

# PROPAGATION OF SUPRAHARMONICS IN THE LOW VOLTAGE GRID

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ELEKTRA





# **Propagation of Supraharmonics in the Low Voltage Grid**

2 to 150 kHz

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## Foreword

Detta är ett postdoktoralt projekt som har bedrivits inom forskningsprogrammet Elektra. Elektras vision är att högskolan i samverkan med industrin ska formulera och lösa forskningsuppgifter som svarar mot industrins problemställningar och som samtidigt leder till utbildning av forskarstuderande samt seniorforskning vid högskola och universitet. Elektra är ett samverkansprogram och finansieras gemensamt av Energimyndigheten och ett antal näringslivsaktörer.

Projektet bidrar med viktig ny kunskap om hur elnätet påverkas av supratoner, det vill säga spänningsövertoner mellan 2 och 150 kHz. Kunskapen om denna typ av övertoner är relativt begränsad, och resultaten i rapporten tyder på att de kan påverka till exempel belysning mer än vad man tidigare har trott. Ansvarig projektledare har varit Sarah Rönnberg, Luleå tekniska högskola.

Stockholm december 2017

## Sammanfattning

**Denna rapport presenterar resultatet från ett projekt som finansierats av Elektraprogrammet och Energimyndigheten, i syfte att ytterligare förstå och sprida kunskap om emission i frekvensområdet mellan 2 kHz och 150 kHz kallat Supratoner (eng. supraharmonics).**

Frekvensområdet över 2 kHz har tidigare ansetts vara "högfrekvent" för de som arbetar med elkvalitet medan frekvenser under 150 kHz har ansetts vara "lågfrekventa" för dem som arbetar med EMC problematik. Termen "supraharmonics" har föreslagits som ett samlingsnamn för all distorsion i detta frekvensområde och termen blir allt mer använd.

En ökande mängd utrustning ger icke försumbara nivåer av supratoner i nätet. Även spänningsdistorsion i detta frekvensområde har visat sig vara icke försumbar på vissa platser.

Distinktionen mellan primär och sekundär emission är mycket viktig för studier på supratoner. Konsekventa definitioner för primär och sekundär emission har utvecklats som en del av detta projekt. En tredje fenomen, växelverkan, införs där icke-linjära egenskaperna hos två eller fler enheter påverkar ström- och spänningsövertoner eller supratoner.

Mätningar som utförts har visat att supratoner kan ha en inverkan på ljusintensiteten hos LED-lampor. Detta är ett nytt fenomen och kan vara en ännu okänd flimmerkälla.

Minskningen av emissionen i det lägre frekvensområdet (övertoner) verkar resultera i en ökning av supratoner från utrustning. Införandet av fler och strängare krav på övertonsnivåer kan således resultera i en oavsiktlig ökning av supratonsnivåer.

Både mätningar och simuleringar visar att resonanser spelar en viktig roll i spridningen av supratoner genom lågspänningsnätet.

## Summary

**This report presents the result of a project, funded by the Electra program and the Swedish Energy Agency, with the aim of further understand and spread knowledge on emission in the frequency range between 2 kHz and 150 kHz known as Supraharmonics.**

The frequency range above 2 kHz has in the past been considered as “high frequency” for the power quality community whereas frequencies below 150 kHz have been considered as “low frequency” for those working with EMC issues. The term “supraharmonics” has been proposed for any distortion in this frequency range and the term is getting more and more used.

An increasing amount of equipment emits non-negligible levels of supraharmonics in the grid. Also voltage distortion in this frequency range has shown to be non-negligible at certain locations.

The distinction between primary and secondary emission is very important for studies on supraharmonics. A consistent set of definitions for primary and secondary emission has been developed as part of this project. A third phenomenon, interaction, is introduced in which the non-linear properties of two or more devices impact harmonic or supraharmonic voltages and currents.

Measurements performed have shown that supraharmonics can have a serious impact on the light intensity of LED lamps. This is a new phenomenon and may be an as yet unknown source of light flicker.

The reduction of emission in the lower-frequency ranges (harmonics) appears to result in an increase in supraharmonic emission by equipment. Setting more strict requirements on harmonic emission may have the unintended consequence of an increase in supraharmonic levels.

Both measurements and simulations have shown that resonances play an important role in the spread of supraharmonic distortion through the low-voltage network.

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# 1 Introduction

Emission within the frequency range 2 to 150 kHz is not new; engineers and constructors of end-user equipment have known about this emission for some tens of years but the amount of research has remained very limited. Only recently has the power quality research community started studying waveform distortion above 2 kHz. The power-engineering group at Luleå University of Technology has played an important role in starting this research, with three PhD thesis and many publications as a result. The group has also become an important source of information for those working with standardization in this frequency range. This report present the result of a project, funded by the Electra program and the Swedish Energy Agency, with the aim for the group of maintaining its leading position in the research covering this frequency range.

The frequency range above 2 kHz has in the past been considered as “high frequency” for the power quality community and frequencies below 150 kHz have been considered as “low frequency” for those working with EMC issues. But in recent years the frequency range has gained interest from both groups. The term “supraharmonics” has been proposed for any distortion in this frequency range and is getting increasingly used now.

There are several activities ongoing within IEC, CENELEC and IEEE to develop standards, e.g. test methods and limits, covering this frequency range. Within IEC SC 77A four groups are working on compatibility, emission, immunity [1] and measuring and testing technology [2]. Work is also ongoing for products like electrical energy meters and active infeed inverters. An overview of existing standards covering the frequency range is given in [3]. Within CENELEC, information is gathered about reported cases of disturbances in this frequency range [69]

## 2 Supraharmonics

Harmonics are mathematically defined as a component with a frequency that is an integer multiple of a fundamental frequency which can be expressed using classical single Fourier series theory. In power quality, the power-system frequency (50 or 60 Hz) is used as the fundamental frequency and the integer multiples (up to the 40<sup>th</sup>) of the fundamental frequency are defined as harmonics. In the frequency range between 2 and 150 kHz there is no commonly-accepted terminology.

The terms “High Frequency harmonics” or “High Frequency distortion” are sometimes used to describe signals in the frequency range 2 to 150 kHz. The term “High Frequency” is however already used by the International Telecommunication Union (ITU) to define the frequency range 3 to 30 MHz.

Low Frequency, LF and Very Low Frequency, VLF are according to ITU used for frequencies within the range 2-150 kHz (VLF, 3-30 kHz and LF, 30-300 kHz) but using these terms within the power quality field is not appropriate. IEC defines Low Frequency up to and including 9 kHz. In the related field of EMC the term “low-frequency emission” is used to refer to the frequency band up to 150 kHz. The use of the term “high-frequency” would lead to severe confusion between the power quality and EMC fields, exactly in the frequency band where input from both sides is needed.

Extending the term harmonics up to 150 kHz would hide the fact that the distortion changes significantly in character somewhere around 2 kHz from mainly narrowband at odd harmonic frequencies to having a more broadband character.

The term supraharmonics was first introduced at the 2013 IEEE PES General Meeting [1]. To use the term Harmonic together with a prefix is already common practice in the field of Power Quality. The term “Interharmonics” refers to frequency components that fall outside the harmonics, i.e. non-integer multiples of the fundamental frequency. The term “Subharmonics” is often used for frequency components below the fundamental frequency. Adding the prefix supra (meaning above or beyond the limits off <sup>1</sup>) when describing components in the frequency range 2 to 150 kHz seems appropriate and coherent with existing terminology within the Power Quality field.

The choice of 2 kHz as a border between (inter)harmonics and supraharmonics is rather arbitrary. So is the choice of 150 kHz as an upper limit. A classification based on phenomena, characteristics of the emission, difference in propagation, etc. would be preferable. However, our knowledge of the disturbances in this frequency range is far too limited for such a classification. It can be especially seen in analysis of modern power systems with high number of grid connected converters introducing switching patterns of high frequency. It is difficult or even impossible to determine, in many cases, the source and origin of the harmonic content and thus universal harmonic terminology and measures are needed. One of the outcomes of future research on this field should be exactly such a classification.

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<sup>1</sup> a prefix meaning “above, over” ( supraorbital) or “beyond the limits of, outside of” ( supramolecular; suprasegmental). <http://www.dictionary.com/browse/supra>

## 3 Primary and Secondary emission<sup>2</sup>

### 3.1 INTRODUCTION

The basic model of harmonic emission by a device or an installation is the ideal current source at the harmonic frequency of interest. The assumption made thereby is that the voltage at the terminals of the device in no way impacts the harmonic current. Although it is generally understood that the model has its limitations: many simulations and measurements show that the terminal voltage does have an impact on the harmonic current.

There are however a number of reason for using the ideal current source model in harmonics studies: the details of the device may still be unknown when the harmonic studies are performed; there is no data available on the way in which the terminal voltage impacts the harmonic current; including the detailed relations would result in unacceptably long calculation times.

### 3.2 SINGLE-PHASE DIODE RECTIFIERS

Already in the classical book by Arrillaga [4] in 1985 it was shown that the harmonic current taken by a television set decreased when more televisions were connected close together. The explanation is that an increased number of diode-rectifiers resulted in a flattening of the voltage waveform which in turn widened the current pulse. This was shown mathematically by Mansoor about ten years later [6][7]. Measurements by Koval [8], done around the same time, showed the diversity of harmonic spectra between computer workstations at different locations in the same low-voltage network.

- The THD ranged from 106 through 117%
- The third harmonic from 83 through 87%
- The fifth harmonic from 54 through 64%
- The seventh harmonic from 26 through 38%

Figure 1 shows the current spectrum for an ordinary office PC measured at two different locations around 2003. The top curve was measured in the laboratory, which was supplied by a dedicated 10 / 0.4 kV transformer during a period when no other equipment was connected in the laboratory. The bottom curve was measured in the office during normal working hours when a lot of other devices were connected. The difference between the spectra is obvious.

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<sup>2</sup> This chapter consists mainly of a paper titled "Primary and Secondary Harmonics Emission; Harmonic Interaction – a Set of Definitions" written by M. Bollen and S. Rönnberg. The paper has been submitted to ICHQP 2016.

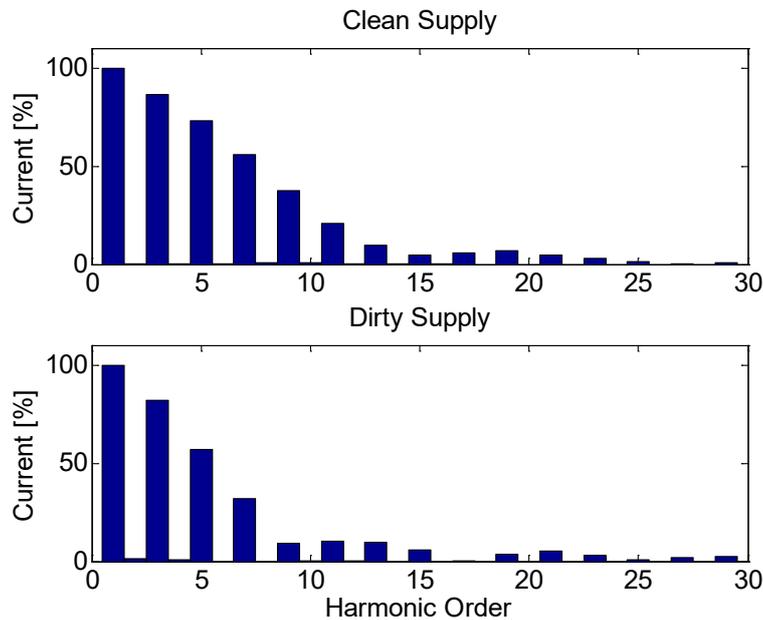


Figure 1. Harmonic current spectrum of the same computer connected to a close to sinusoidal voltage (top) and connected to a voltage with flattened waveform (bottom) [9].

The main harmonic-producing devices in domestic and commercial installations up to about 2005 consisted of a four-pulse diode rectifier and a capacitor on dc side. As all devices were very similar it was possible to perform general simulations and the phenomenon was generally well understood. Two important conclusions that were drawn from those studies were:

- With increasing number of devices, the harmonic current distortion at the main harmonic frequencies decreases. Using the "clean-voltage-spectrum" will thus give an upper limit of the distortion.
- For the common range of values of voltage distortion there are obvious variations in current distortion, but the range is not alarming. It is thus possible to use an average current spectrum to estimate the impact of the emission on the grid.

### 3.3 MODERN DEVICES

#### 3.3.1 Active converters

The last five to ten years have seen a large proliferation of other types of device interface than the diode-rectifier that was dominating before. These modern devices, often using some kind of active switching, produce a different emission spectrum than diode rectifiers. Their emission is in general less, which is one of the reasons for the use of active switching. However, it introduces new challenges, among others for device modeling. The two main challenges that have been identified are:

- There is no longer any "typical device spectrum", but instead a large variation between devices.
- The impact of the background voltage on the emission has become much more unpredictable and also varies strongly between different devices.

The impact of voltage distortion on emission for active converters is studied, among others, in [10] through [14]. With active power-electronic circuits finding their way to equipment, the impact of the background voltage distortion on the emission becomes more complicated and emission can even increase as well as decrease with increasing voltage distortion [10][11][14] whereas it would decrease with the earlier diode rectifiers.

The impact of the terminal voltage on the emission from wind turbines and PV inverters has become an important discussion point in the setting of harmonic limits. Especially for wind turbines and wind parks the impact of this "background voltage" is considered important. However, tests with a sufficiently small background voltage are very difficult, if possible at all, especially as it is often unknown which level could be called "sufficient small".

### 3.3.2 Supraharmonics

The terms "primary emission" and "secondary emission" were introduced in [15] to explain the spread of supraharmonics from fluorescent lamps with high-frequency ballast. Each ballast was modeled as an ideal current source with a capacitance in parallel; the grid was modeled as a 50- $\Omega$  resistance. Despite the simplicity of the model, it was possible to explain the surprising measurements results presented in [16] including the observed amplitude modulation of voltage and current. Measurements at other locations also showed that a large part of the emission from a device flowed to neighboring devices and not to the grid, [17] through [21]. This phenomenon is sometimes referred to, especially where it concerns power-line communication, by the, in this context, somewhat confusing term "damping".

### 3.3.3 Wind power plants

The distinction between primary and secondary emission is not limited to supraharmonics; it has also shown to be useful for the study of (low-frequency) harmonics. The terms have been used, and shown to be useful, to explain the current distortion at the terminals of a wind turbine and at the point of connection between a wind park the grid [22][23]. The terms were defined by [22][23] in the following way:

- Primary emission is the emission originating from the device.
- Secondary emission is the emission originating outside of the device.

A number of assumptions were needed to allow this distinction. In the remainder of this paper these assumptions will be discussed further including what will happen when these assumptions are not valid.

### 3.3.4 Distinction between primary and secondary emission

A distinction between primary and secondary emission through field measurements is not straightforward and might not even be possible without certain assumptions. Controlled experiments can be done where every individual device is measured against a known source to determine the emission spectra from a device. The information obtained from individual measurements can later be used in a mixed load situation to distinguish between primary and secondary emission.

A second approach is to turn individual devices on or off at known instances and thereby gain more information on primary and secondary emission. However, since there often is interaction between connected devices that can affect both primary and secondary emission, neither method is fault proof and in addition rather time-consuming. The second approach was used during the measurements shown in Figure 3 and a combination of the two approaches was used in [28] where laboratory measurements of an installation containing common household equipment are presented (shown in Figure 4). The lack of a good method to distinguish between primary and secondary emission is a serious barrier when studying emission from modern types of devices or installations. Note that the terms primary emission and secondary emission are not broadly used, but they have shown useful in describing and studying phenomena related to harmonic emission.

## 3.4 A GENERAL TREATMENT

### 3.4.1 Two sources and two impedances

A general case of a device connected to the rest of the power system is shown in Figure 2, where the sources and impedance will be at least to some extent non-linear.

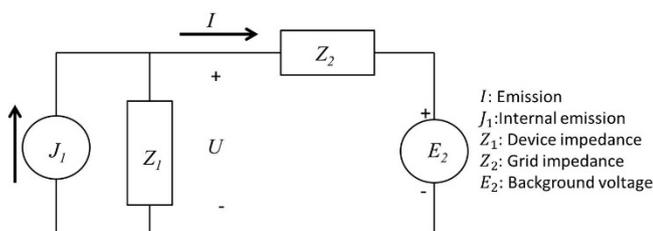


Figure 2. Model for the connection of a device or installation to the rest of the power system; the rest of the power system is to the right of the location at which the voltage  $U$  is obtained.

The discussion covers individual devices as well as complete installations like wind parks, but for simplicity the term device will be used throughout this paper. All elements in Figure 2 are initially assumed to be linear. After that, the case will be generalized to include all non-linear aspects.

### 3.4.2 Contributions to the emission

The emission of a device (i.e. the current  $I$  at the interface between the device and the grid) is impacted in a number of ways. Different phenomena that will have an impact on the emission from a device are listed below. Alternatively, these can be considered as individual contributions such that the current  $I$  is the sum of the different contributions.

The following contributions to the emission have been identified:

1. Device against ideal nominal voltage (background voltage has nominal magnitude and frequency; zero distortion and grid impedance is zero)
2. Voltage is not nominal
  - a. Different voltage magnitude, but still sinusoidal
  - b. Different frequency (the frequency variation is small in most modern power systems and there is no indication that this will notably impact the emission; but it cannot be ruled out).
3. Non-zero grid impedance
  - a. Device impedance conducts part of the internal emission  $J_1$ . This is a linear phenomenon, depending on the ratio between  $Z_1$  and  $Z_2$ .
  - b. Internal emission  $J_1$  changes because of the distorted voltage at the device terminals. This is a non-linear phenomenon, depending on the relation between  $J_1$  and  $U$ .
4. Distorted supply (voltage at grid is already distorted before connection of the device)
  - a. Current through the device impedance  $Z_1$  changes. This is a linear phenomenon, similar to 3a, but with a different source.
  - b. Internal emission changes because the distortion of the voltage at the device terminals is different. This is the same non-linear phenomenon as 3b.
5. The rest of the grid is non-linear (due to non-linear devices being connected close to the device under study).
  - a. Grid impedance changes with terminal voltage
  - b. Background voltage changes with terminal voltage

## 3.5 PROPOSED DEFINITIONS

### 3.5.1 Primary harmonic emission

Primary harmonic emission (harmonic emission in short) is the part of the harmonic current at the device terminals that is driven by sources inside of the device. In terms of the linear (linearized) circuit shown in Figure. 2, the primary emission is

$$I_1 = \frac{Z_1}{Z_1 + Z_2} \cdot J_1 \quad (1)$$

Thus, even when the linear model holds, the primary emission still depends on the grid impedance and is thus not the same at all locations.

The primary emission is not the same as the emission measured during a standardized test. The latter is (intended to be) reproducible, i.e. independent of

time and location; the primary emission is not independent of time and location. Both source impedance and terminal voltage impact the primary emission, as was discussed in Section IV.B.

### 3.5.2 Secondary harmonic emission

Secondary harmonic emission (secondary emission in short) is the part of the harmonic current at the device terminals that is driven by sources outside of the device. In terms of Figure 2, the secondary emission is:

$$I_2 = \frac{1}{Z_1 + Z_2} \cdot E_2 \quad (2)$$

### 3.5.3 Harmonic interaction

The term “harmonic interaction” (interaction in short) is proposed to be reserved for the non-linear phenomena that are part of the list presented in Section 3.4.2. All the non-linear phenomena, under the model presented in Figure 2, can be brought back to the relation between the values of the four network elements (sources and impedances) and the terminal voltage.

## 3.6 SOME FURTHER DISCUSSION

### 3.6.1 Primary emission

In this section, a number of cases will be discussed, all in the form of thought experiments, in which the current only consists of primary emission, i.e. contribution 1 to 3.

#### *Contribution 1, Ideal voltage source*

For the first thought experiment the device is connected to an ideal voltage source, with a constant sinusoidal voltage of nominal voltage  $E_0$  (e.g. 230 V) and nominal frequency  $f_0$  (e.g. 50 Hz). In terms of Figure 2,  $Z_2 = 0$  and  $E_2(f) = 0$  for  $f \neq f_0$  and  $E_2(f_0) = E_0$

The resulting (primary) emission is the internal emission as in Figure 2.

Note that this emission cannot be measured in reality, as it is not possible to create a voltage source with zero impedance. It is however possible to obtain the internal emission from simulations when a sufficiently accurate model is available. From experiments it is possible to estimate the internal emission when it is possible to obtain a sufficiently low “grid impedance”.

#### *Contribution 2, Voltage dependency*

With varying magnitude of the background voltage  $E_2$ , the primary emission typically varies. This is called the voltage dependency of the primary emission against an ideal voltage source. In mathematical terms:

$$\bar{I}_1(f) = \bar{I}_1(f, E_2(f_0)) \quad (3)$$

Note that also this cannot be measured, for the same reasons as for contribution 1: it is in practice not possible to create a voltage source with zero impedance.

#### *Contribution 3, Non-ideal sinusoidal voltage source*

For contribution 3 the voltage source is sinusoidal with non-zero source impedance:  $Z_2(f) \neq 0$ . The primary current depends now on the internal emission and on the ratio between device and grid impedance according to:

$$\overline{I_{prim}}(f) = \frac{\overline{Z_2}(f)}{\overline{Z_1}(f) + \overline{Z_2}(f)} \cdot \overline{J_1}(f) \quad (4)$$

This experiment is the basis of the standard tests to determine the emission level, where a reference impedance is defined.

Note that also this primary emission typically is a function of the amplitude of the background voltage. The non-zero source impedance will result in a distorted voltage at the terminals of the device. This in turn will impact the emission, as was already discussed in Section 3.4.2.

### **3.6.2 Secondary emission**

So far the background voltage has been assumed sinusoidal. The change in current at the device terminals due to the non-sinusoidal background voltage is described by Contribution 4 and is referred to as “secondary emission”.

#### *Contribution 4, Ideal non-sinusoidal voltage source*

Contribution 4, Ideal non-sinusoidal voltage source, starts again with the thought experiment in which the grid impedance is zero. The emission is impacted in three different ways:

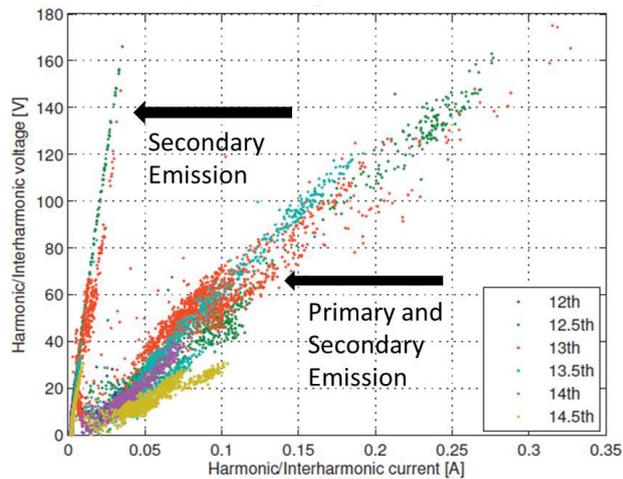
- A non-fundamental component in the background voltage will result in a current, at that frequency, through the device impedance.
- A non-fundamental component in the background voltage will result in a change in the internal emission at that frequency.
- A non-fundamental component in the background voltage will result in currents at one of more other non-fundamental frequencies.

The former impact can be modeled as a linear device in parallel with the (remainder of) the non-linear device. This second impact can be described as a non-linear relation between voltage and current at the non-fundamental frequency.

#### *Harmonics at the terminals of a wind turbine*

In Figure 3a measurement of the voltage and current at one individual wind turbine is shown [29]. This turbine is part of a wind park with 14 turbines in total. The measurements were done over a period of about ten days and during the period this turbine was occasionally turned off (zero production) while the other turbines were still operating and producing power. Two distinct lines can be seen in Figure 3: the almost vertical line on the left in the figure shows the instances when the turbine is not producing any power. Any emission present at the terminal of the wind turbine at those times is due to the voltage distortion present at the

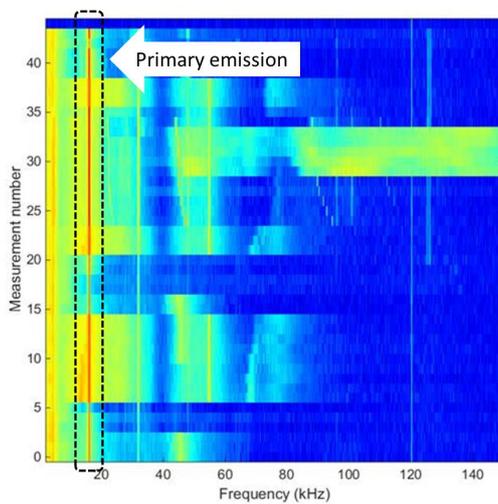
connection point and is hence secondary emission. The second line, to the right in Figure 3, represents the instances when the turbine is producing power and consists partly of secondary emission and partly of primary emission.



**Figure 3** Voltage subgroups versus current subgroups measured at one individual wind turbine within a wind park. The different colors refer to harmonic and interharmonic subgroups as indicated in the legend [29].

#### *Supraharmonics in a domestic installation*

Figure 4 shows the results from a controlled experiment where common household devices were connected and disconnected while the current at the terminal of one of the devices (a PV inverter) was measured for every alteration, 45 in total.



**Figure 4** Spectrogram of the current taken by the PV-inverter for 45 measurements while neighbouring devices are connected and disconnected. The component at 16 kHz (inside the black square) is the primary emission originating from the PV.

The component at 16 kHz (shown inside the dashed black square in Figure 4) is the primary emission from the inverter; all other components that appear and disappear are due to secondary emission.

#### *Interaction*

The third impact (“harmonic interaction”) is more difficult to describe. It relates to the non-linearity of the grid due to the connection of non-linear devices. In frequency domain it would result in an impedance matrix where the off-diagonal elements link a voltage at one non-fundamental frequency with a current at another non-fundamental frequency. This relation will in general be non-linear as well. Study of harmonic interaction almost certainly requires time-domain models of the devices involved.

The impression of the authors from measurements and simulations, but not supported by a thorough systematic study, is that a large part of the observed phenomena can be explained by linear models, as in Figure 2. Further studies, most likely a lot of further studies, are needed to form a scientifically-based opinion about this.

Also, the contribution of the non-linearity is likely to be rather different at the terminals of a low-voltage device than at the terminals of a large installation as a wind power plant. Also this requires further studies to be confirmed.

### **3.7 HARMONIC FINGER PRINTS**

The three different impacts: primary emission, secondary emission and interaction can be measured and described with the use of harmonic fingerprints [30]. The fingerprint is obtained by measuring a device first connected to a non-distorted voltage source and then stepwise adding known harmonic distortion. Consider a linear device, i.e. a time-independent impedance. Such a device will not emit any primary emission, but it will emit secondary emission when the background voltage distortion is non-zero.

For the ideal voltage source, with zero source impedance, the secondary emission of the linear device is:

$$\overline{I_{sec}} = \frac{\overline{E_2}(f)}{\overline{Z_1}(f)} \quad (5)$$

The harmonic fingerprint for such a device will contain points along a number of straight lines through the origin, as described in [22].

The measurement of the harmonic fingerprint will require, as mentioned before, a voltage source with very small impedance at the harmonic frequencies of interest.

The harmonic fingerprint approach only cover primary and secondary emission as listed in the previous sections. It is possible to extend the concept to the third impact, interactions, as well, but that is a much more complex case.

## 4 Sources of Supraharmonics

The two main sources of supraharmonics, that have been identified, are power-electronic converters with active or passive switching (non-intentional emission) and transmitters of power-line communication (intentional emission). With the introduction of self-commutated valves, emission has shifted from harmonic to supraharmonic frequencies. Products have been designed for satisfying emission limits at harmonic frequencies but instead having increased emission at higher frequencies. Some examples of devices that have been found to emit supraharmonics are listed below:

- Industrial size converters (9 to 150 kHz)
- Oscillations around commutation notches (up to 10 kHz)
- Street lamps (up to 20 kHz)
- EV chargers (15 kHz to 100 kHz)
- PV inverters (4 kHz to 20 kHz)
- Household devices (2 to 150 kHz)
- Power line communication, AMR (9 to 95 kHz)

In Figure 5 to Figure 7 some examples of common household devices are shown in time domain (Figure 5), frequency domain (Figure 6) and combined time and frequency domain, spectrogram or short-time Fourier transform (STFT) (Figure 7).

It should however be emphasized that these are just examples, there are for instance LED lamps with completely different emission patterns [24][25][26] and the same holds for the other types of devices.

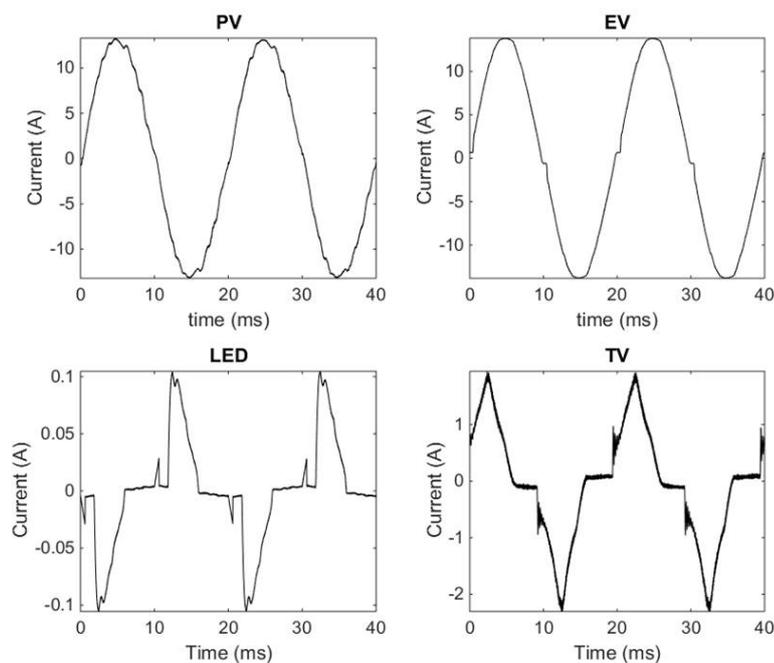


Figure 5 Current drawn by four different household devices: Photovoltaic inverter (top left), Electric vehicle charger (top right), LED lamp (bottom left) and an LCD TV (bottom right)

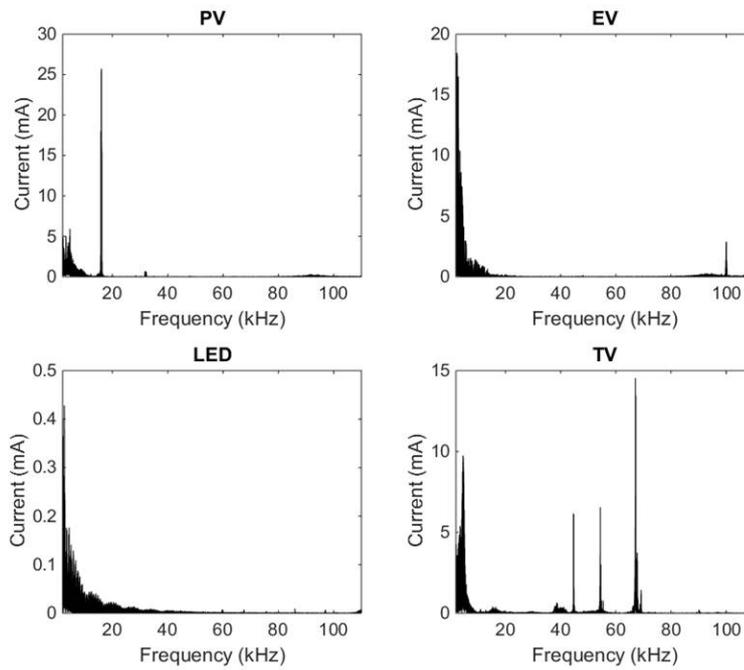


Figure 6 Supraharmonic emission from four different household devices: Photovoltaic inverter (top left), Electric vehicle charger (top right), LED lamp (bottom left) and an LCD TV (bottom right) shown in the frequency domain.

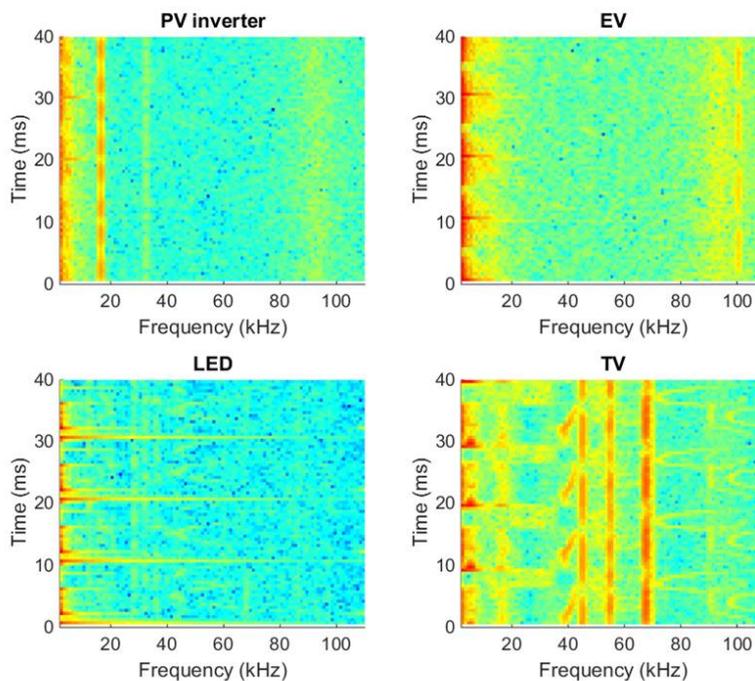
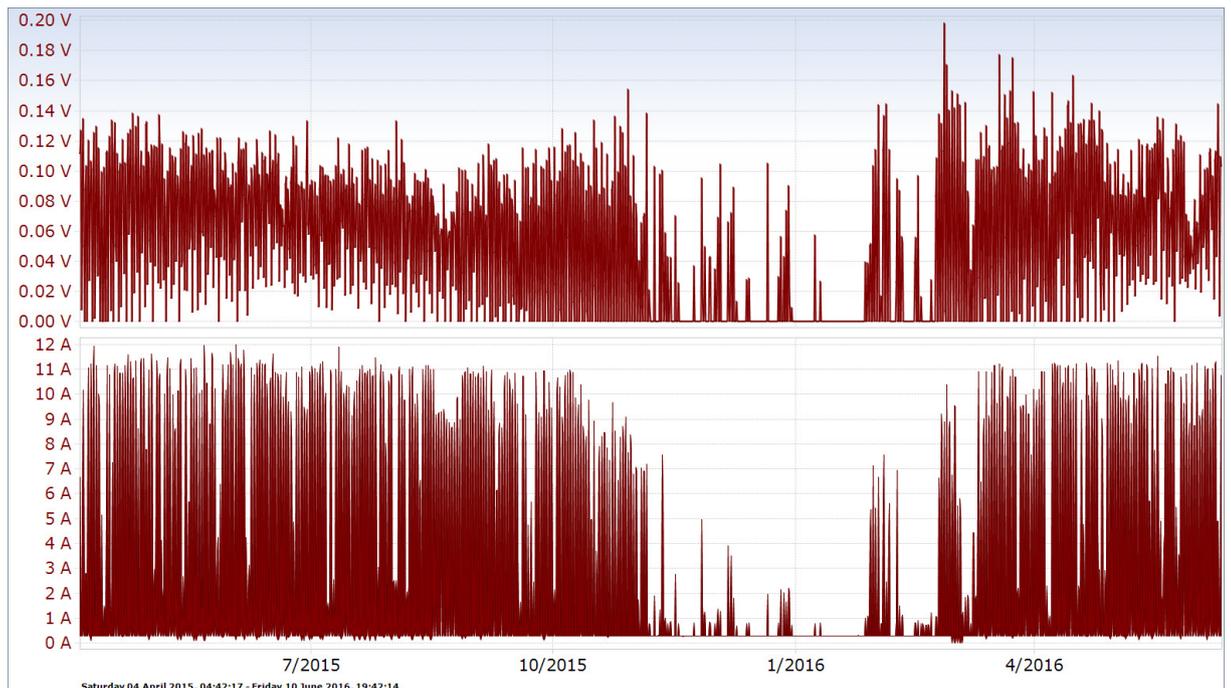


Figure 7 Supraharmonic emission from four different household devices: Photovoltaic inverter (top left), Electric vehicle charger (top right), LED lamp (bottom left) and an LCD TV (bottom right) shown as spectrogram.

In addition, a long-term (one year) measurement of a 2.5 kW PV inverter (the same inverter as shown top left in Figure 5 to 7) is shown in Figure 8. Top figure shows the 10 minutes average of the voltage component at 16 kHz which corresponds to the switching frequency of the inverter and the bottom figure shows the 10 minutes average rms current injected by the PV system. As can be seen in Figure 8, the 16 kHz component is not visible in for example parts of January when the PV system is not producing any power and the inverter is consequently turned off.



**Figure 8.** Voltage component at 16 kHz (top) and rms current (bottom) measured at the terminal of a PV inverter.

## 5 Propagation

Measurements as well as simulations have shown that the emission from an installation, in the frequency range from a few kHz, is much less than the sum of the emission from the individual devices. Supraharmonic emission tends to flow in between connected devices to a great extent [31][32][18][34][35]. A number of experiments have been conducted in order to study the propagation of emission from different devices connected inside the same installation. A distinction has been made between emission from the installation as a whole (impacting the grid) and emission propagating inside the installation (impacting individual devices). The importance of making that distinction is illustrated in Figure 9 where the current spectrum for one individual CFL and the spectrum of the combined current taken by three lamps are shown [34]. This experiment was extended to up to 48 fluorescent lamps with electronic ballasts [36] with similar results. As more lamps are added, the amplitude of the current between 40 kHz and 50 kHz (the switching frequency of the lamps) at the delivery point drops. At the same time the amplitude increases at the individual lamps. This behavior was explained by a model in [15]. However, it cannot be concluded that supraharmonics will always stay within the installation. The current drawn by the lamps shown in [36] also contains a reoccurring oscillation of a few kHz around the zero crossing of the voltage. This component increased in amplitude as more lamps were added to the installation, as shown in [32].

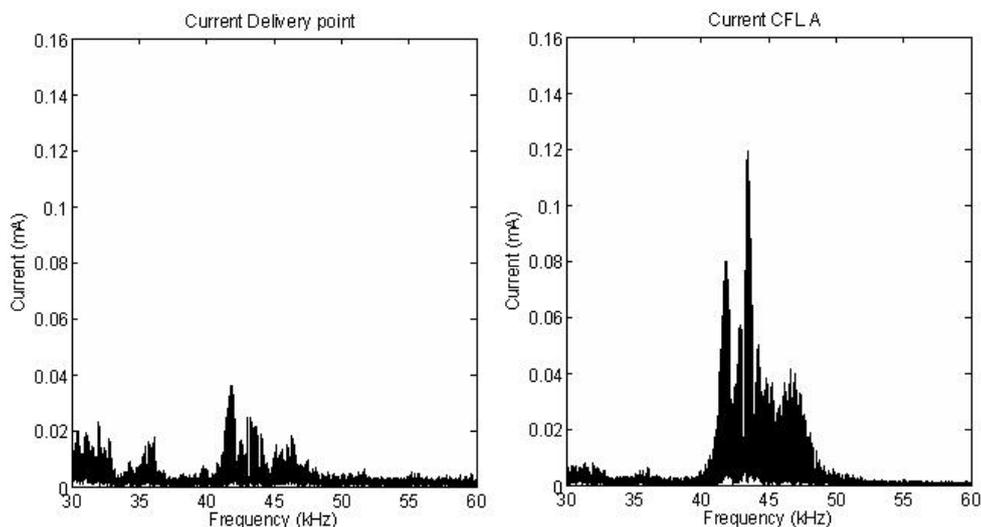


Figure 9 Supraharmonic current measured at the terminals of one individual CFL (right) and the combined current taken by three lamps (left) [31], the measurements are taken at the same moment.

Depending on the type of emission, residues from the switching circuit or recurring oscillation, the impact will differ. The residues from the switching circuit, typically above some tens of kHz, propagate between individual devices. The amplitude of the emission from an installation reaching the grid will be low in most cases. The main impact will be on individual devices within the installation. The opposite holds for the recurring oscillation. It is not clear if this difference in

propagation is due to the difference in frequency or the difference in the emission mechanism.

The propagation of currents in the supraharmonic frequency range is influenced by the impedance of neighboring devices in relation to the impedance of the grid. Two types of devices have been found to affect the impedance at supraharmonic frequencies: devices equipped with diode rectifiers and smoothing capacitors (typical energy saving lamps) and devices equipped with an EMC-filter. In the presence of for example some LED lamps the impedance for supraharmonic frequencies varies during the time that the voltage takes to complete one cycle, 20 ms in a 50 Hz system [37]. When the diodes are conducting, the capacitor behind them will decrease the impedance and as a consequence signals at fundamental voltage zero crossing will not experience the same impedance as a signal at voltage peak. This time variance is illustrated in Figure 10 where the impedance measured during one cycle of the power system frequency at a LV network in Germany is shown [33].

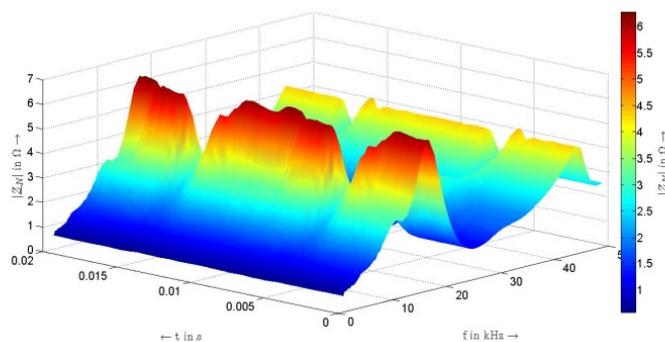


Figure 10 Variation in impedance measured at a LV network during one cycle of the power system frequency [33].

## 6 Immunity and Interaction

The immunity of equipment against supraharmatics is an important aspect to study. Measurements have shown that connected devices will interact with each other in several ways; the full consequence of this interaction is still not understood. Five types of interaction between power line communication and end-used equipment were identified in [17] that illustrate the complexity of the interaction. Three types out of the five (as numbered in [17]) directly apply to any kind of interaction (i.e. not specific to communication)

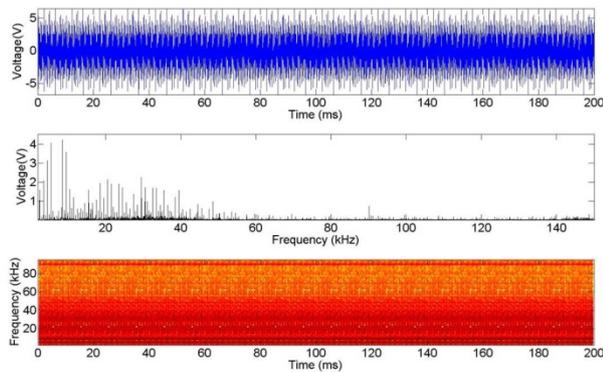
- III. A voltage signal results in large currents through a device. This can result in overheating of components or other interference with the functioning of the device.
- IV. Non-linear devices exposed to a voltage at a supraharmonic frequency results in currents at other frequencies, typically at integer multiples (i.e. harmonics).
- V. Distortion of the voltage waveform feeding a device results directly in mal-operation of the device.

Several incidents of equipment malfunctioning or behaving in unwanted ways due to the presence of supraharmatics have been reported [62]. Examples include clocks running too fast, hair dryers turning on by them self and flickering lights. In addition, a device subjected to frequencies below 20 kHz (i.e. in the audible range) can produce audible noise due to stimulation of a mechanical resonance. Animals are able to hear higher frequencies and could therefore be impacted by supraharmatics at even higher frequencies.

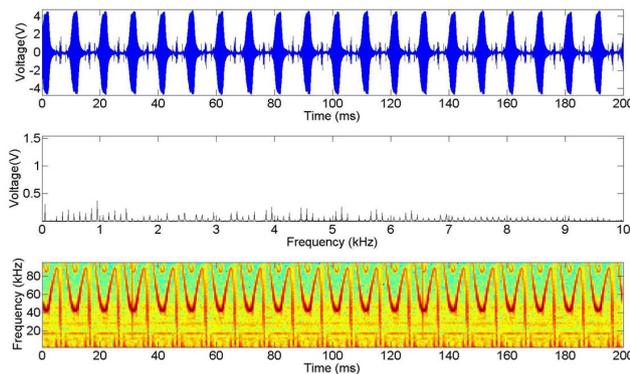
The main components expected to be damaged by supraharmonic currents, driven by supraharmonic voltages, are the electrolyte capacitors commonly used in EMC-filters and as smoothing capacitors connected after a diode rectifier [37]. Currents of any frequency will contribute to the heating of this capacitor. Overheating of an electrolyte capacitor will reduce its life expectancy. As the capacitor reaches the end of the lifetime the equivalent series resistance (ESR) of the capacitor will start to increase and as a consequence also the output ripple voltage [39]. This could lead to complete failure of the capacitor and possible damage to other components. The function of a device will often not be affected if the EMC-filter fails. The result will simply be that the emission at unwanted frequencies increases.

Several studies also indicate that high levels of supraharmonic voltages at higher voltage levels could result in insulation failures in cables [40][41]. A well-published and studied example is the failure of cable terminals after the connection of a VSC HVDC installation [40]. The failures occurred in compact type cable terminations, rated at 24 kV, with resistive/refractive stress grading. The problem was resolved by installing another type of cable termination, generally called "geometric type", whose insulation characteristic is expected not to be dependent on frequency. Additionally various power system components have higher losses (e.g. conduction losses due to the skin effect, eddy current losses in ferrite cores, etc.) for higher frequencies which can cause overheating and accelerated aging.

The immunity of LED lamps was tested by exposing them to two different test-signals containing supraharmonics that had previously been recorded at two different locations in the grid, the two signals are shown in Figure 11 and Figure 12.

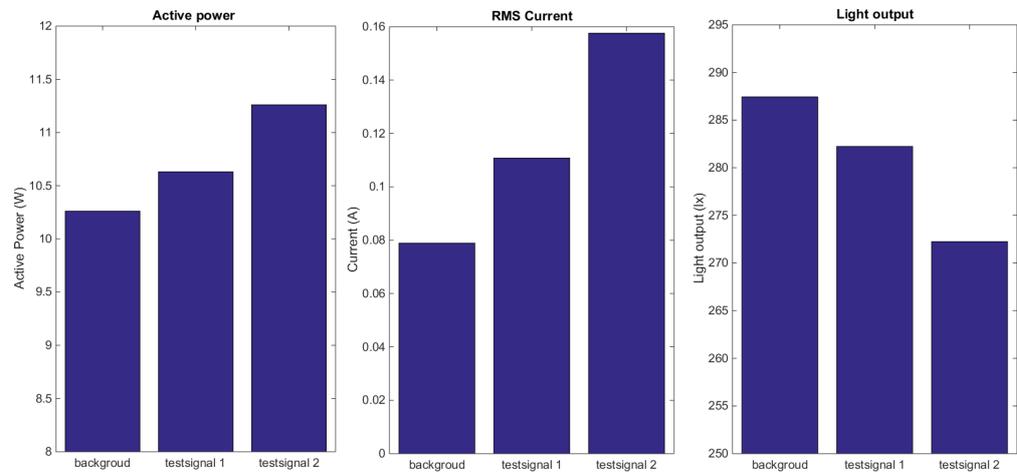


**Figure 11** Test-signal 1 shown in time-domain (top), frequency domain (middle) and as spectrogram (bottom).



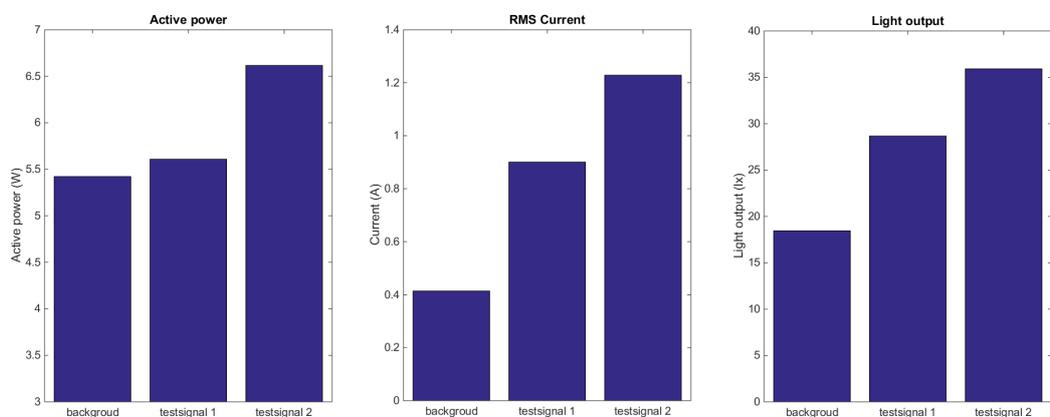
**Figure 12** Test-signal 2 shown in time-domain (top), frequency domain (middle) and as spectrogram (bottom).

The light output was measured as the test-signals were superimposed to the grid voltage in the Pehr Högström laboratory at Luleå University of Technology, Skellefteå. An example from a measurement with an 11 W LED lamp is shown in Figure 13. It can be seen in Figure 13 that with the lamp fed from the grid voltage (i.e no added distortion) used as a reference, the active power and rms current increase whereas the light output from the LED lamp decrease when the lamp is subjected to both test-signals. At the same time the light output decreases. The impact from test-signal 2 is greater than from test-signal 1



**Figure 13** Active power (left), rms current (middle) and average light output for an 11 W LED lamp as supraharmonics are present in the voltage

Another example is shown in Figure 14, where the results from a 6 Watt LED are presented. As the two test-signals are applied, the active power as well as the rms current and light output increase; again the impact is greater from test-signal 2.



**Figure 14** Active power (left), rms current (middle) and average light output for an 6 W LED lamp as supraharmonics are present in the voltage

The same LED lamp as shown in Figure 14 was measured for a duration of 30 seconds and after five seconds test-signal 1 was superimposed onto the voltage feeding the lamp. The voltage and current waveform for the total duration of the measurement are shown in Figure 15. The change in both voltage and current is clearly seen five seconds after the start of the measurement. The 30 second window was divided into 150 windows of 200 ms each and voltage THD, active power, RMS current, and average light output were calculated for every 200 ms window. The change in all aforementioned parameters as the test-signal is applied is clearly visible in Figure 16.

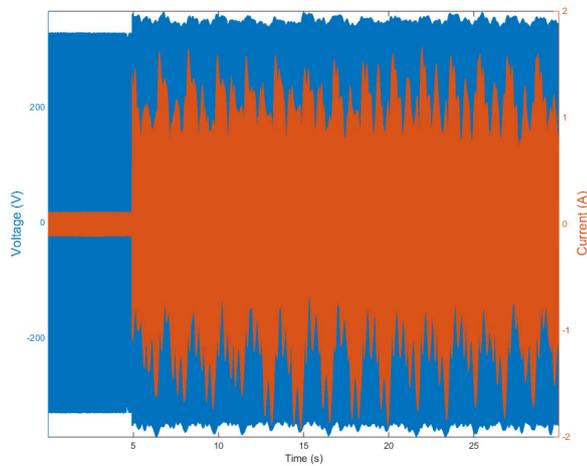


Figure 15 Voltage and current waveform measured at the terminals of a 6 W LED lamp

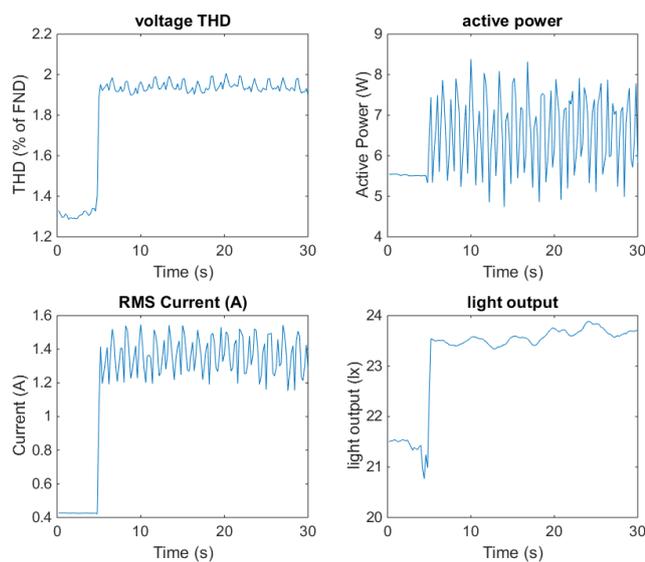


Figure 16 Voltage THD (upper left), active Power (upper right), rms current (lower left) and average light output (lower left) for a 6 W LED lamp as supraharmonics are introduced to the voltage feeding the lamp.

This indicates that the LED lamps are not immune to the presence of supraharmonics in the voltage but the consequences and mechanism behind this need to be investigated further.

## 7 Mitigation<sup>3</sup>

The reduction of emission in the lower-frequency ranges appears to result in an increase in supraharmmonic emission by equipment. Power electronics has emerged as a ubiquitous technology, which plays a critical role in almost any areas. Power electronics converter is an important source of waveform distortion, but, as shown in this paper, power electronics can also be the key to mitigate distortion, when the proper technology is employed.

From the earliest times, power electronics (PE) has been mainly driven to improve the voltage and current-handling capability and the switching speed of power semiconductor devices. Nonetheless, even nowadays it is hard to connect a single power semiconductor switch directly to medium voltage grids. The series connection of standard low-voltage switching devices enables to synthesize a medium voltage output, while the individual power semiconductors need to withstand only part of the voltage. The addition of several low voltage cells per arm provides high scalability, leading to reduced cost and volume of the entire solution. Moreover, it allows a more creative use of these additional switches in novel modulation strategies, which enable to enhance the quality of output voltages and input currents, originating the multilevel converter (MC) technology.

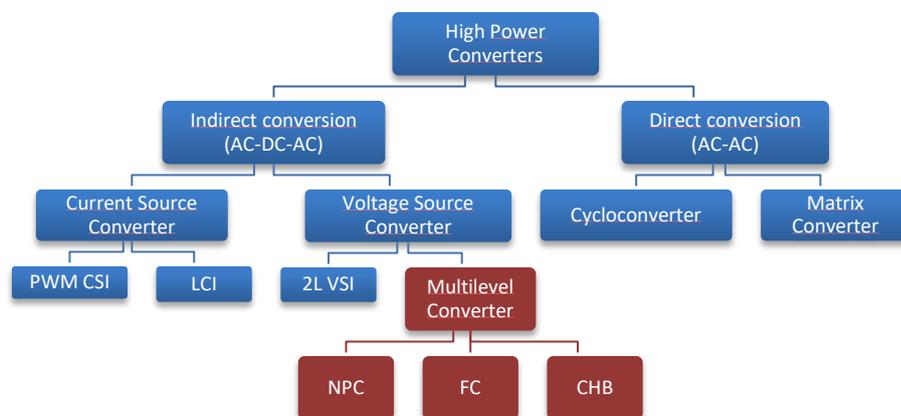


Figure 17 Overview of topology of high power converters

Since their first appearance in the mid-nineties, MCs have been gaining considerable popularity across all industries, mostly in the medium and high power applications. The recent applications of MCs have a variety including induction machine and motor drives, active rectifiers, power quality filters, interface of renewable energy sources, flexible AC transmission systems (FACTS), and HVDC. A comprehensive historical review can be found in [44]. Nowadays, the most common and established topologies are the neutral point clamped (NPC) or diode clamped, the flying capacitor (FC) or capacitor clamped, and the cascaded

<sup>3</sup> This chapter mainly consists of papers [42][43]

H-bridge (CHB). A brief comparison among their characteristics is presented in Table 1. Their schemes and detailed operation can be found in [45].

Table 1

Topology	NPC	FC	CHB
Power semiconductor switches	$2(m-1)$	$2(m-1)$	$2(m-1)$
Clamping diodes per phase	$(m-1)(m-2)$	0	0
DC bus capacitors	$(m-1)$	$(m-1)$	$(m-1)/2$
Balancing capacitors per phase	0	$(m-1)(m-2)/2$	0
Voltage unbalancing	Average	High	Very small
Applications	Motor drive, FACTS	Motor drive, FACTS	Motor drive, PV, fuel cells, battery system

In addition to these topologies, several modulation and control strategies have been developed or adopted for MC including the following: multilevel sinusoidal pulse width modulation (SPWM), multilevel selective harmonic elimination (SHE-PWM), and space-vector modulation (SVM). As in two level converters, it is very common practice in MC to use Third Harmonic injection PWM (THPWM). As seen in Figure 5, the modulation methods used in MC can be classified according to switching frequencies as follows [46]: 1) fundamental switching frequency, where each inverter has only one commutation per cycle, for example, multilevel SHE-PWM or SVM, and 2) high switching frequency, where each inverter has several commutations per cycle, for example, multilevel SPWM or SVM. For high-power applications, high switching frequencies are considered those above 1 kHz.

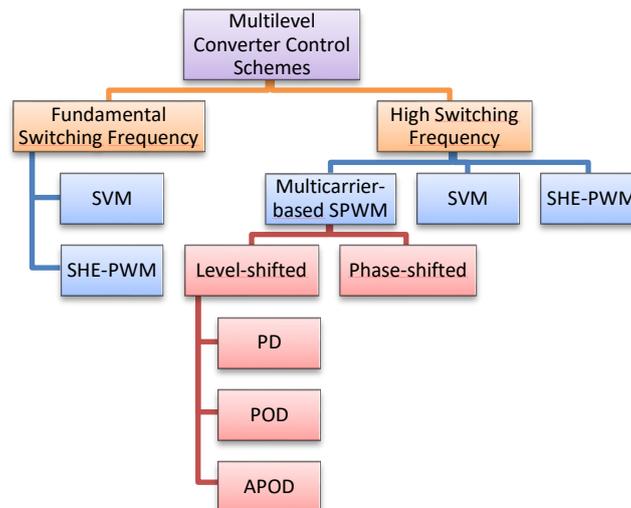


Figure 18 Overview of control schemes for multilevel converters

Methods that work with low switching frequencies generally perform one or two commutations of the power semiconductors during one cycle of the output voltages, generating a staircase waveform. Representatives of this family are the SHE-PWM and the SVM; techniques that can be easily extended to all MC.

Space-vector PWM methods generally have the following features: good utilization of dc-link voltage, low current ripple, and relatively easy hardware implementation. These features make it suitable for high-voltage high-power applications [47].

The SHE-PWM is one of the low-switching frequency strategies most used today, in which a few (generally from three to seven) switching angles per quarter fundamental cycle are predefined and pre-calculated via Fourier analysis to eliminate selected specific harmonics in the voltage and, thereby, in the current [48][49].

Multicarrier-based PWM uses several triangular carrier signals, which can be modified in phase (Phase-shifted PS-PWM) or vertical position (Level-shifted LS-PWM) in order to reduce the output voltage harmonic content.

PS-PWM is the most commonly used technique, specifically for FC and CHB, because it offers an evenly power distribution among cells and it is very easy to implement. In a MC with  $m$  voltage levels,  $(m - 1)$  triangular carriers are required. Thus, a phase shift of  $\frac{360^\circ}{(m-1)}$  is introduced between carrier signal, producing a phase-shifted between the unipolar switching pattern of contiguous cells. An advantageous feature is that the effective switching frequency of the load voltage is  $(m - 1)$  times the switching frequency of each cell, as determined by its carrier signal. This allows a reduction in the switching frequency of each cell, thus reducing the switching losses. Thereby, a better total harmonic distortion (THD) is obtained. (e.g.  $m = 7, m - 1 = 6, f_m = 60\text{Hz}, m_f = 10, f_{sw,dev} = f_{cr} = f_m \cdot m_f = 600\text{Hz} \rightarrow f_{sw,inv} = (m - 1) \cdot f_{sw,dev} = 6 \cdot f_{sw,dev}, THDV_{AN} = 18.8\%, THDV_{AB} = 15.6\%$ )

LS-PWM is widely used in NPC converters, since each carrier can be easily associated to two power switches of the converter. They can be arranged in vertical shifts, with all the signals in phase with each other, called in phase disposition (PD); with all the positive carriers in phase with each other and in opposite phase of the negative carriers, known as phase opposition disposition (POD); and alternate phase opposition disposition (APOD), which is obtained by alternating the phase between adjacent carriers. Among them, the PD is preferred because it provides the best harmonic profile. However the switching devices operate at different switching frequency with various conduction times, with an "average" device switching frequency equal to  $f_{sw,dev} = \frac{f_{sw,inv}}{(m-1)}$ .

LS-PWM leads to less distorted line voltages since all the carriers are in phase compared to PS-PWM. However, this method produces an uneven distribution of power among cells, which produces a high harmonic content in the input current.

An example of a voltage spectrum obtained from both a multilevel converter and a PV installed in Scandinavia is shown in Figure 19.

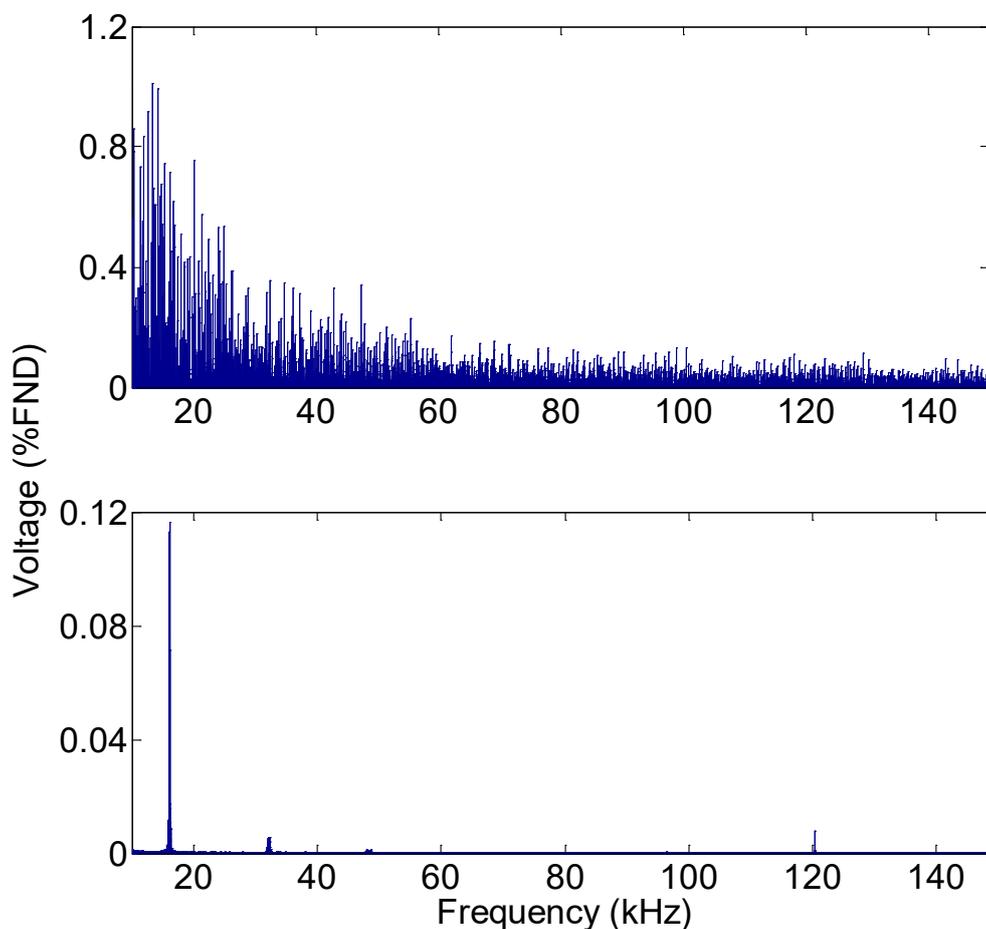


Figure 19 Spectrum of the voltage in percentage of the FND (10 to 150 kHz). In the upper curve from a multi-level converter simulated. In the lower curve a measured spectrum from a PV inverter in a real installation is shown.

The upper figure contains no distinct switching frequency in the supraharmonic range, while in the lower figure is possible to see the switching frequency from the inverter at 16 kHz. The measurement of the conventional inverter (Figure 19 lower curve) is done at the grid side of an inverter operating in the LV-grid. The multilevel converter is designed for use on MV grid and the data is from a simulation made of the DC side of the inverter. The comparison of emission levels between the two is therefore not appropriate. However, the comparison shows that the spectrums are different and the narrowband component originating from the switching in the inverter is not visible in the spectrum from the multilevel converter.

## 8 Measurement, Testing and Data issues

New power quality phenomena like supraharmonics and the availability of new and affordable measurement techniques have driven the introduction of new types of monitors and sensors. The latest technological developments allow state-of-the-art power-quality monitoring devices to sample the voltage and current waveforms at higher frequencies, analyze them faster, timestamp the events more accurately using GPS technology, save data in standardized formats (e.g. PQDIF/IEEE Std. 1159.3 and COMTRADE/ IEEE Std C37.111) and use wireless communication. The shifting to higher frequency, up to 150 kHz, will require new types of sensors, which will replace the traditional instrument transformers. Traditional instrument transformers already present into the network should be carefully characterized up to this frequency in order to take into account any systematic measurement errors during a power quality measuring campaign. New indices are needed for supraharmonics; however more research is needed to fully understand how to appropriately set these indices.

### 8.1 MEASUREMENT ACCURACY

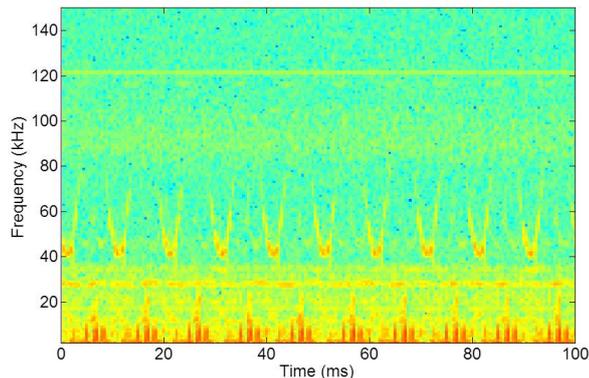
A detailed description of measurement techniques for conducted supraharmonic emission is given in [32]. Challenges for measuring and analyzing supraharmonics are also discussed in [50][51]. It is shown that obtaining sufficient measurement accuracy for supraharmonics is not trivial. Measurements of supraharmonic currents require current transformers or other sensors that have high accuracy for both amplitudes and phase angle over a wide frequency range. If voltage transformers have to be used for measurement (e.g. in medium voltage), their frequency response can result in considerable measurement errors [52]. The voltage needs to be analogue high-pass filtered to obtain sufficient dynamic range. This filtering should have minimal impact on the signal. A correction might be needed to compensate for the frequency response of the filter. In [51] two methods for measuring supraharmonics regarding the necessity of filters, chosen bandwidth, impact of band boundaries and methods for aggregation in time are discussed.

Supraharmonics are typically not linked to the power system frequency. This provides some limitations to measurement methods introduced in IEC 61000-4-7 where window synchronization based on phase-locked loop is prescribed.

### 8.2 TIME-FREQUENCY DOMAIN ANALYSIS

The classical way of representing emission, by means of a spectrum obtained over a relatively long period, is not sufficient for supraharmonics. Measurements show that signals in the supraharmonic frequency range often change in amplitude and frequency on timescales down to milliseconds as seen in Figure 20. A similar phenomenon is shown in [53] but for a much higher frequency band. A joint-time-frequency domain analysis tool like the short-time Fourier-transform (STFT) or sliding-window ESPRIT [54] is a more appropriate tool to analyze these changes. With the STFT a signal is divided into smaller time windows (with or without

overlap); for every such window a spectrum is obtained. These time-dependent spectra are then combined to create an image of the changes in the spectrum over time (the spectrogram) as shown in Figure 20. The type of signal shown is typically emitted by end user equipment with active power factor correction (APFC) where the current is forced to follow the voltage waveform thus producing narrowband components with short duration that shift in frequency [32].



**Figure 20 Combined time and frequency domain representation (spectrogram) of the current drawn by a fluorescent lamp.**

The STFT or sliding-window DFT is equivalent to applying a set of band-pass filters [55]. A broadband signal is therewith decomposed into a set of time-varying narrowband components at different frequencies. This gives a lot of additional information compared to the spectrum obtained over a longer time window.

For the so-called “recurrent oscillations”, neither the conventional spectrum, nor the spectrogram is an appropriate tool. A recurring oscillation is described in [32] as a signal that consists of damped oscillations occurring every 10 ms (in a 50 Hz system). The origin of the signals can be found in active PFC circuits but other equipment may also emit this kind of disturbance. The characteristics of the recurrent oscillations observed show similarities with the characteristics of commutation notches due to dc motor drives or certain types of UPS. Voltage measurement in stores with larger quantities of fluorescent lamps with high frequency ballast shows that the recurrent oscillations can reach values up to several volt [32]. To use a time-domain analysis is most convenient to quantify and study recurrent oscillations, like ESPRIT used in [32] to estimate frequency and amplitude of recurrent oscillations.

### 8.3 TESTING ISSUES.

To test individual appliances with the use of a line impedance stabilization network (LISN) might not be suitable in the supraharmmonic range for several reasons. In [56], it was shown that when a non-linear load was exposed to voltage distortion at any frequency, it produced currents at integer multiples of that frequency. It was shown in [31] that the connection and disconnection of neighboring devices could affect the magnitude of the emission. It was also shown [31][56] that some devices (for instance CFLs or LED lamps) have an impact on the

supraharmonic impedance that varies on a timescale shorter than 20 ms. Neither of these phenomena is included during a test in a distortion free environment with static impedance as when using an LISN.

The results of this is that a test performed with an LISN, i.e. a standardized test, gives a value for the emission that cannot be used as an estimate for the emission of that device when being used in a real installation. This is in itself not a concern; it also holds for harmonics in the lower-frequency range. However, with harmonics the emission in an installation is somewhat different but almost always less than the emission observed during a standardized test. When all equipment complies with the test, the voltage distortion in an installation will thus not be surprisingly high.

This is no longer the case for supraharmonics. There are indications that the emission from a device in a real installation may be significantly higher than the emission under a standardized test. The voltage distortion in an installation, even well all equipment complies with the standardized tests, may therefore be surprisingly high. This aspect of supraharmonics needs serious attention in research and in standardization.

## 9 Modeling and Simulation

### 9.1 PROPAGATION

How supraharmonic currents will propagate depend on the impedance at every branch seen by the source, as is the case with currents at any frequency. Considering an installation, like the installation in a detached house, there will be impedances introduced by the wiring, the devices that are connected within the installation and by the grid to which the installation is connected. The wiring will offer impedance that is mostly resistive and inductive. It will vary with length and frequency but it will be static over time (i.e. the impedance will not change with time). Connected devices can be classified into three main types;

- Type I includes devices whose impedance is a function of frequency but that can be seen as constant impedance over the duration of one cycle of the fundamental frequency,
- Type II includes devices whose impedance will vary with time over one cycle of the fundamental frequency,
- Type III includes purely resistive devices, whose impedance is neither dependent on time nor dependent on frequency.

The first type consists of devices equipped with EMC-filters of LCL-type or CLC-type (e.g. computers or television sets) and the second type, devices equipped with a diode rectifier (e.g. LED lamps) [37]. The impedance of devices of type one will hence vary with frequency but not with time (at least not on a time scale of one cycle of fundamental frequency). The impedance of devices of type two will vary with frequency and time (on a time scale of one cycle of fundamental frequency). The instance of the transition from high impedance to low impedance for type two devices will depend on the voltage, i.e. at what voltage the diode rectifier starts to conduct and the device starts to draw current. The impedance, in ohms, will depend on the component sizes used in the devices. Impedance of all types of devices will however vary in time as devices will be connected and disconnected. This takes place on a longer time scale and is not the subject of this chapter.

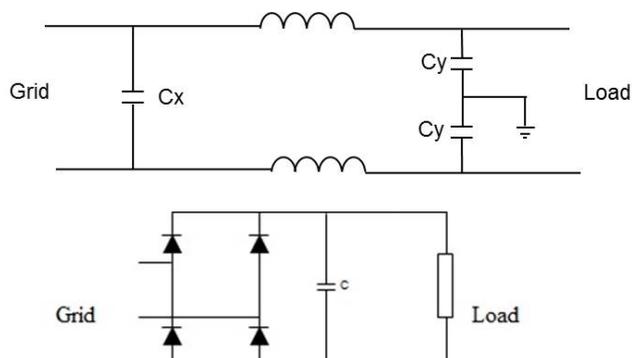


Figure 21 Devices of type I (upper) and II (lower)

The impedance of the grid consists of two main parts: impedance of transformers and impedance of cables and overhead lines. In [67] it is reported that the

impedance of a 25 kVA energized MV/LV transformer lies roughly between  $1 \Omega$  and  $10 \Omega$  in the 2 to 150 kHz region (lower value for lower range). Moreover it is shown that the impedance at supraharmmonic frequencies varies with time corresponding to the cycles of the fundamental frequency. According to [68] standard impedance values for a low voltage cable are  $L=0.25$  to  $0.31$  mH/km and  $C=0.34$  to  $0.8$   $\mu$ F/km. Using these values, the characteristic impedance for a low voltage cable lies between  $18 \Omega$  and  $30 \Omega$ . Overhead lines are more inductive and less capacitive than cables and hence have higher characteristic impedance.

In [69], a proposed model of the propagation of supraharmatics using a cascade of two port networks with ABCD parameters as shown in Figure 22 is described. Each two port corresponds to the different elements in the grid; transformers, cables and lines. Any two-port and transformation between them could in principle be used (impedance, admittance, hybrid or ABCD) depending on which parameters are known. One advantage of the two-port model is that its parameters can be found from a limited number of measurements.

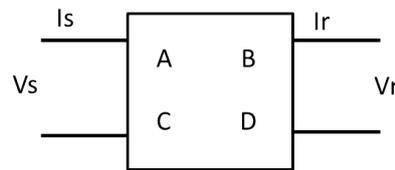


Figure 22 ABCD model for the two-port

Using the ABCD parameters;  $A$  gives the voltage ratio,  $B$  gives the impedance (transfer impedance),  $C$  gives the admittance and  $D$  gives the current ratio. This will allow for computation of the voltage ( $V_r$ ) and current ( $I_r$ ) at the receiving port if the voltage ( $V_s$ ) and current ( $I_s$ ) at the supply port are known. The ABCD parameters can be derived from the characteristic impedance of a cable:

$$Z_c = \sqrt{(R + j\omega L)/(G + j\omega C)} \quad (7)$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (8)$$

Thus making the ABCD model [74]:

$$ABCD_{cable} = \begin{bmatrix} \cosh(\gamma l) & Z_c \sinh(\gamma l) \\ \sinh(\gamma l) / Z_c & \cosh(\gamma l) \end{bmatrix} \quad (9)$$

Knowing the emission (voltage and current) of a source would thus allow for calculation of the emission levels at the end of a cable of  $l$  meters.

In many cases the impedance of the grid is higher than the impedance of neighboring devices and supraharmonic emission does not propagate outside the installation to any great extent. However, there are exceptions when the grid impedance is small e.g. due to a resonance and the grid is not always “emission free” either. Recurring oscillation is one type of emission that tends to propagate from the installation towards the grid. Power line communication is another

example where the emission is intentionally injected into the grid and the cables and overhead lines are used to carry a signal between the customer site and the transformer substation.

## 9.2 RESONANCES

Not much has been reported in scientific papers about high frequency resonances involving low-voltage appliances. For resonances in the harmonic frequency range (defined as being up to harmonic number 40, i.e. 2 kHz in a 50 Hz system) there have been some studies done. In [73] resonance phenomenon in a micro-grid with multiple inverters is examined. In [75] harmonic resonances between PV-installations and non-linear loads are presented. In [76] harmonic emission due to resonances in a LV network with PV-installations is discussed and a resonance frequency at 1.2 kHz is found.

For a resonance to occur there has to be an inductive reactance and a capacitive reactance. The equation for finding the resonance frequency is the same for series and parallel resonance

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (10)$$

where  $L$  is the equivalent inductor value,  $C$  is the equivalent capacitor value.

At the resonance frequency the only thing left to damp a signal is the resistive part of the circuit. Inside an installation like a detached house, capacitances will be present in the form of appliances (in their EMC filter or in the form of the dc-side capacitor behind a diode rectifier) and inductances in the form of wires and some appliances (directly-connected motors). The resistive elements are present in the wiring and in some appliances (e.g. espresso machines and tea-water cookers). The latter contribution is reducing in number, among others by the replacement of incandescent lamps with electronic lighting. As there are no available comparative network impedance measurements which could indicate the reduction of damping due to changing types of equipment, simulation results can be used as a reference, as presented in [70][71]. Interpretation of the results is difficult and no clear conclusions can be drawn from these studies yet.

In [78] a series of measurements were conducted to see the impact from the wires on the impedance in an installation. It was shown that by varying the length of the wires (and as a result also the inductance) to an appliance equipped with a capacitor at its terminals the frequency dependent impedance changed consequently. The length of the power cord was altered from 0 to 46 meters and as a result the frequency with minimum impedance shifted from 78.6 kHz to 38 kHz, all the time within the supraharmmonic range. In [79] it was shown that a common mode resonance is likely to occur in the frequency range 2 to 150 kHz between parallel connected EMC-filters.

Based on the theory that the wires in an installation can have an effect on the resonance in the higher frequency range, some calculations and simulations were performed. In all cases the appliances are considered as a current source behind a capacitor, in the same way as in [15]. The case of a single appliance connected to

the grid via a wire is shown in Figure 23 where  $I_0$  and  $C_1$  represent the appliance responsible for the primary emission,  $L_1$  represents the wire,  $R_1$  the wave impedance of the grid,  $R_2$  and  $L_2$  the low frequency resistance and inductance of the grid. The impedance of the grid,  $Z_{Grid}$  would hence be  $R_1$  in parallel with  $R_2$  and  $L_2$  and the external impedance,  $Z_{ext}$ , seen by the appliance consequently a series connection of  $L_1$  and  $Z_{Grid}$ .

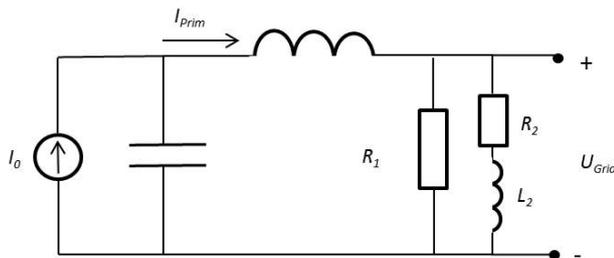


Figure 23 Schematic of a single appliance connected to the grid via a wire

The primary emission at the terminal of the appliance in Figure 23 could be described as the transfer function:

$$\frac{I_{Prim}}{I_0} = \frac{1}{1 + j\omega C_1 Z_{ext}} \quad (11)$$

And the transfer impedance is defined as:

$$\frac{U_{Grid}}{I_0} = Z_{Grid} * \frac{I_{Prim}}{I_0} \quad (12)$$

A longer wire would shift the resonance peak to a lower frequency and somewhat increase the amplification. Both transfer function and transfer impedance show a decrease with increasing cable length.

When a second appliance in form of a capacitor  $C_2$  is connected, through a wire with inductance  $L_3$ ; as shown in Figure 24 an additional resonance frequency will appear.

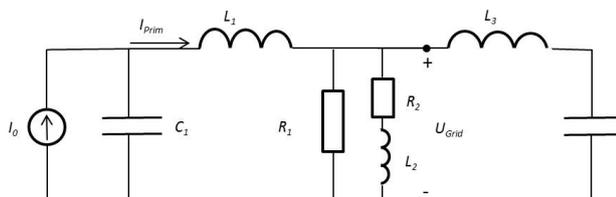


Figure 24 Schematic of two appliances connected to the grid via a wire

$Z_{Grid}$  will remain the same as in the case with one appliance connected but the external impedance at the terminals of the first appliance is now:

$$Z_{ext} = j\omega L_1 + \frac{Z_{Grid} * (j\omega L_2 + \frac{1}{j\omega C_2})}{Z_{Grid} + j\omega L_2 + \frac{1}{j\omega C_2}} \quad (13)$$

Equation (5) will still hold for the transfer function using  $Z_{ext}$  from (6) and the transfer impedance will be:

$$\frac{U_{Grid}}{I_0} = \frac{I_{Prim}}{I_0} * \frac{Z_{Grid} * (j\omega L_2 + \frac{1}{j\omega C_2})}{Z_{Grid} + j\omega L_2 + \frac{1}{j\omega C_2}} \quad (14)$$

The transfer function and transfer impedance according to the case shown in Figure 24 are plotted in Figure 25.

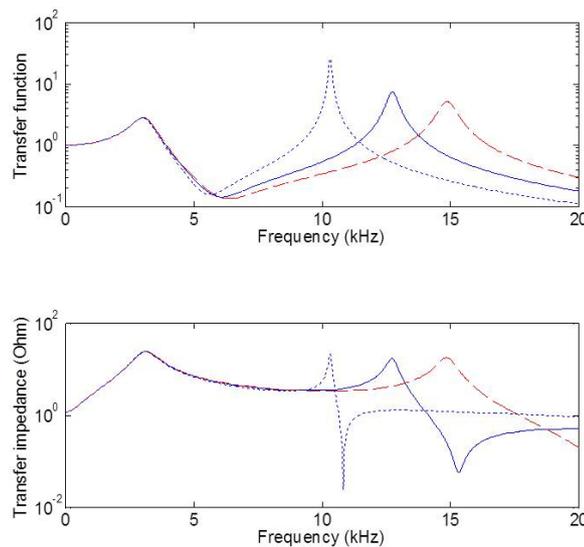


Figure 25, Transfer function (top) and transfer impedance (bottom): second appliance connected to grid by cable of length 10 meter (red dashed), 20 meter (blue solid) and 40 meter (blue dotted).

The following parameter values have been used:

$$\begin{aligned} C_1 &= 5 \mu\text{F} \\ L_1 &= L_3 = 3 \mu\text{H/m} \\ C_2 &= 1.8 \mu\text{F} \\ R_1 &= 50 \Omega \\ L_2 &= 350 \mu\text{H} \\ R_2 &= 1.2 \Omega \end{aligned}$$

The values have been chosen based on realistic wire length in a detached house and the capacitance values found in common household devices (e.g. TV sets and computers).

As seen in Figure 25 it is feasible that the connection of a second appliance will create a resonance point at a frequency between 10 kHz and 20 kHz; moreover the simulations show that the length of the wire will shift this resonance frequency. The figure also shows that depending on the length of the wire connecting the second appliance, the primary emission from the first appliance can vary by a factor of more than 10. The primary emission from an appliance can thus not be considered as constant, but instead it depends on the properties of the grid and of other appliances connected in the neighborhood.

A simulation of a similar installation as described above was done where a PV inverter and additional devices were added and for every addition the impedance was monitored at two places (terminals of the PV and terminals of Device 1). The schematic for three additional devices is shown in Figure 26. As can be seen in Figure 27 every additional device will affect the resonant point as well as the overall impedance in the frequency range.

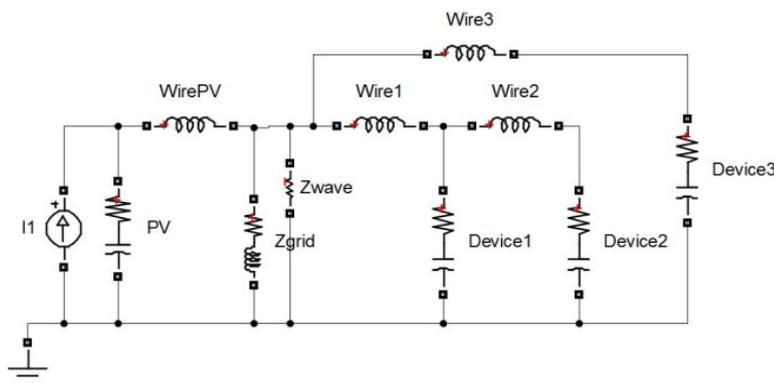


Figure 26 Schematic of the simulated circuit

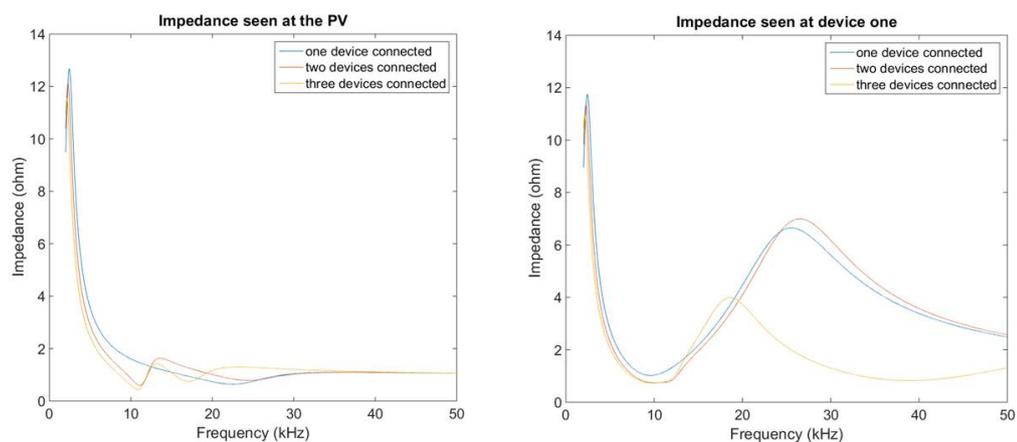
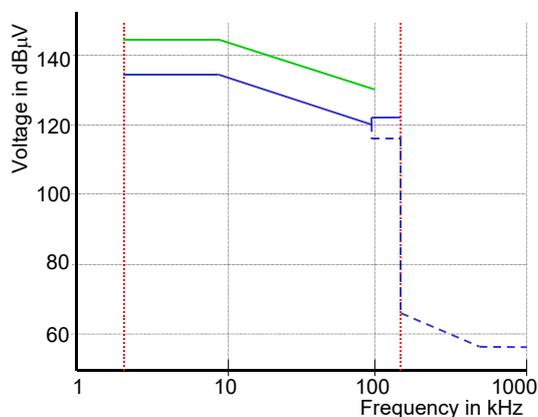


Figure 27 Impedance seen at the PV inverter (left) and at device one (right) as shown in Figure 26.

## 10 Standardization<sup>4</sup>

The frequency range between 2 and 150 kHz is generally known as a range without any standardization. Terms like “desert-like” and “wild west” are often used. This is however not a fair description, as there are actually a number of standards covering this frequency range. An overview of these is given in [80] where a distinction is made between “narrowband limits” and “broadband limits”, where narrowband limits are in practice the limits for power-line communication. An overview of limits in existing standards is also given in Annex A of IEC 61000-4-19. The existing narrowband limits are summarized in Figure 28; the limits for broadband signals in Figure 29. The two vertical red lines indicate the frequency range of interest (2 to 150 kHz).



**Figure 28.** Voltage characteristics for narrow-band signals according to EN 50160 (green solid line) and emission limits for narrow-band signals according to EN 50065 (blue solid line) and IEC 61000-3-8 (blue dashed line). Up to 95 kHz the limits are the same for these two standards.

Maximum emission due to power-line communication is given in the form of voltage limits in EN 50065-1 and in IEC 61000-3-8. Voltage characteristics are given in EN 50160, where they are referred to as “voltage levels of signal frequencies”. Note that the emission limits are expressed in terms of voltage. There is no reference impedance associated with this limit; the voltage after injection of the communication signal shall not exceed the indicated limit in the actual network. For frequencies up to 95 kHz the limits are the same for both standards. EN 50065 does not cover frequencies above 150 kHz. IEC 61000-3-8 does give limits but these are an order of magnitude more restrictive than below 150 kHz. This is to prevent interference with commercial broadcasting (the long-wave band starts at 148.5 kHz).

The limit according to EN 50065 and IEC 61000-3-8 is at 134 dBµV (about 2 % of 230 V) for frequencies between 3 and 9 kHz. The voltage characteristic according to EN 50160 is equal to 5 % of the nominal voltage. The margin between the emission

<sup>4</sup> This section consist of parts of the paper “Standards for supraharmonics (2 to 150 kHz)” by M. Bollen, M. Olofsson, A. Larsson, S. Rönnberg and M. Lundmark [3]

limit and the voltage characteristic is to allow for the presence of multiple devices and for amplification of voltage distortion due to resonances. At 100 kHz, the emission limit according to EN 50065 is at 120 dB $\mu$ V (about 0.5 % of 230 V) whereas the voltage characteristic is slightly above 1 %.

It is proposed in [80] to set the compatibility levels for narrowband signals equal to the voltage characteristics in EN 50160. The voltage characteristics for lower frequencies are also similar to the compatibility levels, so this proposal would simply be an extension of the practice at lower frequencies. The immunity limits are proposed to be set 6 dB above the compatibility levels.

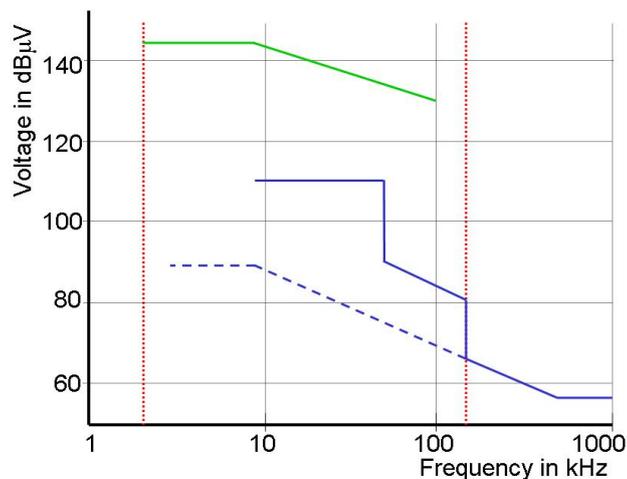
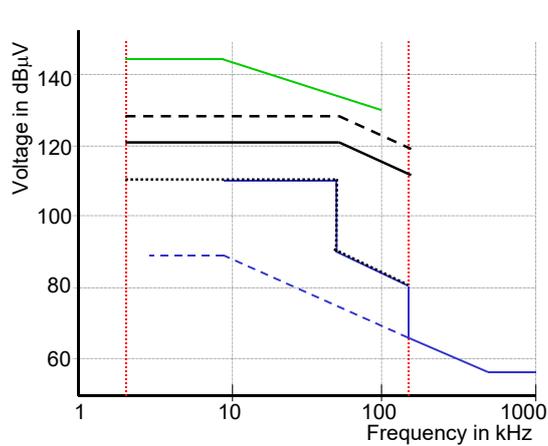


Figure 29. Emission limits for broadband signals according to CISPR 15 (blue solid line) and EN 50065 (dashed line). The voltage characteristics for narrowband signals according to EN 50160 (green solid line) are given as a reference.

Emission limits for broadband signals by lighting equipment are given in CISPR 15. These limits are given as a voltage against a reference impedance. Limits for the emission by power-line communication equipment at frequencies not used for communication purposes are given in EN 50065. For frequencies above 150 kHz those emission limits are the same as those in CISPR 15.

Also for broadband signals, compatibility levels and immunity limits are proposed in [80]. It is proposed to extend the CISPR-15 limits to lower frequencies (from 2 kHz) and to apply them to all equipment. It is further recommended to set a compatibility level about 6 dB above the emission limit and an immunity limit another 6 dB above the compatibility level, as shown in Figure 30.



**Figure 30.** Proposed compatibility levels (black solid line) and immunity limits (black dotted line) for broadband signals.

Reference [80] was intended as a discussion document, not as a proposal for a complete set of standard limits. This discussion has however still not started, which is the reason for the authors to repeat the proposal here.

There are a number of properties of supraharmonics that are different from those observed for harmonics. Before setting up a standardization framework it is important to consider these. Three of those properties that we will briefly discuss in this section are: the presence of recurrent oscillations; the spread of emission through an installation; and the dominance of secondary emission in many cases.

Measurements as well as simulations have shown that the emission from an installation, in the frequency range from a few kHz, is much less than the sum of the emission from the individual devices. It has even been shown that the total emission from a lighting installation actually decreases with an increasing number of lamps [15][16]. Setting limits on the total installation (as in IEEE Std. 519) and setting limits on individual devices (as in IEC 61000-3-2) would no longer serve the same aim. A related issue is that strengthening the grid (i.e. reducing the source impedance at 50 or 60 Hz) will have very limited impact on the supraharmonic voltages.

For the recurrent oscillations occurring around the voltage zero crossing, a different aggregation law applies and the emission levels are shown to increase rather quickly with the number of devices [16]. Although as yet no quantitative model exists that explains this behavior, it is important to consider this in the standardization. It is also important to realize that the impact on equipment may be completely different for recurrent oscillations than for continuous signals with the same amplitude in the spectrum. For the emission limits, the spectral approach may still be used, but the special character of the emission should be considered. Without considering the special-character of the emission, very high time-domain emission can result without exceeding the frequency-domain limit. A time-domain approach would therefore be more appropriate. Also for the setting of immunity standards (or immunity recommendations) a time-domain approach should be used.

When testing equipment against emission limits, two things should be considered: the test should be reproducible and the test results should give a realistic representation of the behavior of the equipment in a real installation. The former requirement is taken care of by defining a reference impedance and a clean source in the form of a line-impedance stabilization network (LISN). With supraharmonics, the current at the equipment terminals depends however strongly on the presence of other equipment in the neighborhood of the emitting device. To describe this and include it into emission models, a distinction is made between primary emission and secondary emission in [15], where primary emission is driven by the power-electronics in the device and secondary emission by sources elsewhere.

## 11 Findings

An increasing amount of equipment emits non-negligible levels of supraharmonics in the grid. Voltage distortion in this frequency range has shown to be non-negligible at certain locations. No overall information is available on the existing levels as large-scale field measurements remain both technically and economically a challenge.

The distinction between primary and secondary emission is very important for studies on supraharmonics. A consistent set of definitions for primary and secondary emission has been developed as part of this project. A third phenomenon, interaction, is introduced in which the non-linear properties of two or more devices impact harmonic or supraharmonic voltages and currents.

Measurements performed partly within this project and partly in another project<sup>5</sup> have shown that supraharmonics can have a serious impact on the light intensity of LED lamps. This is a new phenomenon and may be an as yet unknown source of light flicker.

The reduction of emission in the lower-frequency ranges appears to result in an increase in supraharmonic emission by equipment. Setting more strict requirements on harmonic emission may thus result in the unintended consequence of an increase in supraharmonic levels.

Resonances play an important role in the spread of supraharmonic distortion through the low-voltage network.

There is a large interest from the international standard-setting community in knowledge in the frequency range 2 to 150 kHz. At the same time research is ongoing at a number of locations, and the amount of groups working on this frequency range has increases, as seen from the growing number of publications on the subject. The work done at Luleå University of Technology is heavily cited by almost everybody working on this field.

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<sup>5</sup> "Energy-efficient lighting under high levels of electromagnetic disturbance levels" project number 31550-2

## 12 Recommendations

There is a need for a consistent terminology and within this project the terms Supraharmonics, Primary emission and Secondary emission are proposed and defined.

A proposal has been made for setting limits in this frequency range [3]. The proposal is based on existing standards and is meant to be for discussion. A distinction is thereby made between narrowband and broadband signals.

There are a number of differences between harmonics and supraharmonics that are not covered by the proposed set of limits.

- Emission from individual devices flows mainly between devices, not into the grid. Therefore limits for individual devices no longer serve the same aim as limits for complete installations.
- Recurrent oscillations make that the time-domain character of the disturbance should be considered. This holds especially for immunity standards.
- The emission from a device measured for a clear voltage does not give a good estimation for the emission in a real installation. This should be considered in the emission standards.

## 13 Further studies and open issues

The following research challenges and opportunities for future research have been identified.

### 13.1 EMISSION

- Relations between converter configuration and control, EMC filter, and primary emission
- Origin of recurrent oscillations and their aggregation with multiple emitting devices
- Impact of voltage magnitude, distortion, source impedance, and the presence of other end-user equipment nearby, on the primary and secondary emission
- Time-varying nature of the emission

### 13.2 PROPAGATION

- Transfer between devices and from individual devices to the grid, especially the impact of resonances and damping
- Aggregation of emission from different devices, including the aggregation between primary and secondary emission
- Propagation from sources of emission at medium or high voltage to lower voltage levels
- Distinction between primary and secondary emission by means of modeling and measurements

### 13.3 INTERFERENCE

- The impact of end-user equipment (emission and impedance) on the performance of power-line communication
- The impact of short-duration high magnitude emission on end-user equipment
- Emission at new frequencies from non-linear equipment due to background distortion
- Impact of voltage distortion on performance and life length of end-user equipment and equipment in the grid
- Methods for increasing immunity of end-user equipment

### 13.4 MEASUREMENTS

- Methods for accurate and reproducible measurement of voltages and currents at higher frequencies
- Methods for systematic extracting time-domain, frequency-domain and time-frequency-domain features from measured waveforms

### 13.5 STANDARDIZATION

- Standardized methods for quantifying voltage and current distortion in the range 2 to 150 kHz
- Emission and Immunity limits and standardized tests
- The concept of compatibility levels for supraharmonics need to be evaluated if it can be applied
- A classification of emission based on phenomena, characteristics of the emission and difference in propagation

### 13.6 MODELING AND SIMULATION

- Models for components in the grid and for end-user equipment connected to the grid
- Models for active converters that can be used to predict their emission, their impact on the emission, and the spread of disturbances from neighboring devices
- Modeling guidelines for different frequency ranges and different phenomena

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# PROPAGATION OF SUPRA-HARMONICS IN THE LOW VOLTAGE GRID

Här redovisas ett postdoktoralt projekt vars syfte är att ytterligare beskriva och sprida kunskap om emission i frekvensområdet mellan 2 kHz och 150 kHz kallat supratoner, eller supraharmonics på engelska. Termen supraharmonics är ett samlingsnamn för all distorsion i detta frekvensområde och termen används allt oftare.

Mätningar har visat att förekomsten av supratoner kan påverka LED-lampans ljusintensitet. Det är ett nytt fenomen och kan vara en ännu okänd källa till ljusflimmer. Resultaten visar också att spridningen av supratoner genom lågspänningsnätet varierar över tid ner på tidskalor under 20 ms och påverkan från angränsande apparater samt förekomsten av resonanser spelar en viktig roll i denna spridning.

Både mätningar och simuleringar visar att resonanser spelar en viktig roll i spridningen av supratoner genom lågspänningsnätet.

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