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THE NEW MEASURE OF LOW-FREQUENCY DISTURBANCES IN POWER SYSTEM

The paper presents new approach to voltage disturbances measurement in electric power network. It is assumed that analyzed disturbances are caused by simultaneous amplitude and phase modulation. Analytic signal is used for detection of amplitude and phase changes which are next measured as variation of a function. The proposed method is illustrated and verified by field experiment.

Keywords: analytical signal, fundamental component compensation, function variation, voltage fluctuation

1. INTRODUCTION

The paper concerns the measurement of power system voltage fluctuations. The main cause of these fluctuations are changes in the system load. Nominally, the system voltage is a sinusoidal, multi-phase signal, of frequency 50 [Hz] (in Europe) and phase-to-neutral amplitude of $230V_{sk}\sqrt{2}$. Actually, under normal operating conditions, it is an aggregate signal of variable amplitude and frequency with a time-varying spectrum with bands ranging from below to above the nominal frequency, as well as exceeding it significantly. Most often these fluctuations are kept within permissible limits, though sometimes these limits are significantly exceeded. Deviations from the nominal wave shape and other parameters of the system voltage, referred to as disturbances, have the measures used for assessing the quality of electric power supplied to consumers, as well as the extensive literature and standardization, both national and international [4, 7 - 11].

The system voltage disturbances are categorized, employing frequency criteria, into two groups according to their cause and occurrence. The first group comprises harmonic and interharmonic disturbances, with spectra above the nominal frequency [5]. The second one includes low-frequency disturbances, referred to as the voltage fluctuation or "flicker", with spectra within 50 [Hz] ± 35 [Hz] band [9].

The mechanism of low-frequency disturbances consists mainly in transferring the variation of a system load impedance to the voltage fluctuation by load currents, which cause voltage drops across the internal impedances of supply sources, i.e. the impedances of transformers and network conductors. These disturbances have the form of a product modulation of the voltage system which amplitude and phase depend nonlinearly on variable values of a load impedance [1, 6, 7]. Under simplifying assumptions on the symmetry of the system voltages and currents and their mutually linear relationship [1], the modulated signal of the voltage system can be expressed as:

$$\underline{u}_r(t) = u_0(t)a(t) = u_0(t)a_m(t)e^{j\varphi_m(t)}, \tag{1}$$

$\underline{u}_r(t)$ - disturbed modulated signal of the system voltage,
$u_0(t)$ - sinusoidal signal of the voltage system with nominal parameters,

$\underline{a}(t)$ - dimensionless modulating complex factor of variable amplitude $a_m(t)$ and variable phase $\varphi_m(t)$.

Taking into consideration the ranges of amplitude and frequency variation for low-frequency disturbances given in standard [9, 10, 11], the permissible values of the amplitude $a_m(t)$ variation were taken (0.95;1.05) and the permissible values of frequency variation were assumed (0;35) [Hz]. The range of the phase angle $\varphi_m(t)$ variation is not defined. The level of low-frequency disturbances is determined using the measure of flicker severity P_{st} [9]. It takes into account both: static and dynamic characteristics of a standard light source (60 [W], 230 [V] incandescent lamp), an averaged physiological response of human eye and brain, and assumes a random nature of the disturbance. A critical analysis of characteristics of this measure is presented in [2]. The authors of this paper have undertaken a work on the proposal of a new measure based on the norm of a function variation, on determining its properties and on the method for its measurement.

2. A NEW DEFINITION OF THE MEASURE OF LOW-FREQUENCY DISTURBANCES IN POWER SYSTEM VOLTAGE

Applying the Hilbert transform to signal $u_r(t)$ we create an analytical signal $u_a(t)$ of the form:

$$\underline{u}_a(t) = u_r(t) + jH[u_r(t)]. \tag{2}$$

Given the nominal signal of the power system voltage is represented as $u_0(t) = u_{0m}\sin(\omega_0 t + \varphi_0)$, assuming the initial phase φ_0=0, considering the variation of factor $\underline{a}(t)$ to be slow compared with the system frequency and, for the convenience of transformations, applying the Rice notation to the analytical signal, we get expressions for the amplitude and phase of the modulating factor:

$$a_m(t) = \frac{1}{u_{0m}}\sqrt{[u_r(t)]^2 + \{H[u_r(t)]\}^2}\,, \tag{3}$$

$$\varphi_m(t) = \tan^{-1}\frac{H[u_r(t)]}{u_r(t)} - \omega_0 t\,. \tag{4}$$

The composition of signals (3) and (4) according to expression (1), yields the modulating factor $\underline{a}(t)$, which represents the system voltage disturbance in two possible forms: polar and rectangular co-ordinates.

$$\underline{a}(t) = a_m(t)e^{j\varphi_m(t)} = a_m(t)[\cos\varphi_m(t) + j\sin\varphi_m(t)] = \mathrm{Re}[a(t)] + j\,\mathrm{Im}[a(t)]. \tag{5}$$

The function $\underline{a}(t)$ has therefore the character of an envelope normalized by the amplitude u_{0m} or of a complex amplitude, and it is the composition of two real-valued functions. We define a functional of variation on the function $\underline{a}(t)$ over the time interval $(0,T_a)$ for all components of $a(t)$. We assume the components are of bounded variation, i.e. are bounded and continuous, or they have at most a countable number of points of discontinuity (e.g. jump discontinuities). The definition of variation of an arbitrary bounded function $x(t)$ has the general form [3]:

$$\underset{(0,T_a)}{Var}\, x(t)) = \sup\left[\sum_{i=0}^{n-1}\left|x(t_{i+1}) - x(t_i)\right|\right], \tag{6}$$

while $\underset{(0,T_a)}{Var}\, x(t)$ in the interval (0, T_a) is a supremum of the sum (6) for all possible partitions of this interval by points i = 0, 1, ... , n-1. Practically, the supremum is obtained when the points $\{t_i\}$ are ordinates of local extrema (maxima and minima) of the function $x(t)$. The functional of variation (6) has the following properties [3, 12]:

W1. The variation is a nonnegative, rational number.

W2. For $x(t)$=const. within the interval (0, T_a) there is: $\underset{(0,T_a)}{Var}\, x(t) - [x(0) + x(T_a)] = 0$.

W3. For each real number λ the condition of homogeneity is: $\underset{(0,T_a)}{Var}\, \lambda x(t) = \lambda \underset{(0,T_a)}{Var}\, x(t)$.

W4. For $x(t) = x_m \sin \Omega t$ and $\frac{T_a \Omega}{2\pi} = n, n = 1, 2, ...$ there is: $\underset{(0,T_a)}{Var}\, x(t) = 4 x_m n$.

The definition of system voltage disturbances, based on the functional of a function variation for rectangular co-ordinates, will be introduced by calculating the real part $Re[\underline{a}(t)]$ and imaginary part $Im[\underline{a}(t)]$ of the complex function $\underline{a}(t)$ and applying the definition of the functional of variation (6) and its property W2, to each of these functions:

$$V_R = \frac{1}{T_a} \underset{(0,T_a)}{Var}\, \mathrm{Re}[\underline{a}(t)] - \{\mathrm{Re}[\underline{a}(0)] + \mathrm{Re}[\underline{a}(T_a)]\}, \tag{7}$$

$$V_I = \frac{1}{T_a} \underset{(0,T_a)}{Var}\, \mathrm{Im}[\underline{a}(t)] - \{\mathrm{Im}[\underline{a}(0)] + \mathrm{Im}[\underline{a}(T_a)]\}. \tag{8}$$

Thus the defined measure of disturbances is a numerical vector with two co-ordinates [V_R, V_I]. It allows numerical determination of a variation only of the variable component of the modulating factor on the time interval (0, T_a), while the initial value $a(0)$ and the end value $a(T_a)$ of this factor are eliminated. There could be also defined a joint, and to some extent justified, measure P_V:

$$P_V = \sqrt{V_R^2 + V_I^2}. \tag{9}$$

Functionals (7), (8), (9) have the following properties V1-V5, resulting from the mentioned above properties of variation W1-W4:

V1. They are nonnegative, rational numbers, of physical dimension [1/s];

V2. Their values equal zero if the power system voltage signal $u_0(t)$ is not disturbed;

V3. Components (7) and (8) are linearly dependent on the amplitude of a disturbance signal and, through the functions $\cos(\varphi_m(t))$ and $\sin(\varphi_m(t))$, on the phase angle of the disturbance;

V4. For each component (7) and (8) the influence of two additive disturbance signals on the measure of a disturbance is no greater than the sum of measures of each of these signals;

V5. The proposed measures are non-unique, in the meaning that several different disturbance signals can correspond to one value of the measure, what is characteristic for the measures having the form of a functional, whereas only one value of the measure corresponds to each disturbance signal.

Let us now normalize the Eqs. (7), (8) and (9). For this purpose we use the property W4 of a functional of variation, and we apply the assumed limit values of amplitude (0.95; 1.05) and frequency (0; 35) [Hz] variation of the modulating factor. We therefore assume that in the boundary case the variable component of the modulating factor is sinusoidal with parameters: $a_{mg}(t) = 0.05\sin(2\pi\, 35t)$. The variation of this function in the time interval (0, T_a), where $T_a\, 35\frac{1}{s} = n;\ n = 1, 2, 3\ldots$, equals: $V_{ag} = \frac{1}{T_a}\underset{(0,T)_a}{Var}\, a_{mg}(t) = \frac{1}{T_a} 4\cdot 0.05\cdot 35\cdot T_a 1/s = 7[1/s]$ and it does not depend on T_a.

Hence the normalized value of the measures (7), (8) and (9) can be computed from relations:

$$v_R = \frac{V_R}{V_{ag}}, \quad v_I = \frac{V_I}{V_{ag}}, \quad p_v = \frac{P_V}{V_{ag}}. \qquad (10), (11), (12)$$

The definition of voltage disturbances, based on the functional of a function variation for polar co-ordinates will be introduced as follows:

$$V_a = \frac{1}{T_a}\underset{(0,T_a)}{Var}\, a_m(t) - [a_m(0) + a_m(T_a)], \qquad (13)$$

$$V_\varphi = \frac{1}{T_a}\underset{(0,T_a)}{Var}\, \varphi_m(t) - [\varphi_m(0) + \varphi_m(T_a)]. \qquad (14)$$

The values of functionals (13) and (14) are the vector measure [V_a, V_φ] with two numerical co-ordinates. It allows numerical determination of a variation only of the variable component of the modulating factor on the time interval (0, T_a), while the initial value $a(0)$ and the end value $a(T_a)$ of this factor are eliminated. Each of these co-ordinates has the properties V1-V5 of measures in rectangular co-ordinates. For each case the following normalization can be made:

$$v_a = \frac{V_a}{\frac{1}{T_a}\underset{(0,T_a)}{Var}\, a_{mg}(t)} = \frac{V_a}{V_{ag}}, \qquad (15)$$

$$v_\varphi = \frac{V_\varphi}{\frac{1}{T_a}\underset{(0,T_a)}{Var}\, \phi_g(t)} = \frac{V_\varphi}{V_{\varphi g}}, \qquad (16)$$

where $\phi_g(t)$ is the permissible limit value for variation (deviation) of the phase disturbance angle of the system voltage sinusoidal signal $u_0(t)$ over the time T_a. As the maximum (limit) deviation of the phase φ_m is not determined, also the similar value for its measure cannot be determined. Let us therefore arbitrarily assume the value $V_{\phi g} = \frac{1}{T_a}\underset{(0,T_a)}{Var}\, \phi_g(t) = 2\pi$ [rad] as a normalizing factor for the measure V_φ.

The proposed method for determination of disturbances in the form of the complex factor (5) provides an additional option of computing a time characteristic of the instantaneous frequency deviation from the nominal frequency ω_0 as $\Delta\omega(t) = \frac{d\varphi_m(t)}{dt}$. Because the variation of a power system angular frequency is bounded to the interval 2π(49.5; 50.5) [Hz], the maximum absolute value of variable $\Delta\omega(t)$ in the interval $(0, T_a)$, normalized to width of the limit values interval, can be used as the measure of this variable:

$$\Delta_\omega = \frac{\max\limits_{(0,T_a)} |\Delta\omega(t)|}{2\pi \, 1Hz}. \tag{17}$$

The differences between the proposed measure of disturbances based on variation and the measure of flicker severity are as follows:

R1. The measure of disturbances in power system voltage, determined by the presented relations, has a simple physical interpretation and physical dimension, and can be normalized.
R2. Its definition comprises no arbitrary chosen relationships, including dynamic operations and their coefficients, as the flicker severity measure does.
R3. The determination of this measure does not require assuming the existence of any formerly known (determined over a sufficiently long time) statistical properties of disturbances; on the contrary - even a single determined disturbance, e.g. a jump of the system voltage amplitude is measured.
R4. For the known model and parameters of a power system the measure of a sum of disturbances can be evaluated from the measures of all these disturbances, at an arbitrarily chosen point of the system.
R5. Where the new definition is applied, the amplitudes of disturbance components and their measures are linearly dependent.
R6. A practical use of the new definition requires only simple operations on the signal of measured voltage.
R7. The standard of the proposed measure for a disturbance calibrating signal (e.g. sinusoidal) is computable, therefore the calibration of a measuring instrument, which determines the measure, is simple and unambiguous.
R8. The value of the measure for harmonic disturbances depends on both: their amplitude and frequency; for non-periodic disturbances it depends on their amplitude and the number of fluctuations over time.

3. DETERMINATION OF THE MEASURE ON A REAL NETWORK DISTURBED VOLTAGE

A passive experiment on a real network has been carried out in order to illustrate the properties of the proposed measure of disturbances. The signal of network voltage supplying an arc furnace was recorded and processed in both weakly and strongly disturbed conditions. The results of measurements and calculations are depicted in Figs. 1 and 2. Increased disturbances at time instant $t = 260$ min are caused by switching the arc furnace to operation. In Fig. 1 the results of calculations of the proposed measure of network voltage disturbances are compared with the flicker severity P_{st} values measured with a flickermeter over a period of 400 minutes.

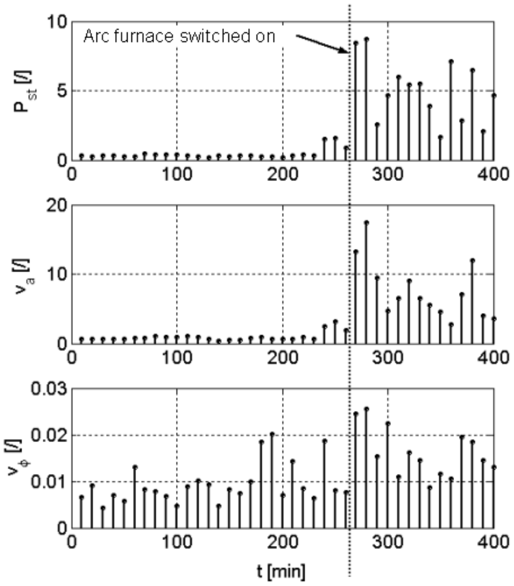


Fig.1 Comparing flicker severity P_{st} with the measures of disturbances v_a i v_ϕ computed over 600-second periods as defined by equations (15) and (16).

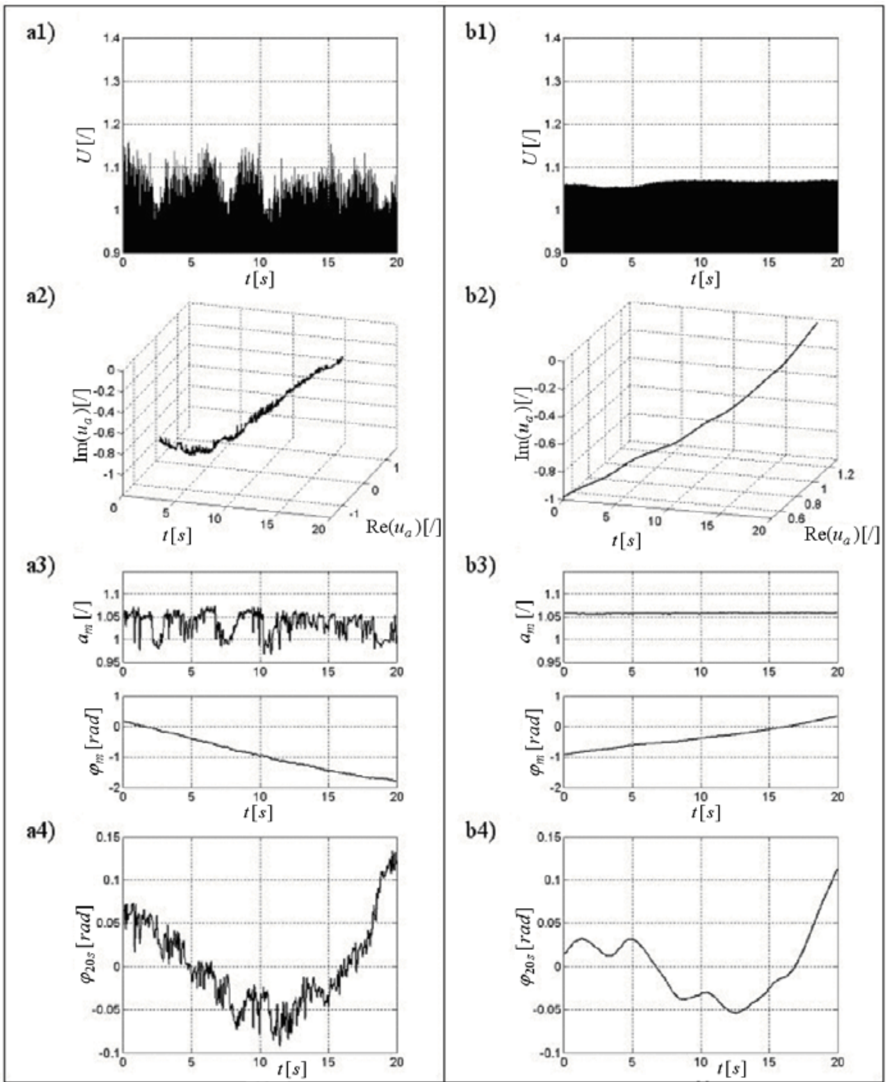
Time interval (0, T_a) was equal 600 [s]. Relative measures of variation of complex polar components of the modulating factor were applied. To illustrate the method of computing the proposed measure the results of subsequent stages of calculation of the measure values (v_a,v_ϕ) over time period of 20 [s] are shown in Fig. 2 for the case of strong (a) and weak (b) disturbances.

Fig. 2 shows: a1, b1 the disturbed voltage waveform; a2, b2 the analytical signal waveform; a4, b4 the variation of phase of the analytical signal after subtraction of the best approximation line over the period of 20 s. The case a) corresponds to the time t = 280 min, and the case b) to the time t = 30 min, in the graphs of variation measures in Fig. 1. For the sake of clarity of the method for computing the presented measure, the time characteristics in Fig. 2 are determined in 20-second intervals.

A large variation of the network voltage signal amplitude, seen in Fig. 2 a1, is caused by the arc furnace during its starting phase operation (melting), that is by a modulation of the network voltage amplitude by the time-varying furnace impedance. The voltage signal of the same network, when not loaded with the furnace variable impedance is shown in Fig. 2 b1. The short term flicker severity has been determined on both signals, it equals P_{st} = 8.7 for the case a) and P_{st} = 0.22 for the case b). The proposed measures are computed on these signals, basing on the time characteristics of complex components of the analytical signal (2): in rectangular co-ordinates (Fig. 2 a2 and 2 b2), and in polar co-ordinates (Fig. 2 a3) and 2 b3)).

The measures: v_a = 17.35 [V/s] for the case a) and v_a = 0.599 [V/s] for the case b) have been computed for waveforms of the analytical signal modulus $a_m(t)$, i.e. for the envelope of this signal. In the case a) it is a time-characteristic which variation range is greater than 5% of the normalized value (Fig. 2 a3). It has been found that determination of the measure v_φ requires, apart of calculation $\varphi_m(t)$ according to the formula (4), an additional correction which consists in elimination of the component $\omega_0 t$ over the period of 20 [s]. The measures: v_φ=0.0255 [rad/s] for the case a) and v_φ=0.0064 [rad/s] for the case b) were therefore determined on the time-characteristics $\varphi_{20\mathrm{s}}(t)$ shown in Fig. 2 a4 and 2 b4.

The comparison of the values of measures P_{st} and the measures v_a and v_φ for the cases a) and b) indicates their equivalent effectiveness in detection of a network voltage variation.



The measure values, calculated for:	
the case a)	the case b)
$P_{st}=8.7$; $v_a=17.35$ [V/s]; $v_\varphi=0.0255$ [rad/s]	$P_{st}=0.22$; $v_a=0.599$ [V/s]; $v_\varphi=0.0064$ [rad/s]

Fig. 2. The network voltage disturbances caused by the arc furnace operation and their measures for a strongly disturbed voltage (a) and weakly disturbed voltage (b).

4. CONCLUSION

The paper presents definitions of the proposed measures of power system voltage disturbances, based on the functional of a function variation, and their example application. These measures differ significantly from the “flicker severity” measure, the differences between them are listed in subparagraphs R1-R8. In the light of these differences the properties of the proposed measures seem to be interesting and competitive with regard to the measure being currently in use. They will however need a further practical verification of their properties and the effectiveness of their application should be assessed. The following issues are of particular interest from the point of view of the method for determining the new measure: the sensitivity of the measure to disturbance level, additivity of the measure for many disturbance sources, the influence of measurement errors of the modulus and phase variation of the modulating factor on the measure indeterminacy (uncertainty), the relation between the variability with time of the measure and various dynamic phenomena in an electrical power system.

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NOWA MIARA ZABURZEŃ NISKOCZĘSTOTLIWOŚCIOWYCH W SIECI ENERGETYCZNEJ

Streszczenie

Artykuł przedstawia nowe podejście do pomiaru zaburzeń w sieci energetycznej. Koncepcja przedstawionej w artykule, nowej metody pomiaru zaburzeń niskoczęstotliwościowych, w napięciu sieci elektroenergetycznej, polega na odejściu od zasady traktowania tych zaburzeń jako przyczyny migotania światła, a więc na odejściu od struktury *flickermetera*.

Wyniki badań prowadzonych przez autorów wskazują, że zaburzenia niskoczęstotliwościowe mają postać nieliniowej modulacji amplitudy sinusoidy napięcia sieci przez dolnopasmowy czynnik modulujący, którego widmo zawarte jest w paśmie ok. 0.01 do ok. 35 Hz [9]. Zatem widmo sygnału napięcia sieci zmodulowanego w amplitudzie zawiera się (w Europie) w paśmie od ok. 15 Hz do ok. 85 Hz przy częstotliwości podstawowej 50 Hz. Przyjęto założenie, że analizowane zaburzenia są spowodowane modulacją amplitudy i fazy. Do detekcji zmian amplitudy i fazy zastosowano sygnał analityczny, natomiast do pomiaru tych zjawisk wahanie funkcji. Niskoczęstotliwościowy sygnał zakłócający wyznaczany jest za pomocą wysokorozdzielczych pomiarów cyfrowych, filtrowany i poddawany transformacie Hilberta w celu wyznaczenia sygnału analitycznego. Na tak wyznaczonym sygnale określana jest miara w postaci normy wahania funkcji, w naturalny sposób związana z właściwościami sygnału, w tym także ze sposobem powstawania zaburzeń niskoczęstotliwościowych. Przedstawiono właściwości metody i wstępne wyniki badań eksperymentalnych skuteczności jej stosowania, przeprowadzonych na rzeczywistej strukturze modelowanej sieci. W artykule przedstawiono również własną interpretację sposobu powstawania zaburzeń na dość uniwersalnym przykładzie struktury sieci, której model równocześnie stosowano do badań symulacyjnych metody. Proponowana metoda została zilustrowana i zweryfikowana poprzez eksperyment na działającej sieci energetycznej.