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NEW POSSIBILITIES OF MONITORING ELECTRIC POWER QUALITY BY MEANS OF WAVELET-TRANSFORM APPARATUS

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Abstract: The problem of estimating various voltage disturbances in electric networks considering the enumeration of normative and recommended indices of electric power quality is under consideration. The differential wavelet-transform-based method of evaluating the processes of voltage changes caused by connecting up electrotechnical objects as well as algorithms of identifying those quality indices are proposed in the work enlightening the complete characteristic of the mentioned voltage change processes in networks.

Key words: electric energy, quality indices, voltage fluctuations and distortions, wavelet-transform.

Introduction

In a fixed mode of network functioning, the vast majority of electrotechnical and electronic equipment are affected by both the instability of the quadratic average value (QAV) of a feeding voltage and the level of its nonlinear distortions. This deterioration of electric power (EP) quality causes an increase in its losses and a decrease in reliability and work efficiency of different equipment patterns.

The consumers themselves are frequently the causers of network voltage fluctuations and distortions because of consuming EP in an irregular manner or connecting up nonlinear loadings to the network, consequently of what, relatively slow (1-2 seconds) deviations and fluctuations of voltage signals accompanied by the alteration of its spectral composition arise. Moreover, besides limited voltage QAV changes [1], namely ±10% of nominal value $U_{ном}$, we ought to notice the accidental variations of most voltage parameters as functions of time and frequency. The control of such processes with the help of known methods of signal investigations, for example, using the Fourier transform, does not ensure the reliability of results.

Thus one of the most important tasks in this field of science is to improve monitoring approaches and means along with the analysis of negative situations in electric networks on the basis of new mathematical principles of voltage signal processing, which enables us to form new requirements to the feeding supply of electric equipment in the future.

Regulatory evaluation of slow negative phenomena in electric networks

According to [1], slow changes of integral values and distortion of network voltage spectrum are regulated by such EP quality indices (QI): the steady-state deviation of the voltage QAV $\vartheta u_{в}$, the swing of voltage QAV deviation ϑu_t, the frequency of voltage changes F_{Ut}, a flicker dose $P_{\partial\phi}$, a voltage waveform distortion factor k_{UcS} and the n-th voltage harmonic component k_{Un}.

Earlier [2], due to occasional nature of loading fluctuations in networks, when the spectral composition of voltage function $f_U(t)$ changes was investigated, as an EP quality index a voltage fluctuation dose was also used for evaluating such an alteration:

$$\psi_{ut} = \frac{1}{t_{cn}} \cdot \int_{t-t_{cn}}^{t} dt \int_{0}^{25} k^2 \left[\vartheta u_t \right] \cdot S(f,t) df , \qquad (1)$$

where $k[\vartheta u_t]$ is the coefficient of levelling the real swings ϑu_t to certain equivalent values, $S(f,t)$ is the frequency spectrum of an alteration process $f_U(t)$ at the moment t, and t_{cn} is a time interval equal to 10 minutes.

The proposed expression is quite rough, since it takes into account the voltage spectrum only till the restricted number $n_{\max}$ =25, although in fact $n_{\max}$ could reach 100 [3]. Apart from this, the structural realisation of the expression (1) seems to be also problematic even without increasing the value of $n_{\max}$.

According to the international regulatory-technical documentation and the available experience of foreign specialists [4-9], in order to analyze the processes of EP consumption in detail, to reveal the reasons of EP quality worsening and, finally, to solve the problem of its removing we should additionally apply the following QI:

the energetic dose of voltage fluctuations

$$D_u = \int_0^{t_{cn}} \vartheta U_t \, dt \,, \qquad (2)$$

that integrally describes its alteration during the observation time interval t_{cn};

- the energetic estimation of voltage fluctuations as an average square of the voltage deviation $\vartheta u_в$ during the time interval t_{cn}:

$$\left(\vartheta U_{ск}\right)^2 = \frac{10^4}{t_{cn}} \cdot \int_0^{t_{cn}} \left[\vartheta u_y(t)\right]^2 dt \,. \qquad (3)$$

These QI enable us to determine the average value of $\vartheta u_в$ during t_{cn} that henceforward could be used for conducting a statistical voltage disturbance processing, the voltage considered as a random value.

According to the data [10, 11], for some power semiconducting devices (thyristor, TRIAC) integrated into electric equipment, the threshold values of a voltage alteration velocity s_U are regulated. To some extent, the time variations $\vartheta u_в$ and ϑu_t are characterized by QI F_{Ut}, but the latter could not be treated as the exhaustive description of the time-dependent behaviour of $f_U(t)$. Therefore, in our opinion, the velocity of voltage QAV alteration $\left(s_{Un}\right)_{ск}$ between the neighbouring repetition periods T_{f1} and T_{f2} as well as the interval velocity of voltage QAV alteration $\left(s_{Un}\right)_r$ are important indices. [12,13] These EP QI are determined by the following expressions:

$$\left(s_{Un}\right)_{ск} = \frac{2\left(U_{ск2} - U_{ск1}\right)}{T_{f2} + T_{f1}} \,, \qquad (4)$$

$$\left(s_{Un}\right)_r = \frac{2\left(\left(U_{ск}\right)_{r2} - \left(U_{ск}\right)_{r1}\right)}{t_{cn2} + t_{cn1}} \,, \qquad (5)$$

where $\left(U_{ск}\right)_{r1}$ and $\left(U_{ск}\right)_{r2}$ are voltage QAVs measured during the neighbouring time intervals t_{cn1} and t_{cn2}, while $t_{cn1} \rangle T_{f1}$.

Taking into consideration the proposed EP QI enumeration and modern tendencies of microelectronic technology development, we should underline that the accomplished analysis of the mentioned negative processes of voltage changes in networks requires the methods and means enabling us to get the most complete and trustworthy measuring information concerning the indicated values. In the circuits of electric consuming objects under the conditions of abrupt changing and nonlinear loadings, the form and spectral composition changes of the controlled electric signals causing the appearance of methodical errors in EP QI measurements performed with the known devices take place. As a result, it will become the reason for incorrectness of the whole measures taken for the provision of optimal and effective work modes for both EP consumption and supply chains.

Perfection of electric power quality assessment based on the wavelet-transform

According to [3], the network voltage signals with the spectrums of two types could be distinguished:

- comprising the enumeration of harmonic components, whose frequencies are integrally multiple to the industrial frequency and higher than it is;
- comprising signal interharmonics, namely harmonic components with frequencies nonmultiple to or sometimes lower than the industrial frequency.

In the regular modes of network functioning, the voltage levels characterizing the slow deviations and distortions are substantially lower than $U_{ном}$. Therefore, the differential method of evaluating these processes is proposed for their efficient control [14]. This method suggests the subtraction from the function of the controlled actual voltage $f_U(t)$ the ideal function $f_{US}(t)$ being the first harmonic with the sinusoid QAV $U_{ном}$ standardized according to [1] for suggested networks. Thus, there remains only the function of the process of a slow voltage disturbance

$$\Delta f_{U\Sigma}(t) = f_U(t) - f_{US}(t) \,. \qquad (6)$$

After the analogue-digital transformation of the function $f_U(t)$ into $\{f_U(k)\}$, we apply the discrete wavelet-transform (DWT) with the help of wavelet-functions – a scale $\varphi_{j+1,x}(t)$ and a detail $\psi_{j+1,x}(t)$, here $(j+1)$ is a current decomposition level, x is a parameter depending on the interval of these functions' time shifting in any $(j+1)$ interval. Those functions are matched with the correspondent decomposition filters: a low-frequency one with *n* weight coefficients $\{g_n\}$, and a high-frequency one with weight coefficients $\{h_n\}$. Furthermore, the orthogonal decomposition of the controlled function $f_U(t)$ is made in the following way:

k_{j+1} scale coefficients at the $(j+1)$-th level:

$$a_{j+1,x} = \left(f_U(k), \varphi_{j+1,x}\right) = \sum_n \overline{g_n} \cdot a_{j,n+2x} \,, \qquad (7)$$

and k_{j+1} detail coefficients at the $(j+1)$-level

$$d_{j+1,x} = \left(f_U(k), \psi_{j+1,x}\right) = \sum_n \overline{h_n} \cdot a_{j,n+2x} \,, \qquad (8)$$

using the information from the previous *j*-th transformation (the array $a_{j,2n+x}$) [15].

Moreover, in the beginning of the transformation only instant values $\{f_U(k)\}$ are applied directly, but the number k_{j+1} of coefficients $\{a_{j+1,x}\}$ and $\{d_{j+1,x}\}$ is variable $k_{j+1} = \frac{k_j}{2^{j+1}}$ and $j = 1,2,...,N$.

As a consequence of $\{f_U(k)\}$ DWT, we obtain the matrix $\left|DA_f\right|$ consisting of the totality of the detail coefficients d_{j,k_j} with the last row of the scale coefficients a_{J,k_J}

Primarily, the analogical wavelet-transform of the ideal voltage function $f_{US}(t)$ resulting in the matrix $\left|DA_{f0}\right|$ is being performed. Henceforth, according to (6), the subtraction is done between those matrixes and, moreover, we should assure the simultaneousness of the signals $f_U(t)$ and $f_{US}(t)$ in order to provide high measurement accuracy.

As a result, the following matrix corresponds to the process of slow voltage disturbance:

$$\left|DA_{\Delta f}\right| = \begin{vmatrix} \Delta d_{11}\Delta d_{12}..............\Delta d_{1k1} \\ \Delta d_{21}\Delta d_{22}..............\Delta d_{2k2} \\ .... \\ \Delta d_{j1}\Delta d_{j2}.............\Delta d_{jkj} \\ .... \\ \Delta d_{N1}\Delta d_{N2}...........\Delta d_{NkJ} \\ \Delta a_{N1}\Delta a_{N2}...........\Delta a_{NkJ} \end{vmatrix}. \quad (9)$$

Thus, after DWT of the functions under consideration, the obtained coefficient matrix reflects their behaviour in the manner of the signal spectral composition alteration during the observation time interval. In addition, $\left|DA_{\Delta f}\right|$ describes the distribution of the signal energy at the levels j into some frequency bands, and the value $j_{\max} = J$ is chosen from the possible $f_U(t)$ spectral range.

In order to conduct the efficient analysis, we should divide the slow network voltage disturbances and changes into two frequency ranges.

The first one characterizes the slow spectrum changes of $f_U(t)$ due to presence of high-frequency interharmonics and classical harmonics (integrally proportional to the industrial one), including the range of angular frequencies ω_s from $50 \cdot \pi$ till $10^4 \pi \frac{rad.}{s.}$.

The second range is referred to the slow voltage QAV deviations which are treated as conditional periodic components of $f_U(t)$ with the change of angular frequencies within the range $\omega_s = 2\pi \cdot (0.25...25)\frac{rad.}{s.}$.

In consideration of the quite large total interval ω_s of the investigated function $f_U(t)$, it is expedient to use the proposed method of slow voltage disturbance and change measurement in the following way [15].

At the first stage we could chose the frequency range of $f_U(t)$ analysis within the limits $\omega_s = (\omega_{sH})_1 \dots (\omega_{sB})_1$. Let us consider the practical variant of the analysis with the help of DWT when $(\omega_{sH})_1 = 0.5\pi \frac{рад.}{c.}, (\omega_{sB})_1 = 10^3 \pi \frac{рад.}{c.}$.

Hereby, for example, it is enough to provide $J = 10$. Using (8) and (9), we could determine the energy value at any *j*-th level of DWT during the total measurement time t_B:

$$E_{j\Sigma} = \sum_{n_{B,j}} (E_j)_{n_{B,j}} = \sum_{n_{B,j}} \sum_{p_j} \left(\Delta d_{jp_j}^2\right)_{n_{B,j}}, \quad (10)$$

where $n_{B,j} = 1,2,...(n_{B,j})_{\max}$ is the current number of some uniform measuring interval, any of which having the duration $t_{вм} = (1\dots 2)T_f$, and $(n_{B,j})_{\max} = \frac{t_B}{t_{вм}}$ is a constant till some j_{cm}, henceforth decreasing till two,

$p_j = \frac{k_1}{(n_{B,j})_{\max} \cdot 2^{j-1}}$ is the number of wavelet-coefficients stored in any interval $n_{B,j}$ at the *j*-th level of DWT.

While j is rising, k_j and p_j are proportionally decreasing, and at the moment $p_j = 1$, for $j \ge j_{cm}$ it is settled that any $n_{B,j}$ contains one wavelet-coefficient.

In general case, at the last J-th level, the energy is

$$E_{J\Sigma} = \sum_{n_{B,J}} \left[\sum_{p_J} \left(\Delta d_{Jp_J}^2 + \Delta a_{Jp_J}^2\right)_{n_{B,J}} \right]. \quad (11)$$

Owing to the calculation of $E_{j\Sigma}$, we could form an opinion about the spectral composition of the investigated function $\{f_U(k)\}$, according to some frequency band $[\omega_{\min}, \omega_{\max}]_j$ with the width different for every j–th DWT level.

Let us consider the examples of DWT for probable spectral compositions of distorted signals $f_U(t)$. If besides the main harmonic U_{m1} of the industrial frequency ω_1, slow voltage deviations and fluctuations take place, then we should treat them as $\Delta f_{U\Sigma}(t) = 7B \cdot \sin\left(2\pi \cdot 49.5 \frac{\text{рад.}}{c.} \cdot t\right) + 7B \cdot \sin\left(2\pi \cdot 5.9 \frac{\text{рад.}}{c.} \cdot t\right)$, i. e. the time variation of the amplitude U_{m2} and frequency ω_2 of some low-frequency component of the investigated signal $f_U(t)$. In Fig.1 the graphs represent wavelet-coefficients of nine levels of the resulting DWT decomposition $(\Delta d_1, \Delta d_2, ..., \Delta d_9, \Delta a_9)$ of the given signal performed by the pair of basic functions $\varphi(t)$ and $\psi(t)$ being discrete Meyer functions (*dmey*). We should take into consideration that in the case of the frequency ω_s of $f_U(t)$ component getting into the interval between the values of central frequencies of neighbouring DWT levels, the energy of this component is distributed between those levels [15].

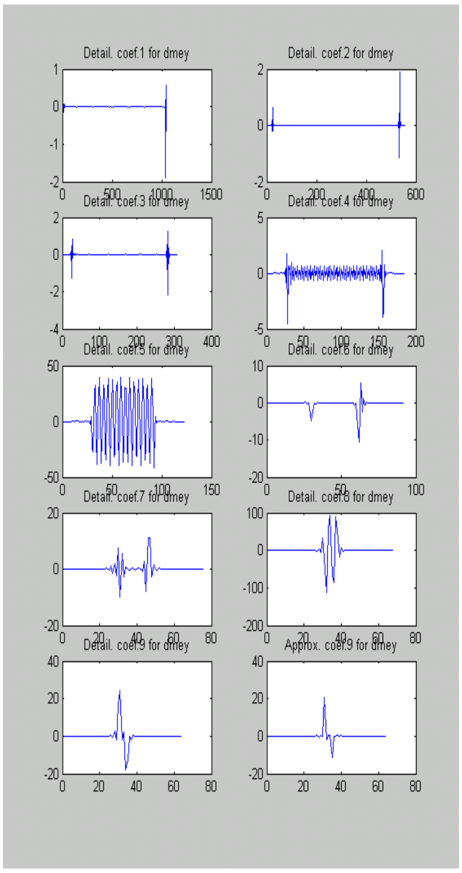

Fig. 1. Graphs of wavelet-coefficients of nine DWT levels of a signal $\Delta f_{U\Sigma}(t)$ with a low-frequency harmonic component

If the considerable $f_U(t)$ distortion caused by the harmonics higher than the industrial frequency takes place, the large values of the energy $E_{j\Sigma}$ arise at the first level of DWT. In this case, it is expedient to perform also the second stage of the $f_U(t)$ discrete transformation, selecting the frequency range of the analysis $\omega_s = (\omega_{sH})_2 \dots (\omega_{sB})_2$ [15]. Taking into account the mentioned above limits of measuring the first frequency range, we set the following values $(\omega_{sH})_2 = 10\pi \frac{\text{рад.}}{c.}, (\omega_{sB})_2 = 10^4 \pi \frac{\text{рад.}}{c.}$ for the second stage. Similarly to the first stage, the values $E_{j\Sigma}$ and $E_{J\Sigma}$ for the chosen DWT levels at the second stage are calculated using the expressions (10) and (11).

The example of such $f_U(t)$ is the combination of the signal with the industrial frequency ω_1 and the high-frequency harmonic component which is described by the subtracting function

$$\Delta f_{U\Sigma}(t) = 7B \cdot \sin\left(2\pi \cdot 49.5 \frac{\text{рад.}}{c.} \cdot t\right) + 7B \cdot \sin\left(2\pi \cdot 400 \frac{\text{рад.}}{c.} \cdot t\right)$$

In the Fig.2 the graphs of DWT decomposition with applying *dmey* of the given $\Delta f_{U\Sigma}(t)$, analogical to the first stage, are shown [15].

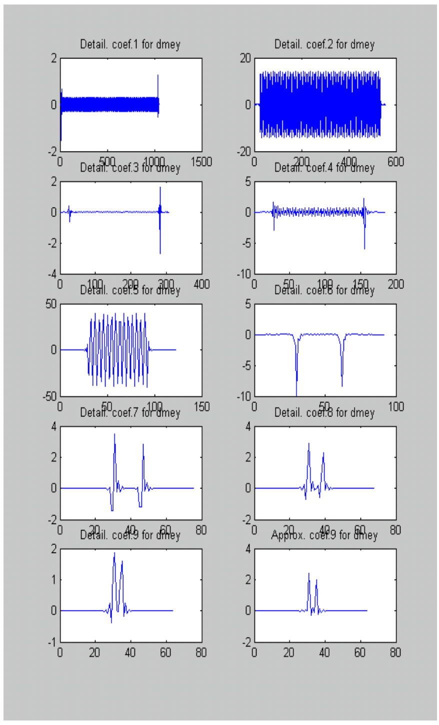

Fig. 2. Graphs of wavelet-coefficients of nine DWT levels of the signal $\Delta f_{U\Sigma}(t)$ with a high-frequency harmonic component

According to data [2], QAV of the function $f_U(t)$ is applied in order to determine most EP QI-s mentioned above. Considering the properties of basic wavelet-functions, QAV of a slow disturbance function could be represented as

$$(\Delta f_{U\Sigma})_{c\kappa} = \sqrt{\frac{1}{N_B}\cdot\left[\begin{array}{l}\sum\limits_n (\Delta a_{J,n+2x})^2 + \\ +\sum\limits_n \sum\limits_{j\ge j_0} (\Delta d_{j,n+2x})^2\end{array}\right]}, \quad (12)$$

moreover, N_B is the number of discretization points $\{f_U(k)\}$ during the time period t_B.

Using the last expression, we could immediately determine one of the EP QI-s [2,15]

$$\vartheta u_B = \frac{(\Delta f_{U\Sigma})_{c\kappa}}{U_{\text{ном}}}. \quad (13)$$

The distortion of the investigated function $f_U(t)$ and its temporal spectrum variation could be estimated with the help of the indices k_{UcS} and k_{Un} determinable using the expressions:

$$k_{UcS} = \frac{1}{(\Delta f_{U\Sigma})_{c\kappa}}\cdot\sqrt{\frac{1}{N_B}\cdot\left[\begin{array}{l}\sum\limits_n (\Delta a_{J,n+2x})^2 + \\ +\sum\limits_n \sum\limits_{j\ge j_0}^{j_н} (\Delta d_{j,n+2x})^2 + \\ +\sum\limits_n \sum\limits_{j_в}^{J} (\Delta d_{j,n+2x})^2\end{array}\right]}, \quad (14)$$

$$(k_{Un})_m = \frac{\left[\sqrt{\frac{1}{N_B}\cdot\sum\limits_n (\Delta d_{j,n+2x})^2}\right]_j}{(\Delta f_{U\Sigma})_{c\kappa}}, \quad (15)$$

where $j_н$ and $j_в$ are the lower and upper DWT levels neighbouring the level j_n which concerns the industrial frequency [15]. It is worth noticing that calculating k_{UcS} after (14) may include some methodical error due to ignoring the information that is stored in j_n and could contain the energy of an appropriate spectrum part of $f_U(t)$.

However, according to [3], the probability of the appearance of these voltage disturbances in a network is quite low. Besides, providing the measurement of these EP QI on the level not exceeding ±0.5%, this error can be neglected.

This deterioration of the EP quality, caused by over-slow voltage fluctuations described by the flicker dose $P_{\partial\Phi}$ and the repetition frequency of voltage alteration F_{Ut}, could be determined using the expressions (12) and (15), as voltage QAV and $(k_{Un})_m$ at the last DWT levels.

In terms of work reliability and efficiency of power electrotechnical equipment the velocities of voltage alteration in time are of great importance, notably those generalized for QAV $(s_{Un})_{c\kappa-y}$ and little interval values $(s_{Un})_{rT}$ [15]. After performing DWT with the help of the described above approach to energy calculation (10) and (11), considering (4) and (5), the given EP QI could be found in the following way. If there is a need for the control of the voltage alteration velocity during the period of time $0.5\ldots5.0$ s, the following calculation is made:

$$(s_{Un})_{c\kappa-y} = \frac{(\Delta f_{U\Sigma})_{c\kappa,l+1} - (\Delta f_{U\Sigma})_{c\kappa,l}}{t_B}, \quad (16)$$

moreover l – current QAV of the investigated function $f_U(t)$ according to (12).

For shorter analysis time periods, for instance such as $t_{вм}$, another EP QI $(s_{Un})_{rT}$ characterising the dynamics of temporal integral values' variation $\Delta f_{U\Sigma}(t)$ may be applied. This QI could be determined as matrix

$$\left[(s_{Un})_{rT}\right]_\Sigma = \left|\begin{array}{l}\left[(s_{Un})_{rT}\right]_{1,1}\ldots\left[(s_{Un})_{rT}\right]_{n_B,1}\ldots\left[(s_{Un})_{rT}\right]_{(n_B)_{\max}-1,1} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \left[(s_{Un})_{rT}\right]_{1,j}\ldots\left[(s_{Un})_{rT}\right]_{n_B,j}\ldots\left[(s_{Un})_{rT}\right]_{(n_B)_{\max}-1,j} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \left[(s_{Un})_{rT}\right]_{1,J}\end{array}\right|, \quad (17)$$

where, the unitary interval velocity of the voltage change of the j-th level is determined as:

$$\left[(s_{Un})_{r-T}\right]_{n_{B,j}} = \frac{1}{(\Delta t_{dr-T})_j}\cdot \left[\begin{array}{l}\sqrt{\frac{1}{P_N}\cdot\sum\limits_{p_j}\left(\Delta d^2_{jp_j}\right)_{n_{B,j}+1}} - \\ -\sqrt{\frac{1}{P_N}\cdot\sum\limits_{p_j}\left(\Delta d^2_{jp_j}\right)_{n_{B,j}}}\end{array}\right], \quad (18)$$

moreover, some discretization points $P_N = \frac{N_B}{n_{B,1}}$ at $j\langle j_{cm}$ and $P_N = \frac{N_B}{n_{B,1}}\cdot 2^{j-j_{cm}}$ contained in the unitary time interval $(t_{вм})_j = (\Delta t_{dr-T})_j$ are taken from the vector $\{f_U(k)\}$. Then, at the last level:

$$\left[\left(s_{Un}\right)_{r-T}\right]_{1,J} = \frac{\sqrt{\left(\Delta d_J^2 + \Delta a_J^2\right)_2} - \sqrt{\left(\Delta d_J^2 + \Delta a_J^2\right)_1}}{\left(t_B/2\right) \cdot \sqrt{N_B/2}} . \quad (19)$$

It is worth emphasizing, that the array $\left[\left(s_{Un}\right)_{r-T}\right]_{n_{B,j}}$ corresponds to the level $\left(s_{Un}\right)_{ск-у}$. Thus, the notified EP QI enable us to display more thoroughly than ϑu_t the processes of time changes $\left(\Delta f_{U\Sigma}\right)_{ск}$ during the observation period.

The advantages of the proposed method of investigating negative processes of slow voltage changes in a network make it possible to apply it to both one- and three-phases' electrical circuits and also to control them with the help of the uniform approach. It enables us to develop the improved means of EP QI measurements using modern and highly effective one-crystal microcontrollers.

Conclusions.

The proposed differential method allows one to obtain the extended information about the course of notified voltage disturbances and improves monitoring as well as the EP quality level.

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НОВІ МОЖЛИВОСТІ З МОНІТОРИНГУ ЯКОСТІ ЕЛЕКТРОЕНЕРГІЇ ЗА ДОПОМОГОЮ АПАРАТУ WAVELET-ПЕРЕТВОРЕННЯ

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Розглянуто проблематику оцінки різноманітних збурень напруги в електричних мережах з врахуванням переліку нормативних та рекомендованих показників якості електричної енергії. Запропоновано диференційний метод оцінки процесів зміни напруги, викликаних підключенням електротехнічних об'єктів, на основі wavelet-перетворення та запропоновано алгоритми для визначення цих показників якості, що дозволяє в повному об'ємі охарактеризувати зазначені процеси зміни напруги в мережах.

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