A Robust Measurement Method for Supraharmonics Under Power Frequency Deviations

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***Abstract*—This paper introduces a new measurement method for supraharmonic distortion with improved robustness against power frequency deviations. The proposed method is based on wavelet analysis and it is designed to analyze a 10 cycles measurement interval. Fourier-based methods, instead, must analyze a fixed 200 ms window in order to avoid apparent shifts of the supraharmonic frequency components. The results of the experimental measurements presented in the paper show that the Fourier-based method suggested in IEC 61000-4-7 standard produces results affected by the value of the power frequency. The proposed method, instead, provides results completely independent of the power frequency. This feature also removes the need of a previous high pass filtering stage, required for the IEC method. Moreover, the proposed method has the additional advantage of working on the same measurement interval as traditional harmonics (below 2 kHz), feature that can reduce the complexity of measurement instruments.**

***Index Terms*—High frequency distortion, power quality, supraharmonics, measurement techniques, voltage distortion**

I. Introduction

The distortion in the range from $2\,\mathrm{kHz}$ to $150\,\mathrm{kHz}$ (supraharmonics) is intrinsically different from the harmonic emission. The classical harmonic emission, in the range below $2\,\mathrm{kHz}$, is mainly made of waves whose frequency is a positive integer multiple of the fundamental frequency. Such waves are known as harmonics and, in power systems, the fundamental frequency is the power frequency (nominally $50\,\mathrm{Hz}$ or $60\,\mathrm{Hz}$, although in this paper only $50\,\mathrm{Hz}$ systems are considered). The term supraharmonics, instead, refers to the emission beyond (supra) the harmonic range, but not necessarily multiple of the power frequency. Thanks their nature, the use of Fourier analysis is a very effective way to analyze harmonics in power systems. The frequency resolution of the Fourier spectrum is given by $1/t$, where t is the measurement interval. Therefore, the Fourier analysis performed on an integer number of cycles of the fundamental wave provides a spectrum where the harmonic spectral components are perfectly represented by the resulting frequency resolution (assuming that the signal can be considered stationary and periodic). This is the case of IEC 61000-4-7 harmonics measurement method, that requires the measurement of 10 cycles of the power frequency f_N, resulting in a $f_\mathrm{N}/10$ frequency resolution, that matches the harmonic emission at f_N, $2f_\mathrm{N}$, $3f_\mathrm{N}$, etc. [1]. Even in the case of a slight deviation of the power frequency from its nominal value, the frequency resolution would still be a submultiple of the power frequency, regardless of its value, allowing a correct evaluation of all the harmonic components.

Supraharmonic distortion, however, is independent of the power frequency, as it typically originates from devices whose internal behavior is not correlated with the power frequency [2], [3]. Power electronic converters, whose emission depends on their switching frequency, are a typical example of devices where the supraharmonic emission is not a positive integer multiple of the power frequency. In this case, the Fourier analysis should be performed carefully, as some drawbacks could arise. In case of a deviation of the power frequency from its nominal value, as said, all its multiple frequencies will shift accordingly and the frequency resolution will change as well, modifying all the frequency bands. The supraharmonic components, however, are not affected by the deviation of the power frequency, maintaining their values. The resulting effect would be an apparent shift of the supraharmonic emission with respect to whole spectrum.

This effect is well known and, in order to avoid it, the IEC 61000-4-7 standard suggests performing the Fourier analysis of supraharmonics using a fixed $200\,\mathrm{ms}$ window, instead of the traditional 10 cycles window [1]. In this way the frequency resolution is fixed and no apparent shift is observed. This solves the problem of the apparent shift, but creates another issue. Fourier analysis is based on the assumption that the analyzed signal is infinitely periodic or, at least, strictly periodic inside the measurement window. However, in case of a deviation of the power frequency from the nominal value of $50\,\mathrm{Hz}$, a fixed $200\,\mathrm{ms}$ window will not contain exactly 10 fundamental cycles anymore. The periodicity assumption of

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the Fourier analysis is therefore not valid anymore, resulting in energy leakage across the frequency spectrum, especially from the fundamental component, which has the highest magnitude. Moreover, the use of a different measurement interval for harmonics and supraharmonics analysis requires flexible power quality analyzers, with two different processing threads, which increases their complexity and, therefore, price. This paper proposes a measurement method for supraharmonics analysis based on Wavelet Packet Decomposition (WPD), suitable for working with a 10 cycles window (synchronized measurement) without being affected by power frequency deviations. This feature makes the method more robust against typical deviations from ideal conditions. The robustness of the method is proved by showing that the drawbacks of a fixed $200\,\mathrm{ms}$ window approach are avoided without compromising the accuracy. Moreover, the proposed method does not require any pre-processing stage, while the Fourier analysis should be preceded by high pass filtering in order to achieve good accuracy under power frequency deviations. The rest of the paper is structured as follows: Section II presents the standard supraharmonics measurement methods and the proposed method. In Section III the robustness of the method is proved showing the results of the performed experimental measurements. Finally, the conclusions are presented in Section IV.

II. Measurement of Supraharmonics

A. Methods Existing in Standards

The supraharmonic distortion still lacks a commonly accepted measurement method [4]. A lot of research is being carried out and the development of international standards is still ongoing [5]–[7]. Currently, the informative Annex C of the IEC 61000-4-30 standard on power quality measurement methods describes three different approaches. The first one is the only one suggested for the $2\,\mathrm{kHz}$–$9\,\mathrm{kHz}$ range and coexists with the other two options for the $9\,\mathrm{kHz}$–$150\,\mathrm{kHz}$ range.

The first option ($2\,\mathrm{kHz}$–$150\,\mathrm{kHz}$) is the extension of the same measurement technique described in IEC 61000-4-7 for harmonics i.e., Discrete Fourier Transform (DFT), up to $150\,\mathrm{kHz}$. This method employs a $200\,\mathrm{ms}$ rectangular analysis window. The obtained spectral components are then grouped into $200\,\mathrm{Hz}$ bands, centered in odd multiples of $100\,\mathrm{Hz}$, via the Root Sum Square (RSS) [1].

The second option is to use the method of CISPR 16-1 [8], based on measurements performed in the frequency domain with a scanning receiver. Using a super-heterodyne analyzer, a narrowband filter is tuned on a $200\,\mathrm{Hz}$ frequency band and the CISPR peak, quasi-peak, and rms values are measured. The full bandwidth is covered by shifting the filter step-wise.

Finally, the third option is a new approach proposed in IEC 61000-4-30, again based on DFT analysis, but with some differences to the IEC 61000-4-7 method. An analysis window of 10 cycles is employed. Within this window, 32 approximately equally spaced measurements are taken, collecting 512 samples at $1024\,\mathrm{kHz}$ sampling frequency ($0.5\,\mathrm{ms}$) for each interval. The measured samples are then processed using DFT, resulting in a $2\,\mathrm{kHz}$-wide bands. For every 10 cycles window, minimum, maximum and average values are recorded. This last method is less accurate (wider bands) and less complete (more than $90\,\%$ of each window is ignored) than the previous ones, but it has the advantage of requiring less data storage and being less expensive.

It is important to note that the IEC methods based on DFT have fixed frequency resolution, as the measurement intervals are not synchronized with the power frequency. As a consequence, they suffer from important energy leakage from the fundamental component, as explained in Section I. As a possible mitigation strategy, the use of a previous filtering stage is suggested in the standard, although the exact filter specifications are not provided. In [9] a 3$^{\text{rd}}$ order elliptic digital filter is proposed, while in [10] a 10$^{\text{th}}$ order elliptic digital filter is proposed and implemented with a zero-phase filtering technique. Both High Pass Filters (HPFs) have been used in this work when implementing the IEC measurement method, along with the unfiltered implementation, in order to provide a complete comparison. More details on the measurement methods can be found in [7], [11].

B. Proposed Method

The WPD is a wavelet transform, introduced by Coifman, Meyer and Wickerhauser [12], that generalizes the link between wavelets and Multiresolution Analysis (MRA). The WPD is particularly suitable for harmonic analysis since an accurate selection of the decomposition structure can lead to uniform frequency bands of the desired size. For this reason, it has been proposed in the past as a tool for harmonics analysis, being especially effective under fluctuating conditions, where the basic requirements of the Fourier analysis (linearity and stationarity) do not hold [13]–[15]. In this work, the WPD is implemented through banks of filters. Although a supraharmonics measurement method based on (analog) filter banks was proposed in [6] with the purpose of reducing the sampling capability requirements of power quality analyzers, they are not to be confused. The method presented here is based on a recursive (digital) filtering and subsampling structure, derived from the wavelet theory. Only another approach to supraharmonics based on WPD can be found in the literature, in [16], but only a small fraction of the supraharmonic range could be analyzed (up to only $10\,\mathrm{kHz}$). Moreover, a frequency resolution of $1250\,\mathrm{Hz}$ and a measurement interval of (fixed) $80\,\mathrm{ms}$ were proposed, instead of the $200\,\mathrm{Hz}$, $200\,\mathrm{ms}$ used in IEC and CISPR standards. The method proposed in the present work is not only suitable for the whole frequency range but also provides results comparable with IEC and CISPR standards. Similarly to the implementation proposed in [14] for harmonics measurement, in this work at every decomposition step the signal is filtered using a Quadrature Mirror Filter (QMF) pair and then downsampled by a factor of 2, recursively. Starting from a signal made of 10 cycles of the power frequency (node 0), at every decomposition step each node is filtered in two further nodes whose bandwidth is half of the original one. Therefore, every decomposition step will create bands of half the bandwidth of the previous one. The first three

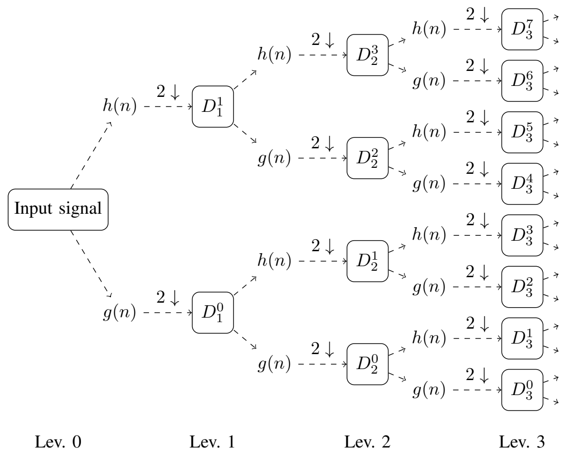


Fig. 1. Scheme of the first three levels of the WPD decomposition tree. The full decomposition tree is made of ten levels.

levels of decomposition are shown in Fig. 1, while the full structure is made of 10 levels. The initial sampling frequency of 409 600 Hz allows to obtain, for each node at the last level (10th), a bandwidth of 200 Hz i.e., the same resolution as the methods suggested in IEC 61000-4-7 and CISPR 16-1. The wavelet coefficients at level l, node i, are obtained from the convolution of the input signal at the previous level with the filters coefficients and subsequent downsampling.

$$D_{\mathrm{l}}^{2\mathrm{i}}(k)=\sum_{n}h(n)D_{\mathrm{l}-1}^{\mathrm{i}}(2k-n) \tag{1}$$

$$D_{\mathrm{l}}^{2\mathrm{i}+1}(k)=\sum_{n}g(n)D_{\mathrm{l}-1}^{\mathrm{i}}(2k-n) \tag{2}$$

where $i=0,1,\ldots,2(l-1)-1$ and $h(n)$ and $g(n)$ are low-pass and high-pass filter coefficients, respectively. The employed filters are Infinite Impulse Response (IIR) Butterworth QMFs of order 29, selected following the procedure described in [14]. The filtering is performed employing the Zero-Phase Filtering (ZPF) technique described in [17], which offers the advantage of keeping phase information, although in this specific work it is not strictly necessary. The output nodes of the WPD contain the energy of the associated frequency intervals and can be used for measuring their Root Mean Square (rms) amplitude:

$$x_{\mathrm{rms}}(l,i)=\sqrt{\frac{\sum_{\mathrm{k}}\left(D_{\mathrm{l}}^{\mathrm{i}}(k)\right)^{2}}{N}} \tag{3}$$

where $D_{\mathrm{l}}^{\mathrm{i}}(k)$ are the N coefficients at level l, node i. These values can be compared with the rms values obtained from the Fourier analysis proposed in IEC standards.

Beside being suitable for analyzing fluctuating signals, another interesting feature of the proposed method is the use of a 10 cycles rectangular measurement window, while IEC and CISPR methods rely on a fixed 200 ms window that, as discussed, results in large energy leakage. For this work, the 10 cycles window is obtained by detecting the zero crossing of the fundamental component. With this strategy, a precision of 2 µs on the window length was achieved. Moreover, this feature removes the need of using different measurement intervals for low and high frequency distortion and has the potential for reducing the complexity of power quality instruments.

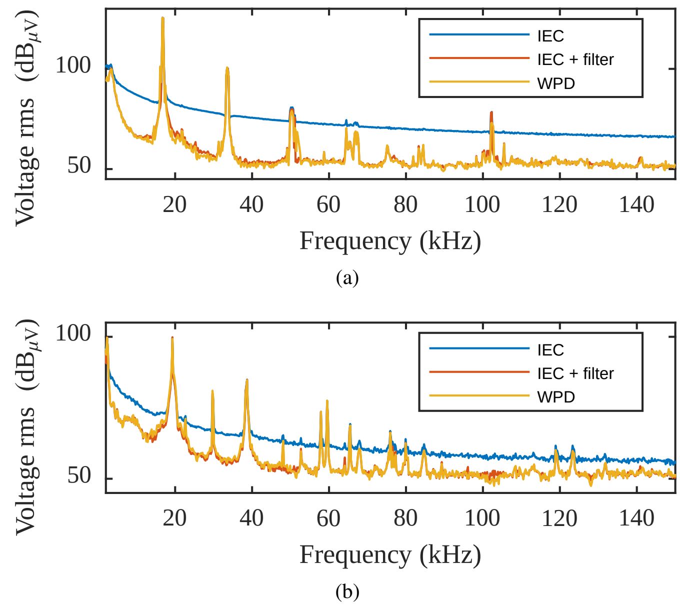


Fig. 2. Voltage of PV inverter (a) and an EV charger (b) measured on the grid and analyzed with the proposed method and the IEC method (with a previous filtering stage according to [9] and without filtering).

C. Examples of the Performance of the Proposed Method

In this section the performance of the WPD method is briefly illustrated, showing that the results match the performance of the Fourier method presented in IEC 61000-4-7, with very similar results (when proper filtering is implemented). A full characterization of the method performance is beyond the purpose of this paper. Among the three options described in II-A, in this paper only the first one, the IEC 61000-4-7 method (which will be called *IEC method* in the following), is considered for comparison, because of its full signal coverage, frequency resolution and simplicity. The second method (CISPR method) was developed to test equipment emission under laboratory conditions and, as stated in the IEC standard, it is considered too complex and expensive for in-situ power quality measurements. The third option (IEC 61000-4-30 method), instead, covers only the 8 % of the signal and with worse frequency resolution, making it unsuitable for comparison.

As an example, Fig. 2 illustrates the frequency spectra obtained with the proposed WPD method and the IEC method (both with and without a previous filtering stage). Fig. 2(a) shows the supraharmonic voltage emission of a Photovoltaic (PV) inverter, while Fig. 2(b) shows the supraharmonic voltage emission of an Electric Vehicle (EV) charger, both connected to the grid. Only for this comparison, and in order to better highlight the differences, the spectra are presented using logarithmic units $\mathrm{dB}_{\mu\mathrm{V}}$, which is defined using 1 µV as reference level (it follows that $0\,\mathrm{dB}_{\mu\mathrm{V}}$ correspond to 1 µV and each decade is represented by 20 dB). It can be seen that the WPD performance is very similar to that of the IEC method with a previous filtering stage. The IEC method without filtering, instead, has a worse performance, especially due to higher background levels, caused by energy leakage. The reason was found to be a deviation of the power frequency from its nominal value. It was indeed measured that the power frequency was $49.92\,\mathrm{Hz}$ in the PV case and $50.02\,\mathrm{Hz}$ in the case of the EV. This is not an uncommon situation in the grid, since small deviations are allowed. According to EN 50160 the power frequency must stay in the range between $49.5\,\mathrm{Hz}$ to $50.5\,\mathrm{Hz}$ during $99.5\,\%$ of a year for grids with synchronous connection to an interconnected system, and between $49\,\mathrm{Hz}$ to $51\,\mathrm{Hz}$ during $95\,\%$ of a week for grids with no synchronous connection to an interconnected system [18]. Fig. 2 shows that even a small frequency deviation can affect the DFT results.

D. Metrics

In order to quantify the differences between two spectra, a specific index – called Mean Spectra Difference (MSD) – is defined as follows:

$$MSD = \frac{1}{N}\sum_{\mathrm{bins}} 100\frac{|x_{\mathrm{i}} - y_{\mathrm{i}}|}{y_{\mathrm{i}}} \tag{4}$$

where $x_{\mathrm{i}=1,\ldots,\mathrm{N}}$ are the N bins of the first spectrum, while $y_{\mathrm{i}=1,\ldots,\mathrm{N}}$ are the N bins of the second spectrum, taken as reference. Therefore, the obtained value expresses the mean difference between the two spectra per bin, in percentage. In this work, the reference spectrum is the spectrum obtained at nominal power frequency $50\,\mathrm{Hz}$.

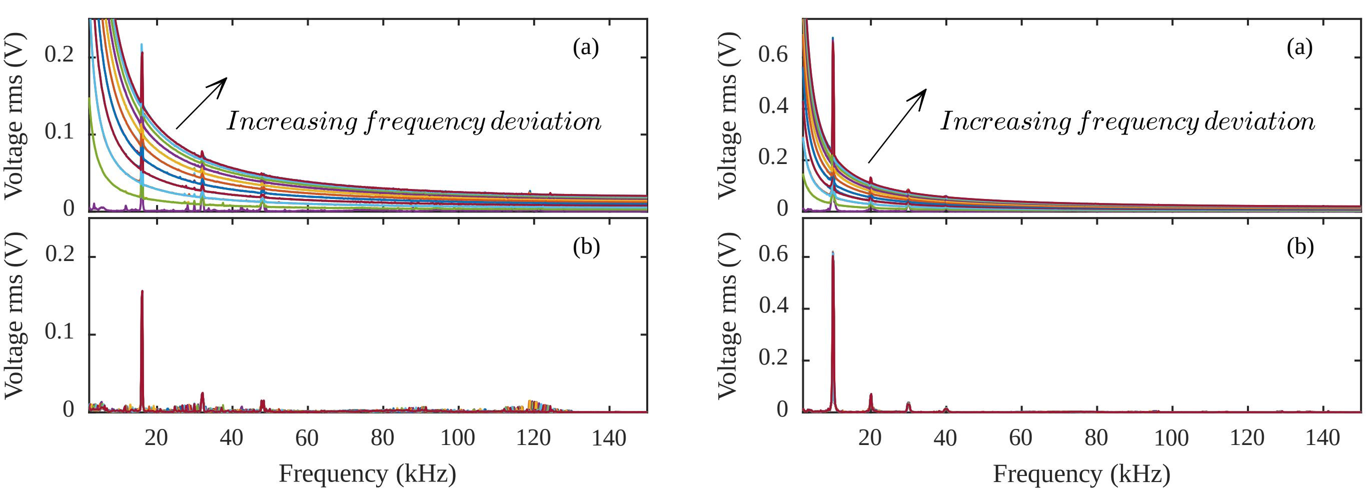
III. Robustness

This section presents the analysis of the robustness of the proposed method under power frequency deviations, and compares it to the IEC method based on DFT. The analysis is the result of a set of experimental measurements, taken at the point of connection of a PV inverter and an EV charging system (different than those presented in Section II-C). The measurements were performed under controlled laboratory conditions, initially at nominal power frequency $50\,\mathrm{Hz}$. In order to assess the robustness of the methods, the measurements were repeated with the same configuration but different values of power frequency f_{i}, ranging from $49.0\,\mathrm{Hz}$ to $51.0\,\mathrm{Hz}$, with $0.1\,\mathrm{Hz}$ steps. The results were then compared with the reference case of nominal power frequency and the deviations were quantified. The power supply, a pure sine wave at frequency f_{i}, was generated using a Spitzenberger & Spies PAS 15000, with a voltage output accuracy $< \pm 0.1\,\%$, from DC to $15\,\mathrm{kHz}$ ($-3\,\mathrm{dB}$). For every value of the power frequency, a voltage waveform was acquired using a Dewe 2600 measurement system and its voltage module (Dewetron HSI-HV), sampling at $1\,\mathrm{MS/s}$ and setting the measurement range to $\pm 400\,\mathrm{V}$. The reported accuracy for this range is given by $\pm\,(0.016f)\pm 0.1\,\%$ of range, where f is the signal frequency in Hz. The measurements resulted therefore in 21 spectra for each device under test and for each measurement method.

In order to assess the variation between the results obtained at different power frequencies and the reference case, three approaches were employed: (i) by measuring the MSDs between the spectra obtained at frequency f_{i} and the spectrum obtained at $50\,\mathrm{Hz}$ (Section III-A); (ii) by comparing the magnitude of the peaks located at the switching frequencies, for the different values of the power frequency (Section III-B); (iii) by measuring the MSDs between the spectra obtained at frequency f_{i} and the spectrum obtained at $50\,\mathrm{Hz}$, but excluding the peaks at the switching frequencies (Section III-C). This last approach allows to assess the variation of the leakage produced in the background.

A. Variations of Results with Power Frequency

Fig. 3(a) shows the 21 voltage spectra of the PV inverter obtained at different values of the power frequency, with the IEC method and with the proposed WPD method. Fig. 3(b)



(a) (b)

Fig. 3. Comparison of voltage spectra measured with IEC method (top) and WPD method (bottom) at varying power frequency. A PV inverter is shown in (a), while a and a EV charger is shown in (b).

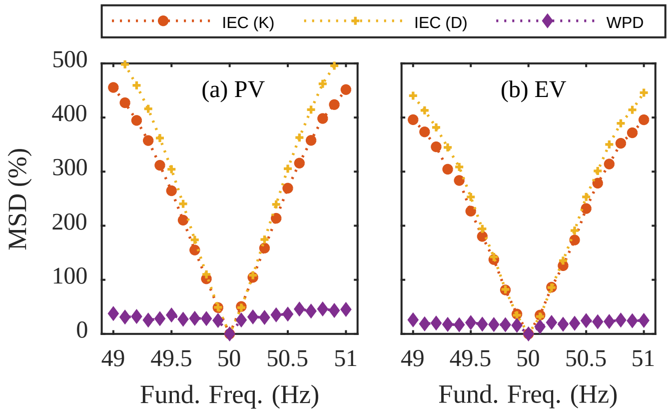


Fig. 4. Variations in the results of the different measurement methods at varying power frequency. The PV inverter is shown in (a) and the EV charger in (b).

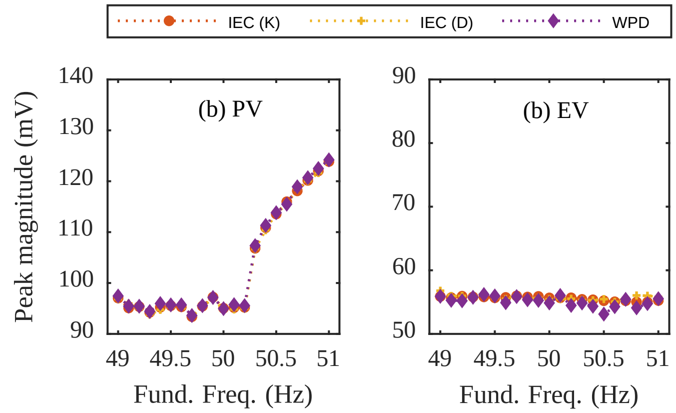


Fig. 5. Magnitude of the 16 kHz peak of the PV inverter (a) and of the 20 kHz peak of the EV charging system (b) at varying power frequency, assessed with different measurement methods.

shows the same comparison but for the EV charger. It can be seen that, although measuring the same signal, the IEC results show very large differences depending on the power frequency. This holds for both the EV charger and the PV inverter. On the other hand, the proposed method provides more stable results. High leakage is observed in the case of Fourier analysis, as expected, since the analysis window is not a multiple of the fundamental cycle. However, in all cases there is no shift in the position of the peaks, as expected, since the frequency resolution is fixed.

In order to quantitatively assess the variations, the MSD is calculated for every value of f_i for the following methods: the proposed WPD method, the IEC method with no filtering, and the IEC method with the implementation of two different HPFs: according to [9] (identified by letter K) and [10] (identified by letter D). The results are shown in Fig. 4. For the sake of clarity, the results of the IEC method without filtering are not plotted due to the large errors produced, one order of magnitude larger than the IEC method with the filtering stage. It can be observed that the results of the IEC method are largely affected by the power frequency. The larger the frequency deviation, the larger the difference between the spectra. It must be noted that the very high percentage values are due to the very low background values obtained in the reference case (50 Hz), which is at the denominator in 4. Moreover, it can be observed that the type of filter produces little differences in the results. The proposed WPD method is the only method that does not show any correlation with the power frequency. The MSD values are constant around 20 %, one order of magnitude less than the IEC method with the filtering stage. It is interesting to note that the behavior is the same for the two cases of the PV inverter and the EV charging system, regardless of their different power electronics topologies.

B. Magnitude of Switching Frequencies

Another possibility to assess the variation is to only look at the peaks corresponding to the switching frequencies and their multiples. As shown in Fig. 3(a), peaks at 16 kHz and multiples were detected, suggesting that 16 kHz is the switching frequency of the PV inverter, while from Fig. 3(b) it can be deduced that the EV charging system has a switching frequency of 10 kHz. One peak for each device was selected and its magnitude was compared with the magnitude of the same peak under different values of the power frequency, in order to track its variation. The selected peaks are the main peak of the PV inverter spectrum – at 16 kHz – and the second harmonic of the switching frequency of the EV charger spectrum, at 20 kHz. These peaks have been chosen for having similar magnitude. In both cases the two adjacent bands are included in the calculation (for a total bandwidth of 600 Hz) in order to cover the whole energy of the emission band, as suggested in [3]. Fig. 5 shows the magnitude of these peaks at varying power frequency. Again, both devices show the same behavior. In this case, the IEC method (not shown) still produces large, frequency dependent errors. In this case, however, the filtering stage is able to remove this effect, producing results that are independent of the power frequency. The proposed WPD method is also able to provide results with no correlation to the power frequency, and the results are comparable with those of the IEC method with a previous HPF stage. In the case of the PV inverter, with frequency higher than 50 Hz, a slight variation was observed. This behavior was attributed to the configuration of the PV and its response to power frequency deviations, rather than to the sensitivity of the method.

C. Magnitude of the Leakage

The last approach to assess the variation is complementary to the one discussed in Section III-B. In this case the focus is on the variation of every frequency component except those related to the switching frequencies i.e., the background content. In order to do so, the MSD is calculated as in Section III-A, but excluding the switching frequencies and their multiples from the calculation. Similarly to the procedure described in III-B, the adjacent bands are excluded as well, as they contain the energy of the switching frequencies. The results are shown in Fig. 6 and they can be interpreted as the average background

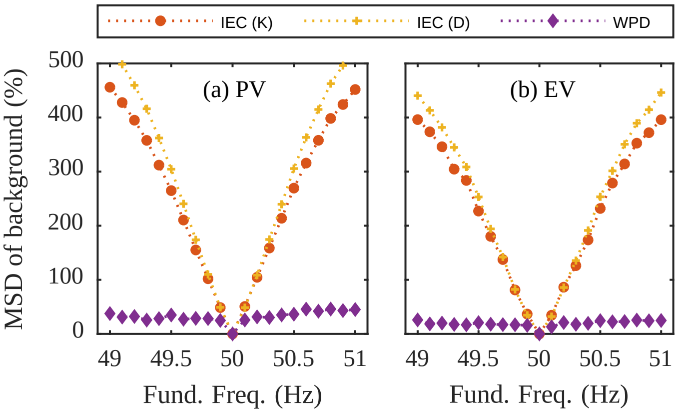


Fig. 6. Comparison of the variations of the background at varying power frequency, with different measurement methods. The PV inverter is shown in (a) and the EV charger in (b).

level. Any difference is due to energy leakage. Again, the IEC method without the filtering stage produces large errors and, therefore, is not plotted. The IEC methods with the filtering stage produce spectra whose background level is affected by leakage and largely dependent on the power frequency. The proposed WPD method, instead, shows lower background levels and it is insensitive to power frequency variations.

IV. Conclusions

The paper presented a novel WPD-based measurement method for supraharmonics. The proposed method analyzes a 10 cycles window synchronized with the power frequency and shows overall robustness against power frequency deviations, which is an important drawback of the Fourier-based methods proposed in IEC standards. The robustness has been compared with the IEC 61000-4-7 method through experimental measurements. The results of the proposed method are constant and independent of the power frequency value, both for the peak values and for the energy leakage. As expected, the IEC method performs worse, producing results that are largely affected by leakage and correlated with the value of the power frequency. It has also been shown that the implementation of a previous filtering stage, as suggested by the IEC standard, improves the behavior of the method, especially for the peak values, but does not remove the dependence on the power frequency of the background values. This could represent an issue in case of low Signal-to-Noise Ratio (SNR). The improved robustness makes the proposed algorithm suitable for environments with high frequency volatility, such as weak grids or islanded operations.

Moreover, the proposed method uses a 10 cycles measurement interval, synchronized with the power frequency, instead of a fixed 200 ms measurement interval. This is a valuable feature as it is the same measurement interval used for harmonics analysis and therefore allows to measure harmonics and supraharmonics on the same interval, which has the potential of simplifying measurement equipment.

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