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ALTERNATIVE INDICATORS OF POWER OF ELECTRIC ENERGY IN A SINGLE-PHASE CIRCUIT WITH POLYHARMONIC CURRENT AND VOLTAGE

Introduction. Many electrical engineering issues use a power balance. It is compiled from averaged power values, and equivalent power is used to characterize power of transient processes. To account electricity, both mono- and polyharmonic currents and voltages use active and reactive power, the quality of electricity is not taken into account. *Problem.* A number of works are declared a certain number of power components that reflect indicators of quantity and quality of electrical energy. These components of power are subject to criticism. The order of determining power components requires algorithmization, as well the task of determining indicators that will reflect poor quality of energy. *Goal.* Development of a technique for determining the components of power in single-phase circuits with polyharmonic current and voltage, for definition electrical energy transmission indicators. *Methodology.* Based on analysis of power components determined in known papers and order of their calculation, the features of taking sign of sine and cosine orthogonal components are marked, depending on combination of numbers a current and voltage harmonics. Using Fourier theory of series and elements of the logic algebra, an algorithm for determining components of electric power energy is developed. *Results.* Highlighting active and reactive powers of the fundamental harmonic of current and voltage; active and reactive power; canonical power components; non-canonical power components, and proposed indicators of quality of transmission of electrical energy. *Originality.* Based on analysis of power represented by trigonometric Fourier series, the specific calculation of canonical and non-canonical components with use of a number of indicators of electric energy transmission is proposed that reflect its quality. *Practical value.* The proposed power components of transmission of electrical energy can be used in technical accounting systems. References. 12, figures 6.

Key words: power of electric energy, quality indicators, power norm, quantity and quality of electric energy.

Мета. Розробка методики визначення компонент потужності, в однофазних колах з полігармонійними струмом та напругою, для формування показників передачі електричної енергії. *Методика.* Використовуючи теорію рядів Фур'є та елементи алгебри логіки, відмічені особливості винесення знаку ортогональних компонент потужності в залежності від комбінації номеру гармонік струму та напруги. *Результати.* Відокремлюючи активну та реактивну потужності основної гармоніки струму та напруги; активну та реактивну потужності; канонічні компоненти потужності; неканонічні компоненти потужності, запропоновано показники якості передачі електричної енергії. *Наукова новизна.* Потужність, представлена тригонометричним рядом Фур'є, містить канонічні та неканонічні компоненти, які відбивають якість електричної енергії. *Практична значимість.* Компоненти потужності, та показники передачі електричної енергії можуть бути використаними в системах технічного обліку для вимірювання обсягів якісної та неякісної енергії. Бібл. 12, рис. 6.

Ключові слова: потужність електричної енергії, показники якості, норма потужності, кількість та якість електричної енергії.

Цель. Разработка методики определения компонент мощности, в однофазных цепях с полигармоническом током и напряжением, для формирования показателей передачи электрической энергии. *Методика.* Используя теорию рядов Фурье и элементы алгебры логики, отмеченные особенности вынесения знака ортогональных компонент мощности в зависимости от комбинации номера гармоник тока и напряжения. *Результаты.* Отделяя активную и реактивную мощности основной гармоник тока и напряжения; активную и реактивную мощности; канонические компоненты мощности; неканонические компоненты мощности, предложены показатели качества передачи электрической энергии. *Научная новизна.* Мощность, представленная тригонометрическим рядом Фурье, содержит канонические и неканонические компоненты, которые отражают качество электрической энергии. *Практическая значимость.* Компоненты мощности, и показатели передачи электрической энергии могут быть использованы в системах технического учета для измерения объемов качественной и некачественной энергии. Библ. 12, рис. 6.

Ключевые слова: мощность электрической энергии, показатели качества, норма мощности, количество и качество электрической энергии.

Introduction. In the electric power, electromechanical and electrical engineering systems and complexes, when solving the problems associated with the transformation of electric energy into other types of energy, the balance of energy or power is used. This allows to check the result of the task solution and estimate the distribution of power flows. In most cases, the balance consists of values averaged over a certain period of time. For a category of problems with stationary processes, such an approach is rational.

In the case of a transient process, such as transforming the power of electric motors in an automated electric drive of technological mechanisms characterized by variable power consumption, additional parameters are

introduced that characterize the mode – S1-S8 [1]. Here, a certain period of time – a cycle is considered. Equivalent mode parameters are used for the cycle, in particular – equivalent power [2].

In modern systems, the generation, transportation and consumption of electric energy are carried out by alternating current except for traction networks of direct current, onboard networks of vehicles, and specialized inserts of direct current [3]. The latter only in a certain approximation operate with direct current, in the general case, the current is alternating.

When operating networks that provide electric energy consumers, regardless of the nature of the current,

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problems arise in the account of electrical energy. For DC networks, the average (at a specified interval) power value is used as the accounting indicator, for AC networks – active and reactive power [4, 5]. In this way, the volume of electric energy is accounted, and reactive power in some way characterizes poor quality. The reactive power is uniquely determined for periodic monoharmonic currents and voltages. In case of distortion of current or voltage, for accounting indicators determined by averaged current and voltage are used. The resulting poor quality of electric energy is estimated by certain indicators, normalizing their acceptable values [6], but accounting low-quality energy is not performed.

Analysis of previous research. A well-known Standard [7], which is a product of many years of work by a group of scientists, declares a certain number of components of electric energy power, each of which reflects characteristic indicators. The determination of the power components of electric energy occurs on the basis of the currents and voltages presented in the trigonometric form of the Fourier series. Using well-known vector forms and concepts of full, active, inactive, reactive power, distortion power, for three-phase circuits of corresponding fundamental powers of direct, zero and reciprocal sequences, the authors sufficiently multifaceted define a characteristic of the electric energy flux. These power components are based on the Budeanu concept and are criticized [8, 9] from the standpoint of determining the harmonic components of power based on harmonic current and voltage. In [10] the question of the formation of power components, both as power source and elements of electric circuits, both with linear and nonlinear characteristics, is considered in various ways. As in the works previously mentioned, the authors are based on the representation of periodic currents and voltages in the trigonometric form of the Fourier series. The substantiated [11] procedures for the determination of the volt-ampere characteristics of nonlinear elements are also based on the representation of current, voltage and power by periodic polyharmonic functions. The last group of works emphasizes the observance of the law of conservation of energy and the implementation of the Tellegen theorem.

Problem definition. The differentiation of the power component provides an opportunity for a certain assessment of the energy process [7]. The analysis of processes in electric circuits using the representation of currents, voltages and powers by polyharmonic functions is used for tasks of identifying parameters and characteristics of circuit elements [11]. In spite of the fact that in both cases the polyharmonic current and voltage are the basic, the determination procedure and the resulting power components are different. In the latter case, the law of conservation of energy is provided, which makes it more favorable for assessing the indicators of transmission of electricity. But the order of determining the components of power requires algorithmization, and as a consequence the problem of determining the indicators that reflect the poor quality of the flow of electric energy, arises.

The goal of the work is the development of a method for determining the components of power of

electric energy in single-phase circuits with polyharmonic current and voltage, for the formation of indicators of transmission of electric energy.

Main material and results of investigations. In the theory of linear circuits with energy sources which determine the monoharmonic currents in the branches and the corresponding monoharmonic voltages in the nodes, for example

$$u = \sqrt{2}U \sin(\omega t + \psi_u);$$

$$i = \sqrt{2}I \sin(\omega t + \psi_i),$$

where U, I are the effective values of voltage and current; ψ_u, ψ_i are the initial phases of voltage and current; ω is the angular frequency, based on the corresponding power, active P , reactive Q and full S powers are introduced:

$$p = ui = \sqrt{2}U \sin(\omega t + \psi_u) \sqrt{2}I \sin(\omega t + \psi_i) =$$

$$= UI \cos(\psi_u - \psi_i) \cos(0) - UI \cos(\psi_u + \psi_i) \cos(2\omega t) -$$

$$- UI \sin(\psi_u - \psi_i) \sin(0) + UI \sin(\psi_u + \psi_i) \sin(2\omega t) =$$

$$= P \cos(0) - Q \sin(0) - S \cos(2\omega t + \psi_u + \psi_i).$$

We emphasize the well-known fact that the full power in this case is determined by the product of effective values of current and voltage. At that, obviously

$$\left[(UI \cos(\psi_u - \psi_i))^2 + (UI \sin(\psi_u - \psi_i))^2 \right] = [UI]^2;$$

$$\left[P^2 + Q^2 \right] = S^2.$$

In the case of polyharmonic currents and voltages

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

$$= \sqrt{2} \sum_k (U_k \cos(\psi_{uk}) \sin(k\omega t) + U_k \sin(\psi_{uk}) \cos(k\omega t)) =$$

$$= \sum_k (U_{a,k} \sin(k\omega t) + U_{b,k} \cos(k\omega t));$$

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

$$= \sqrt{2} \sum_n (I_n \cos(\psi_{in}) \sin(k\omega t) + I_n \sin(\psi_{in}) \cos(k\omega t)) =$$

$$= \sum_n (I_{a,n} \sin(n\omega t) + I_{a,n} \cos(n\omega t)),$$

where k, n are the numbers of harmonics of voltage and current; U_k, I_n are the effective values of harmonics of voltage and current; ψ_{uk}, ψ_{ik} are the initial phases of voltage and current; $U_{a,k}, U_{b,k}$ are the amplitudes of cosine and sine components of harmonics of voltage; $I_{a,k}, I_{b,k}$ are the amplitudes of cosine and sine component of harmonics of current, expression for power is considerably complicated

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

$$- \sum_{k,n} U_k I_n \cos[(k+n)\omega t + \psi_{uk} + \psi_{in}]; \quad (1)$$

As indicated in [12] from the last expression, the instantaneous power function contains harmonics whose order (s) is defined as the difference $(k-n)$ and the sum $(k+n)$ of the orders of the harmonics of voltage and current, that is $s = k \pm n$. Thus, instantaneous power

$$p = \sum_s P_s = P_0 + P_1 + \dots + P_{k-n} + \dots + P_{k+n} + \dots + P_z, \quad (2)$$

where the numbers of harmonics are defined by the set $Z = \{0, 1, 2, \dots, s, \dots, z\}$. The spectrum of the harmonics of the power function depends on which harmonic numbers are represented in the voltage and current spectrum. It must be borne in mind that different, but certain combinations of harmonics of voltage and current form harmonics of power of one order (for example, if $k = n + 1$, then the difference $s = k - n$ equals one for any numbers $s = k$ and $s = n$), so the actual number of harmonics of power may be less than maximum, but not less than twice the number of harmonics of voltage or current.

In this case, it is accepted to use active, reactive and full power in the form

$$P = p_0 = \sum_{k=n} U_k I_n \cos(\psi_{uk} - \psi_{in});$$

$$Q = \sum_{k=n} U_k I_n \sin(\psi_{uk} - \psi_{in});$$

$$S = \sqrt{P^2 + Q^2},$$

but as is known from the functional analysis, the Cauchy-Budianovsky-Schwartz inequality is fulfilled [6] and in the case under consideration, as noted in [4, 12]:

$$S \neq UI.$$

Without going into Budeanu theory and its generalization in work [4] in the part of inactive power and components of the distortion power, we consider the order of formation of the power components of (2) based on (1).

In [12] the conditional distribution of the power components is used in the form of the sum:

$$p = p_0 + \sum_{\substack{s=k+n \\ s=2k=2n}} (p_{a.c.s} + p_{b.c.s}) +$$

$$\left[\sum_{\substack{s=k \pm n \\ s=2k \cap 2n}} (p_{a.pc.s} + p_{b.pc.s}) + \sum_{\substack{s=k \pm n \\ s \neq 2k \cap 2n}} (p_{a.nc.s} + p_{b.nc.s}) \right], \quad (3)$$

where p_0 is the zero component of power (active power) for all harmonics; $p_{a.c.s}$ are the cosine canonical components; $p_{b.c.s}$ are the sine canonical components; $p_{a.pc.s}$ are the cosine components of non-canonical order – pseudo-canonical components; $p_{b.pc.s}$ are the sine components of non-canonical order – pseudo-canonical components; $p_{a.nc.s}$ are the cosine noncanonical components; $p_{b.nc.s}$ are the sine noncanonical components.

Direct calculation and differentiation of indicated power components by expression (1) requires a lot of time and effort. Therefore, an algorithm for calculating the power components, the general form of which is shown in Fig. 1, is developed. The algorithm can be divided into four stages: preparation of measured signals of current and voltage; fast Fourier transform of voltage and current; definition of power components; calculation of indicators of transmission of power of electric energy.

At the first stage, the measurement of current and voltage, depending on the characteristics of the equipment, setting the discretization rate, discretization time and the maximum number of harmonics. Also, instantaneous power and its quadratic norm are

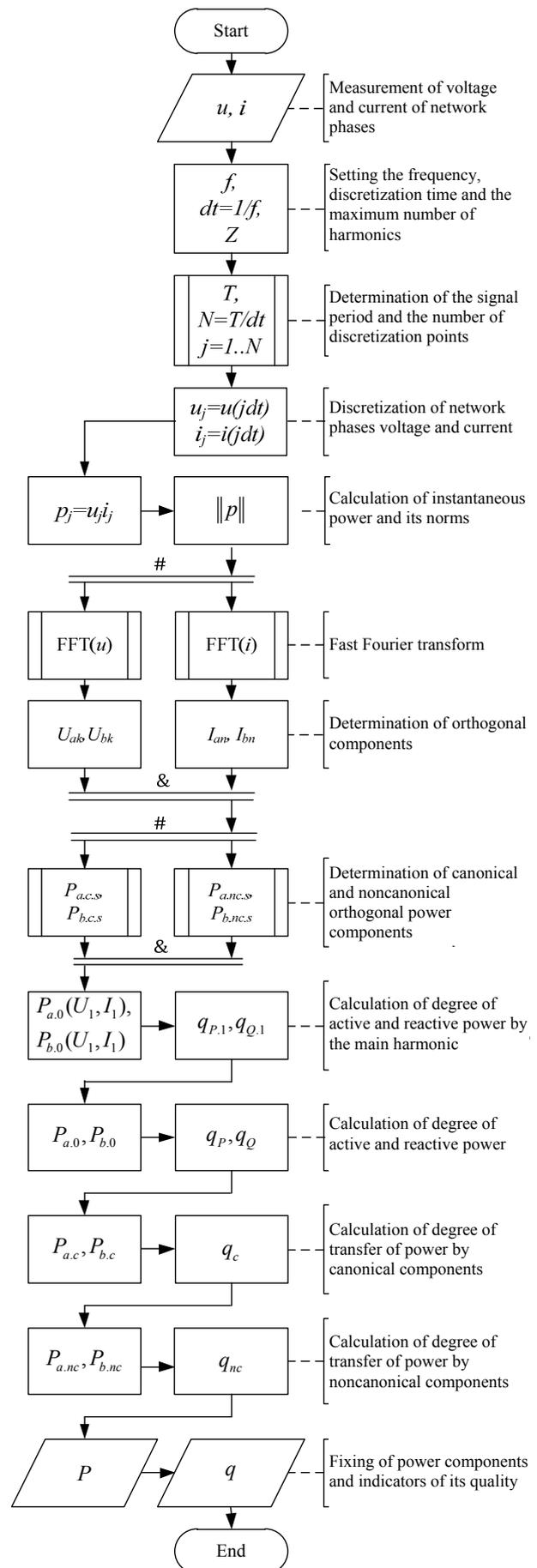


Fig. 1. The algorithm for determination of power and its qualitative indicators

determined. At the second stage, fast Fourier transform of voltage and current is performed, as a result of which their orthogonal components are determined. On the basis of this, at the third stage, the definition of canonical and noncanonical power components is performed. The procedure for determining these components has a certain peculiarity and can be implemented by performing the algorithm shown in Fig. 2.

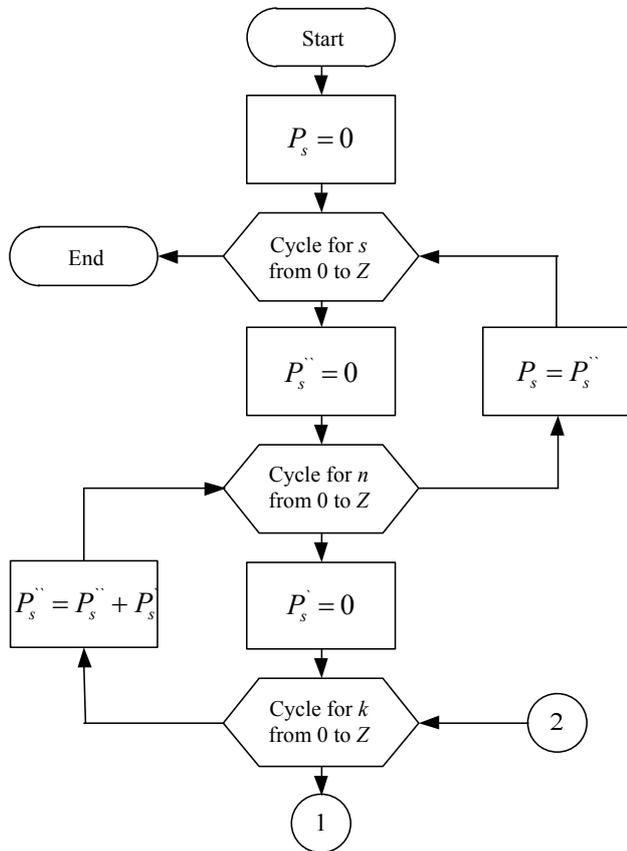


Fig. 2. The algorithm for determining orthogonal power components

Cycles of the definition of orthogonal power components, the input in each of which is indicated by the number 1, and output by the number 2 (see Fig. 2), by the structure are the same. The specified cycles differ in the essence of the conditions and are shown in Fig. 3-6. As a result of calculations by the algorithm (Fig. 2) using cycles (Fig. 3-6), for all combinations of harmonics of current and voltage, the following components of power are determined:

1. Active and reactive power of the main harmonic of current and voltage

$$\begin{cases} P_{a,1-1} = 0.5(U_{a,1}I_{a,1} + U_{b,1}I_{b,1}); \\ P_{b,1-1} = 0.5(U_{a,1}I_{b,1} - U_{b,1}I_{a,1}). \end{cases} \quad (4)$$

2. Active and reactive powers

$$\begin{cases} P_{a,0} = 0.5 \sum_{k-n=0} (U_{a,k}I_{a,n} + U_{b,k}I_{b,n}); \\ P_{b,0} = 0.5 \sum_{k-n=0} (U_{a,k}I_{b,n} - U_{b,k}I_{a,n}). \end{cases} \quad (5)$$

3. Canonical power components ($k = n$)

$$\begin{cases} P_{a.c.s} = \begin{cases} 0.5 \sum_{|k+n|=s} (U_{b,k}I_{b,n} - U_{a,k}I_{a,n}); \\ 0.5 \sum_{|k-n|=s} (U_{b,k}I_{b,n} + U_{a,k}I_{a,n}); \end{cases} \\ P_{b.c.s} = \begin{cases} 0.5 \sum_{|k+n|=s} (U_{a,k}I_{b,n} + U_{b,k}I_{a,n}); \\ 0.5 \sum_{|k-n|=s} (U_{a,k}I_{b,n} - U_{b,k}I_{a,n}) \text{sign}(k-n). \end{cases} \end{cases} \quad (6)$$

4. Noncanonical power components $P_{a.nc.s}$, $P_{b.nc.s}$, which are calculated by the system of equations (6) at the condition ($k \neq n$).

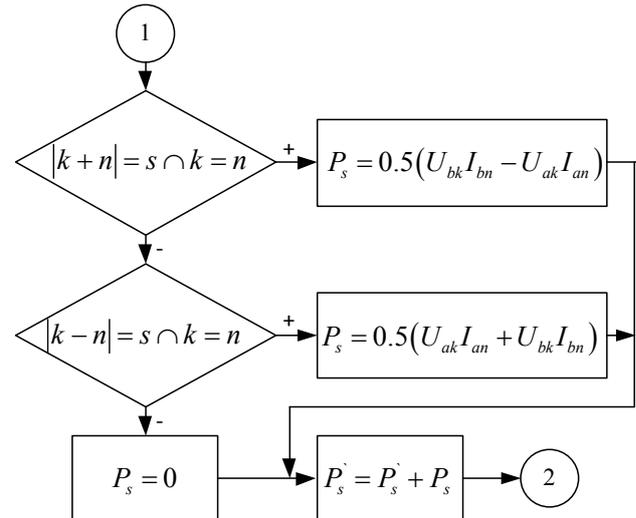


Fig. 3. The cycle of definition of cosine canonical components

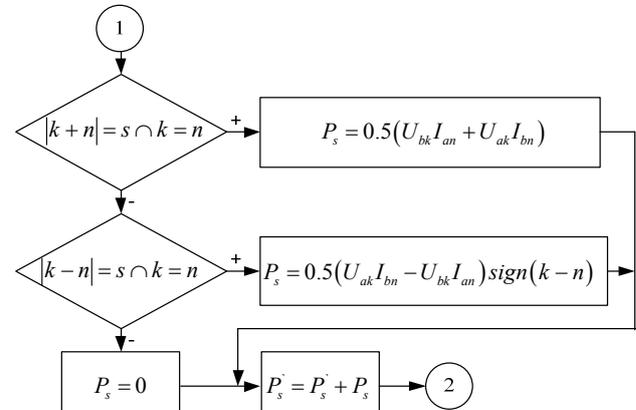


Fig. 4. The cycle of definition of sine canonical components

Thus, the power can be represented in a trigonometric form by the following series

$$p = P_{a,0} \cos(0) + \sum_{s \neq 0} (P_{a.c.s} + P_{a.nc.s}) \cos(s\omega t) + P_{b,0} \sin(0) + \sum_{s \neq 0} (P_{b.c.s} + P_{b.nc.s}) \sin(s\omega t),$$

The above-mentioned power components characterize in a certain way the process of transmission of electric energy. In general, this process can be characterized using a quadratic power norm

$$\|p\| = \sqrt{\frac{1}{T} \int_t^{t+T} p^2 dt}.$$

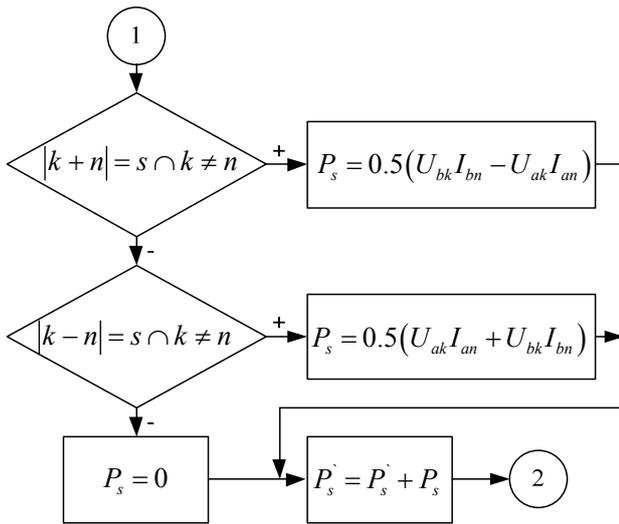


Fig. 5. The cycle of definition of cosine noncanonical components

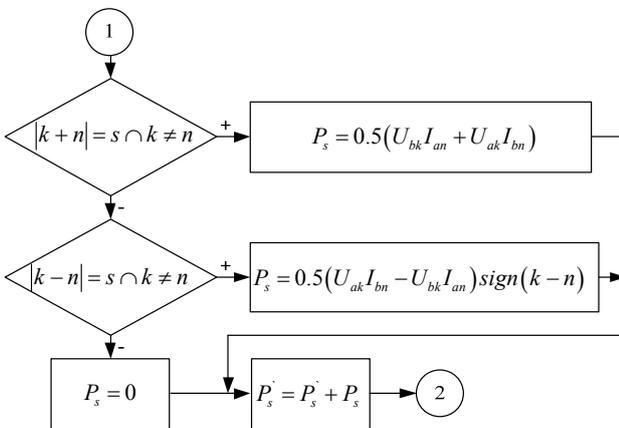


Fig. 6. The cycle of definition of sine noncanonical components

Using similar relations and previously used power components, a number of indicators have been proposed that characterize the process of energy transmission:

1. The degree of active and reactive power by the main harmonic

$$q_{P,1} = \frac{P_{a,1-1}}{\|p\|}; q_{Q,1} = \frac{P_{b,1-1}}{\|p\|}.$$

2. The degree of active and reactive power

$$q_P = \frac{P_{a,0}}{\|p\|}; q_Q = \frac{P_{b,0}}{\|p\|}.$$

3. The degree of transfer of power by canonical components

$$q_c = \frac{\sqrt{\sum P_{a.c.s}^2 + \sum P_{b.c.s}^2}}{\|p\|}.$$

4. The degree of transfer of power by noncanonical components

$$q_{nc} = \frac{\sqrt{\sum P_{a.nc.s}^2 + \sum P_{b.nc.s}^2}}{\|p\|}.$$

These indicators reflect the quality of the transmission of energy, both in the case of its consumption and generation, taking into account

components that are caused by higher harmonics of current and voltage. These indicators require a detailed substantiation from the standpoint of the processes of energy conversion in electric circuits and can be expanded, in particular, in part with regard to the influence of the transition of pseudo-canonical harmonics of power on canonical harmonics, the order of which coincides.

Conclusions and directions of further research.

The methodology and procedure for determining the power based on the measured current and voltage are proposed, as a result of which the power components and indicators of its quality are recorded.

For circuits with polyharmonic currents and voltages on the basis of their orthogonal components, using known power distribution division into constant, canonical, noncanonical components, a calculation algorithm and corresponding cycles for each of the components are developed.

A set of indicators characterizing the process of electric energy transmission taking into account quality is determined: the degree of active and reactive power by the main harmonic; the degree of active and reactive power; the degree of power transfer by canonical components; the degree of power transfer by noncanonical components.

The proposed indicators need to be substantiated from the standpoint of the physical processes of the distribution of electric energy in the elements of electric circuits, and more importantly, the power supply systems.

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