THEORY AND PRACTICE OF FORENSIC EXAMINATION

Scientific article
UDC 614.841; DOI: 10.61260/2304-0130-2025-2-68-77

ANALYTICAL VOLTAGE AND EXAMPLES OF ITS USE IN FIRE-TECHNICAL EXPERTISE OF ESTABLISHED NON-SINUSOIDAL MODES OF ELECTRICAL CIRCUITS

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Abstract. A new approach to the expert analysis of steady-state electrical circuits using the concept of complex analytical voltage is proposed. The analysis is based on the idea that current in an electrical circuit flows as a result of the action of this analytical voltage. The actual voltage applied to an electrical circuit, as well as the voltage associated with it by the Hilbert conversion, are the result of vector decomposition of the analytical voltage into orthogonal components. The proposed approach avoids ambiguity in assessing the steady-state modes of an electrical circuit in cases where the shape of the voltage applied to the circuit does not match the shape of the current flowing through the circuit.

Key words: electrical circuits, analytical voltage, Hilbert conversion, steady-state modes, non-sinusoidal modes, full power, active power, reactive power, distortion power

For citation: Agunov M.V., Verbova N.M. Analytical voltage and examples of its use in fire-technical expertise of established non-sinusoidal modes of electrical circuits // Supervisory activities and forensic examination in the security system. 2025. № 2. P. 68–77. DOI: 10.61260/2304-0130-2025-2-68-77.

Introduction

The purpose of the fire-technical expertise of the established non-sinusoidal modes of electrical circuits is the nessecity to assess the energy characteristics of the «source–load» system in order to detect fire hazards in it, as well as to develop recommendations for ensuring the fire safety of system elements.

Non-sinusoidal modes of electrical circuits are caused by the increasing amount of electric appliances in everyday life, industrial enterprises, (in particular in welding, railway transport, ships, aircraft, drilling rigs, etc.). Non-sinusoidal modes are associated with significant distortions of mains voltage and current. They are characterized by the presence of higher current harmonics in the electrical network, which in turn cause accelerated aging of the insulation, resonances leading to overvoltages, increased heating of the elements of the electrical circuit and other fire hazards.

In non-sinusoidal modes, under the action of a supply voltage *u(t)* applied to an electrical circuit, a current flows in it, the shape of which in the general case may not coincide with the shape of the applied voltage. This trend began to be clearly noticeable with the advent of electric traction power valve converters of electric power at the beginning of the 20^{th} century, and since that moment attempts have been made to develop methods for analyzing such circuits [1–4].

With the advent of power semiconductor converters and their widespread adoption as secondary power sources, the problem of finding methods for analyzing electrical circuits with non-sinusoidal modes has become more acute and widespread [5–11].

The weak point of the existing methods was the inaccuracy of their estimation, and seldom correct results. This forced the researchers to continue their work into the 21st century [12–25].

Theoretical basis

The proposed approach avoids ambiguity in assessing the steady-state modes of an electrical circuit by using the concept of a complex analytical voltage, and assuming that current in the circuit flows as a result of the action of this voltage [26]. A certain complex analytical voltage is assigned to the actual voltage u(t):

$$U(t) = A(t) \cdot \psi(t) = u(t) + ju_1(t),$$

where *A(t)* – envelope; *Ψ(t)* – instantaneous phase; $u_1(t)$ – *u(t)* voltage-conjugated function.

u(t) voltage-conjugated function $u_1(t)$ must meet the following requirements:

– small changes in the instantaneous amplitude should correspond to the small changes in the initial voltage u(t)

$$A(t) = \sqrt{u^2(t) + u_1^2(t)}$$

and to the instantaneous phase

$$\psi(t) = m\pi + arctg\frac{u_1(t)}{u(t)},$$

– with the constant form of the voltage, its phase should not depend on the amplitude.;

– for harmonic voltages, the concepts of instantaneous amplitude, instantaneous phase, and instantaneous frequency equal to:

$$\omega(t) = \frac{d\varphi(t)}{dt}$$

and must express regular definitions of amplitude, phase and frequency.

Such requirements are satisfied only by function $u_1(t)$, conjugated with *u(t)* by Hilbert conversion [27]:

$$u_1(t) = H\{u(t)\} = -\frac{1}{\pi}\int_0^{\infty}\frac{u(t+\tau) - u(t-\tau)}{\tau}d\tau ;$$

$$u(t) = \frac{1}{\pi}\int_0^{\infty}\frac{u_1(t+\tau) - u_1(t-\tau)}{\tau}d\tau .$$

Let's observe, how the function $u_1(t)$, conjugated with the initial *u(t)* by Hilbert transformations, can be used in the expert analysis of steady-state modes in alternating current electric circuits.

Each steady-state mode of the electrical circuit corresponds to a strictly defined energy state. For an electrical circuit, in the case of a sinusoidal supply voltage, it is characterized by the values of active, reactive and full power. Traditionally [28], these values are introduced through the concept of instantaneous power equal to the product of instantaneous voltage and instantaneous current. The mathematical converstions of this product for circuits with reactive loads give two components: the constant *UIcos(φ)* and the variable *UIcos(2ωt – φ)*. The constant component of instantaneous power is associated with active power, which is found as work done in one period:

$$P = \frac{1}{T}\int_0^T u(t)\cdot i(t)dt.$$

The variable component is associated with full and reactive power. The total power is called the amplitude of the variable component *UI*. The fact that the variable component takes negative values in some time intervals is associated with the energy exchange between the source and the receiver. The exchange is measured by reactive power as *Q* = *UIsin(φ)*.

Using the Hilbert function conjugate to the voltage u(t) allows us to find the reactive power similarly to the active one [29]:

$$Q = \frac{1}{T}\int_0^T H\{u(t)\}\cdot i(t)dt,$$

where *H{u(t)}* – Hilbert's conversion for applied voltage *u(t)*. If the voltage is *u(t)* harmonious, Hilbert's conversion for *u(t) = cos(ωt)* gives ort *H{u(t)} = sin(ωt)*; for *u(t) = sin(ωt)* gives ort *H{u(t)} = -cos(ωt)*.

As an example of the proposed approach, let us consider an electrical circuit with active, inductive, and capacitive resistances.

With voltage equal to:

$$u(t) = U_{\mathrm{m}}\sin(\omega t)$$

A current *i* is generated in the power supply in a circuit containing active inductive and capacitive elements (Fig. 1). The current creates voltage drops on the circuit elements:

– on an element with active resistance:

$$u_{\mathrm{R}}(t) = i(t)\cdot R;$$

– on an element with inductance:

$$u_{\mathrm{L}}(t) = -e_{\mathrm{L}}(t) = L\frac{di(t)}{dt};$$

– on an element with a capacity:

$$u_{\mathrm{C}}(t) = \frac{q_{\mathrm{C}}(t)}{C} = \frac{1}{C}\int i(t)dt.$$

According to Kirchhoff's second law, for a given chain, we can do as follows:

$$u(t) = u_{\mathrm{R}}(t) + u_{\mathrm{L}}(t) + u_{\mathrm{C}}(t)$$

or

$$U_m \sin(\omega t) = i(t) \cdot R + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)dt\ .$$

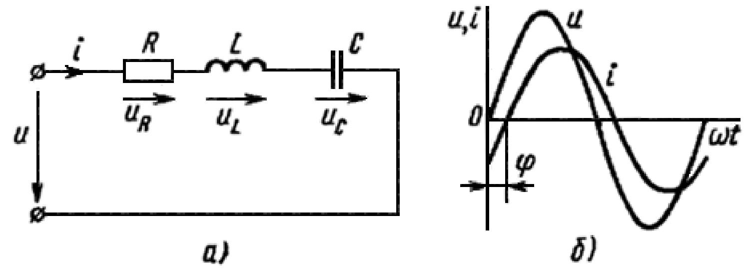


Fig. 1. **An example of an electrical circuit with active, inductive, and capacitive elements: a) electrical diagram; б) changes of the instantaneous values of voltage and current**

A particular solution of this equation for the steady-state mode will be:

$$i(t) = I_m \sin(\omega t - \varphi)$$

or

$$i(t) = I_m \cos(\varphi)\sin(\omega t) - I_m \sin(\varphi)\cos(\omega t)\ ,$$

where $I_m = U_m/Z$;

– total circuit resistance:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}\ ;$$

– the phase shift angle between the current in the circuit and the voltage supplying the circuit:

$$\varphi = arctg\frac{X_L - X_C}{R}\ .$$

The value of the angle *φ* depends on the ratio between the reactive *X* and active *R* resistances. The greater the reactance, the greater the angle *φ*. The sign of the angle φ depends on the ratio between the inductive and capacitive resistances. If *XL* is greater than *XC,* then the angle *φ* is positive, and the current is out of phase with the voltage by the angle *φ*. If *XL* is less than *XC*, then the angle *φ* is negative, and the current is out of phase with the voltage by an angle *φ*.

Fig. 1 b shows how the voltage and current in the circuit shown in fig. 1 a change, provided $X_L > X_C$.

The active power consumed by the electrical circuit will be equal to

$$P = \frac{1}{T}\int_0^T u(t)\cdot i(t)dt = \frac{1}{T}\int_0^T U_m \sin(\omega t)\cdot I_m \sin(\omega t - \varphi)dt = \frac{U_m \cdot I_m}{\sqrt{2}\cdot\sqrt{2}}\cos(\varphi) = U \cdot I\cos(\varphi)\ ,$$

and the reactive power

$$Q = \frac{1}{T}\int_0^T H\{u(t)\}\cdot i(t)dt = -\frac{1}{T}\int_0^T U_{\text{m}}\cos(\omega t)\cdot I_{\text{m}}\cos(\omega t - \varphi)dt = \frac{U_{\text{m}}\cdot I_{\text{m}}}{\sqrt{2}\cdot\sqrt{2}}\sin(\varphi) = U\cdot I\sin(\varphi).$$

The total, active and reactive capacities are also related here as follows:

$$P^2 + Q^2 = (U\cdot I)^2\left(\cos^2(\varphi) + \sin^2(\varphi)\right) = (U\cdot I)^2 = S^2.$$

In other words:

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

Thus, the results are completely consistent with the results of the traditional approach.

Similarly, electrical circuits with a different number of elements and a different type of their connections are analyzed.

Steady-state modes in electrical circuits with time-varying (parametric) resistance.

The energy state of an electrical circuit in the case of a non-sinusoidal supply voltage and / or current is traditionally [28] characterized by the values of active and full power. The active power of a non-sinusoidal current is understood as the average value of the instantaneous power over the period of the first harmonic:

$$P = \frac{1}{T}\int_0^T u(t)\cdot i(t)dt.$$

The total power is equal to the product of the effective value of the non-sinusoidal voltage and the effective value of the non-sinusoidal current. No other concepts characterizing energy processes in non-sinusoidal modes are mentioned.

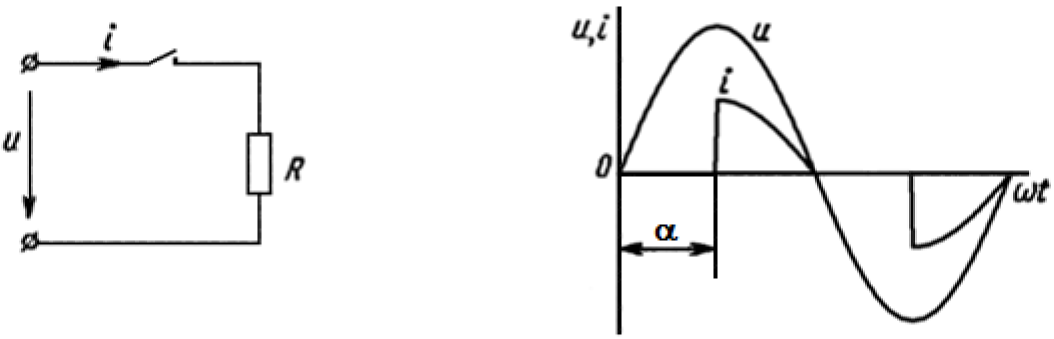
A distinctive feature of the proposed approach is that in circuits with modes of this kind, it allows you to calculate the reactive power.

Consider a circuit consisting of an active resistance and an ideal key (Fig. 2a), symmetrically closing during each half-cycle of the network frequency at some moments $(n\pi+\alpha)/\omega$ and opening up in moments $\pi(n+1)/\omega$ (рис. 2 б), where n = 0,1,2... .

The voltage and current in such a circuit will be described on the period as follows:

$$u(t) = U_{\text{m}}\sin(\omega t);$$

$$i(t) = \begin{cases} 0, & 0 \le \omega t < \alpha; \\ I_m\sin(\omega t), & \alpha \le \omega t < \pi; \\ 0, & \pi \le \omega t < \pi + \alpha; \\ I_m\sin(\omega t), & \pi + \alpha \le \omega t < 2\pi. \end{cases}$$



a b

Fig. 2. **An electrical circuit consisting of an active resistance and an ideal key: a) an electrical circuit; b) a change in the instantaneous values of voltage, current and instantaneous power for α = π/2**

Let's represent the current *i(t)* as a Fourier series:

$$
\begin{aligned}
i(t) &= I_m\sin(\omega t)-\frac{\alpha}{\pi}I_m\sin(\omega t)+\frac{\sin 2\alpha}{2\pi}I_m\sin(\omega t)+\\
&+\frac{\sin 4\alpha}{4\pi}I_m\sin(3\omega t)-\frac{\sin 2\alpha}{2\pi}I_m\sin(3\omega t)+\\
&+\frac{\sin 6\alpha}{6\pi}I_m\sin(5\omega t)-\frac{\sin 4\alpha}{4\pi}I_m\sin(5\omega t)+\\
&+\frac{\sin 8\alpha}{8\pi}I_m\sin(7\omega t)-\frac{\sin 6\alpha}{6\pi}I_m\sin(7\omega t)+\ldots-\\
&-\frac{\sin^2\alpha}{\pi}I_m\cos(\omega t)+\\
&+\frac{1}{4\pi}I_m\cos(3\omega t)+\frac{\cos 4\alpha}{4\pi}I_m\cos(3\omega t)-\frac{\cos 2\alpha}{2\pi}I_m\cos(3\omega t)+\\
&+\frac{1}{12\pi}I_m\cos(5\omega t)+\frac{\cos 6\alpha}{6\pi}I_m\cos(5\omega t)-\frac{\cos 4\alpha}{4\pi}I_m\cos(5\omega t)+\\
&+\frac{1}{24\pi}I_m\cos(7\omega t)+\frac{\cos 8\alpha}{8\pi}I_m\cos(7\omega t)-\frac{\cos 6\alpha}{6\pi}I_m\cos(7\omega t)+\ldots\quad .
\end{aligned}
$$

As can be seen from the result of decomposition in the current *i(t)*, three of its components can be distinguished:

– the active component $i_a(t)$ collinear to voltage *u(t)*:

$$
i_a(t)=I_m\sin(\omega t)-\frac{\alpha}{\pi}I_m\sin(\omega t)+\frac{\sin 2\alpha}{2\pi}I_m\sin(\omega t)=\left(1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi}\right)I_m\sin(\omega t);
$$

– the reactive component $i_p(t)$ collinear to voltage $H\{u(t)\} = -U_m cos(\omega t)$ conjugated with voltage $u(t)$ according to Hilbert:

$$i_{\text{р}}(t) = -\frac{\sin^2\alpha}{\pi} I_m \cos(\omega t);$$

– the distorting component $i_u(t)$ orthogonal to the voltage $u(t)$, and to voltage $H\{u(t)\}$:

$$\begin{aligned} i_{\text{и}}(t) &= \frac{\sin 4\alpha}{4\pi} I_m \sin(3\omega t) - \frac{\sin 2\alpha}{2\pi} I_m \sin(3\omega t) + \\ &+ \frac{\sin 6\alpha}{6\pi} I_m \sin(5\omega t) - \frac{\sin 4\alpha}{4\pi} I_m \sin(5\omega t) + \\ &+ \frac{\sin 8\alpha}{8\pi} I_m \sin(7\omega t) - \frac{\sin 6\alpha}{6\pi} I_m \sin(7\omega t) + \ldots + \\ &+ \frac{1}{4\pi} I_m \cos(3\omega t) + \frac{\cos 4\alpha}{4\pi} I_m \cos(3\omega t) - \frac{\cos 2\alpha}{2\pi} I_m \cos(3\omega t) + \\ &+ \frac{1}{12\pi} I_m \cos(5\omega t) + \frac{\cos 6\alpha}{6\pi} I_m \cos(5\omega t) - \frac{\cos 4\alpha}{4\pi} I_m \cos(5\omega t) + \\ &+ \frac{1}{24\pi} I_m \cos(7\omega t) + \frac{\cos 8\alpha}{8\pi} I_m \cos(7\omega t) - \frac{\cos 6\alpha}{6\pi} I_m \cos(7\omega t) + \ldots \quad . \end{aligned}$$

The active power consumed by the electrical circuit will be equal to

$$\begin{aligned} P &= \frac{1}{T}\int_0^T u(t)\cdot i_{\text{a}}(t)dt = \frac{1}{T}\int_0^T U_{\text{m}} \sin(\omega t)\cdot\left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right) I_m \sin(\omega t)dt = \\ &= \left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right)\frac{U_{\text{m}}\cdot I_{\text{m}}}{\sqrt{2}\cdot\sqrt{2}} = \left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right) U\cdot I, \end{aligned}$$

and the reactive power

$$\begin{aligned} Q &= \frac{1}{T}\int_0^T H\{u(t)\}\cdot i(t)dt = \frac{1}{T}\int_0^T U_{\text{m}} \cos(\omega t)\cdot\frac{\sin^2\alpha}{\pi} I_m \cos(\omega t)dt = \\ &= \frac{\sin^2\alpha}{\pi}\cdot\frac{U_{\text{m}}\cdot I_{\text{m}}}{\sqrt{2}\cdot\sqrt{2}} = \frac{\sin^2\alpha}{\pi} U\cdot I. \end{aligned}$$

Note that in the considered electrical circuit there are no elements capable of storing energy and returning it back to the power source. Thus, the loading of the source of the reactive component of the power does not necessarily have to be accompanied by the circulation of «exchange» energy between the load and the source. For its occurrence, it is sufficient to create a pulsating one-sided energy flow, since a pulsating flow can always be interpreted as the result of the addition of two or more flows, one of which is one-sided and the other two-sided [30].

The last two expressions also show that with a value of α equal to zero, the total power is equal to the active power, and with any other values of α, it is always less than the square root of the sum of the squares of the active and reactive powers. This is because part of the total power, the distortion power D, is spent on the distorting component i and (t) of the current.

Since the distorting component of the current $i_u(t)$ is orthogonal to the voltage *u(t)* and to the voltage *H{u(t)}*, conjugated with voltage *u(t)* according to Hilbert, the distortion power *D* can only be characterized by the current value. For sinusoidal voltage *u(t)*

$$D = \sqrt{\frac{1}{2T}\int_0^T \sum_{\substack{n=0 \\ n\neq 1}}^{\infty} \left(u(t)\cdot i_n(t)\right)^2 dt}.$$

The error in calculating the distortion power is determined by the number of terms of the Fourier series used in the calculation.

The distortion power is measured in volt-amperes of distortion (VAd) [31].

Steady-state modes in electrical circuits in case of non-sinusoidal supply voltage.

In the case of a non-sinusoidal supply voltage, which is of interest for limited-power supply systems, in particular marine ones, reactive power can be consumed at some harmonics and generated at others. In this case, it can also be characterized by an effective value [32].

$$Q_{\text{д}} = \sqrt{\sum_{n>0}^{n=\infty} Q_n^2},$$

where Q_n – reactive power of voltage and current harmonics with number *n*. Note that if the function describing the non-sinusoidal supply voltage consists of the sum of harmonic components:

$$f(t) = \sum_{n=1}^{n=\infty} (a_n \cos n\omega t + b_n \sin n\omega t),$$

then, when calculating the reactive power, the Hilbert transform can be performed by [26]:

$$f_1(t) = H\{f(t)\} = \sum_{n=0}^{n=\infty} n\omega \int_0^t f_n(\tau) d\tau .$$

As a result:

$$f_1(t) = \sum_{n=1}^{n=\infty} (a_n \sin n\omega t - b_n \cos n\omega t).$$

With a non-sinusoidal supply voltage, the active power equals to [32]

$$P = \sum_{n=0}^{n=\infty} P_{\text{n}},$$

and the distortion power [32]

$$D = \sqrt{\frac{1}{2T}\int_0^T \sum_{\substack{m=0 \\ m\neq n}}^{\infty} \sum_{n=0}^{\infty} \left(u_m(t) i_n(t) - i_m(t) u_n(t)\right)^2 dt}.$$

With non-sinusoidal voltage and current, the total, active, reactive and distortion power are related by the following relation [32]:

$$S = \sqrt{P^2 + Q_{д}^2 + D^2}.$$

It should be noted that knowledge of full capacity is necessary for the implementation and expertise of proper generation and distribution of electricity. Knowledge of the values of active and reactive capacities is necessary for mutual calculations between the supplier and the consumer of electricity [33]. Knowledge of the value of reactive power is also necessary in the development and examination of its compensators. Knowledge of distortion power is necessary in the development and examination of harmonic current filters. [34].

Conclusion

1. This article describes an approach to the analysis of steady-state electrical circuits using the concept of complex analytical voltage.

2. The proposed approach has a number of important advantages over other analytical methods, since it avoids ambiguity in assessing the steady-state modes of an electrical circuit with non-sinusoidal currents and voltages.

3. To assess the validity and reliability of the results of the developed approach, illustrative examples are given showing the close connection between the traditionaland proposed approaches.

4. Analysis of the calculation results shows the acceptability of the proposed approach, which can be recommended in the calculation and examination of steady-state electrical circuits with non-sinusoidal currents and voltages.

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Information about the article: submitted for editing: 20.04.2025; accepted for publishing: 22.05.2025

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