An overview of the origin and propagation of Supraharmonics (2-150 kHz)

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SUMMARY

The interest in waveform distortion in the frequency range 2 to 150 kHz (supraharmonics) is growing for a number of reasons (among others its potential impact on the communication with smart meters). A broad and basic knowledge has been obtained, mainly due to research at Luleå University of Technology. There remain big gaps in qualitative and quantitative understanding of the distortion in this frequency range but the research is on-going at several places now.

The aim of this paper is to give an overview of the current status of the research on supraharmonics, at Luleå University of Technology and elsewhere. Emphasis will be on the low-voltage network. The paper will cover the origin of supraharmonics (remnants of active switching of power electronic converters and power line communication) as well as how supraharmonics propagate between neighbouring devices and through the grid. The propagation strongly depends on interaction between connected devices. A brief overview of the work done by standard setting comities regarding supraharmonics will be given.

KEYWORDS

CFL, Flourescent light, Harmonic Emission, LED, Power Quality, Power line communication, Supraharmonics

1. INTRODUCTION

Harmonics have long been part of the power quality field and an impressive amount of research has been done and is still ongoing on this. The work by Jos Arrillaga [1] remains the fundamental textbook for everybody working on power-system harmonics. Waveform distortion in the frequency ranges above the harmonic range (2 kHz in a 50 Hz system) has long been ignored by the research community. Among others, one cause for this is the difficulty to measure conducted emission in the frequency range between 2 and 150 kHz.
The area of 2 – 150 kHz is presently under high interest for mainly two reasons; there is a lack of standards (emission, immunity and compatibility) and frequencies within this range are used for automated meter reading (9 to 95 kHz). The published research on supraharmonic emission can be summarized in the following list:

- ✓ The emission from equipment in this frequency range contains a number of components. The dominating ones are emission due to the active switching of power-electronic converter; and short-duration oscillations with short-duration that occur around the zero-crossing of the current waveform. [2-10]
- ✓ The highest levels of voltages and currents in this frequency range are associated with power-line communication. [3, 11, 12]
- ✓ The emission due to the active switching decreases in magnitude with increasing numbers of devices. These frequencies mainly flow between individual devices, not into the grid. Simplified models are able to explain this behavior qualitatively. [3, 5, 12-15]
- ✓ Resonances can result in local increases of emission at the switching frequency. The seriousness of this remains unclear. [3, 7]
- ✓ The oscillations around the zero crossing increase in amplitude with increasing number of devices. A clear understanding of this phenomenon is still lacking. [2]

Even the nomenclature for distortion in this frequency range remains a point of discussion and the term "high-frequency distortion" or high frequency harmonics has been used for a while, to be replaced recently by the term "supraharmonics" [3]. In this paper, we will use the term supraharmonics to refer to any waveform distortion in the frequency range 2 to 150 kHz.

2. ORIGIN AND CLASSIFICATION OF SUPRAHARMONICS

In the early days of power electronics, diodes and thyristors were the dominating valves. With these semiconductors, very low order harmonics are generated due to the mechanism for commutating current flows. Such line-commutated rectifiers and converters are generating harmonics dominating from only a few multiples of the fundamental frequency.
With the introduction of self-commutated valves such as transistors, generation of emission has been shifted to higher frequencies. With the rapid growth of electronics and energy saving equipment in our homes the emission in higher frequencies, supraharmonics, are expected to increase.

2.1 Measurement and analyzing techniques

In [2] a detailed description on measurement techniques for conducted supraharmonic emission is given. Measurement in the frequency range above 2 kHz is rather different from those in the harmonic range (below 2 kHz). The main amplitude of the current and voltage supraharmonics is often much smaller than for lower frequencies. Also the fact that the frequency is higher makes measurements more difficult. Measurements of supraharmonic currents require current transformers or other transducers that have sufficiently high accuracy

for both amplitudes and phase angle of the signal components. The voltage needs to be high-pass filtered to obtain sufficient dynamic range. This filtering should have minimal impact on the signal. When using signal conditioners a correction might be needed to compensate for the frequency dependency of the transfer function.
The signals in the supraharmonic range have different characteristics than lower frequency signals. Therefore the analyzing techniques need to be different. The spectra are rather often of a broadband form when compared with harmonics where discrete or narrowband components are found in most cases at integer multiples of the power-system frequency. The signal is often not stationary and will change amplitude over time in the millisecond range. These changes are often synchronized with the power system frequency. The signals can also have other features like time-frequency varying which are not common in the harmonic range. Supraharmonic emission can be described as and divided into:

- ✓ Narrowband signal
- ✓ Broadband signal
- ✓ Recurring oscillations

Examples of narrowband and broadband signals are shown in Figure 1

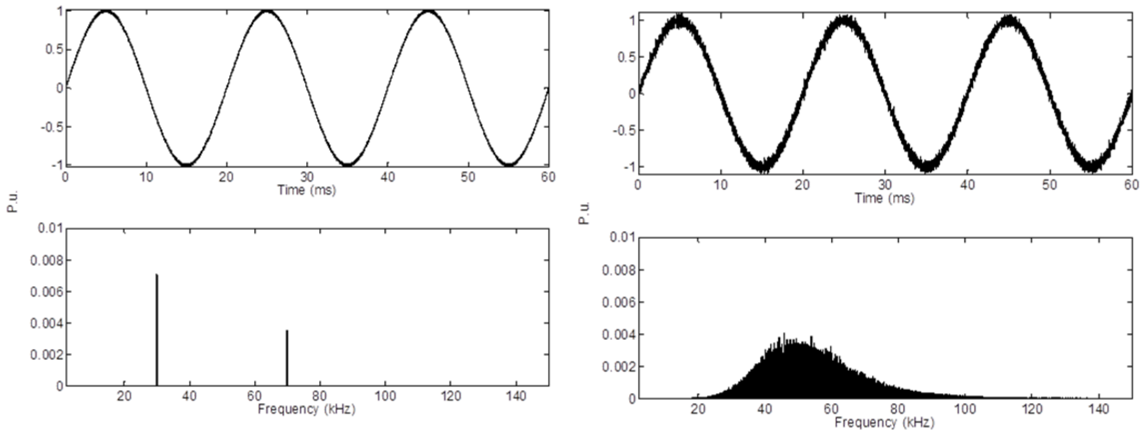

Figure 1 Example of a narrow band signal in the time domain (upper, left-hand side) and frequency domain (lower, left-hand side) and a broadband signal in the time domain (upper, right-hand side) and frequency domain (lower, right-hand side)

A recurring oscillation is described in [2] as a signal that consists of damped oscillations occurring repeatedly with twice the fundamental frequency, i.e. for a 50 Hz system every 10 ms. The origin of the signals can be found in active PFC circuits but some other equipment may also emits this kind of components. 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 volts.

Due to the complexity of the signals found within the supraharmonic range the combined time and frequency domain representation is often used when analyzing measured data. In Figure 2 a synthesized signal containing recurrent oscillations and a broadband signal is shown. What appears as a broadband signal in the frequency domain (Figure 2, upper) is revealed to be a time-frequency varying signal or a narrowband signal repeatedly shifting frequency over a 10 ms period when analyzed in the combined time and frequency domain (Figure 2, lower).

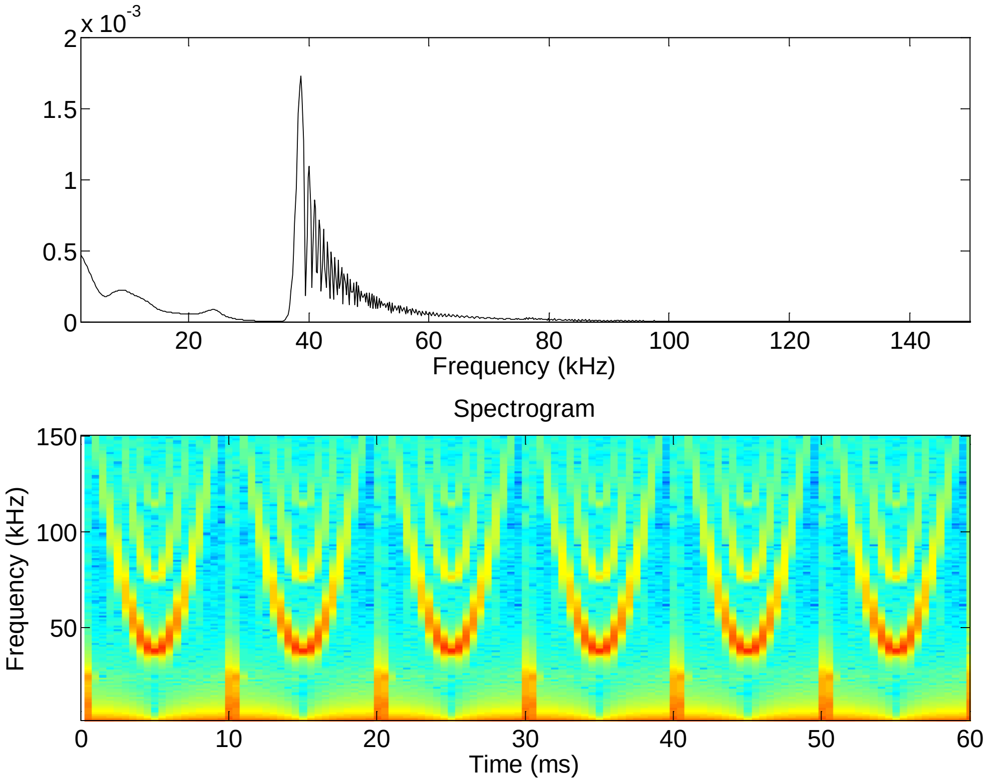

Figure 2 Frequency domain (upper) and combined time and frequency domain representation (lower) of a synthesized signal showing recurrent oscillations

2.2 Stray currents

The origin of stray currents due to supraharmonics is discussed in [7] and explained in Figure 3.

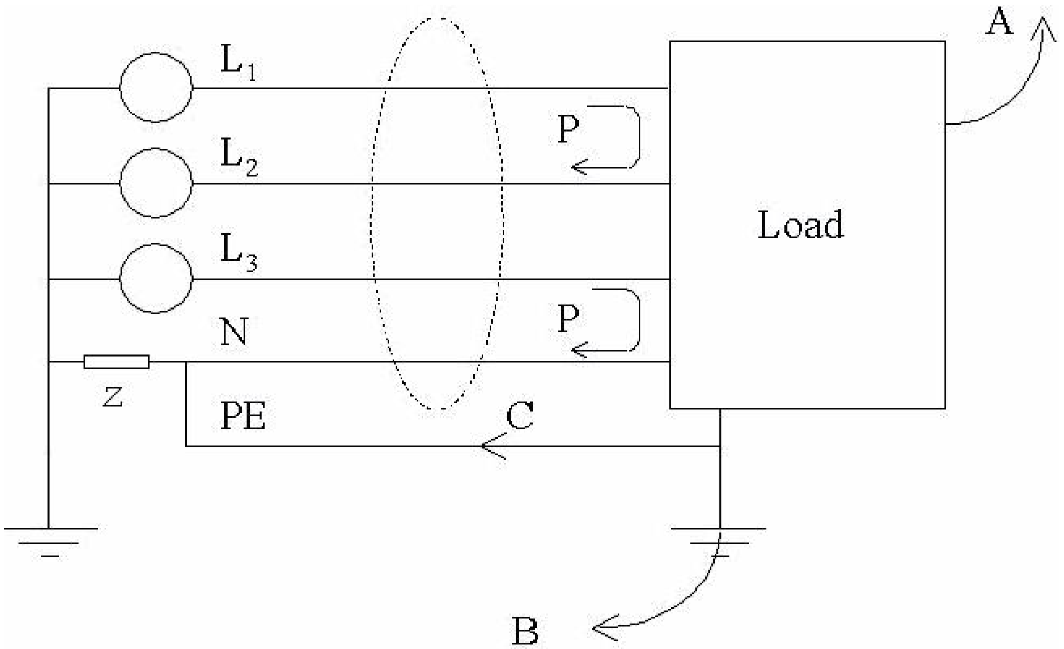

Figure 3 Different types of emission in a three-phase grid.

If the sum of the currents enclosed in the circle in Figure 3 is not zero, some kind of leakage current exists. This leakage shows up as three different types of electromagnetic emission:

- ✓ Radiated emission (A in Figure 3). Radiated emission may interfere with radio communication or induce currents in neighboring equipment that interfere with the correct operation of that equipment.
- ✓ Conducted emission in the form of stray currents (B in Figure 3). The term stray currents refers to the part of the current that does not return through any of the metal conductors but instead finds its way through water pipes, communications network, the armoring of the building, etc. The principle concern with stray currents is that there should be no currents flowing outside of the electricity wires. Further concerns are related to the unpredictability of stray currents and their effects and more recently the magnetic fields due to the large return loops.
- ✓ Conducted emission through the protective earth (C in Figure 3). Currents through the protective earth may find a galvanic path to other devices connected to the same protective earth.

The location of the connection point between the neutral conductor N and the protective earth PE is of importance here. The neutral current causes a voltage difference over the impedance Z of the common PEN conductor. This voltage difference in turn results in currents through the PE conductor which close as stray currents (B in Figure 1) towards the neutral earthing of the transformer. These stray currents, flowing outside of the PE conductor, can cause interference, for example in wire-based communication. The stray currents flow through metallic parts of the building frame, through metallic pipes used for water or heat, etc. The impedance of the common PEN conductor is partly inductive, partly resistive and the impedance will increase with frequency. Capacitive coupling between the neutral and the protective earth, for example inside of equipment, can further result in stray currents. Also the capacitive coupling is stronger for supraharmonics than for harmonics.

3. PROPAGATION OF SUPRAHARMONICS

There are a number of properties of supraharmonics that differ from those observed for harmonics. The propagation of emission through an installation is an important dissimilarity. 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. Within the supraharmonic range it is therefore important to distinguish between primary emission and secondary emission. The distinction between primary and secondary emission is made as:

- ✓ Primary emission is the part of the current that is driven by the internal emission of the device itself
- ✓ Secondary emission is the part of the current that is driven by the internal emission from other devices or that originates elsewhere in the grid.

Measurements and simulations show that the contribution of secondary emission can be a significant part of the total emission measured at the terminal of one device. This is illustrated in Figure 4 were a measurement of the current at the terminal of a CFL is shown. On the left hand side is the primary emission shown when the lamp is connected alone and on the right hand side is the secondary emission emitted by an induction cooker and absorbed by that same CFL. The different colors in the figure corresponds to different settings of the cooker and as seen in Figure 4 the secondary emission is completely dominating, the primary emission component with highest amplitude is 1.4 % of the amplitude of the highest secondary emission component.

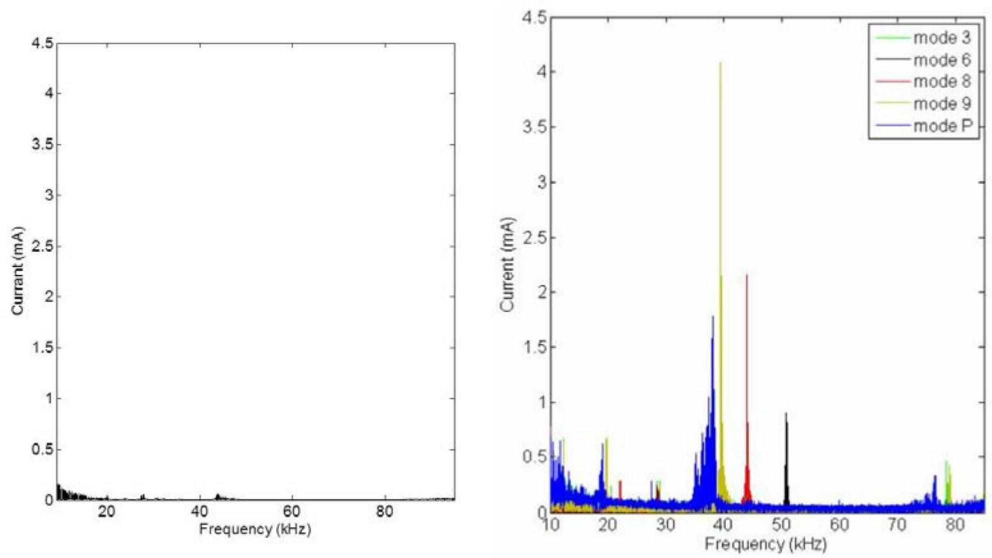

Figure 4 Primary emission measured at the terminal of a CFL (left hand side). Secondary emission emitted by an induction cooker and absorbed by that same CFL (right hand side).

From the viewpoint of an individual appliance primary, emission can be classified as an emission issue and secondary emission as an immunity issue. Measurements and the model developed in [13] show that often both will be present at the same time.
To test individual appliances with the use of a LISN might not be suitable in the supraharmonic range for several reasons. In [12] it was shown that when a non-linear load was exposed to secondary emission at any frequency it produced integer multiples of that frequency with an amplitude that was higher than that of the primary emission. (This

phenomenon could be compared to the injection of harmonics of the fundamental 50 Hz component from non-linear loads.) It was also shown that some devices (for instance a CFL or LED lamps) have an impact of the supraharmonic impedance that varies on a timescale shorter than 20 ms. It was shown in [3] that the connection and disconnection of neighboring devices could affect the magnitude of the primary emission. Neither of these phenomena would be possible to test in a distortion free environment with static impedance as when using an LISN.

The supraharmonic emission measured at the terminal of an appliance is a combination of primary and secondary emission. A number of experiments have been conducted in order to study the interactions between 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 5. In Figure 5 the current spectra measured at three individual CFLs are shown (upper right, lower left and lower right) together with a measurement of the combined current taken by all three lamps (upper left) [16]. The switching frequency of the lamps lies in the range between 40 kHz and 50 kHz. As more lamps are added the absolute amplitude in Ampere of the supraharmonics between 40 kHz and 50 kHz at the delivery point drops. At the same time the amplitude of the supraharmonic current measured at each individual lamp increases. This shows that propagation of supraharmonic current is significantly different compared to propagation of harmonic currents.

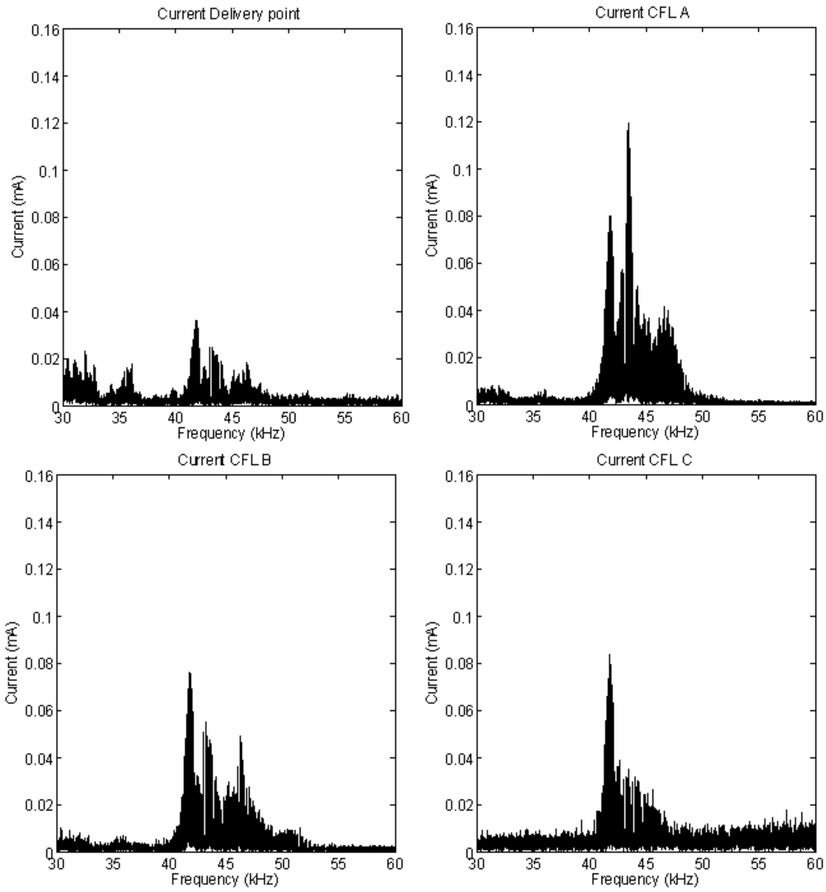

Figure 5 Supraharmonic current measured at three individual CFLs is shown (upper right, lower left and lower right) and the combined current taken by all three lamps (upper left).

The same result as shown in Figure 5 was found in [2] during an experiment involving 48 fluorescent lamps equipped with high frequency ballast. It was shown that the amplitude of the residues from the switching of the power electronic converters lies between 50 kHz and 90 kHz decreased at the point of common coupling as more lamps were added to the installation. The current drawn by the lamps also produced an oscillation of a few kHz around the zero crossing of the voltage. This recurrent oscillation seems to propagate differently compared to the emission caused by the switching circuit; this frequency component increased at the delivery point approximately proportional to the number of lamps to the power of 0.7 in amplitude as more lamps were added.

3.1 Resonances

When introducing modern energy efficient appliances into homes the likelihood of resonance phenomena in the frequency range between 2 and 150 kHz increases. Modern household-equipment is seldom purely resistive, instead they can be considered as either inductive or capacitive depending on the topology used.

In [7] it is shown, through simulations and measurements, that a common mode voltage in the supraharmonic range, in combination with the ungrounded modem power input, is enough to disturb a communication modem. A resonance at 16 kHz between an inverter and a TV is described in [3].

4. POWER LINE COMMUNICATION

Power line communication used for automated meter reading is becoming more common in Europe with the introduction of smart meters. Frequencies used for communicating with the meter lies within the supraharmonic range (9-95 kHz). Power line communication can be treated as a special case of supraharmonic emission; it is injected in a controlled way at predefined instances at predefined frequencies. The amplitude of the communication signals are also somewhat higher than emission originating from other devices connected at the low voltage grid. However, the propagation and interaction with end-user equipment remains the same regardless of the origin of the signal is a communication device or a non-communicating one.
Five types of interaction between power line communication and common household equipment have been defined and explained in more detail in [11, 12] that illustrate the complexity of the interaction:

I. High voltage or current levels at the communication frequency due to emission by end-user equipment. This can result in loss of the communication signal or in transmission errors.
II. The end-user equipment creates a low-impedance path at the communication frequency. The result is that only a small part of the communication signal arrives at the location of the receiver.
III. The voltage signal used for communication results in large currents through the end-user equipment. This can result in overheating of components or other interference with the functioning of the equipment.
IV. Non-linear end-user equipment exposed to a voltage at the communication frequency results in currents at other frequencies, typically harmonics of the

communication frequency.

V. The distortion of the voltage waveform due to the communication signal results directly in mal-operation of end-user equipment.

Type II appears to be the most common cause of failed communication on the low voltage grid. The shunting of the communication signal by end-user equipment also leaves the communication more susceptible to high levels of emission present on the grid (Type I). The same low-impedance path results in high currents through the end-user equipment (Type III) and with certain types of equipment, the generation of new frequencies (Type IV). The low impedance created by end-user equipment is due to the capacitor used in common EMC-filters (used in for instance computers or TVs) or the capacitor connected behind the diode rectifier (used in compact fluorescent lamps and LED lamps). Interactions of type I and II are adverse impact of equipment on the communication. With interactions of type III and V it is the communication that adversely impacts the equipment. For Type IV there is no direct adverse impact, but the additional disturbances may have an adverse impact by themselves.

5. STANDARDS

The existence of narrow- and broadband components has been known and is also considered in standards. The recurrent oscillations that are observed with individual lamps and with large installations are not covered by any standard. Work is ongoing in several standardization comities regarding supraharmonics. An overview of existing standards covering the frequency range 2 to 150 kHz is given in [17, 18].

6. FUTURE WORK

There still remains a lack of knowledge to understand origin and spread of supraharmonics. Such knowledge is needed to avoid future interference, but also to avoid the setting of unnecessary strict requirements on end-user equipment or on network operators. Models for equipment and low-voltage networks in this frequency range have to be further developed. Such models can be used to study the propagation of signals.

The results from [2, 3] indicate that high order supraharmonics do not propagate beyond nearby devices. It was however also shown in [3, 7] that resonances are likely to occur. An important part that remains to be studied is the possibility that certain resonance situations could result in spread of these signals to other customers or even to the medium-voltage networks.

It was also shown in [12] that it is feasible that an electrolyte capacitor, like the one used in CFLs, might get overheated due to high levels of supraharmonics. The effect on equipment due to supraharmonics need to be studied further.

7. CONCLUSION

In this paper it was shown that the emission in the supraharmonic range tends to stay inside an installation and mainly flow between connected devices. This is due to the low impedance offerd by connected devices in relation to the impedance of the grid.

The emission at the terminal of a device might be higher than from the total installation. In a mixed load situation with devices of various sizes and power ratings it is especially important to consider the emission levels at the terminal of the devices. It was also shown that it is feasible that resonances within the supraharmonic range are likely to exist.

The practice of a static impedance like an LISN is not as useful in the supraharmonic rage but other standardized tests need to be developed.
Power line communication was shown to interact with connected devices in several ways. However, from the viewpoint of a connected appliance, a signal can be considered as a disturbance regardless of if the origin is a communication device or a noncommunication device.

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BIOGRAPHY

Sarah Rönnberg received the Licentiate degree and PhD degree from Luleå University of technology, Skellefteå, Sweden in 2011 and 2013 respectively. Currently she is working as a associate senior lecturer in electric power engineering at the same university. Her main research contributions are in the study of emission in the frequency range 2 to 150 kHz and in understanding the interaction between power-line communication and end-user equipment in this frequency range.

Math Bollen received the MSc and PhD degrees from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1985 and 1989, respectively. Currently, he is professor in electric power engineering at Luleå University of Technology, Skellefteå, Sweden and R&D manager power systems at STRI AB, Gothenburg, Sweden. Earlier he has among others been a lecturer at the University of Manchester Institute of Science and Technology (UMIST), Manchester, U.K., professor in electric power systems at Chalmers University of Technology, Gothenburg, Sweden and technical expect at the Energy Markets Inspectorate, Eskilstuna, Sweden. He has published a few hundred papers including a number of fundamental papers on voltage dip analysis, two textbooks on power quality, “understanding power quality problems” and “signal processing of power quality disturbances”, and two textbooks on the future power system: “integration of distributed generation in the power system” and “the smart grid - adapting the power system to new challenges”.

Anders Larsson received the Licentiate and Ph.D. degrees from Luleå University of Technology, Skellefteå, Sweden in 2006 and 2011, respectively. Currently he is a Senior lecture at the same university. During his employment at Luleå University of Technology, since 2000, the main focus has been on research on power quality and EMC issues. During this time he has made significant contributions to the knowledge on waveform distortion in the frequency range 2 to 150 kHz. At the moment his research is focused towards lighting installations and power quality issues. Anders is an active member of two IEC working groups with the task to bring forward a new set of standards regarding the frequency range between 2 and 150 kHz. At the moment he is also involved in teaching and managing a B.Sc. program in electric power engineering.

Martin Lundmark received the MSc. degree from the Royal Institute of Technology, Stockholm, Sweden, 1989 and the PhD degree from Luleå University of Technology, Sweden, in 2009. Before joining Luleå University of Technology in 1992 as a Lecturer, he was a Research Engineer with ABB Corporate Research, Västerås. He has been involved in research on supraharmonics for some 30 years, long before they were known under that name.

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