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APPLICATION OF THE DISCRETE HILBERT TRANSFORM FOR POWER SUPPLY VOLTAGE FLICKER ESTIMATION

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Abstract. Voltage fluctuations in the power supply are important characteristic of power quality in general-purpose power grids. They are caused by disruptions in the operation of power stations, the operation of power equipment with large cyclically varying loads, faults on power lines, and so on. This results in short-term or periodic voltage fluctuation, which adversely affects the operation of the power grid and modern electronic and automated systems, including control, communication and measurement equipment. In particular, they lead to increased power losses, uneven load distribution among power system components, overheating, a reduction in the service life of electrical equipment and a decrease in the overall reliability of the power system. The purpose of the article is to analyze the possibilities of using the discrete Hilbert transform (DHT) to estimate parameters of power supply voltage flicker, including estimation of flicker modulation depth, frequency, duration, short-term and long-term flicker indices. For achievement of this goal, a method for estimating the parameters of voltage flicker has been developed, which consists in using DHT to obtain the envelope of the voltage signal. Application of DHT makes it possible to accurately determine the points of start and end of voltage flicker, as well as to identify sections of the signal where flicker occurs. Further analysis is carried out on these sections, including the estimation of the modulation depth range and the flicker frequency, which are essential parameters for the quantitative estimation of the power supply voltage flicker. The effectiveness of the proposed method is confirmed by simulation studies, in which the absolute errors of the estimates of the modulation depth range, flicker frequency and duration did not exceed 5 mV, 5 mHz and 4 ms, respectively.

Keywords: voltage flicker evaluation; general-purpose power grid; power quality; Hilbert transform.

Introduction

Disturbances in the regular operation of power generation stations, power-line faults, and using electrical equipment with non-linear or cyclically changing load cause deviations of power quality characteristics the norms set by standards. Such power quality characteristics include deviations in the voltage and frequency of the supply voltage from the rated values, distortion of the supply voltage waveform, voltage flicker, voltage dips, overvoltage, etc. The permissible and limit values for most power quality characteristics are established by DSTU EN 50160:2023 [1]. Some quality characteristics, such as power supply voltage flicker, are defined in accordance with DSTU EN 61000-4-15:2018, which is the Ukrainian analogue of IEC 61000-4-15:2010. Deviations of any of the power quality characteristics from the permissible values disrupt the functioning of electrical equipment and may lead to malfunctions. Such malfunctions cause a reduction in the service life of electrical equipment, overloading and overheating, data loss, malfunctioning of automation, and flickering of lighting equipment, which can potentially affect human health.

Power supply voltage flicker is a periodic short-term fluctuation in the voltage of the power supply grid, which appears as a fluctuation in the brightness of lighting equipment – light flicker. The causes of flicker are the connection of powerful electrical equipment with nonlinear or cyclically changing load to the power grid, which occurs when its operation modes change, power-line faults, disturbances in the regular operation of power generation stations, etc. Sources of voltage flicker can include rolling mills, electric arc furnaces, electronic thermostats, etc., which are capable of generating both smooth sinusoidal and step voltage changes. For example, the use of a powerful wood [2]. chipper results in a rectangular wave flicker, which is caused by a cyclical increase in energy consumption during wood chopping and decrease to zero after the end of this process.

The Ukrainian DSTU EN 61000-4-15:2018 and the European IEC 61000-4-15:2010 [3] standards for the quality of power supply voltage flicker establish the short-term and long-term flicker indices P_{st} and P_{lt} as the main parameters for assessing voltage flicker. Their values should not exceed 1. 0 and 0.8, respectively. The short-term flicker index P_{st} is calculated on the basis of the obtained values of the flicker modulation depth obtained at a ten-minute interval using weighting factors that take into account the impact of light flicker on human health. The long-term flicker index P_{lt} provides an estimate of the long-term effect of flicker over a period of 2 hours.

The flicker of the supply voltage is closely related to the flicker of lighting equipment, so the American lighting quality standard IEEE 1789:2015 [4] sets three parameters as the main parameters of light flicker: modulation depth, frequency and flicker index, the permissible values of which are set taking into account the impact on human health.

Depending on the frequency, depth and flicker indices, the impact of light flicker on a person can lead to negative consequences: discomfort, eye fatigue and strain, weakness, reduced visual performance, headaches, migraines, neurological problems, etc. (Fig. 1).

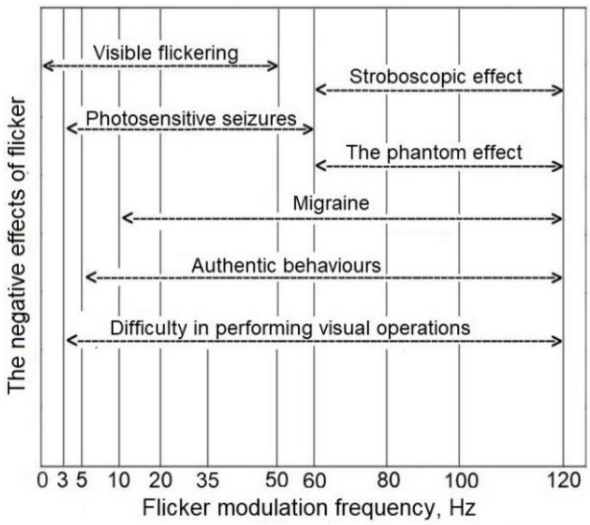

Figure 1 – Negative effects of light flicker on human health [5]

Thus, accurately estimating flicker parameters, including modulation depth, frequency and flicker index, is essential for minimizing adverse effects on human health and ensuring an acceptable power quality.

The aim of the article is to analyze the possibility of using the DHT method to assess the parameters of voltage flicker in general-purpose power supply grids.

Analysis of methods for estimating voltage flicker parameters

To evaluate the parameters of voltage flicker, methods of accurate isolation of the supply voltage envelope flicker are used, which makes it possible to analyze the flicker and identify the moments of occurrence and termination of both single-frequency and multi-frequency voltage modulation. To achieve this goal, various methods are used, for example, the standard DSTU EN 61000-4-15:2018 [6] recommends the use of the quadratic method of detecting the envelope flicker, which consists in preliminary filtering of the supply voltage using bandpass filters, which makes it possible to eliminate the DC component of the supply voltage and higher harmonic, quadrature detection, smoothing, scaling the obtained envelope to the sensitivity parameters of the human eye, which makes it possible to calculate the flicker indices P_{st} and P_{lt}. The disadvantage of this method is the low accuracy of determining the parameters of multi-frequency flicker modulation.

The quality of power supply voltage flicker analysis depends not only on the accuracy of detecting the envelope voltage, but also on the accuracy of estimating the flicker parameters. To increase the accuracy of determining the flicker parameters, linear integral transforms are used: discrete Fourier transform (DFT), discrete Hilbert transform, Wavelet transform, and others. The most widely used is the DFT, for example, the authors of [7] proposed a method that consists in calculating the root mean square value of the voltage, analyzing its frequency spectrum obtained using the DFT, obtaining instantaneous flicker values, conducting statistical analysis and calculating the flicker indices P_{st} and P_{lt}. The method proposed in this paper makes it possible to determine the supply voltage flicker with high accuracy in the low frequency range, but the error increases with the increase in the voltage flicker frequency.

The method for isolating the envelope voltage, which makes it possible to determine the parameters of voltage flicker under both single-frequency and multi-frequency modulation of the supply voltage flicker, is given in [8]. The authors propose the use of the analytical mode decomposition (AMD) method for detecting the envelope voltage, which consists in applying the voltage spectrum correction by means of an advanced fast Fourier transform (FFT). The AMD method implements the function of bandpass filters used in traditional methods, which makes it possible to simplify the process of detecting voltage flicker, and provides high noise immunity and high accuracy in estimating the parameters of power supply voltage flicker.

However, the use of FFT has a significant drawback – the effect of FFT spectrum leakage, which is caused by a disagreement between the sampling rate, analysis time, and fundamental voltage frequency. The appearance of this effect causes the energy of the real spectral components of the signal to be distributed over a number of adjacent frequencies, which leads to a decrease in the accuracy of spectral analysis and requires the use of additional methods to minimize the effect of this effect. For example, in [9] it was proposed to adjust the data acquisition parameters by varying the sample length. The criterion for minimizing the spectrum leakage effect is to obtain the maximum values of the spectral components of the DFT of the analyzed voltage. To solve this problem, in [10] the method of refining the fundamental harmonic frequency was used, and in [11] the short-time Fourier transform (STFT).

An example of the use of STFT to detect and evaluate the parameters of power supply voltage flicker is given in [12]. The authors propose the use of a short-term Blackman window Fourier transform (B-STFT), which makes it possible to obtain the frequency spectrum of the analyzed signal, and on this basis to determine the envelope of the flicker and calculate the values of the fundamental frequency and the frequency of flicker modulations. The proposed method enables high-precision estimation of voltage fluctuation, high noise immunity and is effective for estimating both steady-state and time-varying fluctuations.

In addition to the DFT, the S-transform is also used to assess voltage flicker. The authors of [13] propose a new comprehensive method for measuring the quality of power supply voltage based on the use of the S-transform, which allows to identify 14 types of power supply voltage disturbances from the oscillogram of the output signal of the power grid: voltage dips, interruptions, overvoltage, voltage flicker, transients, higher harmonics, etc., which appear in six different combinations. The effectiveness of the method has been confirmed by a wide range of simulation experiments both in the presence of noise and in the absence of the noise component. The obtained results demonstrate an acceptable accuracy in identifying power quality disturbances and estimating their parameters. The method has a low sensitivity to various noise disturbances.

A certain disadvantage of the above method is the complexity of calculations and the high load on information processing facilities, which limits its practical application due to the fixed form of its Gaussian window function. Therefore, the authors of [14] proposed a method that consists in maximizing the value of the criteria for measuring frequency-time concentration, which makes it possible to optimize an additional parameter of the Gaussian window function. The effectiveness of the method was confirmed by the results of experimental studies, which led to the following conclusion: the method allows determining the parameters of voltage flicker with greater accuracy and simultaneously ensuring high noise immunity.

The computational complexity of the above methods leads to a decrease in the speed of determining the parameters of voltage flicker. The Teager energy operator developed in [15] allows reducing the computational load and quickly extracting the parameters of the flicker envelope wave, and the additional use of the Rife-Vincent windowed spectral correction method based on the DFT allows correcting computational artifacts of the obtained flicker envelope wave. The results of the simulation experiments show that the proposed technical solution makes it possible to quickly identify the moments of inception and recovery of the supply voltage flicker, to isolate the envelope flicker, and to calculate the flicker parameters with high accuracy, which allows the method to be used for real-time monitoring of flicker. However, the method is highly sensitive to noise components and requires additional filtering methods.

To increase the noise immunity of the method for determining voltage flicker, a discrete Hilbert transform [16] can be applied, which not only increases the noise immunity but also provides high accuracy in the extraction of a constant voltage envelope wave and flicker parameters, but it has a pronounced edge effect that manifests itself in the event of a sudden change in the supply voltage over time. To improve the results of measuring voltage flicker, the authors of [17, 18] proposed the use of the Hilbert-Huang transform, which is a complex application of the DFT and the empirical mode decomposition (EMD) method, which allows processing nonlinear nonstationary signals and achieving high accuracy of analysis in both time and frequency domains. The method consists of decomposing the supply voltage into internal modal functions (IMFs). The application of DFT to IMFs makes it possible to determine the amplitude and frequency of harmonics, as well as voltage flicker indicators. However, the use of EMD can lead to mode mixing, which makes it difficult to decompose the components of the flicker envelope wave. To eliminate this drawback, a method is proposed in [19] that consists in the integrated application of the DFT and the Variational Mode Decomposition (VMD) method, the optimal modal number of which is determined by observing the central frequencies of the mode components and the orthogonality index of the mode components. The application of VMD makes it possible to decompose the envelope flicker of the supply voltage into a number of amplitude and frequency modulation functions. The subsequent application of the DFT to them makes it possible to obtain the instantaneous amplitude, fundamental frequency, and flicker frequency. The proposed method makes it possible to determine nine types of power quality disturbances, overcome the problem of mode mixing, provides high noise immunity, and improves the performance of determining power quality characteristics compared to the Hilbert-Huang transform.

The conducted analysis of literature sources made it possible to identify a set of methods for assessing the voltage flicker of the power supply, which should be improved in order to improve the results of isolating the voltage flicker and determining its parameters: flicker frequency, flicker modulation depth, as well as short-term and long-term flicker indices P_{st} and P_{lt}. Among these methods, special attention should be paid to an in-depth study of the capabilities of DHT, which allows monitoring the power quality in real time.

Methodological support for the process of determining the parameters of the supply voltage flicker

The general representation of the output voltage of the power grid with flicker is

$$u(t)=\begin{pmatrix} U_n \sin\left(2\pi f_1 t-\varphi_1\right)+ \\ +\sum_{h=2}^{H} U_h \cos\left(2\pi h f_h t-\varphi_h\right)\end{pmatrix}\times$$

$$\times\Big(1+M\left(\sin\left(2\pi f_{fliker} t-\varphi_{fliker}\right)\right)\cdot I(t)\Big), \quad (1)$$

$$t\in T_a > 1/f_{fliker},$$

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

where U_n is the rated supply voltage, U_h is the higher harmonic voltage, M is the flicker modulation depth, f_1, f_h and f_{fliker} are the rated supply frequency, higher harmonic frequency (h is the harmonic number) and flicker frequency, respectively, $f_h > f_1$, φ_1, φ_{fliker}, φ_h are the initial phases of the fundamental frequency of the supply voltage, higher harmonics and voltage flicker φ_1, φ_{fliker}, $\varphi_h \in [0, 2\pi)$, H is the number of the maximum observed higher harmonic, T_a is the analysis time, T_{fliker} is the flicker duration, $I(t)$ is the indicator function of the presence of voltage flicker.

The voltage model (1) can be represented as a general model of a narrowband signal

$$u(t)=\mathrm{U}(t)\cos\Phi(t),\ t\in T_a, \quad (3)$$

where $U(t)$ and $\Phi(t)$ are the envelope and phase of the supply voltage, respectively.

The application of an analogue-to-digital conversion to the supply voltage (3) makes it possible to obtain its discrete version $u[j]$, and the application of the DFT [20] to this sequence makes it possible to obtain the Hilbert image of this sequence $\tilde{u}[j]$. On this basis, the envelope voltage of the power supply $U[j]$ is calculated, which is defined as

$$U[j]=\sqrt{u^2[j]+\tilde{u}^2[j]},\ j=\overline{1,J},\ J=\left[T_a/T_d\right]^+,\ (4)$$

where J is the sample size, T_d is the sampling period, and $[\cdot]^+$ - is the operation of selecting the whole part of the number.

The analysis of the envelope voltage of the power supply $U[j]$ makes it possible to determine the point of inception of voltage flicker (POI) and the point of recovery (POR) of the power supply voltage, for which it is advisable to determine the second derivative of the envelope voltage. The discrete representation of the second derivative is

$$U''[j]=\frac{U[j+1]-2U[j]+U[j-1]}{T_d}.\ (5)$$

The POI and POR moments are determined by the time sequence $t[j]$ and correspond to the indices of two adjacent peaks in the sequence $U''[j]$ and allow to decompose the envelope voltage $U[j]$ into separate sections of the supply voltage $U_i[j]$ (i is the number of the envelope section), which contain different values of the frequency and modulation depth of the supply voltage flicker. The flicker duration is calculated as

$$T_{fliker}=t_{POR}-t_{POI},\quad T_{fliker}\in T_a.\qquad (6)$$

For each i-th section of the supply envelope voltage, the constant voltage component is eliminated and the zero-crossing method is applied, which makes it possible to distinguish each period of the analyzed supply envelope voltage. For each period of the supply envelope voltage, its maximum U_{max} and minimum U_{min} values are determined, and the modulation depth range of the supply voltage flicker d_i is calculated using the formula:

$$d_i[j]=\frac{U\max_i[j]-U\min_i[j]}{U_n},\ i\in[1,N],\ (7)$$

where N is the number of envelope voltage sections with supply voltage flicker.

To take into account the effect of flicker of lighting equipment on the human eye caused by voltage flicker, the scaling of the modulation depth of the supply voltage $d_i[j]$ is applied according to the flicker frequency f_{fliker}. The scaling of the modulation depth is achieved by amplifying it for the frequency range from 8.8 Hz to 10 Hz and reducing it for other frequencies

$$d_s[j]=g(f_{fliker})\cdot d_i[j],\qquad (8)$$

where g(f_{fliker}) is the weighting coefficient for the effect of light flicker on the human eye (see Table 1).

Table 1 –Definition of a function g(f_{fliker})

Flicker frequency f_{fliker}, Hz	**Weighting coefficient for the influence of light flicker g(f_{fliker})**
0.1	0.05
0.5	0.1
1.0	0.3
2.0	0.7
5.0	0.9
8.8	1.0
10.0	1.0
15.0	0.8
20.0	0.5
25.0	0.3
30.0	0.2
35.0	0.1

The estimation of the flicker frequency of the supply voltage is carried out by repeatedly applying the DHT to each i-th section of the envelope $U_i[j]$, which is determined at each i-th time interval T_i, which makes it possible to calculate its Hilbert image $\tilde{U}[j]$, phase estimation and flicker frequency using the formulas [21].

$$\Phi_i[j]=arcth\frac{\tilde{U}_i[j]}{U_i[j]}+K(\tilde{U}_i[j],U_i[j]),\quad (9)$$

$$f_{fliker_i}=\frac{1}{2\pi}\cdot\frac{\Phi_i[j_2]-\Phi_i[j_1]}{(j_2-j_1)T_d},\ j\in\left[\frac{T_i}{T_d}\right]^+,\ (10)$$

where **K**(*) is the phase unwrapping operator outside the interval [-π/2, π/2).

When performing simulation experiments and knowing the set values of f_{fliker} and T_{fliker}, the absolute error in estimating the frequency, duration of flicker and the error in estimating the magnitude of the modulation depth $d_i[j]$ of the supply voltage flicker are determined by:

$$\delta_f = f_{flicker} - f_{flicker}, \qquad (11)$$

$$\delta T_{flicker} = T_{flicker} - T_{flicker}, \qquad (12)$$

$$\delta_{d_i} = \frac{1}{J_i}\sum_{j=1}^{J_i} d_i[j] - 2M,\ j \in [1, J],\ i \in [1, N], \qquad (13)$$

where N is the number of envelope voltage sections distorted by voltage flicker, J_i is the sample size of each section of the flicker voltage U_i [j].

The assessment of voltage flicker quality according to the IEC 61000-4-15:2010 power supply quality standard involves determining the short-term flicker index P_{st} and long-term flicker P_{lt}, which are calculated in four stages.

1. Dividing the modulation depth range sequence $d_s[j]$ on a logarithmic scale into at least 10 classes and then calculating its probability density function (PDF). To calculate the PDF, it is necessary to determine the number of samples of the sequence $d_s[j]$ that are in each class and divide by the total number of samples.

2. Calculate the cumulative probability function (CPF), which consists in sequentially adding the PDF probability values from the largest class to the smallest.

3. P_{st} is calculated based on the values of the flicker level P_k determined for the cumulative probability k%. The value of the short-term flicker index P_{st} is calculated as

$$P_{st} = \sqrt{0.0314 P_{0.1} + P_{1S} + P_{3S} + P_{10S} + P_{50S}}, \qquad (14)$$

where

$$\begin{aligned} P_{1S} &= 0.0525(P_{0.7} + P_1 + P_{1.5})/3, \\ P_{3S} &= 0.0657(P_{2.2} + P_3 + P_4)/3, \\ P_{10S} &= 0.28(P_6 + P_8 + P_{10} + P_{13} + P_{17})/5, \\ P_{50S} &= 0.08(P_{30} + P_{50} + P_{80})/3. \end{aligned} \qquad (15)$$

4. P_{lt} is calculated using 12 samples of P_{st}

$$P_{lt} = \sqrt[3]{\frac{(Pst_1^3 + Pst_2^3 + \ldots + Pst_{12}^3)}{12}}. \qquad (16)$$

Results of a simulation experiment to estimate the parameters of power supply voltage flicker

To estimate the flicker parameters of the supply voltage corresponding to model (1), as well as to estimate the limits of correct use of DHT, at which the values of the flicker parameters do not exceed the permissible limits. The rated supply voltage is U_n = 230 V, the rated supply frequency is $f_n = f_1$ = 50 Hz. To simplify the calculation, the number of higher harmonics H = 0. Six sections of the supply voltage are distorted by voltage flicker, the flicker frequency of which is: $f_{fliker1}$ = 5 Hz, $f_{fliker2}$ = 8 Hz, $f_{fliker3}$ = 10 Hz, $f_{fliker4}$ = 15 Hz, $f_{fliker5}$ = 20 Hz, and $f_{fliker6}$ = 25 Hz, and the flicker modulation depth is: $M_1 = 1\%$, $M_2 = 2\%$, $M_3 = 10\%$, $M_4 = 4\%$, $M_5 = 8\%$ and $M_6 = 5\%$.

The moments of appearance of t_{POI} and the end of the flicker t_{POR} of the supply voltage are as follows:

t_{POI1} = 2 s, $t_{POR1} = t_{POI2}$ = 9.48 s,
$t_{POR2} = t_{POI3}$ = 22.96 s,
$t_{POR3} = t_{POI4}$ = 29.44 s,
$t_{POR4} = t_{POI5}$ = 38.04 s,
$t_{POR5} = t_{POI6}$ = 45.52 s and t_{POR6} = 58 s.

The supply voltage is subjected to analogue-to-digital conversion with a sampling rate of f_d = 6.4 kHz (128 samples per period), which corresponds to a sampling period of T_d = 156.25 μs, total analysis time $T_a = 60$ s, initial phases φ_1, φ_{fliker}, $\varphi_h = 0$.

The following power quality characteristics are subject to definition and assessment:

- Flicker frequency;
- Flicker modulation depth;
- Flicker duration;
- Short-term and long-term flicker indices P_{st} and P_{lt}.

To be investigated:

- Possibilities of using DHT to evaluate the flicker indices of general-purpose power grid voltage.

The computer simulation experiment for estimating the parameters of power supply voltage flicker was carried out as follows. The formation of the power supply voltage $u(t)$ (1) is carried out on the basis of the initial data – M, f_{fliker}, f_1, T_a. The application of an analogue-to-digital conversion with a sampling rate f_d to the voltage $u(t)$ makes it possible to obtain the sequence u[j] to which the DPH is applied and the envelope voltage U[j] is determined

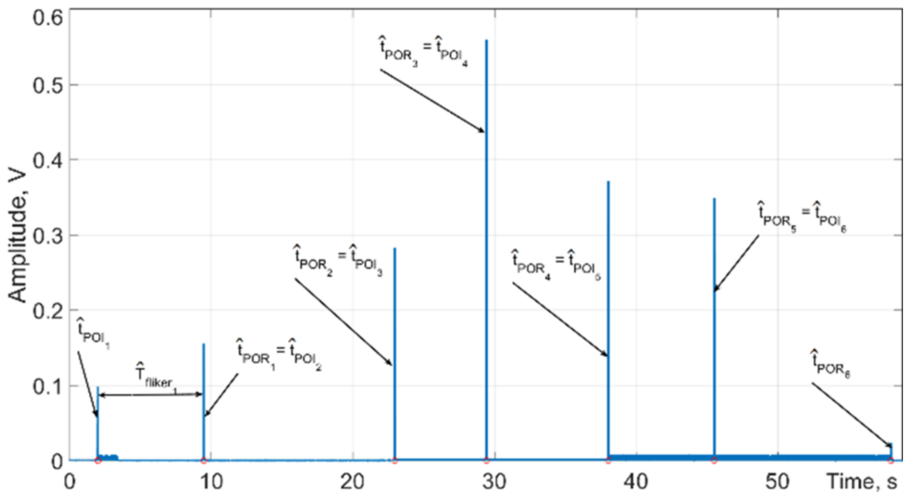

Figure 2 – Determination of POI and POR moments of power supply voltage flicker

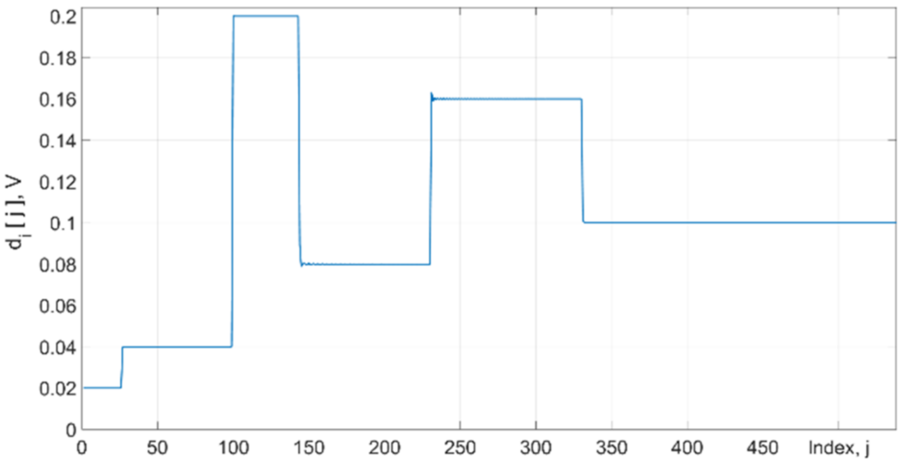

Figure 3 – Result of determining the range of flicker modulation depth $d_i[j]$

(4). Applying formula (5) to the sequence $U[j]$ makes it possible to calculate the moments of POI and POR of the voltage flicker and divide the sequence $U[j]$ into 6 sections with different values of the frequency and modulation depth of the supply voltage flicker.

The results of identifying the POI and POR moments, based on the input data, are shown in Fig. 2:

$\hat{t}_{POI1}$ = 1.998 s,

$\hat{t}_{POR1} = \hat{t}_{POI2}$ = 9.479 s,

$\hat{t}_{POR2} = \hat{t}_{POI3}$ = 22.959 s,

$\hat{t}_{POR3} = \hat{t}_{POI4}$ = 29.438 s,

$\hat{t}_{POR4} = \hat{t}_{POI5}$ = 38.04 s,

$\hat{t}_{POR5} = \hat{t}_{POI6}$ = 45.522 s

and $\hat{t}_{POR6}$ = 57.998 s.

Respectively, the duration of each *i*-th flicker area is equal:

$T_{fliker1}$ = 7.481 s, $T_{fliker2}$ = 13.48 s,

$T_{fliker3}$ = 6.479 s, $T_{fliker4}$ = 8.602 s,

$T_{fliker5}$ = 7.482 s and $T_{fliker6}$ = 12.476 s.

The absolute error in determining the duration of the supply voltage flicker δT_{fliker} is calculated by formula (12) and does not exceed 4 ms by absolute value.

The next step is to eliminate the DC component of the envelope voltage $U[j]$ and apply the zero-crossing method to it, which makes it possible to select 6 separate sections of this sequence. For each section, the maximum and minimum voltage are determined, and the flicker modulation depth range $d_i[j]$ is calculated according to (7).

The result of determining the flicker modulation depth range is shown in Fig. 3.

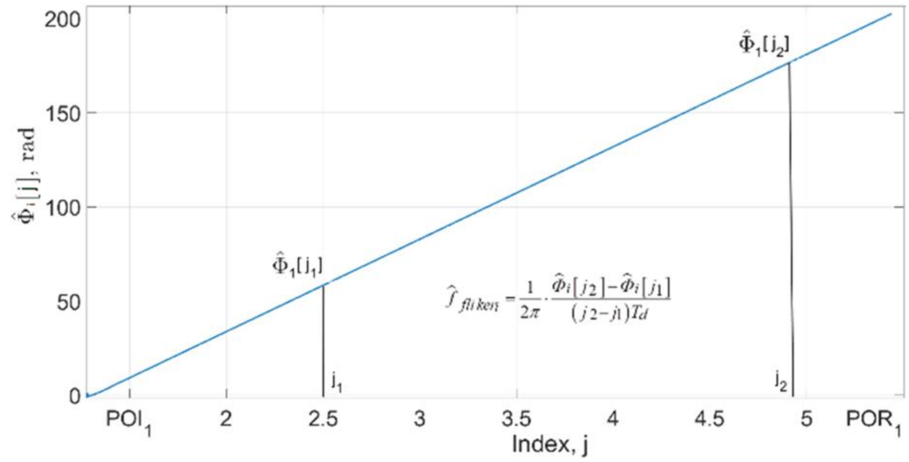

Figure 4 – Calculation of flicker frequency $\hat{f}_{fliker_1}$ by phase $\hat{\Phi}_1[j]$

The absolute errors in estimating the range of the supply voltage flicker modulation depth for each of the six sections are calculated using equation (13) and are δd_1 = 1 mV, δd_2 = 2 mV, δd_3 = -5 mV, δd_4 = 0.1 mV, δd_5 = 3 mV and δd_6 = -2 mV respectively.

The absolute error in determining the range of the flicker modulation depth for all sections does not exceed ±5 mV.

The estimation of the flicker frequency of the supply voltage is carried out according to formulas (9, 10) and consists in applying the DHT to each *i*-th section of the envelope voltage $U_i[j]$, obtaining estimates of the phase response $\Phi_i[j]$, and calculating the flicker frequency f_{fliker_i} (i = 1:6). To improve the accuracy of frequency estimation, it is recommended to select the middle section of the phase response.

An example of calculating the flicker frequency of the first section of the envelope voltage $U_1[j]$ is shown in Fig. 4.

The flicker frequency f_{fliker_1} is calculated for the values of j_1 = 25600 and j_2= 47872, the respectively values of the phase response $\Phi_1[j_1]$ and $\Phi_1[j_2]$ is 61.250 rad and 170.575 rad, therefore

$$f_{fliker1} = \frac{170.575 - 61.250}{2\pi \cdot (47872 - 25600) \cdot 0.156 \cdot 10^{-3}} =$$

$$= \frac{109.325}{21.830} = 5.008 \text{ Hz}.$$

Analogously, the flicker frequency is calculated for other sections of the envelope voltage $U_{2\text{-}6}[j]$:

$$f_{fliker2} = 7.995 \text{ Hz},\ f_{fliker3} = 9.997 \text{ Hz},$$

$$f_{fliker4} = 14.996 \text{ Hz},\ f_{fliker5} = 20.002 \text{ Hz}$$

$$\text{and } f_{fliker5} = 24.997 \text{ Hz}.$$

The absolute errors in the estimation of the flicker frequency are calculated using equation (11) and are equal to

$$\delta_{fliker1} = -8\cdot10^{-3} \text{ Hz},\ \delta_{fliker2} = 5\cdot10^{-3} \text{ Hz},$$

$$\delta_{fliker3} = 3\cdot10^{-3} \text{ Hz},\ \delta_{fliker4} = 4\cdot10^{-3} \text{ Hz},$$

$$\delta_{fliker5} = 2\cdot10^{-3} \text{ Hz and } \delta_{fliker6} = 3\cdot10^{-3} \text{ Hz}.$$

The modulation depth range $d_i[j]$ is scaled using (8) to reproduce the effect of lighting equipment flicker caused by voltage flicker on the human eye, the weighting coefficient are calculated according to Table 1.

The scaling result $d_s[j]$, obtained with the weighting coefficient: g(5) = 0.9, g(8) = 1.0 g(10) = 1.0, g(15) = 0.8, g(20) = 0.5, g(25) = 0.3 is shown in Fig. 5.

The first step in determining the short-term voltage flicker index P_{st} is to calculate the probability density function (PDF) [6], which consists in dividing $d_s[j]$ into 10 classes and determining the ratio of the number of samples included in each class to the total amount.

The result of determining the probability density function for $d_s[j]$ is shown in Fig. 6.

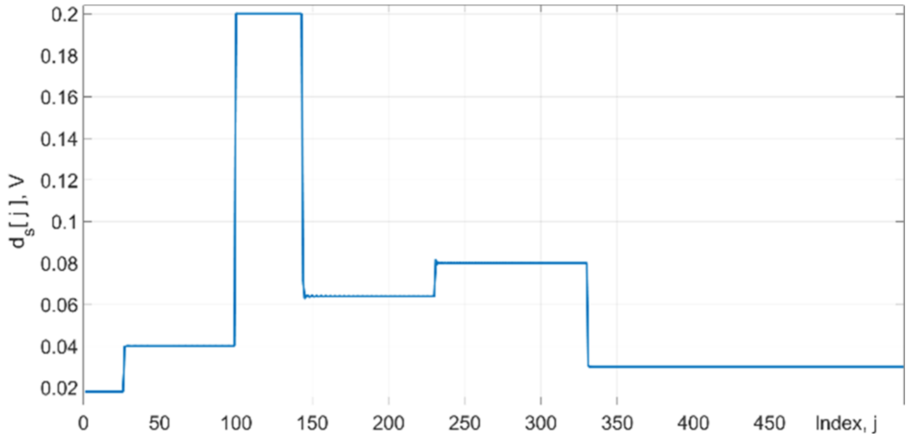

Figure 5 – The result of scaling the modulation depth range of the supply voltage flicker

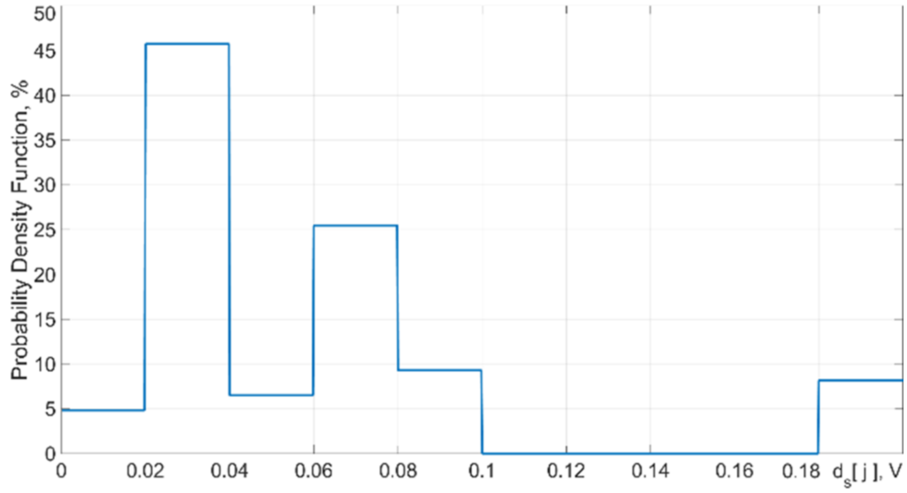

Figure 6 – The result of calculating the probability density function (PDF) estimate

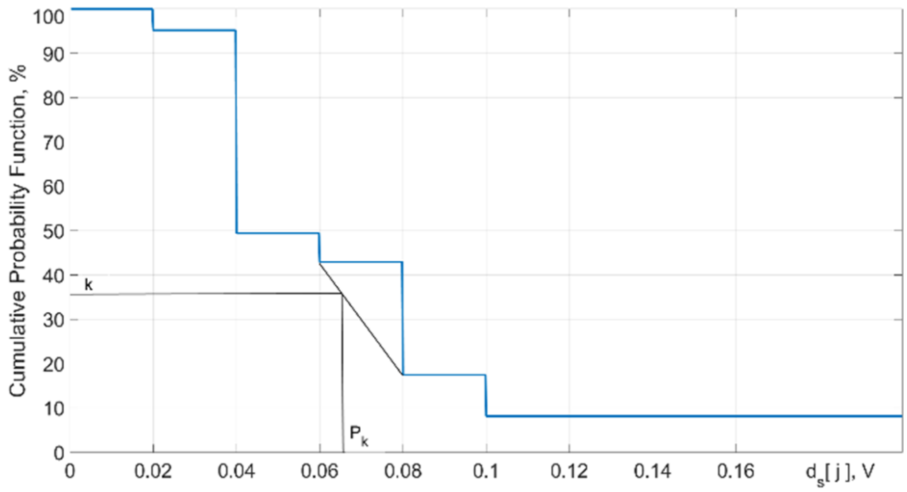

Figure 7 – The result of calculating the cumulative probability function

Based on the probability density function, it is necessary to calculate the cumulative probability function (CPF), which is achieved by summing the probabilities of each previous class starting from the last one. The result of determining the CPF is shown in Fig. 7.

To calculate the short-term flicker index, we use the probability values P_k obtained from the cumulative probability function (14, 15)

$$P_{10S} = (0.097 + 0.092 + 0.08) / 5 = 0.054,$$

$$P_{50S} = (0.07 + 0.04 + 0.025) / 3 = 0.045,$$

$$P_{st} = \sqrt{0.28 P_{10S} + 0.08 P_{50S}} = 0.137.$$

The calculation of the long-term flicker index P_{lt} was carried out according to formula 16, for its calculation it is assumed that 12 samples of P_{st} have the same value, therefore

$$P_{lt} = \sqrt[3]{\frac{(0.137^3 \cdot 12)}{12}} = 0.137.$$

Thus, the proposed method for estimating the parameters of power supply voltage flicker makes it possible to identify the flicker parameters with high accuracy. In the simulation experiment, the moments of inception of voltage flicker and the moment of recovery form of the power supply voltage were determined with an absolute error of no more than 4 ms, the estimation of the modulation depth and frequency of the flicker voltage were determined with absolute errors of no more than ±5 mV and ±5 mHz, respectively, and the flicker indices P_{st} and P_{lt} with a relative error of no more than 5%.

Conclusions

1. Power supply voltage flicker is a change in the amplitude value of the voltage over time, caused by disturbances in power generation conditions, imbalances between generation and consumption capacity, as well as the use of devices with nonlinear or cyclically varying loads by consumers. Voltage flicker requires continuous monitoring and control, as it not only affects the operation of light-sensitive devices and equipment, but can also have a negative impact on human health.

2. A method for determining the parameters of power supply voltage flicker has been developed, which consists in using a DHT to obtain the envelope voltage of the power supply, identify the moments of the beginning and end of voltage flicker, dividing the envelope voltage into voltage sections with existing flicker and estimating for each of them the value of the flicker modulation depth range, flicker frequency and flicker duration. The correctness of the study results was confirmed by simulation experiments, in which the absolute error of the supply voltage flicker depth δ_d did not exceed ±5 mV, the flicker frequency δ_{fliker} – ±5 mHz, and the flicker duration δT_{fliker} – ±4 ms. The relative error of estimating the short-term and long-term flicker P_{st} and P_{lt} calculated in accordance with IEC 61000-4-15 did not exceed ±5 %.

3. Further research will be aimed at estimating the parameters of voltage flicker in the presence of higher harmonics in the spectrum of supply voltage, estimating the parameters of voltage flicker under multi-frequency modulation of flicker, and determining the limits of correct application of DHT in this task.

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None.

Conflict of Interest
None.

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ЗАСТОСУВАННЯ ДИСКРЕТНОГО ПЕРЕТВОРЕННЯ ГІЛЬБЕРТА ДЛЯ ОЦІНЮВАННЯ МЕРЕХТІННЯ НАПРУГИ ЕЛЕКТРОПОСТАЧАННЯ

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Анотація. Мерехтіння напруги електропостачання є важливою характеристикою якості електроенергії в електромережах загальної призначеності. Їх поява зумовлене порушеннями в роботі електростанцій, експлуатацією енергетичного обладнання з великим циклічно змінним навантаженням, аваріями на лініях електропередачі тощо. Внаслідок цього виникають короткочасні або періодичні коливання напруги, що негативно впливають на функціонування електромережі, сучасних електронних і автоматизованих систем, включаючи засоби керування, зв'язку та вимірювальної техніки. Зокрема, вони призводять до зростання втрат електроенергії, нерівномірного розподілу навантаження між елементами енергосистеми, перегріву, скорочення терміну служби електрообладнання та зниження загальної надійності енергосистеми. Метою статті є аналіз можливостей застосування дискретного перетворення Гільберта (ДПГ) для оцінювання деяких параметрів мерехтіння напруги електропостачання, зокрема глибини модуляції мерехтіння, частоти мерехтіння, тривалості, а також короткострокових і довгострокових індексів мерехтіння. Для досягнення цієї мети розроблено метод оцінювання параметрів мерехтіння напруги електромережі, що полягає у застосуванні ДПГ для отримання обвідної сигналу напруги. Застосування ДПГ дає змогу точно визначити моменти початку та закінчення мерехтіння напруги, а також виявити ділянки сигналу, де відбувається мерехтіння напруги. На кожній з цих ділянок проводиться оцінювання діапазону глибини модуляції та частоти мерехтіння, які є важливими параметрами для кількісного оцінювання мерехтіння напруги електропостачання. Ефективність запропонованого методу підтверджена модельними дослідженнями, в яких абсолютні похибки оцінювання розмаху глибини модуляції, частоти та тривалості мерехтіння не перевищували 5 мВ, 5 мГц та 4 мс відповідно.

Ключові слова: оцінювання мерехтіння напруги; електромережа загальної призначеності; якість електроенергії; перетворення Гільберта.