Відомі теоретичні результати стосовно проблеми електричної потужності спотворення, втілені в чинних стандартах, підлягають обґрунтованій критиці щодо формування потужності спотворення струмом і напругою, які мають різні частоти. У роботі запропоновано підхід, який базується на порядку формування компонент миттєвої електричної потужності залежно від поєднання (сума або різниця) частот струму і напруги. Отримано аналітичні вирази для компонент миттєвої електричної потужності кола з гармонійним струмом, яке складається з послідовно з'єднаних конденсатора, котушки індуктивності та резистора. Для цього випадку серед отриманих чотирьох компонент миттєвої потужності виокремлені дві – активна і реактивна, а також ортогональні складові потужності, осцилюючі з подвійною частотою. Показано, що сума квадратів активної та реактивної складових і сума квадратів зазначених ортогональних складових збігаються, і дорівнюють повній (уявній) потужності. Використовувана методика розвинена для загального випадку полігармонічних струму і напруги. У цьому випадку виявлено, що серед компонент миттєвої потужності можливо виокремити активну та реактивну потужності як ортогональні квадратурні складові нульової частоти, водночас повну потужність виокремити неможливо. Виконано два чисельні експерименти з періодичними струмом і напругою, які містять по три гармоніки. Діючі значення струмів і напруг в кожному з експериментів були прийняті рівними. При цьому амплітуди другої та третьої гармонік струму мінялися місцями. На цьому прикладі показано, що інтегральні показники повної потужності та потужності спотворення, розраховані за відомими методиками, в обох випадках виявилися однаковими, що є некоректним. За таких самих умов серед запропонованих компонент миттєвої потужності виявлені такі, значення яких виявилися різними для кожного з експериментів. Унаслідок цього запропоновано використовувати середньоквадратичне значення названих компонент для оцінювання ступеня спотворення відносно середньоквадратичного значення миттєвої потужності

Ключові слова: потужність електричної енергії, норма потужності, активна потужність, реактивна потужність

UDC 621.3.016.24/.25
DOI: 10.15587/1729-4061.2019.160513

IDENTIFICATION OF DISTRIBUTION FEATURES OF THE INSTANTANEOUS POWER COMPONENTS OF THE ELECTRIC ENERGY OF THE CIRCUIT WITH POLYHARMONIC CURRENT

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1. Introduction

In electric power, electrotechnical and electromechanical systems and complexes, to solve the problems related to the conversion of electric energy into other types of energy, one uses energy or power balance equations. Balance equations are used to verify the results of the problem solution or to assess the distribution of power fluxes. In most cases, the balance equation is formed according to the corresponding values averaged at a certain time period.

The values of power in most problems of electrical engineering and electrical mechanics provide the generalizing numerical characteristic and are used for the comparison of the power indices of the electric system elements – the observance of balance by the active and reactive powers. During the operation of the networks supplying the electric energy to consumers, independently of the current character, there appear problems of electric energy accounting. The average (at a certain period of time) value of power is used as an accounting index for direct current networks, the values of the active and reactive power are used for alternating current networks [1, 2]. Electric energy distortions caused by the action of the energy source or load are neglected during electric energy accounting. So, the problems of determining the power components reflecting the nature and level of electric energy distortion are topical.

2. Literature review and problem statement

Electric power systems are used for the generation and transmission of the energy that is primarily determined for the electric circuit by active power:

$$P = \frac{1}{T}\int_{t_0}^{t_0+T} ui\mathrm{d}t,$$

where u is instantaneous voltage; i is instantaneous current; t is time; t_0 is the time of the countdown start; T is the countdown period.

If the circuit contains elements capable of energy accumulation, the result of the voltage and current interaction is analyzed with the use of the Cauchy – Schwarz – Bunyakovsky inequality [3] reduced to the following level:

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

where τ is an intermediate variable.

In the case of harmonic currents and voltages, the following equation is obtained:

$$P^2 = S^2 - Q^2, \qquad (1)$$

where S is total power; Q is reactive power (the power of the energy accumulating elements).

The presence of the elements with a nonlinear volt-ampere characteristic in the electric circuit makes it impossible to use the notion of «reactive power» for expression (1). In paper [4], based on the Budeanu theory, this notion is referred to as inactive power N. The latter joins reactive power Q of the energy accumulating elements, and distortion power D caused by the elements with a nonlinear volt-ampere characteristic, i. e.:

$$P^2 = S^2 - N^2 = S^2 - \left(Q^2 + D^2\right).$$

A number of papers deal with the research of the methods for determining distortion power D. In particular, the paper [1] reveals the cause of distortion power depending on current and voltage distortion, but the distortion power dependence on the harmonic order relation is ignored. In the paper [5], the author compares the methods for the determination of reactive power and comes to the conclusion as to the difference of the results of the calculation in circuits with polyharmonic current. At present, power components are most clearly systematized in the IEEE standard [6]. The standard declares a certain number of electric energy power components, each of which reflects characteristic indices. Using the known vector forms and notions: total, active, inactive, reactive power, distortion power, additionally dividing them for the fundamental and higher harmonics of current or voltage, the authors multilaterally determine the power flux characteristic. With this purpose in view, the representation of currents, voltages and instantaneous power in the trigonometric form of the Fourier series is used. The mentioned power components are based on the Budeanu concept, but in some papers, e. g. [7], the determination of power harmonic components based on harmonic components of current and voltage is criticized.

At the same time, the determination of power components with the use of harmonic components of current and voltage, as stated in papers [8, 9], creates the ground for the assessment of the energy process. The authors of paper [10] use the analysis of polyharmonic functions of current, voltage and power provided the analysis of the electric machine mode is performed, and in paper [11], it is used to solve the problems of identifying the parameters and characteristics of the equivalent circuit elements. In this case, the energy conservation law and Tellegen's theorem are observed, which makes this approach more acceptable for the assessment of electric power. The author of paper [12] emphasizes this and substantiates the relation of power distortion and formation of the electric energy cost.

All this allows us to state that it is reasonable to research the order of determining the electric power components in a circuit with polyharmonic current.

3. The aim and objectives of the study

The aim of the paper consists in the analytical determination of the components of instantaneous electric power in a polyharmonic current circuit with the separation of active and reactive power.

The following objectives were set to achieve the aim of the paper:

– to determine the instantaneous electric power for a harmonic current electric circuit;

– to find the reactive and apparent powers of the alternating harmonic current circuit;

– to take into account the correlation of the polyharmonic current and voltage harmonic frequencies in the calculation of the instantaneous electric power and its components;

– to assess experimentally the level of the proposed components in the instantaneous electric power.

4. Determination of the instantaneous electric power for a harmonic current electric circuit

Let us consider an elementary circuit with resistive impedance R, inductive L and capacitive C elements connected in series. The harmonic current flux in the linear circuit (Fig. 1, a) is provided by the action of the voltage supply. The mode parameters are considered harmonic and are written down as follows:

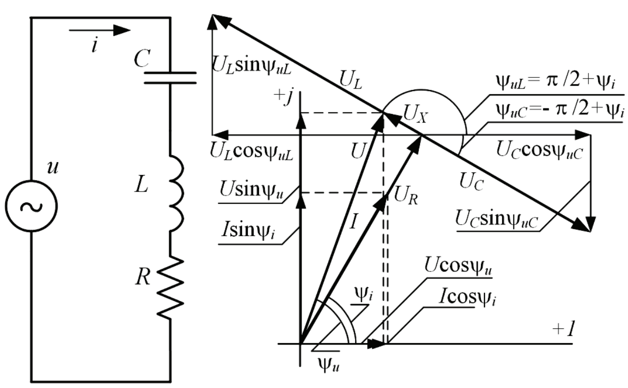
$$i = I\sin\left(\omega t + \psi_i\right); \quad u = U\sin\left(\omega t + \psi_u\right),$$

where U, I are the amplitudes of voltage and current, respectively; ψ_u, ψ_i are the initial phases of voltage and current, respectively; ω is the angular frequency.

For the circuit in Fig. 1, *a*, the voltage and current of the circuit are related in the following way:

$$u=u_R+u_L+u_C=i_R R+L\frac{di_L}{dt}+\frac{1}{C}\int i_C \mathrm{d}t=$$
$$=I_R R\sin(\omega t+\psi_{iR})+L\omega I_L\cos(\omega t+\psi_{iL})-$$
$$-\frac{I_C}{C\omega}\cos(\omega t+\psi_{iC})=U\sin(\omega t+\psi_u),$$

where u_R, u_L, u_C; i_R, i_L, i_C; I_R, I_L, I_C; ψ_{iR}, ψ_{iL}, ψ_{iC} are the voltages, currents, current amplitudes, phases of the currents of the resistor, inductance and capacitor, respectively.



a *b*

Fig. 1. Researched circuit: *a* — circuit; *b* — vector diagram

Taking into account the serial connection of the elements:

$$i_R=i_L=i_C;\;\; I_R=I_L=I_C=I;\;\; \psi_{iR}=\psi_{iL}=\psi_{iC}=\psi_i.$$

Then it is possible to write down:

$$u=I\left(R\sin(\omega t+\psi_i)+\left[L\omega-\frac{1}{C\omega}\right]\cos(\omega t+\psi_i)\right).$$

Instantaneous power *p* of the circuit with the set current and voltage:

$$p=I\sin(\omega t+\psi_i)I\begin{pmatrix}R\sin(\omega t+\psi_i)+\\+\left[L\omega-\frac{1}{C\omega}\right]\cos(\omega t+\psi_i)\end{pmatrix}=$$
$$=I^2\begin{pmatrix}R\sin^2(\omega t+\psi_i)+\\+\left[L\omega-\frac{1}{C\omega}\right]\sin(\omega t+\psi_i)\cos(\omega t+\psi_i)\end{pmatrix}=$$
$$=\frac{I^2R}{2}\cos(0)+\frac{I^2}{2}\left[L\omega-\frac{1}{C\omega}\right]\sin(0)-$$
$$-\left(\frac{I^2R}{2}\cos 2\psi_i-\frac{I^2}{2}\left[L\omega-\frac{1}{C\omega}\right]\sin 2\psi_i\right)\cos 2\omega t+$$
$$+\left(\frac{I^2R}{2}\sin 2\psi_i+\frac{I^2}{2}\left[L\omega-\frac{1}{C\omega}\right]\cos 2\psi_i\right)\sin 2\omega t.$$

We introduce the following designations:

$$P_R=\frac{I^2R}{2},\;\; P_L=\frac{I^2L\omega}{2},\;\; P_C=\frac{I^2}{2C\omega},$$

then the expression for the instantaneous power will be as follows:

$$p=P_R\cos(0)+[P_L-P_C]\sin(0)+$$
$$+(-P_R\cos 2\psi_i+[P_L-P_C]\sin 2\psi_i)\cos 2\omega t+$$
$$+(P_R\sin 2\psi_i+[P_L-P_C]\cos 2\psi_i)\sin 2\omega t=$$
$$=P_{a.1-1}\cos(0)+P_{b.1-1}\sin(0)+$$
$$+P_{a.1+1}\cos 2\omega t+P_{b.1+1}\sin 2\omega t, \qquad (2)$$

where $P_{a.1-1}$, $P_{b.1-1}$ are the amplitudes of the cosine and sine components of the power harmonic caused by the current and voltage harmonics whose frequencies are subtracted; $P_{a.1+1}$, $P_{b.1+1}$ are the amplitudes of the cosine and sine components of the power harmonic caused by the current and voltage harmonics whose frequencies are summed up.

5. Determination of reactive and total power of the alternating monoharmonic current circuit

Deliberately not excluding the component of the function sin (0) that does not participate in the formation of instantaneous power from the analysis, we indicate that $P_{a.1+1}\neq P_{a.1-1}$, $P_{b.1+1}\neq P_{b.1-1}$. We introduce the following designations:

– the active power of the circuit –

$$P=P_{a.1-1}=P_R=\frac{I^2R}{2};$$

– the reactive power of the circuit –

$$Q=P_{b.1-1}=[P_L-P_C]=\frac{I^2}{2}\left[L\omega-\frac{1}{C\omega}\right];$$

– total power –

$$S=\sqrt{P_{a.1+1}^2+P_{b.1+1}^2}=\sqrt{P_R^2+[P_L-P_C]^2}=$$
$$=\sqrt{P^2+Q^2}=\sqrt{P_{a.1-1}^2+P_{b.1-1}^2};$$

– the initial phase of the total power –

$$\psi_s=\mathrm{arctg}\frac{(P_R\sin 2\psi_i+[P_L-P_C]\cos 2\psi_i)}{(-P_R\cos 2\psi_i+[P_L-P_C]\sin 2\psi_i)}.$$

To preserve a certain written form, we rewrite equation (2) in the following form:

$$p=P\cos(0)+Q\sin(0)+S\sin(2\omega t+\psi_s).$$

Such an approach clearly indicates the place of active *P*, reactive *Q* and total *S* powers in the instantaneous power. It is a well-known fact that the balance in the electric circuit is not reproduced by the total power. It should be mentioned that it is also impossible to reproduce the instantaneous power in the circuit by the components of active, reactive and total power. This is caused by the impossibility of determining the initial phase of the oscillating power. The power components with amplitudes $P_{a.1-1}$, $P_{b.1-1}$, $P_{a.1+1}$, $P_{b.1+1}$ completely reproduce the instantaneous power.

It is rational to additionally use the indices characterizing the power as a signal [1, 3]: maximal $P_{\max}$, average P_{av} and root-mean-square P_{rms} values:

$$P_{\max}=\max(p)=P+S;$$

$$P_{av}=\frac{1}{T}\int_{t_0}^{t_0+T}p\mathrm{d}t=P;$$

$$P_{rms}=\sqrt{\frac{1}{T}\int_{t_0}^{t_0+T}p^2\mathrm{d}t}=\sqrt{P^2+\frac{S^2}{2}}.$$

The latter index is the RMS value of the instantaneous power signal $P_{rms}=\|p\|$.

With the use of the initial written form of current and voltage and their initial phases, the expression for power will be of the following form:

$$\begin{aligned}p&=0.5[UI\cos(\psi_v-\psi_i)]\cos(0)+\\&+0.5[-UI\sin(\psi_v-\psi_i)]\sin(0)+\\&+0.5[-UI\cos(\psi_v+\psi_i)]\cos(2\omega t)+\\&+0.5[UI\sin(\psi_v+\psi_i)]\sin(2\omega t).\end{aligned}\quad(3)$$

Comparing expressions (2) and (3) we obtain:

$$P_{a.1-1}=0.5[UI\cos(\psi_u-\psi_i)]=P$$

– active power;

$$P_{b.1-1}=0.5[-UI\sin(\psi_u-\psi_i)]=Q$$

– reactive power;

$$P_{a.1+1}=0.5[-UI\cos(\psi_u+\psi_i)]$$

– the cosine component of the total power;

$$P_{b.1+1}=0.5[UI\sin(\psi_u+\psi_i)]$$

– the sine component of the total power.

Thus, the total power components, pulsating with double frequency, are not active and reactive powers, but they are orthogonal components of the oscillating total power S, having the initial phase ψ_s. These components are artificially reduced to active and reactive powers, which some authors perform by means of a corresponding phase shift of the cosine and sine components of the total power.

6. Taking into account the correlation of the polyharmonic current and voltage harmonic frequencies in the calculation of the instantaneous electric power and its components

Let us consider the polyharmonic current and voltage:

$$\begin{aligned}u&=\sum_k u_k=\sqrt{2}\sum_k U_k\sin(k\omega t+\psi_{uk})=\\&=\sqrt{2}\sum_k\big(U_k\cos(\psi_{uk})\sin(k\omega t)+U_k\sin(\psi_{uk})\cos(k\omega t)\big)=\\&=\sum_k\big(U_{a.k}\sin(k\omega t)+U_{b.k}\cos(k\omega t)\big);\end{aligned}$$

$$\begin{aligned}i&=\sum_n i_n=\sqrt{2}\sum_n I_n\sin(n\omega t+\psi_{in})=\\&=\sqrt{2}\sum_n\big(I_n\cos(\psi_{in})\sin(k\omega t)+I_n\sin(\psi_{in})\cos(n\omega t)\big)=\\&=\sum_n\big(I_{a.n}\sin(n\omega t)+I_{a.n}\cos(n\omega t)\big),\end{aligned}$$

where k, n; U_k; I_n; ψ_{uk}, ψ_{ik} are the numbers, acting values, initial phases of voltage and current harmonics, respectively; $U_{a.k}$, $U_{b.k}$; $I_{a.k}$, $I_{b.k}$ are the amplitudes of the cosine and sine components of voltage and current harmonics, respectively.

Then the expression for the instantaneous power will be as follows:

$$\begin{aligned}p&=\sum_k u_k\sum_n i_n=\sum_{k,n}U_kI_n\cos[(k-n)\omega t+\psi_{uk}-\psi_{in}]-\\&-\sum_{k,n}U_kI_n\cos[(k+n)\omega t+\psi_{uk}+\psi_{in}].\end{aligned}$$

As stated in [6], it follows from the latter expression that the function of the instantaneous power contains harmonics whose order s is determined by both difference (k–n) and sum (k+n) of the orders of voltage and current harmonics, i. e. $s=k\pm n$. Thus, the instantaneous power

$$\begin{aligned}p&=\sum_s p_s=\sum_s P_s\sin(s\omega t+\psi_{p.s})=\\&=\sum_s\big(P_s\cos(\psi_{p.s})\sin(s\omega t)+P_s\sin(\psi_{p.s})\cos(s\omega t)\big)=\\&=\sum_s\big(P_{a.s}\sin(s\omega t)+P_{b.s}\cos(s\omega t)\big),\end{aligned}\quad(4)$$

where s is the number of power harmonics; p_s is the power harmonic; P_s is the amplitude of power harmonics; $\psi_{p.s}$ is the initial phase of power harmonics; $P_{a.s}$, $P_{b.s}$ are the amplitudes of the cosine and sine components of power harmonics.

Performing certain transformations of the instantaneous power equation and reducing it to the form (3), we determine four power components:

$$\begin{aligned}p&=\sum_{k,n}[U_kI_n\cos(\psi_{uk}-\psi_{in})]\cos(k-n)\omega t+\\&+\sum_{k,n}[-U_kI_n\cos(\psi_{uk}+\psi_{in})]\cos(k+n)\omega t+\\&+\sum_{k,n}[-U_kI_n\sin(\psi_{uk}-\psi_{in})]\sin(k-n)\omega t+\\&+\sum_{k,n}[U_kI_n\sin(\psi_{uk}+\psi_{in})]\sin(k+n)\omega t.\end{aligned}$$

In this case, it is possible to divide power components by their nature with the use of the concept stated in [3]:

1. The cosine component of zero frequency (active power):

$$p_{a.0}=\sum_{k,n}[U_kI_n\cos(\psi_{uk}-\psi_{in})]\cos(k-n)\omega t=P\cos(0)$$

for $k-n=0$.

2. The sine component of zero frequency (reactive power):

$$p_{b.0}=\sum_{k,n}[-U_kI_n\sin(\psi_{uk}-\psi_{in})]\sin(k-n)\omega t=Q\sin(0)$$

for $k-n=0$.

3. The cosine components caused by the action of the harmonics of current and voltage of the same frequency:

$$\begin{aligned}p_{a.c}&=\sum_{k,n}[-U_kI_n\cos(\psi_{uk}+\psi_{in})]\cos(k+n)\omega t=\\&=\sum_s P_{a.c.s}\cos(s\omega t)\end{aligned}$$

for $s=k+n=2k=2n$,

where $P_{a.c.s}$ is the amplitude of the cosine component caused by the action of the harmonics of current and voltage of the same frequency.

4. The sine components caused by the action of the harmonics of current and voltage of the same frequency:

$$p_{b.c}=\sum_{k,n}\left[U_k I_n \sin\left(\psi_{uk}+\psi_{in}\right)\right]\sin\left(k+n\right)\omega t=$$
$$=\sum_{s}P_{b.c.s}\sin(s\omega t)$$

for $s=k+n=2k=2n,$

where $P_{b.c.s}$ is the amplitude of the sine component caused by the action of the harmonics of current and voltage of the same frequency.

5. The cosine components caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides a paired result:

$$p_{a.pc}=\sum_{k,n}\left[U_k I_n \cos\left(\psi_{uk}-\psi_{in}\right)\right]\cos\left(k-n\right)\omega t+$$
$$+\sum_{k,n}\left[-U_k I_n \cos\left(\psi_{uk}+\psi_{in}\right)\right]\cos\left(k+n\right)\omega t=$$
$$=\sum_{s}P_{a.pc.s}\cos(s\omega t)$$

for $s=|k\pm n|=(2k \text{ or } 2n)$ and $k\neq n,$

where $P_{a.pc.s}$ is the amplitude of the cosine component caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides a paired result.

6. The sine components caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides a paired result:

$$p_{b.pc}=\sum_{k,n}\left[-U_k I_n \sin\left(\psi_{uk}-\psi_{in}\right)\right]\sin\left(k-n\right)\omega t+$$
$$+\sum_{k,n}\left[U_k I_n \sin\left(\psi_{uk}+\psi_{in}\right)\right]\sin\left(k+n\right)\omega t=$$
$$=\sum_{s}P_{b.pc.s}\sin(s\omega t)$$

for $s=|k\pm n|=(2k \text{ or } 2n)$ and $k\neq n,$

where $P_{b.pc.s}$ is the amplitude of the sine component caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides a paired result.

7. The cosine components caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides an unpaired result:

$$p_{a.nc}=\sum_{k,n}\left[U_k I_n \cos\left(\psi_{uk}-\psi_{in}\right)\right]\cos\left(k-n\right)\omega t+$$
$$+\sum_{k,n}\left[-U_k I_n \cos\left(\psi_{uk}+\psi_{in}\right)\right]\cos\left(k+n\right)\omega t=$$
$$=\sum_{s}P_{a.nc.s}\cos(s\omega t)$$

for $s=|k\pm n|\neq(2k \text{ or } 2n)$ and $k\neq n,$

where $P_{a.nc.s}$ is the amplitude of the cosine component caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides an unpaired result.

8. The sine components caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides an unpaired result:

$$p_{b.nc}=\sum_{k,n}\left[-U_k I_n \sin\left(\psi_{uk}-\psi_{in}\right)\right]\sin\left(k-n\right)\omega t+$$
$$+\sum_{k,n}\left[U_k I_n \sin\left(\psi_{uk}+\psi_{in}\right)\right]\sin\left(k+n\right)\omega t=$$
$$=\sum_{s}P_{b.nc.s}\sin(s\omega t)$$

for $s=|k\pm n|\neq(2k \text{ or } 2n)$ and $k\neq n,$

where $P_{b.nc.s}$ is the amplitude of the sine component caused by the action of the harmonics of current and voltage of different frequencies, whose sum or difference provides an unpaired result.

Consequently, the active and reactive powers are unambiguously separated in the instantaneous power in the available representation; in this case, it is impossible to separate total power S among the components of the instantaneous power [3].

The way of the representation of the instantaneous power in the form:

$$p=p_{a.0}+p_{b.0}+p_{a.c}+p_{a.pc}+p_{b.c}+p_{b.pc}+p_{a.nc}+p_{b.nc}, \quad (5)$$

complies with the energy conservation law and Tellegen's theorem [3]. In this case, the power signal is generalized by the RMS value P_{rms}.

7. Experimental assessment of the level of the proposed components in the instantaneous electric power

The rationality of using such representation of the instantaneous power can be illustrated by the following example. Let us assume that the current and voltage are set by three harmonics with corresponding amplitudes and initial phases (Table 1), and the frequency of the fundamental harmonic is ω=314 s^{-1}. We consider two numerical experiments performed in the Mathcad package, which differ in the values of the amplitudes of the second and third current harmonics (they interchange their positions).

Table 1

Data of numerical experiments with different amplitudes of current harmonics

Experiment	1				2			
Harmonic	*h*1	*h*2	*h*3	*RMS*	*h*1	*h*2	*h*3	*RMS*
I, A	20	1	10	15.83	20	10	1	15.83
U, V	220	10	10	155.89	220	10	10	155.89
ψ_i, deg	0	0	0		0	0	0	
ψ_u, deg	30	60	60		30	60	60	
P, Wt	1.933				1.933			
Q, VAr	1.148				1.148			
S, VA	2.467				2.467			
D, VAr	1.017				1.017			

The diagrams of current and voltage for the first and second experiment are given in Fig. 2, *a*, *c*, respectively, the resulting diagram of power – in Fig. 2, *b*, *d*. Obviously, if there are different values of current harmonics, different power will be obtained, but the integral indices [5]: active *P*, reactive *Q*, total *S* powers and even distortion power *D* remain unchanged. As seen in Fig. 2, *b*, *c*, the character of power distortion is different, which results in different values of the maximum power.

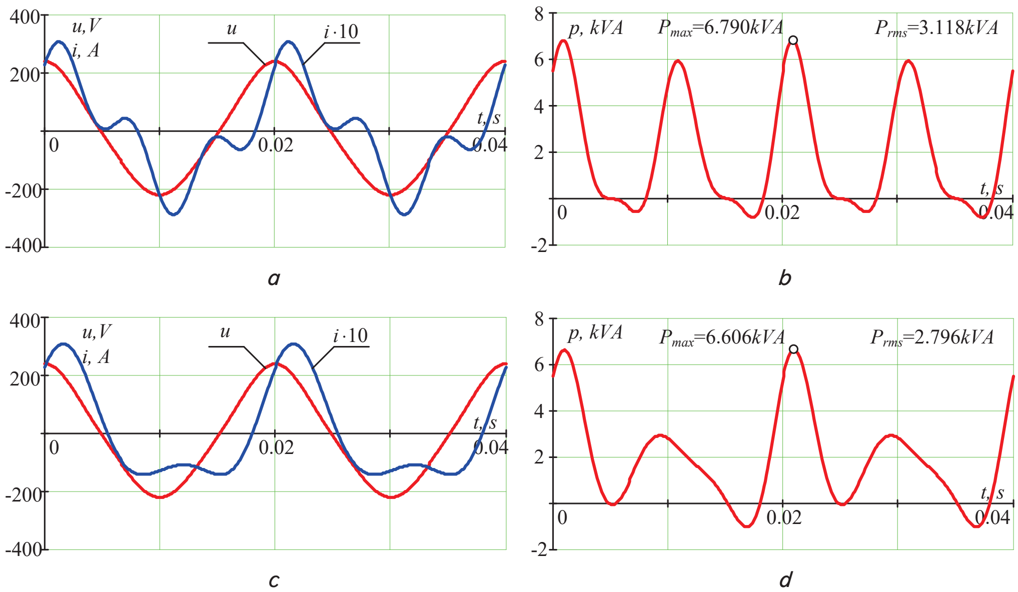


Fig. 2. Time diagrams of: *a* — current and voltage for experiment 1; *b* — power for experiment 1; *c* — current and voltage for experiment 2; *d* — power for experiment 2

Table 2 contains the values of the orthogonal components of power for the first and second experiments obtained according to expression (4). The components with zero frequency $P_{a.0}=P$ and $P_{a.0}=Q$, whose values coincide in Tables 2, 3, are determined unambiguously. It is impossible to relate the components of other frequencies with the mentioned powers or total power S, but this way of the representation of the instantaneous power allows one to differentiate instantaneous power p obtained in the two proposed experiments.

It is necessary to point out different values of the power quadratic norm and its maximal value for each of the experiments. Additionally, one should pay attention to the coincidence of the values of the orthogonal components of the power fifth harmonic ($s=5$), caused by the interaction of the second and third harmonics of voltage and current. The values of the orthogonal components of the power sixth harmonic ($s=6$) are different by one order as they are caused by the interaction of exclusively third harmonics of current and voltage. Separately, it is necessary to pay attention to the values of the orthogonal components of the power second harmonic ($s=2$) that indicates the interaction of the current and voltage harmonics, for which $n\pm k=s=2$. In this case, apart from the first harmonic of current and voltage, all other harmonics of current and voltage, for which the condition $n\pm k=s=2$ is true, take part in the generation of this power component.

Table 3 contains the values of the orthogonal components of power for the first and second experiment according to the components obtained by formula (5). In this case, the values of the orthogonal components of zero harmonic and harmonics with numbers $s=5$ and $s=6$ coincide with the values given in Table 2.

The orthogonal components of the power second harmonic ($s=2$) are divided into two components according to formula (5). Table 3 contains the following designations: canonic components of power (index «*c*»), indicating the action of the components of current and voltage of one frequency $n=k=1$; pseudo-canonic components of power (index «*pc*»), indicating the action of the harmonics of current and voltage of different frequencies $n\neq k$. That is why the values of the canonic parts of the power harmonics orthogonal components $s=2$ coincide for both experiments and for the non-canonic ones they differ.

Table 2

Amplitudes of the orthogonal components of the instantaneous power by harmonics

No.	$P_{a.0}$, VA	$P_{b.0}$, VA	$P_{a.1}$, VA	$P_{b.1}$, VA	$P_{a.2}$, VA	$P_{b.2}$, VA	$P_{a.3}$, VA	$P_{b.3}$, VA	$P_{a.4}$, VA	$P_{b.4}$, VA	$P_{a.5}$, VA	$P_{b.5}$, VA	$P_{a.6}$, VA	$P_{b.6}$, VA
*Exp*1	1.933	1.148	169.3	84.2	2.542	2.003	0.015	145.3	639.1	1.007	27.5	47.6	25	43.3
*Exp*2	1.933	1.148	664.3	863.7	2.047	1.145	0.011	1.003	166.6	188.5	27.5	47.6	2.5	4.3

Table 3

Amplitudes of the orthogonal components of the instantaneous power by components

No.	$P_{a.0}$, VA	$P_{b.0}$, VA	$P_{a.nc.1}$, VA	$P_{b.nc.1}$, VA	$P_{a.c.2}$, VA	$P_{a.pc.2}$, VA	$P_{b.c.2}$, VA	$P_{b.pc.2}$, VA	$P_{a.nc.3}$, VA	$P_{b.nc.3}$, VA	$P_{a.c.4}$, VA	$P_{a.pc.4}$, VA	$P_{b.c.4}$, VA	$P_{b.pc.4}$, VA	$P_{a.nc.5}$, VA	$P_{b.nc.5}$, VA	$P_{a.c.6}$, VA	$P_{a.pc.6}$, VA
*Exp*1	1.933	1.148	169.3	84.2	1.905	636.6	1.100	902.6	0.02	145.3	2.5	636.6	4.3	1.003	27.5	47.6	25	43.3
*Exp*2	1.933	1.148	664.3	863.7	1.905	141.6	1.100	45.3	0.01	1.003	25	141.6	43.3	145.3	27.5	47.6	2.5	4.3

8. Discussion of the results of the research of the order of generating the electric power instantaneous components in a polyharmonic current circuit

The amplitude of the sine and cosine orthogonal components of power harmonics depends on the current and voltage harmonics whose frequencies difference or sum is equal to the frequency of the power harmonic. The method, used in the research, proposes to separate the power components depending on the combination of the current and voltage harmonics frequencies. The calculation of the power components is complicated with the increase of the number of current and voltage harmonics, because it is necessary to verify if certain combinations of the frequencies of current, voltage harmonics and the frequency of the power harmonic meet particular conditions. If the number of current and voltage harmonics is limited, a certain error in the calculation of the power components is possible. Taking into account the high level of the info- and knoware of modern signal-processing devices, the mentioned errors can be minimized. The further development of the research consists in the substantiation of the indices of the power components contribution into the instantaneous electric power. In this case, some difficulties related to the power fluxes separation in the nodes of electric power systems are possible.

For a harmonic current electric circuit, resulting from a combination of orthogonal components of current and voltage, the sine and cosine orthogonal components of power harmonics are determined (2). Components corresponding to the active, reactive and oscillating (apparent) power are singled out from them. The method used during the research of the polyharmonic current circuit proposes to separate power components depending on the combination of the frequencies of current and voltage harmonics (4). The advantage of the proposed solution over the existing one is illustrated by numerical experiments with different instantaneous powers for which the known indices turned out equal. The calculation of the proposed power components is complicated with the increase of the number of current and voltage components. If the number of current and voltage harmonics is limited, a certain error of the power components calculation is probable. Taking into account the high level of the infoware and knoware of the modern signal processing equipment, the mentioned errors can be reduced to the minimal admissible value. The development of the research consists in the substantiation of the indices of the power components contribution into the instantaneous electric power of electric power system units. In this case, probable difficulties relate to the power fluxes branching in the mentioned units.

9. Conclusions

1. Unlike the conventional analytical expression of the instantaneous power of the alternating harmonic current circuit, an alternative expression has been proposed. It includes components corresponding to the active, reactive and total power. The power sine orthogonal components with the function zero argument have not been excluded from the analysis.

2. The low efficiency of the indices of the total power and distortion power in a circuit with polyharmonic current and voltage, calculated according to the known methods, has been proved. These indices appeared to be unchanged under the conditions of two numerical experiments in which the acting values of current and voltage and their initial phases were set equal. In this case, the current amplitudes of the second and third harmonics interchanged their positions. This resulted in the change of the power root-mean-square value $P_{rms1}=1.11P_{rms2}$, and it's maximal value $P_{\max1}=1.03P_{\max2}$.

3. Dividing the power harmonics into orthogonal components, observing the condition of pairness and unpairness of the combinations of the current and voltage harmonics frequencies, the analytical expressions for the determination of the power components: zero frequency, canonic, pseudo-canonic and non-canonic, have been obtained.

4. For the numerical experiments using the proposed methods for the determination of the power components, we have found the values of the canonic parts of the power second harmonic components, which coincide in both experiments, and the pseudo-canonic parts, which differ. This can be used in the formulation of the instantaneous power indices.

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UDC 631.364:621.311.243
DOI: 10.15587/1729-4061.2019.162948

RESULTS OF EXPERIMENTAL RESEARCHES INTO PROCESS OF OAK VENEER DRYING IN THE SOLAR DRYER

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Розроблено нову конструкцію геліотермічної сушильної установки з активною системою використання сонячної енергії. Запропоновано для діагностики основних параметрів повітрообміну у геліосушарці і прогнозування інтенсивності протікання тепломасообмінних процесів сушіння дубового шпону використовувати автоматичну систему керування К1-102. Це дозволяє підвищити технологічну та енергетичну ефективність процесу сушіння дубового шпону у геліосушарці в 2 рази.

Визначено закономірності впливу фізичних параметрів навколишнього середовища та погодозалежних факторів на тепло-, масо- і вологообміні процеси сушіння дубового шпону у геліосушарці. Наведено оцінку енергетичних, кінетичних та динамічних параметрів процесу сушіння дубового шпону. Експериментально визначено тривалість технологічного процесу сушіння у геліосушарці. Досліджено робочі характеристики об'єкта сушіння, залежно від поставлених технологічних задач (прогрівання або сушіння матеріалу) за стандартних режимів сонячного освітлення і типових метеорологічних умов.

Встановлено, що необхідно регулювати повітрообмін, вологовиділення, раціональне видалення вологого теплоносія, концентрацію надходження сонячної енергії відносно прогнозованої зміни мінімальних та максимальних піків коливань погодозалежних факторів. Це є важивим для інтенсифікації процесів сушіння дубового шпону і зниження питомих енергетичних витрат на процес сушіння за рахунок сонячної енергії.

Отримані результати можна використати під час розробки та вдосконалення технічних засобів сушіння дубового шпону, для підвищення технологічної та енергетичної ефективності процесу

Ключові слова: сонячна енергія, геліосушарка, температурно-вологісні поля, тепломасоперенесення, інтенсифікація, конвективне сушіння

1. Introduction

High-quality drying of oak veneer is one of the most popular technological processes in the forest complex of Ukraine. Today in the market, there are many high-temperature automated devices for high-quality drying of wood in «soft modes». However, their application is unprofitable with small volumes of timber processing in small household and utility carpentry shops. This is primarily due to high capital investments. In addition, a major problem for small household and utility carpentry shops that provide timber drying services is the ultimate quality of wood after drying. There