METHODS FOR THE EVALUATION OF NEW POWER QUALITY PARAMETERS: A REVIEW OF RAPID VOLTAGE CHANGES AND SUPRAHARMONICS

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ABSTRACT

The present paper reviews the measurement methods of supraharmonics and Rapid Voltage Changes. Supraharmonics still lack a unique measurement method, needed for the definition of compatibility levels. A standard measurement method for Rapid Voltage Change, instead, has recently being published, but several drawbacks are reported in the literature. These power quality parameters are briefly introduced, then the status of international standards and the most recent scientific works are reviewed.

INTRODUCTION

In the last decades, power grids have been going through major change and improvements that, as a downside, brought a new set of disturbances whose presence was previously not known or not significant. The main drivers have been the shift towards Distributed Generation (DG) and the rapid development of power electronic devices, whose presence is continuously increasing.

Among new power quality issues, high frequency distortions in the 2 kHz – 150 kHz range (supraharmonics) and Rapid Voltage Changes (RVCs) are receiving increasing attention from research community. Although they are not new phenomena, they have never been properly addressed, resulting in lack of standardization, especially from the point of view of measurements. The present paper provides a review of these power quality issues and their measuring methods, pointing out weaknesses and possible room for improvement.

A RVC is a quick transition in rms voltage occurring between two steady-state conditions, not exceeding the dip/swell thresholds [1]. They have an occasional character, typically associated with single events such as motor starting or capacitor bank switching [2] and, due to their effect on flicker, they are a concern for Power Quality. Therefore, the last edition of IEC 61000-4-30 includes a method to detect and characterize these voltage events [1]. However, this method has only been available for short time, and some limitations have been detected, especially in relationship with the traditional flicker assessment. The present paper reviews the standard measurement methods and the works present in the literature that analyze them, pointing out drawbacks. It will be shown that much work remains to be done.

Supraharmonics refers to distortions in the range of 2 kHz – 150 kHz. Although not being a new phenomenon, intensive research in this field started only a few years ago, triggered by the rapid increase of presence of this kind of disturbances [3]–[6]. From the point of view of standardization, a consistent measurement method is lacking. Different approaches are proposed in different international standards, but a commonly accepted measurement strategy is still missing, making difficult not only the correct supraharmonics assessment, but the definition of emission and compatibility levels as well.

This paper briefly introduces supraharmonics and reviews measurement methods, both the ones presented in international standards and more recent ones, proposed in the literature.

RAPID VOLTAGE CHANGES

An RVC is a voltage fluctuation where a quick transition in the rms voltage occurs between two steady-state conditions. Its amplitude is less than 10%, which is the threshold of a voltage dip/swell. They could be isolated events or repetitive changes, periodic or aperiodic in nature [2]. Figure 1 shows an example of two RVCs measured on the low voltage network close to a water pumping station. They are due to the starting and the stop of a 160 kW water pump equipped with a star delta starter [7]. RVCs are usually expressed as a percentage of the nominal or declared voltage and, as shown in Figure 1, they can produce a voltage decrease as well as a voltage increase [2].

RVCs are a power quality issue and need to be controlled. The main reason for limiting them is the fast change in the voltage that generates flicker i.e., visual annoyance for power grid users. For instance, a 10% reduction in the voltage produces a 34% reduction in the light intensity in the case of a 60 W incandescent lamp [8]. However, negative effects different than flicker have also been reported in the literature, such as the malfunctioning of control systems acting on voltage angle, braking or accelerating moments from motors, or impairment of electronic equipment [9].

RVCs have been traditionally caused by single events or by events that may occur repetitively but with long times existing between them. Some examples are, typically, switching operations e.g., of shunt reactors, capacitors and transformer tap-changers, as well as switching of large loads and generator units. However, new sources of RVCs are appearing and their presence in the grid is growing due to the change in the paradigm that is undergoing in the electrical grids, namely the increasing penetration of DG, especially in the form of Renewable Energy Sources (RES). The introduction of solar and wind power is expected to lead to an increase of RVCs occurrence [10]–[14]. This is due to the variations in wind speed and insolation as well as to the impact of the tower on the rotating blades, in the case of wind power [15], [16].

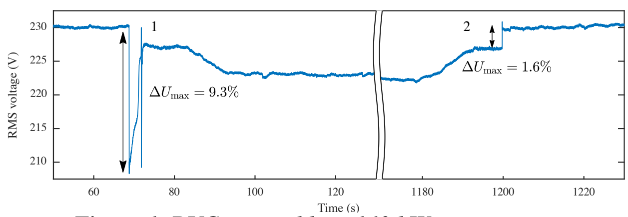

Figure 1. RVCs caused by a 160 kW water pump.

Therefore, considering the global effort to increase the power production from RES, RVCs are recently attracting attention from the research community and standard setting organizations.

The way to standardization

Although being a known flicker source, the RVC standardization has been deficient for many years. Bollen et al., in [17], [10], were among the firsts to claim the need of new power quality indices, dedicated to RVCs, in recognition of the increasing importance of these disturbances. Among the reasons for introducing additional voltage-quality indices, the authors highlighted the absence of a method for measurement and characterization of these events. This issue was also addressed by the CIGRE/CIRED joint working group JWG C4.108, which analyzed the increasing presence of RVCs in the grid and concluded that RVCs needed a fully unique definition and a standardized measured method [2], [18]. Brekke et al, in [8], showed that the effect of RVC on flicker depends on the RVC magnitude, the rate of change of the voltage during the RVC, and the duration of the steady-state condition between RVCs. In their work, the authors demonstrated the need of setting limits for RVCs as they produce annoyance for customers. Moreover, based on RVC parameters, the authors provided minimum requirements for characterizing RVCs and ensuring reliable measurements.

These efforts led to the IEC 61000-4-30:2015 standard, which provides a clear definition and a precise measurement method for the detection and characterization of RVCs [1].

RVC standard measurement method

The IEC measurement procedure is based on the calculation of the rms voltage computed over one-cycle intervals, starting at a fundamental zero crossing, and refreshed each half-cycle. This value, denoted $U_{rms(1/2)}$, is used to establish whether the rms voltage is in a steady-state condition or not. $U_{rms(1/2)}$ is compared with the arithmetic mean of its previous values over the last 100/120 cycles (for 50 Hz/60 Hz systems) and, if their difference is larger than a certain threshold (not specified and set by the user, typically between 1-6%), the steady-state condition is not met. Every time the $U_{rms(1/2)}$ signal leaves the steady-state condition, an RVC event is detected. The RVC event ends when the steady-state condition is met again. If a voltage dip/swell –with amplitudes above the 10% limit– is detected during an RVC event, the RVC event is discarded. An RVC is characterized by its start time, duration, ΔU_{max} and ΔU_{ss} (Figure 2).

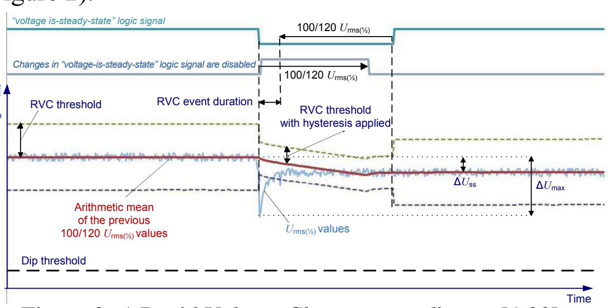

Figure 2. A Rapid Voltage Change according to [4-30].

Limitations of the measurement method

Although the proposed method represents an important step forward from the standardization point of view, several drawbacks have been reported in the literature. The lack of definition of the threshold for RVC detection (and hysteresis) has been identified as an issue that can lead to different measurement results [19], and that depends on the instrument measurement uncertainty [20]. Macii et al. discussed the high sensitivity of the rms estimator to phase changes in [21] and proposed, in [22], a new estimator with better performances. Barros et al. also pointed out limitations of the IEC method in [19], as the rate of change of the voltage is not considered nor defined in the standard, but has a direct effect on flicker. Moreover, a minimum aggregation time to separate consecutives RVC events is proved to be necessary. The same group also studied the relationship between RVC parameters and flicker in [23], revealing that the instantaneous flicker perception is a better indicator for correlation than the more commonly used flicker severity. The instantaneous flicker perception is also employed in [7] to study the effect of RVCs on flicker of modern lighting technologies, suggesting that this index could be effectively used to characterize RVCs.

SUPRAHARMONICS

Supraharmonics is a term created to define current and voltage distortions in the range of 2 kHz – 150 kHz. Although not being a new phenomenon, the interest of the research community for this kind of disturbance has been limited until few years ago, when the research output started to increase. The main drivers have been the use of Power Line Carrier (PLC) as part of the smart grid metering architecture and, mainly, the large-scale introduction of power electronic devices in the grid [5].

PLC are sources of (intentional) supraharmonics emission, as they employ the same frequency range for communication [24]. On the other hand, power electronic converters employ switching frequency in the supraharmonics range, generating non-intentional emissions. The penetration of power electronic devices is steadily increasing, since their evolution and the new switching techniques allow to drastically increase energy efficiency in the AC-DC conversion processes. However, these new techniques, with switching frequencies in the range of tens of kHz, introduced more disturbances in the grid, whose character is strongly non-linear, non-stationary, and changes noticeably even within one fundamental cycle. Some of the most common examples of sources of supraharmonics emissions are photovoltaic (PV) inverters, electric vehicle chargers, and drivers of modern lighting technologies [25]–[29]. Figure 3 shows an example of the current feeding a fluorescent lamp.

A summary of the effects of supraharmonics so far identified can be found in [30] and includes additional heating, audible noise, malfunction of equipment, and wrong PLC meter readings [4], [31]–[34].

Rönnberg et al, in [5], presented a comprehensive review of the open issues (i.e. research opportunities) in the field of supraharmonics. Among them, the need of the definition of an appropriate measurement method is affirmed. The authors identify the short-time variations of supraharmonics as the main challenge, requiring appropriate instruments and methods, as well as standardization.

Standard measurement standards

Currently, there are no normative measurement methods for supraharmonics. However, a lot of research is ongoing and the IEC 61000-4-30 standard on power quality measurement methods proposes different methods in its Annex C, although it is not normative [1].
One method is the extension of the same measurement technique described in IEC 61000-4-7 for harmonics up to 9 kHz i.e., Direct Fourier Transform (DFT), up to 150 kHz. This method employs a 200 ms rectangular analysis window and requires the grouping of the Fourier spectral components into 200 Hz bands, centered in odd multiples of 100 Hz, using the Root Sum Squared (RSS), as described in IEC 61000-4-7 [35]. This first method is the only one proposed for the range from 2 kHz to 9 kHz.
For the 9 kHz – 150 kHz range, two alternatives to the first method are suggested. One option is to use the method of CISPR 16 [36], which is based on measurements performed in the frequency domain with a scanning receiver. Using a super-heterodyne analyzer, a narrowband filter is tuned on a frequency band and the CISPR peak, quasi-peak, and rms values are measured. The procedure is then repeated to cover the entire bandwidth. The CISPR method, however, was developed to test equipment emission under laboratory conditions and is therefore not suitable for in-situ power quality measurements, as stated in the standard.
Finally, a new method is proposed in IEC 61000-4-30. This third method is also based on DFT analysis, but with some differences. First of all, the standard specifies a filtering technique for selecting only the range of interest. Then, every 10/12 cycles, 32 approximately equally spaced measurements are taken, at a sampling frequency of 1024 kHz and lasting 512 samples (0.5 ms) each. The obtained samples are then processed using DFT, resulting in a 2 kHz resolution spectrum. For every 10/12 cycles window, minimum, maximum and average values are recorded. This last method is less accurate and less complete (more than 90% of each window is not measured), but has the advantage of requiring less data storage.
Reference [37] presents a comparison of the standard measurement methods here described, using synthetic test signals.

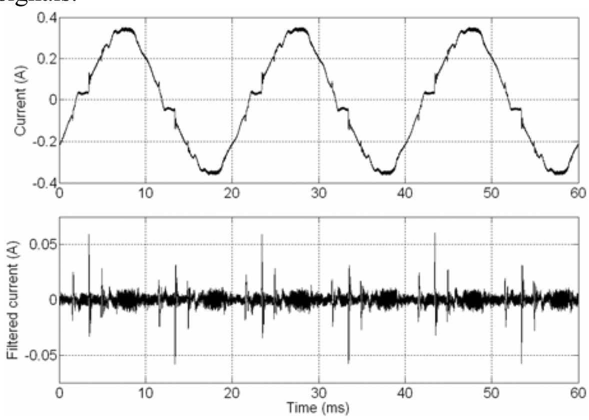

Figure 3. Current feeding a fluorescent lamp, taken from **[3].**

The authors claim the urgent need of standardization, showing that the current standard methods can lead to different results, even for the same method, due to the many parameters left undefined.

Other measurement methods

Frequency-domain methods appear to be unsuitable for power quality measurements, since supraharmonics are rarely constant but rather varying in frequency and/or magnitude, even within one fundamental cycle. Time-domain or time-frequency domain methods have shown to be more appropriate to detect short-time behavior and transients [5], [38], [39].
In this regard, the Short Time Fourier Transform (STFT) is typically used to characterize such features [3], [40]. It requires to divide the measurement interval in shorter windows and perform DFT in each window, assuming that the signal is stationary in each window. This way, a time varying spectrum is obtained and can be displayed as a spectrogram, as shown in Figure 4. However, STFT suffers from poor frequency resolution and important energy leakage. To overcome this issue, Alfieri et al., in [41], presented a modified Estimation of Signal Parameters by Rotational Invariance Technique (ESPRIT) method. They proposed the use of a Discrete Wavelet Transform (DWT) and a sliding-window modified ESPRIT method (SW MEM) in two successive steps. This parametric method is able to provide high accuracy for highly time-varying high-frequency components in the estimation of parameters e.g., frequencies, amplitude and phase. References [42] and [43] discuss the use of wavelets in two different approaches: DWT and Wavelet Packet Transform (WPT), respectively. Yalcin et al. proposed in [44] the use of an Ensemble Empirical Mode Decomposition (EEMD) method to decompose the supraharmonics waveforms into so called Intrinsic Mode Functions (IMFs). This strategy, which is at the base of the Hilbert–Huang transform, is an empirical approach, particularly suitable for nonstationary and nonlinear data. However it might be not compatible with the traditional harmonics analysis and is known to have issues in distinguishing different components in narrow-band signals [45]. Finally, Mendes et al., in [46], proposed a workaround to the high hardware and software requirements for supraharmonics measurement, taking advantage of the extended Nyquist theorem for signals of

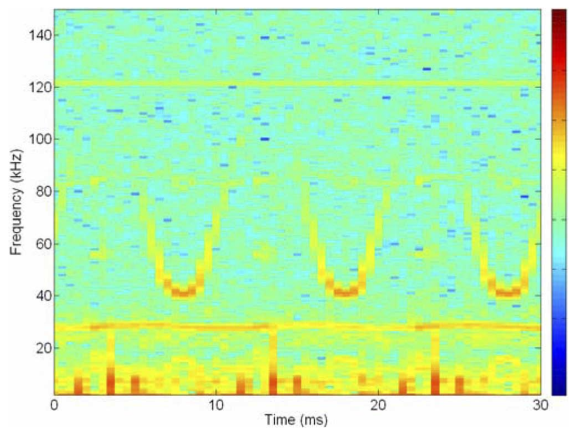

Figure 4. STFT spectrogram of the current feeding a fluorescent lamp, taken from **[3].**

band-limited spectrum. Such signals can be analyzed at a much lower rate than their maximum frequency. Combining this feature with band-pass filtering, the authors showed the possibility to reduce power quality analyzers requirements.

CONCLUSIONS

In this paper, two power quality disturbances that have recently started to attract more attention have been reviewed. It has been shown that supraharmonics lack of a standardized measurement method and that research is ongoing to find an appropriate measurement strategy. However, agreement is yet to be found. RVCs, instead, can count on a reference measurement method. This method, however, have been shown to have some drawbacks and works remain to be done to correctly define its relationship with flicker.

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