ISSN 2786-7102 (Online), ISSN 2786-7633 (Print)
https://doi.org/10.15407/srenergy2024.02.071

UDC 621.316.1

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APPLICATION OF HILBERT TRANSFORM FOR POWER QUALITY INDICATORS MONITORING IN GENERAL PURPOSE GRIDS

Abstract. *During the operation of power grids, abnormal modes occur that lead to a decrease or increase in the grid voltage beyond permissible values, the appearance of high-frequency noise components and grid signal fading's, which fading's the power quality and can lead to the failure of electrical equipment. This requires constant monitoring of power quality indicators. The methods of measuring power quality indicators have been examined and analyzed in the article, their advantages and limitations have been considered, and the inefficiency of using the Fourier transform for estimating of power quality indicators in time domain has been justified. The application of Hilbert transform has been suggested for monitoring the indicators of power quality in general-purpose grids, which include measuring the duration and magnitude of voltage dips, the duration of voltage fading, localization and determination of the duration of high-frequency noise interference in the power grid, determination of phase shift during voltage dip. A simulation of the process of determining the indicators of power quality in time domain and the time intervals during which these indicators exceed the established limits has been performed, which confirmed the effectiveness of using the Hilbert transform in the systems of their monitoring.*

Keywords: general purpose power grid, power quality indicators, Hilbert transform.

1. Introduction

The integration of the Ukrainian power grid into the power grid of continental Europe necessitates compliance with the requirements of electricity supply to consumers according to EU standards. The power quality is ensured by suppliers' compliance with standardized quality indicators according to DSTU EN 50160:2023 [1], which establishes permissible and limit values at which electrical devices and equipment remain functional. The deviation of any of the indicators disrupts the operation of electrical devices and leads to malfunctions in the operation of electronic equipment, which manifests itself in the reduction of their service life, loss of data, disruption of automation, increase in the error of measuring equipment, etc.

According to the standard, the nominal supply voltage is 230 V, and the nominal frequency of the electricity voltage is 50 Hz. To ensure the power quality, the voltage and frequency of the power grid must be within 209–231 V for voltage (deviation no more than 5 %) and 49.8–50.2 Hz for frequency (deviation no more than 1 %), and the non-sinusoidal coefficient should not exceed 5 % [2]. The deviation of power quality indicators is caused not only by the technological process of electricity production but also by the occurrence of emergency modes of operation of the power system, features of transmission, distribution and consumption of electricity.

The power quality indicators are known to be divided into 3 groups. The first includes deviations of voltage and frequency from the nominal value, the second includes the distortion coefficients of the power grid voltage, the sources of which are individual consumers of electricity, and the third includes the magnitude and duration of dips and overvoltages etc., which are caused by emergency modes, commutations or lightning discharges in the power supply line.

Measuring the quality indicators of the first group is not a problem. The determination of the distortion coefficients of voltage forms and the identification of the presence of dips, overvoltages and their duration are more difficult. There is no unique measurement methodology for these indicators, a significant number of different methods of their determination are used. Most of the known methods of measuring indicators of the second and third groups are based on the application of linear integral transformations such as discrete Fourier transform (DFT), Herzel transform, wavelet transform, etc. One of the main problems of low-quality electricity is the presence of higher harmonics, which appear as a result of connecting devices with a non-linear load and are estimated by the total harmonic distortion coefficient (THDC), which belongs to the second group of indicators of power quality. In [3], two methods of determining the THDC using DFT have been considered. The first consists of dividing the monitored signal into harmonics of the fundamental frequency and a set of higher harmonics, followed by measuring the root mean square value of each of these two parts and calculating the THDC. The second method consists of measuring the harmonic amplitude of the fundamental frequency and each harmonic and then using these measurements to calculate the THDC from the amplitudes of each harmonic.

The output voltage of the electrical grid, in addition to higher harmonics that are multiples of the fundamental frequency, may contain interharmonics that are not multiples of the fundamental frequency. The task of determining their frequency and amplitude to obtain the correct value of THDC based on the application of DFT has a certain specificity. In works [4–8], the authors proposed solutions that make it possible to determine with high accuracy the frequencies and amplitudes of harmonics and interharmonics based on DFT. In particular, work [4] provides an improved method for determining the THDC based on the DFT, which consists of calculating the difference between the signal distorted by higher harmonics and the reference signal. THDC is calculated as the ratio of the received effective value of the difference to the effective value of the first harmonic of the controlled voltage. The method ensures a measurement error of THDC of no more than 1 % and also allows taking into account all harmonics and interharmonics, which provides higher accuracy compared to other methods.

In [8], the authors proposed a method for estimating harmonics and interharmonics using the vortex search algorithm, designed to estimate harmonics and interharmonics of the power system voltage for their significant changes over time. In addition, the results are compared with the results obtained by the method of least squares, DFT, and Kalman filtering. According to the obtained results, the above algorithm demonstrates better estimation performance in a noisy environment and lower computational complexity.

The main drawback of using the DFT in the above methods is the limited frequency resolution and the insufficient accuracy of estimating the frequency of individual harmonic components under time-varying grid voltage. To overcome this limitation, the application of short-time Fourier transform (STFT) is proposed in [9]. The authors performed a comparative analysis of the efficiency of the DFT and STFT in measuring the THDC utilizing modelling and simulation in the MATLAB/Simulink environment. The obtained results confirmed the effectiveness of the application of STFT for the analysis of time-varying signals, which consists in the use of a DFT with a sliding window and provides a fixed frequency resolution for all frequencies. However, because the fundamental frequency does not always correspond to the nominal value, frequency analysis using the STFT can give erroneous results depending on the deviation of the fundamental frequency from its nominal value. Methods of frequency analysis are used to solve this problem. For example, in work [10], the authors used a Kalman filter, which works on the principle of recursive stochastic technique and provides optimal estimation by the method of least squares and makes it possible to perform frequency analysis with minimal error covariance and determine power grid quality parameters with a low signal-to-noise ratio.

In addition to interharmonics, the presence of broadband noise also affects the result of the THDC determination. The method of determining the THDC with the possibility of filtering broadband noise is represented in [11]. The proposed method is implemented by filtering a signal based on the Herzel transform, which has a frequency response with a frequency bandwidth of 1 Hz. Due to the filtering of the measurement data set, broadband background noise is filtered out, and the accuracy of the THDC measurement is increased. In addition, this method has less computational complexity, requires less memory usage than a typical fast Fourier transformation, and does not require saving a complete set of measurement readings in the memory of the THDC meter.

An important indicator of the power quality is active, reactive and total power. Methods of their determination have been described in [12], as well as experimental calculations of power components and power quality indicators for polyharmonic signals have been carried out.

The work [13] considers the possibilities of increasing the accuracy and informativeness of the assessment of the quality of electrical energy by individual components of the instantaneous power. The effectiveness of using the unit power component of distortions and consumer identification coefficients, which cause nonlinear distortions in the power grid, calculated using the entered value of the effective power, has been proven. The obtained results can be used as part of the technical electricity accounting systems to create effective systems for compensating nonlinear distortions.

An important (third) group of quality indicators is formed by indicators that characterize the change in time of the characteristics of the amplitude values of the grid voltage, which include: deviation of the root mean square values of the voltage from the nominal values, voltage dips, overvoltage, short-term distortion of the voltage by high-frequency noise, etc. The indicators of this group are determined by transformations that allow analyzing signals in the amplitude-time domain and identifying the moment of appearance and termination of dips or overvoltages. To measure these indicators, it is not possible to apply DFT, since it consists in the transition from the amplitude-time domain to the amplitude-frequency domain [14]. The authors of this paper, through model experiments, have proved the inefficiency of using DPF to measure overvoltages and voltage dips, instead, they describe a way to determine these indicators of power quality by applying a wavelet transformation, which allows you to represent the voltage of the power grid in the form of a two-dimensional and three-dimensional wavelet spectrogram, which clearly shows the moments of the occurrence of overvoltages, voltage dips, the appearance of a high-frequency signal and their duration are visible. The disadvantage of using the wavelet transformation is the impossibility of obtaining information about the phase characteristics of the analyzed signals.

In the paper [15], the authors have proposed the use of wavelet transformation with the sequential decomposition of the analyzed signal into frequency-ordered spatially orthogonal levels in the monitoring systems of electric energy quality in decentralized power supply systems. The method makes it possible to detect the time of occurrence of signal distortions and their duration due to equal, sequential reduction of the scale, as a result of which the signal is divided into frequency sub-bands, which are associated with the determination of the relevant parameters of the quality of electrical energy, which makes it possible to monitor them online.

In addition to using the wavelet transformation to determine the parameters of the third group, in [16], it is proposed to use the Hilbert-Huang transformation to decompose the output voltage of the power grid into separate frequency components. After decomposing the data using this method, an algorithm is proposed to accurately detect the start and end times of the voltage dip. The proposed algorithm is further extended for the automatic detection of transition segments for accurate detection of time variables and individual characteristics of power quality indicators, such as magnitude of voltage dip and phase angle jump.

The analysis of the latest research works on the problems of monitoring electricity quality indicators in general-purpose networks proved that this topic has not lost its relevance. Of great practical interest is the finding of new and improvement of known methods for determining power quality indicators of the third group. Therefore, determining an effective method of monitoring power quality indicators related to the characteristics of the amplitude values of the grid voltage is an urgent task for the power industry.

The purpose of the article is to consider the application of the Hilbert transformation in power quality monitoring systems to determine power quality indicators in the time domain.

2. Problem statement

This work analyzes the power quality in the grids of general purpose, for which the nominal supply voltage is $U_{\text{н}}$ = 230 В, and nominal frequency of electricity voltage f_{n} = 50 Гц. As a result of the action of various factors, indicators of the power quality, determined by the stability of the amplitude values of the grid voltage, change over time. The following power quality indicators are subject to determination and evaluation:

- voltage amplitude in the normal mode of electricity consumption;
- amplitude and duration of voltage dips in the power supply grid;
- gaussian noise interference in the power supply grid and its duration;
- the duration of the voltage drop for the general-purpose power grid.

Analyzed signals are observed over time length $T_a >> 1/f_{\text{n}}$ and are represented by discrete samples, obtained with sampling frequency f_d, which is significantly higher than the nominal frequency, that is $f_d >> f_{\text{n}}$.

It is necessary to investigate the possibilities of the discrete Hilbert transformation to estimate the above indicators of power quality in the time domain, the moments when they go beyond the permissible limits and the duration of the intervals of their stay outside the permissible limits. The research method is computer simulation based on models of the investigated signals.

3. Main section

3.1. Voltage model in general-purpose power grids

A harmonic signal with a time-varying envelope and a time-limited additive noise component is used to solve the given problem. Thus, in the conducted model experiments, the following expression of the voltage in general-purpose power grids was used, which makes it possible to investigate the process of determining the indicators of the power quality in the time domain:

$$u(t)=U(t)\cos(2\pi f_{\text{n}}t-\varphi)+\xi(t)\cdot I(t), \varphi\in[0, 2\pi), t\in[0, T_a], \tag{1}$$

where $U(t)$ is the envelope of signal, φ is the initial phase of the harmonic component of the signal, $\xi(t)$ is the realization of Gaussian noise component of the signal (1), which is centered and has a variance σ^2, $I(t)$ is an indicator function that determines the duration of the noise component

$$I(t)=\begin{cases}1, \; t\in T_\xi\subset T_a, \\ 0, \; t\notin T_\xi, \end{cases} \tag{2}$$

where T_ξ is time interval, during which the noise component acts, $T_\xi << \dfrac{1}{f_{\text{n}}}$.

The indicators of the power quality in the time domain are determined by the envelope of the signal (1). In turn, estimates of the envelope as well as other characteristics of the signal (1) can be determined using the Hilbert transformation. Various aspects of the application of this transformation in the analysis of the characteristics of cyclic information signals are given in works [16, 17]. The peculiarities of using the Hilbert transformation in energy informatics have been considered in the work [18]. In general, this transformation makes it possible to obtain the Hilbert image of the signal (1) – $u_h(t)$, which is in quadrature to the signal (1). On this basis, the estimate of the envelope of this signal is determined in the following form:

$$\hat{U}(t)=\sqrt{\left(u(t)\right)^2+\left(u_h(t)\right)^2},\, t\in\left[0,T_a\right], \tag{3}$$

and estimation of its phase as:

$$\hat{\Phi}(t)=arctg\frac{u_h(t)}{u(t)}+\frac{\pi}{2}\left\{2-sign\left(u_h(t)\right)\cdot\left(1+sign\left(u(t)\right)\right)\right\}+\mathbf{L}\left(u_h(t),u(t)\right),\, t\in\left[0,T_a\right], \tag{4}$$

where $\mathbf{L}$ is signal phase expansion operator (1) beyond the interval $\left[0;\,2\pi\right)$, sign(*x*) is a sign function of a variable *x*.

In the case of representing the signal (1) in digital form, the continuous time argument *t* should be replaced in this expression to the discrete one jT_d, $j=\overline{1,\left[T_a/T_d\right]^+}$, where $\left[\cdot\right]^+$ is integer part of a number. A discrete Hilbert transform is applied to such sequences, which allows obtaining samples of the envelope and phase of the signal with the frequency $f_d >> f$. This determines the possibility of observing the dynamics of envelope changes of the signals (1) even during its period and determining the fade duration and other violations of quality indicators and the duration of the action of short-term noise components in the grid voltage with a fixed time of the beginning and end of such variations.

3.2. Modelling technique

The methodology for conducting experiments to determine dips, overvoltages, and signal fadings, as well as detection and evaluation of the duration of the effect of voltage noise interference is as follows. At the first stage of modelling, the parameters of the signal (1) are set and a sample of its values is obtained. In the second stage, a discrete Hilbert transformation is applied to this sample and an estimate of the envelope output voltage of the power grid is calculated. In the third stage, the identification and localization of areas where the permissible norms of quality indicators are violated (a sharp deviation of the amplitude by more than 5% from the nominal one) is carried out and their duration is estimated. In the last, fourth stage, estimates of the amplitude and duration of intervals with a violation of quality indicators are obtained, and the instantaneous values of the absolute error of the estimate of the envelope and relative error of the determination of time intervals are determined:

$$\delta_u(t)=\hat{U}(t)-U_n, \tag{5}$$

$$\gamma_t(U_c)=\left|\frac{\hat{T}(U_c)-T_n}{T_n}\right|\cdot 100\%, \tag{6}$$

where $\hat{T}(U_c)$ is the estimation of fading time interval, overvoltages or voltage dips, determined by the value U_c of the threshold voltage, U_n, T_n are given by model parameters (1) – nominal values of the envelope and time intervals.

The simulation was carried out for the following given data: the nominal value of the amplitude of the grid voltage U = 230 В, the nominal value of the power grid frequency f = 50 Hz, sampling rate f_d = 12,8 кГц (256 samples on the period), sampling time t_d = 78,125 μs, duration of analysis T_a = 0,16 s (8 periods of given signal).

3.3. Simulation results

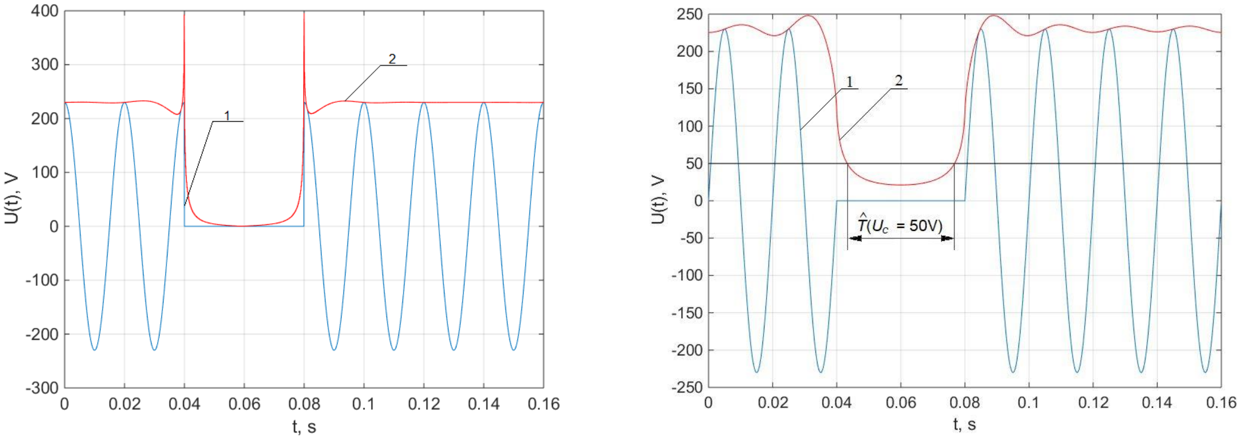
3.3.1. Simulation of the process of detecting a grid voltage drop

The reason for the signal fading is the emergency in the power transmission line due to its short-term interruption, which is indicated by a drop in the voltage of the power grid. In the implemented experiment, the indicator function $I(t)=0, t\in T_a$, the envelope in the expression (1) is represented as

$$U(t)=\begin{cases}230\,\text{V},\ t\in[0,\ 0{,}04)\ \text{s};\\ 0,\ t\in[0{,}04,\ 0{,}08)\ \text{s};\\ 230\,\text{V},\ t\in[0{,}08,\ 0{,}16]\ \text{s}.\end{cases} \tag{7}$$

Therefore, the start and the end of the signal fade are determined by the times 0.04 s and 0.08 s, respectively, and the duration of the fade is 0.04 s.

Figure 1 shows the results of the simulation of the process of detecting the fades in the power grid voltage. Label 1 denotes a graph of the grid voltage with signal fading, and label 2 denotes the result of the calculation according to the formula (3) of the estimation of the envelope of this voltage, performed using the discrete Hilbert transformation for different values of the initial phase of the voltage of expression (1) – $\varphi=0$ (curve 2 on the figure 1a) and $\varphi=\pi/2$ (curve 2 on the figure 1b).



a b

Fig. 1. Diagrams of the output signal of the grid with fading (curves 1), obtained according to expression (1) with the envelope (7), and the calculated estimates of the envelope (curves 2) for different initial phases: a – $\varphi=0$, b – $\varphi=\pi/2$

As can be seen from fig. 1b, in the time interval (0.04–0.08) s, the value of the estimate of the envelope is significantly different from zero (by at least 25 V), and outside this interval its fluctuations around the given value of 230 V are significantly larger compared to the estimate of the envelope in Fig. 1a. Therefore, to increase the accuracy of the estimation of the envelope when detecting the fades of the grid voltage, it is advisable to synchronize the data sampling window in such a way that for the analyzed voltage sample the following condition is fulfilled: $\varphi=0$.

On the Figure 1b, as an example, the determination of the duration of the voltage drop at the level of 50 V has been represented: $\gamma_t(50\ V)$ = 16 %.

On the other hand, the graph of the envelope estimation shown in Fig. 1a contains significant short-term sharp changes in voltage at the moments of its jump-like change. They are caused by computational effects due to the presence of type 1 discontinuities in the grid voltage model.

In fig. 2 and fig. 3 the absolute errors of the envelope $\delta_u(t)$ determination have been shown and the relative errors of estimating the duration of signal fading for the envelope estimates presented in Fig. 1.

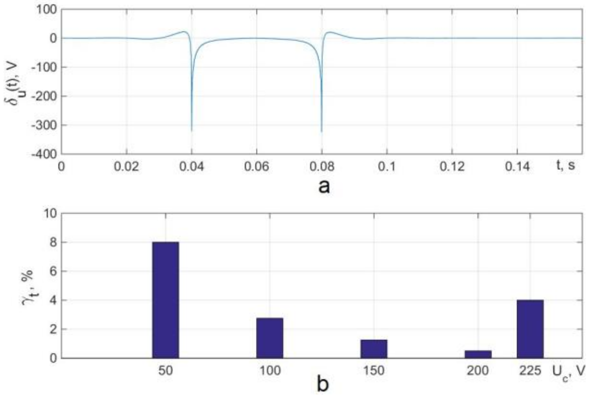


Fig. 2. Errors $\delta_u(t)$ (a) and $\gamma_t(U_c)$ (b), obtained using the values $\hat{U}(t)$ fig.1a

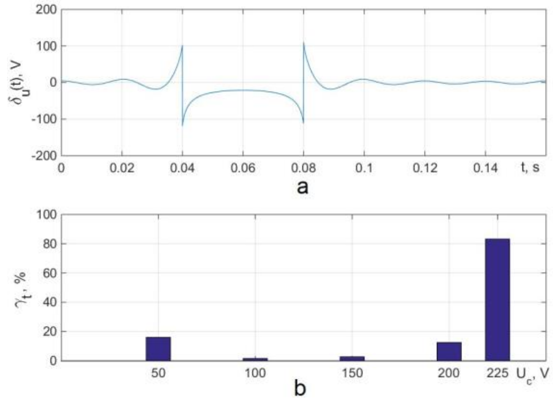


Fig. 3. Errors $\delta_u(t)$ (a) and $\gamma_t(U_c)$ (b), obtained using the values $\hat{U}(t)$ fig.1b

The relative error of determining the duration of signal fading $\gamma_t(U_c)$ calculated for the different values of threshold voltage is: U_c = (50, 100, 150, 200, 225) V. According to the diagram represented on the fig. 3b, we can state that the smallest error value $\gamma_t(U_c)$ is 1,5 % if the level of threshold voltage is 100 V, for U_c = 150 V the error is 2.75 %, outside the interval (100, 150) V the error increases drastically. According to the diagram represented in the fig. 2б it has been concluded, that the relative error of determining the fading duration of the signal is no more then 8 % for all determined levels of U_c, and the smallest error is 0,5 % if U_c = 200 V.

To reduce the relative error in determining the duration of signal fading, it is advisable to calculate the time of the beginning and end of fading according to threshold voltage levels from the range from 100 V to 200 V. The absolute error of calculating the amplitude of the envelope acquires the smallest value in the case of $\varphi = 0$.

3.3.2. Simulation of the process of detecting a short-term grid voltage dip

The envelope of the signal in expression (1) is given as follows:

$$U(t) = \begin{cases} 230\,\text{V},\ t \in [0,\ 0{,}055)\ \text{s}; \\ 115\,\text{V},\ t \in [0{,}055,\ 0{,}095)\ \text{s}; \\ 230\,\text{V},\ t \in [0{,}095,\ 0{,}16]\ \text{s}. \end{cases} \tag{8}$$

In the conducted experiment, the indicator function of the noise component $I(t) = 0, t \in T_a$.

The results shown in Fig. 4a of the simulation of the voltage of the power grid with a voltage dip of half its nominal amplitude value, the duration of the dip in two periods (curve 1), as well as a graph of the envelope estimate calculated according to the algorithm (3) (curve 2). Fig. 4 b, and c show, respectively, the graphs of the absolute error of the envelope determination $\delta_u(t)$ and relative error $\gamma_t(U_c)$ of determination of the duration of voltage dips for different threshold levels U_c.

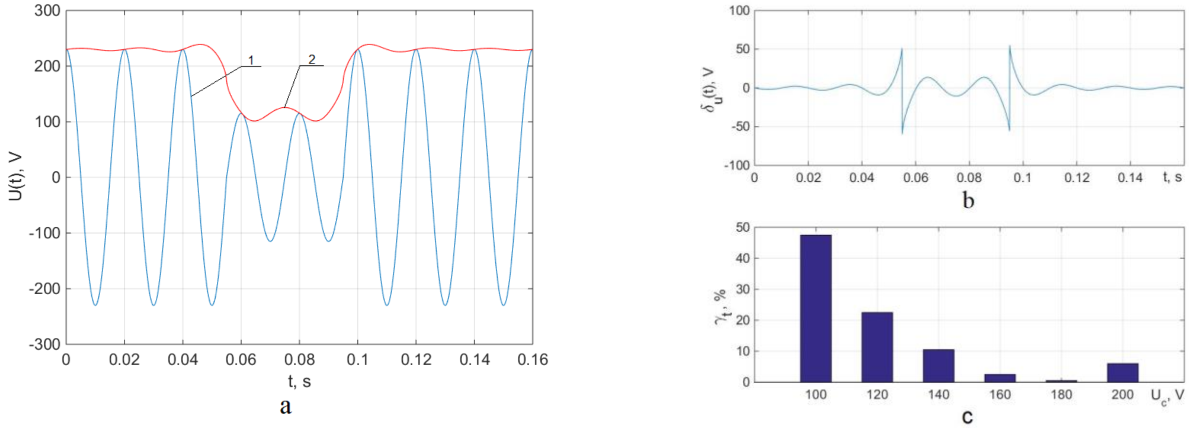


Fig. 4. The results of simulation and calculation: a – grid voltage with dip (curve 1) and estimation of the envelope (curve 2); b – error $\delta_u(t)$; c – error $\gamma_t(U_c)$

From the graph in Fig. 4a, it can be seen that the amplitude of the signal during the dip decreased by 2 times from the nominal, the time of the beginning and end of the dip of the power grid signal is 0.055 s and 0.095 s, respectively, and the duration of the dip is 0.04 s.

The absolute error of determining the envelope signal (Fig. 4b) in the area of the dip is within ±50 V, and the relative error of determining the duration of the dip (Fig. 4c) is no more than 10 % in the range of threshold voltage values from 160 V to 200 V.

3.3.3. Simulation of the process of detecting a short-term overvoltage in the power grid

The signal envelope of expression (1) for simulating a power grid with overvoltage is given as follows:

$$U(t)=\begin{cases}230\,\text{V},\ t\in[0,\ 0{,}055)\ \text{s};\\ 345\,\text{V},\ t\in[0{,}055,\ 0{,}095)\ \text{s};\\ 230\,\text{V},\ t\in[0{,}095,\ 0{,}16]\ \text{s}.\end{cases} \tag{9}$$

In Fig. 5a the results have been represented of simulation the power grid with a 2-period overvoltage. The number 1 indicates the output signal of the grid with overvoltage, and the number 2 – is the result of determining its envelope using the discrete Hilbert transformation. From Fig. 5a we can see that the signal amplitude during the overvoltage increased by 1.5 times the nominal value, and the duration of the overvoltage is 0.04 s.

In the experiment, the indicator function of the noise component was equal to zero, i.e $I(t)=0, t\in T_a$.

In Fig. 5b, c the graphs show the absolute error of the envelope signal amplitude and the relative error of the overvoltage duration, respectively. We can see that in the overvoltage range, the absolute error of the envelope estimate is within the range of ±50 V, and the relative error of the overvoltage duration does not exceed 2.5 % for the threshold levels from 280 V to 300 V.

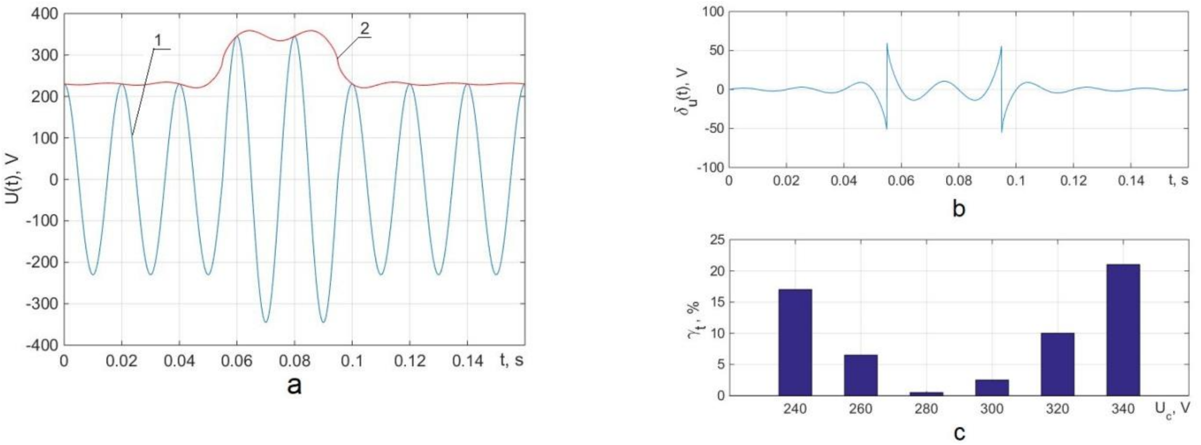


Fig. 5. Results of simulation and calculation: a – overvoltage in the grid (curve 1) and estimation of the envelope (curve 2); b – errors $\delta_u(t)$; c – errors $\gamma_t(U_\text{c})$

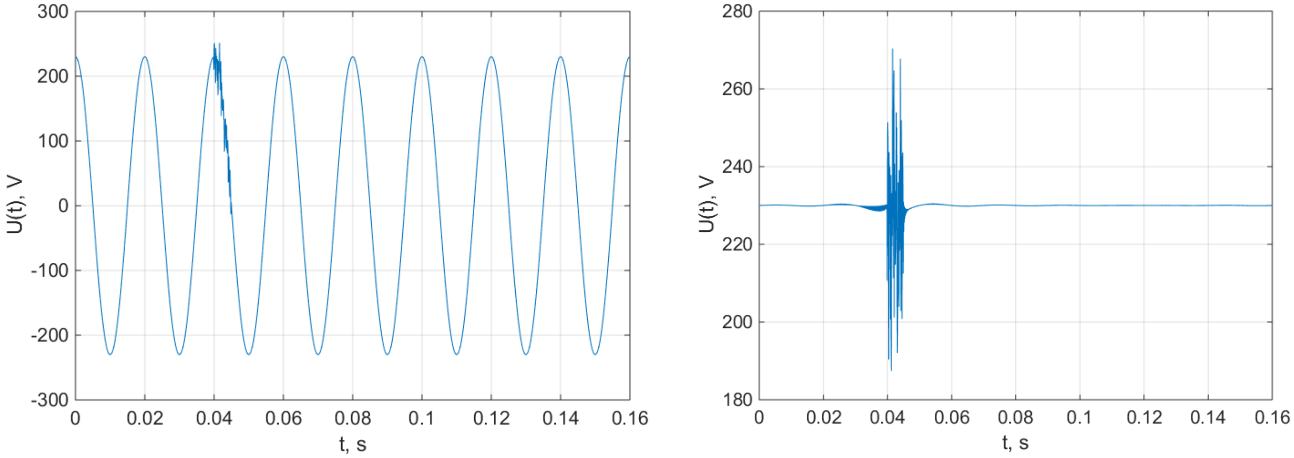
3.3.4. Simulation of the process of detecting a short-term signal distortion by high-frequency noise

The signal envelope of the expression (1) is equal to 230 V, the indicator function of the noise component is given as follows:

$$I(t) = \begin{cases} 1, \ t \in [0{,}04, \ 0{,}045) \text{ s}; \\ 0, \ t \notin [0{,}04, \ 0{,}045) \text{ s}. \end{cases} \tag{10}$$

The Gaussian interference has been used in the experiment with zero mean and standard deviation $\sigma = 23\,V$.

In Fig. 6a the result of the simulation of the power grid voltage with the presence of a short-term interval of Gaussian noise has been represented. Fig. 6b shows the result of determining the envelope of such a signal.



a b

Fig. 6. Graphs of the voltage of the power grid with high-frequency noise interference (a) and estimates of its envelope (b)

3.3.5. Simulation of the process of determining a phase shift during voltage dip

In many practical applications, when determining the characteristics of voltage dips, it is important not only to estimate their duration and depth but also to detect and determine the phase shift jumps at the beginning and the end of the voltage dip. Further, we consider a simulation experiment performed to test the effectiveness of applying the Hilbert transformation to solve this problem.

The general voltage model is given as follows:

$$u(t)=\begin{cases} U_m(t)\sin(2\pi f_n t),\, t\in[0,\ 0.03)\,s; \\ U_{sag}(t)\sin(2\pi f_n t-\Delta\varphi),\, t\in[0.03,\ 0.045)\,s,\, \Delta\varphi\in[0,\, 2\pi)\ \text{rad}; \\ U_m(t)\sin(2\pi f_n t), t\in[0.045,\ 0.08]\,s. \end{cases} \qquad (11)$$

Simulations were performed for the following given data: voltage of the dip U_{sag} = 115 V; the value of the phase shift jump during the voltage dip $\Delta\varphi = 60^0$; other simulation parameters remained unchanged.

The envelope of the signal in the model (11) is given as follows:

$$U(t)=\begin{cases} 230\,\text{V},\ t\in[0,\ 0.03)\,s; \\ 115\,\text{V},\ t\in[0.03,\ 0.045)\,s; \\ 230\,\text{V},\ t\in[0.045,\ 0.08]\,s. \end{cases} \qquad (12)$$

The results of the simulation of the process of determining the phase shift jump during the voltage dip have been shown in Fig. 7. In particular, Fig. 7a shows the graph of the output signal of the grid with a voltage dip, on which the starting point POI (Point of Interruption) and the endpoint POR (Point of Restoration) of the voltage dip are indicated. Phase shift Δφ between the signal in the section with a voltage dip and the reference signal without a dip (indicated by a dotted line) is determined by the zero transition method. Fig. 7b shows the graph of the estimation of the envelope of the signal with a voltage dip, obtained using the discrete Hilbert transformation, which clearly shows the start and end points of the voltage dip. The voltage envelope, which is determined by (3), has an oscillating character due to the presence of a methodical calculation error. Therefore, to increase the accuracy of its estimation, the magnitude of the dip should be determined as the difference between the average values of the envelope on the section before the POI and on the section between the POI and POR.

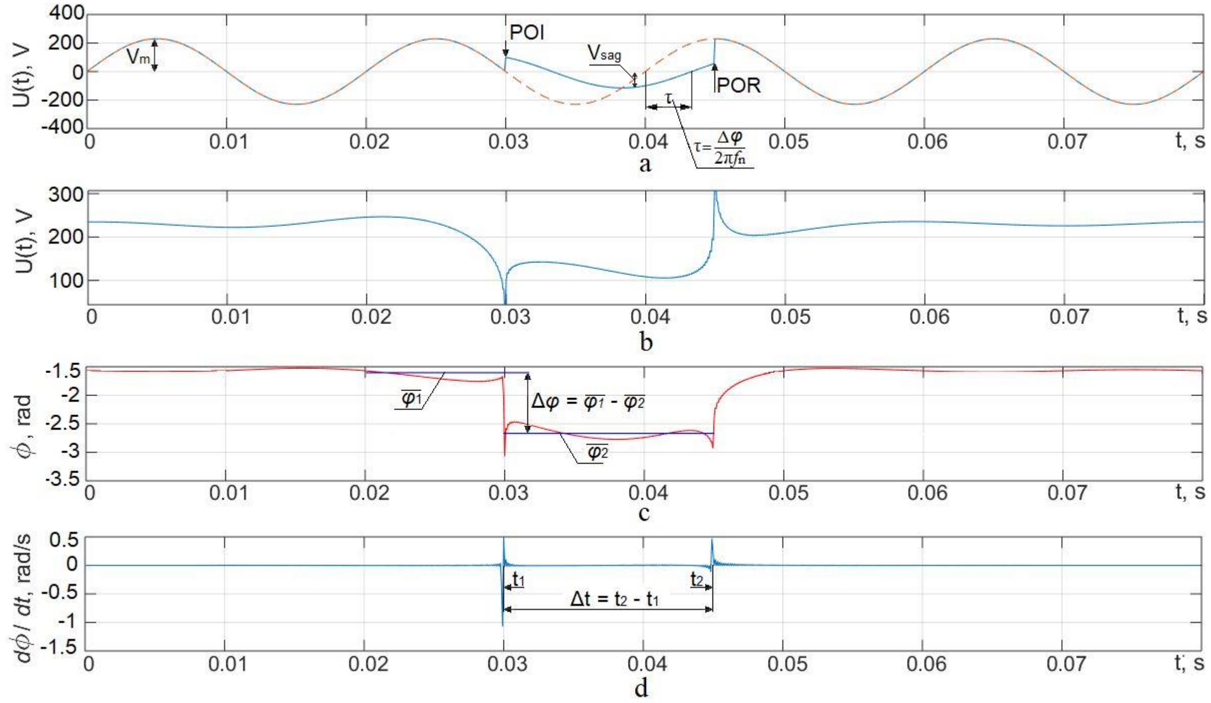


Fig. 7. Results of simulation of the process of determining the phase shift during voltage dip and its duration and depth: (a) grid voltage graph with dip, (b) estimation of voltage envelope, (c) phase shift $\varphi(t)$ with determination of phase shift Δφ at the points POI and POR, (d) derivative of the phase shift

Fig. 7c illustrates the idea of calculating the phase shift Δφ at the time points of the beginning POI and the end POR of the voltage dip by processing the difference in the estimation of the voltage phase (4) and the reference voltage phase

$$\varphi(t) = \hat{\Phi}(t) - 2\pi f_n t,\ t \in [0, T_a]\,. \quad (13)$$

Phase shift Δφ is calculated as a difference between the average values of the phase shift $\bar{\varphi}_1$ and $\bar{\varphi}_2$ obtained on the time intervals without dip and with dip respectively. The absolute error of determining the phase shift, according to the proposed method, does not exceed the values ±1.4°.

The representation of the derivative of the phase shift $d\varphi/dt$ has been shown in the Fig. 4d. It allows to define moments in time t_1 and t_2 of the beginning and the end of the voltage dip. According to this plot, the duration of the dip Δ*t* is determined with standard deviation $\sigma_{\Delta t} = \frac{t_d}{\sqrt{6}} \approx 32\ \mu s$.

It can be seen from the obtained graphs that the discrete Hilbert transformation makes it possible to determine short-term (much shorter than the period of the grid voltage) distortions of the envelope grid voltage, to fix their appearance in time and to determine the duration. For the identified noisy interval of the envelope, the calculated value of the standard deviation of the voltage was $\hat{\sigma} = 22.91\,V$. The relative error of determining the duration of the noise component did not exceed 10 % in the range of threshold levels (230–240) *V*.

4. Conclusions

1. Electricity, as a known product of material production, is characterized by quality indicators that change over time, which are affected not only by the conditions of generation but also by the modes of its transmission to consumers, the nature of the load of consumers, maintaining the balance of generating and consumer capacities, etc. This requires constant monitoring and control of power quality indicators.

2. An important group of power quality indicators is made up of indicators that reflect the change in time of the characteristics of the amplitude values of the grid voltage, which include: deviation of the root mean square values of the voltage from the nominal values, voltage dips, overvoltage, short-term distortion of the voltage by high-frequency noise, etc. The indicators of this group are determined by transformations that can analyze signals in the amplitude-time domain and can identify the moment of exit/return of such indicators to acceptable limits.

3. According to the analysis of methods for controlling the quality of the power grid voltage, the discrete Hilbert transformation, in contrast to the discrete Fourier transformation, makes it possible to estimate the duration of the deviation from the permissible limits of such indicators of the quality of the power grid as voltage dips, signal fading, the presence of Gaussian noise and overvoltage during their monitoring.

4. To confirm the effectiveness of the proposed method of measuring such quality indicators as voltage drop, overvoltage, signal fading and determining the presence of Gaussian noise interference, model experiments were conducted, according to the results of which it was established that the largest absolute error in determining the amplitude of the envelope is no more than 50 V, and the relative measurement error duration of time intervals with violations of quality indicators for selected threshold levels does not exceed 10 %.

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ЗАСТОСУВАННЯ ПЕРЕТВОРЕННЯ ГІЛЬБЕРТА В МОНІТОРИНГУ ПОКАЗНИКІВ ЯКОСТІ ЕЛЕКТРОЕНЕРГІЇ В МЕРЕЖАХ ЗАГАЛЬНОЇ ПРИЗНАЧЕНОСТІ

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Анотація. *В процесі експлуатації електромереж виникають нештатні режими, які призводять до зниження або підвищення напруги мережі за межі допустимих значень, появи високочастотних шумових складових та завмирань сигналу мережі, що погіршує якість електроенергії та може призвести до виходу з ладу електричного обладнання. Це вимагає постійного контролю показників якості електроенергії. У статті розглянуто та проаналізовано методи вимірювання показників якості електроенергії, відмічені їх переваги та обмеження, відзначено неефективність застосування перетворення Фур'є для оцінювання змінюваних в часі амплітудних показників якості електроенергії. Перспективним, на думку авторів даної роботи, є застосування перетворення Гільберта для розкладання вихідної напруги електромережі на окремі частотні компоненти з відповідним алгоритмом для точного виявлення часу початку та закінчення провалу напруги, а також сегментів переходу для точного обчислення змінних у часі окремих характеристик показників якості електроенергії, таких як величина провалу напруги та стрибок фазового кута. Метою статті є розгляд можливостей перетворення Гільберта для моніторингу амплітудних показників якості електроенергії у мережах загальної призначеності, які включають вимірювання тривалості та величини провалів напруги, тривалості завмирання напруги, локалізацію та визначення тривалості високочастотної шумової завади в електромережі. Амплітудні показники якості електроенергії визначаються за обвідною сигналу, а оцінки обвідної, у свою чергу, як і інші характеристики сигналу, можуть бути визначені за допомогою перетворення Гільберта. Комп'ютерне моделювання проведено на моделях гармонічних сигналів зі змінною в часі обвідною та обмеженою в часі шумовою складовою. Виконано моделювання процесу визначення амплітудних показників якості електроенергії та інтервалів часу, впродовж яких ці показники виходять за встановлені межі, що підтвердило ефективність використання перетворення Гільберта для моніторингу амплітудних показників якості електроенергії.*

Ключові слова: електромережа загальної призначеності, показники якості електроенергії, перетворення Гільберта.

Надійшла до редколегії: 14.03.2024