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MODEL STUDY ON COMPLEX MODULATION AND DEMODULATION OF POWER NETWORK VOLTAGE SIGNAL LOADED WITH TIME-VARIABLE IMPEDANCE

Variability of power network voltage degrades the quality of power supplied to customers. Several power quality measures connected with voltage variability have been agreed on international scale. However, it turns out that the measures of electric power quality determined by the instruments which measure the short-term flicker severity index P_{ST} of light sources may lead to ambiguous quality assessment because of different measurement values for the same measured signals. Physical interpretation of phenomenons occurring in power network based on measurement results is therefore difficult. In this article we propose the conception of carrying this kind of analysis using a mathematical model of influence of load variability on power network voltage signal. These analyses rely on detecting factors influencing the signal shape. The article presents part of results including model studies.

Presented results may be, in our opinion, basis for reasonable questioning of correctness, and especially ambiguity of currently used method for measuring time-variability of power network voltage parameters, based on determining flicker severity index. Especially doubtful are the flicker severity index definition and method of calibrating measurement devices based on it.

Considering achieved results, we express the opinion about need for a new, more reliable and unambiguous measure of power network voltage variability caused by load fluctuations. It should consider signal properties, have simple physical interpretation and be simple to calculate.

Keywords: voltage variation, flickermeter, power quality

1. INTRODUCTION

Time variability of network load power and current, i.e., the variability of power receiver parameters, is one of main causes of uncontrolled time variability of power network voltage. The power network voltage variability degrades the quality of power supplied to consumers. Several power quality measures connected with voltage variability have been agreed on international scale. The measures are calculated using the measured network voltage signal as averaged measures of random variability of voltage amplitude or as the measures of deviation from normal values of voltage parameters and sine shape [9, 10, 11]. However, it turns out that the averaged random measures of electric power quality determined by the instruments which measure the short-term flicker severity index P_{ST} of light sources may lead to ambiguous quality assessment because of different measurement values for the same measured signals [8]. Moreover, because of the formal complexity of definitions of such measures and the lack of reference to the causes of voltage variability, the physical interpretation of phenomena in power network subject to nonstationary load is considerably hindered [5, 8]. The question therefore arises of how to define the causes of these measuring difficulties. In this paper we are putting forward an idea of how to carry out such investigations based on the mathematical model of load variability affecting the network voltage signal. The investigations consist in making on this signal a correct detection of the factors influencing the signal shape.

The assumption on the network voltage linear modulation being the effect of load variability is adopted when defining the average random measure called the "light flicker severity index". The definition of this measure consists of a series of linear dynamic and nonlinear static operation on the voltage signal mapped practically in the abovementioned light flickermeters [1, 9]. The meters are calibrated with signals modulated linearly in amplitude, obtained by multiplying the network voltage signal sinusoid by the modulating signal. The investigations into the causes of ambiguity of the results obtained during determining the light flicker severity index lead to the following conclusions [7]:

- the power network voltage modulation caused by the network load variability is complex, i.e., it is not only voltage amplitude modulation but also phase angle modulation;
- the modulation is nonlinear in regard of the components of the network variable impedance load, so the voltage signal spectrum is more complex than in the case of linear modulation.

The above conclusions have been confirmed in model and experimental studies. In consequence, a suggestion has been made of introducing new definitions of electric energy quality measures that take into account abovementioned factors influencing the network voltage signal modulation [3, 5]. The presented paper is an attempt to present a part of the results of these studies, the part that includes the model study only.

2. MODEL OF NETWORK VOLTAGE MODULATION BY TIME-VARIABLE LOAD IMPEDANCE

As we will use the mapping method in the model to calculate the analytical relationship between the network voltage signal and load impedance, then because of the complexity and diversity of the network we will have to simplify these relationships to a sufficient and acceptable degree. Let then adopt the following simplifying assumptions:

a) the network is symmetrical in respect of supply and load, so the three-phase system may be replaced with a single-phase system,
b) the primary (input) voltage u_s of the voltage source (supply transformer) is independent of the load while the secondary voltage, i.e., the load feeding voltage, u_o, depends on the load,
c) the supply transformer impedance may be replaced by single impedance $\overline{Z_{ts}}$, serial to the load impedance $\overline{Z_o}$,
d) impedance $\overline{Z_{ts}}$ is fixed in time while impedance $\overline{Z_o}$ is variable in time according to a known and determined way,
e) impedances $\overline{Z_{ts}}$ and $\overline{Z_o}$ do not depend on the network load current i,
f) impedances $\overline{Z_{ts}}$ and $\overline{Z_o}$ may be presented as a serial connection of an equivalent resistance and reactance of inductive character.

The assumptions listed are often used for building simplified models of power networks [2, 4, 7]. Let assume that this model is as follows:

$$u_s = u_o + R_{ts}i + L_{ts}\frac{di}{dt}, \tag{1}$$

$$u_o = R_o i + i\frac{dL_o}{dt} + L_o\frac{di}{dt} = i(R_o + \frac{dL_o}{dt}) + L_o\frac{di}{dt}. \tag{2}$$

The network equivalent circuit for such a simplified model is presented in Fig. 1.

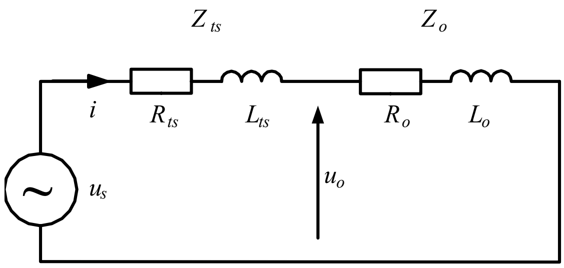

Fig.1. The equivalent circuit for simplified model of power network.

Let assume now that the reactance component X_o of load impedance $\underline{Z}_o$ varies sinusoidally in the network model while the resistance component R_o is fixed in time. For the sine primary voltage u_s we have: $L_o=L_{ou}+L_{om}\sin\omega_m t$ and $\overline{u}_s = u_{sm}e^{j(\omega_s t+\varphi_s)}$ (relative to maximum value), where: $0 < \omega_m \le \omega_{mmax}$ and $\omega_{mmax} << \omega_s$, and $\omega_s=const$. Employing symbolic notation for these assumptions we get:

$$\overline{u_o} = \overline{u_s}\,\frac{R_o + L_o^{'} + j\omega_m L_o}{R_o + L_o^{'} + R_{ts} + j\omega_m (L_o + L_{ts})}, \tag{3}$$

where: $L_o^{'} = \dfrac{dL_o}{dt}$.

It is therefore possible to show approximate expression (3) in the form:

$$\overline{u_o} = \overline{u_s}\,\overline{a^*(t)} = \overline{u_s}\,a_m^*(t)e^{j\varphi_m^*(t)} \tag{4}$$

Expression (4) represents the effect of product modulation of network voltage signal $\overline{u_s}$ of circular frequency ω_s by a modulation factor $\overline{a^*(t)}$ of variable amplitude $a^*_m(t)$ and phase angle $\varphi^*_m(t)$, slowly varying in time with circular frequency ω_m. These variable may be calculated from the following formulas:

$$a_m^*(t) = \sqrt{\frac{(R_o + L_o^{'})^2 + \omega_s^2 L_o^2}{(R_o + L_o^{'} + R_{ts})^2 + \omega_s^2 (L_o + L_{ts})^2}}, \tag{5}$$

$$\varphi_m^*(t) = tg^{-1}\,\frac{\omega_s[L_o R_{ts} + L_{ts}(R_o + L_o^{'})]}{(R_o + L_o^{'})(R_o + L_o^{'} + R_{ts}) + \omega_s^2 L_o (L_o + L_{ts})}. \tag{6}$$

Despite the fact that the Eqs. (3), (4), (5) and (6) are only approximations, they may justify the finding that the power network voltage signal modulation by time-variable load impedance is an amplitude complex product modulation, and that both the amplitude and phase angle of the modulation factor depend nonlinearly on the time-variable load impedance component. In consequence, the assumption mentioned in the introduction and employed in the definition of energy quality measure concerning the form of the network voltage signal linearly modulated in amplitude only is erroneous. In [6], the variability of bulb light flicker severity in the case of phase angle modulation at no flickering was experimentally proven.

Therefore, a question arises of correct reproduction of the amplitude and phase angle of the modulation factor based on the presented model and the measurements of supply voltage of power network receivers. The question can be solved by demodulating this voltage through determining the components of the complex envelope.

3. MODEL OF DEMODULATION OF SUPPLY VOLTAGE OF NETWORK DEVICES

The demodulation method used consists in determining complex envelope $\overline{a(t)}$ of signal voltage u_o obtained though numerical solution of Eqs. (1) and (2) [7]. Based on this signal, an analytical signal u_{oa} is determined composed of a cophasal u_o and quadrature $H[u_o]$ components where $H[\cdot]$ is the Hilbert transform:

$$u_{oa} = \overline{u_o} + j\mathrm{H}[\overline{u_o}] = Ae^{j\psi}, \tag{7}$$

where:

$$A = \sqrt{u_o^2 + \{H[u_o]\}^2}, \tag{8}$$

$$\psi = \mathrm{tg}^{-1}\frac{H[u_o]}{u_o}. \tag{9}$$

Taking into account a slightly different form of Eq. (4) for $\varphi_s = 0$:

$$\overline{u_o} = u_{sm}a_m(t)e^{j[\omega_s t + \varphi_m(t)]} \tag{10}$$

it is possible to determine the amplitude and phase angle of the complex envelope (i.e., the modulating factor) $a(t)$ from the following expressions:

$$a_m(t) = \frac{A}{u_{sm}}, \tag{11}$$

$$\varphi_m(t) = \psi - \omega_s t. \tag{12}$$

Assuming the parameters of the modelled network, i.e., adopting the coefficients of model (1) and (2) from Eqs. (5), (11), (6), (12), an approximated and exact (taking into account the network model simplifications) form of the components of the modulation factor may be determined. As this factor maps the influence of the power network load variability onto the supply voltage signal, it can be used for determining electric energy quality measures by functionals defined specifically for both components $a_m(t)$ and $\varphi_m(t)$.

4. MODEL STUDY

Model study were carried out assuming the following values of the coefficients of Eqs. (1) and (2):

$$\omega_s L_{ou} = 2\Omega,\quad \omega_s L_{om} = 0{,}5\Omega,\quad \omega_s L_o = \omega_s L_{ou} + \omega_s L_{om}\, sin\, \omega_m t,$$
$$R_{ou} = 2\Omega,\quad R_{om} = 0{,}5\Omega,\quad R_o = R_{ou} + R_{om}\, cos\, \omega_m t,$$
$$\omega_s L_{ts} = 0{,}06\Omega,\quad R_{ts} = 0{,}02\Omega,\quad \omega_s = 2\pi[50Hz],\quad u_{sm} = 300V.$$

The circular frequency ω_m of modulation factor were given values from the set: $\{2\pi[1Hz,\ 10Hz,\ 20Hz,\ 35Hz]\}$.

Time courses of the complex envelope amplitudes and phase angles resulting from the network model (1) and (2) and Eqs. (11) and (12) as well as similar courses obtained from approximations (5) and (6) were the primary results of the model study. In each case, the time window width equalled 10 s, which with sampling frequency of f_s = 1000 Hz produced vectors of 10,000 samples for each course. This number was sufficient for given above frequencies of modulated and modulating signals.

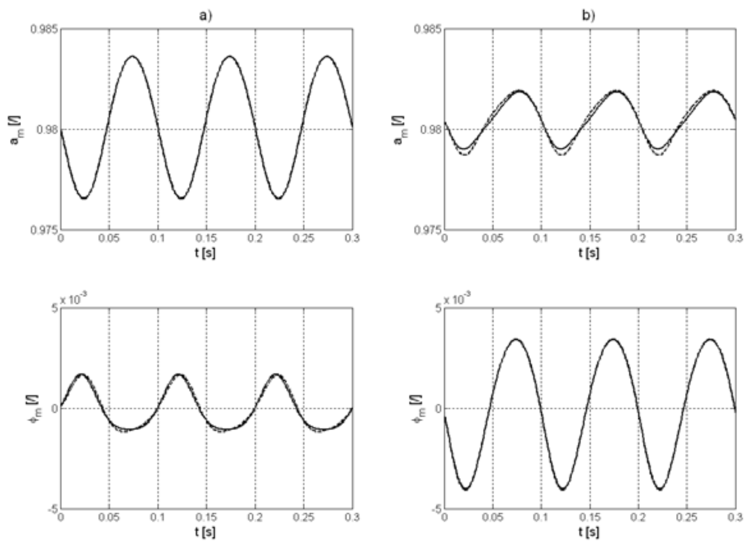

Fig.2. Time courses of the complex envelope amplitude and phase angle for $\omega_m = 2\pi 10$ rad/s and: a) for the amplitude of the load reactance component $X_{om} / X_{on} = 0{,}25$; b) for the amplitude of the load resistance component $R_{om} / R_{on} = 0{,}25$. Continuous line denotes the courses determined from Eqs. (5) and (6), the dashed line denotes the courses determined from Eqs. (1) and (2).

In Fig. 2, as an illustration of the scope of further studies, there are presented selected time courses of the complex envelope amplitudes and phase angles for modulation frequency ω_m=2π·10 rad/s and for the relative changes of load parameters $\frac{X_{om}}{X_o} = \frac{R_{om}}{R_o} = 0{,}25$. The courses resulting for Eqs. (5) and (6) are denoted with a continuous line while the dashed line denotes the courses resulting form Eqs. (1), (2) and (11), (12). The following conclusions may be drawn form this figure:

- the envelope of the modulated network voltage signal has two components: amplitude and phase angle,
- there are visible significant linear distortions of complex envelope amplitude and phase angle courses,
- the differences between the signal courses calculated using Eqs. (11) and (12), and (5) and (6) are not too large.

Summarizing, the primary results of the study point at the strong influence of modulation frequency ω_m and the parameters of load variability on the amount of nonlinear distortion. For this reason the numeric assessment of the level of nonlinear distortion of the complex envelope $a_m(t)$ versus the undistorted (sine) envelope accepted in ISO documents as the basis of the calibrating signal for flickermeters was the main goal of the study. To this aim, the signal obtained from (11) was compared with the signal envelope:

$$u_o^* = u_{sm}\left(1 - \frac{\Delta u_{sm}}{u_{sm}} \sin \omega_m t\right) \sin \omega_s t \,, \tag{13}$$

where $\frac{\Delta u_{sm}}{u_{sm}}$ is the amplitude of the envelope of linear modulation of network voltage amplitude with sine signal. It is accepted in abovementioned documents that the value of this amplitude ranges from 0.002 to 0.05, i.e., the amplitude modulation depth ranges from 0.2% to 5.0%. The envelope of the modulated network voltage signal is then defined as:

$$a_m^*(t) = \frac{1}{2} \frac{\Delta u_{sm}}{u_{sm}} \sin \omega_m t \,. \tag{14}$$

The phase angle of the envelope of linear modulation of network voltage amplitude with sine signal is zero.

The nonlinearity errors of the signal amplitude complex envelope $a_m(t)$ referred to $a_m^*(t)$ were determined as mean square errors:

$$\delta_{aa*} = \sqrt{\frac{\sum_{i=1}^{N} \left[a_m(t) - a_m^*(t) \right]^2}{\sum_{i=1}^{N} \left[a_m^*(t) \right]^2}} \,, \tag{15}$$

assuming that $\max_{(0,T_m)} |a_m(t)| = \frac{1}{2} \frac{\Delta u_{sm}}{u_{sm}}$, i.e., the maximum values of both envelopes of network voltage signal are identical.

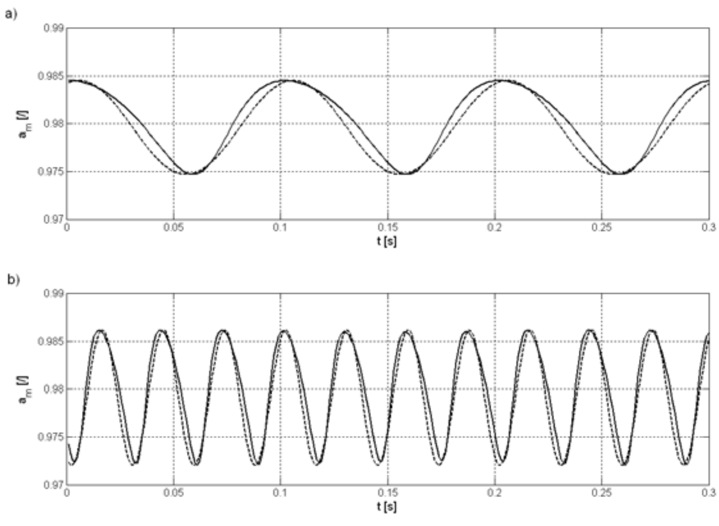

Fig.3. Time courses of the complex envelope amplitude $a_m(t)$ (continuous line) and the envelope of amplitude linear modulation $a_m^*(t)$ (dashed line) for modulation frequency a) f_m = 10 Hz, and b) f_m = 35 Hz.

In Fig. 3 two typical time courses of signals $a_m(t)$ and $a_m^*(t)$ for $\omega_m = 2\pi 10$ rad/s, $\omega_m = 2\pi 35$ rad/s and $\frac{X_{om}}{X_{on}} = \frac{R_{om}}{R_{on}} = 0{,}25$ are presented.

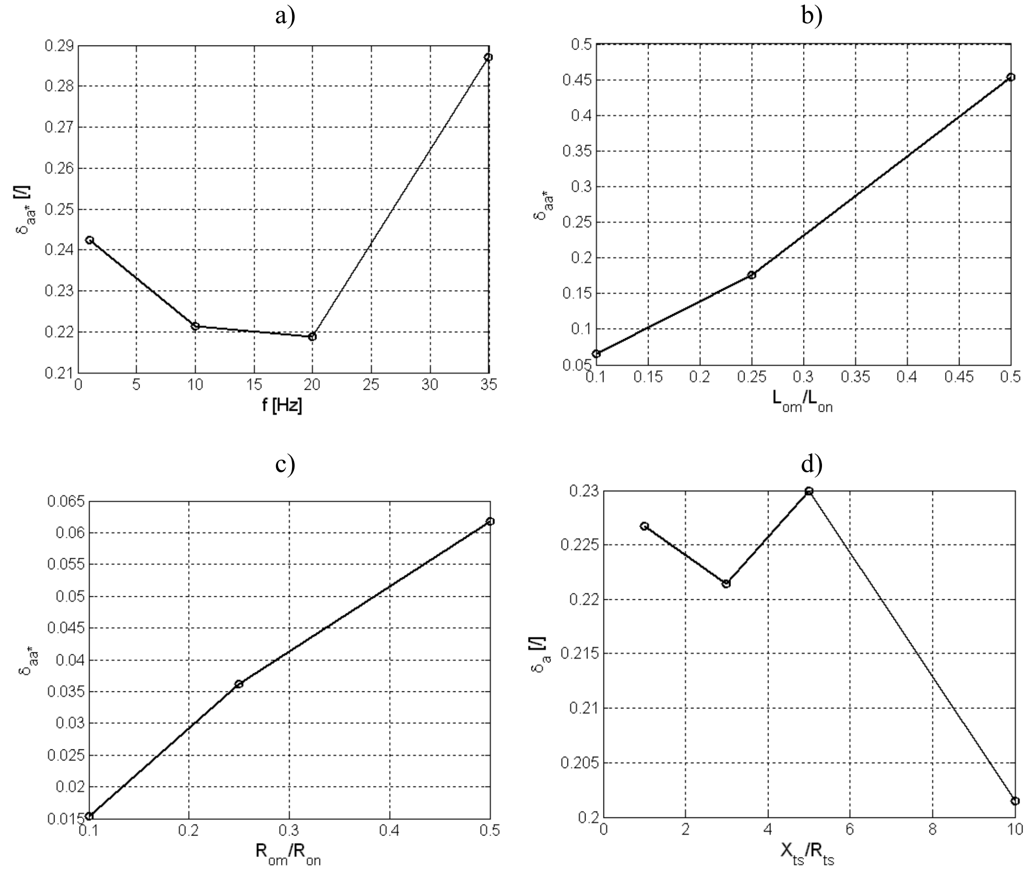

Fig.4. Relationship of the nonlinearity errors vs. modulation parameters: a) frequency ω_m, b) load reactance amplitude X_{om} / X_{on}, c) load resistance amplitude R_{om} / R_{on}, d) supply reactance to resistance ratio X_{ts} / R_{ts}.

In Fig. 4, the results are presented of the study on the relationships of the nonlinearity errors (15) vs. the following modulation parameters: frequency ω_m, relative amplitude $\frac{X_{om}}{X_{on}}$ of the reactance and $\frac{R_{om}}{R_{on}}$ of the resistance load component variability, as well as the values of the components X_{ts}, R_{ts} of the network source resistance.

Large nonlinerity errors justify the doubts concerning the correctness of the adopted flickemetr calibration method. They also constitute the grounds for looking for the reasons for discrepancy in the readings of many flickermeters connected to the same modulated network voltage.

Very characteristic influence of modulation nonlinerity can be seen in the spectra of the modulated voltage signal u_o compared with the signal spectrum u_o^*. In Fig. 5, these spectra are presented vs. the abovementioned modulation parameters. Strong distortions can be seen of the spectra compared with the symmetrical linear modulation spectrum, consisting in an increase of number and amplitude for side lines on one side of the main line (50 Hz). Not as in the case of the complex modulation spectrum, the spectrum of network voltage amplitude linear modulation with a sine signal of frequency $\omega_m \ll \omega_s$ has the shape of two symmetrical lines of frequencies ω_s-ω_m and ω_s+ω_m around the main line of frequency ω_s. As it was shown in [7], the spectrum distortion is connected with the modulation of the complex envelope phase angle.

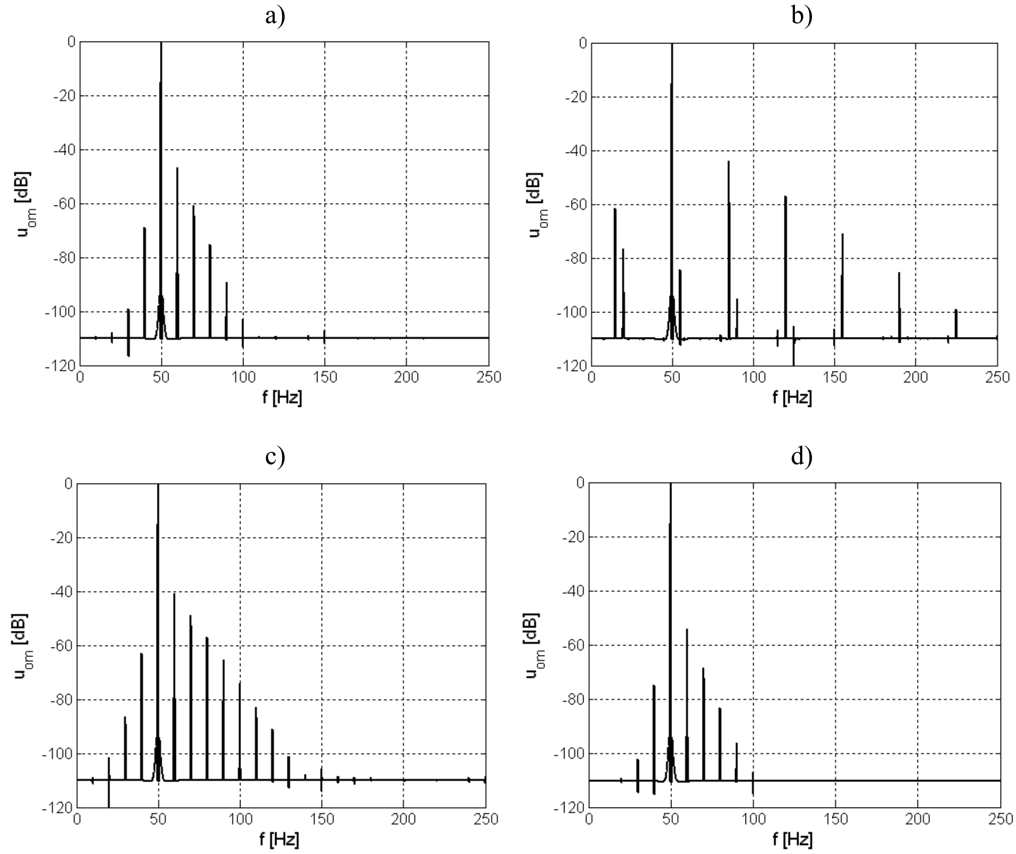

Fig.5. Spectra of network voltage signal modulated sinusoidally with the time-variable load impedance of the following modulation parameters: a) f_m =10 Hz, $R_{om}/R_{on} = X_{om}/X_{on} = 0.25$, $X_{ts}/R_{ts}= 3$; b) f_m= 35 Hz, $R_{om}/R_{on} = X_{om}/X_{on} = 0.25$, $X_{ts}/R_{ts}= 3$; c) f_m=10 Hz, $R_{om}/R_{on} = X_{om}/X_{on} = 0.5$, $X_{ts}/R_{ts}= 3$; d) f_m= 10 Hz, $R_{om}/R_{on} = X_{om}/X_{on} = 0.25$, X_{ts}/R_{ts}=10

To determine how large is the discrepancy between the values of the light short-term flicker severity index P_{st} for the both abovementioned modulation methods, model study was carried out with the flickermeter model developed in [3, 5]. The values of P_{st} were calculated for the voltage signal modulated with a complex factor determined from Eqs. (1), (2) and for the signal amplitude modulated linearly according to the adopted flickermeter calibration method specified by Eq. (13). It was assumed that the modulation parameters of both signals: the relative values of envelope amplitude, i.e., modulation depth, and the modulation frequency, were the same. A fixed, not very large modulation depth, of 0.85 % was adopted. In the first case, the load impedance was changed sinusoidally, i.e., a natural network voltage distortion source was simulated. In the second case, a linear sine amplitude modulation was applied as a standard signal. Additionally, the values of P_{st} were determined for network voltage linear modulation with a square signal also in accordance with the adopted calibration method. The results of this model study are presented in Fig. 6.

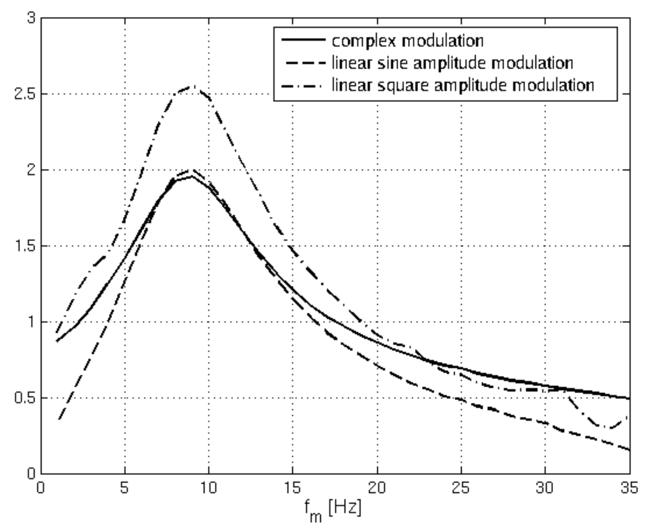

Fig.6. The relationship of the short-term flicker severity index P_{st} vs. modulation frequency: a) complex modulation (continuous line), b) linear sine amplitude modulation (dashed line), c) linear square amplitude modulation (dashed-dotted line)

A conclusion can be drawn from Fig. 6 that even at low modulation depths for which comparing amplitude envelope still makes sense because the complex envelope is not considerably disturbed, the values of P_{st} for both cases under consideration significantly differ. Because of the nonlinearity of complex modulation at larger modulation depths, larger differences may be expected. The least differences occur in the vicinity of the frequency of about 8 Hz, characteristic for flickermeters, important for physiological reasons [11, 12].

5. CONCLUSIONS

In our opinion, the presented study results may form the grounds for justified doubts concerning the correctness and, especially, the uniqueness of the currently used method of measuring the time variability of power network voltage parameters which consists in determining the light flicker severity index. The doubts concern mainly the definition of this measure and the calibration methods of measuring instruments based on this definition. Of course, we see the merits of this definition in its assessing the physiological effects of light flickering. However, as we have shown above, this definition together with the applied calibration method does not take fully into account the essence of the phenomenon of the network voltage modulation with the time variable load. This is because the modulation of this kind is complex and nonlinear modulation in respect of the load impedance. The envelope amplitude and phase angle nonlinear distortion errors are large and the respective spectrum differs considerably from the linear amplitude modulation spectrum of the used standard signal, which significantly influences the flickermeter filter operation. In consequence, differences occur between the flicker severity index calculation results for both methods of network voltage modulation.

Taking into account the findings of the study, we express the view that it is necessary to search for a new, more reliable and more unequivocally defined measure of power network voltage parameter variability resulting from load fluctuations. This measure should represent the properties of the signal, have simple physical interpretation and simple algorithm of calculations. The investigations we have been carrying to this end point at the norm of function fluctuations as meeting the listed requirements.

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BADANIA MODELOWE MODULACJI I DEMODULACJI ZESPOLONEJ SYGNAŁU NAPIĘCIA SIECI ELEKTROENERGETYCZNEJ OBCIĄŻONEJ ZMIENNĄ W CZASIE IMPEDANCJĄ

Streszczenie

Jedną z głównych przyczyn niekontrolowanej zmienności w czasie parametrów sygnału napięcia sieci elektroenergetycznej jest zmienność w czasie mocy i prądu obciążenia sieci, tj. zmienność parametrów odbiorników energii elektrycznej. Zmienność sygnału napięcia sieci obniża jakość energii elektrycznej dostarczanej odbiorcom. W drodze ustaleń międzynarodowych określono szereg miar jakości energii związanych ze zmiennością napięcia. Są one obliczane na mierzonym sygnale napięcia sieci bądź to jako uśrednione miary losowej zmienności amplitudy napięcia, bądź też jako miary odchyleń od normalnych wartości parametrów i kształtu sinusoidy napięcia sieci [9, 10, 11]. Okazuje się jednak, że losowe uśrednione miary jakości energii elektrycznej wyznaczane przez przyrządy pomiarowe mierzące wskaźnik uciążliwości migotania źródeł światła P_{ST} mogą prowadzić do niejednoznacznej oceny jakości z powodu różnych wartości wyników pomiarów dla tych samych sygnałów mierzonych [8]. W dodatku, z powodu formalnej złożoności definicji takich miar oraz braku odniesienia do przyczyn zmienności napięcia, fizyczna interpretacja zjawisk w sieci elektroenergetycznej poddanej niestacjonarnym obciążeniom jest znacznie utrudniona [5, 8]. Powstaje zatem zagadnienie określenia przyczyn tych trudności pomiarowych. W niniejszej publikacji proponujemy koncepcję przeprowadzenia takich badań w oparciu o model matematyczny oddziaływania zmienności obciążeń na sygnał napięcia sieci. Badania te polegającą na wykonaniu na tym sygnale poprawnej detekcji czynników wpływających na kształt sygnału.

Jednym z założeń przyjętych przy definiowaniu uśrednionej miary losowej o nazwie "wskaźnik uciążliwości migotania światła" jest założenie o liniowej modulacji napięcia sieci, uważanego za efekt zmienności obciążenia. Definicja tej miary ma postać złożonego ciągu liniowych dynamicznych i nieliniowych statycznych operacji na sygnale napięcia, odwzorowanych praktycznie we wspomnianych miernikach uciążliwości migotania światła [1, 9]. Mierniki te wzorcowane są sygnałami liniowo zmodulowanymi w amplitudzie, uzyskiwanymi przez mnożenie sinusoidy sygnału napięcia sieci i sygnału modulującego. Badania przyczyn niejednoznaczności wyników wyznaczania miary wskaźnika uciążliwości migotania światła prowadzą do następujących wniosków [7]:

- modulacja napięcia sieci elektroenergetycznej, spowodowana zmiennością obciążenia sieci jest modulacją zespoloną, a więc nie tylko modulacją amplitudy ale i kąta fazowego napięcia,

- modulacja ta jest nieliniowa względem składowych zmiennej impedancji obciążającej sieć, a zatem widmo sygnału napięcia jest bardziej złożone niż w przypadku modulacji liniowej.

Powyższe wnioski zostały potwierdzone w badaniach modelowych oraz eksperymentalnych. Ich konsekwencją jest sugestia wprowadzenia nowych definicji miar jakości energii elektrycznej uwzględniających wymienione wyżej czynniki wpływające na modulację sygnału napięcia sieci [3, 5]. Niniejsza publikacja jest próbą przedstawienia fragmentu wyników wspomnianych prac, obejmującą wyłącznie badania modelowe.