BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 63 (67), Numărul 1, 2017
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

# PROGRESS IN THE POWER QUALITY INDICATORS SYSTEM

BY

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Received: February 15, 2017
Accepted for publication: March 22, 2017

**Abstract.** The Power Quality is appreciated by an indicator system, made up of a set of characteristic parameters, some of which can be normalized. One of the recognized properties of the indicator system is the perfectibility, which is supported by a series of recently published articles by the paper authors.

Regarding the variations of the voltage r.m.s. value, it is proposed to highlight and separate the voltage variations due to intervention actions performed or recorded at the level of the dispatchers. In this way, fewer harmonics of voltage slow variations remain to be interpreted.

Reconsidering the calculation relationship of voltage fluctuations better reflects the visual perception phenomenon. Differences obtained by using the proposed formula will significantly affect the values of the flicker indicators.

The proposed characteristic parameters for voltage sags and overvoltages complete the indicators family of the voltage r.m.s. value, some of which will be normalized in the future.

**Key words:** power quality; voltage slow variations; voltage fluctuations; voltage dips; overvoltages.

## 1. Introduction

Among aspects related to power quality (PQ), the voltage variations and shape are priorities in the relationship between supplier and end-user (Maier,

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2003). Although the characteristic variables are defined for different types of voltage variations, with relationships proposed for their calculation, there is no systematic way to analyze voltage variations by now, leading to interpretable conclusions and appropriate compensatory measures (Arrilaga, 2000; Dugan, 2003). Also some computational relationships are questionable (*IEC 61000-4-15,* 1997), when real phenomena modelling is desired through more accuracy.

Although literature recognizes that for some Power Quality (PQ) disturbances insufficient indicators are defined (Golovanov, 2001), no proposals have been made for these, only in authors' works.

The network voltage variations, under or over the voltage rated value are monitored both as r.m.s. and instantaneous values. As r.m.s. value, the working voltage $U_s$ can be either periodically higher than the rated one, in the frame of voltage slow variations (VSV) or the rapid ones, also called voltage fluctuations (VFL), or non-periodically, but with significant decreasings or increasings related to the rated voltage, aspects designated by the terms of voltage sags (VSG or dips) and of short time overvoltages (STOV), respectively (Arrilaga, 2000; Hasse, 2000).

The necessity of an expressive analysis of voltage variations led to idea of the voltage wave decomposition in actions and harmonics that represents a new concept of voltage variations analysis. The unitary step actions are equivalent to an infinite harmonics numbers. In terms of electric power systems these actions are found in the interventions of the dispatcher, supplier or end-user for maintaining the r.m.s. voltage within limits. The highlighting of voltage wave levels and then the modulation harmonics analysis of the voltage variations is proved to be the most accurate method of VSV analysis (Leşe, 2012).

Some of voltage r.m.s. disturbances are non-periodic and unilateral, like VSG and STOV, only that they are in the opposite sense: while the VSG represent a significant decreasing of the working voltage under the rated value, STOV represent a significant overcoming of the rated value by the working voltage, one. The overvoltages main consequence is the insulation stress which, from some voltage values and in some conditions, can be pierced; in addition, some receivers can step in overload regime (Maier, 2016b).

## 2. Voltage r.m.s. Value Variations

### 2.1. Basic Indicators of VSV

The periodic r.m.s. voltage variations can be slow variations, consisting in deviations up to ±20% of its rated value and with the periodicity in the interval of (5 min÷24 h) and fast variations, called fluctuations, with deviations up to ±10% and periodicity in the range of (40 ms÷5 min) (Maier, 2012).

To appreciate the VSV, also called voltage irregularity, indicators are used to express the voltage deviation from its nominal value, $U_n$, specific to each power system segment (Beleiu, 2010). The real voltage, in considered point of the network and in the specified moment is called working voltage, $U_s$, and since the use of relative quantities is expressive and convenient, the parameter named relative working voltage $u_s$ or voltage level is introduced by the relation:

$$u_s = \frac{U_s}{U_n}, \tag{1}$$

which can be used as above or in percentage expression.

The PQ indicators for VSV are concentrated in Table 1, versus the r.m.s. voltage, as absolute parameter and versus its relative values, the percentage working voltage

$$u_{s\%} = \frac{U_s}{U_n} \cdot 100, [\%] \tag{2}$$

and the voltage level $u_s$ (relation 1).

**Table 1**
*Calculus Relations of VSV Specific Indicators, in Relation to the Absolute and Relative Voltage*

| Parameter | Working voltage $U_s$, [V] | Working voltage percentage, $u_{\%} = 100 \cdot U_s / U_n$, [%] | Voltage level $u_s = U_s / U_n$ |
|---|---|---|---|
| Voltage mean | $\overline{U_s} = \sqrt{\frac{1}{N_T}\sum_{k=1}^{N_T} U_{sk}^2}$ | $\overline{u_{\%}} = \sqrt{\frac{1}{N_T}\sum_{k=1}^{N_T} u_{\%k}^2}$ | $\overline{u_s} = \sqrt{\frac{1}{N_T}\sum_{k=1}^{N_T} u_{sk}^2}$ |
| Voltage deviation | $\Delta U = U_s - U_n, [\text{V}]$ | $\Delta u_{\%} = u_{\%} - 100, [\%]$ | $\Delta u_s = u_s - 1$ |
| Voltage mean deviation | $\overline{\Delta U} = \frac{1}{T_0}\sum_{k=1}^{N_T} \Delta U_k T_k, [\text{V}]$ | $\overline{\Delta u_{\%}} = \frac{1}{T_0}\sum_{k=1}^{N_T} \Delta u_{\%k} T_k, [\%]$ | $\overline{\Delta u_s} = \frac{1}{T_0}\sum_{k=1}^{N_T} \Delta u_{sk} T_k$ |
| Square mean deviation | $\sigma_U = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_T} (U_{sk} - \overline{U_s})^2 T_k}$ | $\sigma_U = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_T} (u_{\%k} - \overline{u_{\%}})^2 T_k}$ | $\sigma_U = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_T} (u_{sk} - \overline{u_s})^2 T_k}$ |
| Voltage variation coefficient | $C_U = \frac{\sigma_U}{\overline{U_s}}$ | $C_{u\%} = \frac{\sigma_{u\%}}{\overline{u_{\%}}}$ | $C_{us} = \frac{\sigma_{us}}{\overline{u_s}}$ |

### 2.2. Method of VSV Analysis

Recent studies performed by the authors (Leşe & Maier, 2012) led to the idea of the voltage wave decomposition first in actions and then in harmonics. As actions, are considered all technical interventions of the dispatcher, the supplier or the end-user in the power system to maintain the r.m.s. working voltage in the prescribed standards. The actions are “nothing-all” or “0-1” type in binary, which may be characterized as durations and action mode through unitary step functions. The appreciation of the gap produced by actions requires previous quantitative assessments of the voltage variations monitoring and analyzing process to allow cause-effect type identifications.

Graphically, the action functions are represented as unitary step signal, for which a general form has been considered and the corresponding Fourier development, consisting of an infinite amount of harmonics has been also determined. The harmonic decomposition of the of unitary step function argue, as a first step in the VSV analysis, the emphasizing of the "nothing-all" or "0-1" actions, these ones corresponding to the continuous components. It is known that the dc component in the Fourier analysis is determined by the relationship (Maier, 2012):

$$U_0 = \frac{1}{2p} \cdot \sum_{k=0}^{2p-1} U_k \text{ , [V],} \tag{3}$$

where: (2$p$) is the total number of samples (values) for the considered period equal to the observation time; $U_k$ – a sample parameter, equal in this case with the voltage r.m.s. value or with one of the medium voltage values, on very short (3s) or short time (10 min) interval.

Fig. 1 shows the set of four fictive levels pointed out on a variation of the working voltage wave. Each level $i$ is characterized by the mean square $\overline{U_{pi}}$, $i \in \{1, 2, 3, 4\}$, which may be situated above or below the rated value $U_n$ as well as the corresponding beginning moments $t_{i0}$.

Further on, the Fourier analysis of the considered voltage variations is highlighting the main modulation harmonics of the VSV with a periodicity greater than 5 min, as an expression of some periodical actions within the power consumption.

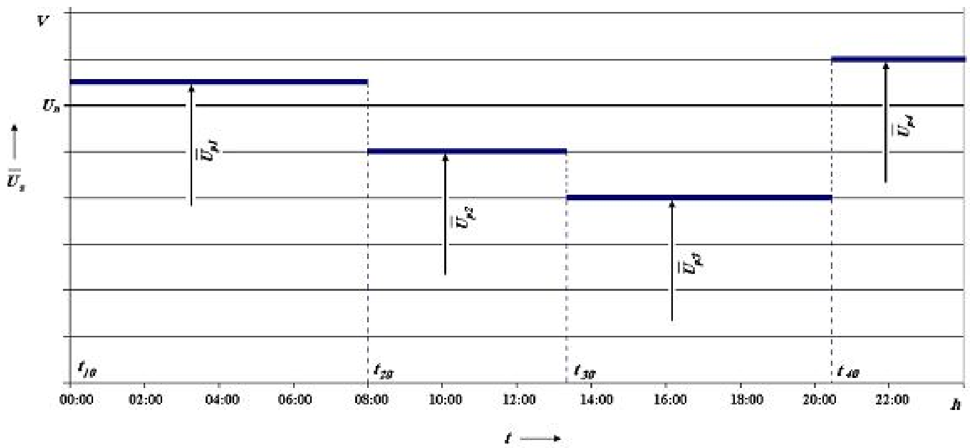


Fig. 1 – The highlighted levels in the voltage variations graph, on the observation period, for a day and their time intervals.

Finally, the voltage variations that are not justified either by actions or by load variations can be attributed to voltage variations in the network supplying point, downstream the one where the voltage losses were considered by calculation. The analysis of processes which take place at the end-users supplied from the distribution point represented by the measurement point would be revealing the existence in technological processes of those periodicities, which have manifested with striking in the slow voltage variations.

The interpretation of differences between levels or steps might be done in better conditions, if an interventions list would exist at the territorial dispatcher level, under which the monitored point of consumption is also located (*673*-27.07.04, 2004). As some actions, such adjusting switches plots, take place without the intervention of the human operator, identifying them is relatively difficult and requires complex monitoring of the power system.

### 2.3. Voltage Fluctuations and the Flicker Phenomenon

Fluctuations or voltage fast variations represent the r.m.s. or peak values (amplitudes) variations of the voltage wave, in the limits of ±10%, produced in the frequency range of (0.003…25) Hz, which corresponds to periodicities in the range (40 ms ...5 min).

The voltage fluctuation amplitude is defined by the relationship (Maier, 2012):

$$\delta U_j = \frac{|U_j - U_{j+1}|}{\sqrt{2}U_n} \cdot 100\,,\ [\%], \tag{4}$$

where: $U_j$ and $U_{j+1}$ are two consecutives and different values of the voltage amplitude and $U_n$ represents the r.m.s. of the corresponding rated voltage; reporting to amplitude was preferred because this one is easier to be identified analytically or graphically. To note that the voltage fluctuation amplitude is a positive quantity and two or more voltage fast variations, which occur in less than 30 ms, may be considered as one variation. The amplitudes of the maximum allowable voltage fluctuations are normalized according to their shape and frequency. These amplitudes fall between 0.3% at the 8 Hz frequency and 3% at the 0.013 Hz frequency in the case of sinusoidal variations.

Flicker term, as is adopted even in Romanian Standards, defines the impression of visual sensation instability produced by a light stimulus whose luminance or spectral distribution fluctuates with time. Considering voltage as the cause of visual perception variations, flicker indicators, such as flicker dose and flicker severity (Golovanov, 2001), are based on the definition (4) of the voltage fluctuations amplitude.

It should be noted that the relationship (4) does not correctly model the flicker phenomenon, in accordance to the standard definition. This is because it has no sense to report the voltage variation to the rated voltage, taking into account that the human eye and brain don't have set the perception at such a reference parameter. A more correct modeling of the visual perception imposes to use the visual sensation from the moment $t_j$ (when the voltage amplitude is $U_j$) as reference parameter. So, the following relationship is proposed (Maier, 2012),

$$\delta U_j = \frac{|U_j - U_{j+1}|}{U_j} \cdot 100 \text{ , [\%],} \tag{5}$$

which leads, obviously, to different results from those obtained by the relation (4), especially when $U_j < U_{j+1}$.

The comparison of results obtained with relationships (4) and (5) is made for the concrete case of the following voltage wave (Maier, 2015):

$$u(t) = 230\sqrt{2}\begin{bmatrix} 1 + 0.02\sin(50\pi t - 2\pi/3) + \\ +0.05\sin(100\pi t/3) \end{bmatrix}\sin(100\pi t) \text{, [V],} \tag{6}$$

which simulates an industrial frequency voltage, modulated by amplitude with 25 Hz and 16.7 Hz.

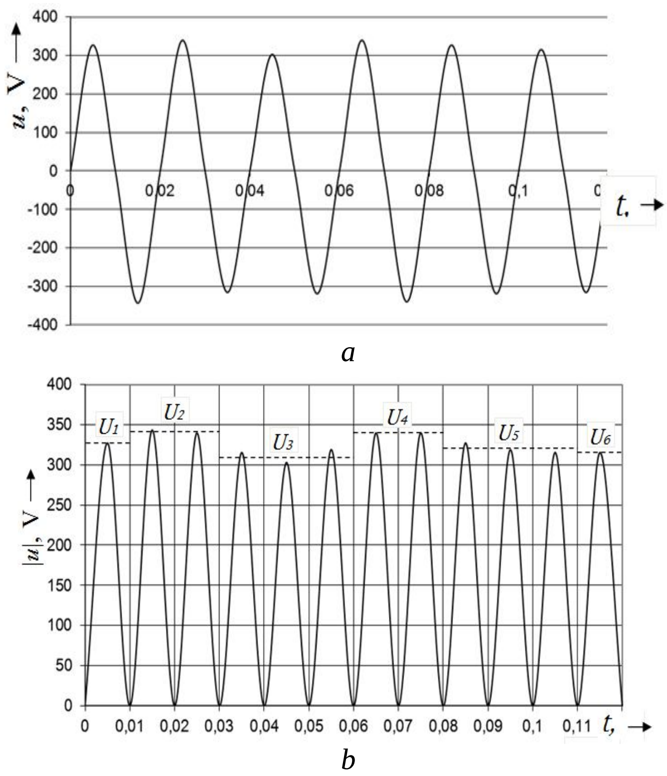


Fig. 2 – Analyzed voltage waveform; *a* – instantaneous values on first 0.12 s; *b* – voltage amplitudes highlighting.

The oscillogram from Fig. 2*a* presents the voltage wave aspect during the first 0.12 s, meanwhile the voltage absolute value $|u|$ is emphasized in Fig. 2*b* in order to highlight the voltage consecutive amplitudes $U_j$. The two modulation voltages, simulated in the bracket from relationship (6), have the amplitudes of 2% respectively 5% of the rated voltage amplitude, at the industrial frequency.

The voltage amplitudes values, calculated with (6) for the first 0.115 s as well as the voltage fluctuations amplitudes, for three different situations, are presented in Table 2. The time values from the first table line indicate the moments where the voltage wave amplitudes are registered. On the second line the voltage amplitudes $U_i$ are specified, in absolute values, considered for the situation when the r.m.s. value is quite the rated value, $U_n$=230 V.

**Table 2**
*Voltage Fluctuation Amplitudes*

| No. | Parameter | Time-voltage coordinates of the amplitudes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $t$, [ms] | 5 | 15 | 25 | 35 | 45 | 55 | 65 | 75 | 85 | 95 | 105 | 115 |
| 2 | $\lvert U_i \rvert$, [V] | 327.1 | 343.2 | 339.7 | 315.5 | 302.7 | 318.8 | 338.7 | 339.9 | 327.1 | 318.8 | 315.3 | 315.5 |
| 3 | $\lvert U_j \rvert$, [V] | 327.1 | 341.45 | | 312.4 | | | 339.3 | | 323.0 | | 315.4 | |
| 4 | $\delta U_{nj}$, [%] | 3.566 | 4.412 | | 8.931 | | | 8.270 | | 5.011 | | 2.337 | |
| 5 | $\delta U_j$, [%] | 3.710 | 4.387 | | 8.508 | | | 8.611 | | 4.804 | | 2.353 | |
| 6 | $\delta U_{n+j}$, [%] | 3.744 | 4.633 | | 9.378 | | | 8.684 | | 5.262 | | 2.454 | |

Analyzing the rectified oscillogram of the voltage wave (Fig. 2, *b*), the $U_i$ voltage amplitudes values as well as the standard recommendation of merging the small variations that occur within a range less than 30 ms, leaded to highlighting the $U_j$ different voltage amplitudes in the 3$^{rd}$ line of Table 2.

Further on, the voltage fluctuations amplitudes $\delta U_{nj}$ were determined in % using relationship (4), through reporting the differences between voltage consecutives amplitudes to the rated voltage amplitude $U_{nM} = 230\sqrt{2} = 325.27$ V. The square mean of these fluctuations amplitudes on the considered range is:

$$(\delta U_n)_{med\,2} = \sqrt{\frac{1}{6}\sum_{j=1}^{6}(\delta U_{nj})^2} = 5{,}929\% . \tag{7}$$

The voltage fluctuations amplitudes, calculated with the proposed relationship (5), as an adaptation to the flicker phenomenon definition, are included on the 5th line of the Table 2. The relative differences, in percentage, between $\delta U_{nj}$ (calculated with rel. 4) and $\delta U_j$ (calculated with rel. 5) are framed in the range $\varepsilon_{\delta U} \in (-4, +5)\%$. The square mean of the fluctuations amplitude, with reporting to the previous value, on the same interval, is:

$$(\delta U)_{med\,2} = \sqrt{\frac{1}{6}\sum_{j=1}^{6}(\delta U_j)^2} = 5.89\% , \tag{8}$$

which differs by less than one percent (0.66%) versus the value given by relationship (7).

Another important observation, regarding the use of relationship (4) for the fluctuations amplitudes, is that while its numerator can vary proportionally with the working voltage, as a result of the voltage adjusting actions, the denominator remains constant. This situation is reflected in the 6th line of Table 2, when the working voltage was considered 5% higher than the rated voltage. Therefore, for the voltage fluctuations amplitudes the following relationship is considered:

$$\delta U_{n+j} = \frac{|U_j - U_{j+1}|}{\sqrt{2}U_n} \cdot 105\,,\ [\%], \qquad (9)$$

which leads to values of the corresponding fluctuations amplitudes higher than $\delta U_{nj}$ values (the 4th line, Table 2); it does not happen when using the proposed relationship (5). The square mean of these fluctuations amplitudes, on the same interval, is $(\delta U_{n+j})_{\text{med2}}$ = 6.075%, which is 3.14% higher than the mean $(\delta U)_{\text{med2}}$, calculated according to the relationship (8).

The relationship (4) sensitivity at working voltage variations, as shown above, is another argument of using the proposed relationship (5), based on reporting the voltage or luminance variations to the corresponding previous values.

#### 2.4. The flicker dose

The effect in time of the luminance fluctuations over a human subject is more accurately estimated by the flicker dose than through the fluctuation amplitudes. The estimation of the voltage fluctuations influence is normalized to be made in accordance with the cumulative principle, based on recording the eyes accumulated fatigue up to the dose when work becomes impossible (Maier, 2012). The reasoning is based on the equivalence of fluctuations having the frequency $f_i$ and the amplitude $\delta U_{fi}$ with a fluctuation having the 10 Hz reference frequency and the equivalent percentage amplitude

$$(\delta U_{10})_i = g_{fi}\, \delta U_{fi}\,,\ [\%], \qquad (10)$$

in order to determine an identical discomfort; the fluctuations equivalence coefficients $g_{fi}$ are experimentally determined in report with the source type and the fluctuation frequency.

Overlapping the effects of different frequency fluctuations is realized with the relationship:

$$\delta U_{10} = \sqrt{\sum_i \left(g_{fi}\, \delta U_{fi}\right)^2}\,,\ [\%], \qquad (11)$$

and the flicker dose is defined through the relationship:

$$\varepsilon_F = \int_0^{T_0} \left(\delta U_{10}\right)^2 \mathrm{d}t, \quad (\%)^2\cdot\text{min}, \tag{12}$$

where: $T_0$ represents the disturbance estimating duration. The flicker dose expresses the total discomfort, which is felt by the human "eye" on the $T_0$ duration, being normalized in the value-duration coordinates.

Relating to the integral relationship (12), the following observations can be formulated:

a) knowing the modulation voltages $\delta U_{fi}$ requires a Fourier analysis for the corresponding wave of the r.m.s. voltage values, on a minimum 5 min. interval, which corresponds to the maximum periodicity of the standardized voltage fluctuations;

b) an instantaneous value of the equivalent percentage amplitude $(\delta U_{10})$ does not exist; but we can speak only about a valid value on the properly Fourier analysis range;

c) the integral relationship of the flicker dose definition cannot be accepted even at limit. Consequently, this integral form has to be replaced by the relation (Maier, 2015):

$$\varepsilon_F = \sum_{k=1}^{N_k} \left(\delta U_{10}\right)_k^2 T_{0k}, \quad (\%)^2\cdot\text{min}, \tag{13}$$

where: $(\delta U_{10})_k$ represents the equivalent percentage amplitude on the voltage wave analysis interval "$k$", having $T_{0k}$ duration of minimum 5 min; $N_k$ – number of the Fourier analysis intervals, on the entire observation time $T_0$:

$$T_0 = \sum_{k=1}^{N_k} T_{0k}, \quad [\text{min}]. \tag{14}$$

As in the case of the voltage fluctuation amplitudes, the flicker dose exemplifying in terms of values is considered edifying. For this, the resulting modulation voltage is considered having the form as the one contained in brackets in relationship (6), including the modulation harmonics as follows:

i) a modulation harmonic with $f_1$ = 25 Hz frequency, having $\delta U_{f1}$ = = 0.2% amplitude, for which the equivalence coefficient has the value $g_{f2}$=0.836;

ii) for the $f_2$ = 16.7 Hz frequency, the modulation harmonic has the amplitude $\delta U_{f2}$ = 0.5% and the equivalence coefficient $g_{f2}$ = 0.836.

It comes out that modulation harmonics were adopted with amplitudes ten times smaller than in the case of determining fluctuations amplitudes, where the graphical highlighting of the voltage wave amplitudes represented a methodological necessity. Further on, the percentage equivalent amplitude $\delta U_{10}$ is determined (relationship 11):

$$\delta U_{10} = \sqrt{(0.827\times 0.2)^2 + (0.836\times 0.5)^2} = 0.4495\%. \qquad (15)$$

Calculating the flicker dose with relationship (13), for an observation range $T_{01}$=15 min, it will be obtained:

$$\varepsilon_F = (\delta U)_1^2 T_{01} = 0.4495^2 \times 15 = 3.03\ (\%)^2 \cdot \mathrm{min}, \qquad (16)$$

that exceeds more than 2.3 times the corresponding admissible value $\varepsilon_{F\mathrm{adm}}$ = 1.3 $(\%)^2$·min (Maier, 2012).

### 2.5. Voltage Sags

VSG represent significant decreases of (10÷90)% of voltage r.m.s. value, on short time periods between (10 ms ÷ 3 s) (Dugan, 2003). In other words, during VSG the relative working voltage is situated in the interval $u_s \in$ $\in$ [0.1 ÷ 0.9]. There are opinions and even stipulations which lowers the VSG inferior limit till zero, but this means already the voltage absence and so of the electrical power (Maier, 2012). Practically, one cannot speak about a poor quality of a product (here, electrical power), found in unavailability (absent). For the same reason, neither the interruptions, being even short term, cannot be included in PQ issues, these ones being under the quality of the electrical power supply service. VSG during more than 3 s are also included in interruptions category (Arrillaga, 2000).

VSG analytical indicators, known from the literature, are their amplitude, duration and frequency (Golovanov, 2001). Further on, for defining some additional indicators for the VSG, is adopted the simpler shape, close to the quadrilateral one, namely the triangular shape VSG, according to the representation from Fig. 3.

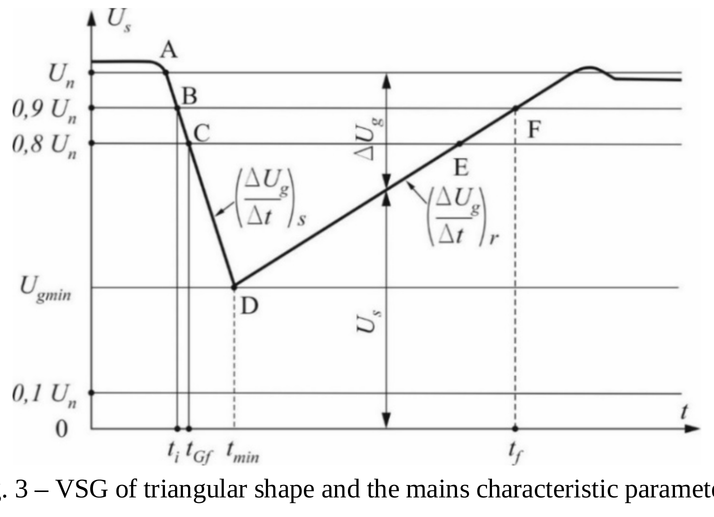


Fig. 3 – VSG of triangular shape and the mains characteristic parameters.

The VSG recording algorithm starts when the working voltage value drops below $U_s$ = 0.8$U_n$, corresponding to the point C from the voltage r.m.s. graphic, so the time variable parameter, from this moment, can be retained as being important and proposes for this the term "VSG confirmation time" and the notation $t_{cf}$ (Fig. 3). Going back in the data file, the moment when the voltage passed through the value $U_s$ = 0.9$U_n$ is searching, this becoming the initial moment $t_i$ of the VSG (point B, Fig. 3). After reaching in point D the minimum value $U_{g\min}$, the working voltage is starting to increase for reaching the value $U_s$ = 0.9$U_n$ in point F, of which abscissa will represent the VSG final moment $t_f$.

Based on this representation, the completion of the VSG characteristic indicators is proposed with the following parameters (Maier, 2016 a):

**-relative voltage sag maximum amplitude** $\Delta u_{gM}$, corresponding to the time moment $t_{\min}$, when the working voltage reaches the minimum value $U_{g\min}$, calculated with the relationship

$$\Delta u_{gM} = \frac{\left|U_{g\min} - U_n\right|}{U_n} \times 100\text{, [\%]}, \tag{17}$$

but where the difference of the numerator was taken in absolute value, considering that the respective parameter presents more expressivity, in rendering the voltage decreasing depth, in ration with the rated value;

**– voltage sag decreasing slope**, during the VSG, given by the relationship:

$$\left(\frac{\Delta U_g}{\Delta t}\right) = \frac{U_{g\min} - 0.9U_n}{t_{\min} - t_i}\text{, [V/s]}; \tag{18}$$

**– voltage sag recovering slope**, from the minimum value $U_{g\min}$, to the rated voltage value,

$$\left(\frac{\Delta U_g}{\Delta t}\right)_R = \frac{0.9U_n - U_{g\min}}{t_f - t_{\min}}\text{, V/s}, \tag{19}$$

**– the undelivered degree**, for which is proposed the following relationship:

$$\varepsilon_G = \sum_{k=1}^{N_T}\left(\frac{U_s - U_n}{0.01U_n}\right)_k^2 T_k\text{, }(\%)^2\cdot\text{s}, \tag{20}$$

expressing, to a certain degree, the undelivered electrical power during the VSG, relative to which can be appreciated the VSG consequences. In the relationship (20), $N_T$ represent the fundamental periods number, highlighted on the VSG duration $t_g$, the current period having the duration $T_k$;

**– voltage irregularity degree** during the VSG, for which is proposed the relationship:

$$\varepsilon_{UG}^{2}=\frac{1}{t_g}\sum_{k=1}^{N_T}\left(\frac{U_{sk}-U_n}{0.01U_n}\right)^2 T_k\text{ , }(\%)^2; \tag{21}$$

**– dangerousness function of the voltage sag**, showing the dependence between the working voltage value during the sag, with values in the range $U_s \in$ $\in [U_{g\min} \div (0.9U_n)]$ and the absence of that voltage value, in the function form of $t_{Ug}(U_s)$. For exemplification, two representative points, from the proposed graphic, can be highlighted in the sense of indicating the coordinates pair abscissa (working voltage) – ordinate (duration, Fig. 3): $((0.9U_n), t_g)$ and $(U_{g\min}, 0)$;

**– mean relative voltage, during the sag**, given by the relationship:

$$\overline{u_{sg}}=\frac{1}{t_g}\sum_{k=1}^{N_T}\left(\frac{U_{sk}}{U_n}\right)\cdot T_k\text{ .} \tag{22}$$

The necessity to introduce the maximum, relative amplitude of the VSG $\Delta u_{gM}$ (relationship 17) is that some VSG consequences are determined precisely by this indicator.

Decreasing, respectively recovering slopes of the working voltage during a sag capture the dynamic performance of the sag, allowing an evaluation of a VSG overall consequences, correlated with the maximum, relative amplitude and with the VSG duration. In addition, the recovering slope of the working voltage $(\Delta u_g/\Delta t)_R$ represents a warning for possible causes of working insulation puncture.

### 2.6. Short Time Overvoltages

STOV represent increases of the working voltage r.m.s, in the range of $(1.1 \div 1.8)U_n$, for time intervals of $(0.5T \div 1$ min), where $T$ represents the fundamental period. The STOV represent PQ disturbance with significant economic consequences, both for end-users and for suppliers also (Ryan, 2001). Currently, there are defined too few characteristic parameters of this one, insufficient for a correct assessment of their consequences. The scientific basis for defining new indicators for STOV is represented by the electrical insulation stresses.

Overvoltages can be characterized, in a first stage, by the **relative working voltage** (or voltage level)

$$u_s=\frac{U_s}{U_n}, \tag{23}$$

parameter which was chosen even for the graphic representation of an STOV general profile $u_s(t)$, shown in Fig. 4. The point A is considered **the initial moment** of STOV (Fig. 4) with $t_i$ as abscissa, when the working voltage exceeds with 10% the rated voltage and the slope of the working voltage variation, in this point, is maintained positive (Maier, 2012).

During the STOV, the working voltage reaches a **maximum value $U_{SM}$** (Fig. 4), that can exceed up to 80% the respective rated voltage; $t_M$ represents the moment when this maximum value is reached. From this maximum value the working voltage starts to decrease to the point D, with a constant or variable slope, when the value ($1.1 \cdot U_n$) is reached again, but this time downward the voltage variation; the D point abscissa is called the final time $t_f$ of the STOV (Maier, 2016b).

The quadrilateral profile of a STOV (Fig. 4) generalizes the practically possible cases, existing a direct link between the cause that produce the overvoltage and its time profile, as in VSG case.

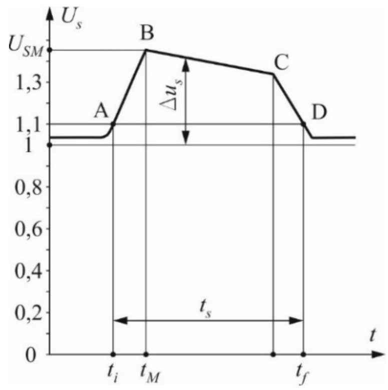


Fig. 4 – Voltage variation during a short time overvoltage and the main characteristic parameters.

In practice is preferred the percentage expression of the relative working voltage, given by relationship:

$$u_{s\%} = \frac{U_s}{U_n} \times 100\,,\ [\%]\,. \qquad (24)$$

The voltage **percentage deviation** (Maier, 2012), given by the relationship:

$$\Delta u_{s\%} = \frac{U_s - U_n}{U_n} \times 100\,,\ [\%], \qquad (25)$$

and the **overvoltage duration** $t_s$, determined as difference between the final and initial times (Fig. 4):

$$t_S = t_f - t_i\,,\ [\mathrm{s}] \qquad (26)$$

are belonging to the consecrated indicators of STOV.

Given the above statements, the following indicators for STOV will be added further on, by assuming the responsibility for their future utility and perfectibility (Maier, 2016 b):

– overvoltage **maximum amplitude** $U_{SM}$ (Fig. 4), recorded at the moment $t_M$, as expression of the electric insulating materials stresses from their dielectric rigidity viewpoint, expressed either in absolute values (Volts), or related to the rated voltage, in percentage:

$$u_{SM\%} = \frac{U_{SM}}{U_n} \times 100, \text{ [\%]}; \tag{27}$$

– **medium relative overvoltage** (weighted by time), given by the relationship:

$$\overline{u_S} = \frac{1}{t_S} \sum_{j=1}^{N_T} \left( \frac{U_{sj}}{U_n} \right) T_j, \tag{28}$$

where: $j$ is the index for the current fundamental period, of $T_j$ period, during which the working voltage r.m.s. $U_{sj}$ is determined and $N_T$ is the number of fundamental periods, on the overvoltage duration $t_S$;

**– increasing slopes** of the working voltage, during the overvoltage, as instantaneous values, maximum and medium. As instantaneous value, the voltage increasing slope is determined with the relationship:

$$\left( \frac{\Delta U_S}{\Delta t} \right)_j = \frac{U_{s(j+1)} - U_{sj}}{T_{j+1}}, \text{ [V/s]}, \tag{29}$$

and from their string values the **maximum value** $(\Delta U_S/\Delta t)_M$ is identified, representing the recorded maximum slope. Regarding the voltage increasing medium slope the following relationship is proposed:

$$\left( \frac{\Delta U_S}{\Delta t} \right)_{\text{med}} = \frac{U_{SM} - 1.1U_n}{t_M - t_i}, \text{ [V/s]}; \tag{30}$$

**– stress level**, defined through the following relationship:

$$\lambda_S = \sum_{j=1}^{N_T} \left( \frac{U_{sj}}{0.01U_n} \right)^2 T_j, \ (\%)^2 \cdot \text{s}, \tag{31}$$

expressing with a certain irregularity degree the additional energy, lost in insulations or in electrical conductors during the overvoltage. In the relation (31), $N_T$ represents the number of fundamentals periods, highlighted on the overvoltage duration $t_S$, the current fundamental period having the duration $T_j$;

– **voltage irregularity degree** during the overvoltage, for which is proposed a relationship similar with the one proposed for VSG (Maier, 2012):

$$\varepsilon_{US}^2 = \frac{1}{t_S} \sum_{j=1}^{N_T} \left( \frac{U_{sj} - U_n}{0.01U_n} \right)^2 T_j, \ (\%)^2, \tag{32}$$

written in the discreet character hypothesis of the $U_s(t)$ function, determined by the data acquisition type.

Reasons for which to define additional indicators for STOV was considered appropriate derive from the necessity of evaluating their consequences over the insulations, electrical installations and equipment. Thus, the overvoltage maximum amplitude $U_{SM}$, the maximum increasing slope of the overvoltage positive front $(\Delta U_S/\Delta t)_M$ and the stress level $\lambda_S$ present an important interest in order to characterize the STOV influence on insulations.

Regarding the overload type stresses, which occur during the overvoltages at the resistive and inductive receivers and capacitors also, the following indicators are considered important: the medium relative overvoltage $\overline{u_S}$ , the stress level $\lambda_S$ and the voltage irregularity degree $\varepsilon^2_{uS}$ , during the overvoltage.

## 3. Conclusions

Through the successive contributions of recent works, the PQ indicators system development for the voltage r.m.s. variations became important and remarkable.

Defining and applying the concept of voltage wave decomposition, indicating the r.m.s. values of voltage variations, in the actions and modulation harmonics represents the basic idea of the VSV analysis. Graphically, functions corresponding to the actions are represented as unitary step signals, for which a general form was considered and the corresponding Fourier development was determined, consisting in an infinite amount of harmonics, but in a certain relation of amplitudes and phases.

A new relationship was proposed for voltage fluctuations calculation which realize a more correct modeling of the human eye visual perception. Also, a sum form relationship is proposed for the flicker dose calculation, taking into account that a harmonic analysis of the modulation voltage is impossible on infinite small time intervals; so the integral form relationship is not valid. Because the upper limit of the voltage fluctuation periodicity is 5 min, this duration would be the minimum period for the flicker phenomenon analysis. The discomfort produced by luminance or light color fluctuations as well as a flicker dose accumulation are felt at the human brain level, leading to an instable visual perception, so nonconforming with the reality. These aspects could favor accidents at work and on the road traffic routes as well.

The rationality of completing the indicators family for VSG resides in the necessity of their more complex characterization, so that to be able to estimate synthetic and unequivocally the influence degrees of the VSG on sensitive installations and equipment. By analyzing each equipment family, using at least some of the proposed indicators, it would be possible to highlight their sensitivity at VSG. On this basis, it can be made a more accurate estimation of the VSG consequences, by their depth and durations, which will allow a more accurate dimensioning of the parameters regarding the VSG effects limitations.

The equipment and conductors insulations are stressed owing to the voltage high values during the STOV, but also because of the voltage high increasing gradient. In addition, the resulted stresses from the voltage increases accelerate the insulations aging, reducing the life operating time of the electrical equipment and conductors. A more accurate estimation of the STOV consequences may be made depending their parameters and durations, which will allow a more appropriate choice of the measurements taken in order to limit the STOV effects.

The association between the known indicators and the new defined ones leads to a complete indicators family for these aspects of the PQ. The practice of the additional indicators use, proposed for the voltage r.m.s. value variations, will be able to consecrate some of them, the most significant ones following to be normalized. Even if not all indicators, which now constitute the voltage variations indicators family will be rated, it must not be forget that some of the indicators expressivity can support the highlighting of some important aspects for the supplier – end-user relation.

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## PROGRESE ÎN DEFINIREA UNUI SISTEM DE CALITATE A ENERGIEI ELECTRICE

(Rezumat)

Calitatea energiei electrice este apreciată printr-un sistem de indicatori, alcătuit dintr-un ansamblu de mărimi caracteristice, dintre care unele pot avea valori normate. Una dintre proprietățile recunoscute ale sistemului de indicatori este perfectibilitatea, aspect susținut printr-o serie de articole recent publicate, de către autorii lucrării.

Referitor la variațiile valorii efective a tensiunii rețelei, se propune evidențierea şi separarea variațiilor de tensiune datorate unor acțiuni de intervenție, efectuate sau înregistrate la nivelul dispeceratelor. În acest fel, rămân de interpretat mai puține armonici ale variațiilor lente de tensiune.

Reconsiderarea relației de calcul a fluctuațiilor de tensiune redă mai bine fenomenul percepției vizuale. Diferențele obținute prin utilizarea formulei propuse vor influența semnificativ valorile indicatorilor de flicker.

Mărimile caracteristice propuse pentru goluri şi supratensiuni completează familia de indicatori ai variațiilor valorii efective a tensiunii,, urmând ca în viitor să fie normați cei mai importanți dintre aceştia.