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Characterization of non-intentional emissions from distributed energy resources up to 500 kHz: A case study in Spain

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ABSTRACT

Narrow Band Power Line Communications (NB-PLC) systems are currently used for smart metering and power quality monitoring as a part of the Smart Grid (SG) concept. However, non-intentional emissions generated by the devices connected to the grid may sometimes disturb the communications and isolate metering equipment. Though some research works have been recently developed to characterize these emissions, most of them have been limited to frequencies below 150 kHz and they are mainly focused on in-house electronic appliances and lightning devices. As NB-PLC can also be allocated in higher frequencies up to 500 kHz, there is still a lack of analysis in this frequency range, especially for emissions from Distributed Energy Resources (DERs). The identification and characterization of the emissions is essential to develop solutions that avoid a negative impact on the proper performance of NB-PLC.

In this work, the non-intentional emissions of different types of DERs composing a representative microgrid have been measured in the 35–500 kHz frequency range and analyzed both in time and frequency domains. Different working conditions and coupling and commutation procedures to mains are considered in the analysis. Results are then compared to the limits recommended by regulatory bodies for spurious emissions from communication systems in this frequency band, as no specific limits for DERs have been established. Field measurements show clear differences in the characteristics of non-intentional emissions for different devices, working conditions and coupling procedures and for frequencies below and above 150 kHz. Results of this study demonstrate that a further characterization of the potential emissions from the different types of DERs connected to the grid is required in order to guarantee current and future applications based on NB-PLC.

1. Introduction

Distributed Energy Resources (DERs), including Distributed Generation (DG) and Distributed Storage (DS), are being progressively integrated in the Low Voltage (LV) section of the electrical network and their management needs to be accomplished for the proper functioning of the Smart Grids (SGs).

For this purpose, several technologies of NarrowBand Power Line Communications (NB-PLC) to provide data transmission in smart metering systems have been developed [1,2]:

- PRIME (PoweRline Intelligent Metering Evolution) specification [3], published by International Telecommunication Union in Recommendation ITU-T G.9904 [4], includes 2 versions: PRIME v1.3.6 [5] and PRIME v1.4 [6,7].
- G3-PLC specification [8], published in Recommendation ITU-T G.9903 [9].
- IEEE 1091.2 standard [10].

These NB-PLC technologies operate in the 3–500 kHz frequency range, which includes CENELEC bands (3–148.5 kHz) defined by the Comité Européen de Normalisation Electrotechnique, the FCC band (9–490 kHz) set by the United States Federal Communications Commission, and the ARIB band (10–450 kHz) specified by the Japanese Association of Radio Industries and Businesses [11]. Most of the recently developed communication technologies avoid the lowest frequency range (3–30 kHz) due to the high level of noise and interfering emissions existing in the electrical grid.

Although NB-PLC technologies allow the use of robust modulation and coding techniques, strong disturbances present in the transmission

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channel may degrade the communications in some cases. These channel disturbances are mainly non-intentional emissions in the NB-PLC frequency bands generated by devices connected to the electrical grid, such as electronic appliances and lightning devices, but also DERs such as photovoltaic (PV) inverters, battery chargers, hydropower systems or wind turbines. As more renewable power generators, electric vehicle (EV) chargers and energy-efficient devices are added to the grid, the number and amplitude of the emissions increases. The proper characterization of the different types of non-intentional emissions is required to know in advance the potential interferences that NB-PLC will have to face. As a reference, in December 2017, the IEC established a joint working group of TC77A and CISPR SC/H to define requirements for the regulation of emissions from 2 kHz to 150 kHz, in order to ensure the compatibility of electrical products. CENELEC has recently recommended the analysis of the non-intentional emission levels both in time and frequency domains also [12].

Moreover, the characterization of non-intentional emissions in the electrical grid has been mainly limited to the frequency range up to 150 kHz; however, there is an increasing interest in Europe to extend the frequency range for NB-PLC up to 500 kHz. As few field measurements have been carried out for these higher frequencies, particularly for DERs, a detailed characterization of the different types of non-intentional emissions in the frequency range up to 500 kHz is needed, in order to estimate if these emissions might cause problems in the communications, and therefore, if they should be limited through regulation. A potential solution is that the future coding techniques used by NB-PLC in these higher frequencies must be adapted to face the different types of disturbances of the propagation channel, in order to ensure the data transmission.

In this paper, non-intentional emissions generated by different types of DERs that compose a representative microgrid have been measured and characterized in the frequency range from 35 kHz to 500 kHz. This frequency range includes current and expected frequencies used by the above-mentioned NB-PLC transmission technologies. Field measurements were carried out according to the measuring methods recommended by CISPR (Comité International Spécial des Perturbations Radioélectriques) for compliant receivers, including two types of detectors: CISPR quasi-peak and CISPR average [13–15]. The emissions recorded in the field measurements have been compared to the limits defined by the European Standard EN-50065-1 for conducted perturbations from mains communicating equipment [16], as no specific limits for DERs have been established. The results of the paper will help to enable the proper performance of NB-PLC in an electrical grid with a high number of DERs.

The paper is organized as follows. First, non-intentional emissions analyzed in different previous measurement campaigns are summarized in Section 2. Then, in Sections 3 and 4 the measurement campaign that has been specifically carried out in this work and the analysis of the results obtained from measurements are thoroughly described, respectively. Finally, the main conclusions, including the potential effect of non-intentional emissions on NB-PLC, are described in Section 5.

2. Non intentional emissions generated by devices connected to the grid

Throughout the literature, non-intentional emissions have been mainly classified in three different types [17,18]:

- Impulsive noise: the switching procedure of power transistors used to DC/AC conversion generates impulsive signals of high amplitude around 100 kHz and above.
- Harmonics of the switching frequency: switching devices generate spurious signals in multiples of the switching frequency, which is usually above 10 kHz, or in other cases even above 20 kHz to be inaudible.
- Colored background noise: this kind of noise is usually higher in lower frequencies and it can be characterized by several sources of white noise in non-overlapping frequency bands.

CENELEC, the European committee for electro-technical standardization, launched the SC 205 Working Group 11 to promote, gather and analyze non-intentional emissions in electrical grids, and to determine adequate immunity levels for communications. The problematic of non-intentional emissions is summarized in the study report SC 205 A of CENELEC [12]. Additionally, the IEC has launched a joint working group of TC77A and CISPR SC/H to define requirements for the regulation of emissions, in order to ensure the compatibility of electrical products in the frequency band assigned to NB-PLC.

According to the requests of these regulatory bodies and standardization committees, in this report, some examples of non-intentional emissions generated by a wide range of devices for the 2–150 kHz range are analyzed, and at a lower extent, for frequencies up to 500 kHz:

- Power supplies: These devices usually include a small inverter that employs switching techniques and, as observed in some measurement campaigns, the levels of the generated non-intentional emissions could be high [19–21]. It was also demonstrated in other studies based on measurements that the power supplies of different electronic devices generated emissions that affected the NB-PLC [22–29].
- Electronic devices including inverters: The power devices that include inverters (such as elevators or uninterrupted power supplies) are being more frequently used both in commercial and residential environments [30]. Some research carried out in different environments with different types of inverters (including PV systems) proved that the harmonics of the switching frequencies reached considerable levels [19,31,32]. The non-intentional emissions generated by devices such as PV inverters, inverters for the control of engines or the ones included in some washing machines sometimes disturbed the communications [23,33–37].
- Electric tools: Tools such as drills and saws also generated emissions, in this case, up to 500 kHz, as demonstrated in [19].
- Lightning equipment: The non-intentional emissions generated by compact lamps, fluorescent lamps and LED lamps were also analyzed in some measurement campaigns up to 500 kHz [38–40]. In other studies, it was observed that the communications between different devices were sometimes lost [41,42].
- Other equipment such as the rectifiers included in cell towers and fiber switches sometimes affected the communications [43,44].

This Working Group is now demanding recent results in this area that provide the basis for updated criteria and reference levels [12].

Apart from the study report SC 205 A of CENELEC, other measurements campaigns have been carried out in the last years, although the analyzed frequency range has been mainly limited to 2–150 kHz [18,45–59]. All these studies demonstrate the need to carry out additional field measurements, mainly for DER devices, due to the wide variety of devices that generate emissions of different nature, level and variation in time and frequency.

In many of the described studies, the voltage levels were usually compared to limits defined by CISPR specifications:

- Non-intentional emissions generated by lightning equipment (CISPR15, EN 55015) [60].
- Non-intentional emissions generated by induction cooking equipment (CISPR11, EN 55011) [61].
- Intentional emissions generated by mains communicating equipment (EN 50065-1).
- Non-intentional emissions generated by mains communicating equipment (EN 50065-1).

These limits, together with the voltage limits for intentional

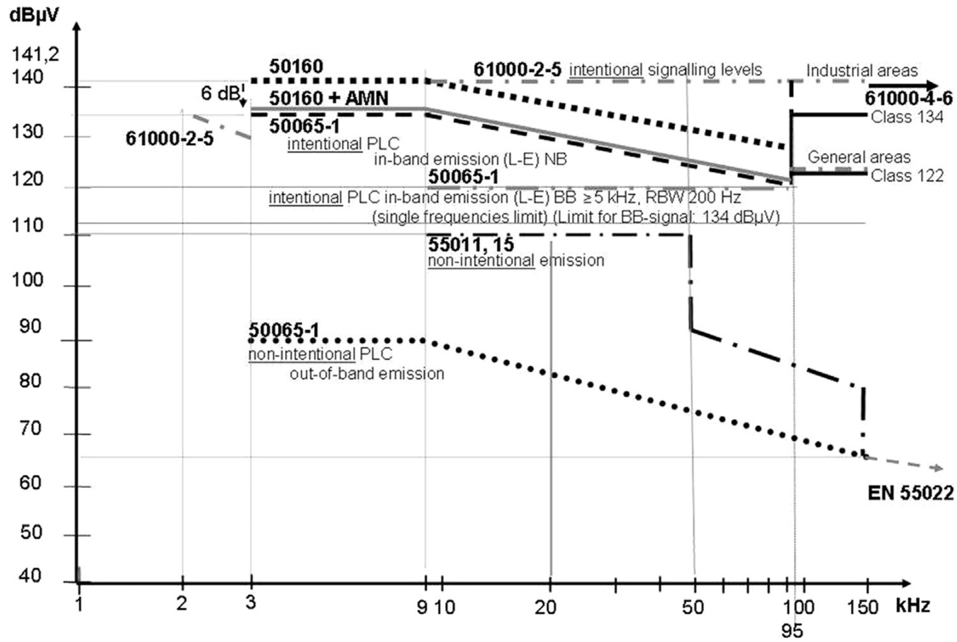

Fig.1. Recommended emission limits below 150 kHz for different scenarios [64]. The curve on the bottom represents the limits for non-intentional out-of-band emissions from PLC transmitters.

communication signals given in IEC 61000-2-5 [62] and the limits given in EN 50160 [63], related to electric power quality, were published by IEC in the document TS 62578 Ed. 2:2012 [64] (see Fig. 1).

However, specific limits for non-intentional emissions from DERs and other types of equipment have not been established yet, so that the limits for perturbations generated by mains communicating equipment given in EN 50065-1 have been generally used as a reference [18]. These specific limits are labeled in Fig. 1 as 'non-intentional PLC out-of-band emission'. A compelling reasoning for this assumption is proposed in [45], based on the fact that the emission limits for PLC devices according to EN 50065-1, which are the most restrictive limits, should be applied to ensure the proper performance of the communications. For this reason, in the present study, the non-intentional emissions obtained in the field measurements will be compared to the limits determined by EN 50065-1 for PLC devices, shown in the above-mentioned curve, at the bottom in Fig. 1.

Additionally, the EN 50065-1 defines different levels of the limits, considering that CISPR quasi-peak and CISPR average detectors can be used [13–15]. Originally, these detectors were defined to be implemented by analog components; nowadays, they are usually implemented using digital signal processing, as in this work [13]. The quasi-peak detector is intended to detect the maximum values of the signal, but applying RC filtering in order to smooth the transitions, as the peak value is reached after the charging time of the charge RC filter and the discharge transition is flattened by the response of the discharge RC filter. The output of these filters is then sent to another filter that simulates a critically damped meter. In the case of the average detector, it averages a set of input values and again the result is fetch to a critically damped meter. The charging and discharging RC filters and the critically dumped meter are digitally implemented by IIR filters. The curves determined by EN 50065-1 for PLC devices, considering quasi-peak or average detectors, are represented in Fig. 2, up to 500 kHz. Unlike Fig. 1, they are represented in linear scale, to facilitate a direct link to the results of the field measurements.

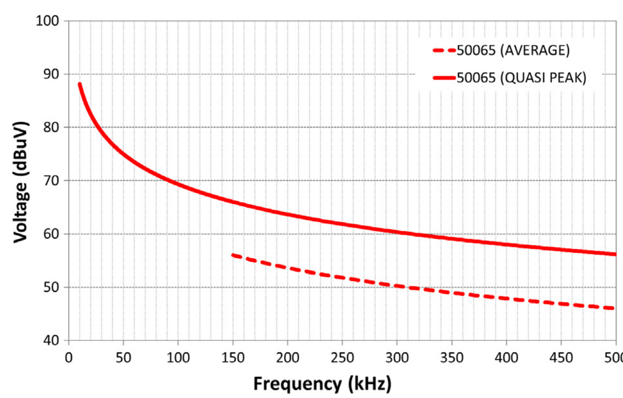

Fig. 2. Limits determined by EN 50065-1 for non-intentional out-of-band emissions for PLC devices, up to 500 kHz, in linear scale.

3. Measurement campaign and data processing

3.1. Microgrid equipped with distributed energy generation and storage

The measurement campaign was carried out at CEDER-CIEMAT facilities, a national institution for the research, growth and promotion of renewable energies, where a real microgrid was installed to be managed and monitored [65]. As Fig. 3 shows, this microgrid is composed of seven Medium Voltage (MV) to Low Voltage (LV) Transformation Centers (TCs), each TC provided with one or two Power Transformers (PTs). A wide range of DG and DS systems are present at the different LV parts of the microgrid, including PV inverters, batteries and battery chargers, wind turbines, and a hydropower system composed of a turbine and a pump. They form a representative distributed microgrid that includes distributed renewable generation, storage and consumption. Each device is provided with a smart meter (SM) that implements PRIME v1.3.6 standard for advanced metering, control and monitoring.

Fig. 4 shows a more detailed scheme of one of the seven TCs of the microgrid (PEPA III). This is one of the two centers with two PTs, so that two LV branches are linked to this TC. In one branch, three single-phased PV inverters (PV1, PV2 and PV3) and a battery charger (BC) are

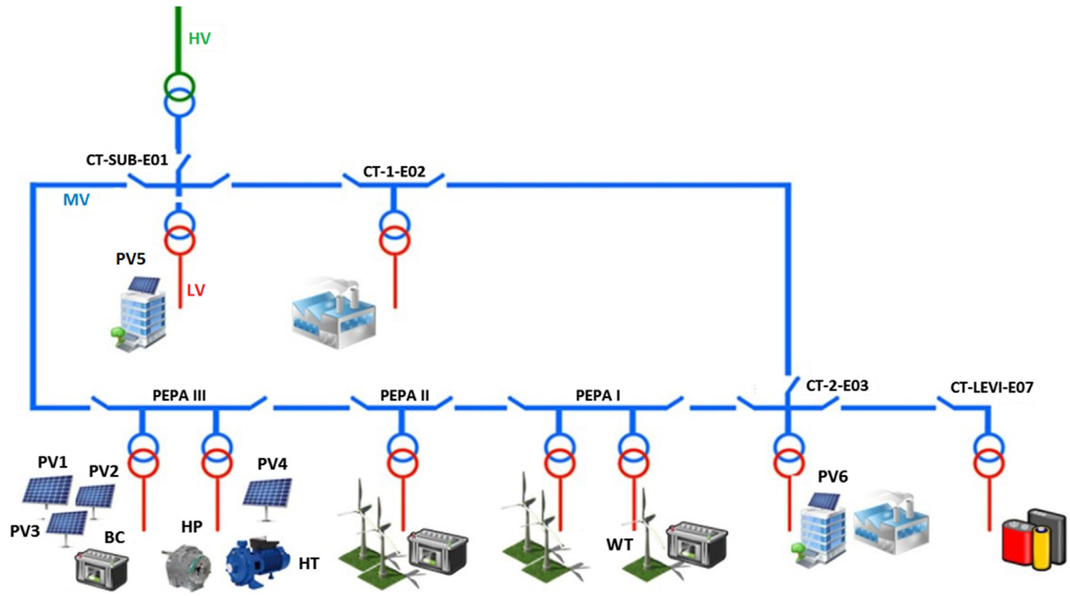

Fig. 3. Outline of the electrical architecture of the microgrid at CEDER-CIEMAT [65].

located; in the other branch, a three-phased PV inverter (PV4), the hydropower turbine (HT) and the hydropower pump (HP). Measurements of potential non-intentional emissions from all of these devices in the frequency range up to 500 kHz were recorded.

Measurements were also taken in a wind turbine (WT) located in a LV branch of the other TC provided with two PTs (PEPA I in Fig. 3). Finally, potential non-intentional emissions from rooftop PV panels located in two office buildings were also recorded and analyzed (PV5 and PV6 in Fig. 3).

Table 1 summarizes the most relevant features of the devices included in the analysis. As it can be observed, the microgrid under test is a representative example of a medium-size microgrid, and the DERs that compose the microgrid are typical devices of common microgrids based on renewable resources.

Table 1
List of the main features of the devices included in the analysis (operating power, switching frequency of the inverters and corresponding TC.

Type of device	Features	TC
Hydropower turbine (HT)	60 kW, three-phased	PEPA III
Hydropower pump (HP)	18 kW, three-phased	PEPA III
PV inverter (PV1)	5 kW, single-phased @ 16 kHz	PEPA III
PV inverter (PV2)	5 kW, single-phased @ 16 kHz	PEPA III
PV inverter (PV3)	5 kW, single-phased @ 16 kHz	PEPA III
PV inverter (PV4)	15 kW, three-phased @ 16 kHz	PEPA III
PV inverter (PV5)	10 kW, three-phased @ 5 kHz	CT-SUB-E01
PV inverter (PV6)	10 kW, three-phased @ 5 kHz	CT-2-E03
Battery charger (BC)	8 kW, single-phased	PEPA III
Wind turbine (WT)	3.2 kW, single-phased	PEPA I

3.2. Measurement methodology

The measurements were performed between the neutral and the phase at the input of the associated SM of each device (in the three-phased elements only one of the phases was considered).

Measurement set was composed of the following equipment:

- TABT-2 – LV capacitive coupler [66], which allows measuring the NB-PLC signal and/or the noise present at that point. The frequency range of this device is 10–600 kHz.
- Anritsu MS2690A Signal Analyzer [67]. This measurement equipment operates from 50 Hz to 6 GHz.

The Anritsu MS2690A Signal Analyzer digitizes and records the measurement data in IQ (In-phase, Quadrature) samples, which allows signal post-processing for spectral and temporal analysis. This is in line

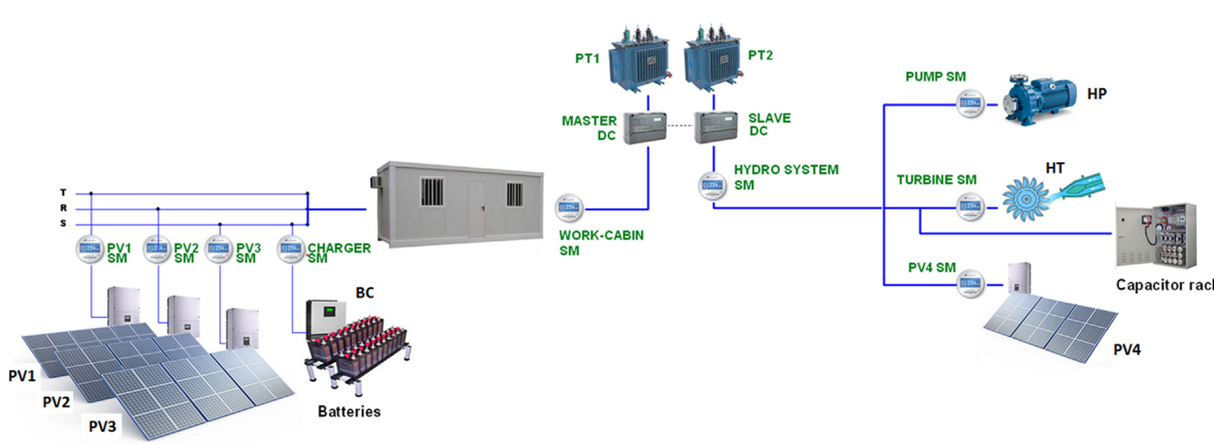

Fig. 4. Scheme of PEPA III TC and the DERs in the LV branches [47].

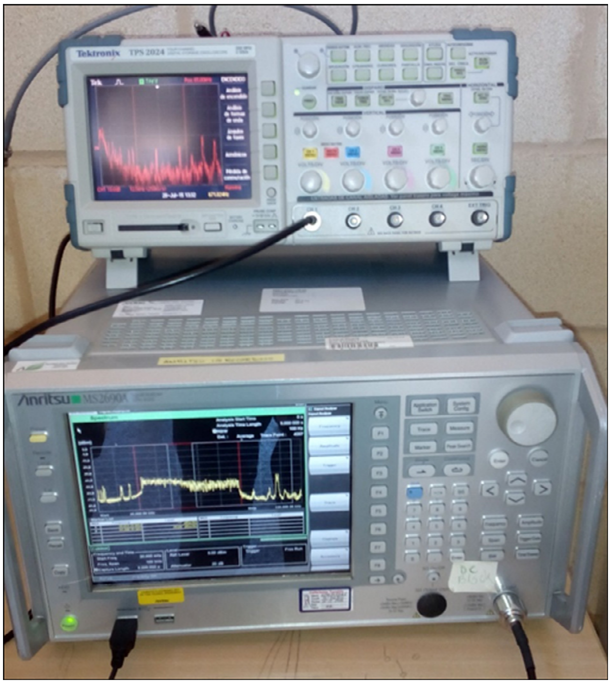

Fig. 5. Field trials: measurements developed by an oscilloscope and the Signal Analyzer used in the study.

with the recent recommendation from CENELEC to analyze the non-intentional emission levels both in time and frequency domains [12].

Signal analyzers have two advantages when compared to oscilloscopes. First, the signal analyzer used in these measurements provides 16 bits of resolution, which represents a higher resolution with respect to the common high-speed Analog-to-Digital Converters ADCs. Second, longer measurement periods can be recorded when a signal analyzer is used. In these field trials, it was decided to limit the measurement interval of each IQ file to 5 s, which allows the analysis of the signal variations during the common performance of the devices, including the transition periods between different operational states. The frequency range was limited to the band of interest from 35 kHz to 500 kHz, as it includes current and expected frequencies for the above-mentioned NB-PLC transmission technologies in Europe. Fig. 5 shows a snapshot of the trials previous to the field measurements, where a comparison between the results provided by an oscilloscope and the above-mentioned Signal Analyzer was carried out.

With the purpose of characterizing each device, avoiding the potential influence of contiguous devices in operation in the same LV branch, each device under test was electrically isolated during the measurements. Only PV5 and PV6 did not fulfill this requirement, as it was not possible to isolate the inverters of these devices from other equipment located in the same building.

Since the measurements were recorded in form of IQ samples, the spectral analysis was carried out by applying the Fast Fourier Transform (FFT) to time domain scan, which reduces significantly the measurement time without degrading the accuracy of the results. This method meets the requirements of the specification published in CISPR 16-1-1 [13], which includes the use of FFT-based instruments in standard-compliant measurements.

3.3. Data processing

The datasets obtained in the field measurements were processed according to CISPR specifications [13–15]:

- A Gaussian time-windowing composed of a 6 dB bandwidth of 9 kHz in the 150–500 kHz range and a 6 dB bandwidth of 200 Hz in the 35–150 kHz range was applied.
- A time overlap of more than 75% is required to ensure that measurement uncertainty of the pulse amplitude remains within ± 1.5 dB. An overlap of 93% was employed in this case, in order to ensure that this condition was fulfilled.
- The frequency step size should be equal or less than the half of the required values of 6 dB bandwidth. Accordingly, in this analysis the number of points of the FFT was selected to be a quarter of the required bandwidth (50 Hz for the 35–150 kHz range and 2.25 kHz for the 150–500 kHz range).
- The required charge and discharge time constants and the meter time constants for quasi-peak and average detectors were digitally implemented by means of Infinite Impulse Response (IIR) filters.
- The minimum measurement time was 10 ms in the 35–150 kHz band and 0.5 ms in the 150–500 kHz band [15]. In these trials, longer measurement intervals were used, in order to characterize the signal time-variability of the emissions.
- The time slots where PRIME v1.3.6 signal bursts were present were removed, in order to avoid that the communication signals distort the results and to ensure that only non-intentional emissions were considered.

Following this methodology, the quasi-peak and average voltage values of the non-intentional emissions generated by each device were obtained. Then, they were compared to the limits defined by EN-50065-1, which proposes quasi-peak voltage limits for the frequency range up to 500 kHz, but average voltage limits only for the 150–500 kHz range, as it has been described in Section 2. This comparison provides useful information to evaluate the significance of the non-intentional emissions recorded in the measurements.

Spectrograms of each recorded IQ sample set were also calculated and represented in a color scale, in order to analyze the evolution in time of the Power Spectral Density (PSD) values. Hence, both spectral and time performance of each device in different working regimes could be properly characterized. A Gaussian time-windowing of 200 Hz bandwidth was used for this purpose, with a 50 Hz step size.

Additionally, the variability with time of the emissions was quantified by calculating the standard deviation of the signal envelope (in a 200 Hz or 9 kHz bandwidth, depending on the frequency range, according to CISPR specifications [13–15]).

4. Results

In this section, the results of the measurement campaign are described. They show graphically and numerically the amplitude and variability of the non-intentional emissions of each device for different working regimes. Results are classified according to the DERs that compose the microgrid.

4.1. Hydropower system

The hydropower system is composed of a CMC Hydro Pelton turbine [68] with a three-phased asynchronous IPS generator [69] and a Sterling SIHI pump [70]. The turbine generates energy from the water flow falling from a tank located in a higher place, while the pump is activated sporadically to refill the tank.

4.1.1. Hydropower turbine (HT)

Fig. 6 shows the spectrogram of the non-intentional emissions of the HT during the coupling to the mains power process. During the coupling process, the PSD levels of the non-intentional emissions were considerably higher, mainly for lower frequencies. Once the HT was coupled and working at a normal condition (ON state in the spectrogram), a set of harmonics of 9.1 kHz of decreasing amplitude was generated by the HT. This is related to the fact that the asynchronous generators are generally designed to have various power electronics

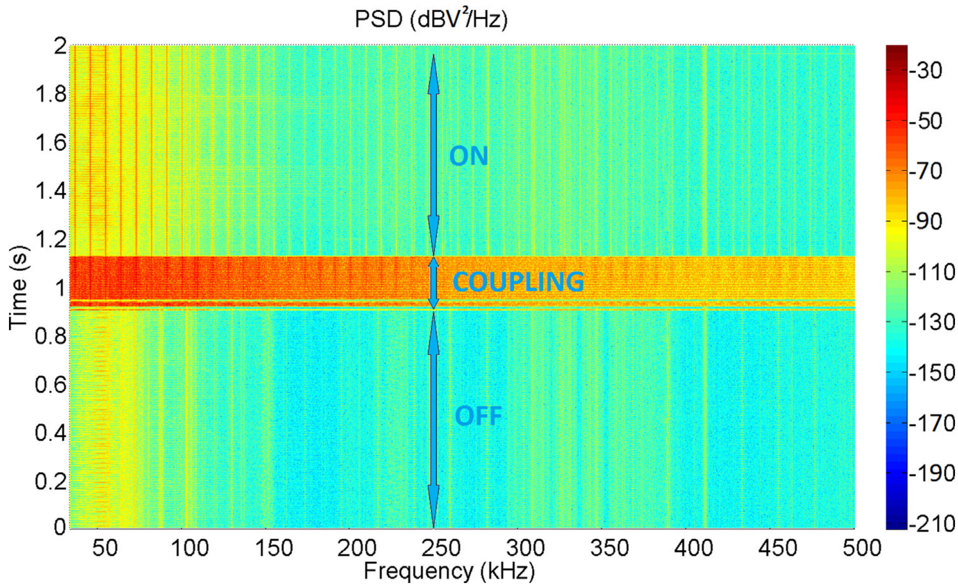

Fig. 6. Spectrogram of the non-intentional emissions of the HT during the coupling to the mains power process.

converters, which internally apply switching techniques [71–73]. Therefore, harmonic frequencies are multiple values of the switching frequency of the switching device of the turbine.

Fig. 7 shows the quasi-peak and average voltage levels of non-intentional emissions of the turbine in normal operation (ON state), together with the limits stated in EN-50065-1. Results show that harmonics of 9.1 kHz were generated by the HT over colored background noise, without exceeding the limits (except a single narrowband component at 102.4 kHz).

It should be noted that the sharp transition at 150 kHz is caused by the different bandwidth values used in the time-windowing applied for frequency ranges below and above 150 kHz, as described in the data processing procedure, and it is not due to a sudden increase of noise level at these frequencies. It should also be reminded that EN-50065-1 proposes quasi-peak voltage limits for the whole frequency band, but average voltage limits are defined only for the 150–500 kHz range; this is the reason for calculating the average levels only for this range.

As the coupling process occurs in a very short time (approximately in 0.2 s), shorter than the time constants used to calculate the quasi-peak and average voltage levels, representative values of the coupling process cannot be calculated. However, the PSD levels obtained in the spectrogram indicate that the voltage levels were considerably higher during this short time period.

Regarding the time variability during ON state, standard deviations values were in the range from 1.5 to 3 dB for harmonics of 9.1 kHz, whereas in the rest of frequencies, standard deviation values between 5 and 9 dB were obtained.

In order to provide a more detailed characterization of the non-intentional emissions, the CDF (Cumulative Distribution Function) of the emissions at specific frequencies has been calculated. The CDF of the noise present in the grid has been also calculated and included as a reference (see Fig. 8). The selected frequencies have been identified with colored arrows in the corresponding frequency response and spectrogram (Figs. 6 and 7), and included in Fig. 8, for clearly relating

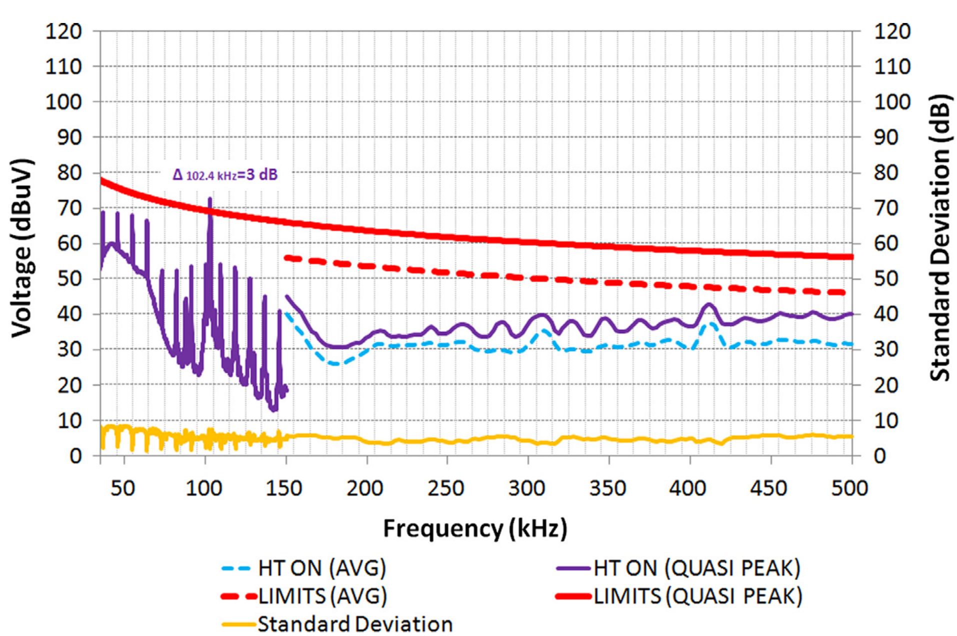

Fig. 7. Voltage levels and standard deviation of the non-intentional emissions generated by the HT in ON state.

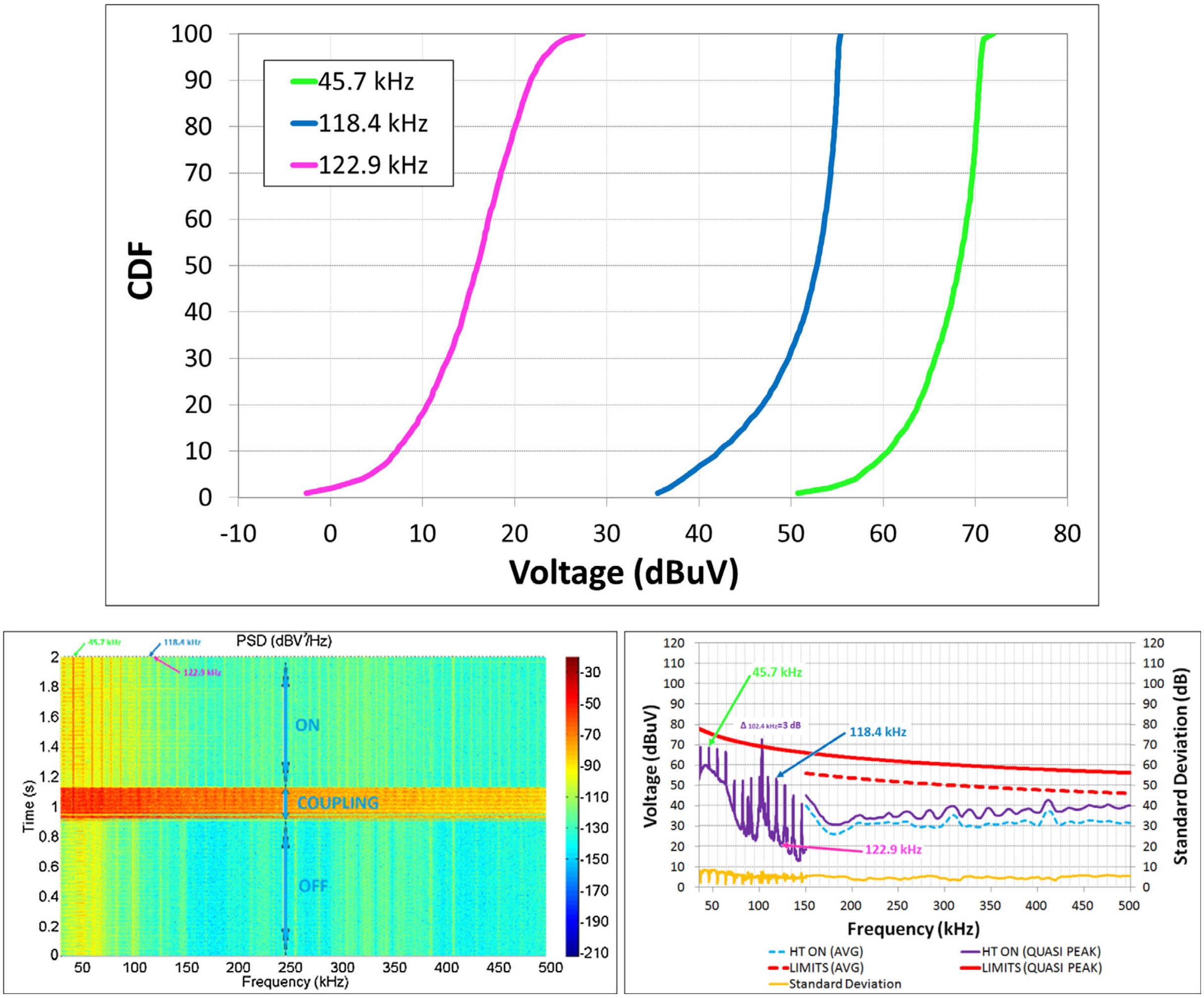

Fig. 8. Above, Cumulative Distribution Function of non-intentional emissions at two different frequencies (45.7 kHz and 118.4 kHz) and noise present in the electrical grid (122.9 kHz). Below, identification of these frequencies in the frequency response and in the spectrogram of the measurements (Figs. 6 and 7).

the variation with time and frequency and the CDF:

Results of the CDF demonstrate that the non-intentional emissions generated by switching modules are high amplitude emissions stable in time, while the noise values follow a typical Gaussian curve of lower level. This characteristic is fulfilled by the non-intentional emissions from all the switching devices; it is described only for this device as a representative case.

4.1.2. Hydropower pump (HP)

Fig. 9 shows the spectrogram of the non-intentional emissions of the HP when it was turned on. During a transitory state, the PSD levels of the non-intentional emissions were higher than in the ON state, mainly below 150 kHz. The spectrogram also shows that the non-intentional emissions were colored background noise shaped plus a strong narrowband noise component at 87.5 kHz.

The quasi-peak and average voltage levels of the non-intentional emissions during the transitory state are shown in Fig. 10 and compared to the limits. The quasi-peak levels for lowest frequencies were approximately 5 dB higher than the limits, while in the 70–150 kHz range they were below the limits, with the exception of a narrowband component at 87.5 kHz, which exceeded the limit in 8 dB. For the 150–500 kHz range, the quasi-peak levels exceeded the limits in up to 24 dB and the average levels in up to 19 dB.

Fig. 11 shows the levels of non-intentional emissions during the normal operation (ON state) of the HP. The quasi-peak levels below 150 kHz decreased considerably when the HP started the normal working regime, and remained below the limit for all this frequency range, except the narrowband component at 87.5 kHz, which exceeded in 8 dB. However, for the 150–500 kHz range, the levels remained high, with the exception of the average levels around 180 kHz.

With respect to the time variability of the non-intentional emissions, standard deviation values up to 17 dB were obtained, with higher values in the 150–500 kHz range for both the transitory state and the ON state.

4.2. PV inverters

Three single-phased Ingeteam [74] PV inverters (PV1, PV2 and PV3) and other three three-phased PV inverters (PV4, PV5 and PV6) were analyzed in the field trials. All these inverters use switching techniques to transform the DC power into controlled AC power with two different switching frequencies: 16 kHz for PV1, PV2, PV3 and PV4 and 5 kHz for PV5 and PV6.

Four of them (PV1, PV2, PV3 and PV4) could be isolated from the rest of the power devices in the grid, and therefore, an individual analysis was carried out.

4.2.1. Single-phased PV inverters

In Fig. 12, the spectrogram of the coupling of PV1 to mains is represented. During the ON state, harmonics of the switching frequency (16 kHz), with a decreasing amplitude with frequency, are generated. The coupling process shows a high level of colored background noise

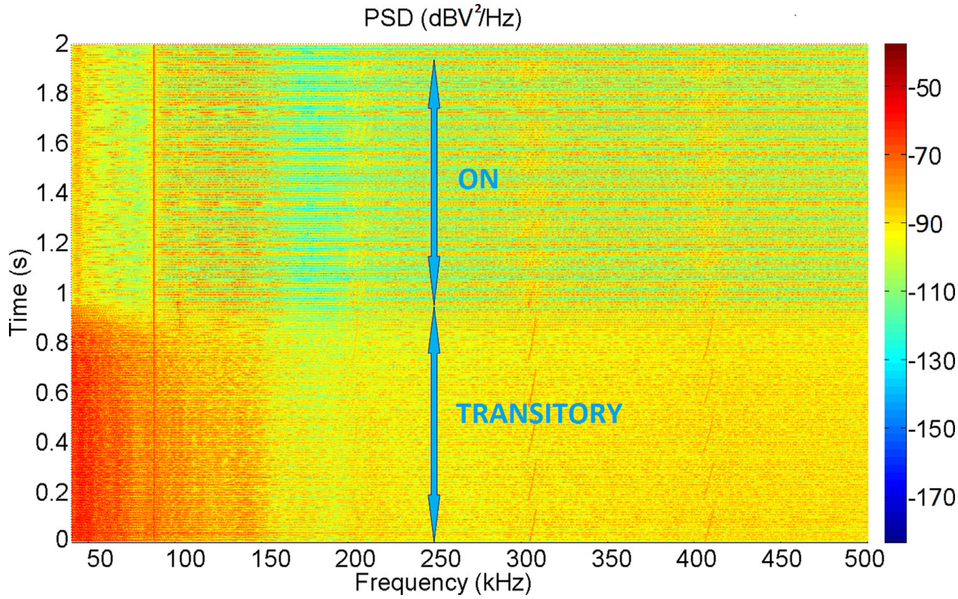

Fig. 9. Spectrogram of the non-intentional emissions of the HP when it was turned on.

during a few milliseconds.

The quasi-peak and average voltage levels, together with the standard deviation of the variability of non-intentional emissions for the three single-phased PV inverters in ON state are shown in Figs. 13–15. As it can be observed, high amplitude harmonics of the switching frequency (16 kHz) arose over colored background noise in the three cases, especially in the 35–150 kHz range, with levels of 32, 18 and 27 dB over the limits at the third harmonic of switching frequency (48 kHz) for PV1, PV2 and PV3, respectively.

For frequencies higher than 150 kHz, the emissions from PV1 were of high-level (20 dB over the limits at 176 kHz), the voltage levels from PV2 were below the limits, while for PV3 the colored background noise exceeded the quasi-peak and average limits for a wide range of frequencies in up to 8 dB and 14 dB, respectively (see Figs. 13–15).

With respect to the time variability, the highest standard deviation values were found in the 150–500 kHz range for PV1.

4.2.2. Three-phased PV inverters

The quasi-peak and average voltage levels of the emissions for the three-phased PV inverters showed lower levels during ON state, as only a component at 48 kHz in the PV4 exceeded the limit in 7 dB (see Figs. 16–18). In the 150–500 kHz range, the emissions were below the limits for the three inverters, with the exception of the PV5. It is remarkable that, for inverters PV5 and PV6, the colored background noise did not decrease with frequency, as it can be observed in Figs. 17 and 18, and therefore, the average levels of emissions of PV5 exceeded the limits in the 430–500 kHz range.

With respect to the time variability, standard deviations lower than 10 dB were found in the three devices.

Last, the coupling process was very similar to that shown in Fig. 12.

4.3. Battery charger (BC)

Fig. 19 shows the non-intentional emissions during transition to ON state of the Studer battery charger [75], where high PSD levels can be observed in the 35–500 kHz range during the short transition period.

Once the charger was ON, harmonics of 12 kHz arose, generated by the internal switching techniques used by the BC (see Fig. 20). Only the

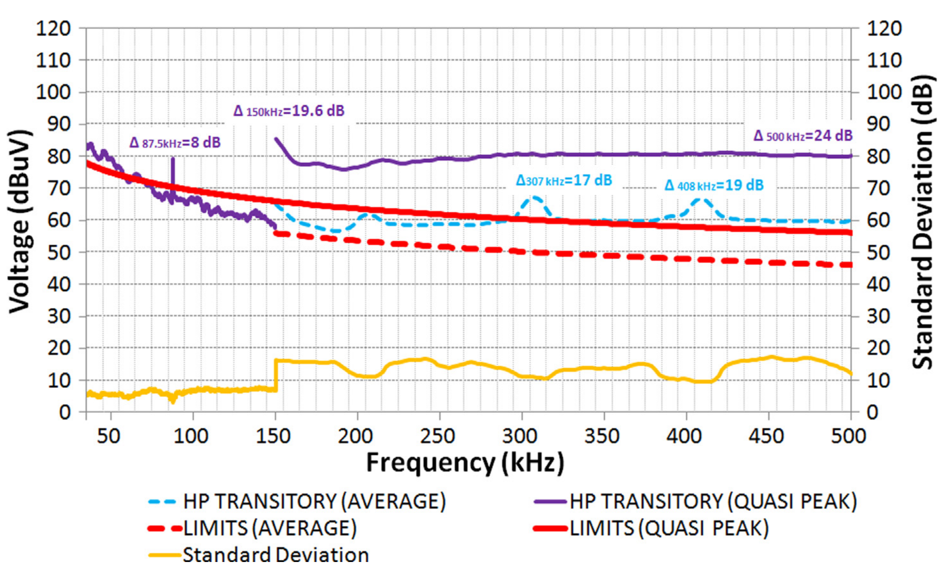

Fig. 10. Voltage levels and standard deviation of the non-intentional emissions generated by the HP in the transitory state.

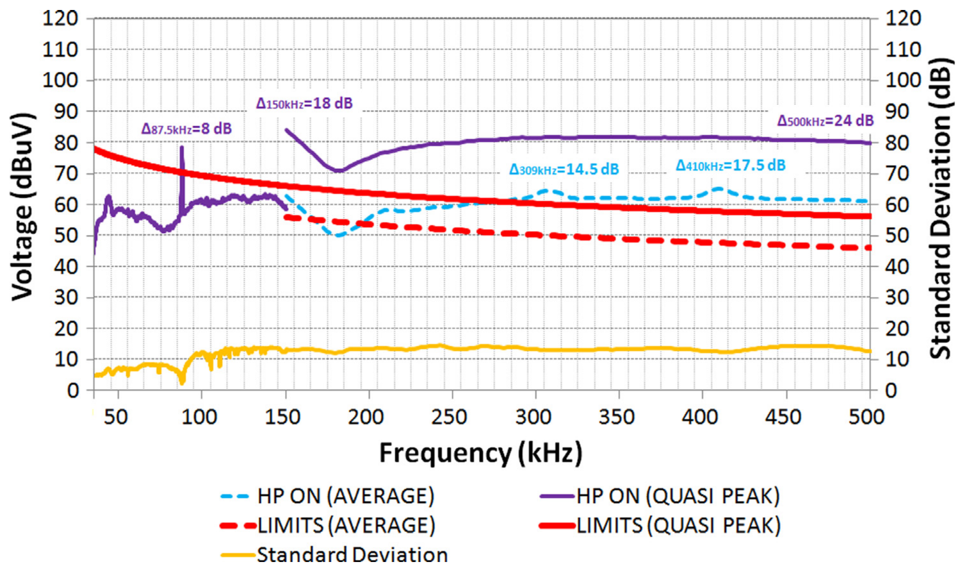

Fig. 11. Voltage levels and standard deviation of the non-intentional emissions generated by the HP in ON state.

third and fifth harmonics of 12 kHz exceeded the limits in 27 and 8 dB, respectively, so that for frequencies higher than 72 kHz, almost all the measured levels remained below the limits.

Regarding the time variability, the time standard deviation values varied between 1 and 10 dB in the entire band.

4.4. Wind turbine (WT)

Finally, an Ennera [76] wind turbine containing an internal direct drive permanent magnet, a synchronous generator and a converter was analyzed in the field trials. Fig. 21 shows that the nature of the non-intentional emissions of the WT in normal working regime was a colored background noise, together with some narrowband emissions separated approximately 20 kHz in the 70–150 kHz range. In the 35–150 kHz range, the levels were below the limits, except for the 115–117 kHz frequency range; however, in the 150–500 kHz range the levels were up to 16 dB over the limits. As described above, this sharp transition at 150 kHz is caused by the different bandwidth values used in the data processing for frequency ranges below and above 150 kHz.

Regarding the time variability, the standard deviation varied between 6 and 17 dB in the entire band.

5. Discussion and conclusions

In this section, the non-intentional emissions generated by different DERs in the measurement campaign are analyzed both in frequency and in time domains. Additionally, the potential impact on NB-PLC is evaluated, by comparing the results to the limits ascertained in EN-50065-1 [16].

5.1. Analysis in the frequency domain

Four types of non-intentional emissions have been observed in the frequency domain:

- A set of high amplitude narrowband emissions at harmonic frequencies of the switching frequency of the PV inverters, the BC and the HT.

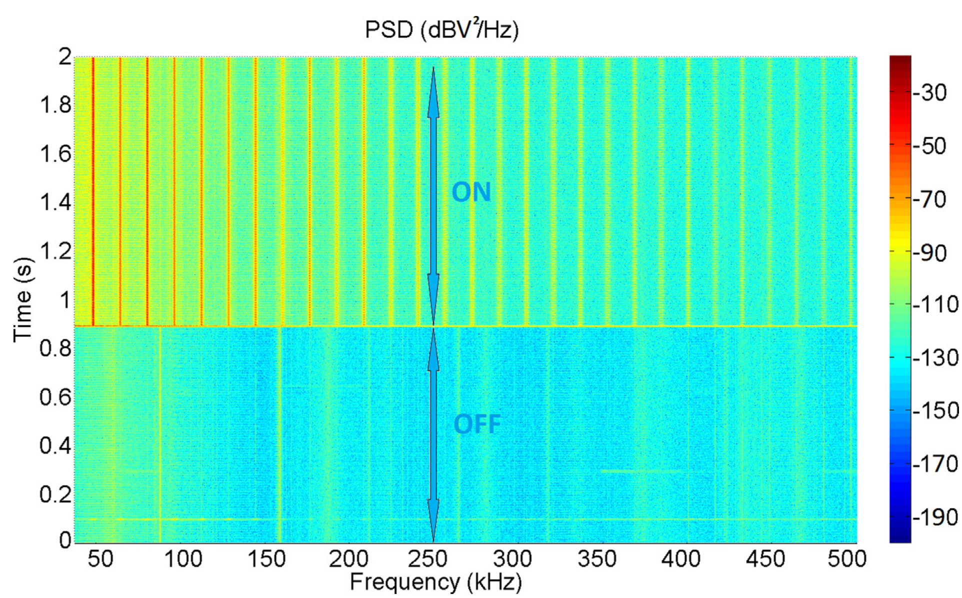

Fig. 12. Spectrogram of the non-intentional emissions of the PV1 during the coupling to the mains power process.

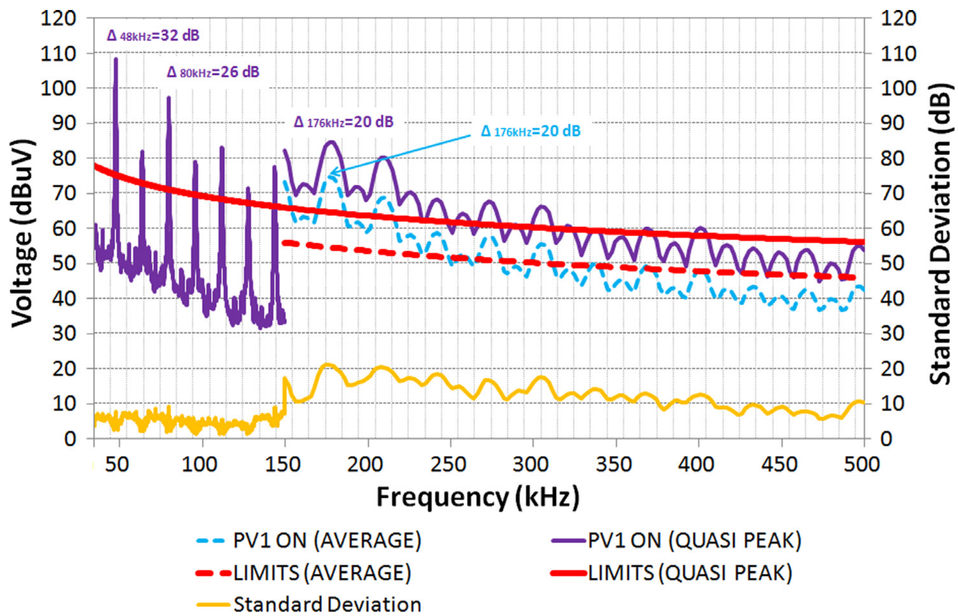

Fig. 13. Voltage levels and standard deviation of the non-intentional emissions generated by the PV1 in ON state.

- Additional narrowband emissions in the WT, the HT and the HP.
- Colored background noise, present in all the devices.
- Transitory periods containing emissions of high level, mainly due to coupling processes.

The emissions of highest levels are those composed of a set of narrowband signals at harmonic frequencies of the switching frequencies. Therefore, the performance of the switching devices is the key aspect to be considered in order to reduce the levels of the non-intentional emissions. In all the cases included in this representative analysis, the amplitude of the harmonics of the switching frequencies decreases with frequency, accordingly, the potential impact of this type of emission may be of less significance than in lower frequencies. In a practical point of view, for a specific switching device, it is possible to estimate the frequencies potentially affected, as they are located at multiple values of the switching frequency, and consequently, it is possible to know in advance the frequency channels that might be affected by these emissions.

Other narrowband interfering signals of high amplitude can be also generated by DERs at specific frequencies. The frequency and amplitude of these signals depend on the electronics of each specific device, and they can be characterized by measuring the non-intentional emissions of the device in different working regimes.

The colored background noise is present in all the devices analyzed in this study, mainly during the coupling processes, with varying characteristics both in frequency and in time. The amplitude does not clearly decrease with frequency as in the case of the harmonics, and in some cases, higher amplitudes are shown at frequencies between 300 and 500 kHz.

These results are in line with the results obtained by other research groups (described in the Section 2 and in references [17–59]). Hence, the non-intentional emissions caused by switching devices show patterns composed of harmonics of the switching frequency, with decreasing amplitude for higher frequencies, while other narrowband interfering signals can be also generated at specific frequencies; the amplitude of these emissions depend both on the specific device and on

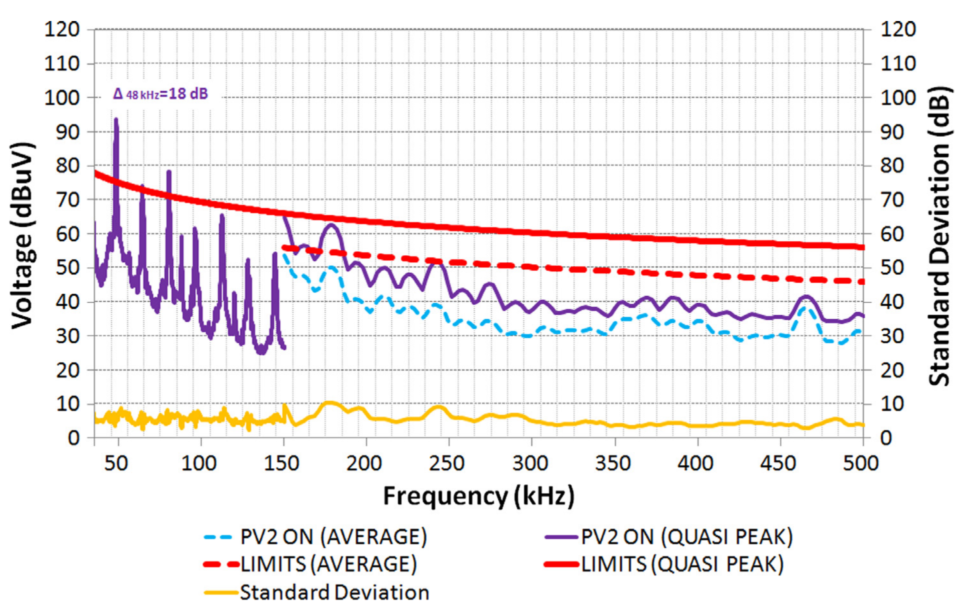

Fig. 14. Voltage levels and standard deviation of the non-intentional emissions generated by the PV2 in ON state.

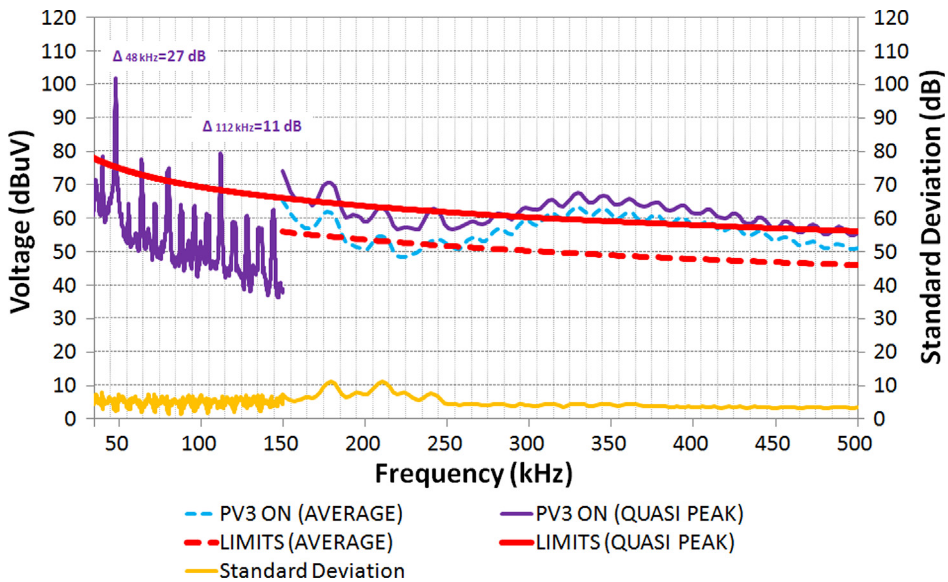

Fig. 15. Voltage levels and standard deviation of the non-intentional emissions generated by the PV3 in ON state.

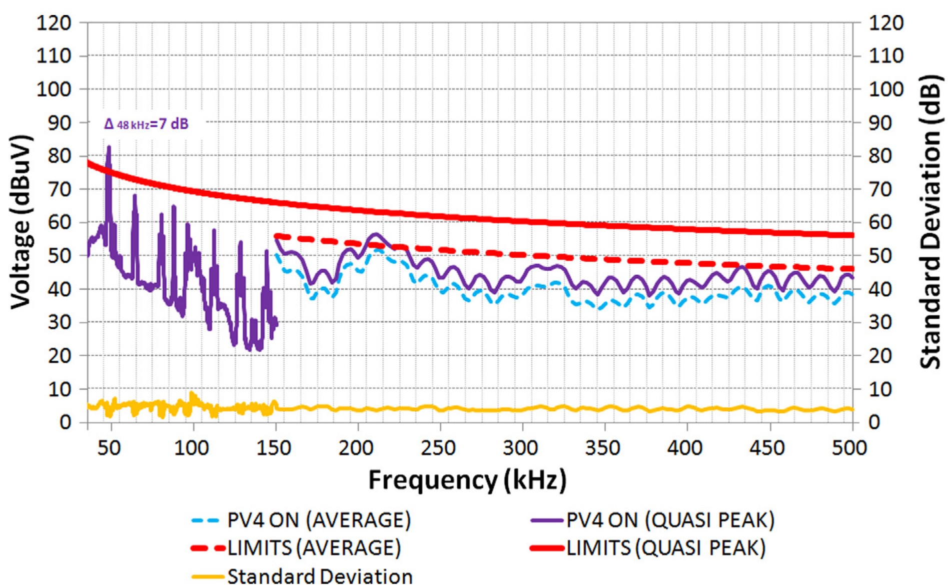

Fig. 16. Voltage levels and standard deviation of the non-intentional emissions generated by the PV4 in ON state.

the matching of the impedances of devices and electrical grid. The colored background noise is always present, but the noise level varies with frequency and also from one device to another.

5.2. Analysis in the time domain

The time analysis has been carried out by calculating spectrograms from the measurement recordings of each DER. They clearly show the variation with time of the PSD of non-intentional emissions for different working regimes; hence, the specific performance of each device during transition periods of special interest, such as the coupling process (for the PV inverters and the HT) or the moment when they were turned on (for the BC and the HP), can be easily evaluated.

Results obtained in the measurements during normal operation show that the level of the non-intentional emissions remains stable along the time, mainly for the narrowband emissions. The standard deviation values of time variation are lower than 10 dB in most of the devices throughout the entire 35–500 kHz range; only the HP and the WT in all the frequency range, and the PV1 in the 150–500 kHz range, show higher standard deviation values, up to 20 dB.

During the transition periods, the PSD levels were considerably higher in all the analyzed devices and they exceeded the evaluated limits during these short periods.

When compared to other studies, the transitory periods may differ considerably for different device models, both in frequency response and in time duration. As they only occur from time to time, their effects on the communications might be limited to sporadic cases.

5.3. Potential effects on NB-PLC and techniques to increase the robustness

As previously mentioned, there are no limits established for non-intentional emissions from DERs in the frequency band of interest. Therefore, these emissions have been compared to the limits given in EN 50065-1 for non-intentional emissions generated by mains communicating equipment, as proposed in [45]. Moreover, when average and quasi peak values of the emissions are calculated, it is important to remark that CISPR proposes different bandwidth values in the assessment methodology for frequency ranges below and above 150 kHz,

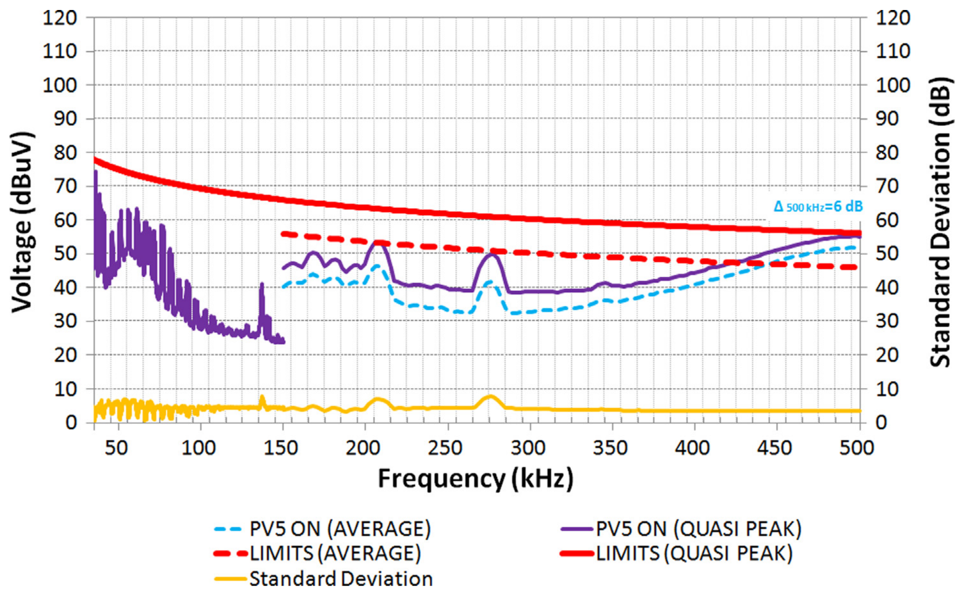

Fig. 17. Voltage levels and standard deviation of the non-intentional emissions generated by the PV5 in ON state.

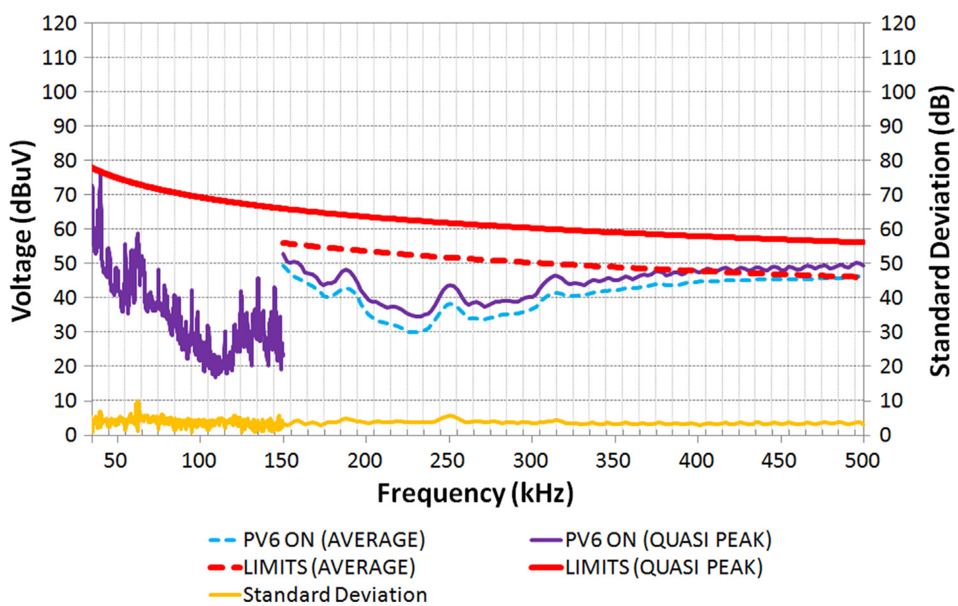

Fig. 18. Voltage levels and standard deviation of the non-intentional emissions generated by the PV6 in ON state.

which generates both a sharp transition at 150 kHz and higher values above this frequency.

Results show that the levels of the colored background noise are higher for frequencies above 150 kHz, in most cases higher than the limits recommended by EN-50065-1. In contrast, the harmonics generated by the single-phased PV inverters and the BC are above the limits in the 35–150 kHz range, but they decrease significantly with frequency and they are only of high amplitude at frequencies higher than 150 kHz for PV1 and PV3.

In order to evaluate the potential effects on NB-PLC, the amplitude of the non-intentional emissions generated by the HP and HT in normal operation is compared to the instantaneous PSDs of two recorded Smart Metering signals over PLC (see Fig. 22), as in similar approaches [77–79]. As it can be seen in the figure, five harmonics of 9.1 kHz generated by the HT are located within the frequency range dedicated to communications, and depending on the smart metering signal level, the communications could be disturbed in a greater or lesser extent. The HP, however, only adds a narrowband component at 87.5 kHz of similar level to the smart metering signals.

Similar conclusions can be obtained from Fig. 23, where the same smart metering signals are represented, together with the instantaneous PSDs of the non-intentional emissions of the single-phased PV1 and the three-phased PV4. The switching frequency is the same for both devices (16 kHz) and only three harmonics are located within the frequency band assigned to communications. As it is shown in the figure, the PSD levels of the harmonics generated by the PV1 exceed the levels of one of the metering signals, whereas the PSD levels generated by the inverter PV4 are at a lower level.

In conclusion, measurements show that non-intentional emissions of typical DERs exceed in some cases the limits ascertained for avoiding disturbances in the 35–500 kHz range and, in consequence, they may generate negative effects on the NB-PLC used in SG applications.

In summary, emissions generated by harmonics of the switching frequencies are the main interfering source for frequencies below 150 kHz, while colored noise shaped emissions are the predominant interference for frequencies higher than 150 kHz. In the first case, the

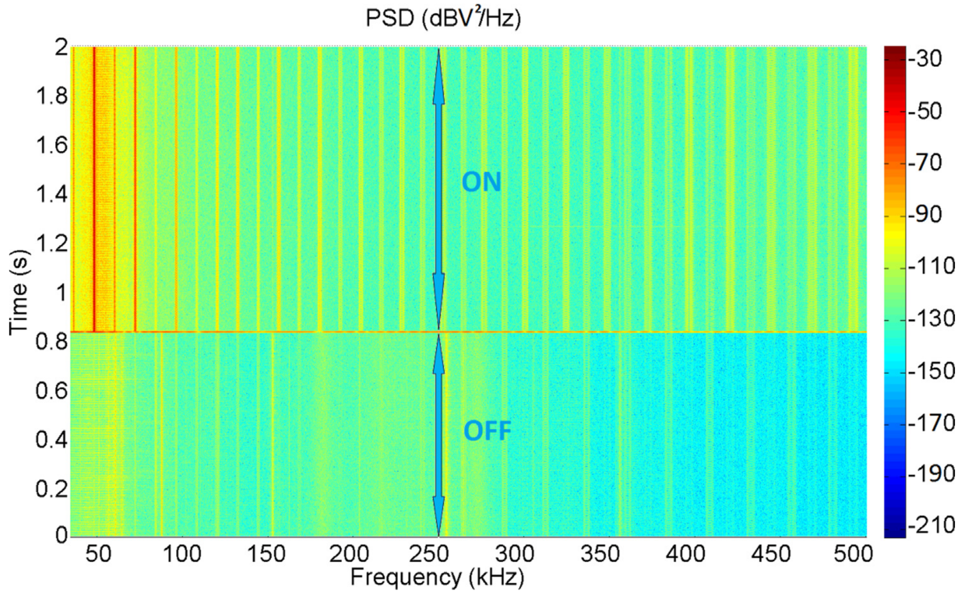

Fig. 19. Spectrogram of the non-intentional emissions of the BC when it was turned on.

amplitude and specific frequencies depend on the switching device, while the colored noise for higher frequencies shows different time and frequency patterns for each specific device. Rapid transitory effects, such as those generated by coupling and decoupling processes, generate the highest levels of non-intentional emissions for all the frequency range, from 35 kHz to 500 kHz.

The potential impact of these emissions on the quality of the data throughput largely depends on the transmission techniques used to increase the robustness of the communications against interferences and impulsive noise, and therefore, to overcome the communication impairments. These techniques mainly consist in the use of coding and modulation schemes or in the addition of time interleaving.

- The Orthogonal Frequency Division Multiplexing (OFDM) technique is widely employed in NB-PLC systems. It was selected by its good performance against frequency selective fading and narrowband interferences, because data are divided in multiple carriers, and therefore, narrowband interferences would affect only a small part of the bit stream. Therefore, it is a useful tool against interferences such as the high amplitude harmonics of the switching frequencies generated by switching devices.
- Coding techniques are based on inserting redundant information, which means a lower net throughput, and therefore, a less efficient use of the spectrum. Convolutional coding is performed in PRIME [3], G3-PLC [8] and IEEE 1091.2 [10] specifications. Additionally, G3-PLC and IEEE 1091.2 allow the additional use of Reed-Solomon coding [2].
- Robust modulation schemes transmit a lower number of bits per symbol, whenever the limitation in the bit rate required by the selected modulation scheme could be assumed. Three different modulation schemes were selected by PRIME, G3-PLC and IEEE 1091.2 specifications, in order to provide different rates of robustness at the expense of net throughput (DBPSK, DQPSK and D8PSK), while other schemes could be used in G3-PLC and IEEE 1091.2, depending on the required robustness (PSK, QPSK, 8PSK and 16QAM).
- The time interleaving consists in interlacing the bits in time before

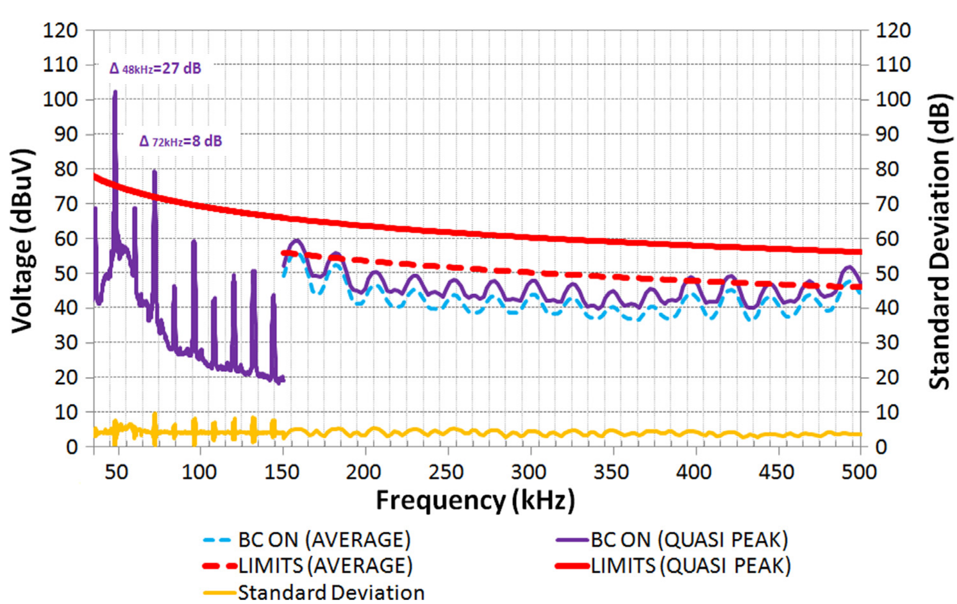

Fig. 20. Voltage levels and standard deviation of the non-intentional emissions generated by the BC in ON state.

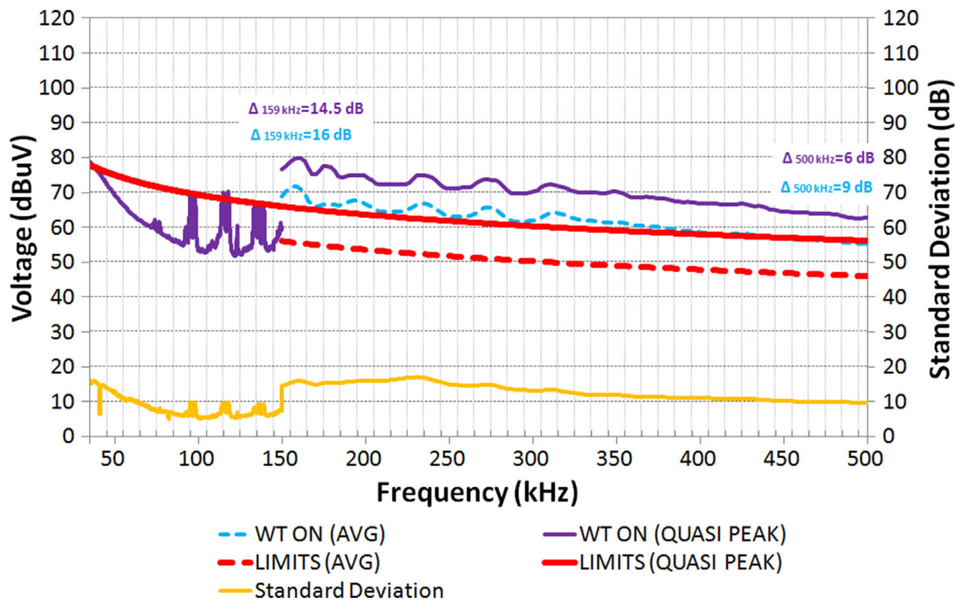

Fig. 21. Voltage levels and standard deviation of the non-intentional emissions generated by the WT in ON state.

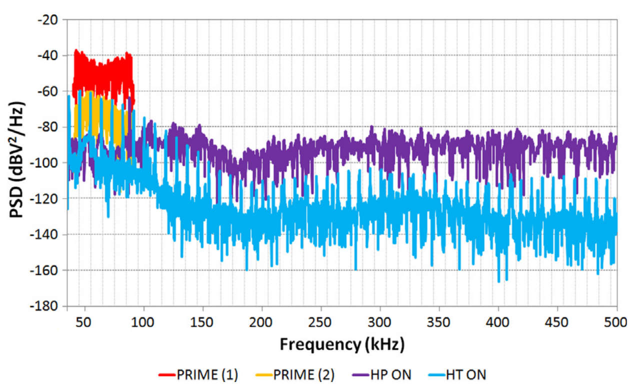

Fig. 22. PSDs of two PRIME v1.3.6 bursts and the non-intentional emissions of the HP and the HT in ON states.

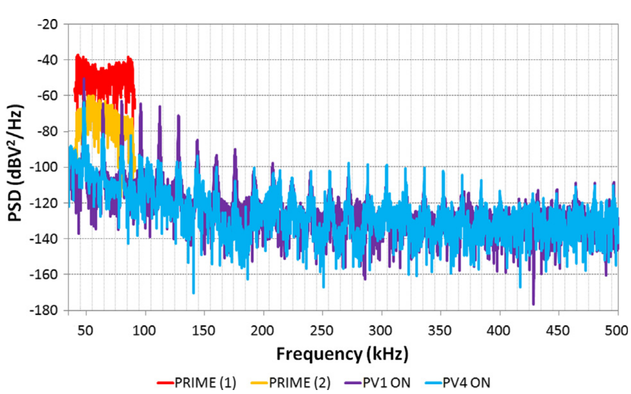

Fig. 23. PSDs of two PRIME v1.3.6 bursts and the non-intentional emissions of the PV1 and the PV4 in ON states.

they are transmitted, and then, undoing this operation in the receiver. This way, a short impulsive interference would affect consecutive bits in the transmission channel; but when they are reordered in the receiver, the erroneous bits are separated in time and they can be more easily detected and fixed by decoding techniques. Consequently, time interleaving increases the effectiveness of coding techniques, and therefore, the robustness of the transmission against impulsive noise or rapid transitions in the propagation channel performance.

- Additionally, repetition techniques increase the success probability in the messages reception, but also the occupancy of the channel and the percentage of the packet collisions [6,7].

In any case, new strategies that provide both a more robust performance against interferences and an efficient use of the frequency band should be developed and tested in real environments. On the side of the devices connected to the grid, the implementation of specific filters that reduce the level of the non-intentional emissions within the frequency bands used by NB-PLC would minimize the negative effect on the communications.

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