FINAL PUBLISHABLE REPORT

Grant Agreement number	18NRM05
Project short name	SupraEMI
Project full title	Grid measurements of 2 kHz -150 kHz harmonics to support normative emission limits for mass-market electrical goods

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Report Status: PU Public

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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1 Overview

The overall aim of this project is to develop new normative measurement techniques to enable regulation of interference caused by mass-market electrical products. The build-up of product emissions in the supraharmonic frequency range of 2-150 kHz, threatens to cause malfunction of other electrical products, power line communications, and critical infrastructure. Unlike other frequency ranges, the 2-150 kHz band has no effective regulation or normative measurement framework. This project has worked with standards committees to develop a new measurement framework to facilitate the setting of realistic and credible 2-150 kHz conducted interference limits and enable the regulation and compliance testing of mass-market goods.

2 Need

Mass-market electrical products emit interference into the grid conductors, which has been shown to cause malfunctions of other connected products, power line communications equipment and grid infrastructure. At frequencies below 2 kHz, this conducted harmonic interference has been regulated for some years by normative standards and associated compliance testing as part of the EMC (electromagnetic compatibility) directive. However, advances in electronics, and the growth of electric vehicle chargers and renewable energy, have led to increasing amount of interference at higher frequencies in the so-called “supraharmonic” range of 2-150 kHz. This interference is not regulated, and its growth is now causing serious concern to utilities and product manufacturers. In 2017, this led to action from the standards community with the establishment of a working group (WG) of the Power Quality (PQ) community (International Electrotechnical Commission’s subcommittee: IEC SC77A) and the radio interference community (Comité International Spécial des Perturbations Radioélectriques: CISPR), to determine the gaps in the normative and regulatory requirements of the supraharmonic band.

One such gap is the lack of a rigorous, repeatable, and acceptable measurement method, which is essential to establish a regulatory system for the 2-150 kHz range. To address this gap, IEC SC77A convened an expert task force under WG9, to establish and publish a new normative method for the main PQ measurement standard IEC 61000-4-30. This WG9 has expressed their urgent need to develop a new metrological sound method suitable for measurements in electrical power grids.

In order to develop emissions limits, compatibility levels must reflect the prevailing amount of interference that mass-market goods and grid equipment should operate without malfunction. Interference levels are presently defined taking only the laboratory testing environment into account. How well this assumption compares to real grid conditions and resulting behaviour of appliances must be confirmed. This requires measurements of real products using an artificial mains network (AMN) which are then be compared with measured emissions when the same products are connected in different electricity low voltage (LV) networks.

Emission testing of mass-market goods to ensure compliance against the limits will need to be done in the laboratory rather than the grid. This requires a realistic simulation of the grid which is achieved using an AMN. The AMN impedance characteristics are critical to ensure representative emission results. New grid impedance measurement data is needed to determine whether the AMN impedance characteristics are a realistic representation of the LV networks impedance over the full 2-150 kHz frequency range.

To enable 2-150 kHz regulation, there is a clear need to develop a measurement framework that must be robust, credible, and acceptable to mass-market product manufacturers, PQ instrument manufactures, testing laboratories and grid utilities. The involvement of key WG conveners, a range of stakeholders and the close association of the project JRP Chief Stakeholder, is critical to smooth the path to timely new normative methods.

3 Objectives

The overall objective of the project is to develop a measurement framework for supraharmonics in the electricity network, such that realistic, credible and measurable procedures for compliance assessment can be incorporated into normative standards. The specific objectives of the project are:

1. To formulate a new normative method to measure supraharmonics (2 to 150 kHz) in electricity networks suitable for inclusion in the redefinition of IEC 61000-4-30 Edition 4, and which should be compatible with the method defined by CISPR 16, which is only appropriate for equipment emission measurements in laboratory. In addition, to implement the new method using suitable portable and traceable instrument(s) to measure voltage and current in the supraharmonic frequency range with accuracies of ≤ 1 %.
2. To validate the new method by conducting a laboratory comparison of the new method with the existing methods in IEC 61000-4-7 (2-9 kHz) and CISPR 16 (9-150 kHz) using the respective artificial mains networks (AMN) to represent the impedance of the electricity network, and examining emissions from a selection of electrical appliances.
3. To determine the suitability of supraharmonic compatibility levels (as defined in IEC 61000-2-2) by measuring the emissions from a selection of electrical appliances connected in a selection of LV networks. To use these on-site LV network measurements and to compare with the laboratory measurements to determine the suitability of the AMN approach as a realistic laboratory representation of LV network conditions.
4. To verify the applicability of the AMN characteristics by measuring network impedance characteristics of a number of typical LV electricity networks with a target uncertainty of 5 %. Measurements below 9 kHz will be used to verify the IEC 61000-4-7 AMN and measurements in the range 9 to 150 kHz will be used to verify the CISPR 16 AMN.
5. To contribute to the standards development work of the technical committees IEC SC77A WG 1, 8 and 9, and CISPR 16 by providing recommendations on improvements to supraharmonic measurement methods (4-30), and the normative specification for the AMN in-line impedances (4-7 and 2-2) as well as how these new methods should be applied to compare levels measured in the electricity network with supraharmonic compatibility levels (2-2), and ensure that the outputs of the projects are aligned with their needs, communicated to those developing the standards and to those who will use them, and in a form that can be incorporated into the standards at the earliest opportunity.

4 Results

4.1 Objective 1, A new normative method to measure supraharmonics (2 to 150 kHz) in electricity networks.

The purpose of the new method is to measure conducted emissions on the electricity grid in a range of frequencies between 2 kHz and 150 kHz, a range of frequencies which until now, has no surveillance and no regulation. The method relies on sampled data of the voltage (and sometimes current) waveforms in the grid, but primarily the challenge of this work is to develop a new algorithm to process the sampled waveform data for produce a spectrum of magnitude values across the frequency range.

The new method is aimed at a new edition of established international standard IEC61000-4-30 which defines power quality (PQ) measurement methods for power grids. This standard is controlled by an international electrotechnical committee (IEC) working group, IEC SC77A WG9 and as such the development of the method has been carried out with close cooperation and engagement with WG9 and its convener who was the “chief stakeholder” for this project. During this project the project partners NPL, TUD and EPV/EHU attended some eight meetings of WG9 and led sessions of meeting to discuss and agree the approach for the new method.

A major constraint on the development of the method is the need to demonstrate compatibility with a historic radio standard defined in CISPR16-1-1 (C16) [1] which is used with an analogue radio receiver to sweep across the frequency band to look for emissions. C16 includes the 2-150 kHz band and as such has established itself in several EMC and PQ standards as the only available measurement method. For example, the basis of EMC is the definition of Compatibility Levels (CL) which is the maximum level of interference on the electricity grid for which any connected appliance should ever expect to be exposed to. The CLs must be measured and monitored in grids, but in the absence of a suitable measurement method, the committee in charge (WG8) refer to C16, thus creating the constraint that a new practical method for grid measurements must respect.

Apart from developing and specifying the algorithmic method, it must also operate in a practical instrument for grid use and there was a need to conduct a number of laboratory and grid measurements to test and prove the applicability of the methos in the real world. This implementation using suitable portable and traceable instruments for measurements in the supraharmonic frequency range is also described in this section.

Specification of the method

In order to measure CLs in the grid, it is necessary to deploy many instruments to conduct continuous survey measurements to examine disturbances as the daily and weekly electricity generation and usage patterns change. So, this give a number of design constraints, most obviously that the instrument and analysis process should be low-cost so it can be mass produced for widescale deployment and use.

The method must resolve the amplitude of emissions in the 2-150 kHz range which implies a decision on the frequency resolution for each amplitude in the spectrum. The higher the resolution chosen the more data the instrument will produce leading to issues with storage, data presentation and interpretation. However, if the resolution is too low, is will not be possible to determine the emission problem frequencies preventing the tracing of the source of the emission and its mitigation. Taking the lead from CISPR16, a frequency resolution of 200 Hz was chosen,

Computationally, calculating the 2-150 kHz magnitude spectrum is extremely demanding and the algorithm used needs to be as efficient as possible, so the processing requirements of the instrument are realistic within the low-cost constraints, which over the 2-150 kHz spectrum leads to 740 frequency results every measurement period.

Defining the measurement period (or time resolution) has similar constraints on storage and interpretation and is also fundamentally constrained by the selection of the frequency resolution. A basic measurement update time of 200 ms (every ~10 cycles of a 50 Hz grid) was selected and aggregations over periods of 3 s and 10 minutes are suggested for CL surveys to reduce storage and interpretation issues. Aggregations at each frequency, are the root sum of squares of all the 200 ms each value for the given frequency, over the aggregation period.

The required accuracy of the measurement (method and instrument hardware etc) is 10% of each measured frequency value for all values greater than 5% of the instrument range.

Emissions cause problems to connected equipment on the grid these can manifest themselves as follows:

- equipment malfunction which is generally associated with the peak value of an emission.
- shortening of equipment lifetime due to increased heating associated with the rms value of the emission.

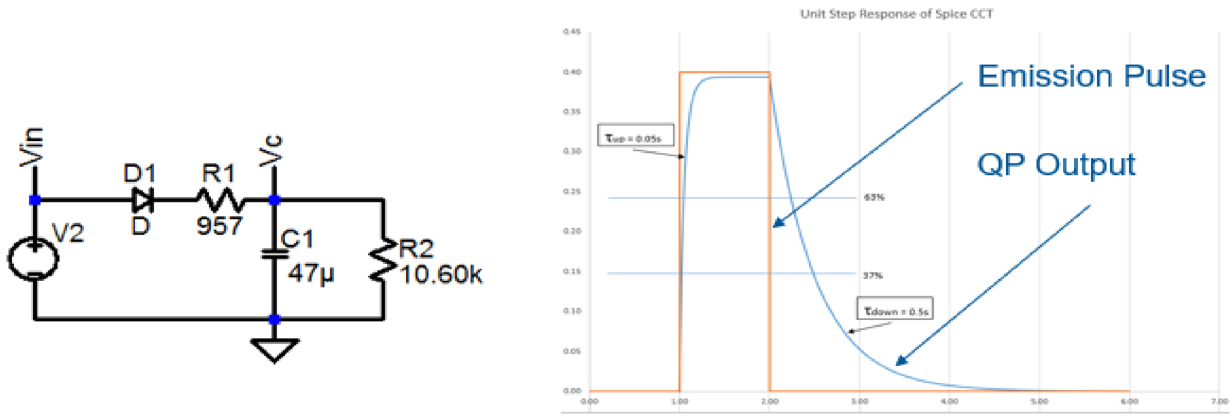


Fig.1, QP detector as implemented in CISPR16 using analogue components. A rectangular emission pulse at V2 will produce a QP output a Vc with a rise-time time constant of 0.05s and a decay with a time constant of 0.5s. If the pulses repeat, the higher the repeat rate of the pulses, the higher the QP output.

So, the new method should be able to measure both peak and rms of the individual frequency vales across the spectrum. C16 already addresses these measurements but introduces a third type called the quasi-peak (QP) value which is based on an analogue circuit implementing a peak hold and decay function. IEC SC77A WG8 has chosen this QP value to be the basis of CLs and therefore the new method has a requirement if implement this analogue method. So, the new method must also produce this QP output using digital filters to mimic the performance of the analogue circuit.

Measurement and complex processing of some 740 separate frequency components, reported every 200ms and processed according to the peak, rms and QP methods, aggregated and output to a display/file implies considerable processing requirements. As already explained, there is an imperative that the commercial instrument which will eventually implement these methods are low cost for mass-roll-out, so in selecting a new normative method it the efficiency of the waveform transform kernel that finds the frequency components from the time domain waveform samples is paramount. The computational cost in terms of memory usage and processor speed should be a primary constraint on the new algorithm, especially for so-called Class S instruments that are used for statistical surveys in the grid. More accurate Class A instruments used to settle contractual issues, must still be cost-effective, but have some flexibility to implement more complex algorithms such as a digital implementation of the C16 analogue method.

Review of existing algorithms

It is possible to implement C16 digitally using discrete Fourier transforms (DFT) and digital filters. As C16 is an analogue instrument, there are several degrees of freedom on the implementation of the various modules of the instrument. Specifically, the window shape to select the 200ms block of data and condition it for the DFT (the window gives the DFT the 200 ms time resolution and the transform is then referred to a short time Fourier transform or STFT) is undefined. As overlap of the 200ms windows is generally used and this overlap is also undefined. The implementation of the QP detector is not fixed. In order to determine the reproducibility of the C16 method, simulations were made of possible implementations varying these degrees of freedom which gave rise to 334 different compliant implementations. Testing each implementation with a dynamic test signal containing narrowband and broadband emissions, it was found that the CISPR16 implementations gave a spread of results of 30% for the narrowband signal and 42% for the broadband signal. These levels of spread are unsuitable in the context of a 10% accuracy method, and it will be necessary to fix each of the degrees of freedom at an some arbitrary configuration to enforce repeatability across vendors of future instrument.

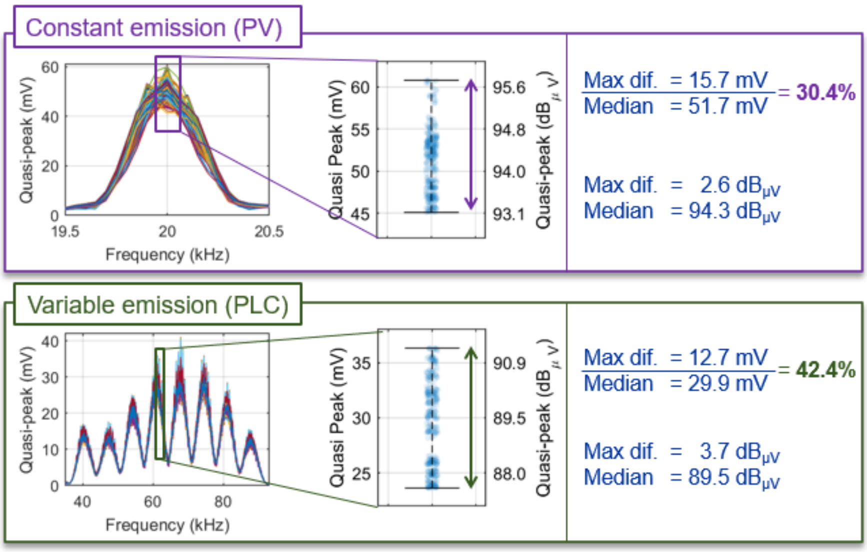


Fig.2 Inherent reproducability issues in the C16 method. Plots show the spread in results for 334 different compliant implementations of the C16 method.

It is important to note that an arbitrary selection of design parameters underlines the fact that the C16 is not a physical measurement related to the SI system, rather it is a so-called operationalist measurement. By extension, the fact that the CLs are based on this method implies a 42% tolerance on these levels, which would not have been acceptable if the information had been available and communicated to WG8. Nevertheless, C16 is the de-facto standard and all work on new method must respect this historical context.

Alternative Algorithms

Significant work was conducted on investigating published algorithms and implementing them for testing. This work was carried out in corporation with the authors of several published methods. The resulting review is available in [2].

The project also developed its own novel algorithms on based on a superheterodyne methods (as used by the C16 radio receiver) at [3] and a method developed by METAS based on compressive sensing techniques [4]. Whilst these methods had their advantages, they were probably too complex to implement in an international standard, however they could be useful for more detailed investigations.

The most obvious method to perform spectral analysis on a fluctuating amplitude signal is the windowed DFT (STFT). This is the traditional PQ approach used in IEC61000-4-7 for harmonics up to 9 kHz where the frequency resolution used was 50 Hz. The STFT is conceptually simple (relatively), well known in industry and efficient to implement. It is relatively simple to adapt it to 200 Hz resolution, 200 ms update rate and conduct analysis in in the 2-150 kHz frequency range. There is, however, a requirement to implement a QP detector and the required aggregation.

UPV/EHD led the development of adaption of the C16 method, known as the Light-QP method, which is a 2-stage procedure: first, a STFT (time window + DFT); second, a QP detector. The first stage is the adaptation of the IEC61000-4-7 to 9-150kHz band, and it gives RMS values, which are a complementary result to the QP outputs of the second stage. The second stage consists of a digital implementation of a QP detector and provides outputs comparable to the CISPR 16-1-1 method.

The Light-QP adaptation of the IEC61000-4-7, basically, consists of: 20 ms windows (instead of 200 ms), averaging by RMS to 200 ms, and symmetrical grouping (instead of asymmetrical). The 20 ms window implies less computational cost and a more frequent update of the RMS results. It also allows a better identification of the highest values by the calculation of the MAX(RMS) every 20 ms.

The implementation of the QP detector stage is performed through two infinite impulse response digital filters as proposed by [5].

Standards Development

The primary purpose of this normative project was to propose a new method for the measurement of 2-150 kHz conducted emissions in grids, to be included in the next edition of IEC61000-4-30. To this end, NPL, TUS and EHU/UPV have worked closely with IEC SC77A WG9, including the WG9 convener and project chief stakeholder.

Presentations have been made at eight separate meetings of IEC SC77A WG9. Agreement has been reached on many of the new method's requirements and performance criteria and draft normative annexes for Light-QP and digital C16 were prepared by the project. The rationale for including two methods is that the C16 is most compatible with its historic predecessor and whilst Light-QP is highly compatible with C16, a fixed digital C16 implementation is required to settle any disputes that may exist. Light-QP in some 10 to 20 times more efficient to implement in software and provided a compatible route for practical manufacturers to provide an economic mass-produced instrument, particularly for CL survey work.

After a year of discussion, the new committee draft (CD) version of the international standard was finally completed in April 2022. This is now circulated to individual national committee, and following their comments, this may be amended and will result in a committee draft for voting (CDV) and if approved become a final draft international standard (FDIS) before final publication.

Measuring Instruments

Once a measurement algorithm is selected it needs to be implemented in a measuring instrument that can be used in the grid. In this project, a portable instrument is required to perform laboratory and grid measurements as part of the other following project objectives. In the future a mass-produced instrument will be needed to make grid measurements for trouble shooting and CL surveillance.

Any instrument will most likely have the same generic stages a used in the two different devices that were developed by VSL and NPL respectively in this project:

1. Input transducers to covert the grid voltage and/or currents to measurable low voltage signals.
2. Multiple channel inputs (maybe three phase voltage and current), protected against overload.
3. Input filtering, significantly attenuating the 50 Hz fundamental, so that any 2 to 150 kHz signals remain.
4. A high-speed multichannel digitiser based (at least 500 kS/s)
5. A computer or processor to capture the digitiser samples and run the processing software
6. Processing software to implement the algorithm and display and store the results.

Traceability for voltage and current transducers was established by SUN. For voltage, a method based on two high accuracy DMMs has been used, up to 150 kHz. For current, a comparison method using a wideband current shunt, up to 100 kHz, has been used. This has been published at [6].

The NPL and VSL instruments both developed resistive and capacitive voltage dividers as voltage transducers. The NPL instrument included a wideband optical isolation stage. These achieve a response flatness accuracy of 0.2% to 100 kHz and 1.2% at 150 kHz. Rogowski coils are used for current measurement and these have also been characterised and 2 % from the nominal value, phase angle error up to 13 degrees.

The input filtering is required to block the large 50 Hz signal so that the digitiser can apply its full measurement range to the 2 -150kHz band and maximise its measurement resolution. The filters also need to remove higher frequency components above twice the sampling frequency of the digitiser in order to avoid aliasing problems. Passive component filters are used in both instruments.

Both VSL and NPL based their instruments around a commercial digitiser with sufficient bandwidth and accuracy has been selected, purchased, and characterised against ac voltage standards. Sampling rates of some 1 MS/s were used and channel resolutions of up to 12 bits. The high data rates on multiple channels were transferred by USB3 to a computer.

Real-time waveform sampling software has been developed with capabilities to store raw data for off-line processing. A multithreaded architecture has been used to allow data flow and processing in real time. This is a universal platform which allows for the implementation of various algorithms for real time sample processing, display and storage.

The two independent systems were built and were successfully compared by VSL and NPL.

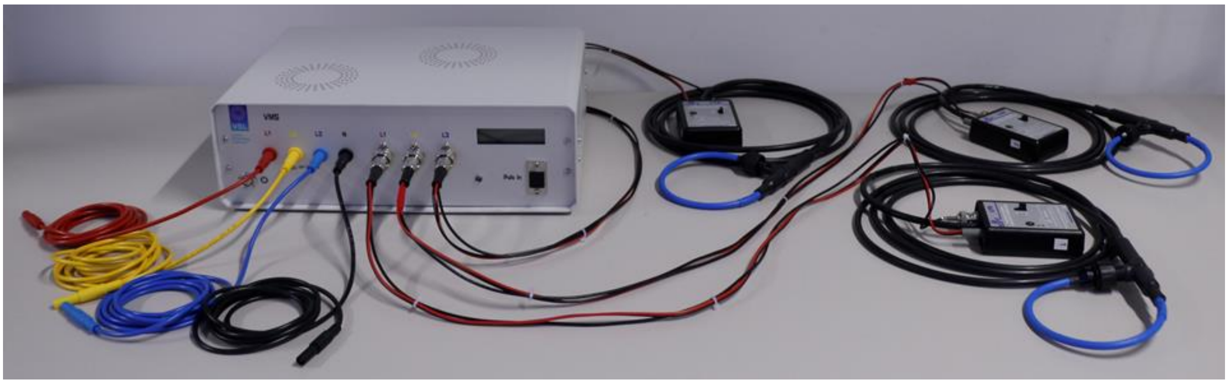


Fig.3 VSL 2-150kHz measurment system. Red, yellow and blue three pahse voltage input leads shown on left. Black boxes on right show Rogowski coils for 120 A or 1200 A peak current input in range 0.3 Hz - 150 kHz.

The project successfully achieved this objective, and a new normative method was published as a CD and a new instrument is available for supraharmonic measurements.

4.2 Objective 2, To validate the new method by laboratory comparison with the existing methods.

As described in Objective 1, two different potential normative methods are proposed by this project for emission measurements between 2 and 150 kHz, namely Light-QP and digital C16. In this objective, a laboratory comparison of the Light-QP method is made against a commercial C16 receiver with associated respective artificial mains networks (AMN) to represent the impedance of the electricity network. This comparison is made by examining the emissions from a selection of electrical appliances.

VSL Laboratory Setup for measuring appliance emissions using an Artificial mains networks (AMN)

IEC61000-4-7 and CISPR 16 propose different impedance networks to represent the impedance of the electricity network, namely an AMN and a LISN respectively. The method used by VSL in the laboratory using an AMN is shown in Fig.4, a similar arrangement is used for the C16 case of the LISN for LNE. The EUT in Fig.4 is the appliance that is the source of any emission. The measurement is made at point B and the low voltage output of either U or the coil at I_{EUT} is measured by the VSL portable instrument explained in Objective 1.

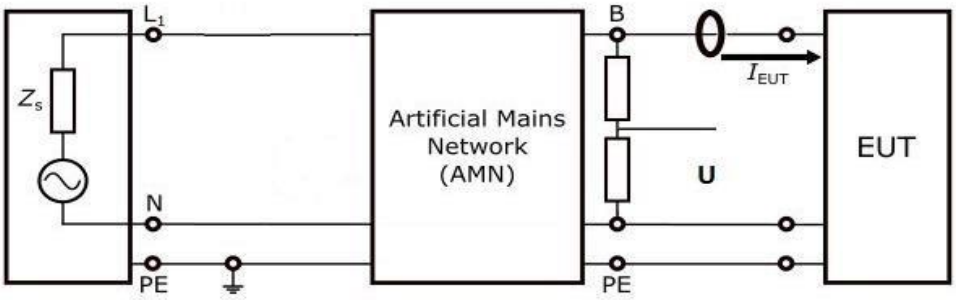


Fig.4 VSL laboratory measurement with the equipment under test (EUT) of supraharmonics with an AMN. PE is protecive earth.

VSL built an AMN according to the specification in IEC61000-4-7 which was measured to be within ±5 % of the characteristic given by the standard in the range 2 kHz to 9 kHz.

LNE Laboratory setup for measuring appliance emissions using a Line Impedance Stabilisation Network (LISNs)

LNE performed C16 measurements in the laboratory using the setup shown in Fig.5.

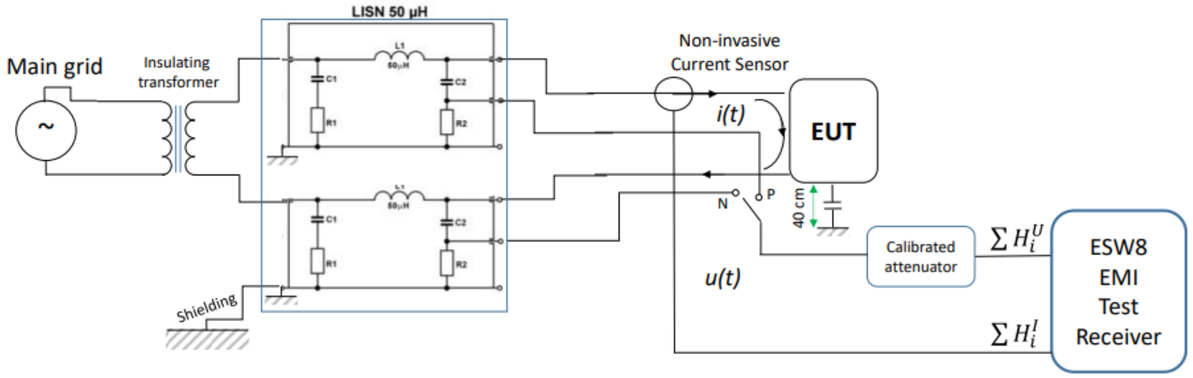


Fig.5, Laboratory setup used at LNE to measure supraharmonic emissions from household appliances

The LNE measurements were performed between phase/neutral and the ground in an electromagnetic anechoic chamber that helps minimising the amplitude of unwanted ambient signals. The main sources of such disturbances are the components switching at high frequencies, internal circuit sources or coupling between cables. The setup relies on:

Insulating transformer used to avoid noise coming from the main supply grid:

- LISN (Line Impedance Stabilization Network) of 50 µH (type ESH3-Z5), used to simulate a stabilized network and crucial for obtaining comparable measurements in the future.
- EMI Test Receiver type ESW 8. The real-time spectrum analysis with spectrogram function in line with CISPR 16 permits getting the frequency components in the analysed signal.
- Non-invasive inductive current sensor type FCC (Fischer Custom Communications) F35-1. The appropriate corrections were implemented in the acquisition software such that to compensate the non-linear frequency characteristic of the current sensor. The current sensor is placed at 40 cm between the EUT (Equipment Under Test) and the probe.

Fig.6, LNE Setup to measure harmonic emission for combined appliances: induction cooker, desktop computer and LED lamp

So that results obtained from appliances using the C16 receiver using the LNE setup can be compared with the VSL measurements with their AMN and Light-QP method, the raw sampled data from the appliances was also recoded using a digital oscilloscope with 12-bit resolution and a sampling rate of 500 kHz. As explained in Objective 1, a similar input high-pass-filter was used to suppress the fundamental component and to achieve sufficient resolution for the non-fundamental components above 2 kHz.

<u>Selected mass market appliances used to conduct comparison of emissions using alternative methods</u>

To demonstrate the compatibility between the Light-QP method and a commercial C16 receiver, measurements were performed on a collection of mass market appliances which are thought to give relevant emissions. The selected appliances were as follows:

- LED lamps with active PFC
- PC switching power supply with active PFC
- EV charger AC/DC converter
- Induction cooker
- Mix of above appliances

A measurement protocol was written specifying the operation modes, warm-up time, measurement time and other conditions to ensure that the appliances were always tested in a similar way.

Method of comparison

The appliances were shipped back and forth between LNE and VSL and measurements were performed according to the protocol described above. Three measurement results are compared:

1. The measurements at LNE were performed using the CISPR 16 receiver (referred to as “LNE CISPR”).

2. Simultaneously, at LNE, the emission waveforms were recorded without further analysis. These waveforms were processed and analysed at VSL using the Light-QP method. (“LNE New”).

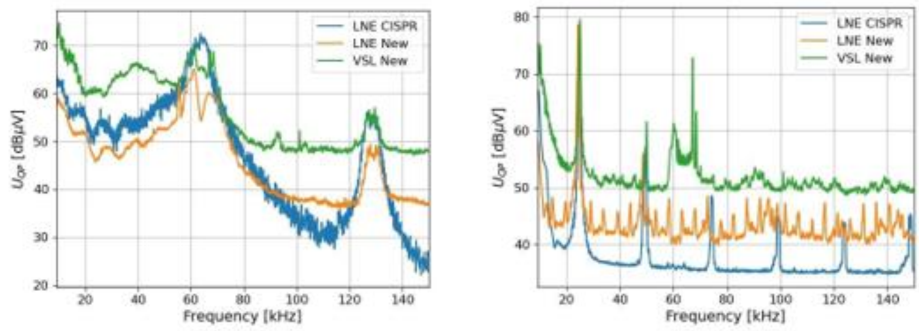
3. The measurements at VSL were performed using the Light-QP method with the portable instrument described Objective 1 (referred to as “VSL New”).

The first two measurements are performed under the same circumstances and potential differences are primarily caused by the algorithms. The third set of measurements uses different hardware and potential differences might be due to differences in emissions of the appliances under different circumstances and after traveling.

Comparison of measurement results

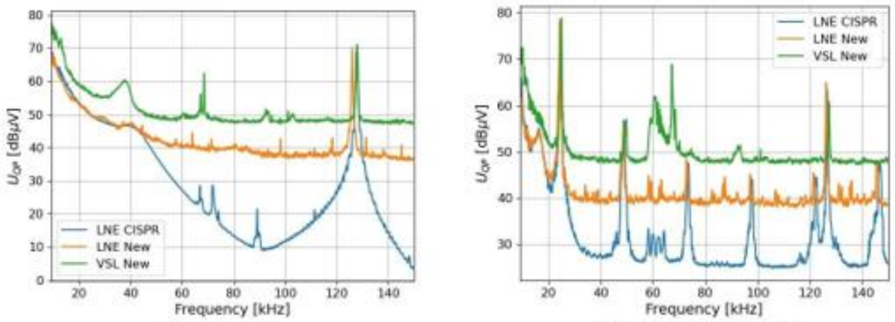
Fig. 7 a-e show the quasi-peak spectra of emissions of the selected household appliances as measured by the set-up of VSL compared with the results of the LNE CISPR receiver and the new method processing the LNE waveforms, as described in the previous subsection. A few observations can be directly obtained from these figures:

- The appliances typically show relatively low levels of conducted emission in the (9-150) kHz range, which makes it challenging to perform accurate measurements.
- The CISPR method shows the lowest background noise. This is to be expected of a laboratory measurement system.
- The “LNE New” measurements show higher noise floor, but still lower than the VSL measurements. This might be due a better input filter used by LNE to suppress the fundamental frequency component, thus allowing for a lower digitizer input range.
- Some of the VSL measurements show distortions around 60-70 kHz that are not observed by LNE. This is probably due to the non-idealized circumstances used for the VSL measurements.
- The three measurements seem to agree on some specific disturbances, which are apparently emitted by the appliances. These are the ones to further analyse.



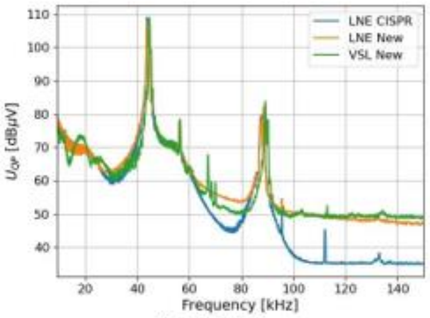
(a) LED lamp

(b) Induction cooker



(c) PC 40%

(d) Mix of appliances



(e) AC/DC converter

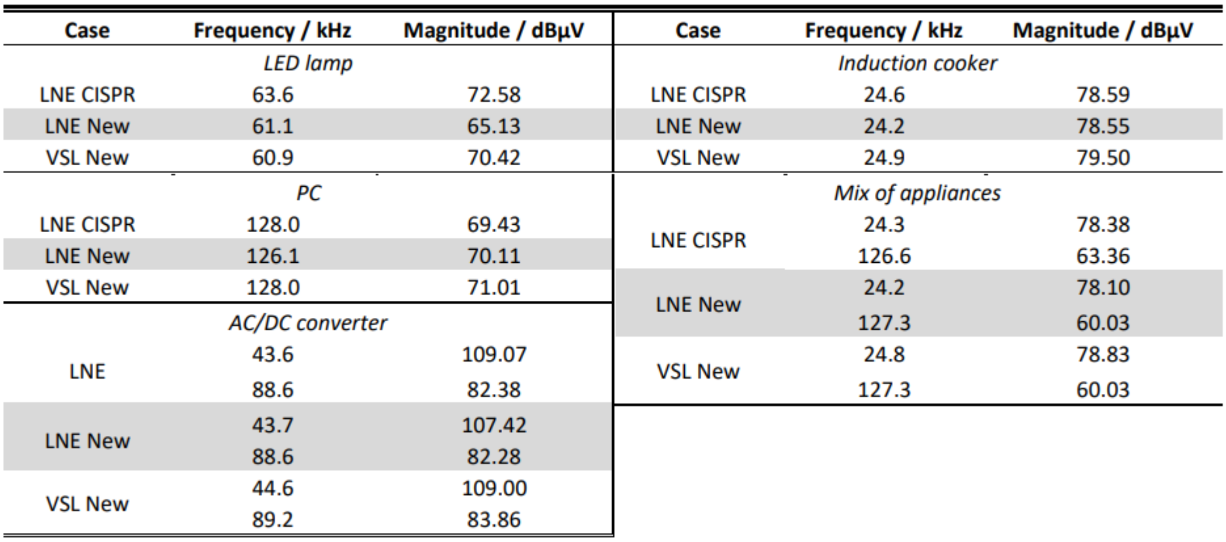
Fig. 7, the emissions measured by the CISPR 16 and the Light-QP method (different systems)

In Table 1, the maximum magnitudes of emissions as obtained from the LNE and VSL results are presented. Some observations can be made here as well:

- For the LED lamp, the frequency has a 2.7 kHz difference. The magnitude found by VSL is about 2 dBµV lower than the LNE CISPR result, whereas the “LNE New” result is more than 7 dB lower. These differences might be related to the specific waveform which shows a broad range of distortions rather than well-defined peaks.

- Typically, the frequency differences for the maximum emissions are on the order of 1 kHz, with some more pronounced differences at specific cases.

- Similarly, magnitudes typically differ by less than 2 dBµV, dependent on the specific case.



Case	Frequency / kHz	Magnitude / dBµV	Case	Frequency / kHz	Magnitude / dBµV
	LED lamp			*Induction cooker*	
LNE CISPR	63.6	72.58	LNE CISPR	24.6	78.59
LNE New	61.1	65.13	LNE New	24.2	78.55
VSL New	60.9	70.42	VSL New	24.9	79.50
	PC			*Mix of appliances*	
LNE CISPR	128.0	69.43	LNE CISPR	24.3	78.38
LNE New	126.1	70.11		126.6	63.36
VSL New	128.0	71.01	LNE New	24.2	78.10
	AC/DC converter			127.3	60.03
LNE	43.6	109.07	VSL New	24.8	78.83
	88.6	82.38		127.3	60.03
LNE New	43.7	107.42			
	88.6	82.28			
VSL New	44.6	109.00			
	89.2	83.86			

Table 1, Maximum magnitudes of emission measured in the laboratory using the three methods.

The selected appliances provide low-level emissions that are challenging to accurately measure and thus to compare measurement results. Especially the proposed Light-QP method to measure supraharmonic emissions is designed for operation under non-ideal circumstances and therefore low-level distortions are inherently difficult to obtain. Nevertheless, the results show that the two methods are in good agreement when focussing on the emission levels, although some minor differences are observed. These differences are caused by the reproducibility of the emissions of the appliances, differences in the measurement approach, differences in the measurement equipment such as the filters incorporated, and limitations due to the measurement uncertainties.

In conclusion, the proposed Light-QP method is demonstrated to provide results in line with the CISPR 16 method. Furthermore, the Light-QP method is shown to be a compatible, repeatable and efficient real-time processing technique when implemented in a practical measurement system developed for on-site measurements.

The project successfully achieved this objective and has made a comparison of the existing methods with the new proposed normative method.

4.3 Objective 3, To determine the suitability of 2-150 kHz compatibility levels by measuring the emissions from a selection of electrical appliances connected in a selection of LV networks

The aim of this objective is to study the emission characteristics of appliances under different LV network conditions and to compare them with the emission measured in the laboratory in Objective 2. Specifically, a grid measurement is made of the emission of the same mass-market appliances described measured in the laboratory in Objective 2 and the results are compared. All the grid and laboratory measurements produced raw sampled values, which have then been analysed with a digital implementation of the CISPR 16 measurement method. The same raw data has also been analysed by the newly proposed Light-QP method.

The Light-QP method has been devised as a suitable method to measure voltage distortion in the 2-150 kHz frequency region, providing useful power quality indicators, harmonised with measurement methods employed in power quality below 2 kHz. At the same time, the Light-QP method can be used to determine the suitability of the compatibility levels (as defined in IEC 61000-2-2) in the 9-150 kHz range using quasi-peak values. Moreover, the computational requirements for the Light-QP method are far less demanding than those of the CISPR 16 method.

The results from the laboratory measurements have been taken following the procedure described in CISPR 16 standard, which includes the use of a standardised LISN (effectively an AMN). The results from the grid measurements rely on the prevailing impedance of the LV network, hence no AMN has been employed. Analysing the differences between the measurements taken in the laboratory and the measurements taken on the grid can be used to determine the suitability of the AMN approach as a realistic laboratory representation of LV network conditions.

On-Site Grid Measurement Method

On-site LV network measurements performed by TUD and NPL using the same mass-market appliances described measured in the laboratory in Objective 2. These appliances are effectively used here as known source of emission (when the impedance is that of the AMN). By connecting these appliances into several different LV grids and operating the appliances according to the protocol used in the laboratory in Objective 2, the plan is to determine the voltage emission levels in the grids and compare it with the known laboratory emissions.

TUD have performed two sets of measurements in Germany: one in an urban environment and one in a rural environment. NPL have performed two sets of measurements in the same industrial environment in the UK at different (electrical) distances: one next to the appliances under test, and the other one further away from them, close to the nearest distribution board. In both cases sampled values have been collected and the same digital C16 method has been applied for the analysis. Similarly, the Light-QP method has been applied offline to all the raw data.

Grid CISPR 16 quasi-peak results

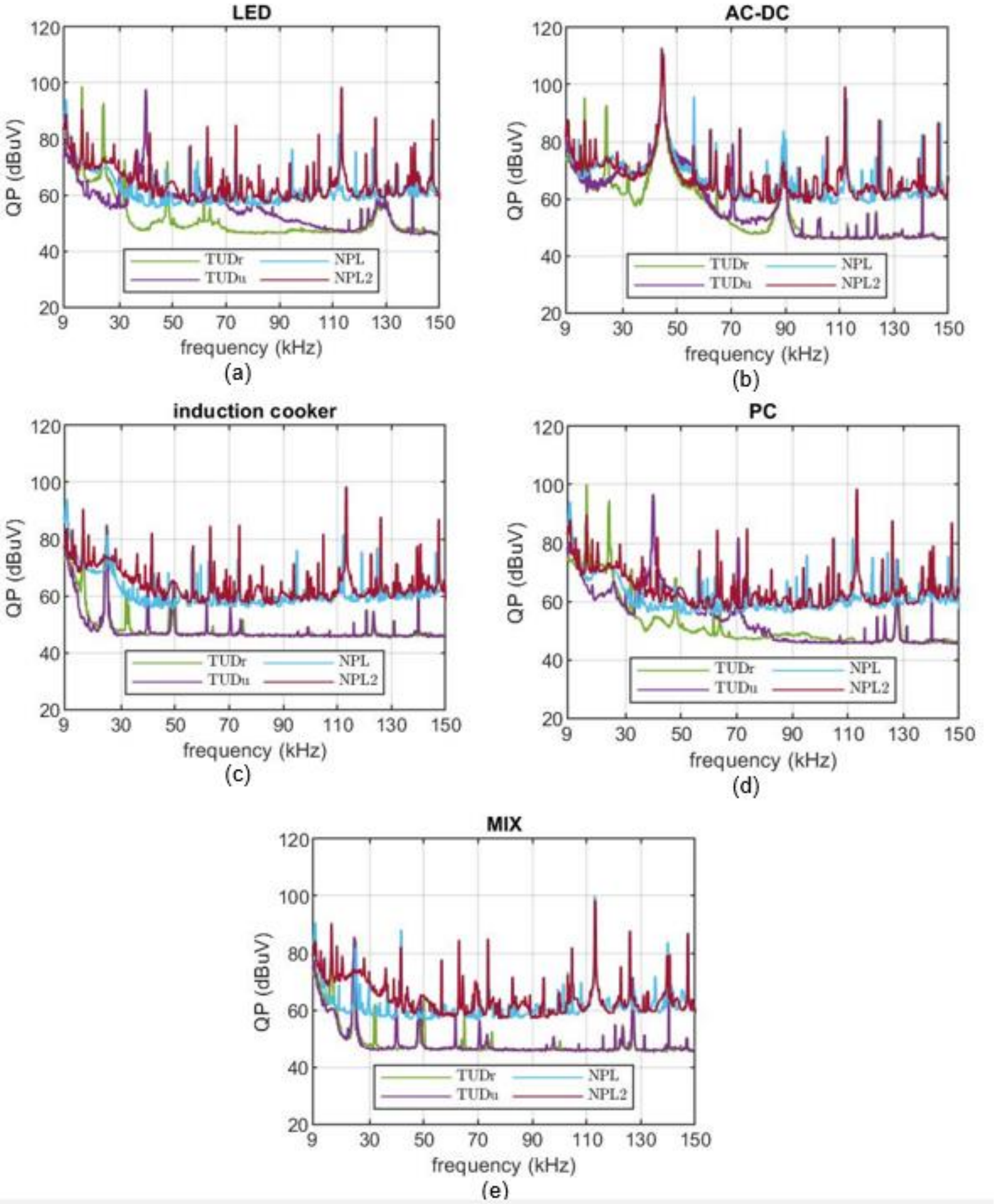
Fig.8 a-e show the quasi-peak spectra of emission of test appliances measured on the grid. The spectra include TUD urban location (TUDu), TUD rural location (TUDr), NPL industrial location close to the appliances (NPL), and the second measurement point at the same NPL industrial location but further away from the appliances (NPL2). These measurements give an insight into the suitability of the compatibility levels (as defined in IEC 61000-2-2) in different grid with different impedances.

From the LED results (Fig.8a) it can be seen how the different locations affect the spectra differently. This can be due to different types of connected equipment generating different emissions, which is probably the case in the lower frequency part of the spectrum (approx. 9-70 kHz. Additionally, the differences can also be due to different characteristics of the grid impedance in different locations. This could be the case of the mid-high frequency region of the spectrum (approx. 70-120 kHz) where there are less peaks but still different spectral profiles, with differences up to 10 dBμV.

Differences can also be seen in the AC-DC spectra (Fig.8b), where the first harmonic of the switching frequency (i.e. the peak at 89.3 kHz) can have an amplitude 10 dBμV lower or higher if measured in different locations, even with the same instrument. This can be observed, for instance, for the urban and rural measurements from TUD. The switching frequency peak at 44.65 kHz, instead, shows the same amplitude in all cases.

Another interesting observation comes from the NPL measurements taken at the second location, which is far away from the appliances. In several cases, the emissions cannot be seen, probably because they are below the noise level, or because they have been attenuated with the distance, limiting their propagation in the grid.

Finally, another insightful observation comes from the test of combined appliances. The emission around 24-25 kHz (from the induction cooker) has a comparable amplitude to the same emission measured from the individual appliance, but the location in frequency is slightly different. The same can be observed for the PC emission at approximately 128 kHz where the amplitudes are also different in this case, up to 6-7 dBµV lower.



(a)

(b)

(c)

(d)

(e)

Fig.8, CISPR 16 quasi-peak results of the appliances emissions in the LV network: (a) LED lamp; (b) AC-DC converter; (c) induction cooker; (d) desktop PC, (e) combined LED+PC+induction cooker.

Light-QP results

The same raw waveform data from obtained from the appliances was also analysed using the Light-QP method in order to compare Light-QP quasi-peak spectra with the C16 quasi-peak spectra. This analysis gives an indication of the suitability of the Light-QP method as an alternative to the computationally intensive C16 method.

For the sake of conciseness, only the following measurement locations are considered for this comparison:

- TUD rural area
- NPL industrial area – location 1 (point of connection of appliances)

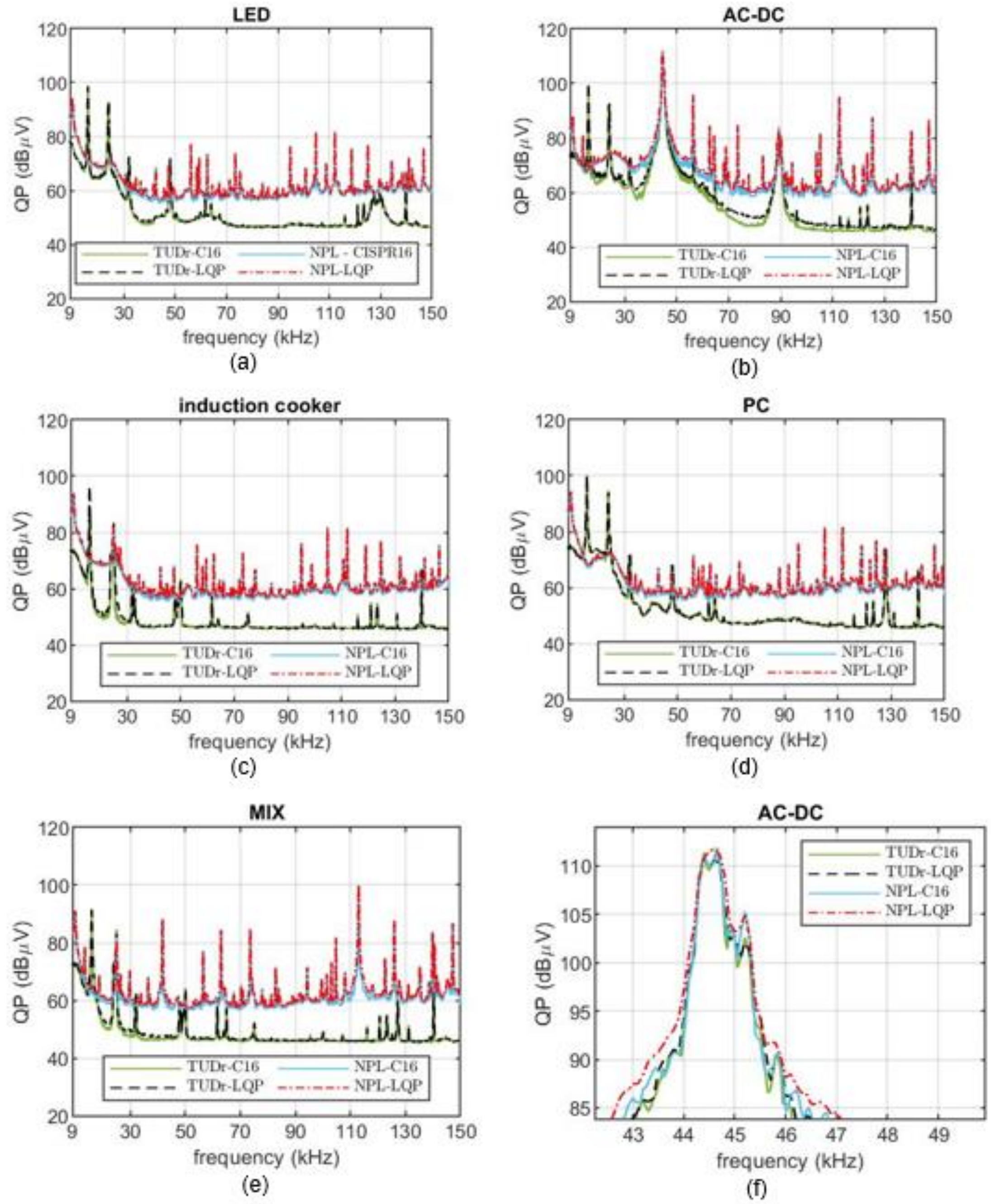


Fig.9, Light-QP and CISPR 16 quasi-peak results of the appliances emissions on the grid: (a) LED lamp; (b) AC-DC converter; (c) induction cooker; (d) Desktop PC, (e) Combined LED+PC+induction cooker. Sub-figure (f) shows a detail of the emission peak of the AC-DC.

As seen Fig.9, the Light-QP method provides quasi-peak values which are highly comparable with those obtained using the digital C16 method. In some cases, few differences can be seen at levels comparable to the noise floor, but the high amplitude peaks have very similar results, always within 1 dBµV.
Significantly, the differences between Light-QP results and digital CISPR 16 results are much smaller than the differences between the same digital CISPR 16 method applied to samples from different laboratories, even when measuring the same appliance with a standardised AMN.

Comparing results between laboratory and grid measurements

A comparison between the results of the measurements of emissions of the appliances in the lab with the AMN and the emissions measured on the grid are presented here. Analysing these differences can be used to determine the suitability of the AMN approach as a realistic laboratory representation of LV network conditions.

For the sake of conciseness, only four spectra per test are shown, two from the laboratory and two from the grid. The reported results are from:
- LNE laboratory measurements with AMN
- VSL laboratory measurements with AMN
- TUD grid measurement Germany, rural area, no AMN
- NPL grid measurement UK, industrial area, no AMN.

The results shown use the C16 and the QP spectra for each appliance are presented in Fig.10.

The case of the LED emission provides an insight on differences on the results for emission at high frequency and low amplitude. The region between 123-135 kHz is a broadband emission from the LED lamp, as already above. The maximum value of this region for the LNE measurements (laboratory) is 49 dBµV. The maximum value of this region for both VSL (laboratory) and TUD (grid) are relatively similar, 57.5 dBµV and 59.2 dBµV respectively. In the NPL spectrum, instead, it is below the noise level. In this case, the two laboratory measurements, with the same AMN, have a difference of more than 7 dBµV, while the grid results (no AMN) are similar to the results obtained in the VSL laboratory (with the AMN). This shows that in some cases there are significant differences even between the laboratory measurements. This is also observed throughout the entire frequency range of the LED spectra, which has relatively low amplitudes.

For the AC-DC, the peaks are well identified. However, for the switching frequency peak (44.6 kHz), both grid measurements detect amplitude values approximately 3 dBµV higher than those measured in the laboratory. For the second harmonic of the switching frequency (89.3 kHz) the results from the grid are comparable with those from the laboratory, but the grid results are still slightly higher than those from the laboratory.

For the induction cooker, a similar outcome is observed, as the amplitude of the peak at 24.8 kHz is above 80 dBµV in the grid (83.6 dBµV from TUD and 81.6 dBµV from NPL), while it is below 79 dBµV in the laboratory (78.6 dBµV from VSL and 78.9 dBµV from LNE). This results in a range of variations of up to 5 dBµV. The peak at 49 kHz (which is not detected by NPL measurement) still has a higher value when measured by TUD in the grid. It is 0.9 dBµV greater than in VSL laboratory and 5.9 dBµV greater than in LNE laboratory.

The emissions from the PC show a similar pattern, as the amplitude of the peak measured in the grid is between 2 and 4 dBµV greater than the amplitude of the peak measured in both LNE and VSL laboratories. As already observed in the previous sections, the PC emission peak at 127 kHz is altered when combined with the emission of the other appliances, most likely due to the interactions with the LED emissions in the same frequency range.

The rest of the emissions in the combined appliances test are similar to the individual appliance tests. These considerations show that in several cases the emissions measured in the laboratory are lower than those measured in the grid for the same piece of equipment (AC-DC, PC, induction cooker). This might indicate an excessive attenuation provided by the AMN. However, the data collected in this activity is not sufficient to be conclusive.

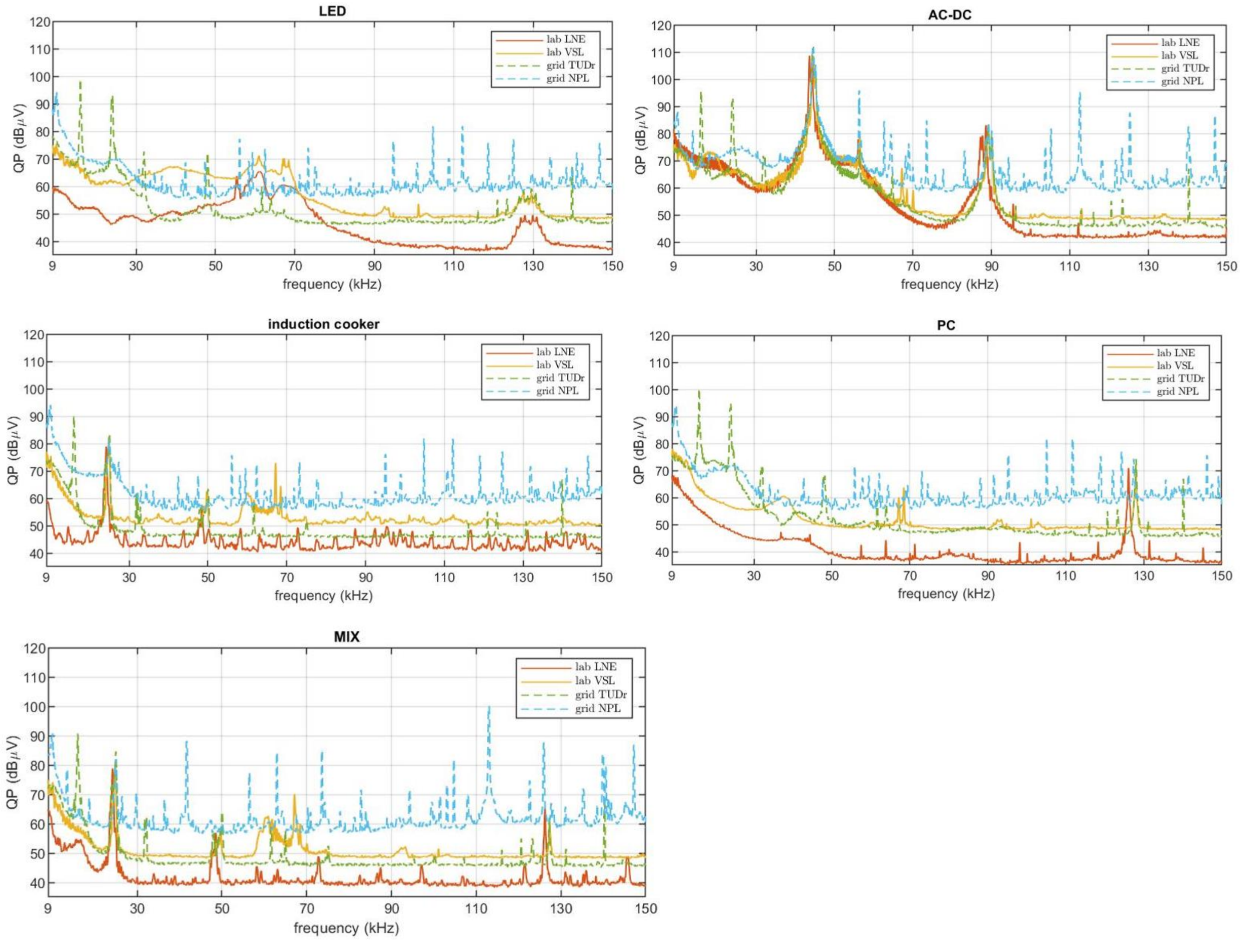


Fig.10, Comparing results between laboratory and grid measurements using the C16 QP results

The Suitability of Compatibility Levels

The compatibility levels for voltage distortion in differential mode from 9 150 kHz shown in Table 2 and are related to disturbance levels between any phase conductor and the neutral conductor. These are defined in IEC 61000-2-2.

Frequency range (kHz)	Compatibility levels (dBµV)
9 to 30	129.5 to 122[1]
30 to 50[2]	122 to 119[3]
50 to 150	113 to 89[4]

Table 2, IEC61000-2-2 Compatibility levels for voltage distortion in differential mode above the 40th harmonic up to 9 kHz

Fig.11 shows the quasi-peak emissions measured for the four considered appliances and the corresponding compatibility levels in the 9-150 kHz frequency region. It can be seen that there is a decreasing level from 9 kHz to 15 kHz, and a common structure between 15 kHz and 30 kHz. This is particularly clear in Fig.11a, Fig.11b, and Fig.11c. This broad structure is not visible in Fig.11c, probably because the emission of the induction cooker at 25 kHz is superimposed and dominates.

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[1] The logarithm of the level decreases linearly with the logarithm of the frequency in the range 9-30 kHz

[2] At the transition frequency, the lower level applies.

[3] The logarithm of the level decreases linearly with the logarithm of the frequency in the range 30-50 kHz

[4] The logarithm of the level decreases linearly with the logarithm of the frequency in the range 50-150 kHz

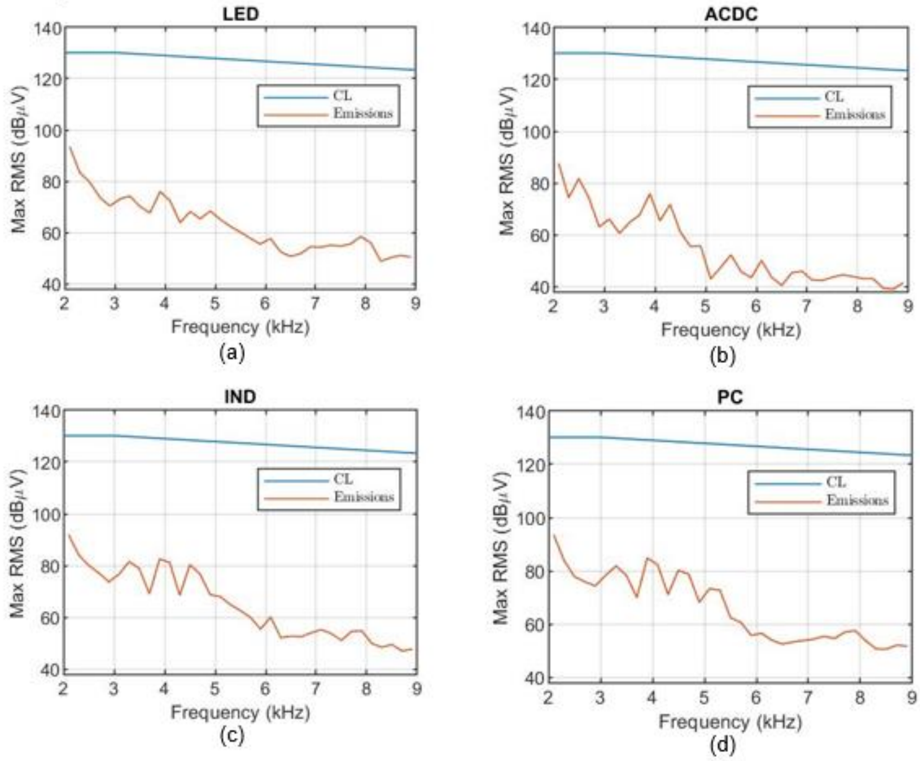


Fig.11, CISPR 16 quasi-peak results of the appliances emission compared against the IEC compatibility levels for the 9-150 kHz range: (a) LED lamp; (b) AC-DC converter; (c) induction cooker; (d) desktop PC.

In terms of comparison with the compatibility levels, it is possible to observe that the maximum values of the CISPR 16 quasi-peak values over the entire measurement interval never exceed the compatibility levels in the 9-150 kHz frequency range. This is especially true for the LED lighting, the desktop PC, and the induction cooker. The emission profile of the AC-DC converter, on the other hand, has a different profile. The main switching frequency at approximately 44 kHz has a quasi-peak amplitude of 111.7 dBµV, which is 8.3 dBµV below the corresponding value of the compatibility levels. This reduces to approximately 5 dBµV if a 3 dB emission margin is considered according to the notes in IEC 61000-2-2.

It was shown above that differences of several dBµV could be found when measuring in different locations in the LV grid, or even when comparing different laboratories and different instruments. Additionally, it must be noted that the compatibility levels are decreasing with frequency. If the same emission peak would have been located 15 kHz higher, it would have exceeded the compatibility levels.

It is worth keeping in mind that the penetration of inverter-based devices in the LV grid is increasing (e.g. PV panels and EV chargers to mention a few). If several inverters similar to the one tested in this section, possibly even the same model, are connected to the same feeder it is reasonable to expect higher emission levels, which is a reason for concern. Finally, it is important to consider unwanted grid interactions such as resonances, which could affect the amplitude of the measured emissions and are not necessarily considered by the 3 dB margin mentioned above.

Objective 3 Discussion

Measurements of voltage disturbances emission from mass-market household electrical appliances have been performed in different locations and test conditions. Two different NMIs, LNE and VSL, have performed laboratory tests connecting the appliances to a power source via an artificial mains network (AMN), and grid measurements have been performed by TUD and NPL in different grid locations, connecting the test appliances directly to the mains electricity network without the use an AMN, replicating the real use of such appliances. The results have been analysed using the C16 and Light-QP measurement methods.

The analysis has found an overall agreement between the results obtained in different locations and conditions, especially where high-amplitude narrowband emissions are concerned. However, some differences have been also identified in the analysis.

Although the emission peaks are always identified, the comparison between the grid measurements and the laboratory measurements have shown that in some cases the laboratory results show peak amplitudes lower than those measured in the grid. This could be an indication of an unrepresentative AMN impedance at certain frequencies. Since the network impedance is not constant but changes in time and space, this is a necessarily imperfect approximation. Therefore, even if in many cases it has been shown that a good agreement between the measurements is obtained, the specific cases indicate that further study might be required to determine whether a revision of the AMN would be needed. The outputs from this project's Objective 4 will also provide further insight on the validity of the existing normative AMN, developing on the impedance measurements performed on the grid.

The results presented in this report also showed, in some cases, differences in the emission when measured in different laboratories, namely the LED and the induction cooker, with differences of 5 dBµV and 8 dBµV in peak amplitude. These measurements were taken using the same normative AMN. This poses some questions on the reproducibility of the measurements and whether there are further aspects to be considered besides the AMN that have an impact on reproducibility.

Finally, the CISPR 16 quasi-peak results have been compared with the quasi-peak values obtained using the newly developed Light-QP measurement method, obtaining very similar results. Differences are always within 1-1.5 dBµV and much smaller than the differences between the variability observed between different laboratories and locations, confirming once again the good comparability between the results produced by the two methods.

The measurements of emissions from selected household appliances when connected to the LV network are compared with compatibility levels. Although the results cannot prove emission limits compliance, provides an insight on the available headroom with respect to the compatibility levels. It is shown that the emission levels for the tested appliances are lower than the compatibility levels. Although this does not necessarily mean that the appliances comply with emission limits, it shows sufficient headroom in this case. Nevertheless, the ACDC converter showed emissions close to the compatibility levels. Further measurements on the grid are required to confirm the initial observations, including longer measurement times.

In particular, considering the ever-increasing presence of devices injecting distortion in the 2 kHz to 150 kHz range, it is important to monitor the evolution of voltage distortion in this frequency range to ensure EMC. Finally, it is important to consider unwanted grid interactions such as resonances, which could affect the amplitude of the measured emissions.

The project successfully achieved this objective and a carried-out grid measurements using the new method to inform the setting of CLs in future normative standards.

4.4 Objective 4, To verify the applicability of the AMN characteristics by measuring network impedance characteristics of a number of typical LV electricity networks.

The aim of this objective is to assess the typical characteristics of public LV networks based on extensive measurements of the frequency dependant network impedance (FDNI). These measurements will be used to verify the applicability of the artificial mains network (AMN) characteristics by measuring network impedance characteristics of a number of typical LV electricity networks.

The FDNI is the link between distorted voltages and currents. It is an essential prerequisite for many applications, including assessment of emission limits for customer installations, simulation of the propagation (damping) behaviour of distortion, and solving distortion-related customer complaints. Furthermore, it has a decisive impact on compliance testing of electrical appliances in a laboratory.

The FDNI of low voltage networks can be represented by an AMN in the frequency range 2-9 kHz (as defined in IEC 61000-4-7) and a line impedance stabilisation network (LISN as defined in CISPR16-1-2) in the frequency range of 9-150 kHz. While realism and the representative nature of reference impedance are crucial to ensure a credible regulation regime, the characteristics of AMN and LISN are based on studies dating back several decades. The applicability of these characteristics is questionable due to the natural development of public LV networks during the last years. In light of the move toward regulation, it is essential to verify that AMN and LISN represent the FDNI of today’s public LV networks.

The following sections introduce the approaches for measurement of the FDNI developed within the project and provide an overview of the measurement campaigns. Finally, the results are critically discussed before the conclusion of the study is provided.

FDNI Measurement Methods

Two approaches for measuring the FDNI developed within the project. The reproducibility and accuracy of both approaches have been validated under controllable laboratory conditions. The validation process reveals strong similarities in results of developed approaches and good comparability with results of existing measurement instruments.

Fig.12 shows the layout and prototype of the measurement system developed by the Technische Universität Dresden (TUD) in collaboration with a manufacturer. It consists of a current source for grid excitation, integrated measurement units, and a power supply with a buffering capacitor.

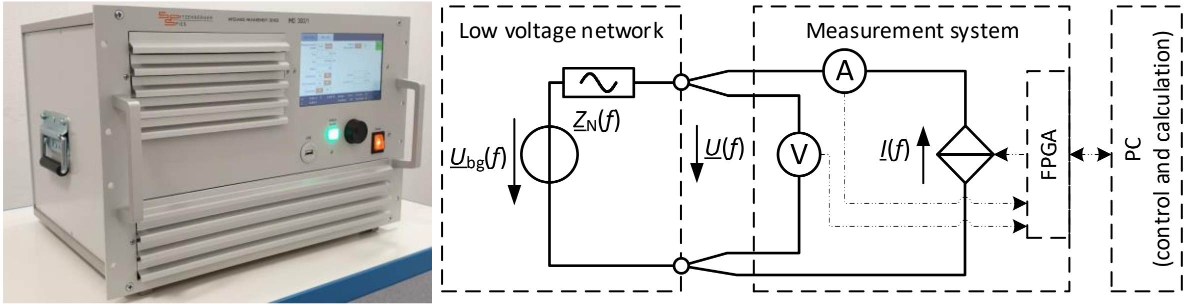


Fig.12, Layout and prototype of TUD measurement system

A linear amplifier generates a current with a maximum magnitude of 2 A in the frequency range up to 200 kHz. Injected current is measured internally, while grid voltage is measured at the connection point. Both voltage and current are sampled with a rate of 10 MS/s and a resolution of 16 bit. The mains energisation of the system is disconnected from the network during the measurement process to ensure that the measurement system itself does not influence the measurements. During the measurement an internal buffering capacitor powers the system.

The measurement is implemented as a stepwise single frequency sweep. The current injection lasts 220 ms for each measurement step, while voltage and current are sampled for 440 ms. Voltage and current values are obtained for both states with and without current injection using a Discrete Fourier Transform (DFT) over a rectangular window of 10 voltage fundamental cycles. The FDNI is calculated for each injected frequency with the difference method according to Equation (1).

$$\underline{Z}(f) = \frac{\Delta\underline{U}(f)}{\Delta\underline{I}(f)} \tag{1}$$

The measurement system utilises the synchronisation to the fundamental frequency of the network to avoid the effect of spectral leakage. The FDNI is measured starting from subharmonic frequencies of the fundamental (e.g. 25 Hz) up to 200 kHz.

Fig.13 shows the layout of the measurement system developed by the University of the Basque Country (UPV/EHU). It consists of a signal generator and capacitive coupler for network excitation, current and voltage probes with an oscilloscope for the measurements, and a battery for the power supply.

The signal generator produces a test signal coupled to the network with a capacitive coupler having a flat frequency response up to 500 kHz. The magnitude of the test signal is limited to avoid damage to other appliances connected to the network. Voltage and current are measured via specially designed probes and sampled with a commercial oscilloscope (Picoscope series 5000) with a sampling rate of 3.9 MS/s and a resolution of 15 bit.

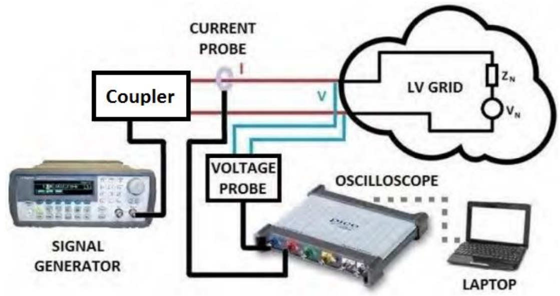


Fig.13: Layout of UPV/EHU measurement system

The measurement is implemented as a stepwise single frequency sweep. Once the voltage and current values are recorded, the sliding window function is applied to select a set of synchronous samples of voltage and current with high resolution. A representative configuration is a sliding window of 20 ms, with a shift step of 5 ms (75 % of overlapping between consecutive windows). A Fast Fourier Transform (FFT) is applied separately to each set of the samples to obtain spectral characterization. Finally, the FDNI is calculated by dividing the voltage and current values of all frequency bins.

The measurement system does not require the synchronisation to the fundamental frequency of the network. Instead, the effect of spectral leakage is eliminated with high-pass filtering of measured voltage and current. As a result, the FDNI is measured in the frequency range of 20-500 kHz.

The TUD and UPV systems were compared in the laboratory by measuring a static impedance reference made from passive components of known characteristics. A good correlation is obtained between the measurement results of TUD and UPV/EHU measurement systems and a precision impedance meter.

Measurements in the LV power network

The first measurement campaign is focused on the characterisation of the FDNI in distributed locations in the LV network. It was conducted in coordination with more than fifteen distribution system operators (DSO) in Austria, the Czech Republic, Germany, Spain, and Switzerland. Each DSO selected two typical public LV networks in urban and rural areas. At least two measurement sites were considered in each network: the LV busbar at the transformer station (TS) and the furthest accessible point in the network (junction box {JB} or customer terminal {CT}). In total, 131 measurements sites with 354 single loop impedances were analysed. Around 60 % of measurements were carried out at JB.

Further measurements focused on the characterisation of the FDNI at socket outlets in residential and office buildings. It included measurements in Germany, Spain, and the United Kingdom. The measurements were conducted during the normal operation of electrical appliances available inside the buildings.

The main part of the measurements took place in fourteen residential buildings, including single- and multi-family houses in rural and urban areas. At least two accessible socket outlets in each accessible room were considered. In total, around 130 individual measurements were conducted. In addition, a measurement took place in two office buildings, where 20 socket outlets were characterised.

FDNI Measurement Results

Fig.14 presents an overview of all impedance measurements in the network and selected percentile curves. For comparability, the representation is complemented with the characteristics of the reference impedances, namely the AMN for the range of 2-9 kHz and the LISN (line-to-neutral connection) for the range of 9-150 kHz.

The great majority of the results for impedance magnitudes lower than the reference impedance characteristics for both frequency ranges. The results show a substantial variation of about two decades. The 50th percentile curve accounts for approximately 10 % of reference impedance magnitude. In comparison with the outcomes of the previous studies (1998 and 2010), a tendency for a gradual decline of the value of the FDNI since those older studies was observed. The wide spread of results does also apply to the impedance angles. Above 10 kHz, about 25 % of the results are below 60° with a considerable variation between sites. In general, a clear capacitive behaviour of the network has to be expected over the whole frequency range.

The impact of location in the network is presented in Fig.15, which shows the difference between impedances measured at different sites of the same network. While the short-circuit power tends to influence the impedance magnitudes in the frequency range below 8 kHz, this dependency becomes less pronounced at higher frequencies. Here, multiple site-specific resonances are observed at junction boxes and customer terminals. The possible causes for these occurrences are modern electrical appliances connected close to the measurement location.

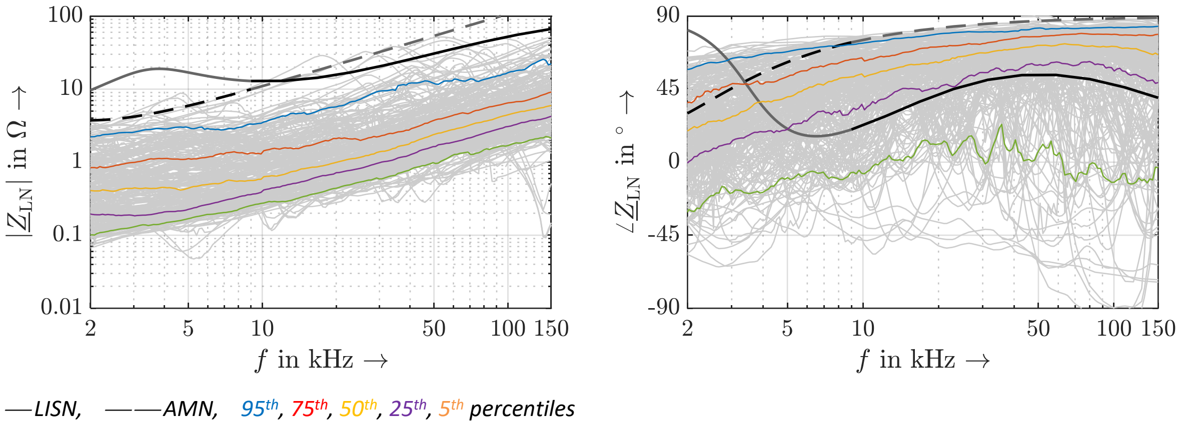
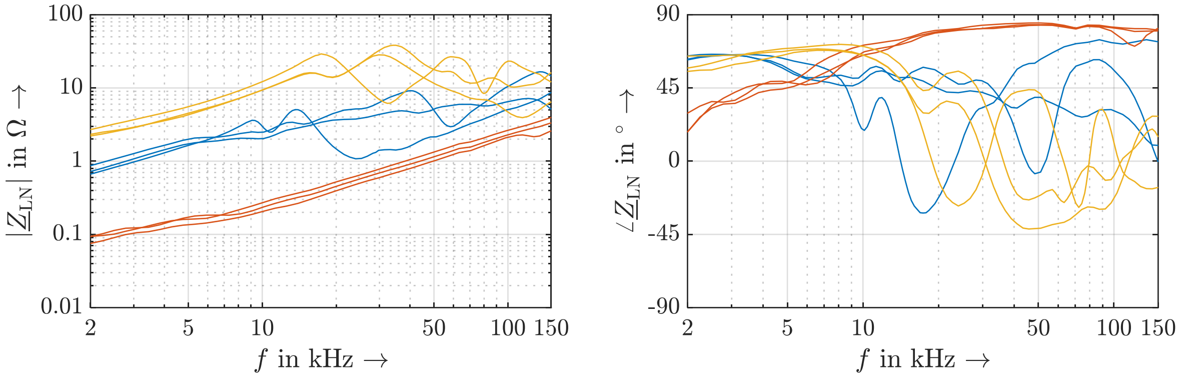


Fig.14: Results of all impedance measurements in the network (grey) including selected percentile curves and characteristics of reference impedances



red: transformer substation, blue: junction box, yellow: customer terminal

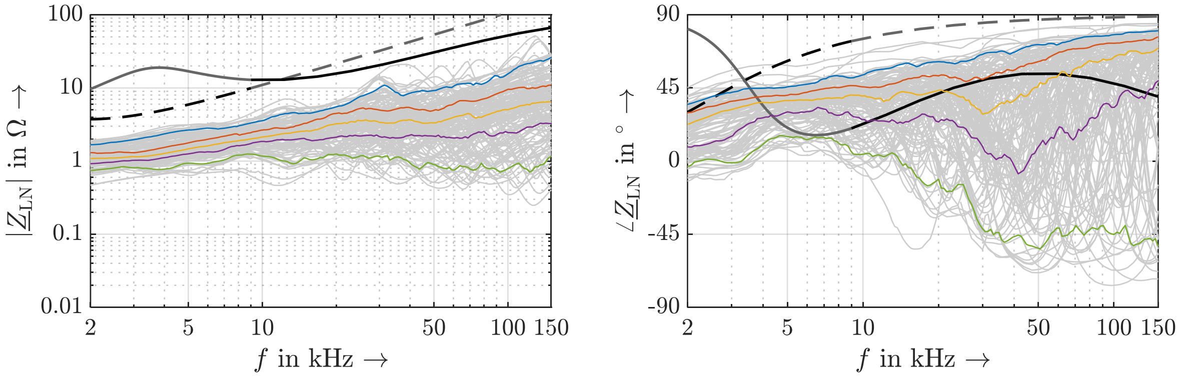
Fig.15: Impedances measured in distributed locations of the same network

Fig.16 presents an overview of all impedance measurements at socket outlets and selected percentile curves. For comparability, the representation is complemented with the characteristics of the reference impedances, namely AMN for the range of 2-9 kHz and LISN for the range of 9-150 kHz.

Similar to the measurements in the network, impedance magnitudes measured at socket outlets are below the reference impedance characteristic for both frequency ranges. While a partly lower variation of impedance magnitudes below 10 kHz is due to a relatively small number of measurement sites, the increased variation at higher frequencies suggests a considerable influence of connected electrical appliances. The results for impedance angles show that resonance occurrences with clear capacitive behaviour induce a large part of these variations.

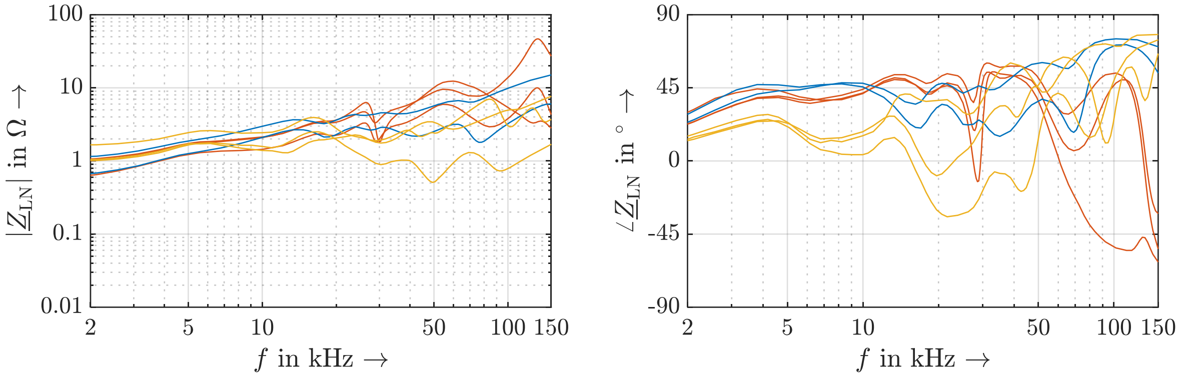
A considerable influence of connected electrical appliances becomes more evident in Fig.17 which shows the results of measurements in different rooms of the same residential building. It reveals a substantial variation of impedance magnitudes with a maximum ratio of 50. Given the knowledge about the layout of electrical installation, a variation between different phase connections can be estimated with a maximum difference factor of 15.

A considerable variation of impedance magnitudes is also observed between different socket outlets connected to the same phase. For example, Fig.18 shows measurements at 18 socket outlets (different pairs of double socket outlets) in a room of an office building. Here, the maximum difference in impedance magnitudes reaches a factor of 1.5 for the socket outlets located around 50 cm apart and a factor of 13 for the socket outlets located in different corners of the room. A closer look at impedance angles suggests a considerable influence of connected electrical appliances having clear capacitive behaviour.



— LISN, — — AMN, 95th, 75th, 50th, 25th, 5th percentiles

Fig.16: Results of all impedance measurements at socket outlets (grey) including selected percentile curves and characteristics of reference impedances



red: kitchen (phase A), blue: bedroom (phase B), yellow: living room (phase C)

Fig.17: Impedances measured at socket outlets in different rooms of the same residential building

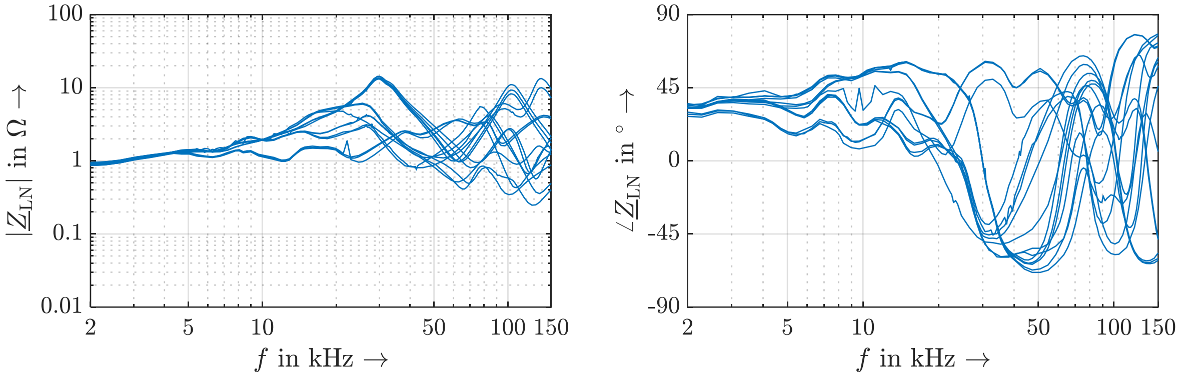


Fig.18 : Impedance measured at socket outlets in the same room of an office building

Discussion of the FDNI Results

The largest part of measured impedance magnitudes is below the reference impedance characteristics. However, some of the measurements are still close or exceed the reference impedance characteristics. Statistical evaluation reveals a tendency for a gradual decline of the FDNI compared to outcomes of previous studies. It indicates a rather conservative character of present reference impedances. This can result in too restrictive emission limits and less effective utilization of LV networks. It should be noted that only measurements from Europe are considered in this survey and further measurements from other regions of the world would be required to initiate a discussion about changing the reference impedances.

The results show a substantial variation of measured impedance magnitudes over two decades. The dependency from the short-circuit power declines with the frequency rise, while resonance occurrences with a clear capacitive behaviour considerably influence the FDNI characteristics starting from 8 kHz. The number of resonances increases with the distance from the transformer substation, suggesting a dominating impact of electrical appliances connected to the LV networks on the FDNI at higher frequencies.

The presented results shall serve as basis to initiate discussions about a possible need for changing existing reference impedances. The following steps include a closer look at the nonlinear behaviour of the FDNI within the power cycle (sub-cycle-impedance) and its variation over time. Other ongoing activities are detailed research on symmetry between the line-to-neutral and neutral-to-earth impedances and extending the frequency range of interest up to 500 kHz.

The project successfully achieved this objective and has presented measurement based information on the FDNI that will inform the setting of future normative AMN specifications.

5 Impact

A total of nine conference papers have been submitted to various events including CPEM 2020, AMPS2021, AMPS2022, CPEM 2022) and 11 open-access articles has been published in peer-reviewed journals (see the list at the end of the document) with two further manuscripts awaiting review. One paper was published for the high-profile electricity system operator conference CIRED2021 and was awarded a “best paper” prize.

An on-line mid-term workshop was held in November 2020 which was well received by the ~70 attendees, the presentations can be downloaded from the project web site. A final workshop was also held in April 2022 attending also by some 70 people. This final event presented the new methods and results obtained from laboratory and site measurements.

In addition, the stakeholder committee established by the project with 26 members. Regular contact via email was maintained with the Chief stakeholder including attendance at the various meetings of IEC SC77A WG9. The project website was set up and updated regularly. A highly successful three-hour tutorial workshop was held at the CIRED conference in September 2021; this conference is attended by distribution network operators throughout Europe.

Impact on industrial and other user communities

Experience has shown that imposing new regulations on large markets is fraught with political and commercial controversy. The multi-million market for electrical goods is highly competitive and small changes to product designs in order to comply with emissions limits can be hugely expensive to manufacturers in component costs and lost time to market for a new product; ultimately these costs are passed on to consumers. Yet without regulation, these same manufacturers, together with consumers, face the prospect of increased product malfunction and/or failure and/or faster product aging. In the longer term, regulation is in everybody’s interest, but rigorous evidence will be needed to prove the case and primarily to agree levels at which product emission limits should be set. The measurement framework developed in this project has a key role to play in this; developing and applying it to determine the levels of emission in the power grid to which other appliances are exposed, is absolutely essential to the credibility and acceptability of new regulations and limits. The regulation of the emissions from mass-market goods should reverse the trend of increasing grid pollution and protect the quality of supply. This is essential to the following stakeholders in the following ways:

Manufacturers of mass market electrical goods and consumers: Although new regulation will bring extra costs, it will protect all appliances from emissions that can cause malfunction or failure. Reliable products are essential to consumers and are important to manufacturer’s reputations. However, regulation cannot be *ad hoc* and through the rigorous, realistic and repeatable measurements that the new methods developed will bring, new compatibility levels that will be determined through grid measurement surveys. These will be the basis for a fit for purpose EMC framework protecting reliability, but not being unnecessarily burdensome.

Providers of strategic infrastructure: In the same way that domestic products can malfunction, so can the electronic equipment and control systems that make up key infrastructure. This might include hospital technology, mass transit systems and utilities. Whilst these systems are well-designed when compared to domestic products, unprecedented levels of supraharmonics could pose a threat to this infrastructure. The new EMC structure will instigate and underpin a framework of normative limit-based controls that will assure operational reliability.

Utilities, Transmission and Distribution Grid Operators: An example of the threat to key infrastructure is the power grid, which is the reluctant receipt of supraharmonic emissions. Their effects include, overheating of power transformers, catastrophic failure of the capacitor banks used to regulate the power, false operation of protection circuit breakers and interference with control signals. The JRP has already conducted some grid-based surveys of prevailing levels and more are planned in various countries working with utilities to determine whether or not they have a build-up of disturbance.

Manufacturers of power line communication (PLC) and mains signalling equipment: PLC and mains signalling use the grid wires for data transmission and for control signals, for example those used to operate smart grids. PLC intentionally emits 2-150 kHz signals into the grid, so users and manufacturers have a very strong interest in ensuring that the pollution from electronic devices does not unintentionally jam communications. In all the outputs of the project have been sent to the standards committee that oversees PLC, namely CLC SC205 to help them understand the issues for future PLC.

Electric vehicles, renewables and energy storage manufacturers – users of power convertors: These technologies are vital to CO_2 reduction and their deployment will increase rapidly in the coming decades.

Power convertors are used to exchange their energy with the grid, but these electronic systems can also generate substantial supraharmonics. Power convertors are also susceptible to emissions which can interfere with the electronics whose purpose is to synchronise to the grid frequency. Testing convertors both in the laboratory and when deployed in large numbers on the grid (e.g. heat-pumps, EV chargers), utilities are anxious to know whether they need to plan for mitigating actions to protect the distance levels on the grid. Partners already plan some work of this sort with utilities after the end of the project.

Impact on the metrology and scientific communities

Development of a suitable new supraharmonic measurement system is scientifically challenging involving advanced DSP techniques, fluctuating signal analysis, data visualisation and complex impedance interactions. This has generated important publications where these techniques have been clearly described, in order to contribute to spread both the results of the work, and the contributions to the standards and new instrumentation. The project has developed test rigs and on-site instruments that will form the basis of new services for NMIs and calibration laboratories who will need to develop their measurement capabilities in the 2-150 kHz range. Using the new method, the test and measurement industry will need to respond with new instruments, AMNs which will be used in EMC Testing Laboratories for routine compliance assessments on mass market goods. Already instrument manufacturers have been involved in standard committees and plan to implement the new methods on their mass-produced PQ instrumentation.

Impact on relevant standards

The main objective of this project was to produce a new supraharmonic measurement method to be included in the main PQ measurement standard IEC 61000-4-30. The convener of the special IEC 77A WG9 Task Force for this method, is this project’s Chief Stakeholder who has been involved in the drafting of this project and its work on the new method. This relationship has ensured a direct link to implement the projects outputs. The method has also be considered by IEC TC85 WG20 responsible for measurement equipment for grids. The new light-QP method and the digital CISPR 16 method have both been included in the CD version of IEC61000-4-30 published in April 2022.

The project has researched the suitability of the normative AMNs as used to simulate the mains in EMC laboratories. This has been reported to the IEC SC77A WG1 and CISPR/H committees and recommendations as to the suitability of the existing AMN specifications will be made to the standards committees responsible for IEC 61000-4-7 and CISPR 16-1-2. Furthermore, information on the cumulative emissions of mass-market goods in grids is essential information for SC77A WG8 who can use the results to consider the suitability of compatibility limits as dealt with in IEC 61000-2-2.

Longer-term economic, social and environmental impacts

Electronic goods and power grid systems are essential elements of the economy and social structure. Credible and fair regulation is required to ensure that these complex systems do not interfere with each other and cause malfunction. The challenge is to set the regulation limits used in to protect the infrastructure, but not overburden manufacturers and consumers with unnecessary costs. Until now, suitable measurement method for the supraharmonics has existed, so any limits are essentially an educated guess. The project has provided the long-term infrastructure to set and assess limits for mass market goods ensuring the reliable operation of products in a market worth hundreds of billions of Euros. Regulating this interference will ensure the reliable operation of smart grids and the prevent issues connecting and operating future renewable energy technologies.

6 List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

7 Contact details

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8 References

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1 C16 standard
2 “Comparison of Measurement Methods for 2-150 kHz Conducted Emissions in Power Networks”, Deborah Ritzmann, Stefano Lodetti, David De La Vega, Victor Khokhlov, Alexander Gallarreta, Paul Wright, Jan Meyer, Igor Fernández and Dimitrij Klingbeil, IEEE Transactions on Instrumentation and Measurement, Early Access, Nov. 2020, https://doi.org/10.1109/TIM.2020.3039302
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