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Supraharmonics in-situ measurements in distribution networks. An experimental case-study analysis of Standards-based metrics

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***Abstract*—This work presents an experimental on-field case-study analysis of Standards-based metrics for supraharmonics (SHs) measurements in distribution networks. IEC 61000-4-30 FFT-based metrics, with some proposed modifications, are compared with measurements according with CISPR 16-1-2, using as reference IEC 61000-2-2 and IEC 61000-2-4 for SHs emissions limits in 9-150 kHz frequency range. Measurements have been carried out on a commercial bidirectional power electronic converter (ac/dc and dc/ac) with a battery storage system, operating in both charging and discharging mode and with different power levels. To investigate the feasibility of the proposed approach, the analysis is extended to both voltage and current waveforms. The obtained results show that, with some modifications, IEC 61000-4-30 FFT-based metrics can provide information comparable with CISPR-based measurements, in the perspective of preliminary in-situ evaluation of SHs emissions levels and without the need of sophisticated on-field instrumentation.**

Keywords— power systems measurements, power electronic converters, supraharmonics, power quality

I. Introduction

Supraharmonics (SHs) are current and voltage spectral components, ranging from 9 kHz to 150 kHz. SHs have evolved as a critical concern in smart grids, due to wide usage of power electronics. This includes the integration of renewable energy sources and storage systems, as well as the mobility electrification, which have led to the increasing diffusion of advanced batteries charging technologies, power electronic converters (PECs) and electric drives designed to improve overall energy efficiency [1]. The trend in PECs is towards increasing switching frequency, primarily to enhance power density and to reduce the components size; but this can lead to generation of a variety of adverse effects, including interference with power line communications (PLC), increased power losses, thermal stress in critical components such as capacitors or transformers, electromagnetic interference (EMI), degradation of power quality levels and energy efficiency, and so on [2]. As the complexity of smart grids continues to increase, it has become ever more imperative to develop robust methodologies for detection, measurement, and analysis of SHs emissions, not only to ensure operational reliability and compliance with standards emissions levels, but also to guide the development of effective measurement-based mitigation strategies [3]. In this framework, different approaches have been proposed in literature for SHs measurement, but the definition of a univocal methodology is still an open issue [4]-[8].

From the Standards viewpoint, the use of the measurement method described in CISPR 16-1-2 standard is currently required to assess the compliance with harmonic emission limits in SHs frequency range [9]. This method provides detailed information for SHs emissions assessment. However, it is difficult to be widespread implemented for in-situ measurements, because of the need of expensive instrumentation. Other standards, such as IEC 61000-4-30 [10] propose the use of other simpler methods, mainly based on FFT analysis. Even if such methods are not intended to be used for compliance assessment with limits for harmonics and SHs emissions, the overall consistency with reference CISPR-based measurements would be useful to provide a more coherent information about power quality levels at in-situ metering section, for "pre-compliance" tests without the need of sophisticated on-field instrumentation.

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In this viewpoint, this work is aimed at investigating the compatibility of the aforesaid simpler metrics with the one described in the standard CISPR 16-1-2, using as reference the SHs emission limits in the 9-150 kHz frequency range, in accordance with IEC 61000-2-2 [11] and IEC 61000-2-4 [12]. Some modifications to the standards metrics are proposed, to enable a better comparison with CISPR results. To carry out the investigation, a real case-study has been considered, i.e. a commercial bidirectional PEC (ac/dc and dc/ac), connected to the low voltage electrical grid on the ac side and a storage system on the dc side. Different tests have been carried out, in both charging and discharging mode and with different power levels. The analysis is extended to both voltage and current waveforms, even if the aforesaid standards provide limits only for voltage. The obtained results show that, with some modifications, IEC 61000-4-30 FFT-based metrics can provide information comparable with CISPR-based measurements, in the perspective of preliminary in-situ evaluation of SHs emissions levels.

The paper is organized as follows. Section II presents an overview of standard requirements and indications for SHs measurements. Section III describes the Standards-based metrics considered for the analysis. In Section IV the experimental case-study setup is described, and some results of metrics comparison are presented and discussed.

II. Analysis of Standards requirements for SHs emissions assessment

From the current standardization point of view, power quality measurements and emission levels are well defined in the low frequency range (mainly up to 40^{th} or the 50^{th} harmonic of the fundamental power system frequency) in terms of both emission levels, measurement metrics and instrumentation metrological requirements. Harmonics measurements are covered in the IEC 61000-4-7 for both voltages and currents, and some requirements are given also for active power measurements. For higher frequency range, from 2 up to 150 kHz, no mandatory univocal solutions are given of possible metrics, instead.

For harmonic emissions evaluation and related limits, IEC 61000-2-2 [11] and IEC 61000-2-4 [12] are the main references for voltage. As regards the current emissions, reference is herein made to IEC 61000-3-12 [13], since it was considered for the certification of the PEC of the case-study system used for tests (the PEC is certified for CEI 0-21 [14] and related standards for equipment with a nominal power lower than 400 kW and a current below 75 A).

IEC 61000-2-2 defines compatibility levels for low frequency conducted disturbances and transmission of signals on public low-voltage supply networks [11]. The frequency range is from 0 Hz to 9 kHz, with an extension to 148.5 kHz for the transmission of signals over the network. The IEC 61000-4-7 method is indicated for harmonics measurement [15]. The signal is observed in a synchronized window of 10 cycles of the fundamental power system frequency, i.e. 200 ms for 50 Hz systems. The DFT/FFT is calculated, with a frequency resolution of 5 Hz up to the 50th harmonic, for instrument of the best class of accuracy (Class I). Grouping algorithm is then processed in 200 Hz band. Measurement must be aggregated over 3 seconds and 10 minutes time intervals.

IEC 61000-2-4 provides electromagnetic compatibility levels for industrial and non-public power networks with nominal voltages up to 35 kV and nominal frequencies of 50 or 60 Hz [12]. It does not apply to power supply systems used in ships, aircraft, offshore platforms, or railways. The specified compatibility levels formerly referred to conducted disturbances in the frequency range from 0 to 9 kHz, referred to the Point of Common Coupling (PCC) within industrial installations or other non-public networks. With the 2024 update, the extension of compatibility levels in the frequency range of 2 kHz to 150 kHz has been introduced.

In more detail, the current standard defines 4 categories of environment classes, which refer to different compatibility levels for conducted emissions:

- Class 1 - This class applies to protected power supply systems, for which harmonic compatibility levels lower than those for public networks are necessary. It relates to the use of equipment which is very sensitive to disturbances in the power supply voltage (e.g. electrical instrumentation in laboratories, special automation and protection equipment, special computers).
- Class 2L - This class is a legacy from IEC 61000-2-4:2002 (second edition) for compatibility levels up to the 40th harmonic. The IPCs (In-plant point of coupling) for class 2L, class 2a and class 2b correspond to the IPCs from the original class 2, hence the typical disturbance level in the frequency range up to the 40th harmonic in class 2L is expected to be similar to class 2a and class 2b. For the frequency range from the 40th harmonic to 150 kHz, class 2L is considered identical to class 2a.
- Class 2a - This class applies to IPCs (IPC1) in industrial locations at which no industrial power electronic equipment is intended to be connected (e.g. offices).
- Class 2b - This class applies to IPCs (IPC2) in industrial locations, at which industrial power electronic equipment is intended to be connected without a separation transformer to class 2a systems, but in which standard non-industrial equipment is also intended to be connected (e.g. light industry, commercial).
- Class 3 - IPCs (IPC3) in industrial locations which are separated by a separation transformer from areas in which non-industrial equipment is intended to be connected.

For the different classes, the limit value of each harmonic component and the compatibility levels are defined. The values of the limits for conducted emissions in 9-150 kHz for the different classes described in [12] are reported in Table I. For the 9-150 kHz frequency range, both IEC 61000-2-2 and IEC 61000-2-4 indicates the standard IEC 61000-4-30 as reference for harmonics measurement (see next section).

TABLE I - Compatibility levels for low voltage networks in the frequency range from 9 kHz to 150 kHz

Frequency Range (kHz)	Class 1, Class 2L, Class 2A - Uh dBμV	Class 2B – Uh dBμV	Class 3 - Uh dBμV
9 to 50	129,5 to 119	137 to 126,5	143 to 141
50 to 150	113 to 89	126,5 to 109	141 to 139

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As regards the current waveform, the standard IEC 61000 – 3 - 12 – "Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ⩽ 75 A per phase" is the main reference for the study herein presented. In this standard, the IEC 61000-4-7 method is indicated for harmonics measurement. For balanced three phase equipment (as in the case of the PEC used for the tests) the standard provides limits for single harmonic components, the Total Harmonic Current (THC) and the Power Harmonic Compliance (PWHC). However, no indications are provided for disturbances in the frequency range over 2 kHz.

III. Standards-based metrics for SHs measurements

A. *IEC 61000-4-30 indications*

IEC 61000-4-30 - "Testing and measurement techniques - Power quality measurement methods" reports, for the considered frequency range, three different methods [10]. It is important to note that no method is mandatory, and different solutions are still under consideration.

The first method is the one proposed in CISPR 16-1-2. As reported in the annex of the standard, this method is not optimized for in-situ power quality measurements because of its complexity and the large amount of data obtained. On the other hand, it is recommended for immunity and emission measurements for equipment under test (EUT).

The second method (named grouping-based method in the following) is an extension of the Annex C - IEC 61000-4-7 method (that is applied in the 2-9 kHz range) up to 150 kHz. The proposed method consists of a grouping process of the DFT output of the signal in bands of 200 Hz. Because of the amplitude of the considered range, a larger grouping bandwidth (1 or 2 kHz) is suggested. This solution can reduce the amount of measurement data, but the resolution penalizes the detailed analysis of a signal, and it may lead to results difficulty comparable with those of CISPR metrics.

A third approach is proposed (named 32-FFT method in the following), as an alternative to the previous method, leading to a resolution of 2 kHz but without the need of grouping process. It consists in acquiring the signal with a sampling frequency of 1.024 MSa/s and performing and FFT analysis on 32 equally-spaced windows of 512 samples (500 µs, frequency resolution of 2 kHz), extracted from the 10-cycles (of the power system frequency) synchronized window used for low frequency analysis, according to IEC 61000-4-7. Starting from these 32-FFT results, minimum, mean and maximum values of each spectral bin are evaluated. Even in this case, the frequency resolution is not well sized. In this viewpoint, possible modifications of the method could be envisaged to obtain a more suitable resolution and results more comparable with the CISPR metrics (see next section).

B. *Metrics under test*

For the case-study comparison herein presented, the IEC 61000-4-30 FFT-based metrics were analysed and compared, in both original and modified implementations. In more details, the following metrics were tested:

- Grouping-based method, i.e. the extension of the IEC 61000-4-7 method for the 9-150 kHz range with RMS grouping band of 0.2, 1 and 2 kHz, respectively. As detailed in the following, if a large grouping band is used, the total harmonic range can be covered with a low number of outputs to manage. However, for a detailed analysis of the spectrum or for the comparison of the results with those obtained with the CISPR method, a 0.2 kHz band is recommended.
- 32-FFT method, according to IEC 61000-4-30 settings, i.e. 1.024 MSa/s and observation window of 512 samples for each FFT. For the experimental setup used for the case-study system measurements (see next section) since data were collected with a sampling frequency of 500 kSa/s, i.e. 250 samples in the considered observation window of 500 µs, a third order interpolation algorithm was implemented to resampling the signal with an equivalent sampling frequency of 1.024 MSa/s and obtain the required number of points for FFT (512). The accuracy of this solution has already been evaluated in previous works [16]-[18].
- 16-FFT method; it is a proposed modification of the aforesaid 32-FFT method, where an observation window of 4096 samples is used for FFT calculations, so to obtain a more suitable trade-off between computational burden, frequency resolution and percentage of signal coverage in the reference 10-cycles synchronized window.

The first two methods are the most used and discussed in literature [6], [19]. In the viewpoint of their suitability for on-field measurements, both have their own advantages and drawbacks, in terms of resolution and computational cost. In detail, the implementation of the 32-FFT method requires the processing of a large number of outputs. In fact, for every set of 512 points, the FFT is processed, and the 9-150 kHz frequency range of interest is covered with 72 output bins. Thus, a total number of 72·32=2304 bins must be managed to calculate minimum, maximum and mean value of every harmonic component. Even adding the FFTs processing to the computational cost, the number of operations required for this method is drastically lower than the implementation of the grouping-based method. In fact, in the case of 2 kHz grouping band, a total number of 400 bins must be square-summed for every group and then the root mean square must be processed. If the frequency band for grouping is reduced, the number of operation-per-band decreases, but it is necessary to calculate a greater number of groups. In any case, to avoid aliasing phenomena in spectral analysis, sampling frequency should be higher than 300 kSa/s, leading to the need of acquiring and processing over 60 kSa in the required synchronized observation window of 10 cycles of the fundamental frequency (i.e. 200 ms for 50 Hz power system frequency).

Another aspect related to the 32-FFT approach is the percentage of signal coverage. In fact, the implementation of 512 points 32-FFT allows covering a low percentage of the signal. With a sampling frequency of 1.024 MSa/s, only a portion p_c, equal to 8% of the signal is covered, i.e.:

$$p_c = 32 \cdot 512 \cdot \frac{1}{1.024 \cdot 10^6} = 16\,\text{ms} \qquad (1)$$

Moreover, as deeply discussed in [5], the equally spaced 512 sets of points do not allow to detect periodic disturbances that may not occur in the covered signal portion. On the contrary, with the grouping-based method, the entire signal is analysed and, reducing the resolution of the grouping band, it is possible to evaluate the spectrum

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with increasing detail. However, possible problems may occur related to the non-stationarity and possible time-varying SHs emissions in the observation window of 10-cycles of power system frequency.

In this viewpoint, the proposed modified approach of the 16-FFT method can help in finding a better trade-off between the signal coverage percentage, the frequency resolution and the computational cost. In detail, in the proposed approach, 16 FFT on 4096 samples are performed (instead of 32 FFT, each with 512 samples). In this way, the portion of covered signal increases to 32%, i.e.:

$$p_c = 16 \cdot 4096 \cdot \frac{1}{1.024 \cdot 10^6} = 64 \text{ ms} \quad (2)$$

Despite the number of points n is four times higher, the number of operations for each FFT is $n\log(n)$, (instead of the n^2 operations required for the DFT). Moreover, in the perspective of using this metric with low-cost microcontroller devices (as already done for PQ measurements in low-frequency range [17]-[18]), the FFT implementation can be optimized and the processing time can be proportionally reduced. Moreover, with the increase of n, the frequency resolution is improved, achieving the value of 0.25 kHz for the case under study (against the value of 2 kHz, for the previous case of 512-points FFT calculation). This allows enabling a more coherent comparison of the 16-FFT method results with those of CISPR 16 - 1 - 2 and 0.2 kHz grouping-based methods. The comparison between the IEC 61000-4-30 approach (32-FFT method) and the modified one (16-FFT method) is depicted in Fig. 1.

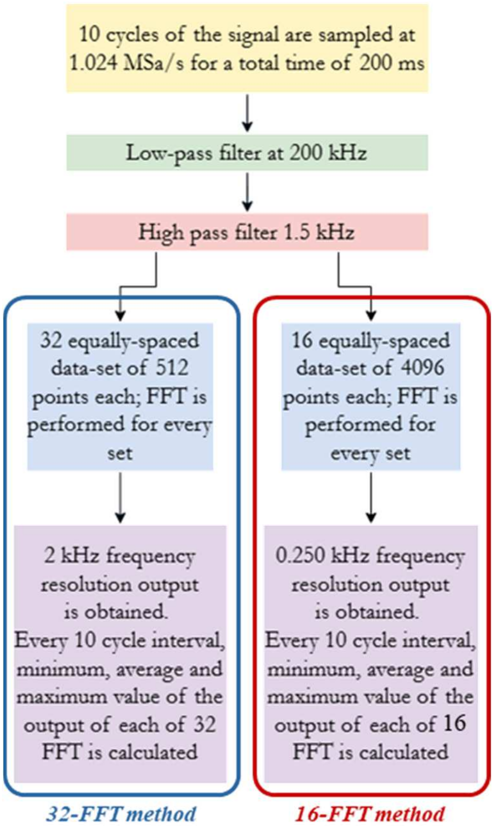

Fig. 1- Flow chart of 32 FFT vs. 16-FFT methods

IV. Experimental tests on case-study system

Experimental tests were carried out to evaluate the possibility of using the second and the third methods instead of the one described in the standard CISPR 16-1-2 for the evaluation of PQ levels in comparison with emission limits. In detail, a case study was set-up using a bidirectional three phase industrial power electronic converter of 20 kW nominal power. It was connected on the DC side to a Lithium-Iron-Phosphate storage system with energy capacity of 23.4 kWh. On the AC side, the power converter is connected to the low voltage (400 V, 50 Hz) electric grid.

The measurement test bench consisted of a National Instruments (NI) PCI eXtension for Instrumentation (PXI) system. It has three Data Acquisition boards (DAQs) NI PXIe-6124 (4 synchronous channels with 16-bit ADC, maximum sampling rate of 4 MHz, and maximum voltage dynamic of ±10V). This system was used for the acquisition of three ac voltages and four ac currents (including neutral), one dc voltage and one dc current, on the DC side of a three-phase power converter. Three voltage sensors LEM CV3-1000 (±1000 V, 500 kHz) [20] and three current sensors Pearson Current Monitor 411 (50 A, 20 MHz) [21] were used. DC current was monitored with a LEM CT 50-T current transducer, while DC voltage with a LEM CV 3-1500 voltage transducer [22]. Voltage and current signals were acquired with a sampling frequency of 500 kSa/s and processed with a virtual instrument (VI) in LabVIEW software. According to IEC 61000-4-30 requirements, a synchronized observation window of 10 cycles of fundamental frequency (i.e. 200 ms at 50 Hz) was chosen for the analysis. In the VI, the metrics described in section III were implemented. The signal processed in LabVIEW was also analysed with a spectrum analyser Tektronix RSA5103B (±0.3 dB absolute amplitude accuracy to 3 GHz) that can perform the CISPR 16-1-2 method with both Peak and Quasi-Peak specification.

Different tests have been carried out to evaluate if it is possible to use the proposed metrics instead of the CISPR 16-1-2 method for the evaluation of harmonic emissions in comparison with standard limits. In detail, the AC voltage and current of the converter, for the three phases, were acquired and processed in different condition:

- Battery charge mode (power acquired from the grid to recharge the batteries) for 5 different values of power (4, 8, 12, 16 and 20 kW)
- Battery discharge mode (power injected into the grid) for 5 different values of power (4, 8, 12, 16 and 20 kW)

In Fig. 2, Fig. 3 and Fig. 4, some results for the case of battery discharge mode are reported. The results show that, as expected, techniques using larger frequency bands (i.e. 32-FFT method and 2 kHz grouping-based method) do not provide comparable results with the method of the standard CIPSR 16-1-2, with values that can overcome the limits for allowed emission levels. This means that, in the perspective of on-field monitoring, results with such metrics could lead to warnings on emission levels, even if the system operating conditions are in compliance with the standards emissions levels. On the other hand, the 200 Hz band grouping algorithm allows to obtain results that are comparable with the spectrum analyser output. The same results are obtained for the 16-FFT method, but with less complexity if compared with the standard CISPR 16-1-2 method.

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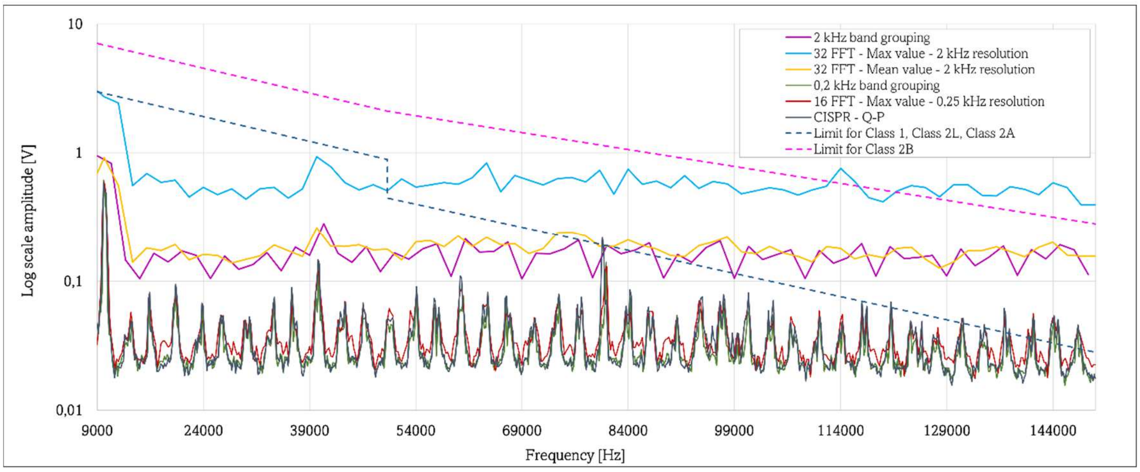

Fig. 2 - AC voltage spectrum (range 9-150 kHz) in battery discharge configuration with 20 kW power; comparison of tested methods results.

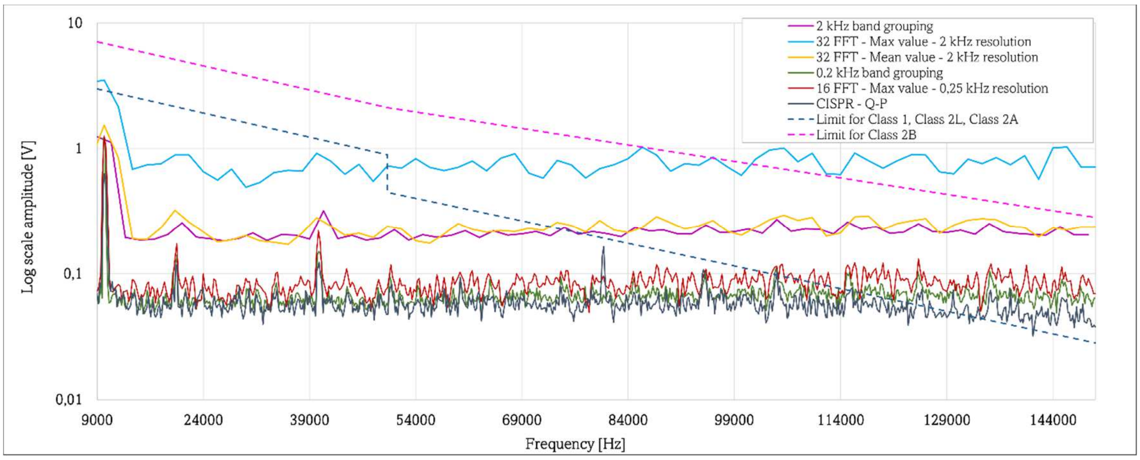

Fig. 3 - AC voltage spectrum (range 9-150 kHz) in battery discharge configuration with 4 kW power; comparison of tested methods results.

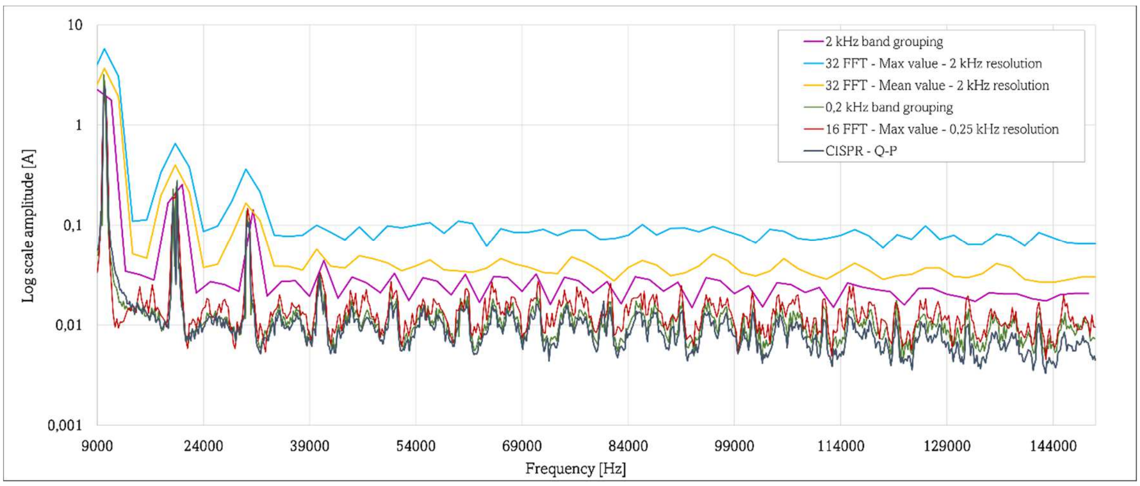

Fig. 4 - AC current spectrum (range 9-150 kHz) in battery discharge configuration with 4 kW power; comparison of tested methods results.

As regards the compliance with standard emission limits, the reason for the different behavior is mainly due to the coarser frequency resolution of the 2 kHz band grouping and 32-FFT methods, if compared with CISPR Q-P. In fact, in the first two methods, each bin captures higher energy from the signal. The results of these two methods are comparable (since they have the same frequency resolution), but they are substantially higher than those computed with the other methods. This consideration could suggest that higher emission limits should be used for such metrics, to properly assess the conducted emissions. On the other hand, the actual limits and finer frequency resolution, as in the case of CISPR Q-P, 200 Hz grouping or the proposed 16-FFT method, can allow detecting some peak disturbances which could go undetected with the increased limits. In fact, in the case of coarser resolution, the dominant bin would be grouped with other adjacent bins and compared with higher limits. But if those adjacent bins are very low in amplitude, the grouped value could remain below the increased limit, even if the single dominant bin is

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higher than the finer-resolution limit. In other words, the use of different limits for finer or coarser resolutions could result in conflicting results of emissions assessment, unless metrics use and limits definition are properly coordinated and standardized.

V. CONCLUSIONS

This work presented an experimental real on-field case-study analysis of Standards-based metrics for supraharmonics measurements in distribution networks, in 9-150 kHz frequency range. IEC 61000-4-30 FFT-based metrics have been compared with measurements according with CISPR 16-1-2, and some modifications have been proposed to improve the coherence among the various metrics. Measurements have been carried out on a commercial bidirectional power electronic converter (ac/dc and dc/ac) with a battery storage system, operating in both charging and discharging mode and with different power levels. The obtained results show that, with the proposed modifications, IEC 61000-4-30 FFT-based metrics can provide information comparable with CISPR-based measurements, in the perspective of preliminary in-situ evaluation of SHs emissions levels and without the need of sophisticated on-field instrumentation.

In this viewpoint ongoing research work is framed in the extension of the presented study to wider case-studies analyses, covering renewable-based generation/storage systems, electrical vehicles chargers and other PECs-based applications in the smart grid context. Moreover, starting from the adopted metrics, further metrological issues are under investigation, in terms of the measurement chain equipment requirements for the development of on-field instrumentation, with reasonable costs and proper accuracy requirements.

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