Introductory results of tests of algorithms for recreation of voltage variation with voltage fluctuation indices

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Abstract—The paper presents results of preliminary research on possibility to recreate a variation of voltage in power grid on the basis of recorded values of measures of the variation. This is a complex issue because the voltage changes that occur in real networks are random. Five algorithms have been proposed and their quality has been verified using the obtained values of $P_{st}$ short-term flicker indicator. Description of the algorithms and results analysis have been preceded by the introduction that aims at short description of selected voltage variation indices.

Index Terms—power quality, voltage variation, voltage fluctuations indices, $P_{st}$ indicator

I. INTRODUCTION

The quality of voltage in power grids is verified with a number of measures. The values of those measures are not only of informative matter, rather they are used in many legal or normative regulations which point out limits for voltage parameters. One of the most important groups of such measures are those which relate to voltage variation. The variation is divided into two main classes: fast and slow changes of voltage. Fast are those changes for which rms value over time changes more than some threshold value (e.g. 1% of rated value of voltage, $U_{ rated}$, over one second). Other changes, which do not fulfill this condition are considered as slow. Fast changes of voltage which occur in series, or manifest itself as persistent changes of rms or peak voltage value, are called voltage fluctuations [1]. The simplest measures of voltage variation are maximal and minimal rms values (in the case of three-phase systems it applies both to phase and line voltages) recorded in subsequent periods (usually of the same duration) [2]. Other measure, which relates directly to rms value, is called voltage fluctuation indices [2], [3]. This measure is in fact a set of values which include: $\delta U$ magnitude and $f_{x-y}$ rates of fluctuations, also recorded over some given discrimination period. There are also other measures in use, which indirectly relate to rms value of voltage. They estimate rather the possible outcome of voltage fluctuations occurrence. As the most frequent effect of the fluctuations is a flicker [4] generated by light sources supplied by such varying voltage, there are measures which evaluate the obnoxiousness of the flicker. The most popular among those are short-term flicker indicator, $P_{st}$ (used widely in Europe) [5], [6] as well as $\Delta V_{10}$ index (used in Japan and some other Asian countries) [7]–[10]. The measurement of $P_{st}$ indicator is conducted with so called flickermeters [11], specification for which is given in IEC 61000-4-15 Standard [12]. This paper considers the possibility of recreating the voltage variation in power grid based on recorded values of voltage variability measures. It is a complex task as the changes of voltage present in real grids are of random nature: the time of their occurrence as well as the frequency of repetitions and amplitudes are all random. Throughout the paper it was thus assumed that the variability of voltage is a result of amplitude modulation of harmonic signal with square modulating signal. For voltage of such changeability, using authored numerical tools, voltage fluctuation indices were delimited (considered later as input data in recreating process) along with $P_{st}$ indicator values (treated as reference values for the process). Basing on the input data, five algorithms for voltage recreation were used. To assess the quality of voltage variability recreation, the resulting signal of modulated voltage was in turn input to the flickermeter and the outcome of its measurement was compared with reference $P_{st}$ indicator values.

The paper is composed as follows: section II will be dedicated to the description of voltage fluctuation indices; section III will contain information on voltage processing in flickermeter; section IV will discuss algorithms used for voltage recreation; section V will present some exemplary results which should make it possible to assess the quality of the recreation; section VI will give conclusions and plans for further research.

II. VOLTAGE FLUCTUATION INDICES

Voltage fluctuation indices are a measure of voltage variability which statistically describes voltage changes, providing information about amplitude, $\delta U$ and frequency $f$ of fluctuations recorded over some given period. The basis on which the indexes are derived are discriminated changes of rms value of voltage, $\delta V$. The amplitude of fluctuations, $\delta U$, is usually delimited as the maximal or second maximal $\delta V$.
change recorded over discrimination period $T_w$. Fluctuation rate $f$ is, in turn, the amount of $\delta V$ rms value changes recorded during time unit, usually a minute. That is why the unit for the rate $f$ is $1 \text{cpm}$ - changes per minute. Alternatively, the fluctuations rate $f$ is given as a frequency of modulating signal $f_m$, where the following relation holds: $f [\text{cpm}] = 120 [\text{cpm/Hz}] \cdot f_m [\text{Hz}]$. To increase the diagnostic capabilities of the measure, the fluctuation rate is represented as a set of values, which inform about rates of fluctuations with magnitudes of some selected sub-range of $\delta U$ value. The bigger number of sub-ranges leads on one hand to a better diagnostic insight, but on the other hand it significantly increases the data stream which should be recorded and stored in measuring device. Manufacturers of the meters usually take some compromise and limit the sub-ranges to only a few. The exemplary implementation described in [13], [14] uses 7 sub-ranges, and as a result, after every observation period a set of eight values is recorded, namely: amplitude $\delta U$, seven rates for following ranges of $\delta U$: $(1.0, 0.9) \delta U$, $(0.9, 0.8) \delta U$, $(0.8, 0.7) \delta U$, $(0.7, 0.6) \delta U$, $(0.6, 0.5) \delta U$, $(0.5, 0.4) \delta U$ and $(0.4, 0.0) \delta U$ (which will be further referred as $f_{1.0-0.9}$, $f_{0.9-0.8}$, $f_{0.8-0.7}$, $f_{0.7-0.6}$, $f_{0.6-0.5}$, $f_{0.5-0.4}$ and $f_{0.4-0.0}$). The great advantage of voltage fluctuation indices is the possibility to directly use them in fluctuation obnoxiousness assessment. To that aim a rate-amplitude characteristics $\delta U = f (f)$ are used: measurement results are depicted in $(f, \delta U)$ coordinates, and their position is checked against so called permissible voltage fluctuation borderline. Every point which lies above the borderline indicates the obnoxious fluctuation. As the permissible voltage fluctuation borderline are delimited for various light sources, it significantly widens the possible application range for the measure. The exemplary rate-magnitude characteristic is presented in Fig. 1.

III. A SHORT-TERM FLICKER INDICATOR

As mentioned before, the value of $P_{st}$ indicator is an estimation of obnoxiousness of flicker caused by voltage fluctuations. The standard reference for the indicator assumes that the source for the light is incandescent, 60 W “a coiled filament gas-filled lamp” [12]. To measure this indicator a so called flickermeters are used, built on the reference specification (which resembles processes that take place along the path: light source – eye – brain of the flicker observer). The values of flickermeter’s settings are chosen differently for rated frequency of 50 Hz and 60 Hz and for particular nominal voltages (120 V and 230 V). The characteristics of filters which compose the flickermeter were delimited using the results of tests conducted with representative group of persons. During the tests the threshold for sensing of fluctuations by 50% of testers for each analyzed rate of fluctuations was observed.

The result of $P_{st}$ indicator measurement depends in general on the shape of modulating signal, the depth and frequency of modulation, and for selected set of frequencies also on initial phase of modulation signal. After every recording period the result of $P_{st}$ indicator measurement is a positive number which reflects the level of obnoxiousness of fluctuations. The lack of fluctuations is represented by value close to zero ($P_{st} \approx 0.01$). The greater the value of the indicator the more obnoxious fluctuations were recorded. Standard EN 50160 gives two limits for permissible values of the indicator, each for different value of rated voltage $U_r$: for $U_r$ in $(0.23 – 35)$ kV range the limit is 1.2 and for $U_r > 35$ kV the limit is 1.0 [16]. Despite the indicator is widely used, its main disadvantage is reference specification for only one type of light source [17]-[19]. It may lead to improper estimation of fluctuation obnoxiousness for other types of sources. Moreover, the diagnostic capabilities of the $P_{st}$ indicator are very limited as all phenomena present in the grid are represented by only one, single value delimited within standard 10 min period.

IV. ALGORITHMS FOR VOLTAGE FLUCTUATION RECREATION

The basis for voltage fluctuation recreation attempts will be the recorded values of voltage fluctuation indices. This measure directly provides information on the number of rms value changes which occurred in every recording period, although does not tell unambiguously about the amplitude of the particular change. The $\delta U$ value informs only about the maximal (in some implementations [2] – about the second maximal) amplitude - there is no way to deduce the actual number of changes of such amplitude. If the indices are recorded as a set of values representing number of fluctuations in several sub-ranges of $\delta U$ amplitude, the diagnostic information gathered this way is broaden. Nevertheless, even in such case the added information tells only about the fact of occurrence of voltage changes $\delta V$ in particular sub-ranges of $\delta U$. Moreover, the indices do not provide direct ability to recover the envelope of voltage which was present in the grid, and what follows, to deduce the way of voltage modulation.

On the other hand, the way the indices are detected determines

Fig. 1. An exemplary rate-magnitude characteristic $\delta U = f (f)$ with permissible fluctuation borderline marked

Voltage fluctuation indices, when used properly [13], enable estimation of loads which introduce disruptions in power grid, making it possible to locate the loads, eliminate them or at least limit its influence by the change of its working conditions [15].

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\begin{align*}
\delta U \text{[%]} & = f(f) \\
\text{obnoxious flicker} & \quad \text{permissible voltage fluctuation borderline} \\
\text{non-obnoxious flicker} & \quad \text{0.1} \quad 1 \quad 1000 \\
\end{align*}
\]
that only fast enough changes of rms value will be considered as voltage fluctuation. And, as the measurements conducted in real power grids prove, the main reason for the fluctuations are sudden changes of the state of loads, such as turning it on or off. Of course, there are special cases, as for example the values recorded during work of so called “unsteady” loads, e.g. arc furnaces or welders.

Values of voltage fluctuation indices provide direct information on the number of voltage changes in recording period, although, similar as in the case of amplitude, do not precisely inform about the time of fluctuation occurrence. Taking the above into account, a five different algorithms were proposed for voltage recreation, denoted as A1, A2, A3, A4, and A5. All of them assume that the voltage will be reconstructed with step changes of rms value (which could be interpreted as a result of amplitude modulation with rectangular signal). The input data, namely a set of eight values: $\delta U$ magnitude and $f_{1.0-0.9}$, $f_{0.9-0.8}$, $f_{0.8-0.7}$, $f_{0.7-0.6}$, $f_{0.6-0.5}$, $f_{0.5-0.4}$ and $f_{0.4-0.0}$ rates, were gathered with $T_w = 5 \text{ min}$ registration period.

It was further assumed that the fluctuations from $f_{1.0-0.9}$ to $f_{0.5-0.4}$ will have amplitudes set to the upper limit of the corresponding sub-range of $\delta U$, while the fluctuations in $(0.4, 0.0)$ $\delta U$ range, as usually the most frequent (this range normally includes most of disruptions and noises), will have the amplitude set to the average value of the range, namely $0.2 \cdot \delta U$. Algorithms A1-A3 use the fluctuations alternately when it comes to amplitude: first all of the fluctuations of $f_{0.4-0.0}$ rate are used, then the fluctuations of $f_{1.0-0.9}$ rate, and subsequently $f_{0.5-0.4}$, $f_{0.9-0.8}$, $f_{0.6-0.5}$, $f_{0.8-0.7}$ and $f_{0.7-0.6}$ in that order. The fourth algorithm uses the fluctuations from particular ranges differently: it introduces the fluctuations from the subsequent ranges of $\delta U$ in decreasing order, first from $f_{1.0-0.9}$, then from $f_{0.9-0.8}$, and so on. The fifth algorithm does the opposite: introduces fluctuations from subsequent ranges but in increasing order. Moreover, the algorithms differ in the way they introduce the particular changes and the moments they introduce them:

**A1**) it has been assumed that the rms value should oscillate around the rated value of voltage. For this purpose, the subsequent changes of voltage are introduced in a way which directs the resulting rms value of modulated signal to the rated value - if it is currently greater then the rated rms value, the next change will be introduced with minus sign; if its smaller than the rated value, the next change will be introduced with plus sign. This algorithm introduces subsequent changes evenly in the whole registration period - despite the amplitude the subsequent changes of voltage are added with the same time span. The span is the result of division of total number of seconds in registration period by the total number of fluctuations detected within the registration period.

**A2**) it has been assumed that the voltage changes will be introduced subsequently with toggled sign, despite of the resulting rms value of modulated voltage. As in algorithm A1, the changes will be spread evenly in time in the whole registration period.

**A3**) as in A1, it has been assumed that the rms value should oscillate around the rated value of voltage. Unlike algorithms A1 and A2, in this case it was decided to introduce all changes recorded in the registration period, despite of their actual number, during first 120 seconds of recreated period of voltage.

**A4**) works similarly as A1 but with decreasing order of fluctuations amplitude subranges introduction.

**A5**) works similarly as A1 but with increasing order of fluctuations amplitude subranges introduction.

### V. The exemplary results of voltage fluctuation recreation

In order to test the algorithms of voltage changeability recreation, the deterministic signals were chosen, which resembled the fluctuations caused by amplitude modulation with rectangular signal. For the generated signals voltage fluctuation, $\delta U$ and $f_{x-P}$, were delimitated. Simultaneously a values of $P_{st}$ indicator were measured - this values will be treated as a reference values. The delimited values of voltage fluctuation indices where in turn used as input data for the algorithms. The outcome of voltage recreation algorithms was subsequently used as input signal for measurement of $P_{st}$ indicators, this time marked as $P_{stx}$, where compared with the reference $P_{st}$ values.

The first series of deterministic signals included a few amplitude modulated signals with constant modulation depth, $(\frac{\delta U}{U}) = \text{const}$. The modulation depths used during its generation were equal to 0.827%, 1.405%, and 2.756%. In second series a modulation depth was changed in a way to obtain the constant value of $P_{st}$ indicator for every frequency. The values of $P_{st}$ were set to 0.8, 1.2, 3, and 5.

As it turned out the algorithm A3 led to unacceptable differences of results from the reference values for every input signal. As such its results were excluded from further presentation. Figures 2, 3, and 4 present the results of $P_{st}$ indicator measurement for input signals with constant modulation depth. To ease the analysis the characteristics present the normalized value of the indicator calculated as $\frac{P_{st}}{P_{stx}}$. For an ideal case the characteristics should remain equal to 1 for every modulation frequency.

![Fig. 2. $P_{st} / P_{stx} = f (f_m)$ characteristic for $(\Delta U/U) = 0.827\% = \text{const}$](image-url)
Analysis of Figs. 2–4 clearly indicates that the quality of voltage recreation is the best for algorithm A1 and A2, while the worst for A5. Surprisingly, the algorithms A1 and A2 led to almost identical results for this type of input signals. For every algorithm the values of $P_{stc}$ indicator are lower then expected, and for A1-A4 the results fall in 10% error range. Figures 5, 6, 7, and 8 present the results of $P_{stc}$ indicator measurement for input signals which should lead to constant $P_{stc}$ indicator value. As in previous case the indicator value was normalized with reference $P_{st}$ value.

Similarly to previous case, the resultant $P_{stc}$ values were almost always lower then reference. Once more the best results were obtained with algorithm A1 and the worst with algorithm A5. Interestingly, the $P_{stc}$ values differ the most from reference for low frequencies of modulation, while the overall recreation quality decreases for increasing value of reference $P_{st}$ value. To see if that is the case for even higher values of $P_{st}$ indicator the additional characteristics were composed. A few modulation frequencies were selected, and for each of the frequencies the value of modulation depth was changed to obtain values of $P_{st}$ in a range from 0.1 to 40. The resultant $P_{stc} = f (P_{st})$ for three different modulation frequencies are presented in Figs. 9, 10, and 11. All three characteristic from Figs. 9–11 reveal the same tendency: the higher value of reference $P_{st}$ indicator the greater is the difference between the expected and calculated value. All algorithms tend to give lower values then expected. The situation is different for very high values of $P_{st}$ - above 10. The characteristics for almost all of the algorithms considered (excluding A2) are no longer monotonically decreasing there.

VI. SUMMARY

The presented examples of voltage recreation, verified with the resultant value of $P_{stc}$ indicator, proof in general, that
The best results were obtained for algorithm A1. Although, this does not forejudge its general reliability. One must keep in mind that the presented results are only exemplary and do not expose all of the phenomena possibly present in electrical grids. Rather it should be treated as a good starting point for further tests and search for the optimal algorithm for voltage fluctuation recreation, which would give proper result despite of modulation type. It seems that the improved results may be obtained by taking into account also other measures of voltage fluctuations as for example the simultaneously recorded maximal and minimal rms values of voltage. The future research will be concentrated on this aspect.

REFERENCES


