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The use of variety of measures in voltage fluctuation analysis

Abstract. *The paper presents four measures of voltage variability in a power grid: a short-term flicker P_{st} indicator, voltage fluctuation δU with f indices, maximum $U_{\max}$, and minimum $U_{\min}$ rms voltage values as well as ΔV_{10} index. The major features of these measures have been listed. Dependences of these measures values on voltage variability have been shown on diagrams. An exemplary voltage variability assessment has been conducted basing on the measurement results recorded in a low voltage circuit. In the example, using the $U_{\max}$ and $U_{\min}$ values, it has been stated that the recorded changes of voltage, its rises and falls, can be causing interference in the work of receivers. Moreover, large values of $(U_{\max} - U_{\min})$ differences may be a reason of large voltage variability occurrence. The analysis of $P_{st} = \mathrm{f}(t)$ time plot confirmed the occurrence of obnoxious voltage fluctuation in one phase. It has led to the final statement that the voltage quality failed to meet legal and standard requirements. Moreover, the values of voltage fluctuation indices δU and f have been determined, which made it possible to estimate the properties of the voltage variability source.*

Streszczenie. *W pracy przedstawiono cztery miary zmienności napięcia w sieci elektroenergetycznej: wskaźnik krótkookresowego migotania światła P_{st}, wskaźniki wahań napięcia δU i f, wartości maksymalne $U_{\max}$ i minimalne $U_{\min}$ napięcia oraz wskaźnik ΔV_{10}. Wymieniono podstawowe cechy tych miar. Graficznie zobrazowano zależności wartości tych miar od zmienności napięcia. Na podstawie wyników pomiarów zarejestrowanych w obwodzie nn przeprowadzono przykładową ocenę zmienności napięcia. Wykorzystując wartości $U_{\max}$ i $U_{\min}$ uznano, że zarejestrowane zmiany napięcia, wzrosty i zaniżenia, mogą być przyczyną zakłóceń w pracy odbiorników. Ponadto duże wartości różnic $(U_{\max} - U_{\max})$ zwróciły uwagę na możliwość wystąpienia dużej zmienności napięcia. Analizując przebieg czasowy $P_{st} = \mathrm{f}(t)$ wykryto wystąpienie uciążliwych wahań napięcia w jednej fazie. Na tej podstawie stwierdzono niezachowanie jakości energii elektrycznej w ujęciu prawnym i normatywnym. Określono wartości wskaźników wahań napięcia: amplitudy δU i częstości f. Uzyskano w ten sposób informacje o parametrach źródła zmienności napięcia.* ***(Wykorzystanie różnych miar w ocenie zmienności napięcia)***

Keywords: power quality, voltage variation, voltage fluctuation indices, P_{st} indicator, ΔV_{10} indicator
Słowa kluczowe: jakość napięcia, zmienność napięcia, wskaźniki wahań napięcia, wskaźnik P_{st}, wskaźnik ΔV_{10}

Introduction

The evaluation of voltage variation is one of the major factors contributing to the voltage quality in a power network. It is important to estimate sudden voltage fluctuations as they may affect the work of any receivers. Depending on the receivers' characteristics the disturbance may be manifested with discontinuity or an unwelcome change of their state. The most frequent effect of such a change is flicker. The measurement and evaluation of voltage variation in a power network is a complex measurement process. Therefore it is necessary to use the right measures which will make it possible to describe voltage variation in a way that is simple and easy to read. At the same time it is necessary to consider the voltage variation influence on potential receivers. Several measures have already been described in professional literature [1]. According to the author, the main measures are: maximum and minimum voltage rms values (phase and line), short-term and long-term flicker P_{lt} indicators, voltage fluctuation indices, and the ΔV_{10} index. The main difference between these measures is their diagnostic capability. None of them is good enough to estimate the scope of obnoxious voltage fluctuation or determine the potential obnoxious power receivers. It is necessary to understand the specific features of the given measures in order to carry out a successful diagnostic process [2, 3, 4, 5]. Hence the description of these measures in the article. The dependency of the above measures on the main types of voltage variation has also been presented. Thus the information on the range of their implementation has been obtained. These dependencies have made it possible to compare different measures of voltage variability. The examples of real-life measurement results have provided the basis of indicating the measures' capabilities. It has been shown that in order to obtain a full estimation of power quality as far as the voltage variations are concerned it is necessary to combine the measurement results gathered with different measures of voltage variation.

Voltage variation measures in a power network

The $U_{\max}$ maximum and $U_{\min}$ minimum values of the rms value describe the voltage changes with the use of maximum and minimum values in a discrimination period. Such data as intermediate values, fluctuation frequency and rate are omitted. For voltage variation regenerable with AM modulation, the $U_{\max}$ and $U_{\min}$ values depend on the f_m frequency and $\left(\frac{\Delta U}{U}\right)/2$ amplitude of the voltage enveloping curve. Figure 1 shows the $U_{\max} = \mathrm{f}(f_m)$ and $U_{\min} = \mathrm{f}(f_m)$ dependencies for a constant amplitude $\left(\frac{\Delta U}{U}\right) = \mathrm{const} = 2\%$.

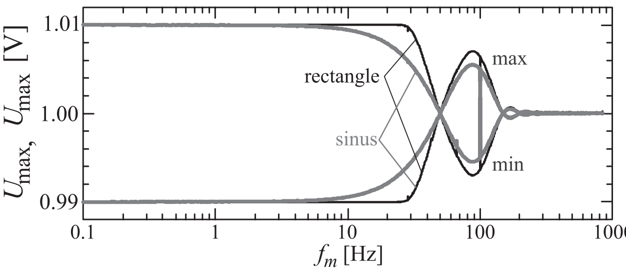


Fig. 1. Dependencies $U_{\max} = \mathrm{f}(f_m)$ and $U_{\min} = \mathrm{f}(f_m)$ for AM modulation with rectangular and sinusoidal signals; $\left(\frac{\Delta U}{U}\right) = \mathrm{const} = 2\%$, $U = 1\,\mathrm{V}$ [6]

The chart allows to find that the $U_{\max}$ and $U_{\min}$ values correctly describe the voltage variation for $f_m < 28\,\mathrm{Hz}$ (rectangular modulating signal) or $f_m < 4\,\mathrm{Hz}$ (sinusoidal modulating signal). In the case where there is only one dominating affecting receiver the maximum $U_{\max}$ and minimum $U_{\min}$ values serve as an effective and easy-to-use measure. As far as diagnostic purposes are concerned the maximum $I_{\max}$ and minimum $I_{\min}$ current rms values become also useful. It is impossible to determine the obnoxiousness of voltage fluctuations with $U_{\max}$ and $U_{\min}$ values. Most power quality analyzers measure and record maximum and minimum voltage values. While using $U_{\max}$ and $U_{\min}$ values one must take into consideration the way they are acquired by a given instrument. It is of utmost importance when it comes to the comparison of results acquired by different meters.

The standard measures in voltage variation estimation are the short-term P_{st} and long-term P_{lt} flicker indicators. This kind of measurement method is regulated by the IEC 61000-4-15 standard [7]. The measurement of the P_{st} indicator is obtained with a flicker gauge (also known as a flickermeter). The indicator value illustrates the level of obnoxious flicker caused by voltage variation in the given measuring conditions (e.g. for a specified light source). In order to estimate the level of obnoxious voltage fluctuation in relation to the generated flicker it is necessary to compare the value of P_{st} indicator and margin values. In MV and LV circuits this value is uniformly set to 1 and in HV circuits it equals 0.8 [8]. For voltage variation (regenerable with amplitude modulation) the value of P_{st} indicator depends on the f_m frequency, $\left(\frac{\Delta U}{U}\right)/2$ amplitude, and shape of voltage enveloping curves [9]. With constant frequency and enveloping curve shapes, the P_{st} value is approximately linearly dependable on the enveloping curves' amplitude [10, 9]. With constant amplitude and enveloping curves, the dependency of the P_{st} indicator on frequency is not linear. The characteristics of $P_{st} = \mathrm{f}\left(f_m\right)$ for $\left(\frac{\Delta U}{U}\right) = \mathrm{const} = 2\%$ and the AM amplitude modulation with rectangular and sinusoidal signals has been presented in Fig. 2.

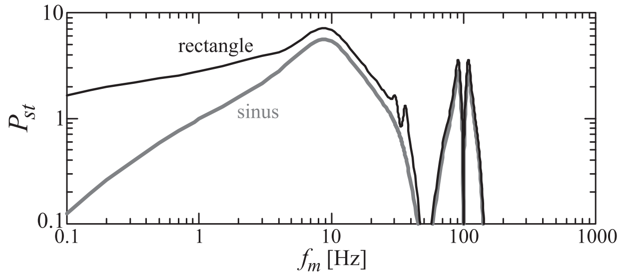


Fig. 2. Flickermeter $P_{st} = \mathrm{f}\left(f_m, \left(\frac{\Delta U}{U}\right) = 2\%\right)$ characteristic for AM modulation with rectangular and sinusoidal signals [9]

If voltage variation corresponds to the signal resulting from FM frequency modulation, the P_{st} indicator value depends on the f_m frequency and the shape of the modulating signal and on Δf_{FM} frequency deviation [11]. These dependencies are not linear. Figure 3 shows the characteristic of $P_{st} = \mathrm{f}\left(f_m\right)$ for $\Delta f_{\mathrm{FM}} = \mathrm{const} = 0.2\,\mathrm{Hz}$.

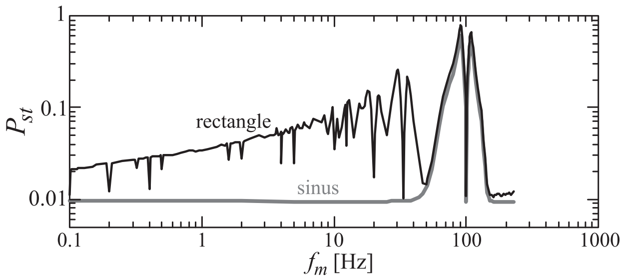


Fig. 3. Flickermeter $P_{st} = \mathrm{f}\left(f_m, \Delta f_{\mathrm{FM}} = 0.2\,\mathrm{Hz}\right)$ characteristic for FM modulation with rectangular and sinusoidal signals [11]

In order to describe voltage variation, sub– and interharmonic components are used alongside the AM and FM modulations. The value of P_{st} indicator depends on the u_i amplitudes and f_i frequencies of these components. Figure 4 shows the $P_{st} = \mathrm{f}\left(f_i\right)$ characteristic for $u_i = \mathrm{const} = 1\%$ and one sub/interharmonic component.

Voltage fluctuation indices, δU amplitude and f frequency of voltage variation constitute the measure of rms voltage value changing [1, 12, 6]. δU and f indices' values are estimated from the set of recorded δV fluctuations. δV value describes a single change of rms value. The frequencies of fluctuation occurrence are specified in counting ranges related to δU value. For example, the f_{a-b} frequency indicates the number of δV fluctuation occurrences within $\langle a, b)\,\delta U$ interval. The discrimination process of these voltage fluctuation indices has been shown in [12]. Figures 5 and 6 present the amplitudes $\delta U = \mathrm{f}\left(f_m\right)$ and frequencies

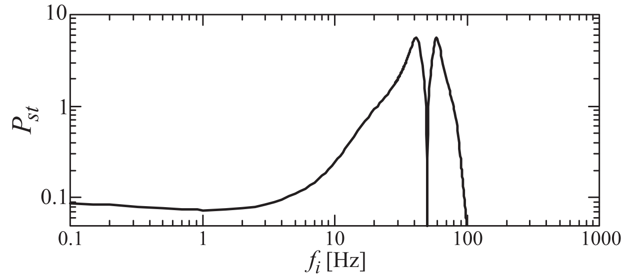


Fig. 4. The $P_{st} = \mathrm{f}\left(f_i, u_i = 1\%\right)$ voltage characteristic with one sub/interharmonic component [6]

$f = \mathrm{f}\left(f_m\right)$ of fluctuations for AM modulation with sinusoidal and rectangular signals. Up to a certain margin value of f_m frequency, the fluctuation indices directly describe the amplitude and the frequency of voltage enveloping curves [6].

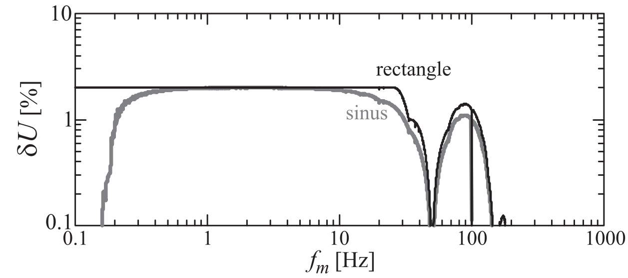


Fig. 5. Dependency $\delta U = \mathrm{f}\left(f_m, \left(\frac{\Delta U}{U}\right) = 2\%\right)$ for AM modulation with rectangular and sinusoidal signals [6]

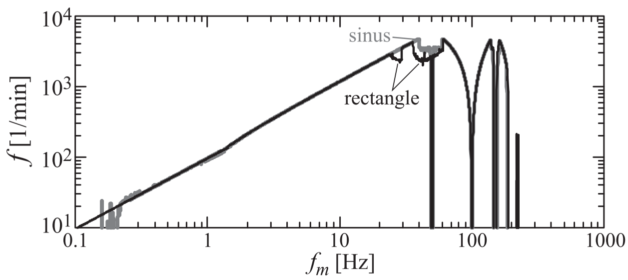


Fig. 6. Dependency $f = \mathrm{f}\left(f_m, \left(\frac{\Delta U}{U}\right) = 2\%\right)$ for AM modulation with rectangular and sinusoidal signals [6]

The evaluation of the level of flicker obnoxiousness on the basis of δU and f indices is more complex than the evaluation of the P_{st} indicator. However, it is possible to come up with such an evaluation for different measuring conditions (e.g. light sources, daylight presence, individual features) where the basis for this evaluation comes from previously observed measuring results. The evaluation of voltage fluctuation obnoxiousness in terms of the effects it causes is performed by an analysis of the measuring points placement in relation to the obnoxious fluctuations borderline [13, 14]. Figure 7 shows an exemplary borderline (corresponding with $\left(\frac{\Delta U}{U}\right) = \mathrm{f}\left(f_m, P_{st} = 1\right)$ for AM modulation with rectangular signal from Fig. 2) with both obnoxious and non-obnoxious fluctuations marked. The fluctuations are obnoxious when the measuring points of $(f, \delta U)$ coordinates are present above the acceptable fluctuations borderline. The fluctuations below the acceptable fluctuations borderline are considered non-obnoxious.

As far as diagnostic purposes are concerned a product of δU amplitude and f frequency marked with PWN symbol comes as a good representation of the fluctuation indicies. If the amplitudes of fluctuations δV are counted in the following ranges: $\langle 1.0 - 0.9)\,\delta U$, $\langle 0.9 - 0.8)\,\delta U$, $\langle 0.8 - 0.7)\,\delta U$,

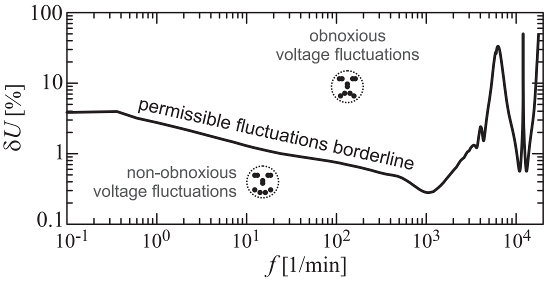


Fig. 7. Exemplary permissible fluctuation borderline with obnoxious and non-obnoxious voltage fluctuations marked [6]

$\langle 0.7-0.6)\,\delta U$, $\langle 0.6-0.5)\,\delta U$, $\langle 0.5-0.4)\,\delta U$ and $\langle 0.4-0.0)\,\delta U$, the PWN could be expressed as

(1)
$$\begin{aligned}\mathrm{PWN} =& \delta U\cdot(f_{1.0-0.9}+0.9f_{0.9-0.8}+0.8f_{0.8-0.7}+\\ &+0.7f_{0.7-0.6}+0.6f_{0.6-0.5}+0.5f_{0.5-0.4}+0.4f_{0.4-0.0})\,.\end{aligned}$$

For the above mentioned counting ranges the resultant f frequency equals:

$$\begin{aligned}f =& f_{1.0-0.9}+f_{0.9-0.8}+f_{0.8-0.7}+f_{0.7-0.6}+f_{0.6-0.5}\\ &+f_{0.5-0.4}+f_{0.4-0.0}.\end{aligned} \quad (2)$$

To determine the obnoxiousness of fluctuations, Far East countries depend on a ΔV_{10} index. The value of this index is determined from the following equation [15]:

$$\Delta V_{10}=\sqrt{\sum_i\left(a_{f_i}\cdot\Delta v_{f_i}\right)} \quad (3)$$

where: Δv_{f_i} – magnitude of sinusoidal voltage component of frequency f_i which results from the development of the effective fluctuation into a Fourier series; a_{f_i} – sensitivity coefficients as a function of frequency of sinusoidal fluctuation, coefficients represent both sensitivity of the human eye and the incandescent lamp.

The value of a_{f_i} coefficient is defined by $a_{f_i}=\mathrm{f}(f_i)$ characteristic shown in Fig. 8.

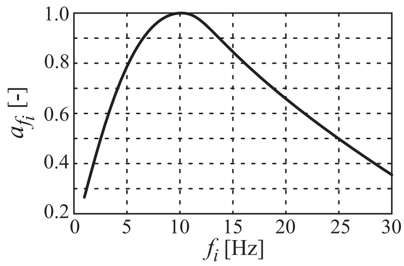


Fig. 8. Visual sensitivity curve $a_{f_i}=\mathrm{f}(f_i)$ [16]

The maximum of this characteristic can be observed at $f_i = 10\,\mathrm{Hz}$. So there is a difference in perception of flicker between this characteristic and the amplitude characteristic of a band-pass filter in a standard signal path of a flickermeter (with a $8,8\,\mathrm{Hz}$ mid-band frequency) and the difference equals $1.2\,\mathrm{Hz}$. The voltage fluctuations are non-obnoxious if two requirements are met: the ΔV_{10} maximum value is lower than 0.45% and the average value is lower than 0.32% [15]. There are some serious impediments in a practical implementation of ΔV_{10} index. These are the problems with frequency and amplitude values determination for particular components. It is necessary to measure the sub/interharmonics. They come as the basis to determine frequency and amplitude values of the components present in (3).

The use of voltage variation measures in voltage diagnosis

The results of LV ($U_n = 230\,\mathrm{V}$, $f_c = 50\,\mathrm{Hz}$) circuit analysis have provided an opportunity to show the diagnostic effectiveness of selected voltage variation measures. In order to do it the results recorded every $10\,\mathrm{min}$, $1\,\mathrm{min}$ and $1\,\mathrm{s}$ have been used. Three available variation measures have been analyzed: $U_{\max}$ and $U_{\min}$ values, the P_{st} indicator and voltage fluctuation indices. The $U_{\max}$ and $U_{\min}$ values have been derived from rms values calculated every half-period for one voltage period. Due to the lack of available measurement results the ΔV_{10} index has been ignored. The order in which particular measures are analysed depends on the goal of the study and the experience of the person who carries it out. According to [8] the basic recording period is $10\,\mathrm{min}$. Therefore the analysis described below starts with the results recorded within this period. Then the obnoxiousness of the voltage fluctuation has been described basing on the P_{st} indicator values. In order to make the description of the voltage variation more detailed the voltage fluctuation indices have been used. The exemplary analyses has been carried out on the basis of voltage and current measurements taken at three points of an LV circuit. Data collected during a selected full-day-long period has been chosen for the analysis. The LV circuit schematic with **R1**, **R2** and **R3** measuring points has been shown in Fig. 9.

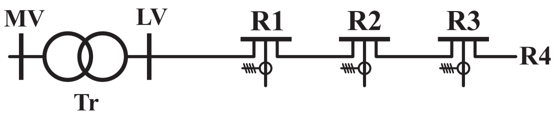


Fig. 9. LV circuit schematic with **R1**, **R2** and **R3** voltage and current measuring points; MV - middle voltage, LV - low voltage, Tr - MV/LV transformer

The first stage of the study consists of the analysis of $U_{\max}$ and $U_{\min}$ time plots. It allows to discover the conditions at which the excess mains voltage increase or decrease protection takes over. [8] assumes that the rms value should not exceed a $\pm 10\% U_n$ range. Figure 10 shows the phase voltage $U_{\max}$ and $U_{\min}$ values' time plots with $207\,\mathrm{V}$ and $253\,\mathrm{V}$ values marked.

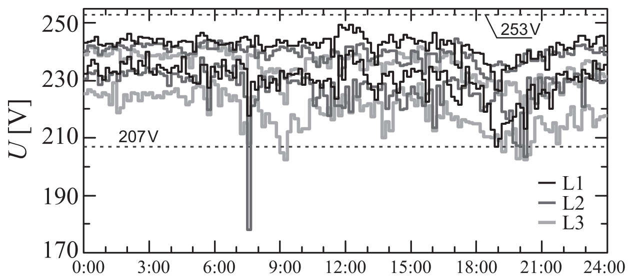


Fig. 10. Phase voltage $U_{\max}$ and $U_{\min}$ values' time plots at point **R1**

Figure 10 time plots indicate that for a short period of time there have been rms values smaller than $207\,\mathrm{V}$ including a one-time slump to a value smaller than $180\,\mathrm{V}$. Such a phenomenon is likely to cause some disturbances to the receivers of these voltages. Due to a low level of legibility of Fig. 10 (especially in a black and white version) and some difficulties with estimating the $(U_{\max}-U_{\min})$ differences' values, Fig. 11 shows the $(U_{\max}-U_{\min})=\mathrm{f}(t)$ time plots.

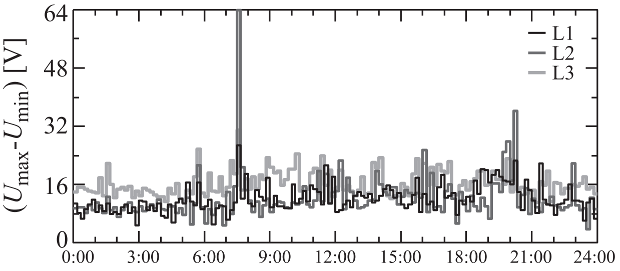


Fig. 11. Phase voltage $(U_{\max} - U_{\min})$ differences' time plots at point **R1**

Most $(U_{\max} - U_{\min})$ values fall within the $8 - 24\,\mathrm{V}$ range. Obnoxious voltage fluctuations are highly likely for such differences. The voltage variation described with $U_{\max}$ and $U_{\min}$ values may be caused by the currents variation at points **R1**–**R3** or come from an MV/LV transformer. In order to identify the cause of the voltage variations the dependencies $(U_{\max} - U_{\min}) = \mathrm{f}\,(I_{\max} - I_{\min})$ become useful. Figure 12 shows the dependency for point **R1**. The dependencies at the other two points are similar. Therefore, there is a characteristic for only one point presented.

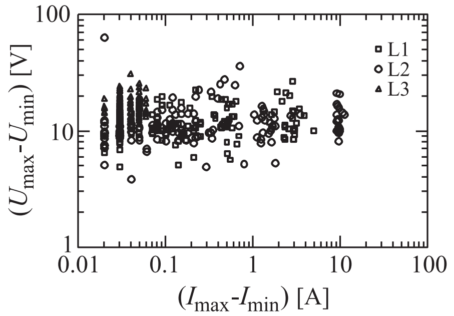


Fig. 12. Dependency $(U_{\max} - U_{\min}) = \mathrm{f}\,(I_{\max} - I_{\min})$ for point **R1**

Figure 12 characteristic does not indicate that the reason behind the voltage variation at point **R1** is the current variation. The $(U_{\max} - U_{\min}) = \mathrm{f}\,(I_{\max} - I_{\min})$ dependencies for points **R2** and **R3** fail to prove it either. Thus the current variation at **R1**–**R3** points is not the reason behind voltage variations of amplitudes close to the $(U_{\max} - U_{\min})$ difference. This current variation however, may be the reason behind variations of smaller amplitudes. The character of a voltage variation may be estimated from time plots of $U_{\max}$, $U_{\min}$ and U_{avg} average values. The location of the time plots in relation to one another is also the key. Figure 13 presents $U_{\max}$, U_{avg} and $U_{\min}$ voltage time plots at L3 phase recorded at point **R1**.

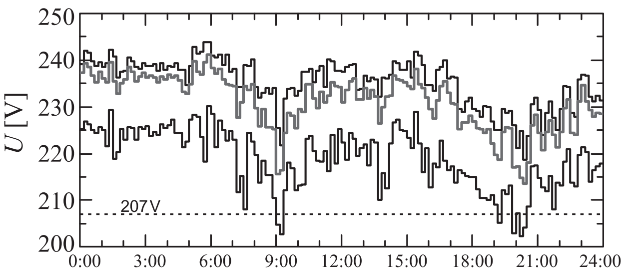
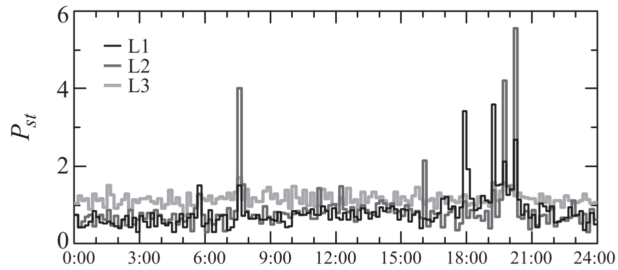
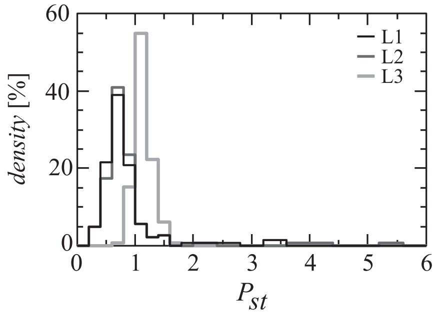


Fig. 13. $U_{\max}$, U_{avg} and $U_{\min}$ voltage time plots at L3 phase at point **R1**

The U_{avg} values lay closer to $U_{\max}$ than $U_{\min}$. This implies that the voltage variation is caused by short-term voltage drops. The $U_{\max}$, U_{avg} and $U_{\min}$ values take a similar position in the other phases. The P_{st} indicator is a standard measure of voltage fluctuations [17, 8]. The time plots or histograms of the indicator come as easy-to-use representation forms. Figure 14 presents the time plot and the histogram of the P_{st} indicator for phase voltages at point **R1**.



(a) P_{st} indicator time plot



(b) P_{st} indicator histogram

Fig. 14. P_{st} indicator for phase voltages at point **R1**

The analysis of Fig. 14 leads to the following conclusions:

– there are short-term boosts of the P_{st} indicator to the level exceeding 3 in phases marked as L1 and L2,
– P_{st} values slightly above 1 dominate the L3 phase, the other two phases are dominated by values slightly below 1, therefore at point **R1** in L3 phase obnoxious voltage fluctuations are present while in the other phases they do not exceed the obnoxiousness threshold,
– the study of P_{st} indicator does not provide such data as the amplitude or frequency of fluctuations, which makes the search for the fluctuation sources difficult.

The analysis of Fig. 12 allowed to draw the conclusion that the voltage fluctuations' increase defined with $(U_{\max} - U_{\min})$ is not caused by the increase of the $(I_{\max} - I_{\min})$ currents. The amplitude of voltage fluctuations responsible for the increase of the P_{st} indicator can be lower than the $(U_{\max} - U_{\min})$ subtraction values. That is why a $P_{st} = \mathrm{f}\,(I_{\max} - I_{\min})$ dependency for point **R1** has been determined, which is shown in Fig. 15.

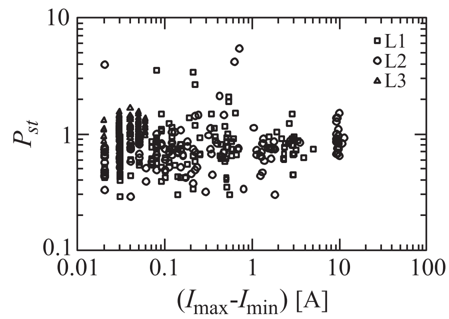


Fig. 15. $P_{st} = \mathrm{f}\,(I_{\max} - I_{\min})$ dependency for point **R1**

The characteristic from Fig. 15 confirms the conclusion drawn from Fig. 12. The increase of the P_{st} indicator is not caused by the increase in the current variations at point **R1**. It is also valid for the current variations recorded at points **R2** and **R3**, which have not been included in this paper. The increase of the P_{st} indicator may stem from the increase of the amplitude and/or the frequency of the fluctuations. It is possible to find some approximate conclusions on the amplitude and frequency's influence on the P_{st} indicator value by using the $P_{st} = \mathrm{f}\left(U_{\max} - U_{\min}\right)$ characteristic. This dependency for phase voltages at point **R1** has been shown in Fig. 16.

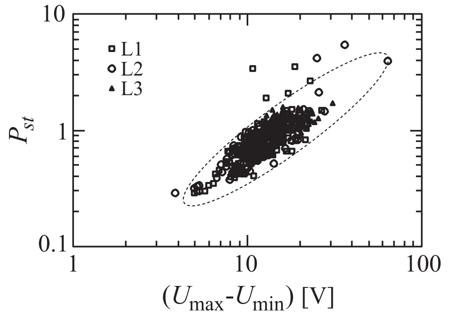


Fig. 16. $P_{st} = \mathrm{f}\left(U_{\max} - U_{\min}\right)$ dependency for point **R1**

According to Fig. 16, for $P_{st} < 2$ the increase of the indicator is linked to the increase of the $\left(U_{\max} - U_{\min}\right)$ voltage variation. On the other hand, for $P_{st} > 2$ the increase of the voltage variation does not correspond to the increase of the indicator (sections L1 and L2). This implies that the P_{st} values' increase is caused by the increase of the voltage fluctuation frequency.

The δU amplitude and the f frequency of the voltage fluctuations are other indices allowing to get more information on the voltage variation. In order to carry out an effective interpretation of the indices it is necessary to illustrate them in the right manner. The measurement results will be presented on both amplitude-frequency characteristics and time plots. The first of these characteristics has been shown in Fig. 17. It has been acquired on the basis of fluctuations counted in the $\langle 1.0 - 0.4)\, \delta U$ range.

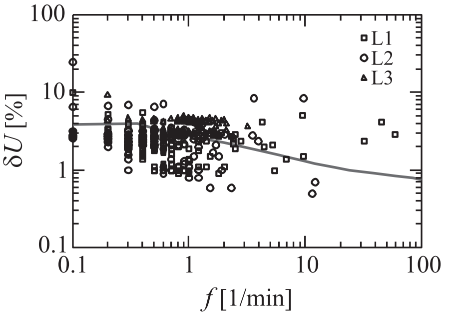
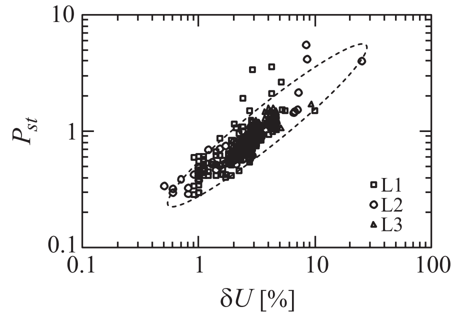


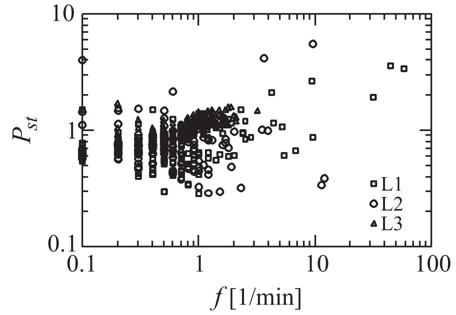
Fig. 17. Amplitude-frequency characteristic $\delta U = \mathrm{f}(f)$ of phase voltage fluctuations at point **R1** along with permissible fluctuation borderline

Some measurement points of the $\delta U = \mathrm{f}(f)$ characteristic from Fig. 17 are located above the permissible fluctuations borderline. This implies the occurrence of obnoxious voltage fluctuations. It is possible to estimate the values of δU and f indices on the basis of the measurement points' location. The δU amplitude lies within $(0.5 - 10)\,\%$ range, the f frequency within $(0.1 - 60)\ \frac{1}{\min}$ range. In Fig. 18, the $P_{st} = \mathrm{f}(\delta U)$ and $P_{st} = \mathrm{f}(f)$ dependencies illustrate the influence of the indices' values on the voltage fluctuation obnoxiousness.

The $P_{st} = \mathrm{f}(\delta U)$ characteristic from Fig. 18(a) implies that the increase of the P_{st} values is caused by the increase of the δU amplitude. This relation vanishes only for $P_{st} > 2$. It is in line with the conclusion from Fig. 16. In the case of the $P_{st} = \mathrm{f}(f)$ characteristic for $P_{st} < 2$ it is evident that there is a connection between the P_{st} and the f values. But this connection is not as evident as for the $P_{st} = \mathrm{f}(\delta U)$ dependency. For $P_{st} > 2$ it is difficult to determine any connection between P_{st} and f. Figure 18 characteristics provide a combined information about fluctuation indices. A detailed analysis of interrelation of these indices is possible on the basis of the time plots which are presented in Fig. 19. In order to simplify the analysis, the $P_{st} = \mathrm{f}(t)$ indicator time plot from Fig. 14 (in a 7:00 to 21:00 time bracket) has been presented here. Such a bracket has been chosen due to the lack of any significant increases of the P_{st} values outside it.



(a) $P_{st} = \mathrm{f}(\delta U)$ dependency



(b) $P_{st} = \mathrm{f}(f)$ dependency

Fig. 18. $P_{st} = \mathrm{f}(\delta U)$ and $P_{st} = \mathrm{f}(f)$ dependencies for phase voltages at point **R1**

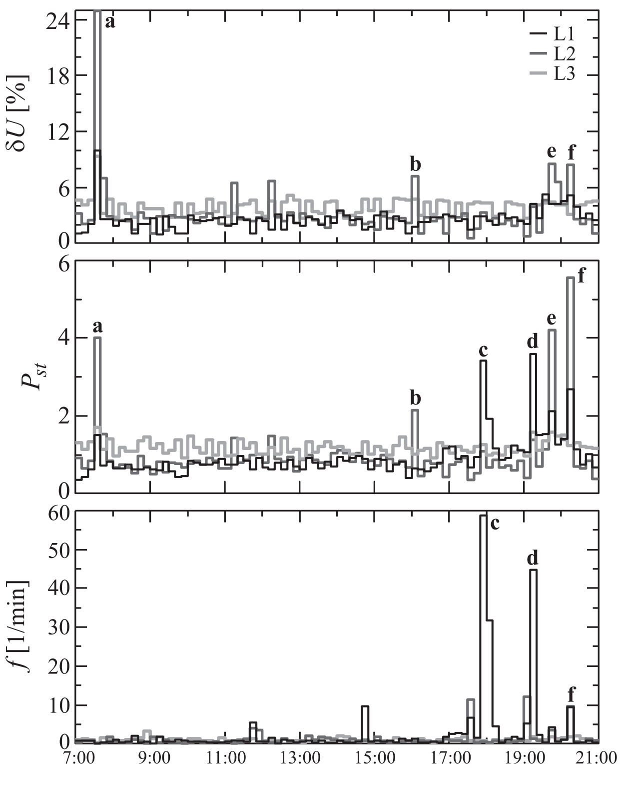


Fig. 19. $\delta U = \mathrm{f}(t)$, $P_{st} = \mathrm{f}(t)$ and $f = \mathrm{f}(t)$ time plots for phase voltages at point **R1**

There are six (marked from **a** to **f**) peculiar fragments on the $P_{st} = \mathrm{f}(t)$ time plot in Fig. 19. The comparison of the three time plots brings the conclusion that the P_{st} index increases marked **a** and **b** are caused by a significant increase of the δU amplitude. The increases marked **c** and **d** are caused by a significant increase of the f frequency. And the increases marked **e** and **f** are caused by a simultaneous increase of the δU amplitude and the f frequency of the voltage fluctuations. All the $U_{\max}$, $U_{\min}$, P_{st}, δU and f measurement results introduced up to this point have been recorded within a $10\,\mathrm{min}$ interval. In order to make a thorough study of the Fig. 19 time plots in ranges **a**, **c** and **e**–**f** the rest of the paper makes a use of the voltage fluctuations' measurement results recorded with a $1\,\mathrm{min}$ interval. Furthermore, in order to provide a detailed study of the voltage fluctuations, $U_{\max}$ and $U_{\min}$ values that have been recorded within a $1\,\mathrm{s}$ interval will be used.

Case *a*

According to Fig. 19, there have been fluctuations of a high amplitude between 7:30 and 7:40. Figure 20 shows the $\delta U = \mathrm{f}(t)$ time plot for phase voltages within 7:20 and 7:50 period.

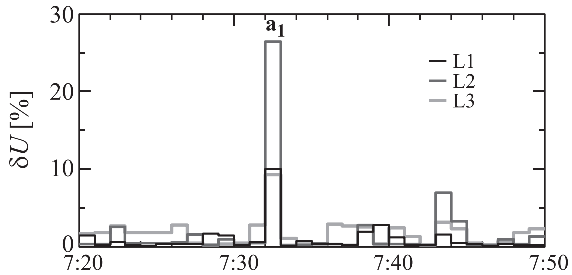


Fig. 20. $\delta U = \mathrm{f}(t)$ time plots for phase voltages at point **R1**

Figure 20 time plot allows to observe that the P_{st} index increase (Fig. 19) is caused by the presence of high amplitude fluctuations. $\delta U = 26.4\%$ (marked $\mathbf{a_1}$) has been detected in the L2 phase within a 7:32–7:33 period. The histogram of the $f_{a-b} = \mathrm{f}(\delta V)$ fluctuations amplitude presented in Fig. 21 provides more information about the fluctuations within this period.

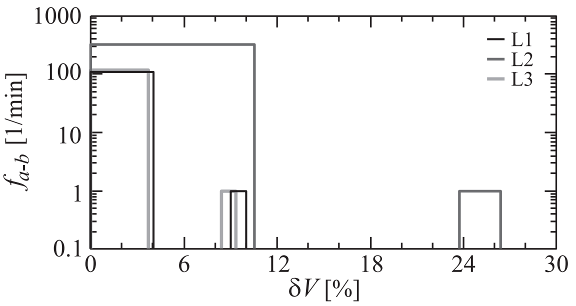


Fig. 21. Histogram of the $f_{a-b} = \mathrm{f}(\delta V)$ fluctuations amplitude in $\mathbf{a_1}$ period of time for phase voltages at point **R1**

The histogram allows to conclude that within the analyzed period of time there have been voltage fluctuations of the $f = 1\,\frac{1}{\mathrm{min}}$ frequency. Taking into account the specificity of the discrimination process an assumption can be made that there were two voltage changes of the δU amplitudes equaling 10%, 26.4% and 9.4% in the respective L1, L2 and L3 phases. Figure 22 shows the time plots of the $U_{\max}$ and $U_{\min}$ phase voltage values illustrating the decrease of the voltage responsible for the $\mathbf{a_1}$ marked fluctuations.

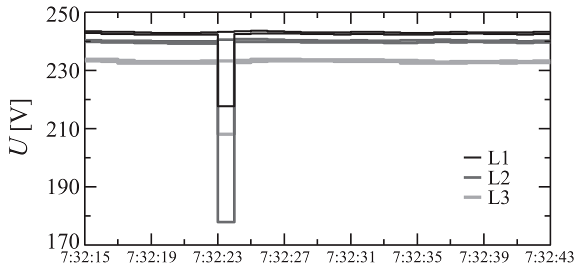


Fig. 22. Time plots of $U_{\max}$ and $U_{\min}$ voltage values in L2 phase at point **R1**, recorded from 7:32:15 until 7:32:43

Case *c*

There was a value increase in the L1 phase of the P_{st} indicator time plot between 17:50–18:10 (Fig. 19). It was not related with the δU amplitude increase. Instead, it has been related with the increase of f fluctuation frequency. Figure 23 shows the $f = \mathrm{f}(t)$ time plot for phase voltages within the time period between 17:45 and 18:15.

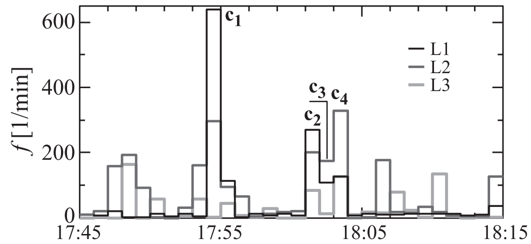


Fig. 23. $f = \mathrm{f}(t)$ time plots for phase voltages recorded from 17:45 to 18:15 at point **R1**

In the Fig. 23 time plot, there are periods of time with an increased frequency: $\mathbf{c_1}$ from 17:54 to 18:55, $\mathbf{c_2}$–$\mathbf{c_4}$ from 18:01 do 18:04. The increase marked $\mathbf{c_2}$–$\mathbf{c_4}$ is not as evident as on the Fig. 19 time plot from 18:00 to 18:10. There is a significant value difference between the f frequency values for **c** period in Fig. 19 and for the $\mathbf{c_1}$ and $\mathbf{c_2}$–$\mathbf{c_4}$ periods in Fig. 23. The frequencies marked $\mathbf{c_2}$–$\mathbf{c_4}$ are about 10 times bigger than the frequency marked **c**. It stems from the specificity of the voltage fluctuation indices discrimination process. If most of the fluctuations occurred during a single minute then the frequency describing these fluctuations during a period of 10 minutes will be around 10 times smaller than the frequency in the one minute period. It is easier to notice the frequency increase marked $\mathbf{c_1}$ at the $\mathrm{PWN} = \mathrm{f}(t)$ time plot given in Fig. 24. The PWN increases in L1 phase, much larger than in the other phases, are coherent with the P_{st} increases in Fig. 19.

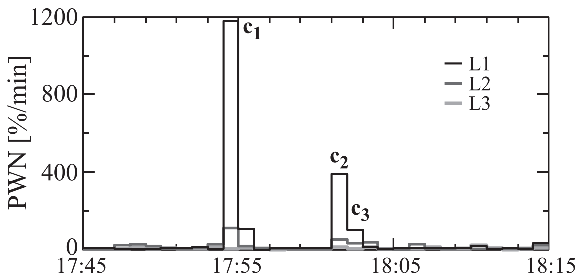


Fig. 24. $\mathrm{PWN} = \mathrm{f}(t)$ time plots for phase voltages recorded from 17:45 to 18:15 at point **R1**

The histograms of the $f_{a-b} = \mathrm{f}(\delta V)$ fluctuations' amplitude presented in Fig. 25 provide more detailed information about the source of the voltage fluctuation. They describe the changing of phase voltages in the $\mathbf{c_1}$ time period. The histograms have been plotted on the basis of δV fluctuations amplitude counting results in the following intervals: $\langle 1.0 - 0.9)\,\delta U$, $\langle 0.9 - 0.8)\,\delta U$, $\langle 0.8 - 0.7)\,\delta U$,

$\langle 0.7 - 0.6\rangle\,\delta U$, $\langle 0.6 - 0.5\rangle\,\delta U$, $\langle 0.5 - 0.4\rangle\,\delta U$ and $\langle 0.4 - 0.0\rangle\,\delta U$.

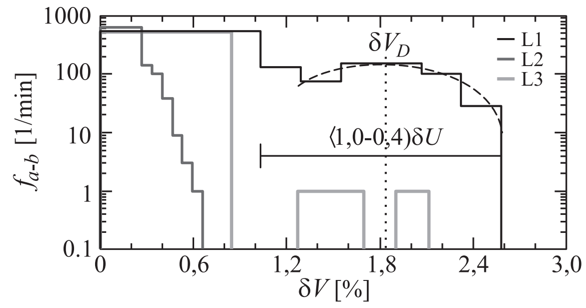


Fig. 25. $f_{a-b} = \mathrm{f}\,(\delta V)$ fluctuation amplitude histograms in the $\mathbf{c_1}$ time period for phase voltages at point **R1**

Figure 25 histogram informs that in the L1 phase the dominant amplitude equals $\delta V_D \cong 19\%$. With the circuit parameters known, it is possible to estimate the current variation of the fluctuation source on the basis of δV_D. For the $\langle 1.0 - 0.4\rangle\,\delta U$ counting interval the resultant frequency equals $f \cong 640\,\frac{1}{\min} \cong 5.3\,\mathrm{Hz}$. The fluctuation frequency acquired in this manner directly specifies the source of the fluctuations. Provided that the receiver works steadily during the period of fluctuations' discrimination, the estimated value of frequency correctly describes the voltage changing. If the receiver did not work throughout the whole discrimination period, the receiver's state changing frequency was respectively higher. In the $\langle 1.0 - 0.4\rangle\,\delta U$ interval, which has been omitted in Fig. 25 histogram the frequency equals $f \cong 440\,\frac{1}{\min}$.

Cases *e–f*

In Fig. 18, there have been two P_{st} indicator's increases marked: **e** from 19:40 to 19:50 and f from 20:10 to 20:20. They are the biggest in the L2 phase. The correlation of those surges with the changes of the $\delta U = \mathrm{f}\,(t)$ amplitude (Fig. 26) and $f = \mathrm{f}\,(t)$ frequency time plots can be noticed. But there is a more vivid correspondence of the P_{st} surges and the $\mathrm{PWN} = \mathrm{f}\,(t)$ time plots shown in Fig. 26.

In order to obtain more specific data about the voltage variation the histograms of the $f_{a-b} = \mathrm{f}\,(\delta V)$ fluctuation amplitude have been built, which are presented in Fig. 27. They describe the phase and line voltage variation in the $\mathbf{e_1}$ and $\mathbf{f_1}$–$\mathbf{f_4}$ time periods. The histograms have been built on the basis of δV fluctuation amplitude counting results in the intervals matching the Fig. 25 ones.

The analysis of the Fig. 27 histograms allows to draw the following conclusions:

- for phase voltages the obnoxious receiver's influence is present in the L1 and the L2 phases. However, the L2 phase is dominated by the fluctuations, and there is "background" influence in the L3 phase;
- for line voltages the influence of the obnoxious receiver is present in L12 (the strongest) and the L23 and L31 (the weakest);
- the most probable cause of the obnoxious voltage fluctuations is the influence of the receiver powered with the U_{L12} voltage;
- taking into account the shape of the histogram it has been assumed that the estimated f frequency is a sum of the f_{a-b} frequencies in the range limited by the ellipsis (which in this case approximately corresponds to the $\langle 1.0 - 0.7\rangle\,\delta U$ counting range), the voltage fluctuation frequency created by the obnoxious receiver's influence equals $f \cong 30\,\frac{1}{\min}$, which means that the change of the receiver's state occurred approximately every $2\,\mathrm{s}$;

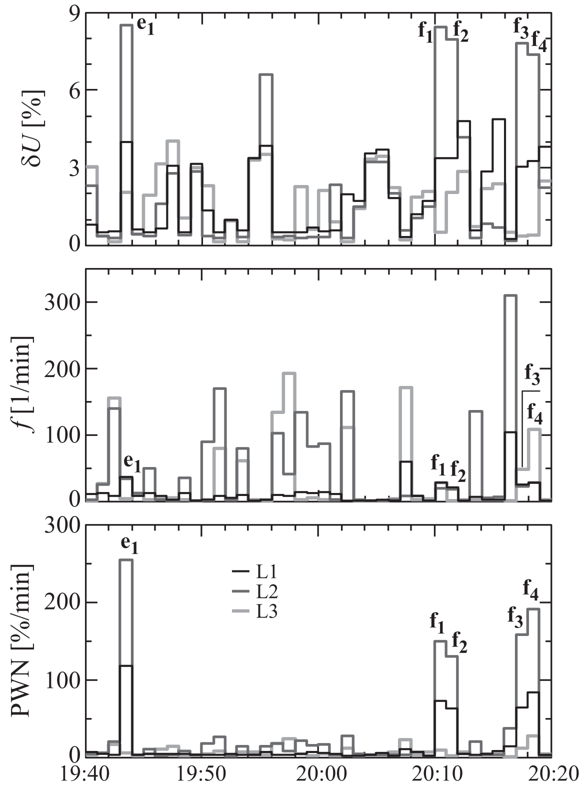
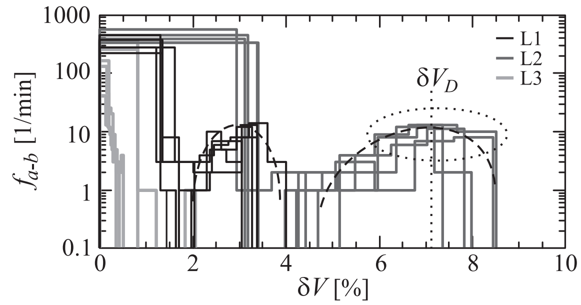
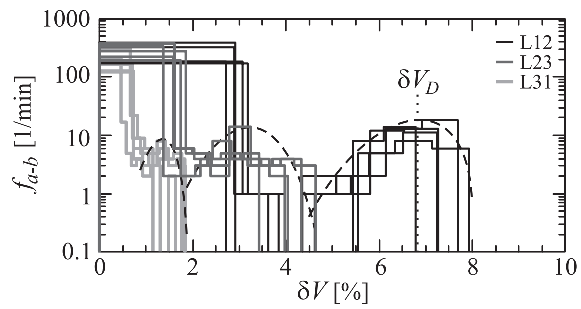


Fig. 26. $\delta U = \mathrm{f}\,(t)$, $f = \mathrm{f}\,(t)$ and $\mathrm{PWN} = \mathrm{f}\,(t)$ time plots for the phase voltages recorded from 19:40 to 20:20 at point **R1**



(a) $f_{a-b} = \mathrm{f}\,(\delta V)$ histograms for phase voltages



(b) $f_{a-b} = \mathrm{f}\,(\delta V)$ histograms for line voltages

Fig. 27. Histograms of the $f_{a-b} = \mathrm{f}\,(\delta V)$ fluctuation amplitude for phase and line voltages at point **R1** in the following time intervals 19:43–19:44, 20:10–20:11, 20:11–20:12, 20:17–20:18 and 20:18–20:19

- the dominating fluctuation amplitude values equal: $\delta V_D \cong 7.2\%$ for U_{L2} and $\delta V_D \cong 6.8\%$ for U_{L12}.

The suggestion that the receiver is powered with the U_{L12} voltage stems from the fact that a receiver connected this way does not influence the U_{L3} voltage. δV_D values depend on the power circuit parameters as well as the receiver current's rms value and phase. It is possible to obtain the voltage fluctuations shown in Fig. 27 in real-life conditions. The knowledge of fluctuations' amplitude for phase and line voltages makes the process of the receiver's current changes estimation much easier. The earlier analysis of the Figs. 12 and 15 characteristics allowed to conclude that the current variations recorded at point **R1** did not cause the examined obnoxious voltage fluctuations. Next it was pointed out that there was no relation between the current variations and the voltages recorded at points **R2** and **R3** observed. The lack of the correlation between the voltages and currents' variations made it impossible to directly indicate the circuit that powered the obnoxious receiver. However, it is possible to infer the location of the supply point for the receiver by analyzing the variation of the δV and δU fluctuations' amplitude values. For the sake of such analysis of the measurement results recorded between 7:00 and 21:00, the δU fluctuations' amplitude histogram has been used for phase voltages at points **R1**–**R3**, presented in Fig. 28.

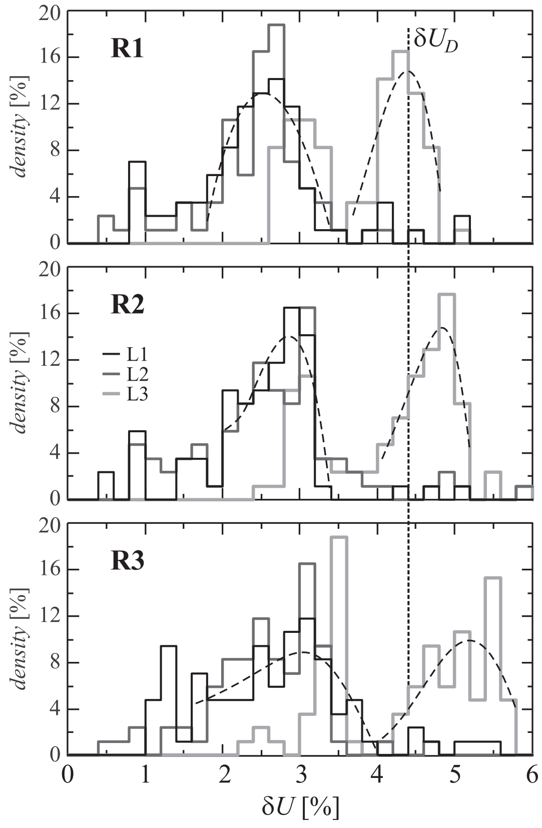
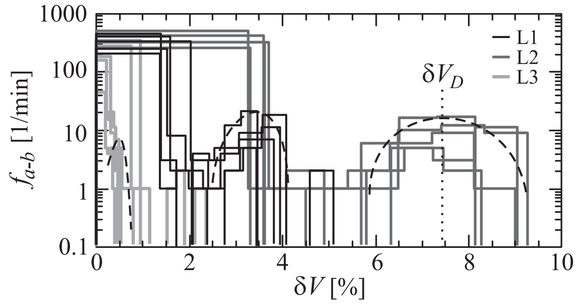
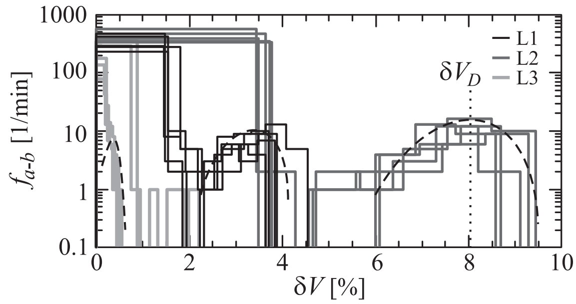


Fig. 28. Histograms of δU fluctuations' amplitude for phase voltages recorded between 7:00 and 21:00 at points **R1**–**R3**

The δU_D dominant value at point **R1** for the voltage in L3 phase has been marked in the Fig. 28 histograms. The dominant values at points **R2** and **R3** gradually increase. It is an indication that the obnoxious receiver is located behind the **R2** point and towards the **R4** point. The analysis with the use of the δU and the δU_D amplitudes comes as an effective tool in diagnosis of the voltage variation taking place in a long enough period of time. To describe the ones taking place relatively shortly (e.g. $1\,\mathrm{min}$) it is more effective to use the δV and the δV_D amplitudes. That is why in order to identify the location of the supply point for the receiver causing obnoxious fluctuations marked $\mathbf{e_1}$ and $\mathbf{f_1}$–$\mathbf{f_4}$ (Fig. 26), the $f_{a-b} = \mathrm{f}\,(\delta V)$ amplitude histograms has been used. The histograms for phase voltages at point **R1** have been shown in Fig. 27, and the ones at points **R2** and **R3** in Fig. 29.



(a) $f_{a-b} = \mathrm{f}\,(\delta V)$ histogram for phase voltages at point **R2**



(b) $f_{a-b} = \mathrm{f}\,(\delta V)$ histogram for phase voltages at point **R3**

Fig. 29. $f_{a-b} = \mathrm{f}\,(\delta V)$ fluctuation amplitude's histograms for phase voltages at points **R2** and **R3** within $\mathbf{e_1}$ and $\mathbf{f_1}$–$\mathbf{f_4}$ time periods

The comparison of the histograms from Figs. 27 and 29, the gradual increase of the dominant δU_D amplitude values is noticeable. It allows to draw a conclusion that the receiver responsible for the examined fluctuations is located behind the **R2** point, and towards the **R4** point. A more detailed location would be possible to obtain after taking into account parameters of the receiver's supply circuit. That stage of the analysis has been omitted in this paper.

Summary

Four measures of voltage variation have been presented in this paper: maximum and minimum voltage rms values, a short-term light flicker P_{st} indicator, voltage fluctuation indices, and a ΔV_{10} index. Main features of these measures have been listed. The charts (Figs. 2–8) have illustrated how these values depend on voltage variation. In the main section of this paper, an evaluation of electrical energy quality has been performed. The measurement results recorded every $10\,\mathrm{min}$, $1\,\mathrm{min}$ and $1\,\mathrm{s}$ in the LV circuit have been chosen for an exemplary evaluation. In the first stage, $U_{\max}$ and $U_{\min}$ as well as $I_{\max}$ and $I_{\min}$ values have been used. It has allowed to identify the presence of phase voltages of less than $90\% U_n$ values. Thus it has been proved that there is a possibility to interfere the work of receivers. What is more, the $(U_{\max} - U_{\min})$ differences, most of which have fallen between $8\,\mathrm{V}$ and $24\,\mathrm{V}$, have signaled that there have been a likelihood of obnoxious voltage fluctuations. In order to estimate the influence of the current variations recorded at a given measurement point on the voltage variation, a $(U_{\max} - U_{\min}) = \mathrm{f}\,(U_{\max} - U_{\min})$ characteristic has been introduced. Such an influence has not been confirmed by the locating the measurement points in this characteristic. On the basis of $U_{\max}$, U_{avg} and $U_{\min}$

time plots comparison (Fig.13) it has been assumed that the main feature of the analyzed voltage variation is a short-term voltage decrease tendency. The obnoxiousness of voltage variation has been estimated with the use of the P_{st} indicator (Fig. 14) and $\delta U = \mathrm{f}\,(f)$ characteristic (Fig. 17). It has been found that obnoxious fluctuations are occasionally present in all phases. However, the obnoxiousness in one phase is bigger than in the other. $P_{st} = \mathrm{f}\,(U_{\max} - U_{\min})$ characteristic has shown that an increase of the obnoxiousness is caused by the increase in voltage variation. $P_{st} = \mathrm{f}\,(I_{\max} - I_{\min})$ dependency confirmed that there was no influence of the recorded current variation on the voltage variation. In order to describe voltage variation to a more detailed extent, voltage fluctuation indices have been used. $P_{st} = \mathrm{f}\,(\delta U)$ and $P_{st} = \mathrm{f}\,(f)$ dependencies (Fig. 18) have proved that the increase of the fluctuations' obnoxiousness is caused by the increase of δU amplitude. A significant influence of the f fluctuations' frequency occurred only for the highest values of the P_{st} indicator. A comparison of δU, P_{st} and f indices' time plots has allowed to identify what actually influenced the particular high voltage obnoxiousness' increases. It has been proved that these increases were caused by either the δU amplitude increase or f frequency increase, or a simultaneous increase of both δU and f. Then, with the use of δU and δV amplitudes' time plots and histograms and the f_{a-b} frequency, a more detailed description of voltage fluctuations in particular periods of higher obnoxiousness level has been provided. With reference to the δU and δV amplitudes' histograms, an effort has been made to identify the location of the supply point for the obnoxious receiver.

The presented description of voltage variation shows that there is no single universal measure of voltage fluctuations. Thus it is justified to use different types of measures. In order to make an effective use of them, it is necessary to understand their specific features. This has been the sole goal of this paper – to provide a description of main characteristics of the measures and their exemplary use in the voltage fluctuations estimation process.

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