Metrics for Conducted Emissions Assessment up to 150 kHz in Grid-connected Systems with Power Electronic Converters

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***Abstract* – This paper presents an analysis of power quality metrics for conducted emissions assessment in ac/dc and dc/ac power electronic converters (PECs), in the frequency range from dc to 150 kHz. As regards the dc side, it is discussed how actual voltage and current waveforms can significantly differ from the ideal constant dc value and alternating components can have not negligible amplitudes. Also at ac side, voltage and current signals are not sinusoidal and they can be affected by the presence of harmonics in a wide frequency range, due to the PECs switching operation. In this framework, metrics to be adopted for conducted emission assessment are not univocally defined, and standards consider different approaches. In the paper the investigated metrics are those considered in current standards for power quality and harmonics measurements in ac systems in the different range up to 150 kHz. The same metrics are adopted for signals analysis at the dc side. The effectiveness of such metrics is investigated by means of experimental measurements, which have been carried out on a real case study test system, consisting of a grid connected PEC and a battery pack, operating in both charging and discharging mode.**

Keywords— power quality, conducted emissions, energy efficiency, power electronic converters, harmonics.

I. Introduction

Power electronic converters (PECs) for ac-dc and dc-ac conversion are crucial in smart grid, primarily due to their role in integrating different energy sources into the grid context and in improving grid efficiency, flexibility and sustainability [1], [4]. In fact, PECs are key elements for the exploitation of renewable energy sources, thanks to widespread diffusion of distributed generation and storage systems. For example, photovoltaic plants generate dc power, which must be converted into ac for enabling grid connection. Wind turbines often generate variable-frequency power, which must be stabilized and converted to the grid ac format through inverters. In smart grid, there is also a strong presence of battery systems for energy storage, which operate in dc, so their connection to the main grid is done by means of bidirectional PECs. They enable storage systems to feed electricity back into the ac grid when needed. Moreover, advanced PECs allow two-way power flow, enabling both charging (ac-dc conversion) and discharging (dc-ac conversion). On the other hand, their presence in power systems poses new issues on grid power quality (PQ) and energy efficiency (EE) levels. In this framework, one important aspect is related to the proper assessment of PECs conducted emissions.

From the standardization point of view, PQ measurements are enough well defined for ac systems, especially in the low frequency range (up to 50^{th} harmonic of the fundamental power system frequency). In higher frequency range, up to 150 kHz, indications are given of possible metrics, even if a consolidated and univocal measurement method is still missing [5]. Power measurements are also defined, although the management of the non-active component of the power due to harmonics and interharmonics is still under discussion [6]. PQ and EE in dc systems are still debated, instead. Ideally, measurements are defined without taking into account the presence of not negligible ac components, which generate a part of energy that is not usable for dc systems. The definition and measurement of dc PQ levels, particularly conducted emissions, is an open issue, as well.

In this framework, this paper presents an analysis of harmonic emissions in the range from the continuous component to 150 kHz, measured on a grid-connected energy storage test system, with a PEC and a battery pack, operating in both charging and discharging modes. The aim of the study is to investigate the effectiveness of the different metrics proposed by the standards IEC 6100-4-X, applied at both ac and dc sides voltage and current waveforms. In fact, considering the relationship between ac and dc components in a grid-connected system, it is interesting to apply the same metrics to both ac and dc measurements, also in the perspective of possible applications for power quality and energy efficiency analysis. In Section II metrics proposed by the standards IEC 61000-4-X are used and compared for ac measurements. In Section III, the same metrics are applied to the dc waveforms. The results are discussed in conclusions.

II. Evaluation of AC Conducted Emissions. Methods and Measurement Setup

To evaluate the harmonic content of alternate voltage and current, main reference is IEC 61000-4-30 "Electromagnetic compatibility (EMC) Part 4-30: Testing and measurement techniques - Power quality measurement methods" [5]. The measurement time interval (observation window T_w) for PQ parameters magnitudes is 10/12 cycles, for nominal power systems frequency of 50/60 Hz, respectively. The cycle measurements are then aggregated over larger intervals, the first of which is 150/180 cycle interval for 50/60 Hz power systems, respectively. In this study, a zero-cross function has been used to synchronize the observation window with the 10 period length required by the standard as already done in previous works concerning harmonic analysis [8], [9].

For harmonics measurement IEC 6100-4-30 refers to IEC 61000-4-7 [7]. Harmonic emissions measurement in low frequency range is processed up to the 40^{th} or 50^{th} order, for Class S or Class A, respectively (i.e. up to 2 kHz or 2.5 kHz, respectively, for 50 Hz fundamental power system frequency). For both classes of instruments, DFT or FFT are considered for spectral analysis, together with grouping in bands of 50 Hz around each harmonic frequency. The Standard IEC 61000-4-30 also contain, in Annex C, information for "conducted emission in the 2 kHz to 150 kHz range" as informative.

For the range from 2 to 9 kHz, the standard refers to Annex B of IEC 61000-4-7. The proposed method consists of a grouping process of the DFT output in bands of 200 Hz, around the central value of frequencies from 2100 to 8900 Hz, to cover the entire range. For the frequency from 9 to 150 kHz, the standard reports that three metrics are under consideration. The first one is an extension of the IEC 61000-4-7 method but with an extended range, up to 150 kHz. With a band of 200 Hz, the total number of outputs would be equal to 705 ($(150e3 - 9e3)/0.2e3$). To reduce the number of outputs, the band can be extended to 1 kHz or 2 kHz. A second and more complex metric is proposed, which can be schematized as reported in Fig. 1 flow chart. The third metric is the one proposed in CISPR 16-1-2. As reported in the annex, this method is not optimized for in-situ power quality measurements and it is complex to implement; for these reasons, it will not be taken into account in the following.

The measurements have been carried out on a test system built with a grid-connected PEC and a battery pack. More in detail, a single-phase ac/dc-dc/ac bidirectional PEC (rated power of 2 kW) was connected to the low voltage ac power grid (230 V, 50 Hz). A 9 kWh Li-ion battery was connected at the PEC dc side. The system was operated in both battery charging and discharging mode (i.e. energy absorption from the ac grid and energy injection into the grid, respectively). Measurements were taken at 50% and 100% of power converter rated power, in both charging and discharging mode. AC current was sensed by using a TCP312A Tektronix probe, and DC current with a TCP303. Each probe was connected to a TCPA300 Tektronix amplifier. AC voltage was sensed by means of a P5200A Tektronix differential voltage probe, and DC voltage with a GW Instek GDP 025 differential voltage probe. The transduced signals were acquired by means of a NI 9223 board (simultaneous sampling, 4 channels, 16 bits, $\pm 10\,V$ input range). Signals were simultaneously sampled at both ac side and dc side (see next section), at the maximum sampling frequency, equal to 1 MSa/s. Ac voltage and current waveforms are reported in Fig. 2 and Fig. 3, respectively.

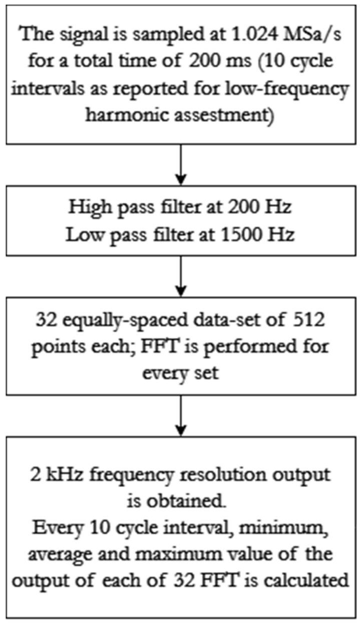

Fig. 1 - Flow chart of the second technique described in the IEC 61000-4-30 Standard

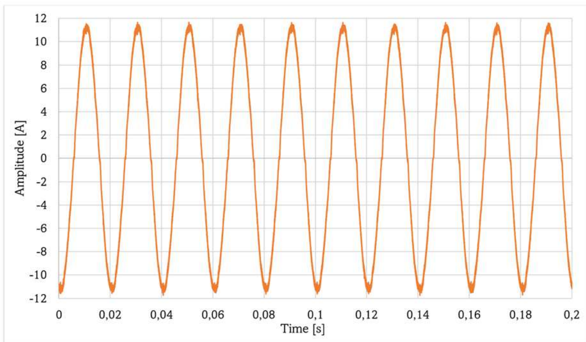

Fig. 2 - AC Current waveform - Discharging mode, 100% rated power

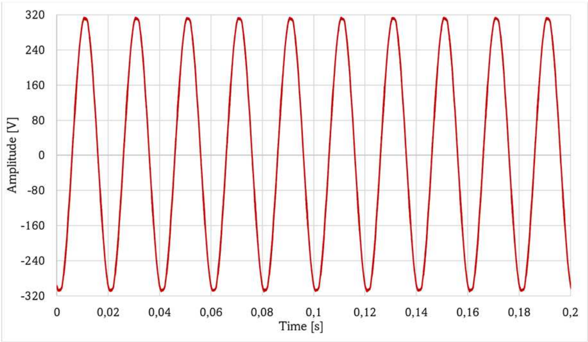

Fig. 3 - AC Voltage waveform - Discharging mode, 100% rated power

Signal processing was implemented on a LabVIEW virtual instrument, according to the aforesaid IEC 61000-4-30 and 61000-4-7 metrics.

The harmonic analysis results are shown in three different ranges: from zero to 2.5 kHz (50^{th} harmonic order according to IEC 61000-4-30 Class A requirement), from 2 to 9 kHz and from 9 to 150 kHz. As example, the voltage harmonic analysis is herein reported, for the case of the discharging mode test, with 100% rated power.

For 0-2.5 kHz range, harmonic analysis was carried out according to IEC 61000-4-7. The results are expressed as the output of the FFT carried out on a portion of signal equal to 200 ms, so the spectral resolution is 5 Hz (see Fig. 4).

For the range from 2 to 9 kHz, the method proposed in the standard described above was applied. The grouping of the output of the FFT was processed with a band of 200 Hz. The results are reported in Fig. 5.

The major pro of this method is that it is possible to enclose information for the entire range in a relatively low number of output values. On the other hand, the grouping doesn't allow having information about the single spectral component. For this reason, a band of 200 Hz can be a good compromise to fill this gap. The results are compared with the FFT in the same frequency range. The use of grouping allows having not detailed information about harmonic pollution; however such information can be managed more easily in terms of computation and memory requirements, if compared with detailed FFT analysis. Also, since the band is quite narrow, this method allows to evaluate the harmonic content with enough fidelity.

For the range between 9 and 150 kHz, the two metrics described above were implemented. More in detail:

- For the first metric, the outputs of the FFT with 5 Hz resolution were grouped in bands of 2 kHz.
- For the second metric, the signal, sampled with a sampling frequency of 1 Msa/s, was interpolated using a third-order time domain algorithm [7]. In this way a number of points equal to 204800 was obtained, i.e. those that would be obtained by sampling the same portion of signal (200 ms) at 1.024 MHz. The processed signal has been filtered according to the standard requirement. Minimum, maximum and mean value of every spectral component are calculated for the 32 FFT processed.

Advantages and disadvantages of these methods are widely discussed in literature [10]-[14]. Furthermore, standards are still in the process of being defined and they propose these metrics for possible, rather than mandatory, implementation.

For the range between 9 and 150 kHz, the two techniques are compared with the FFT processed for the entire sampled signal, i.e. with a spectral resolution of 5 Hz (see Fig. 6). The use of grouping has been already analyzed with pros and cons. In this range, that is wider than the 2-9 kHz one, the use of a band of 2 kHz instead of 200 Hz is recommended to reduce the number of outputs, but this reduces the detailed information about the spectrum.

The implementation of the 32 equally spaced FFTs has the main drawback of a huge number of outputs to be processed. For every set of 512 points, the FFT must be processed and the whole range is covered with 72 output bins (the lowest 8 and the upper 181 bins can be discharged). This means that a total number of $772 \cdot 32 = 2304$ bins have to be managed to calculate minimum, maximum and mean value of every harmonic component. But, even if the processing of the FFT must be added to the computational cost, the number of operations required for this method is drastically lower than the implementation of the method of 2 kHz band grouping. In fact, in the second method, for every group, a total number of 400 bin must be square-summed and then the root mean square must be processed. Those operations are quite expensive on a computational cost point of view [14].

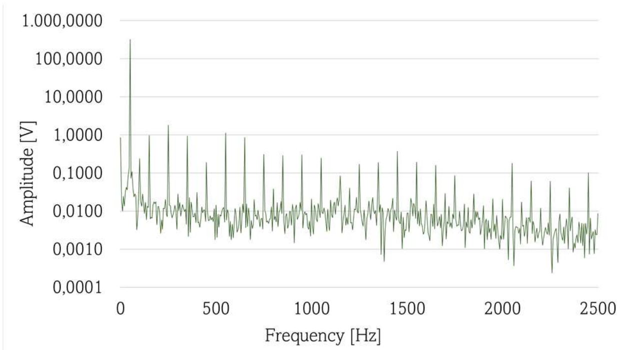

Fig. 4– AC Voltage FFT (log10 scale) output in the 0-2.5 kHz range

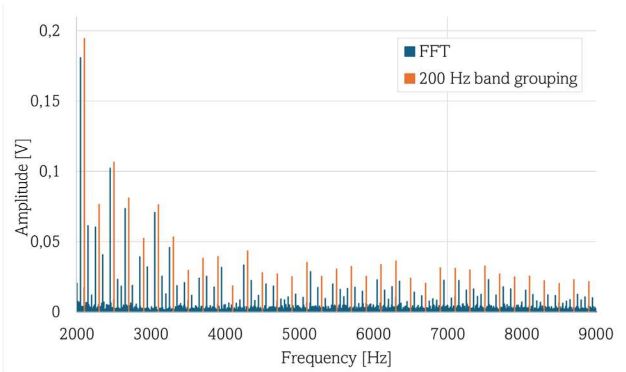

Fig. 5 – AC voltage FFT and grouping output in the 2-9 kHz range

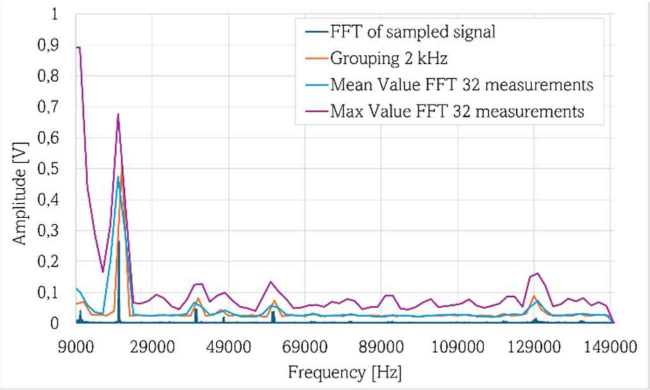

Fig. 6 – AC voltage FFT with 5 Hz resolution, FFT with 2 kHz resolution (mean and max values of the 32 FFT) and grouping output (with a band of 2 kHz) in the 9-150 kHz range

In Fig. 6 is also possible to appreciate that the results of the implementation of the 32 equally spaced FFTs provides the same information of the grouping method if we consider the mean value, but with the maximum value is possible to detect anomalies or harmonic hotspots. The main limitation of this method is that the equally spaced portion of signal cannot cover the entire signal and a phenomenon that appears in the same point of signal outside this portion cannot be detected (for example, this method is not effective with amplitude-modulated signal with variation in a period lower than the interval between the two considered portions [5])[1].

III. Application of metrics for harmonic analysis to DC signals up to 150 kHz

In a PEC that connects a dc storage system to the ac grid, voltages and currents at dc side can be far from the ideal constant waveforms [15]. Firstly, from a purely theoretical point of view, if the ac side power has a variable component, the same would be expected to happen to the dc side power, i.e. to the voltage and current, that will be time-variable as well. Moreover, under real operating conditions, the transformation of energy from ac to dc and vice versa already causes a distortion of the waveforms. The amount of difference between a perfectly sinusoidal quantity and a distorted one depends on the PEC operation (mostly switching), therefore, in the first place, on the PEC itself. Moreover, in real power systems, voltage and current waveforms entering the PEC are far from the ideal sinusoidal ones, even if the PEC presence is neglected. Since ac and dc signals are closely dependent, the presence of harmonic distortion on ac side is necessarily reflected on the dc quantities. In Fig. 7 and Fig. 8, the waveforms of both voltage and current on the DC side of the PEC used for the previous tests, are reported. From the figures it can be observed that a significant oscillating component (at 100 Hz) is present also on DC waveforms (specifically the current). This result is in accordance with the aforementioned studies in literature, where the correlation between the occurrence of such oscillations and the operation of PECs with batteries is discussed [13].

From the standardization point of view, metrics for the analysis of dc signals are still in the process of being updated. In fact, dc systems, whether stand alone or ac grid-connected via PECs, have gained great importance, since renewable sources have become a permanent part of the global energy landscape and also dc systems have gained growing interest (for transportation, dc microgrids, etc.). In this study, the aim was to show if and how the metrics for harmonic analysis used for the ac signals can be effective if used on dc signals, especially for grid-connected systems, where a reference for harmonic frequencies can be assumed from the ac side grid-connection.

To perform the analysis, dc voltages and currents obtained on the measurement setup described in previous section were processed. The IEC 61000-4-30 standard imposes an observation window of 10 fundamental periods of the 50 Hz voltage signal. To synchronize the sampling of the signals, the ac voltage was used as reference with the zero-cross function described in previous section.

The analysis was carried out for the same three frequency ranges analyzed for ac signals, i.e. from 0 to 2.5 kHz, from 2 to 9 kHz, and from 9 to 150 kHz. 0-150 kHz. It should be underlined that for a dc waveform it is not scientifically possible to refer to ac components as harmonics, because of the definition of DC waveform itself. However, considering the relationship between ac and dc components in a grid-connected system, in this paper ac components measured at the dc side are referred to as harmonics, as well. Some significant results are showed in figure from Fig. 9 to Fig. 14.

It can be seen that dc waveforms are highly affected by harmonics, in the whole frequency range of analysis. As regards the adopted metrics, the considerations made for ac signals, apply for dc signals as well, in terms of trade-off between quality of the information and computational and memory requirements. Moreover, depending on the conducted emissions levels and frequencies the different metrics can lead to different results in terms of overall quality of the waveforms. For example, in Fig. 11 significantly higher values are obtained with grouping if compared with the results of the mean and maximum values.

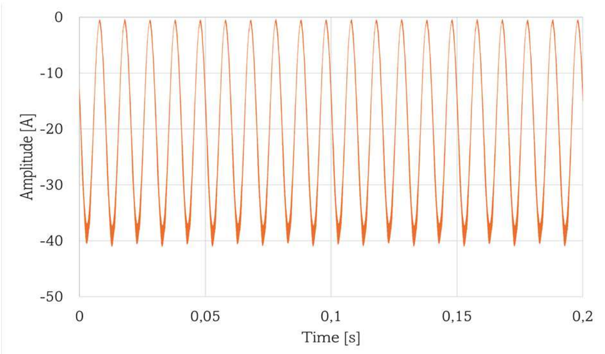

Fig. 7 - DC Current waveform - Discharging mode, 100% rated power.

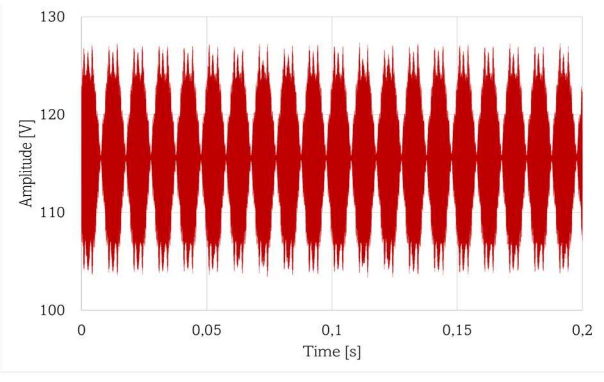

Fig. 8 - DC Voltage waveform - Discharging mode, 100% rated power

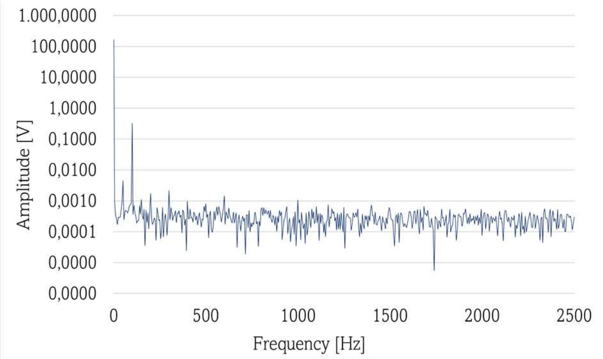

Fig. 9 – DC Voltage FFT (log10 scale) output in the 0-2.5 kHz range.

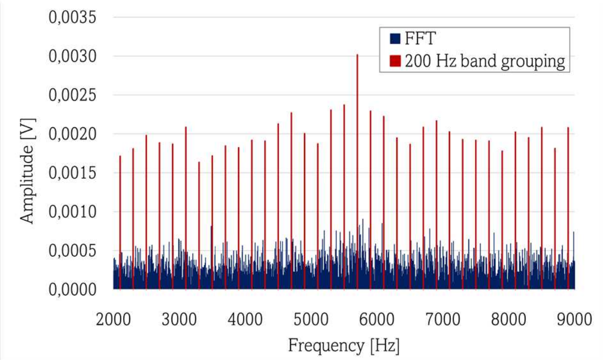

Fig. 10 – DC voltage FFT and grouping output in the 2-9 kHz range

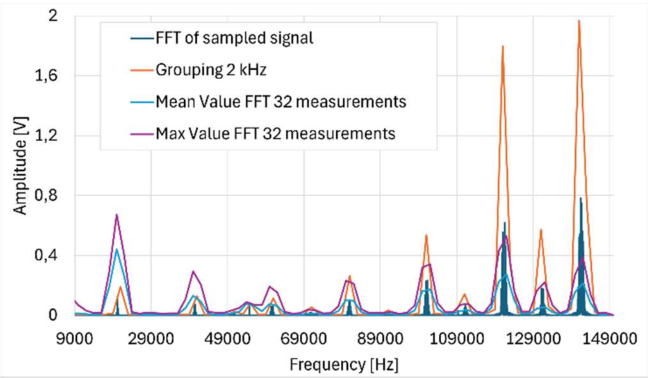

Fig. 11 – DC voltage FFT with 5 Hz resolution, FFT with 2 kHz resolution (mean and max values of the 32 FFT) and grouping output (with a band of 2 kHz) in the 9-150 kHz range

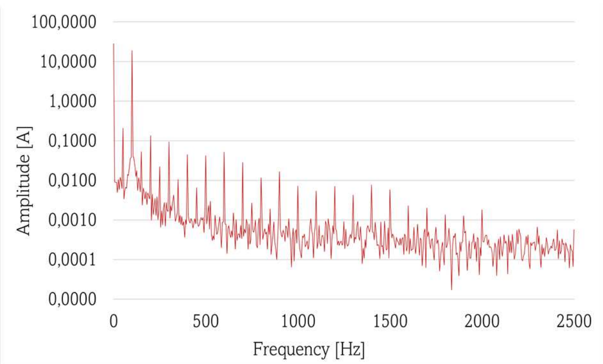

Fig. 12– DC current FFT (log10 scale) output in the 0-2.5 kHz range

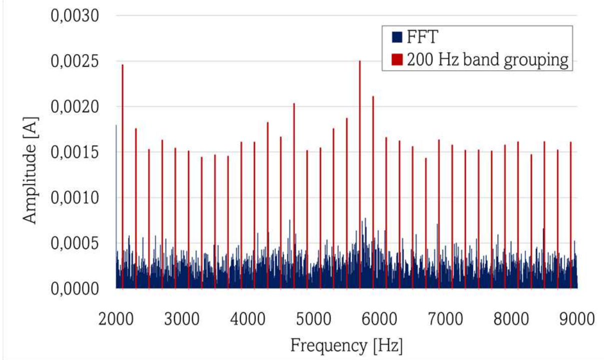

Fig. 13– DC current FFT and grouping output in the 2-9 kHz range

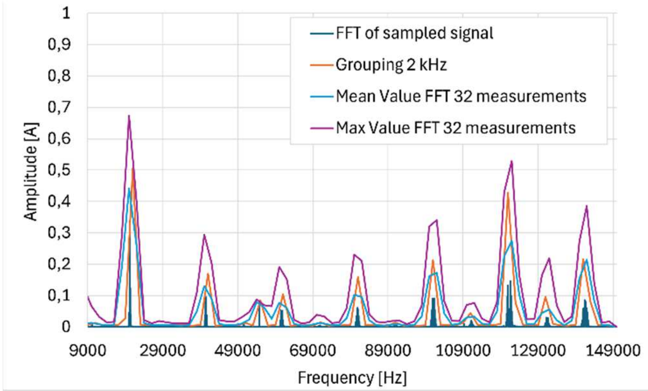

Fig. 14– DC current FFT with 5 Hz resolution, FFT with 2 kHz resolution (mean and max values of the 32 FFT) and grouping output (with a band of 2 kHz) in the 9-150 kHz range

IV. Conclusions

The aim of this work was to test PQ metrics for the measurement of low and high frequency harmonic components (up to 150 kHz) on both ac and dc side of power electronic converters (PEC), used to connect renewable-based distributed generation and energy storage systems. The study was carried out starting from the analysis of voltage and current signals collected at both ac and dc sides of a PEC connecting a storage system to the ac grid. Measurements were taken in both charging and discharging mode. The results showed that both ac and dc signals waveforms are far from the ideal ones (sinusoidal and constant, respectively) and there are harmonic components in the whole considered frequency range, which should be not present, instead (especially at the dc side). Moreover, the results showed that the adoption of different metrics can lead to different conclusions on the quality of the waveforms.

In detail, examples of voltage and current waveforms during the discharge phase, with rated power equal to 100% were reported in the paper. From the results analysis, it is clear that these components are not negligible, especially for the dc side, given that the proportion of useful energy is normally calculated with respect to the continuous component alone. From an energy point of view, conducted emissions and ac components overlapping the main dc one are the cause of several problems. First of all, harmonics entail overheating of cables, equipment and motors, other phenomena between circuit elements and an overall decrease of the quality of the electrical power supply, as well of the energy efficiency, as it happens in dc systems.

Batteries, regardless of type, may also be affected by alternate components during the charging phase. They may become overheated, behave in an abnormal way, have their performance reduced or, in the worst case, be damaged. These phenomena are going to increase with the growth trend of distributed solar and wind energy production sources, which require dc/ac or dual PECs, if a storage system is installed too.

It should be also considered that, as already mentioned, the issue is not yet well defined from a standard point of view. In fact, these problems have been addressed and they are still debated in scientific literature; however, it is not yet defined a standard metric capable to properly assess power quality levels and alternating components present in the voltage and, especially, in the current in dc systems.

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REFERENCES

[1] Azeem, Omar, Mujtaba Ali, Ghulam Abbas, Muhammad Uzair, Ayman Qahmash, Abdulmohsen Algarni, and Mohammad Rashid Hussain. 2021. "A Comprehensive Review on Integration Challenges, Optimization Techniques and Control Strategies of Hybrid AC/DC Microgrid" Applied Sciences 11, no. 14: 6242. https://doi.org/10.3390/app11146242

[2] A. Delle Femine, D. Gallo, C. Landi, M. Luiso, H. E. van den Brom, R. van Leeuwen, "Assessment of Quasi-Stationary Power Quality Phenomena in DC Power Systems", Measurement: Journal of the International Measurement Confederation, 2025, DOI: 10.1016/j.measurement.2024.115844

[3] G. Cipolletta, A. Delle Femine, D. Gallo, M. Luiso, C. Landi, "Design of a Stationary Energy Recovery System in Rail Transport," Energies 2021, 14, 2560. https://doi.org/10.3390/en14092560

[4] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung,"Ac-microgrids versus dc-microgrids with distributed energy resources: A review," Renewable and Sustainable Energy Reviews, vol. 24, pp. 387–405, 2013.

[5] IEC61000-4-30/ 2015-12-Electromagnetic compatibility (EMC) Part 4-30: Testing and measurement techniques - Power quality measurement methods

[6] IEEE Std. 1459-2010 Standard, "Ieee standard definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions,", Tech. Rep., 2010.

[7] IEC 61000-4-7 - 2008 "Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto"

[8] Artale, G., Cataliotti, A., Cosentino, V., Di Cara, D., Ditta, V., Guaiana, S., Panzavecchia, N., Tinè, G."Feasibility of IEC 61000-4-7 Class I Gapless Implementation of Harmonics Measurement on Low-Cost Microcontroller Device". In: 2024 IEEE 14th International Workshop on Applied Measurements for Power Systems (AMPS). pp. 1–6. IEEE, Caserta, Italy (2024)

[9] Artale, G., Cataliotti, A., Cimaz, L., Cosentino, V., Di Cara, D., Ditta, V., Dipaola, N., Guaiana, S., Panzavecchia, N., Sambataro, M., Tinè, G." Processing techniques for metrological improvement of low-cost smart meter hardware solution for IEC 61000-4-7 Class I harmonics" measurements. Measurement. 242, 115898 (2025).

[10] Frigo, G.: Measurement of Conducted Supraharmonic Emissions: Quasi-Peak Detection and Filter Bandwidth. Metrology. 2, 161–179 (2022). https://doi.org/10.3390/metrology2020011

[11] V. Khokhlov, J. Meyer, A. Grevener, T. Busatto and S. Rönnberg, "Comparison of Measurement Methods for the Frequency Range 2–150 kHz (Supraharmonics) Based on the Present Standards Framework," in IEEE Access, vol. 8, pp. 77618-77630, 2020, doi: 10.1109/ACCESS.2020.2987996.

[12] D. Ritzmann et al., "Comparison of Measurement Methods for 2–150-kHz Conducted Emissions in Power Networks," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-10, 2021, Art no. 9001110, doi: 10.1109/TIM.2020.3039302.

[13] A. Gallarreta et al., "Comparison of Measurement Methods for the Assessment of RMS Spectra in the 9-150 kHz Range," 2024 IEEE 14th International Workshop on Applied Measurements for Power Systems (AMPS), Caserta, Italy, 2024, pp. 1-6, doi: 10.1109/AMPS62611.2024.10706675

[14] Thais M. Mendes, Carlos A. Duque, Leandro R. Manso da Silva, Danton D. Ferreira, Jan Meyer, Paulo F. Ribeiro,"Comparative analysis of the measurement methods for the supraharmonic range", International Journal of Electrical Power & Energy Systems, Volume 118, 2020,105801, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2019.105801.

[15] D. Signorino et al., "Analysis of AC Oscillations in a DC Smart Grid," 2024 IEEE 14th International Workshop on Applied Measurements for Power Systems (AMPS), Caserta, Italy, 2024, pp. 1-6, doi: 10.1109/AMPS62611.2024.10706670