Review of voltage fluctuation measures in power quality analyzers

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Similarly to a number of other quantities, those describing voltage variation make it possible to provide a complete assessment of the quality of electrical energy. Voltage variation may be described by measures used to assess the obnoxiousness of voltage fluctuations or measures that help indicate the source of fluctuations. The paper provides a comparison of the three most popular measures: the $U_{\text{max}}$ maximum and $U_{\text{min}}$ minimum rms voltage values, the $P_{\text{st}}$ short-term flicker indicator, and voltage fluctuation indicators. The part that specifies the particular measures (including an additional description of the $\Delta V_{10}$ indicator) also contains their short descriptions. The main part of the dissertation describes the dependence of the voltage fluctuation measures on the frequency of the $f_a$ amplitude and frequency modulating signal. Observations drawn allow to specify the diagnostic capabilities of particular measures. Due to the complexity of voltage fluctuation measures' studies the paper deals with only a certain aspect of it and should be concerned as a step to understanding the idea of voltage fluctuation measures.

1. Introduction

The evaluation of power quality (PQ) is a procedure that compares measured and recorded values from a given set of values with reference values. The quality of power must adhere to legal or standard specifications. A certain level of power quality might also be necessary to meet the technical requirements of a particular measuring point. Inadequate power quality might cause disturbance in receivers or even shut them down. One of the most frequent disturbances is the discontinuity (instability) of the receivers’ operation. In the case of sources of light, the discontinuity may be observed as a flicker. Quantities that describe voltage fluctuation are some of the most fundamental components of power quality evaluation. The phenomenon of a rapid voltage change (i.e. voltage fluctuation) is especially important as it may disturb the operation of receivers. The issues concerning voltage fluctuations which result in a flicker have been present in literature since the beginning of the 20th century [6]. Their importance had grown along with the development and popularity of various electrical energy receivers which on one hand generated voltage fluctuations and on the other hand were easily susceptible to them. The way an obnoxious receiver influences the grid depends on the characteristics of the receiver and the parameters of the electrical
grid. A receiver’s susceptibility depends on its characteristics. Various light sources and measurement control systems are found among the most vulnerable.

Measuring and evaluating voltage fluctuation in a power grid has proved to be a complex measuring task. The measures used in the process must describe the voltage fluctuation as clearly as possible and at the same time take into account the fluctuations’ potential influence on receivers. The type and capabilities of a power quality analyzer used defines the available voltage fluctuations’ measures. Literature lists various measures of voltage fluctuations [3, 8]. According to the author, most important ones should include the following:

- $U_{\text{max}}$ maximum and $U_{\text{min}}$ minimum rms voltage values (phase and line-to-line),
- $P_\text{st}$ short-term and $P_\text{lt}$ long-term flicker indicators,
- $\Delta V_{10}$ indicator,
- voltage fluctuation indicators.

Aside from the ones listed above the literature mentions also the $Dv$ energetic fluctuation dose as well as the $E_{\text{In}}$ energy and the $P_{\text{In}}$ power of voltage fluctuations [3].

In order to take the above measures different methods must be used. Therefore, the measures represent voltage fluctuation in different ways. Their diagnostic capabilities are different as well. Neither provides a thorough diagnosis by clearly stating the extent of voltage fluctuation’s obnoxiousness and pointing the potential obnoxious electrical energy receivers. In order to make the measuring process effective it is necessary to understand the characteristics of particular measures. Therefore, a comparison of voltage fluctuation measures has been carried out. The comparison may be performed in a number of ways. The paper provides a comparison by listing the most important observations of the dependency of the particular measures on the frequency of the amplitude and frequency modulating signal.

2. Basic voltage fluctuation measures

2.1. $U_{\text{max}}$ maximum and $U_{\text{min}}$ minimum rms voltage values

The $U_{\text{max}}$ maximum and $U_{\text{min}}$ minimum rms voltage values describe the $U(t)$ voltage fluctuations with the use of a maximum and a minimum values within the period of discrimination. As a result, such features as transition values or frequency and rapidness of voltage fluctuations are omitted. The $U(t)$ rms value characterizes a periodic signal within a time interval which is a complete multiplication of the signal’s period. In theory, the $U(t)$ rms value may be calculated for any given short interval. However in practice, it is taken at every half-period and synchronized while crossing zero. The rms values used to describe the fluctuation of the $U(t)$ are usually obtained at every half-period within the interval which is equal to the period of the voltage. Fig. 1 shows a block diagram of the $U_{\text{max}}$ and $U_{\text{min}}$ measuring system.
The $U_{\text{max}}$ and $U_{\text{min}}$ values indicated the changes of the RMS value of the voltage. To be more precise – these values are not sheer voltage fluctuation measures. The author’s experience proves that in most cases the Umax and Umin values represent the changes in voltage fluctuation obnoxiousness. Hence, they are a useful diagnostic tool supporting voltage fluctuation analysis. One of the greatest advantages of the measures is that they are available in most power quality analyzers. One of the best methods to improve the diagnostic capabilities is taking the maximum and minimum measurements for both voltage and currents at the same time [5].

2.2. $P_{\text{st}}$ short-term and $P_{\text{lt}}$ long-term flicker indicators

The $P_{\text{st}}$ short-term and $P_{\text{lt}}$ long-term flicker indicators constitute a standard measure of voltage fluctuations [10, 8] listed in the set of basic quality parameters of electrical energy [11]. The PN-EN 61000-4-15 norm specifies the method of taking these measures [9]. In order to measure the $P_{\text{st}}$ indicator, a flicker measuring unit is used (usually referred to as a flickermeter). Fig. 2 shows a simplified block diagram of a flickermeter.

The value of $P_{\text{st}}$ indicator is obtained in consecutive 10-minute intervals. The $P_{\text{lt}}$ indicator is calculated on the basis of 12 consecutive $P_{\text{st}}$ indicator values:
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\[ P_h = \sqrt[3]{\frac{1}{12} \sum_{i=1}^{12} P_{st,i}^3} \]  

(1)

It represents an average 2-hour flicker obnoxiousness caused by voltage fluctuations. In proper measuring conditions (e.g. for a specific source of light), the values of the indicators describe the obnoxiousness of flicker. The evaluation of voltage fluctuation obnoxiousness in terms of a flicker it causes is calculated by comparing the values of the indicator with border values. For MV and LV circuits the border value is 1 and for HV circuits it is 0.8 [11, 8]. For voltage variation reproducible with the (AM) amplitude modulation, the \( P_{st} \) indicator value depends on the \( f \) frequency of the \( (U/U) \) amplitude and the shape of the voltage envelope [3]. With constant frequency and envelope shape, the \( P_{st} \) indicator value is nearly linearly dependent on the envelope’s amplitude [8]. On the other hand, with constant amplitude and envelope shape, the dependence of the \( P_{st} \) indicator on frequency is nonlinear.

### 2.3. \( \Delta V_{10} \) indicator

The \( \Delta V_{10} \) indicator is a fluctuation obnoxiousness measure widely used in the Far East countries. The value of this indicator is calculated from the following dependence [1]:

\[ \Delta V_{10} = \sqrt{\sum_f \left( a_f \cdot \Delta V_f \right)^2} \]  

(2)

where: \( \Delta V_f \) – amplitude of the component of \( f \) \( f \) frequency expressed in relative units, \( a_f \) – scaling coefficient for \( f \) frequency.

The value of the \( a_f \) coefficient is described in Fig. 3’s \( a_f = f(f) \) characteristic. For the purpose of comparison the figure shows also a frequency response of an in-built F2 bandpass filter of a standard flickermeter for \( f_c \) frequency 50 and 60 Hz.

![Fig. 3. \( a_f = f(f) \) vision curve of the \( \Delta V_{10} \) measure and a frequency response of the F2 flickermeter bandpass filter](image)

Fig. 3. \( a_f = f(f) \) vision curve of the \( \Delta V_{10} \) measure and a frequency response of the F2 flickermeter bandpass filter
The $f = 10$ Hz hosts the maximum of $a_f = f(f)$ characteristic. Therefore, there is a 1.2 Hz discrepancy in flicker sensation between this characteristic and the amplitude characteristic of the image band-pass filter in the standard signal chain of a flickermeter (with mid-range frequency of $f_p = 8.8$ Hz). Voltage fluctuations are not obnoxious if two conditions are met: the $\Delta V_{10}$ maximum value is lower than 0.45% and the average value is lower than 0.32% [1].

Fig. 4 shows an exemplary system for taking the $\Delta V_{10}$ measure.

![Exemplary Measuring System](image)

Fig. 4. $\Delta V_{10}$ measure exemplary measuring system; VD – voltage divider, ADC – analog to digital converter, AGC – auto gain amplifier, M1 – multiplier, F1A – low pass filter, F1B – high pass filter, F2 – band pass filter, RMS – one minute rms, statistics – data processing block

The $\Delta V_{10}$ index measuring system’s signal chain from the initial point to F1B filter is the same as the one of the flickermeter’s. However, discrepancies can be observed within the part from the F2 band pass filter to the statistics block.

### 2.4. Voltage fluctuation measures

Voltage fluctuation measures, the $\Delta U$ amplitude, and the $f$ frequency describe the variation of voltage rms value [4, 7, 8]. The values of $\Delta U$ and $f$ indicators are obtained on the basis of the $\Delta V$ fluctuation set. The $\Delta V$ value describes a single change in the rms value. The $f$ fluctuation frequencies are described in counting intervals related to the $\Delta U$ values. The voltage variation in an electro-energetic network usually corresponds to the effects of amplitude modulation. For this kind of variation the $\Delta U$ and $f$ indicators provide a proper reference of the network state up to a certain border value of the voltage variation frequency. Paper [8] presents the process of the discrimination of the voltage fluctuation indicators as well as their dependence on different forms of voltage variation.

Fig. 5 shows a block diagram of fluctuation indexes measuring process.

![Block Diagram](image)

Fig. 5. Block diagram of the $\Delta U(t)$ and $f(t)$ fluctuation indexes measuring process; VD – voltage divider, ADC – analog to digital converter
The $\Delta U$ amplitude and $f$ frequency of voltage fluctuations are statistical quantities that describe the set of $\Delta V$ and $\Delta U$ voltage changes. They are expressed in indirect units. The $f$ frequency is usually expressed with $1/\min$. It is important to notice that the $\Delta V$ describes a single change of the voltage rms value whereas the $\Delta U$ amplitude is a maximum value of the $\Delta V(t)$ voltage change set (and is derived accordingly to the assumed algorithm [8]).

The proper use of this voltage fluctuation measure in the diagnosis of electro-energetic networks requires a proper understanding of the measuring process itself. Practice and experience might be useful as well. The $\Delta U$, $\Delta V$ and $f$ indicators’ values provide direct information on the voltage variation and are very helpful while identifying the sources of voltage fluctuations. The $f$ voltage fluctuation frequency helps to estimate the frequency of state changes of the reason behind the voltage variation. For example, if the recorded value was $f = 120 \frac{1}{\min}$ then it can be assumed that the target receiver changes its state every 0.5 s (which may correspond to amplitude modulation with an $f_m=1$ Hz signal). The information derived from $\Delta U$ and $\Delta V$ indicators combined with the one on circuit impedance allow to determine the current variation. Thanks to this information the electrical features of the target receiver are obtained.

3. Comparison of voltage fluctuation measures

There are similarities and differences between the measures mentioned above. Comparisons can be made from different points of view. Below is a comparison made on the basis of the dependency of these three measures on the $f_m$ frequency of the amplitude (Fig. 6) and frequency (Fig. 7) modulating signal. The $\Delta V_{10}$ indicator has been omitted due to the unavailability of its clear and explicit definition. For the presentation particular measures’ values for the $(\Delta U/U) = 0.281\%$ have been used. For the chosen value of the modulation depth the $P_s$ indicator equals 1 for $f_m = 8.8$ Hz.

While analyzing the dependency of the voltage fluctuation measures on the $f_m$ frequency of the amplitude modulation signal with constant modulation depth $(\Delta U/U)=\text{const}$ depicted in Fig. 6 the following conclusions might be drawn:

- the $(U_{\text{max}} - U_{\text{min}})$ corresponds to the $(\Delta U/U)$ modulation depth for the $f_m$ frequencies less than 25 Hz,
- for the $f_m$ frequencies less than 22 Hz the $\Delta U$ amplitude corresponds to the $(\Delta U/U)$ modulation depth and the $f$ frequency corresponds to the $f_m$ frequency of the modulation,
- the $(U_{\text{max}} - U_{\text{min}})$ difference corresponds to the $\Delta U$ fluctuation amplitude,
- the flicker obnoxiousness described with the $P_s$ indicator changes within the $f_m$ frequency interval from 0.1 Hz to 150 Hz. Three local $P_s = \tilde{f}(f_m)$ dependency
extremes can be observed for $f_m = 8.8, 91.2$ and $108.8$ Hz. There is a very limited level of obnoxiousness for $f_m \approx 50$ Hz and $f_m > 150$ Hz,

- it is impossible to draw any conclusions as to the obnoxiousness of flicker caused by voltage fluctuations just on the basis of the $U_{\text{max}}$ and $U_{\text{min}}$ values or the $\Delta U$ indicator nor the $f$ (however, it needs to be noted that there is a possibility of using the voltage fluctuations’ amplitude-frequency characteristics in order to evaluate the obnoxiousness),

- the value of the $P_{st}$ indicator does not make it possible to define the amplitude or frequency of voltage fluctuations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{\emph{P}_{st}, $\Delta U$, $f$, $U_{\text{max}}$ and $U_{\text{min}}$ dependency on the $f_m$ frequency of the amplitude modulating signal for modulation depth $(\Delta U/U) = 0.281\%$}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{The $P_{st}$, $\Delta U$, $f$, $U_{\text{max}}$ and $U_{\text{min}}$ dependency on the $f_m$ frequency of frequency modulating signal for frequency deviation $\Delta f_{FM} = 0.2$ Hz}
\end{figure}
The comparison of Fig. 6 and Fig. 7 shows that the voltage variations related to amplitude and frequency modulation are much different. On the basis of the dependencies of the voltage fluctuation measures on the fm frequency of frequency modulating signal with constant frequency deviation $\Delta f_{FM} = \text{const}$ depicted in Fig. 7 the following conclusions can be drawn:

- for this kind of voltage variation obnoxiousness flicker is present for the fm frequencies close to 100 Hz. Two local extremes of the $P_{st} = f(f_m)$ dependency can be observed for $f_m = 91.2$ and 108.8 Hz. There is a very limited obnoxiousness for $f_m < 50$ Hz and $f_m > 150$ Hz. The lack of an extreme for the $f_m = 8.8$ Hz is also significant (as it is clearly different than with the variation related to amplitude modulation);
- the increase in the $P_{st}$ indicator corresponds to the increase of the $(U_{\text{max}} - U_{\text{min}})$ and the $\Delta U$ fluctuation amplitude,
- it is impossible to draw any conclusions regarding the obnoxiousness of flicker caused by voltage fluctuations on the basis of the $U_{\text{max}}$ and $U_{\text{min}}$ values, the $\Delta U$ fluctuation amplitude indicator or $f$;
- the values of $(U_{\text{max}} - U_{\text{min}})$, $\Delta U$ fluctuation amplitude, and $P_{st}$ indicator do not make it possible to determine the deviation of the frequency and the frequency of the modulating signal, which results in the fact that the analyzed voltage fluctuation measures can not stand as effective tools for determination of the parameters of the source of voltage fluctuations (for this kind of voltage variation).

4. Summary

The paper features a comparison of three most popular measures of voltage fluctuations: the $U_{\text{max}}$ maximum and $U_{\text{min}}$ minimum voltage rms values, the $P_{st}$ short-term flicker indicator, as well as the indicators of voltage fluctuation, $\Delta U$ amplitude and $f$ frequency.

The part which specifies the particular measures (as well as an additional $\Delta V_{10}$ indicator) features their short descriptions. The main part of the paper hosts Fig. 6 and Fig. 7 showing charts of the dependencies of the compared measures on the fm frequency of the amplitude and frequency modulating signal. These dependencies made it possible to draw observations and define the diagnostic capabilities of the particular measures. It has been observed that it is only the $P_{st}$ indicator that properly (i.e. normatively) describes the obnoxiousness of the voltage (in the work only the $P_{st} = f(f_m)$ dependency was analyzed and the voltage fluctuations’ amplitude-frequency characteristics was not considered). In the case of voltage variation related to amplitude modulation voltage fluctuation measures, the $\Delta U$ amplitude and $f$ frequency stand as a useful tool for the identification of obnoxious
receivers. They are effective for the $f_m$ frequencies of amplitude modulating signal lower than 25 Hz. At the same time it has been observed that there are no such tools for the voltage related to the frequency modulation.

The comparison presented in the paper shows that there is no one universal measure of voltage fluctuations. Hence, it is reasonable to use a variety of measures. Their use, however, requires a good understanding of their nature. The complexity of the subject makes it impossible to present it thoroughly. Therefore this paper should be concerned as a stage on the way to understanding the measures of voltage fluctuations.

References

[12] Rozporządzenie Ministra Gospodarki z 4 maja 2007 r. w sprawie szczegółowych warunków funkcjonowania systemu elektroenergetycznego. (Dz.U. Nr 93, poz. 623, z dnia 29 maja 2007 r.).