Acoustic Noise of Massmarket Equipment caused by Supraharmonics in the Frequency Range 2 to 20 kHz

Paul Martin Körner
Robert Stiegler
Jan Meyer
Institute of Electrical Power Systems and High Voltage Engineering
Technische Universitaet Dresden
Dresden, Germany

Thomas Wohlfahrt
Christian Waniek
Johanna M.A. Myrzik
Institute of Energy Systems, Energy Efficiency and Energy Economics
TU Dortmund University
Dortmund, Germany

***Abstract*—Supraharmonic emission in the frequency range 2 kHz to 150 kHz is growing since more and more electronic mass-market devices are equipped with energy efficient self-controlled switching topologies. Since the audible range up to 20 kHz is covered by supraharmonic emission, it raises the question if these devices are producing considerable disturbing noises. This paper gives an overview of the sound generation mechanism in electronic devices. The impact of supraharmonics on the noise emission of household equipment is studied by a measurement survey with 103 devices.**

***Index Terms*—voltage harmonics, supraharmonics, acoustic emission, power quality, measurements**

I. INTRODUCTION

In order to increase energy efficiency, electronic mass-market equipment, like switch mode power supplies or energy saving lamps, are equipped with circuit topologies with switching frequencies well above 2 kHz. This leads to an increase of the supraharmonic emission, which results in an increase of the supraharmonic voltages in the networks. The increase of supraharmonic voltages may result in an increase in the audible noise produce by the electronic devices, [1]. The switching frequency of many high-power devices is in the audible range which could cause disturbing noises, e.g. industrial rectifiers [1], electric vehicles [2] or large PV inverters [3].

The compatibility levels for the audible frequency range from 2 kHz to 20 kHz are under discussion and an amendment for IEC 61000-2-2 is expected to be published in 2018, where compatibility levels of up to 1,4 % (3.2 V) for non-intentional emission are defined. For mains signalling (intentional emission) EN 50160 defines levels up to 5 % (11.5 V) in the frequency range from 1 kHz to 9 kHz [4]. Immunity test levels for public networks are provided in IEC 61000-4-19 and amount up to 12 V [5]. However, up to now no surveys on the effect of such supraharmonic voltage magnitudes on the acoustic noise emission of devices are available. This paper provides a first overview on this topic.

The paper starts with an overview of the principles of the generation of acoustic noises in components of household devices. In the second part, a measurement framework for the measurement of audible noise is presented and validated with measurements of a capacitor. Finally, the results of the measurements of 103 mass-market equipment are presented, followed with a detailed description of the measurement results from the loudest device.

II. THEORETICAL BACKGROUND

The main reason of the generation of acoustic noise by electronic appliances is the interaction between their electronic components, such as coils and capacitors. Different effects can cause mechanical forces, which can lead to mechanical oscillations. In combination with other parameters such as the size of the oscillating surface or the transmission path to other parts with the ability of vibration, this could lead to noticeable noise.

It is possible to specify more than six effects that can cause acoustic noise by high frequency emission, which can be grouped according to the affected element, i.e. capacitors or coils (Fig. 1). In electric fields, especially in capacitors, the electrostatic principle based on the electrostatic force, electrostriction and the inverse piezoelectric effect are the main effects. In magnetic fields magnetostriction as well as the electromagnetic principle and the magnetodynamic principle

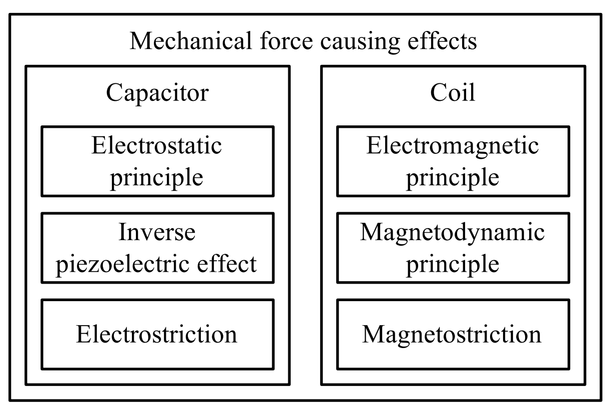

Figure 1.: Overview of mechanical force causing effects

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are the most significant effects. All these effects have been evaluated mainly for wanted sound generation e.g. for speakers, but they can be considered as unwanted sound sources too.

A. Capacitor

As shown in different studies, capacitors can cause sound emission mainly based on three effects: The inverse piezoelectric effect, electrostriction ([6], [7]) and the electrostatic principle.

- The inverse piezoelectric effect mainly occurs in the dielectric material of ceramic capacitors. It is based on its ability to cause an electric charge by strain. Inversing a charge can stimulate create a gradient in the electric field which polarizes the outer atoms in crystal structure
- Electrostriction also occurs in dielectric material by gradient electric field strength. It causes a shift of positive ions in electric field direction and negative ions in opposite direction. This creates a strain in field direction quadratic to its strength with the excited frequency.
- The electrostatic principle is based on Coulomb's law. The electric field between the electrodes will cause an electrostatic force on the electrodes. When the dielectric material is compressible, this will result in a mechanical movement.

It is expected that a capacitor will oscillate with the injected supraharmonic emission frequency or its double frequency at a level that depends on the level of the effect.

B. Coils

The other component producing acoustic noises are coils used in transformers or filter inductances. Magnetostriction, the electromagnetic principle and the magnetodynamic principle are the most relevant noise-producing effects [8].

- Magnetostriction is caused in ferromagnetic materials by oscillating magnetic fields. It can excite a spin-orbit coupling, so the poles of the Weiß domains are continuously changing. This leads to a variation of the length of the material about 10 µm/m [9] with single or double excited frequency, based on Faraday law [10]. This effect is mainly known as humming of transformers with the double mains frequency.
- The effect of the magnetodynamic principle is based on Lorentz force which produces an oscillation of the core windings by changing electric power. The strength of the oscillation mainly depends on the impedance of windings and the mechanical attenuation. The magnetodynamic principle just takes effect in weak attached windings
- The electromagnetic principle occurs in the core of coils with small air gaps. The gap leads to a variation of magnetic resistance, which causes a Maxwell force proportion to the quadratic of the magnetic flux.

Summarizing, coils mainly oscillate by magnetostriction with the single and double of the excitation frequency. As a result of inadequate attachment of windings or small air gaps in the core, oscillation proportion to the winding current or even odd harmonic oscillation is possible [12].

III. Measurement Framework

A. Measurement setup

To measure the sound emission of mass-market equipment, a specific setup was developed. The scheme of the setup is shown in Fig. 2. To avoid the influence of additional noise disturbances generated from the measure system (e.g. fan), the device under test (DUT) is placed together with the sensors in a separate measurement room. The waveform consisting of the fundamental voltage with 50 Hz and the frequency variable supraharmonic component is generated with an analog-digital-converter and amplified with a power amplifier. With a maximum output power of 1.4 kVA, the amplifier is able to power most of the common household devices. A transient recorder measures the voltage and the current at the DUT, and the voltage output of a calibrated condenser microphone for the sound measurement. The transient recorder performs also an A-weighting on the measured acoustic pressure for adaption on the sensitivity of the human hearing sensation range [11]. The A-weighting damps the amplitude at lower and higher frequency ranges which reflects the frequency dependent sensitivity of human hearing. The transient recorder is triggered from the computer when a stable output voltage is applied. Afterward, the recorded data is transferred to the computer for evaluation.

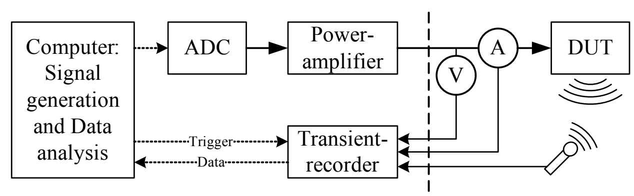

Figure 2.: Scheme of measurement setup

The measured data is processed in three different indexes:

- Acoustic pressure in Pa
- Sound pressure level (SPL) in dB
- Continuous noise level in dB

The acoustic pressure is the local pressure deviation from the ambient atmospheric pressure, caused by a sound wave. The sound pressure level (SPL) is a logarithmic measure of the effective pressure relative to a reference value (20 µPa, typical sound pressure reference in air). The continuous noise level is the average of the measured over long time intervals. The continuous noise level is used for the rating of non-continuous noise emission over long measurement intervals.

The microphone was placed at 50 cm distance of the DUT as a representative position of the users to the equipment. Since the laboratory is not a low-reflection acoustic measurement room, it is possible that the loudness for some frequency ranges depend on the position, because of the sound reflection at the walls and the formation of room modes. Measurements at seven positions around the main microphone show that this phenomenon is present in the laboratory, but it is mostly relevant in the frequency range up to 500 Hz. Since the supraharmonic frequency range is beginning at 2 kHz the influence of the reflections are negligibly for the studied acoustic emission measurements.

For processing a high amount of household devices, two measurements where applied: A continuous and a discrete frequency sweep with constant amplitude, added to the fundamental voltage. In the first step, a quick overview of the sensitivity of the DUT is obtained with the continuous frequency sweep. The discrete sweep was used in the second step on devices with noticeable noise emissions as a more accurate method to quantify the noise emission. It considers the transient oscillation of the system as well as a more accurate analysis of the electric input signal and the resulting sound. For sound emitting equipment in disturbing audible range also a discrete amplitude sweep at a constant frequency was made.

A fundamental voltage with 230 V and 50 Hz was chosen as reference. Supraharmonic voltages with frequencies between 0.5 and 20 kHz were added to the reference signal. The limit of 20 kHz is chosen because the human ear cannot recognize sounds above that frequency. The voltage magnitude range of the supraharmonic was set from zero to five volts, mainly based on empirical values from measurements in distribution networks [1]. For the sweep measurements a value of 2 V is chosen. This is in the range of non-intentional emission limits and much smaller than intentional emission limits as stated in section I. Higher values could cause thermal stress and damages to the equipment.

B. *Validation of measurement setup*

The acoustic noise of a 6.8 µF capacitor mounted in a vibratory housing was measured for validation of the measurement setup. The continuous sweep measurement was performed with a 10 second sweep. The measured sound pressure is analyzed with a FFT with a window size of 100 ms. Since the signal is not stable in the FFT-window, this kind of analysis is not very accurate in the amplitude, but gives a first quick impression of the behavior of the DUT. The result was converted into sound pressure levels (SPL), which can be presented in a spectrogram (Fig. 3).

A linear relation of the applied supraharmonic frequency and the measured sound frequency is clearly visible in the spectrogram of the continuous sweep. The frequency of the measured sound and the applied supraharmonic frequency is the same. The sound pressure level varies with frequency. The highest sound pressure levels can be observed in the frequency range between 8 kHz and 14 kHz.

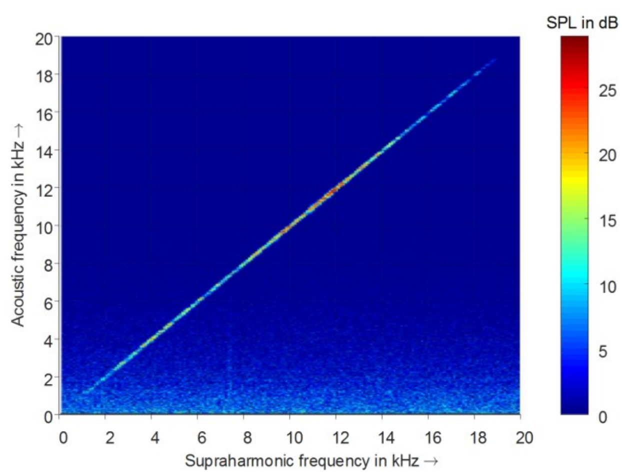

Figure 3.: Continuous sweep result for test capacitor

For equipment with significant acoustic noise in disturbing audible range (values above 20 dB) the discrete sweep is performed. The discrete sweep of the supraharmonic component is performed in 500 Hz steps. The sound pressure was measured for 1 second. This leads to a spectrogram with low noise and exact sound pressure level values (Fig. 4). Another useful representation of the discrete sweep is the peak-hold diagram. The peak-hold diagram presents the maximum of the acoustic pressure and the sound pressure level for each frequency occurred in the discrete sweep (Fig. 5). This figure shows clearly the amplitude of the acoustic frequency as well as the spectrum of them. The capacitor produces a sound pressure level up to 34 dB with a bandwidth of 400 to 1000 Hz. The widespread spectrum around the stimulated supraharmonic frequency is the result of the modulation of the sound with the 50 Hz fundamental.

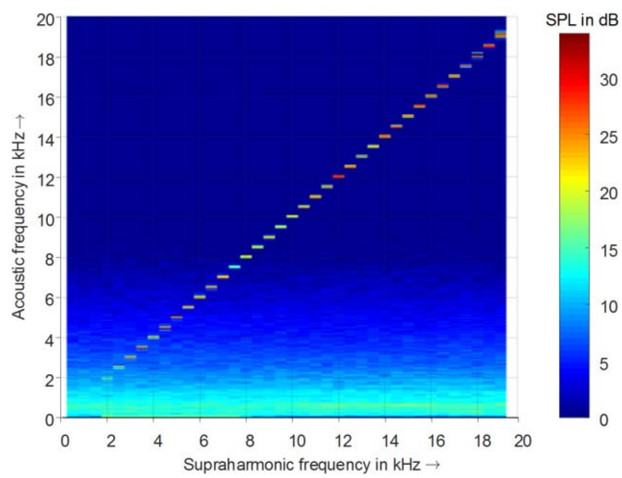

Figure 4.: Discrete sweep result for test capacitor

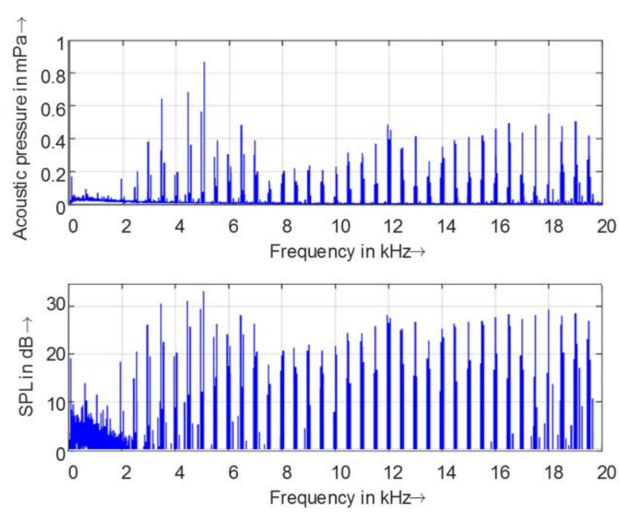

Figure 5.: Peak-hold diagram of discrete sweep

To analyze the influence of the supraharmonic amplitude on the loudness, a discrete amplitude sweep with a fixed frequency is performed. The amplitude of a supraharmonic component at 8 kHz is swept from 0 V to 5 V. Fig. 6 shows the continuous noise level and Fig. 7 the spectrogram of the sound pressure level dependent on the amplitude of the supraharmonic component. It shows a significant rising of the continuous noise level up 38 dB at 5 V supraharmonic amplitude. It shall be noted, that continuous noise level is the overall noise level including all frequencies. With rising supraharmonic voltage the additional noise of the capacitor is dominating the background noise (about 33 dB), and the noise level is increasing linearly.

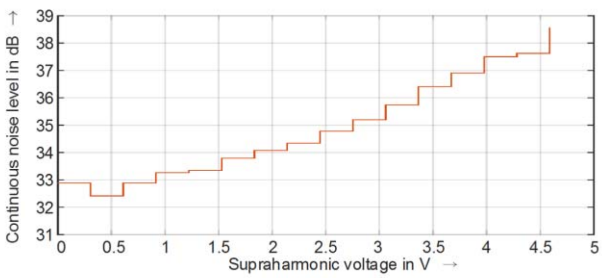

Figure 6.: Continuous noise level of discrete amplitude sweep

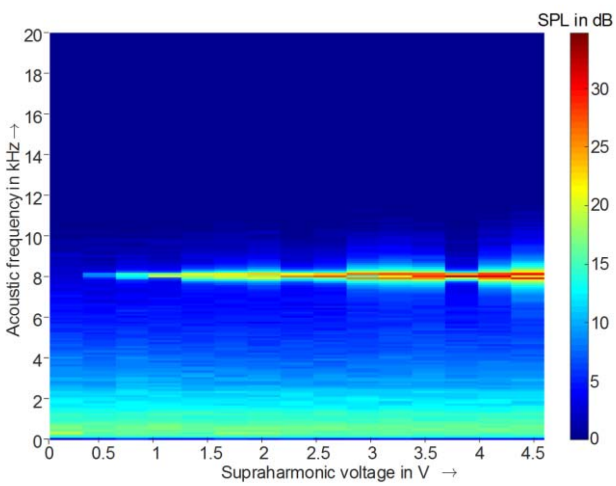

Figure 7.: Spectrogram of discrete amplitude sweep

IV. OVERVIEW OF SURVEY RESULTS

The main goal of the measurement survey is to give an overview of the acoustic noise produced by mass-market equipment when supraharmonic voltages are applied. Because of limits within the measurement setup, equipment with rated power above 1.4 kW could not be tested. Furthermore, all self-generating acoustic noise equipment (e.g. vacuum cleaner) were not tested, as the inherent noise will hide the additional noise caused by supraharmonics. The acoustic response on continuous sweep was measured for 103 different devices and, where applicable, at different operating states (standby/on/off). The devices were divided into seven groups based on usage and technical specifications:

- Audio and video devices (AV)
- LED lamps
- Compact fluorescent lamps (CFL)
- Open power supply units (open PSU, i.e. without closed case like the power supplies used in desktop computers)
- Closed PSUs (power supplies with close cases, like battery chargers)
- Kitchen devices
- and other devices.

An algorithm was implemented to identify the maximum sound emission caused by supraharmonics. It is based on the theory of sound generation, which indicates that mainly acoustic frequencies with integer multiples of the supraharmonic frequency are emitted. In a frequency range from 2 to 20 kHz the continuous sweep response is scanned to find the peaks which are multiples of the applied supraharmonic frequency. To avoid detecting ambient noise, the neighboring spectral components of every peak are analyzed. If a significant maximum can be found, it is assumed that this is a sound generated by the injected supraharmonic. Fig. 8 shows all occurring maximum sound pressure level and its median for all measured devices sorted into device groups.

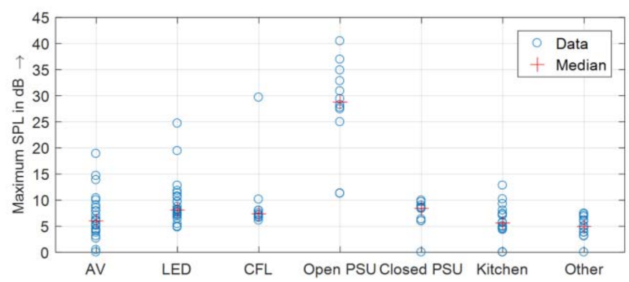

Figure 8.: Maximum sound pressure level of all measured household devices

The majority of equipment have sound emission below 10 dB which is not disturbing. In some cases, emission from 10 to 20 dB can be disturbing for humans, depending on the environment. For example, in a very quiet environment (e.g. bedroom during the night) the human sensitivity for noise is higher. This is relevant for some audio and video devices, as well as LEDs. Emissions above 20 dB are almost always recognized and can be strongly disturbing. Fig. 9 shows the

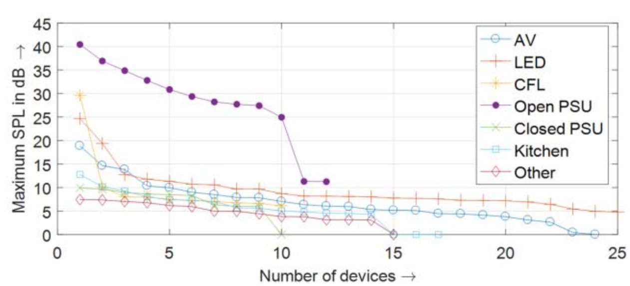

Figure 9.: Sorted maximum sound pressure level of all measured household devices

maximum sound pressure level sorted in descending order. One of the measured compact fluorescent lamp (CFL) and one LED-Lamp produce significant disturbing noise.

Noticeable noise was also measured at open PSUs: ten of twelve measured units have disturbing noise emission resulting from supraharmonic voltages. This result can be explained by the design of the open PSUs. In the first place, the case of open PSUs cannot damp all the noise, because the power supply units have big vents and at least a part of the PSU is usually not covered by the case at all. Actually, the case could increase the radiated noise, since it has big surfaces which can radiate noise generated by the body itself. Secondly, open PSUs have a big circuit board that can radiate the mechanical oscillations. In comparison, closed PSUs have smaller circuit boards and a compact housing as sound barrier, which results in lower noise emission.

V. SELECTED RESULTS IN DETAIL

The highest emissions were seen in the open power supply units. The results of the device with the highest emission are shown in detail below, were also different operating modes of the PSU have been considered. Beside sound pressure level peaks, the frequency response also varies depending on the operating mode. In Fig. 10 and Fig. 11 two measurements of an open power supply unit in the operating modes standby and idle are shown. Operation mode standby means that the power supply unit is switched off, and operation mode idle means that it is switched on but without load.

The operating mode of the device has a significant influence on the sound emission caused by supraharmonics. Also, the bandwidth of high frequency sound varies. In the operation mode idle the device oscillates in audible range with single, double and triple of the excited frequency. It is difficult to clarify whether the second or the triple of the excited frequency is caused by the basic effects of sound generation or by the harmonics of the oscillation (e.g. rattling). The peak hold diagram of operation mode idle shows a similar bandwidth of high frequency levels like the validation measurement (Fig. 13).

The high sound pressure level values of open power supply unit cannot only be explained by the open case, which causes a high potential of sound transmission from structure-borne sound to audible noise. The circuit has a high potential for oscillation, especially due to the grid-side filters with filter capacitors and reactors. The analysis of the voltage and current

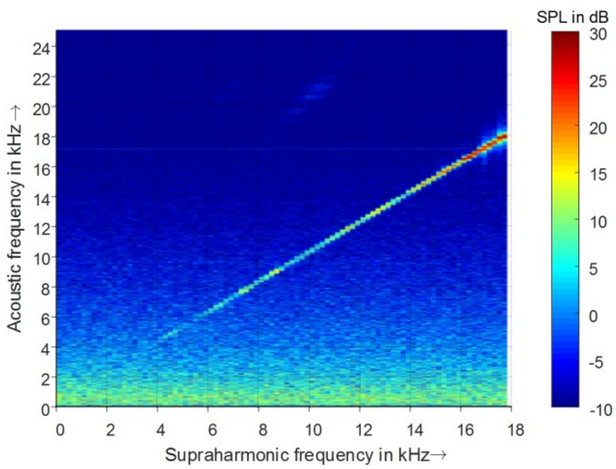

Figure 10.: Continuous sweep result for open casing power supply in standby operation mode

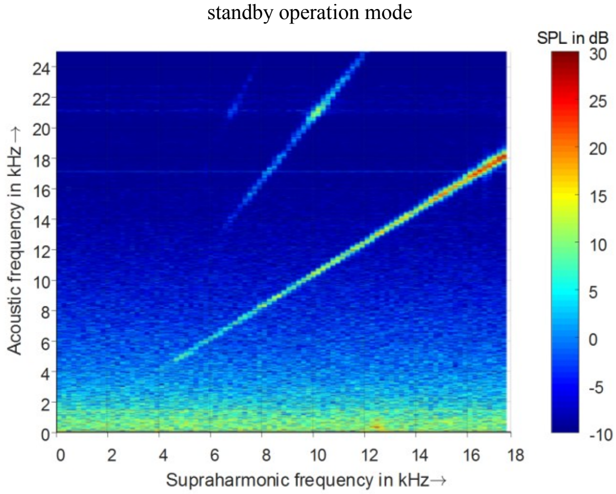

Figure 11.: Continuous sweep result for open case power supply in idle operation mode

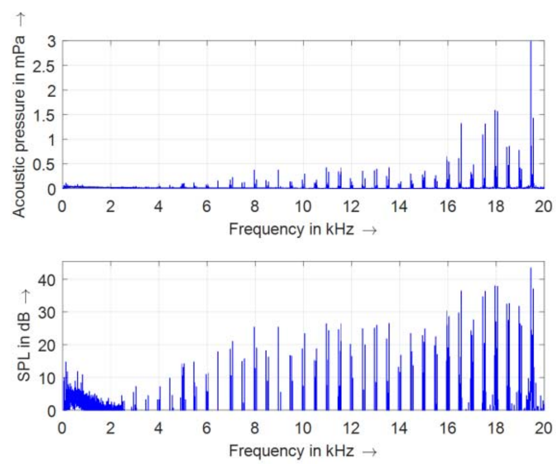

Figure 12.: Peak-hold diagram of standby operation mode

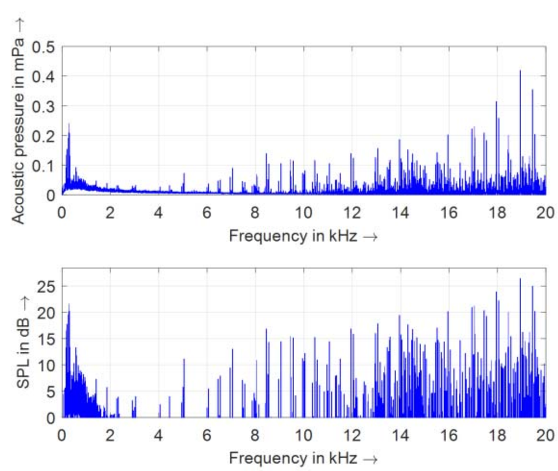

Figure 13.: Peak-hold diagram of idle operation mode

in operation mode standby shows a phase angle between voltage and current supraharmonic of 89.4°, which confirms the theory of an oscillating filter capacity, as in the validation measurement. During idle operation mode, a phase angle of 16° was measured and the peak-hold diagram shows a broadband frequency distribution (Fig. 13), especially in frequency range from 8 to 20 kHz. In the operation status “on” the DC-link capacitor is powered as well as following coils. Consequently, more parts with an oscillation potential are affected by the supraharmonic voltage. It is noticeable, that the power supply unit emits more noise in standby mode than in idle mode caused by the supraharmonic voltages.

The detailed results show that the spread of structure-borne sound has many influencing factors. The oscillating component is based on operation status and power distribution inside the device. This is important for defining the sound-emission-potential of mass-market equipment as well as preventing it.

VI. Conclusions

This paper provides a first overview of the acoustic noise emission of household devices caused by supraharmonic voltages. Sources for mechanical oscillations like capacitors, coils or transformers exists in nearly all modern household devices, and as seen in the measurements nearly all devices are emitting noise caused by supraharmonics. If this noise is reaching a disturbing level depends strongly on the design of the device. Mechanical oscillations are transmitted to big surfaces, where the oscillations radiate as noise to the environment. Also barriers can reduce or increase the noise emission, depending on their design characteristic.

Aside of the design aspects of the devices, compatibility levels as well as immunity levels should not only be discussed based on the electrical emission of the devices but also on the emission of noise.

Next steps in further studies will be the measurement of the noise emission with higher supraharmonic voltages in the range of the immunity levels. This measurements were postponed until other measurements at the household devices were finished, since a realistic chance is given to cause thermal stress and damages to the devices.

VII. References

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