonics of voltage (or current) as well as the members with zero frequency, so it is the combination of the current and voltage components with equal frequency. These components determine the average power of the separate harmonics $P_k = U_k I_k \cos \varphi_k$ and their sum gives the constant average power P which has the important practical value

$$p_{kk0} = \sum_k U_k I_k \cos \varphi_k = \sum_k P_k = P.$$

A well-known (in linear circuits theory) technique for decomposition of voltages and currents into orthogonal-active and reactive components (2, 3) can also be used in the polyharmonics system (Fig. 3, a) for further decomposition in order to detect the variants for instantaneous power analysis.

In this case, the orthogonalization is performed in relation to the current or voltage vector, that is, the given functions of the voltage u and current i in the case of a linear two-terminal network are decomposed into the orthogonal components of the voltage u_a and u_r , or current i_a and i_r , so that the active component of each harmonic of voltage u_{ka} coincides by the phase with this harmonic of current — $u_{ka} \parallel i_k$ and the reactive compo-

Fig. 3. Representation of voltage (a) and current vectors (b) for a separate harmonic

nent u_{kr} is perpendicular to it — $u_{kr} \perp i_k$, similarly $i_{ka} \parallel u_k$ and $i_{kr} \perp u_k$. Function expressions of the orthogonal components according to (8, 9) under the condition $k = n$ have the form

$$\begin{aligned} u_{ka} &= \sqrt{2} U_k \cos \varphi_k \sin(k\omega t + \psi_{ik}); \\ u_{kr} &= -\sqrt{2} U_k \sin \varphi_k \sin(k\omega t + \psi_{ik}); \\ i_{na} &= \sqrt{2} I_n \cos \varphi_n \sin(n\omega t + \psi_{un}); \\ i_{nr} &= \sqrt{2} I_n \sin \varphi_n \sin(n\omega t + \psi_{un}). \end{aligned}$$

With their help, the expression of the instantaneous power function is presented in a different form in two versions, depending on whether the voltage or current is expanded to the orthogonal components

$$\begin{aligned} p &= \sum_k U_k I_k \cos \varphi_k + \sum_k U_k I_k \cos \varphi_k \cos(2k\omega t + 2\psi_{ik}) - \sum_k U_k I_k \sin \varphi_k \sin(2k\omega t + 2\psi_{ik}) + \sum_{k \neq n} U_k I_n \cos \varphi_k \cos \left[(k-n)\omega t + \psi_{ik} - \psi_{in} \right] - \sum_{k \neq n} U_k I_n \cos \varphi_k \cos \left[(k+n)\omega t + \psi_{ik} + \psi_{in} \right] - \sum_{k \neq n} U_k I_n \sin \varphi_k \sin \left[(k-n)\omega t + \psi_{ik} - \psi_{in} \right] + \sum_{k \neq n} U_k I_n \sin \varphi_k \sin \left[(k+n)\omega t + \psi_{ik} + \psi_{in} \right]. \\ p &= \sum_k U_k I_k \cos \varphi_k + \sum_k U_k I_k \cos \varphi_k \cos(2k\omega t + 2\psi_{uk}) + \sum_k U_k I_k \sin \varphi_k \sin(2k\omega t + 2\psi_{uk}) + \sum_{k \neq n} U_k I_n \cos \varphi_n \cos \left[(k-n)\omega t + \psi_{uk} - \psi_{un} \right] - \sum_{k \neq n} U_k I_n \cos \varphi_n \cos \left[(k+n)\omega t + \psi_{uk} + \psi_{un} \right] - \sum_{k \neq n} U_k I_n \sin \varphi_n \sin \left[(k-n)\omega t + \psi_{uk} - \psi_{un} \right] + \sum_{k \neq n} U_k I_n \sin \varphi_n \sin \left[(k+n)\omega t + \psi_{uk} + \psi_{un} \right]. \end{aligned}$$

Accordingly, in the first and second cases instantaneous power is divided into five components

$$p = p_{kk0} + p_{kka} + p_{kkr} + p_{kna} + p_{knr}, \quad (12)$$

i.e. into constant component, active and reactive components of harmonious and interharmonic capacities. Another variant of decomposition of power is possible, when the orthogonal components are allocated only from the harmonic series of power. The appropriate expression can be obtained directly from (11).

In case of the orthogonal decomposition of the current into components they allocate

$$\begin{aligned} p &= \sum_k U_k I_k \cos \varphi_k + \\ &+ \sum_k U_k I_k \cos \varphi_k \cos(2k\omega t + 2\psi_{uk}) + \\ &+ \sum_k U_k I_k \sin \varphi_k \sin(2k\omega t + 2\psi_{uk}) + \\ &+ \sum_{k \neq n} U_k I_n \cos[(k-n)\omega t + \psi_{uk} - \psi_{in}] - \\ &- \sum_{k \neq n} U_k I_n \cos[(k+n)\omega t + \psi_{uk} + \psi_{in}] = \\ &= p_{\cos}^i + p_{\sin}^i + p_{kn} = p_{kko} + p_{kka} + p_{kkr} + p_{kn}. \end{aligned}$$

A similar expression is obtained in the case of the orthogonal decomposition of the voltage into components

$$p = p_{\cos}^u + p_{\sin}^u + p_{kn} = p_{kko} + p_{kka} + p_{kkr} + p_{kn}.$$

According to these decompositions, which are well known in the literature (but only for current) as orthogonal, the cosine $p_{\cos}^i(p_{\cos}^u)$, sine $p_{\sin}^i(p_{\sin}^u)$ and interharmonic p_{kn} components of power were allocated in instantaneous power. As noted in [7], some authors see in this the analogy with the known orthogonal decomposition of the integral value of the apparent power into three orthogonal components of the averaged power values: active, reactive and distortion power

$$S^2 = P^2 + Q^2 + D^2.$$

It was suggested to call these three components of the instantaneous power in accordance with expression (12) as an active instantaneous p_p , a reactive instantaneous p_Q and distortion instantaneous power p_T

$$\begin{aligned} p_p^i &= p_{kko} + p_{kka} = p_{\cos}^i; \\ p_Q^i &= p_{kkr} = p_{\sin}^i; \\ p_D &= p_{kna} + p_{knr} = p_{kn}. \end{aligned}$$

Then instantaneous power p can be divided into three components, respectively

$$p = p_p^i + p_Q^i + p_D,$$

or

$$p = p_p^u + p_Q^u + p_D.$$

But it should be noted that with non-sinusoidal voltage $p_p^i \neq p_p^u$ and $p_Q^i \neq p_Q^u$. Obtaining two values p_p and p_Q in one scheme indicates the formal character of the definition of such components of instantaneous power.

But the described apparatus of the procedure for forming the components of instantaneous power of electric energy creates the possibility of forming the measures of certain energy parameters by power, or by its components.

Let us consider the most generalized case of existence of voltage and current (Fig. 3, b), which are represented by expressions (8, 9), and the expression (10) is rewritten as follows

$$\begin{aligned} p &= \sum_k U_k I_k \cos \varphi_k - \\ &- \sum_k U_k I_k \cos(2k\omega t) \cos(\psi_{uk} + \psi_{ik}) + \\ &+ \sum_k U_k I_k \sin(2k\omega t) \sin(\psi_{uk} + \psi_{ik}) + \\ &+ \sum_{k \neq n} U_k I_n \cos((k-n)\omega t) \cos(\psi_{uk} - \psi_{in}) - \\ &- \sum_{k \neq n} U_k I_n \sin((k-n)\omega t) \sin(\psi_{uk} - \psi_{in}) - \\ &- \sum_{k \neq n} U_k I_n \cos((k+n)\omega t) \cos(\psi_{uk} + \psi_{in}) + \\ &+ \sum_{k \neq n} U_k I_n \sin((k+n)\omega t) \sin(\psi_{uk} + \psi_{in}). \end{aligned} \quad (13)$$

Thus, the power represents the sum of the components

$$p = p_0 + p_{kk,\cos} + p_{kk,\sin} + p_{kn,\cos} + p_{kn,\sin}.$$

The latter combination is a Fourier decomposition of instantaneous power

$$\begin{aligned} p &= p_0 + p_{\cos} + p_{\sin} = \\ &= p_0 + \sum_s P_{\cos,s} \cos(s\omega t) + \sum_s P_{\sin,s} \sin(s\omega t). \end{aligned}$$

In this manner

$$\begin{aligned} p_0 &= P_0; \\ p_{\cos} &= \sum_s P_{\cos,s} \cos(s\omega t) = p_{kk,\cos} + p_{kn,\cos}; \\ p_{\sin} &= \sum_s P_{\sin,s} \sin(s\omega t) = p_{kk,\sin} + p_{kn,\sin}. \end{aligned}$$

Considering that the harmonic components of the power are caused by the combination $k \pm n$, for example, by $k = 1, n = 3, k + n = 4, k - n = -2$, then these combinations are joined to others with the same order. In more detail, this process is illustrated in Fig. 4.

Considering the above-mentioned, the components of the power are

$$p_{\cos} = \sum_s P_{\cos,s} \cos(s\omega t) = p_{kk,\cos} + p_{kn=kk,\cos} + p_{kn \neq kk,\cos};$$

Fig. 4. Contribution of the current and voltage harmonics into the harmonics of power

$$p_{\sin} = \sum_s P_{\sin, s} \sin(s\omega t) = p_{kk, \sin} + p_{kn=kk, \sin} + p_{kn \neq kk, \sin}.$$

Using the analogy similar to expression (12), we can assume that the components of power (which are obtained by the interaction of the voltage and current harmonics that oscillate at the same frequency $p_{kk \cos}$ and $p_{kk \sin}$) are distorted by the interaction of the harmonics of the voltage and current of different frequencies $p_{kn=kk \cos}$ and $p_{kn=kk \sin}$, providing $|k \pm n| = k + k$. These harmonics are sources of interference that distort the cosine and sine power of the corresponding frequency, but $p_{kn \neq kk \sin}$ and $p_{kn \neq kk \cos}$ cause the distortion power for $|k \pm n| \neq k + k$. As a result, the power presents by components

$$P = P_0 + p_{kk \cos} + p_{kn=kk \cos} + p_{kn \neq kk \cos} + p_{kk \sin} + p_{kn=kk \sin} + p_{kn \neq kk \sin},$$

which are calculated for the particular metering point with the harmonic components of voltage and current, and taking into account the proposed terms [8] for the power of electric energy, have the following names: P_0 – constant active power; $p_{kk \cos}$ – canonical cosine oscillating power; $p_{kn=kk \cos}$ – pseudo-canonical oscillating cosine power; $p_{kn \neq kk \cos}$ – non-canonical oscillating cosine power; $p_{kn=kk \sin}$ – canonical sine oscillating power; $p_{kn=kk \sin}$ – pseudo-canonical oscillating sine power; $p_{kn \neq kk \sin}$ – non-canonical oscillating sine power.

Each of these components has a definite influence on the formation of the flow of electricity and should be assessed with regard to the degree of influence and recorded during the accounting. In the general case, these components of power can have both a positive and a negative sign, that is, to be directed at the metering point in opposite directions. Given the probability of a broad spectrum of power components, and, accordingly, the complexity of the assessment of each component, it is necessary to implement the mechanism of their certain generalization by the nature or influence on the electricity system. Thus, there are grounds for an appropriate financial assessment (SS) for effective power (P) as a measure of the process. The calculation can be performed, for example, in two polar expressions, among a large number of individual cases for a specific unit value C_0

$$CC1 = C_0(P_{0C}, P_{0G}, P_{\sin C}, P_{\sin G}, P_{\cos C}, P_{\cos G}),$$

or individual cost per components of power

$$CC2 = C_{0C}P_{0C} + C_{0G}P_{0G} + C_D(P_{\cos} + P_{\sin}),$$

where P_{0C} , P_{0G} are effective consumed and generated constant components of power; $P_{\sin C}$, $P_{\sin G}$ are effective consumed and generated synchronous sine components of power; $P_{\cos C}$, $P_{\cos G}$ are effective consumed and generated alternating cosine power components; $P_{\cos}$, $P_{\sin}$ are effective synonymous cosine and sine components of power.

These expressions, of course, require detailed analysis, decomposition or aggregation, taking into

account the influence of components on the equipment of the consumer or supplier of electrical energy. The purpose of this process is the responsibility for the quality of electric energy and motivation to improve the process of supply and consumption of energy.

Conclusions and recommendations for further research.

1. Insufficient quality of electric energy as a commodity that is produced and consumed is not taken into account by the parties involved in this process at the present stage of the formation of technical and financial calculations between them.

2. Measuring the amount of the electricity consumption and estimating its quality indicators by the level of voltage do not allow taking into account properly the poor quality of energy consumption or energy supplying, and, consequently, differentiating the amount of low-quality and hi-quality commodity (energy).

3. The well-known approach to electricity metering by the allocation of apparent power to the active, reactive and distortion powers to bring the power balance does not reflect the completeness of energy processes into the flow of electric energy.

4. Considering the currents and voltages as the polyharmonic periodic functions, which is a common technique for power systems, and by determining, based on harmonic components, the corresponding components of power, it is proposed to use this technique to estimate the energy flow in the metering point.

5. The mechanism of formation of metering indicators and the corresponding unitary cost requires a thorough analysis of the components of power taking into account the degree of their influence on the electricity system, both from the supplier's side and from the consumer's side.

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Компоненти потужності електричної енергії для її технічного й комерційного обліку

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Мета. Визначення компонент потужності електричної енергії в колах з полігармонічним струмом і напругою.

Методика. Із використанням сучасного обладнання для контролю обсягів електричної енергії та оцінки якості останньої, проведено експериментальне дослідження показників режиму вузла електричної мережі малого підприємства з синхронним генератором середньої потужності, за наявності нелінійного й несиметричного навантаження. На підставі відомих публікацій проаналізована концепція визначення активної й реактивної потужностей з використанням скалярного й векторного добутку миттєвих струмів і напруг.

Результати. У результаті аналізу отриманих показників встановлені факти порушення якості електричної енергії. Відзначено, що вимірювання

кількості відбувається за відомих уявлень про активну й реактивну потужності електричної енергії, а визначення показників якості останньої відбувається опосередковано за струмом і напругою. Для однофазного ланцюга при дії полігармонічних струмів і напруг, методами Фур'є аналізу у тригонометричній формі, виконано розрахунок миттєвої потужності, визначені її складові. До окремої групи винесені складові, обумовлені різними за частотою гармонійними струма й напруги. Зазначено, що саме ці складові, їх комбінації, або ефективні значення можуть бути використані для оцінки кількості та якості електричної енергії.

Наукова новизна. Встановлено, що вимірювання обсягів споживання електричної енергії та оцінка показників якості за рівнем напруги не дозволяють належним чином урахувати неякісність споживання або поставки енергії, і розділяти обсяги неякісного та якісного продукту (енергії).

Практична значимість. Уважаючи струми й напруги полігармонічними періодичними функціями, що є поширеним прийомом для електроенергетичних систем, запропоновано порядок визначення складових потужності для оцінки потоку енергії в перетині спостереження.

Ключові слова: потужність електричної енергії, кількість і якість електричної енергії

Компоненты мощности электрической энергии для ее технического и коммерческого учета

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Цель. Определение компонент мощности электрической энергии в цепях с полигармоническим током и напряжением.

Методика. С использованием современного оборудования для контроля объемов электрической энергии и оценки качества последней, проведено экспериментальное исследование показателей режима узла электрической сети малого предприятия с синхронным генератором средней мощности, при наличии нелинейной и несимметричной нагрузки. На основании известных публикаций проанализирована концепция определения активной и реактивной мощностей с использованием скалярного и векторного произведения мгновенных токов и напряжений.

Результаты. В результате анализа полученных показателей установлены факты нарушения качества электрической энергии. Отмечено, что измерение количества происходит по известным представлениям об активной и реактивной мощности электрической энергии, а определение показателей качества последней происходит опосредованно по току и напряжению. Для однофазной цепи

при воздействии полигармонических токов и напряжений методами Фурье анализа в тригонометрической форме выполнен расчет мгновенной мощности, определены ее составляющие. В отдельную группу вынесены составляющие, обусловленные различными по частоте гармоническими токами и напряжениями. Указано, что именно эти составляющие, их комбинации, или эффективные значения могут быть использованы для оценки количества и качества электрической энергии.

Научная новизна. Установлено, что измерение объемов потребления электрической энергии и оценка показателей качества по уровню напряжения не разрешают надлежащим образом учесть не-

качественность потребления или поставки энергии и разделять объемы некачественного и качественного продукта (энергии).

Практическая значимость. Полагая токи и напряжения полигармоническими периодическими функциями, что является распространенным приемом для электроэнергетических систем, предложен порядок определения составляющих мощности для оценки потока энергии в сечении наблюдения.

Ключевые слова: *мощность электрической энергии, количество и качество электрической энергии*

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