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Vitalii Babak[1], Dr. Sci. (Engin.), Professor, https://orcid.org/0000-0002-9066-4307
Artur Zaporozhets[1]*, PhD (Engin.), Senior Researcher, https://orcid.org/0000-0002-0704-4116
Yurii Kuts[2], Dr. Sci. (Engin.), Professor, https://orcid.org/0000-0002-8493-9474
Leonid Scherbak[1], Dr. Sci. (Engin.), Professor, https://orcid.org/0000-0002-1536-4806
[1]Institute of General Energy of NAS of Ukraine, 172, Antonovycha Str., Kyiv, 03150, Ukraine
[2]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", 37, Prosp. Peremohy, Kyiv, 03056, Ukraine
* Corresponding author: a.o.zaporozhets@nas.gov.ua

SOME FEATURES OF HILBERT TRANSFORM AND THEIR USE IN ENERGY INFORMATICS

Abstract. *Information-measuring technologies (IMT) are an important instrument for solving problems of energy informatics. They allow to form primary information based on the interaction of energy facilities with IMT sensors that form information signals. In many practical applications, the constructive model of information signals is the model of narrowband signals. The article summarizes the features of the discrete Hilbert transform and its application to obtain the primary characteristics of information signals – bypass and phase as functions of time. The main advantages of using the discrete Hilbert transform in signal processing for energy informatics are considered, including the consistency of obtaining frequency and time characteristics, high information content, the ability to analyze the dynamics of changes in signal characteristics, the possibility of obtaining samples of characteristics of information signals of significant volumes, etc. It is proposed to use a phase characteristic to select the time interval that limits the signal sample and sets it to a multiple of the signal period, and the sampling rate of information signals to reduce the errors in estimating their spectrum. The possibility of obtaining on their basis secondary deterministic (voltage level, voltage deviations from the nominal level, attenuation coefficient, signal period, signal phase shift, oscillation frequency, etc.) and statistical (sample characteristic, sample variance, sample median, sample circular variance, sample circular median, sample circular kurtosis, etc.) of signal information characteristics, which allows more complete to use their information resource. These characteristics can be used both for assessing power quality characteristics and for monitoring and diagnosing of energy facilities.*

Keywords: energy informatics, information signals, signal processing, discrete Hilbert transform, amplitude signal characteristics, phase signal characteristics.

1. Introduction

The current stage of development of energy systems is characterized by an increase in the amount of electricity consumed, the integration of various sources of electricity generators into a single system, an increase in the number of energy companies and consumers of electricity, an increase in the length of electricity networks, etc. At the same time, such systems are constantly under the influence of natural and anthropogenic factors that can destabilize their functioning. Ensuring the stable and reliable operation of energy systems, the safety of energy facilities and systems (including environmental safety), the early detection of critical situations that require a prompt response, the maintenance of technological processes for managing them in normal and emergency modes and a guaranteed level of quality of power parameters requires that the information flows steady increase, which in turn requires not only the development and improvement of the processes of monitoring, diagnostics, and control in the energy sector [1] but also a change in the paradigm of operation and development in the energy sector as a whole.

To overcome new challenges in recent years, a new scientific branch has emerged and is actively developing – energy informatics [2], covering the use of information-measuring and information-communication technologies to solve the problems of reducing specific energy consumption, increasing energy efficiency, integrating sources of decentralized renewable energy into a single system, etc. Increasing attention is being paid to various aspects of this issue in scientific periodicals [3–5]. An important component of energy informatics is information-measuring technologies (IMT), which allow to generate and research of the information signals to obtain objective information about the current state of energy facilities [6]. An information signal in the IMT of the power engineering industry is understood as both the electricity generated and transmitted over the network, the parameters and quality characteristics of which must be controlled, and the signals generated by the IMT sensor systems that characterize the current state of individual elements and components of the electric power equipment.

The first step in the study of information signals is to obtain their parameters and characteristics. The accuracy of their assessment largely determines the reliability of the conclusions and the correctness of technological solutions. Therefore, methods and means of information signal processing are important components of IMT.

Modern methods for measuring signal parameters in the time domain of its representation are focused on using the capabilities of digital signal processing. Usually, an analog variable frequency signal is converted into digital, and its parameters – frequency, period, phase shift, amplitude or effective voltage value, etc., are obtained from its instantaneous values. Such a simplified approach leads to the simplest and most economical technical solutions, but it is focused on the analysis of stationary signals with a low level of noise and interference.

In many practical applications of IMT in energy, information signals can be represented by a model of narrowband signals. An efficient method for characterizing such signals in the time domain is the discrete Hilbert transform. This digital signal processing method is widely used in telecommunication technologies. However, in information and measuring technologies, including those focused on the energy industry, it has not yet found proper distribution, and its capabilities have not yet been fully disclosed.

The purpose of the article is to analyze the features of using the discrete Hilbert transform to obtain the characteristics of information signals generated in power systems during their operation.

2. Model of information signals and their information resource

In a broad sense, a signal is understood as a process that characterizes a change in time and space of the physical state of an object and is used to obtain information about this object, as well as to display, register, transmit, receive and process messages. Signals can have different physical nature. In energy informatics, both electrical signals in the power grid and signals in systems for measuring, controlling, and diagnosing power system equipment are considered as informational, which are formed by sensors in the form of electrical signals – time-varying electrical voltage or current, and which are most convenient for processing, storage, and transmission.

A necessary step in the measurement of information signals is the presentation of their model in an analytical form [7, 8]. To solve a significant range of problems in the analysis of energy informatics signals, a narrowband signal model can be used. Its characteristic feature is that the energy spectrum of such signals is concentrated in a small frequency band Δf in the vicinity of a certain center frequency $f_0 >> \Delta f$. The analytical model of such signals has the form

$$u(t,\bar{p}) = U(t,\bar{p})\cos\Phi(t,\bar{p}),\ t \in T_{\text{c}}, \qquad (1)$$

where $U(t,\bar{p})$, $\Phi(t,\bar{p})$ – respectively bypass (amplitude or just amplitude characteristic) and phase of the signal (phase-time or simply phase characteristic); t, T_c – respectively, the current time and the time of signal observation; $\bar{p}$ – vector of informative signal parameters. As informative parameters, there can be quantities and characteristics of technological processes in the energy sector that are different in physical nature, for example, the frequency of the generated electrical signal and its initial phase, the temperature of the coolant in the reactor cooling system and its speed, the rotational speed of turbine rotors, diagnostic parameters of power equipment, level of mechanical vibrations, etc. If necessary (for example, during diagnosing energy systems and networks branched in space), the arguments of the model (1) can be the spatial coordinates of receiving an information signal in the accepted coordinate system. The $u(t,\bar{p})$ signal is considered as a realization of $\xi(t)$ random process belonging to the class of processes with a finite power, i.e. $\mathbf{M}\xi^2(t) < \infty,\ \forall t \in T_{\text{c}}$ (M – mathematical expectation operator).

Electric currents and voltages in power transmission networks are generally represented as periodic polyharmonic signals with a multiple frequency ratio

$$u(t) = \sum_{g=1}^{G} U_g \cos\left(2\pi f_g t - \varphi_g\right),\ t \in T_c,\ f_g / f_1 \in N, \qquad (2)$$

where N – set of natural numbers, U_g, f_g, φ_g – amplitude, frequency, and initial phase of the g-th harmonic respectively. As primary parameters, they are of the greatest interest as objects of measurement for determining the quality of electricity. Based on these signal parameters, some power quality characteristics regulated by the standard [9] can be determined, including the frequency of the power supply voltage, frequency deviation from the nominal value, harmonic voltage, voltage dip, etc. Since $U_g >> U_1$, $j > 1$ condition is satisfied for electrical network signals, we can assume that the energy spectrum of signals (2) is concentrated in the vicinity of the frequency of the first harmonic f_1, therefore, such signals can be considered as narrow-band signals with a certain level of approximation.

3 Results

3.1 Determination of the primary characteristics of information signals

One of the effective methods for analyzing the signals of type (1) is the integral Hilbert transform [10,11]. It makes it possible allows to unambiguously determine the amplitude $U(t,\bar{p})$ and the phase $\Phi(t,\bar{p})$ characteristic of the signal (1). This possibility arises because the Hilbert transform allows determining the quadrature signal $\tilde{u}(t,\bar{p})$, $t\in T_c$, all frequency components of which are shifted by $\pi/2$ relative to the corresponding components of the information signal $u(t,\bar{p})$, $t\in T_c$. This allows to consider and determine the characteristics of $U(t,\bar{p})$ and $\Phi(t,\bar{p})$ for the so-called analytical complex signal of the form

$$\dot{z}(t,\bar{p})=u(t,\bar{p})+i\tilde{u}(t,\bar{p}),\ t\in T_c,\ i=\sqrt{-1}. \quad (3)$$

The procedure for determining the analytical signal is much faster and easier in the discrete version of the frequency domain using the discrete Fourier transform (DFT) [12].

In this case, a sample of values of the sampled information signal $u[j,\bar{p}]$, $j=\overline{1,J}$ is analyzed, and the corresponding analytical discrete signal is represented by a sequence of values $\dot{z}[j,\bar{p}]=u[j,\bar{p}]+i\tilde{u}[j,\bar{p}]$, $j=\overline{1,J}$, where $j=\left[t/T_p\right]^+$ is the signal sample number in the sample, $J=\left[T_c/T_p\right]^+$, T_p is the signal sampling period, $T_p << 1/f_g$.

Using the $\dot{z}[j,\bar{p}]$ signal, the estimates of the desired discrete amplitude characteristics and the phase characteristic limited by the $[0,2\pi)$ interval are determined by the known formulas [10], respectively, as

$$\hat{U}[j,\bar{p}]=\sqrt{\left(u[j,\bar{p}]\right)^2+\left(\tilde{u}[j,\bar{p}]\right)^2},\ j=\overline{0,(J-1)}, \quad (4)$$

$$\hat{\varphi}[j,\bar{p}]=\operatorname{arctg}\tilde{u}[j,\bar{p}]/u[j,\bar{p}]+$$
$$+0.5\pi\left\{2-\operatorname{sign}\tilde{u}[j,\bar{p}]\left(1+\operatorname{sign}u[j,\bar{p}]\right)\right\},\quad (5)$$
$$j=\overline{0,(J-1)}.$$

In formulas (4), (5), and below, the symbol "^" denotes estimates of the corresponding characteristics obtained from the results of processing measurement data.

Function (5) has a sawtooth shape and periodically changes within [0, 2π), i.e. represents the so-called non-unwrapped phase of the signal. The discrete instantaneous unwrapped phase is obtained from (2) as

$$\hat{\Phi}[j,\bar{p}]=\hat{\varphi}[j,\bar{p}]+2\pi q\left(\hat{\varphi}[j,\bar{p}]\right),\ j=\overline{0,(J-1)}, \quad (6)$$

where $q\left(\hat{\varphi}[j,\bar{p}]\right)$ – the step function that increases by one each time the phase changes from 2π to 0. Equation (6) allows us to estimate the reversed phase of the signal as a function of time.

If it is necessary to evaluate phase shifts between two signals of the same frequency (for example, if phase angles between successive linear voltages in three-phase networks are determined), the estimates of the unwrapped phase $\hat{\Phi}_1[j]$, $\hat{\Phi}_2[j]$ of two coherent signals $u_1[j]$, $u_2[j]$ are determined according to formulas (5), (6), and the phase shift between them for all j points as the difference

$$\hat{\varphi}_{2,1}[j]=\hat{\Phi}_2[j]-\hat{\Phi}_1[j],\quad j=\overline{0,(J-1)}. \quad (7)$$

Using the unfolded phase (6), it can be got the instantaneous frequency of the signal using the following formula

$$\hat{f}[j,\bar{p}]=\frac{\left(\hat{\Phi}[j,\bar{p}]-\hat{\Phi}[j-1,\bar{p}]\right)\operatorname{mod}2\pi}{2\pi T_p},$$
$$j=\overline{1,J}. \quad (8)$$

Thus, the use of DHT allows to simultaneously obtain samples of significant amounts of instantaneous values of the amplitude, phase, phase shifts, and frequency of information signals for their subsequent use.

3.2 Determination of secondary characteristics of information signals by their amplitude and phase characteristics

Solving the urgent important problems of energy informatics requires the most complete use of the signal information resource. This requires not only an assessment of the primary parameters and characteristics of information signals but also the identification and selection of secondary characteristics, which may be more informative for some cases of monitoring and diagnostics. The general concept of using information signals in energy informatics is shown in Fig. 1.

Variants of secondary characteristics that can be obtained from the $\hat{U}[j,\bar{p}]$ and $\hat{\Phi}(t,\bar{p})$ functions are presented below. Table 1 shows the secondary deterministic characteristics of information signals. These characteristics change during the operation of energy systems as a whole and their components as a result of the action of various destabilizing factors – fluctuations in load power, the presence of disturbances from operating equipment, the influence of meteorological factors, changes in technological

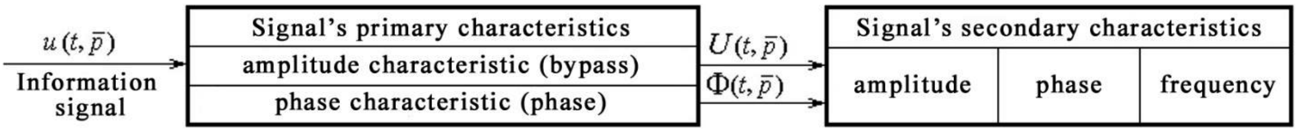

Fig. 1. The general structure of information signal processing in energy informatics

operating modes of equipment, changes in the mechanical or electrophysical parameters of parts and materials of energy equipment, etc.

In emergencies, these characteristics may go beyond the permissible values.

Since information signals in the process of their formation are influenced by various random factors, and their transmission is accompanied by the action of noise, therefore, they can be considered as realizations of random processes, then not only deterministic but also random characteristics should be included to the secondary characteristics. Table 2 shows a list of the most promising secondary statistical characteristics of information signals for use. It is assumed that statistical properties are obtained from samples of corresponding features of a certain size in a stationary mode.

Secondary statistical characteristics for voltage are determined by well-known algorithms for calculating sample characteristics of random variables. The definitions of circular characteristics for sampling the difference in phase shifts of signals are given in [13]. It do not differ from the sampling circular characteristics of random angles on the plane [14, 15, 16], and the analysis of their content is beyond the scope of the article.

In general, the obtained results expand the possibilities of practical use of the discrete Hilbert transform in the implementation of information-measuring signal processing technologies in the energy sector.

4 Analysis of the characteristic features of the DPG for use in energy informatics

Even though considerable attention has been paid to the problem of information signal processing in general, the issues of using DHT as a component of energy informatics have not yet been adequately covered. Let's look at the main advantages of using DHT for signal processing in energy informatics.

1. Consistency in obtaining frequency and time characteristics. Since it is convenient to determine

Table 1. Secondary deterministic characteristics of information signals

	Primary characteristics of the information signal	
	Amplitude characteristic	Phase characteristic
Secondary deterministic characteristics	• Voltage level • Voltage deviation from the nominal value • Symmetry of line voltages • Long and short voltage interruptions • Amplitude modulation signal function • Signal amplitude-shift keying function • Attenuation coefficient (decrement)	• Phase shift of signals • Phase angles between series line voltages • Oscillation frequency (first harmonic) • Frequency deviation from the nominal value • Signal phase modulation function • Signal phase-shift keying function • Signal period

Table 2. Secondary statistical characteristics of information signals

	Primary characteristics of the information signal	
	Amplitude characteristic	Difference in phase characteristic
Secondary statistical characteristics	• Sample characteristic • Sample mean • Sample dispersion • Sample standard deviation • Sample median • Sample moments of higher orders • Sample kurtosis • Sample asymmetry factor • Empirical distribution (histogram)	• Sample characteristic function • Sample sine-moments and cosine-moments • Sample circular average of the phase shift • Sample length of the resulting vector • Sample circular dispersion • Sample circular standard deviation • Sample circular median • Sample circular kurtosis • Sample circular asymmetry coefficient • Empirical distribution of phase shifts (pie chart) • Difference of trends of phase characteristics

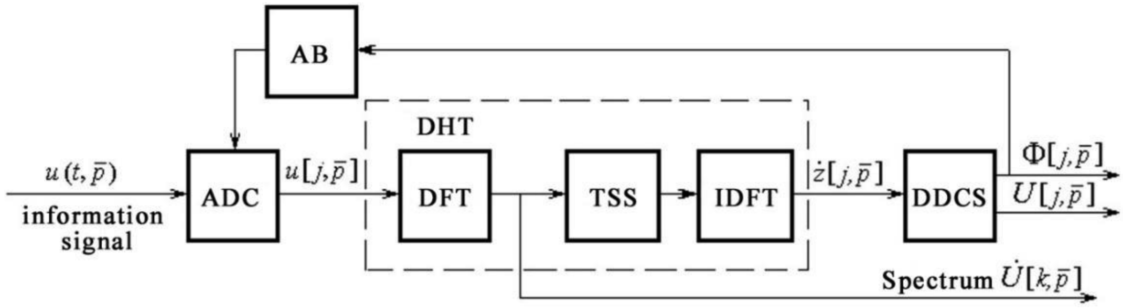

Fig. 2. Obtaining primary information characteristics of signals in the frequency and time domains

the DHT through the discrete Fourier transform (DFT), the integration of information signal processing processes in the frequency and time domains practically does not require additional hardware and software costs (Fig. 2).

Fig. 2 shows the structure where the analog-to-digital converter (ADC) provides a digital copy $u[j, \bar{p}]$ of the analog information signal $\tilde{u}(t,\bar{p})$. The DFT block provides the calculation of the signal spectrum. Transformation of the signal spectrum (TSS) makes it possible to obtain the spectrum of the discrete analytical signal $\dot{z}[j, \bar{p}]$, the samples of which are calculated in the inverse DFT (IDFT) block. The discrete direct and inverse Fourier transform is performed according to [10]:

$$\dot{U}[k,\bar{p}] = \sum_{j=0}^{J-1} u[j,\bar{p}] \cdot e^{-\frac{2\pi i}{J}kj},\ k = \overline{0,(J-1)}; \quad (9)$$

$$\dot{z}[k,\bar{p}] = \frac{1}{J}\sum_{k=0}^{J-1} \dot{U}_{\text{T}}[k,\bar{p}] \cdot e^{\frac{2\pi i}{J}kj},\ j = \overline{0,(J-1)}. \quad (10)$$

where $\dot{U}[k,\bar{p}]$ – transformed signal spectrum $u[j, \bar{p}]$.

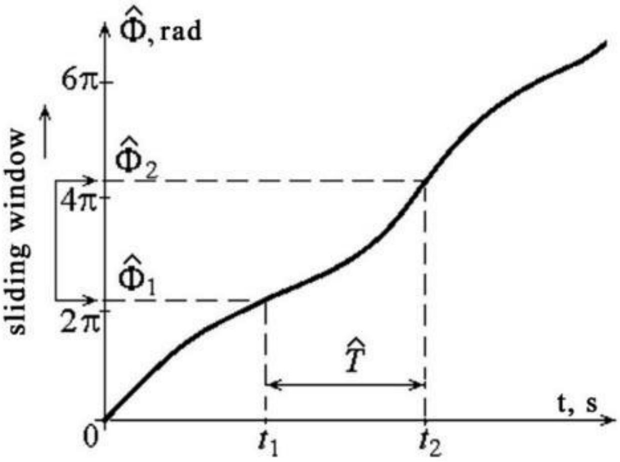

Fig. 3. Graphical representation of the process of determining the period of a signal by its phase characteristic

Calculation of estimates $\hat{U}[j, \bar{p}]$ and $\hat{\Phi}[j, \bar{p}]$ occurs in the block for determining the discrete characteristics of the signal (DDCS).

The phase characteristic $\Phi[j, \bar{p}]$ can be used to select the time interval that limits the signal sampling and makes it a multiple of the signal period, and the ADC sampling rate implemented by the adaptation block AB. This is necessary to eliminate the effect of splitting the spectral components of the $u[j, \bar{p}]$ signal and provide the required frequency resolution. The idea of determining the current value of the signal period by the analog function $\hat{\Phi}(t,\bar{p})$ is illustrated in Fig. 3.

To determine the current period of the signals, the operation of sliding scanning of the values of the signal phase characteristic is performed with a rectangular window with an aperture of 2π (or a multiple of 2π), which displays the sections of the phase characteristic selected by the window on the time axis, determine the corresponding time intervals and evaluate the current values of the period of the studies signal.

$$\hat{T}(t,\bar{p}) = \frac{1}{2\pi} \cdot \frac{\hat{\Phi}_2(t,\bar{p}) - \hat{\Phi}_1(t,\bar{p})}{t_2 - t_1}. \quad (11)$$

2. High information content through the ability to analyze all information related to the integral influence of the parameter vector $\bar{p}$ on the characteristics of the information signal, in contrast to the case of analyzing individual harmonic components obtained using the DFT, when this influence is distributed among different frequency components of the spectrum.

3. The ability to analyze the dynamics of changes in the discrete amplitude, phase, and frequency characteristics of signals over the time interval of their observation T_c, which provides new opportunities for improving the methodology for processing information signals.

4. The ability to obtain a sample of the characteristics of information signals of significant volumes, which creates the prerequisites for a more correct application of statistical methods for processing characteristics.

5. The ability to synchronously calculate the amplitude and phase characteristics of the signal for sharing, extracting new information features, and searching for their functional or correlation relationships with the desired parameters of the processes and objects under study.

6. Since the DHT has the property of linearity, and the modulus of the Hilbert transform complex coefficient is equal to 1, the formation of the Hilbert image of the signals $\tilde{u}(t, \overline{p})$ occurs without distorting the voltage degree (ADC quantization step) with which the $u(t, \overline{p})$ values are measured.

7. The value of the phase characteristic in radians is a value with a dimension of 1, determined by the ratio of two quantities of the same kind – $\tilde{u}(t, \overline{p})$ and $u(t, \overline{p})$ without any use of a separate measure for measuring the signals phase shift (5).

In general, the use of DHT as the basis of the signal processing methodology in energy informatics creates favorable conditions for minimizing the analog part of signal processing systems by expanding digital processing and complicating measurement information processing algorithms, which increases the flexibility of control, diagnostics, and monitoring systems and the possibility of their improvement through modernization software.

5. Conclusions

One of the topical areas in the development of informatics is energy informatics, aimed at the use and management of energy, increasing energy efficiency, integrating sources of decentralized renewable energy into a single energy system, reducing specific energy consumption, and reducing the negative impact of energy systems on the environment. The main results of this research are:

1. It is shown that information and measurement technologies are an important segment of energy informatics, which allow obtaining objective information both about the current state of energy systems and both about the current state of energy systems and networks and about the electricity quality.

2. For a large number of information signals in the energy sector, there is a model of narrowband signals.

3. The characteristic features of the discrete Hilbert transform are considered, which make it possible to determine the primary characteristics of narrow-band signals, their amplitude, and phase characteristics.

4. For the first time it is proposed to use the phase characteristic to select the time interval that limits the signal sampling and sets it to a multiple of the signal period, and the sampling rate of information signals to reduce the errors in estimating their spectrum.

5. The DHT, unlike other well-known signal processing methods, makes it possible to obtain not only the bypass and phase of information signals, but also to determine new secondary deterministic and statistical characteristics due to the obtained significant data arrays. These include, first of all, such sample characteristics as trigonometric moments, circular mean, length of the resulting vector, circular dispersion, circular median, obtained from the phase of the signal, etc. These characteristics can be recommended for use in energy informatics together with generally accepted characteristics in the formation of databases describing the state of power equipment, the quality of electricity and the dynamics of their change.

In general, the obtained results expand the possibilities of practical use of the discrete Hilbert transform in the implementation of information-measuring signal processing technologies in the energy sector.

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ОСОБЛИВОСТІ ПЕРЕТВОРЕННЯ ГІЛЬБЕРТА ТА ЇХ ВИКОРИСТАННЯ В ЕНЕРГЕТИЧНІЙ ІНФОРМАТИЦІ

Віталій Бабак[1], д.т.н., професор, https://orcid.org/0000-0002-9066-4307
Артур Запорожець[1]*, к.т.н, ст.досл., https://orcid.org/0000-0002-0704-4116
Юрій Куц[2], д.т.н., професор, https://orcid.org/0000-0002-8493-9474
Леонід Щербак[1], д.т.н., професор, https://orcid.org/0000-0002-1536-4806
[1]Інститут загальної енергетики НАН України, вул. Антоновича, 172, м. Київ, 03150, Україна
[2]Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», проспект Перемоги, 37, м. Київ, 03056, Україна
* Автор-кореспондент: a.o.zaporozhets@nas.gov.ua

Анотація. *Інформаційно-вимірювальні технологій (ІВТ) є важливим ресурсом для розв'язання задач енергетичної інформатики. Вони дають змогу формувати первинну інформацію на основі взаємодії об'єктів енергетики з сенсорами ІВТ, які формують інформаційні сигнали. У багатьох практичних застосуваннях конструктивною моделлю інформаційних сигналів є модель вузькосмугових сигналів. В статті узагальнено особливості дискретного перетворення Гільберта та його застосування для отримання первинних характеристик інформаційних сигналів – обвідної та фази, як функцій часу. Розглянуто основні переваги використання дискретного перетворення Гільберта в обробленні сигналів для енергетичної інформатики, серед яких: узгодженість отримання частотних та часових характеристик, висока інформативність, можливість аналізу динаміки зміни характеристик сигналів, можливість отримання вибірок характеристик інформаційних сигналів значних обсягів та ін. Запропоновано використання фазової характеристики для вибору часового інтервалу, який обмежує вибірку сигналу і задає його кратним періоду сигналу, та частоти дискретизації інформаційних сигналів з метою зменшення похибок оцінювання їх спектру. Показана можливість отримання на їх основі вторинних детермінованих (рівень напруги, відхилення напруги від номінального рівня, коефіцієнт загасання, період сигналу, фазовий зсув сигналу, частота коливань та ін.) та статистичних (вибіркова характеристика, вибіркова дисперсія, вибіркова медіана, вибіркова кругова дисперсія, вибіркова кругова медіана, вибірковий круговий ексцес та ін.) інформаційних характеристик сигналів, що дає змогу більш повно використовувати їх інформаційний ресурс. Ці характеристики можуть бути використані як для оцінювання показників якості електроенергії, так і для контролю та діагностування об'єктів енергетики.*
Ключові слова*:* енергетична інформатика, інформаційні сигнали, обробка сигналів, дискретне перетворення Гільберта, амплітудна характеристика сигналів, фазова характеристики сигналів.

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