IMMUNITY ASSESSMENT OF HOUSEHOLD APPLIANCES IN THE FREQUENCY RANGE FROM 2 TO 150 KHZ

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ABSTRACT

Advances in power electronics, increasing share of renewables in the energy system and e-mobility cause an increase of disturbances in the frequency range from 2 to 150 kHz, also known as supraharmonics. This emission usually does not propagate very far, but can disturb other end user equipment, which can result in short-term effects (equipment malfunctions, audible noise or light flicker) as well as long-term effects (lifetime reduction due to additional thermal stress). This paper summarizes the results of a comprehensive immunity assessment of more than fifty household appliances with respect to the above mentioned disturbance effects. The results shall serve as a contribution to the ongoing standardization activities in the frequency range 2-150 kHz.

INTRODUCTION

The increasing use of renewables and electric vehicle chargers as well as the continuous rise of energy efficiency in modern mass-market appliances have an impact on Power Quality in the electrical network. In addition to classical harmonic distortion, increasing challenges for both end users and network operators are observed with disturbances in the frequency range 2-150 kHz, which is also referred to as supraharmonics [1]. There is an increasing interest in supraharmonic emission from the research community, but also from Electromangnetic Compatibility (EMC) standardization.

Immunity limits have been published some years ago in IEC 61000-4-19 [2]. The standard distinguishes different immunity classes, but it is not fully clear, which one applies to household appliances. Moreover the application of immunity tests by manufacturers is in general voluntary and the status of implementation of IEC 61000-4-19 by manufacturers is not clear. In addition, the majority of existing household appliances has been developed before IEC 61000-4-19 was published and their immunity against disturbances in the frequency range 2-150 kHz is not known.

Modern household devices tend to be sensitive to supraharmonic emission. A number of malfunctions in form of audible noise, visual interferences, and deviation from correct functionality have been observed [3]. Former research has also shown that supraharmonics cause additional thermal stress for the built-in components and can reduce the expected lifetime of electrical appliances [4]. Reliable knowledge about the immunity of household devices is important for the further development of respective EMC standards, but comprehensive and systematic studies on this topic virtually do not exist.

This paper follows a series of previous research of the authors about grid compatibility in terms of supraharmonics [3]-[6] and aims to analyze the immunity of modern electrical appliances. Only differential mode disturbances, which are the typical source characteristic today, are considered in this paper. Using a laboratory setup, a set of more than fifty household devices from the mass-market segment was examined using the test procedure according to the standard IEC 61000-4-19. Both, the perceptible short-term effects as well as the long-term effect of supraharmonics on the lifetime reduction are considered.

The paper starts with a present status of standardization in the supraharmonic range and provides some theoretical background on the disturbance effects. Next, the measurement setup and procedure for immunity assessment are introduced. Afterwards, the results are summarized and discussed separately for short-term and long-term effects. Finally, conclusions and recommendations are provided.

STATE OF THE ART

Standardization

Compatibility levels for public low voltage network have been recently published in IEC 61000-2-2. As the proper operation of mains communicating systems (MCS, e.g. Power Line Communication) requires a certain signal-to-noise ratio, compatibility levels are defined for intentional emission (MCS-systems) as well as for non-intentional emission (non-communicating equipment).

Non-intentional emission limits exist only for a few types of appliances and only for frequencies above 9 kHz. Emission limits for non-intentional emission exist at present only for a small number of selected devices, namely for induction cookers (EN 55011) and energy efficient lamps (EN 55015). A joint IEC SC77A/CISPR working group is presently working on the extension of the emission limits above 9 kHz to other equipment, IEC SC77A WG1 is working on emission limits between 2 and 9 kHz. Intentional emission limits for MCS can be found for Europe in EN 50065.

Regarding immunity to differential mode disturbances, limits are defined in IEC 61000-4-19. Depending on the environment, four different test levels are proposed. Household devices belong, in the opinion of the authors, to “typical residential, commercial and light industrial appliances”, which corresponds to Class 3. It should be noted that also Class 2 mentions residential environment, which is somewhat ambigous and should be clarified in further revisions of the standard. For this paper all tests are performed using the test levels of Class 3.

Effects of supraharmonic emission

For the purposes of this paper, the effects of supraharmonic emission are grouped in two categories: short-term effects and long-term effects.

Short-term effects are perceived by end-users as an unintentional deviation (malfunction) of appliance operation. These malfunctions can be grouped into three categories: visual interference (flicker, image distortion), audible noise (excitation of mechanical resonances up to 20 kHz) and operational malfunctions (misconfiguration, unexpected results from programed tasks). Previous works reported perceptible malfunction of some household appliances when exposed to voltage disturbances between 2-150 kHz [1], [7].

*Long-term effect*s are perceived as additional thermal stress for the built-in circuit components. The supraharmonics involve additional power consumption, which is followed by the increase of operating temperature. This is a big challenge for the electrolytic capacitor, whose lifetime is expected to decrease to the half in case of 10 K temperature rise [8].

Reference [6] describes the different heating mechanisms of the electrolytic capacitor in detail. The thermal interaction between different circuit elements affect the ambient temperature of the electrolytic capacitor and thermal stress are mainly determined by the housing of a device.

MEASUREMENT FRAMEWORK

The immunity study is based on a set of 240 modern household devices available in the mass-market segment,which has been selected taking the annual market share survey conducted by the German Federal Statistical Office (2014) as well as different price segments and popularity rankings into account.

The layout of the laboratory setup for the immunity assessment is shown in Fig. 1. For safety reasons and in order to ensure constant and reproducible environmental conditions, the Equipment Under Test (EUT) is placed in a special measurement box.

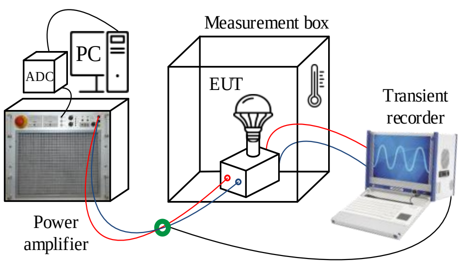

Figure 1 Scheme of measurement setup

The voltage signal with supraharmonic components is generated with an analog-digital converter (ADC) and amplified by a wide-band power amplifier. A transient recorder measures the voltage and the current of the EUT with a sample rate of 1 MHz as well as the voltage output of thermocouples during the temperature measurement. The recorded data is transferred to a computer for further evaluation by MATLAB.

Short-term effects

To provide a comprehensive selection of appliances, the available household devices were classified into six categories according to their main functionality from end-user perspective:

1. Audio/ Video: LCDs, TVs, Game Consoles, DVD-players, Stereos.
2. Heating: Microwaves, Stoves.
3. Lighting: Light Emitting Diode (LED) lamps, Compact Fluorescent Lamps (CFLs).
4. Motor Drives: Hairdryers, Cleaners, Blenders, etc.
5. Power Supplies and Battery Chargers
6. Others: Radio Alarm, Multifunction printers.

At least two devices were taken from each group in order to represent different price segments, rated powers and functionality features. In total, fifty-five appliances were selected for the immunity assessment.

Following IEC 61000-4-19, two types of test signals are used: continuous wave and rectangular pulsed wave. The supraharmonics were superimposed to the signal at main frequency. Two complementary approaches are used to define spectrum and magnitude of the supraharmonic signal content: single frequency emission as defined in IEC 61000-4-19 and multiple frequency emission (emission bands). The RMS voltage of a single frequency emission corresponds to the test level in IEC 61000-4-19. An emission band consists of five regularly spaced single frequency emissions with similar amplitude. The RMS voltage of the emission band also corresponds to the test level according to IEC 61000-4-19.

Frequency sweeps with thirty mainly logarithmical distributed frequencies are performed after a stabilization time and a “base case” measurement of the EUT, which represents a reference case before the immunity tests. Supraharmonic voltages applied to EUT are continuously monitored in order to compensate any deviation from the required amplitudes. Finally, malfunctions are reported as discrete events together with the specific frequency or frequency band of the occurrence.

Long-term effects

Additional thermal stress is most critical for compact devices without active cooling and long operating times. Therefore, the following categories are considered for device selection with regard to long-term assessment:

A. Retrofit lamps with electronic ballast,
B. Micro USB chargers,
C. Laptop portable chargers.

Based on a preliminary analysis, twenty out of the fifty-five devices were selected for long-term analysis. This set of EUT consists of devices with different circuit layouts (various types of Power Factor Correction (PFC) and filter circuits), housing design and rated power.

For temperature measurements, the EUT has been carefully disassembled, equipped with thermocouples and reassembled in order to ensure the initial thermal conditions.

As found in [6], the operating temperature increase is linked to the nonfundamental (supraharmonic) active power losses of a device. Therefore, the long-term effect for each EUT is tested at the frequency of maximal active power consumption.

Since the active power losses depend on the applied voltage level, two complementary approaches are applied to identify the frequencies, which determine the worst case (highest thermal stress of the electrolytic capacitor) for the EUT. Firstly, the EUT is tested with a discrete frequency sweep with supraharmonic amplitudes according to IEC 61000-4-19 Class 3. Second, the EUT is tested with a discrete frequency sweep with constant supraharmonics amplitude of 2.4 V, which corresponds to the minimal test voltage level of Class 3. For both approaches the frequency with the largest active power losses is identified, which determines the worst-case for the EUT and is used for the immunity test.

The final value of temperature increase is calculated using curve fitting based on measurement duration of 3τ. Time constant τ has been individually determined for each EUT [6]. The measurement reproducibility is assured by repeating the measurements between 3 and 5 times. The uncertainty of the temperature measurements has been determined, being less than 0.2 K.

MEASUREMENT RESULTS

Short-term effects

The results have shown that more than half of tested EUT presents malfunctions, which are perceptible by end-users. No operational malfunction (misconfiguration or unexpected results from programmed tasks) was perceived in this assessment. Devices from category "Motor Drives" did not show any short-term effects and seem to be immune to IEC 61000-4-19 Class 3 test levels.

According to Fig. 2, almost a half of EUT produces an audible noise and five EUT have flicker issues. Mostly, flicker appears together with audible noise. Only one EUT produces flicker without audible noise.

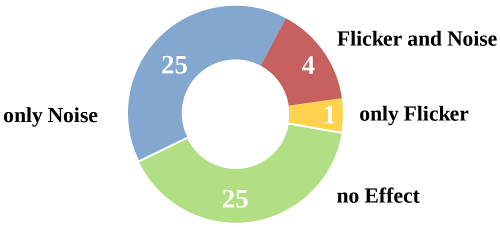

Figure 2 Result of immunity assessment

Since malfunctions were perceived at many different frequencies, results are grouped into four frequency ranges: 2-9 kHz, 9-20 kHz, 20-95 kHz and 95-150 kHz. No interferences have been observed in the last frequency range (95-150 kHz). Due to the characteristic of the human ear, audible noise recognition is limited to the first two frequency ranges.

Audible noise was assessed with both continuous and pulsed test signals. Some of the EUT does not produce an audible noise in case of emission bands. For most of the device categories, audible noise was perceived in both, 2-9 kHz and 9-20 kHz frequency range.

Since lighting equipment were the most affected in the assessment, their immunity characteristics are analysed in more detail. Therefore, the results of lamp assessment are classified into additional three groups, based on their circuit layout, which has been derived from the current waveform characteristics. Devices with active PFC, without PFC and capacitive divider are distinguished. Table I shows the amount of lighting devices with audible noise and flicker issues within each frequency band.

Table I Immunity assessment of lighting equipment

frequency range	2-9 kHz		9-20 kHz		20-95 kHz
	Noise	Flicker	Noise	Flicker	Flicker
aPFC	2/2	2/2	2/2	2/2	0/2
cap. divider	1/2	2/2	0/2	2/2	2/2
no PFC	3/3	0/3	2/3	0/3	0/3

As it is shown in Table I, in the frequency band 2-9 kHz an audible noise is perceived from all lamps except of some with capacitive divider as power supply. The situation is slightly different in the frequency range 9-20 kHz, where the amount of lamps with no PFC topology reported with audible noise decreases and audible noise was not observed in case of the lamps with capacitive divider.

Flicker issues occur in all three frequency ranges from 2 to 95 kHz. Lamps with active PFC topology have flicker issues only in the first two frequency ranges between 2 and 20 kHz when exposed to continuous test signals and single frequency emission. This suggests that the selected samples are more affected by single, high amplitude emission. Lamps with capacitive power supply are affected in all frequency ranges using pulsed test signals, both in case of single emission and emission bands. A rectangular modulation of rectified current results in a visible variation in current, which supplies the LED strings. The selected lamps without PFC do not show any flicker.

In order to understand the differences between results from lighting equipment, a closer analysis of input impedances in frequency domain is carried out. Fig. 3 to 5 show at which frequency ranges audible noise and flicker were detected. For reproducibility purposes, audible noise was recognized up to 18 kHz. For lamps with active PFC malfunctions were observed in the first region of minimum impedance magnitude (series resonance) located at

frequencies below the region of first impedance maximum magnitude (parallel resonance).
The resulting increase in current for low impedance magnitude might excite mechanical resonances in coils and higher currents in boost converter used as active PFC. This could cause audible noise and flicker occurring more or less together. Nevertheless, malfunctions were not perceived above 50 kHz where the impedance magnitude is also low. Although input impedance seems to influence the perceptible malfunction from selected EUT, further research is required in order to accurately determine the root causes of short-term malfunction between 2-150 kHz.

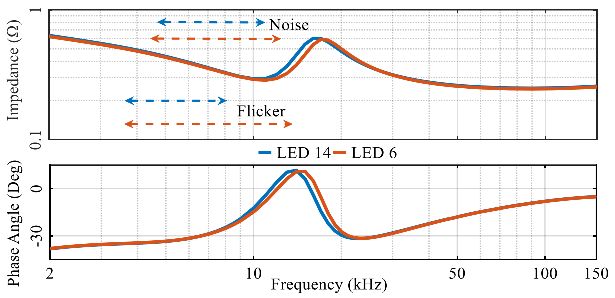

Figure 3 Impedance characteristic of a device with active PFC

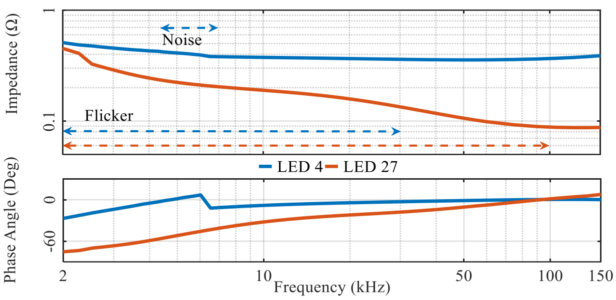

Figure 4 Impedance characteristic of a device with power supply based on capacitive divider

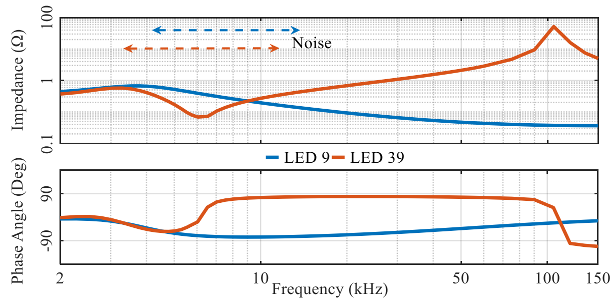

Figure 5 Impedance characteristic of a device without PFC

For lamps with capacitive divider based power supplies, flicker was perceived between 2-30 kHz and 2-100 kHz. This topology can also produce audible noise, because some devices with current waveform similar to capacitive topologies have additional inductors (e.g as part of the grid-side filter circuit), which can also produce mechanical resonances. This seems to be the case for one of the LED lamps shown in Fig. 4, where a very small change in impedance phase matches with the perceived audible noise.

Lamps without PFC have different input impedances compared to active PFC and capacitive divider based lamps. Audible noise was perceived above a frequency range with a maximum impedance magnitude. So again low impedance could result in higher currents, which excite mechanical resonances. However, again further research is needed to properly determine the root causes of short-term malfunction between 2-150 kHz.

Long-term effects

The result of the first test approach (test according to IEC 61000-4-19) is shown in Fig. 6. The ambient temperature has been kept constant at 20°C and equal for each EUT. The electrolytic capacitor can be exposed to additional temperature increase up to 8 K if exposed to supraharmonic voltage levels proposed for Class 3 in IEC 61000-4-19.

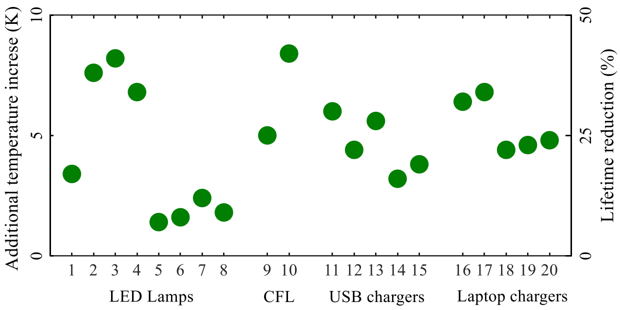

Figure 6 Additional temperature increase and lifetime reduction of EUT under test conditions of IEC 61000-4-19

Additional thermal stress leads to a lifetime reduction of the electrolytic capacitor and put it at the risk of damage. The effect of the temperature increase on the aging of the electrolytic capacitor is calculated. Lifetime L is assessed by the computation of temperature factor K_T that defines the multiplier for the capacitor rated lifetime L_0 at nominal ripple current and upper category temperature. This equation is based on the Arrhenius equation that specifies a lifetime decrease to the half by about 10 K temperature rise [8]:

$$K_T = 2^{-\frac{\Delta T}{10\,K}} \quad (1)$$

$$L = L_0 \cdot K_T \quad (2)$$

According to this model the additional thermal stress can result in a maximum expected lifetime reduction of 40% (permanent presence of single frequency supraharmonic distortion) compared to the undisturbed operation.
A relation between the additional thermal stress and the circuit layout can be drawn from the results of the second test approach (constant supraharmonic voltage level for all frequencies). The measurement results are presented in Fig. 7 as values of supraharmonic active power losses related to the rated power of considering EUT. As can be seen, the measured devices can be grouped into three categories. A closer analysis shows that EUT from each group have similar circuit topologies.

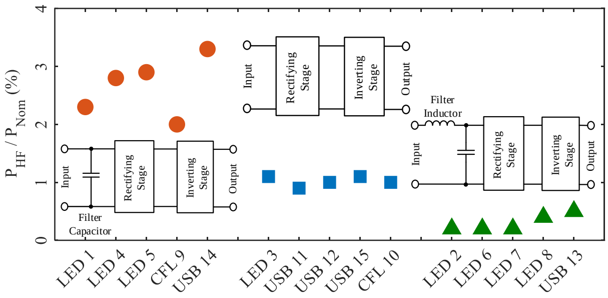

Figure 7 Relative active power losses of EUT caused by supraharmonic emission of 2.4V

Devices with the largest supraharmonic active power losses have usually a capacitive grid-side filter circuit (cf. red dots in Fig. 7). The smallest supraharmonic active power consumption is observed for devices with series inductive elements (cf. green triangles in Fig. 7). Since the additional thermal stress is closely linked to the supraharmonic active power consumption, the EUTs with capacitive elements directly connected to the supply voltage can be treated as most senstive concerning the impact of supraharmonic emission.

CONCLUSIONS

The paper summarizes the result of a comprehensive immunity assessment of modern household devices against distortion in the frequency range 2-150 kHz (supraharmonics). Regarding its impact, short-term effects (noticeable malfunctions) and long-term effects (lifetime reduction) are distinguished. The tests are based on the effective immunity standard IEC 61000-4-19 using test levels according to Class 3. A set of fifty-five representative devices has been tested for short-term effects, twenty devices for long-term effects.

The results show that a considerable share of devices is sensitive to supraharmonic test levels. Most common short-term effects are audible noise at frequencies below 20 kHz and light flicker. The tested devices with motor drives (inductive behaviour) are not affected by supraharmonics. Single frequency emission results in more malfunction cases than emission bands with equal RMS value. The perceived malfunctions seem to be closely linked to the input impedance of the devices. This has been studied in detail for lighting devices, where the sensitivity varies significantly according to the design of grid-side filter circuit and driver topology.

With regard to long-term effects supraharmonic emission causes considerable additional thermal stress for the circuit elements, which can result in a significant lifetime reduction of the electrolytic capacitor and put a device at the risk of damage. Power electronic frontends with capacitive elements in the grid-side filter circuit directly connected to the supply voltage tend to be more affected in the presence of supraharmonic emission. Thermal impact on and interactions between the built-up components must be taken into account for the grid-side filter circuit design.

The results shall attract awareness of device manufacturers that the currently defined immunity limits can have a considerable impact on household appliances. The significant number of observed malfunctions suggests that the EMC coordination does not work properly yet for present household appliances. Besides re-thinking the test levels and class definition given in IEC 61000-4-19, a constructive discussion about additional requirements on the input impedance characteristic of devices in the frequency range 2-150 kHz should be started.

ACKNOWLEDGMENTS

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