QUANTIFYING VOLTAGE VARIATIONS ON A TIME SCALE 
BETWEEN 3 SECONDS AND 10 MINUTES

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INTRODUCTION

There are a number of reasons for introducing additional voltage-variation indices covering the range in time scales between the flicker indices (up to a few seconds) and the slow voltage variations (10-minute rms values). This includes the need to quantify rapid voltage changes, the likely increase of voltage variations with an increasing penetration of distributed energy resources and the susceptibility of equipment against voltage variations in this range.

This paper introduces the very-short-variation indices to quantify the difference between the 3-second and the 10-minute values of the rms voltage. The proposed method will only result in one additional index value for every 10-minute interval. The proposed method is applied to measurements at 10 different locations in five countries. The measurement results are consistent for these 10 locations.

It is further proposed in this paper to use a 1-minute rms voltage next to the 3-second and 10-minute values. The 1-minute values give, among others, a better insight in the performance of the voltage control than the 10-minute values.

THE NEED FOR ADDITIONAL INDICES

The IEC standard for power quality measurements, IEC 61000-4-30, defines two aggregated time intervals for variations in the rms voltage: a 3-second ("very-short-time") interval and a 10-minute ("short-time") interval [1]. Only the 10-minute values are used to quantify the performance of the system, e.g. in EN 50160. The fastest variations ("fluctuations" below 3-seconds) in voltage magnitude are covered by the flickermeter standard, IEC 61000-4-15 and related documents. Looking at the ratios between the time intervals in IEC 61000-4-30, gives the following values:

- 200 ms - 3 seconds: 15 times;
- 3 seconds - 10 minutes: 200 times;
- 10 minutes - 2 hours: 12 times

The step between 3 seconds and 10 minutes is much bigger than the other ones and is thus more likely to cover different phenomena: this may refer to different control means for voltage regulation, but also to different mechanisms for equipment damage due to voltage variations.

In many countries limits or expected values are available for the magnitude and frequency of occurrence of rapid voltage changes. Typical causes of rapid voltage changes are switching operations of shunt reactors, capacitors and transformer tap-changers but also switching of large loads and both large and small generator units. During the design process, the change in rms voltage due to the switching action is typically the main parameter to be limited.

The number of such steps in rms voltage is limited in a number of standard documents, like IEC 61400-21 [2] and IEC 61000-3-7 [3]. In the former document two product specific parameters, "flicker step factor" and "voltage change factor" are defined. Both parameters relate to voltage variations in a fictitious network. But despite the limits placed in a number of documents, no general method exists for measurement and characterization of these kinds "voltage steps" or "rapid voltage changes".

The introduction of distributed energy resources (especially solar power and wind power) will lead to an increase in voltage variations in the time range between 3 seconds and 10 minutes. Variations in wind speed and insolation take place at time scales longer than the flicker range and the resulting voltage variations will thus not be captured by the flicker indices or by the 10-minute values. Flicker resulting from wind power installations is mainly due to the impact of the tower on the rotating blades, much less due to wind-speed variations [4][5]. A study after variations in insolation showed a significant amount of variations in the time range below 10 minutes [6].

An additional likely consequence of the increased penetration of distributed energy resources is an increase in the number of switching actions of voltage-control equipment like transformer tap-changers and capacitor banks. This in turn will lead to an increase in the number of rapid voltage changes.

The literature on fast voltage fluctuations concentrates on light flicker as the main impact. However some non-flicker related consequences are mentioned in [7] (control actions for control systems acting on the voltage angle; braking or accelerating moments from motors, impairment of electronic equipment) which are more likely to be due to variations on a longer time scale than covered by the flicker indices.

All the above-mentioned issues call for the development of voltage-quality indices covering the time range between the flicker indices (up to about 3 seconds) and slow voltage variations (10 minutes). In this paper a number of possible indices will be proposed.
VERY SHORT VARIATIONS

The very-short variation indices to be introduced in this section quantify the difference between the 3-second (very-short time) values and 10-minute (short time) values of the rms voltage [8]. The 10-minute values $U_{sh}$ are obtained as the rms of the 3-second values $U_{vs}$ over the preceding 10 minutes:

$$U_{sh}(t_k) = \sqrt{\frac{1}{N} \sum_{i=k-N+1}^{k} U_{vs}^2(t_i)}$$  \hspace{1cm} (1)

with $N$ the number of 3-second values in the 10-minute window, and $t_k$ a time sample corresponding to the end of a 10-minute clock interval (i.e. a value is calculated at 12:10, at 12:20 at 12:30 etc, over the preceding 10-minute interval).

To characterize the voltage variations at time scales shorter than 10 minutes, the difference between the 3-second values and the 10-minute values is used. The 10-minute value used is updated every three seconds. The "3-second very-short variation value" $\Delta U_{vs}$ is defined as the difference between the 3-second rms voltage and the rms of the 3-second values over the preceding 10 minutes:

$$\Delta U_{vs}(t_k) = U_{vs}(t_k) - U_{sh}(t_k)$$  \hspace{1cm} (2)

where the short-time voltage $U_{sh}(t_k)$ is calculated as in (1), with the difference that the value is updated for every new 3-second value. This can be interpreted as a high-pass residue of the very-short values after taking the 10-minute averages. From the 3-second very-short variation values a 10-minute very-short variation value is calculated for every 10-minute time stamp:

$$\Delta U_{sh}(t_k) = \sqrt{\frac{1}{N} \sum_{i=k-N+1}^{k} \Delta U_{vs}^2(t_i)}$$  \hspace{1cm} (3)

with $t_k$ a time sample corresponding to a 10-minute time stamp, as in (1). The result is that a voltage measurement results in three values over every 10-minute interval:

- The short-time flicker severity $Pst$ as defined in IEC 61000-4-15;
- The 10-minute very-short variation as in (3);
- The short-time (10-minute) rms voltage as in (1).

MEASUREMENT EXAMPLES

The 3-second rms voltages have been measured at 10 different locations in five different countries. The 3-second and 10-minute very-short variations have been calculated from the measurements. The resulting 10-minute very-short variations are shown in Figure 1 through Figure 10.

All recordings show a very similar pattern, with a continuous level up to about 1 Volt with superimposed spikes with amplitudes between 2 and 5 Volt. A closer inspection of the recordings and the intermediate results shows that the continuous level is correlated to the noise that is generally visible on plots showing the 3-second rms voltage as a function of time, being due to the continuous changes in the voltage drop caused by large numbers of small equipment. The spikes are correlated with steps in voltage caused by switching actions in the power system. As we will see later, the spike in the 10-minute very-short variation is about twice the step in voltage magnitude.
Figure 6 Very-short variations for an apartment in Shanghai, China.

Figure 7 Very-short variations for a hotel in Shanghai, China.

Figure 8 Very-short variations for a hotel in Rome, Italy.

Figure 9 Very-short variations for a house in Geulle, The Netherlands.

Figure 10 Very-short variations for a hotel in Brussels, Belgium.

Figure 11 Probability-distribution function of the 10-minute very-short variation (VSV), for ten measurement locations.

Figure 12 Correlation between very-short variation (horizontal scale) and short-term flicker severity (vertical scale).

**CORRELATION WITH FLICKER INDICES**

The probability distribution functions have been calculated for the 10-minute very-short variations of all 10 measurements. The results are plotted Figure 11. The 50-percentiles range between 0.2 and 0.8 Volt (mean: 0.51 Volt; standard deviation 0.17 Volt). The 95-percentiles range between 0.8 and 2.2 Volt (mean: 1.44 Volt; standard deviation 0.40 Volt).

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The aim of the very-short variation indices is to provide an additional index to quantify voltage variations. If these indices were strongly correlated with existing indices, there would be no need for additional indices. The flicker indices also quantify short-duration fluctuations in voltage amplitude. Therefore a comparison was made between the 10-minute very-short variation and the short-term flicker severity at one of the sites with a high flicker level. The results are shown in Figure 12, showing that these two indices are non-correlated. This of course does not rule out that there is no correlation for any of the other sites, but does show that there is no general correlation between the flicker indices and the very-short variation indices.

**VOLTAGE STEPS**

In case of a step in voltage magnitude, the 10-minute sliding-window average will take 10 minutes to rise from the pre-step value to the post-step value. The result is a non-zero value of the 3-second very-short variation during a 10-minute period.
starting at the instant of the voltage step.

But this 10-minute period will rarely correspond to the 10-minute interval over which the 10-minute very-short variation is calculated. A single step in voltage magnitude will thus result in two non-zero values for the 10-minute very-short variation. The rms voltages and very-short variations are shown in Figure 13 for a step from 227 to 232 Volt. The 3-second rms value takes only one sample to reach its new value. The 3-second very-short variation however takes 10 minutes to come back to zero. The 10-minute very-short-variation values are lower than the voltage step: 2.48 Volt and 1.44 Volt in this example.

The calculations leading to Figure 13 have been repeated for different locations of the voltage step within the 10-minute time-aggregation interval. The resulting two non-zero 10-minute very-short-variation values are shown in Figure 14. The horizontal axis gives the time delay between the start of the 10-minute time-aggregation interval and the voltage step. For small values of this delay, the triangularly shaped 3-second very-short variation is almost completely inside of the interval, resulting in a high 10-minute value. With increasing delay, the first 10-minute value decreases and the next one increases until it finally becomes larger than the first value. An interesting observation is that the higher of the two values (the one that causes the peak in the plots of the 10-minute very-short variations) is always close to half the voltage step (2.5 Volts in this case). The 10-minute very-short variation is thus a suitable index for rapid voltage changes (voltage steps).

Figure 13 The 3-second (top) and 10-minute (bottom) rms voltages (left); 3-second (top) and 10-minute (bottom) very-short variations (VSV)(right) for a synthetic step of 5 Volt in voltage magnitude.

Using an additional time scale (window length) of 1 minute would give a better mapping to the control means. The performance of primary, secondary and tertiary control would be covered by the 3-second, 1-minute and 10-minute indices, respectively.

The 1-minute time scale also comes back in a number of power-quality documents and publications to distinguish between dips and undervoltages as well as between short and long interruptions. The original choice of the 1-minute value was made to distinguish between automatic means of voltage recovery (protection and automatic reclosing) versus manual means. This corresponds to the above distinction between secondary and tertiary voltage control.

The first section of this paper addressed the unequal spread of time scales in IEC 61000-4-30. Equally spreading the steps would require an additional interval at $\sqrt{3s \times 10\text{min}} = 42.5s$, so that 1 minute is a reasonable value.

The 3-second, 1-minute and 10-minute rms voltages are plotted in Figure 15 for one of the earlier measurement sites. The rms voltages are shown for only a part of the measurement period to better show the differences. The general pattern of the voltage behaviour is the same for the 3-second and the 1-minute values. However the 10-minute values do not contain information on most of the faster variations.

The probability-distribution functions of the rms voltages over the whole measurement period are shown in Figure 16. Only the highest and lowest 5% are shown to emphasize the differences. The steps in the 3-second values are due to the resolution of the monitor used. The distribution of the 3-second and 1-minute values is about the same. The 10-minute values however contain significantly less extreme values.

The use of a 1-minute rms voltage removes one of the reasons for introducing the very-short variation indices (the large gap
between 3 seconds and 10 minutes) but the other reasons remain. When presenting 1-minute rms values, the very-short variations may be redefined as the difference between the 3-second and the 1-minute values.

![Figure 15](image1.png)

**Figure 15** The 3-sec (top), 1-min (centre) and 10-min (bottom) rms voltages.

![Figure 16](image2.png)

**Figure 16** Probability distribution functions of the 3-sec (solid), 1-min (dashed) and 10-min (dotted) rms voltages.

**CONCLUSIONS**

A number of reasons have been identified for developing voltage-quality indices covering voltage variations in the time range between 3 seconds and 10 minutes. This includes the factor of 200 between these time intervals; the absence of a measurement or characterization method covering rapid voltage changes (voltage steps); the expected increase of voltage variations in this time range due to the increasing penetration of distributed energy resources; and the susceptibility of equipment to variations in this time range.

The very-short variation indices quantify the difference between the 3-second values and the 10-minute values of the rms voltage. The proposed method results in one additional index (the 10-minute very-short variation) for every 10-minute interval. Measurements at 10 different locations in five countries show a similar pattern for this index: a continuous level related to the almost continuous but minor voltage steps related to changes in power consumption by end-user equipment; and a limited number of superimposed spikes correlated with large steps in the voltage magnitude. It is shown that the peak value of the 10-minute very-short variation is about equal to half the step in voltage magnitude. This makes this index a suitable one to quantify rapid voltage changes (voltage steps).

A discussion is started in this paper on the need to introduce an additional 1-minute time interval next to the 3-second and 10-minute intervals in IEC 61000-4-30 and other standard documents. The use of 1-minute rms voltage instead of (or next to) the 10-minute values would provide a better picture of the performance of voltage-control equipment.

The detailed introduction of very-short variations and 1-minute rms values in the various standard documents will remain an issue for further discussions.

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**REFERENCES**

[3] IEC 61000-3-7, Assessment of emission limits for fluctuating loads in MV and HV power systems.