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Adverse Impact of Harmonic and Interharmonic Supply Voltage Distortion on Mass-Market Electrical Appliances

VICTOR KHOKHLOV (Student Member, IEEE), FRIEDEMANN MÖLLER,
JAN MEYER (Senior Member, IEEE), AND
PETER SCHEGNER (Senior Member, IEEE)

Institute of Electrical Power Systems and High Voltage Engineering, TU Dresden, 01062 Dresden, Germany
CORRESPONDING AUTHOR: V. KHOKHLOV (victor.khokhlov@tu-dresden.de)

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ABSTRACT This article presents the results of the immunity evaluation of mass-market electrical appliances subjected to harmonic and interharmonic distortion of the supply voltage. Therefore, the immunity of twenty selected single-phase electrical appliances is evaluated within a comprehensive framework that considers perceptible malfunctions and long-term adverse impacts. Furthermore, a specially designed test procedure is employed to optimize the characterization of appliances with variable operating states and to ensure the reproducibility of results. In light of that, the feasibility of increasing compatibility levels for harmonics and interharmonics is discussed. The results shall serve as input for the ongoing discussion about appropriate compatibility levels in low voltage networks acceptable to all stakeholders.

INDEX TERMS Electromagnetic compatibility, immunity testing, household appliances, power system harmonics, power quality.

I. INTRODUCTION

THE coordination of electromagnetic compatibility (EMC) is based on the definition of compatibility levels, which serve as a reference for setting emission limits and immunity levels. The compatibility levels for harmonic distortion in industrial low and medium voltage networks are currently under revision by IEC SC77A WG8. One of the three environmental classes relates to the connection point to public networks. Consequently, any change in the levels should be reflected in the respective standard for public low voltage (LV) networks in the future.

An increase in compatibility levels allows, on the one hand, a relaxation of emission limits but, on the other, higher requirements on the immunity levels for connected electrical appliances. However, until now, only a few are known about the present immunity of electrical appliances. That results in high ambiguity in the ongoing discussion of the feasibility of the proposed revision.

This article contributes to this discussion by studying the immunity of mass-market electrical appliances. A set of twenty single-phase electrical appliances with high penetration in public LV networks is examined under laboratory conditions. Besides perceptible malfunction, a methodology for considering the adverse long-term impact, such as the additional thermal stress of built-in components, which is not addressed by the present standardization framework, is also considered.

Building on the framework introduced by the authors in their previous work [1], this article extends the analysis by studying the immunity of mass-market electrical appliances to interharmonic distortion. Furthermore, it investigates the feasibility of existing compatibility levels and recent proposals and introduces a method for representative testing of appliances with variable operating states.

The article starts with an overview of relevant standards and previous studies on the adverse impact of harmonics and interharmonics. Next, the evaluation framework introduces the measurement procedure and test appliances. Finally, the results are discussed in detail for one exemplary appliance and all test appliances in an aggregated way before the outcomes are summarized in conclusion.

II. STATE OF THE ART

A. STANDARDIZATION

The following subsection summarizes the present standardization status for harmonic and interharmonic distortion of the supply voltage in terms of compatibility levels, emission limits, immunity levels, and measurement methods.

1) COMPATIBILITY LEVELS

Compatibility levels for harmonics are defined in IEC 61000-2-2 [2] for public LV networks and in IEC 61000-2-4 [3] for industrial LV and MV networks. Both standards distinguish between the impacts of odd non-triplen, even, and odd triplen harmonics and provide more strict requirements for even and odd triplen harmonics, as shown in Fig. 1. This definition is based on the results of field surveys dating back several decades when of primary concern for the EMC coordination were odd non-triplen harmonics produced by electrical appliances containing line-commutating rectifiers.

Modern power electronic appliances, such as active infeed converters, have a different emission characteristic, not limited to odd non-triplen harmonics. They struggle to meet the strict requirements for even and odd triplen harmonics, i.e., due to a certain amplification effect around the resonance frequency of the low pass filter between the 13th and 40th harmonics [4].

Identified needs and related concerns regarding the immunity of mass-market appliances connected to the public LV network are discussed in the recent maintenance of IEC 61000-2-4 [3]. As a result, the internal working document 77A/1082A/DC [4] introduces four proposals (A, B1, B2, C) for modifying compatibility levels for individual even (above 2nd) and odd triplen (above 9th) harmonics without changing the limit for Total Harmonic Distortion (THD). The proposal from the manufacturers of industrial appliances (Proposal A) implies the highest increase in compatibility levels (Fig. 1) and is therefore considered in this study.

Compatibility levels for interharmonics focus on different interference mechanisms. Respective levels are specified for interharmonics below double the fundamental frequency to prevent the light flicker of incandescent lamps [2], [3]. For the protection of mains signaling, a compatibility level of 0.2% is defined for interharmonics close to the mains signaling frequency [2]. In any other case, it is suggested to apply the compatibility level of the next higher even harmonic order [2]. A recent proposal of compatibility for effective limitation of interharmonics considering their impact on LED lighting is provided as an informative annex to IEEE Standard 519 [5].

2) EMISSION LIMITS

Depending on the appliance input current, the harmonic emission limits for appliances are defined in the standards IEC 61000-3-2 [6] and IEC 61000-3-12 [7]. Interharmonic emission limits do not exist.

While emission limits for appliances with input current below 16 A are usually provided for individual harmonics up to the 40th order [6], emission limits for appliances with larger input current are only provided for odd harmonics up to the 13th order [7]. It is accompanied by limiting the Total Harmonic Current (THC), which includes all harmonics up to the 40th, and the Partially Weighted Harmonic Current (PWHC). While both indices are integral values reflecting a group of individual harmonics, the latter gives additional weight to the higher harmonics and considers the additional thermal stress of circuit components, which increases with harmonic order.

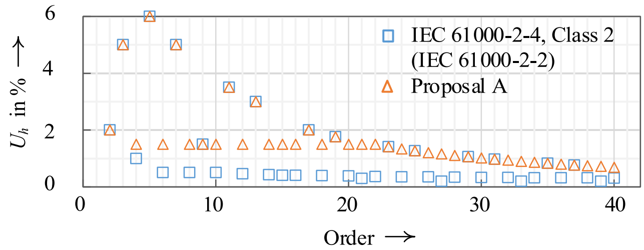


FIGURE 1. Existing and proposed compatibility levels.

3) IMMUNITY LEVELS

IEC 61000-4-13 [8] specifies immunity test levels for different environmental classes. For instance, Class 2 defines test levels for electrical appliances intended to be connected to public LV networks. The test procedure focuses on perceptible malfunctions and intentionally does not consider adverse long-term impacts, such as additional thermal stress. The standard includes test levels for selected individual harmonics, some harmonic mixes, and selected individual interharmonics. The interharmonic immunity levels are based on the levels of mains signaling in LV networks.

Concerning harmonics, at the relation between compatibility levels and respective test levels is usually equal to a factor of about 1.5. The article uses this relationship to define test levels for proposed compatibility levels.

4) MEASUREMENTS METHODS

Measurement techniques for harmonic and interharmonic distortion are introduced in IEC 61000-4-7 [9]. The standard contains specifications on measurement uncertainty and signal processing for instruments to measure harmonics and interharmonics and their evaluation. The measurements and analyses applied in this study are based on this standard.

B. ADVERSE IMPACT OF SUPPLY VOLTAGE DISTORTION

Although some literature exists on the immunity of electrical appliances, systematic and comprehensive studies on the immunity and thermal stress of present mass-market appliances are still lacking.

1) HARMONICS

In general, the adverse impacts of voltage harmonics on electrical appliances are higher losses, resulting in additional thermal stress, acoustic noise, and incorrect operation [10], [11]. Furthermore, even harmonics can also result in increased light flicker and unbalanced magnetization of transformers, which can cause additional thermal stress and the emission of additional harmonic currents [12], [13].

Reference [14] discusses the adverse impact of harmonic distortion on the operation of power supplies. The results show a strong correlation between the impact and circuit topologies of the test appliances. The increase in Total Harmonic Distortion (THD_U) does not affect the operation of the test appliance with active Power Factor Correction (PFC). However, it results in irreversible failure of the test appliance without PFC, but at an excessively high value of 43 %.

Reference [15] discusses the impact of harmonic distortion on the DC link components of a converter for a variable speed drive, such as a bus capacitor and choke inductor. The results indicate a considerable increase in capacitor heating factor (introduced as a new index) and core losses in the presence of harmonic distortion. The severity of the impact depends on the phase angle of the harmonics. Thus, the 2^{nd} harmonic with an unfavorable phase angle leads to an unacceptable capacitor heating factor of as low as 1 %. In contrast, for the 5^{th} harmonic, the same impact does not occur until a magnitude of 20 %.

2) INTERHARMONICS

Besides the typical problems caused by voltage harmonics, such as additional thermal stress, voltage interharmonics cause the light flicker of lighting equipment and malfunctions of power system components (transformers, induction motors, turbogenerators) [2], [16], [17]. Furthermore, interharmonic disturbances pose additional challenges for control, communication, and measurement systems [3], [18].

Reference [19] discusses the impact of interharmonics on the light flicker of incandescent and modern lamps (CFL, LED lamps). The experimental results show that the sensitivity of the latter is not limited to interharmonics below double the fundamental frequency. Light flicker is also observed at frequencies around the other harmonic orders. In particular, a considerably higher sensitivity of modern lamps to interharmonics around odd harmonics is reported in [20].

III. EVALUATION FRAMEWORK

A. METHODOLOGY

The study distinguishes between the short- and long-term adverse impacts of supply voltage distortion on electrical appliances.

The short-term impacts appear to be a perceptible, unintentional deviation from the intended appliance operation. It covers visual interferences (light flicker, image distortion), audible noise, and operational malfunctions such as misconfiguration or unexpected behavior in programmed tasks. Short-term impacts are reported as discrete events along with the specific supply voltage distortion of their occurrence. The evaluation of visual inferences and audible noise is based on the subjective perception of the authors observing the appliance. This qualitative approach identifies appliances with distinct interferences, while its detailed evaluation (e.g., by light flickermeter or sound pressure level measurements) is the subject of other studies [21], [22].

The long-term impact is usually not instantly perceptible to end-users but can lead to premature failure of electrical appliances. One of the most common detrimental mechanisms is the additional thermal stress of built-in components, especially the DC link capacitor. Simplicity and high energy density make the application of the aluminum electrolytic type of capacitors preferable as DC link capacitors for mass-market electrical appliances. Since its lifetime depends on the operating temperature, it is expected to decrease by half at a 10 K temperature rise. The sensitivity of the DC link capacitors is also confirmed by the statistics on breakdowns in electrical appliances [23].

Reference [24] investigates thermal interactions in LED lamps caused by supply voltage distortion in the frequency range of 2-150 kHz. It was found that the additional thermal stress of the DC link capacitor correlates with the change in active power consumption of lamps when supply voltage distortion is applied. Further research by the authors has shown that the dependency of the temperature of the DC-link capacitor on active power consumption also holds for other electrical appliances with passive cooling (e.g., battery chargers and power supplies) [25]. First tests with supply voltage distortion in the frequency range below 2 kHz confirm a similar dependency.

This study uses the outcome of the previous work and evaluates the additional thermal stress of the DC link capacitor by measuring the active power of test appliances when supply voltage distortion is applied. It distinguishes between fundamental and nonfundamental components of active power. Given that the former is not affected by distortion, the latter serves as a measure of the additional thermal stress. The validity of this approach is illustrated in the paper by monitoring the operating temperature of the DC link capacitor of a selected LED lamp.

B. TEST SIGNALS

Table 1 provides an overview of the scenarios developed for this study. In the reference scenario (*Rs*), appliances are supplied with a sinusoidal supply voltage of 230 V. Then, appliances are exposed to supply voltage containing harmonic and interharmonic distortion. It is generated by superimposing the fundamental voltage with one or more harmonic (scenarios *Hi*, *Hm*) and interharmonic (scenario *IHi*) components.

1) INDIVIDUAL HARMONICS (Hi)

The study reflects two different scenarios regarding the magnitude of individual harmonics. The first scenario (Hi 1) considers the existing compatibility levels and utilizes the corresponding test levels as provided in IEC 61000-4-13 [8]. However, due to the lack of information for most even and odd triplen harmonics, their test levels are extrapolated

TABLE 1. Overview of the test scenarios.

Scenario	Label	Distortion	Base for the test level
Reference	*Rs*	no	
Harmonics	*Hi 1*	Individual harmonics	IEC 61000-4-13, Class 2 [6]
	Hi 2		Proposal A, 77A/1082A/DC [4]
	Hm 1	Harmonics mixes	IEC 61000-4-13, Class 2 [6] IEC 61000-2-2 [2]
	Hm 2		Proposal A, 77A/1082A/DC [4]
Inter-harmonics	*IHi 1*	Individual interharmonics	IEC 61000-4-13, Class 2 [6]
	IHi 2		IEEE Standard 519 [5]

from the compatibility levels in IEC 61000-2-2 [2] using the multiplier 1.5 and rounding up to a half or whole percent.

For the second scenario (*Hi 2*), test levels are derived for Proposal A [4] by multiplying the proposed compatibility levels with a factor of 1.5 and rounding the result up to a half or whole percent. It should be noted that the test levels for odd non-triplen harmonics remain constant compared to *Hi 1*.

The tests consider the variation of the phase angles between discrete values of 0° and 180° for all individual harmonics with test levels above 3 % (i.e., 3rd, 5th, and 7th orders). The phase angle of the remaining harmonics is set to 0°.

2) HARMONIC MIXES (Hm)

Similar to the tests for individual harmonics, two scenarios reflecting the existing and proposed compatibility levels (Proposal A [4]) are considered for testing with harmonic mixes. As an increase in compatibility levels is only envisaged for even and odd triplen harmonics, the study considers two kinds of harmonic mixes separately: (a) odd non-triplen harmonics and (b) even and odd triplen harmonics.

The THD_U of each mix is limited to 8 % via simultaneous reduction of magnitudes of harmonics, which are initially chosen similarly to the respective test levels for individual harmonics. The reduction factors for the odd non-triplen harmonic mix (*Hm 1a*) and the even and odd triplen harmonic mix (*Hm 2b*) are 0.81 and 0.96, respectively. As compatibility levels and test levels for odd non-triplen harmonics are not expected to change, the mix (a) results are the same for scenarios *Hm 1* and *Hm 2*.

For each type of mix, three different combinations of harmonic phase angles are tested:
- All phase angles equal to 0°
- Combination of phase angles between 0° and 180°:
  - resulting in lowest crest factor (flat-top waveform)
  - resulting in highest crest factor (pointed-top waveform)

3) INTERHARMONICS (IHi)

Interharmonics are tested in combination with adjacent harmonics to reflect the interference mechanism of light flicker. For this purpose, four sets of even, odd triplen, and odd non-triplen harmonics representing different harmonic ranges are selected and shown in Table 2. While the phase angle of selected harmonics is set to 0°, their magnitudes correspond to scenario Hi 1.

TABLE 2. Selection of individual harmonics for testing in combination with interharmonics.

Range	2nd – 9th	10th – 19th	20th – 29th	30th – 39th
Order	2, 3, 7	11, 12, 13	22, 23, 27	32, 33, 37

Interharmonics are introduced as integer multiples of 5 Hz, as the power frequency for the tests is always kept at 50 Hz. Regarding the distance from the respective harmonics, the study considers two kinds of interharmonics separately: (a) close (±5 Hz) and (b) distant (±25 Hz).

Concerning the interharmonic magnitudes, two scenarios are considered: test levels according to IEC 61000-4-13 [8] (*IHi 1*) and frequency-independent test levels limited to 0.5 % (*IHi 2*). The latter is introduced as a conservative approach based on the informative annex in IEEE Standard 519-2022 [5].

C. TEST APPLIANCES

The study is based on a set of 240 electrical appliances available in the mass-market segment, which has been selected considering the annual market share survey conducted by the German Federal Statistical Office (2014), different price segments, and popularity rankings.

Test appliances are classified into six categories according to their application from the end-user perspective. Finally, twenty appliances are selected for the immunity evaluation, focusing on compact appliances without active cooling, such as LED lamps, battery chargers, and power supplies. Table 3 lists selected appliances and provides additional information about the rated power, operating state, and topology of the electronic circuit.

Relevant operating states of the appliances are identified during initial measurements. Where possible, appliances with variable operating states (i.e., using an internal control system) are forced to operate with constant active power. For instance, a photovoltaic (PV) simulator is used to ensure constant DC-side input power for the PV inverter.

To ensure the reproducibility of the measurement results, the stability of operating states is analyzed by monitoring the active power over time. An operating state is stable if the relative variation of active power is less than 1 % of the mean value during an observation interval. Appliances experiencing a power variation above the given threshold are considered to have a variable operating state and require additional attention in the measurement procedure.

The appliances are classified according to the topology of their electronic circuits. A clear classification based on input current characteristics, as introduced in [26], is possible for all appliances except the air conditioner, refrigerator, and microwave oven. These appliances do not fit the classification

TABLE 3. Overview of the test appliances.

Categorie	Appliance	P_r in W	Operating state	Topology	Categorie	Appliance	P_r in W	Operating state	Topology
Household	LED lamp (5)	2-11	Stable	nPFC(2), pPFCc, pPFCi, aPFC	Kitchen	Induction hob	2000	Variable	aPFC
	Air conditioner	785	Variable	unk.		Refrigerator	120	Variable	unk.
Audio / Video	TV	80	Stable	aPFC		Microwave oven	1200	Variable	unk.
	Stereo	25	Variable	nPFC		Blender	800	Variable	pPFCi
Data processing	Battery charger (3)	13-90	Stable	nPFC (2), aPFC	Bathroom	Hairdryer	1200	Stable	ohm.
	PC power supply (2)	420-500	Stable	pPFCi, aPFC		Washing machine	2000	Variable	pPFCi
Generation	PV inverter	4600	Stable	self.					

scheme and are referred to as "unknown" circuit topology. The following circuit topologies of appliances are considered:

- Linear (ohm.)
- Non-linear (switched)
  - Line-commutated (uncontrolled)
    - No Power Factor Correction (nPFC)
    - Passive Power Factor Correction
      - Based on capacitive divider (pPFCc)
      - Based on series inductance (pPFCi)
    - Active Power Factor Correction (aPFC)
- Self-commutated (self.)

D. MEASUREMENT APPROACH

1) LABORATORY SETUP

The setup for the immunity evaluation is placed in a separate laboratory room with a constant ambient temperature of 20 °C.

The test signals are generated with a linear programmable three-phase power amplifier without additional external impedance. A transient recorder measures voltage and current simultaneously and synchronously with a sampling rate of 50 kHz. Depending on the input current of the test appliances, four different input ranges of current sensors are utilized.

The recorded waveform data is synchronized to the zero-crossings of the fundamental frequency and transferred to the frequency domain [9]. The active power of individual harmonic components P_h and the nonfundamental active power P_H are calculated based on the complex spectral components of voltages and currents. Further, the relative nonfundamental active power p_h is introduced for better comparability between appliances with different rated power.

$$P_h = U_h \cdot I_h \cdot \cos(\varphi_{hU} - \varphi_{hI}) \tag{1}$$

$$P_H = \sum_{h=2}^{40} P_h \tag{2}$$

$$p_h = P_H / P_1 \tag{3}$$

For a selected LED lamp, the operating temperature of the DC link capacitor was monitored. For this purpose, a thermal sensor (type K) was placed on the surface of the DC link capacitor, as shown in Fig. 2. Sensor placement required carefully disassembling and reassembling the housing to ensure the initial thermal conditions within the LED lamp.

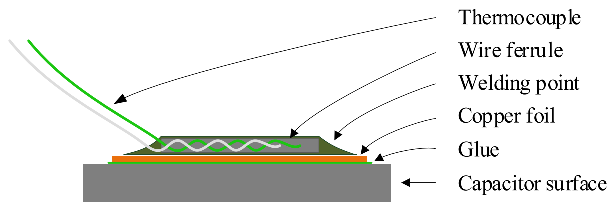


FIGURE 2. Sensor placement for monitoring of the operating temperature of the DC link capacitor.

TABLE 4. Random part of the uncertainty of voltage and current measurements.

Quantity	Uncertainty	Quantity	Uncertainty
U_h	± 13 mV	$\varphi_{h\,U}$	± 0,72°·V / U_h
I_h	± 10 µA ... ±180 µA	$\varphi_{h\,I}$	± (0.56°…10.3°)·mA / I_h

2) MEASUREMENT UNCERTAINTY

According to the specification, the output uncertainty of the programmable amplifier is better than 0.1 % of the RMS value. The uncertainty of the measurement system is determined using a calibrator. Based on a comprehensive set of calibration measurements, systematic and random parts of the uncertainty of voltage and current measurements are evaluated. The systematic part of the uncertainty is compensated, whereas the remaining random part of the uncertainty is listed in Table 4. The uncertainties for current measurements result from different input ranges for the used current sensors, which are selected depending on the test appliance to ensure the best possible utilization of the measurement range.

The uncertainty of nonfundamental active power is estimated using a probabilistic approach [27]. The approach is based on a Monte Carlo simulation and utilizes actual measurements of the appliances to determine input quantities and derive related uncertainties. After 100.000 repetitions, an empirical cumulative distribution function is obtained. The uncertainty of the nonfundamental active power calculation is determined by the maximum value and varies between 0.8 mW and 61.5 mW depending on the different input ranges (c.f., Table 3).

The uncertainty of operating temperature measurements is determined to be less than 0.2 K [24].

3) MEASUREMENT PROCEDURE

A two-step process is used for the immunity evaluation. In the first step, appliances are exposed to the test scenarios by applying each test signal for 5 seconds. The possible short-term impacts are obtained via continuous monitoring of appliance operation. Then, the long-term impact is evaluated based on a continuous acquisition of voltage and current over one second, corresponding to five consecutive measurement intervals according to IEC 61000-4-7 [9]. As a result, the mean values of fundamental and nonfundamental active power are reported.

Different test signals in the first step might be applied to different operating conditions in the test appliances with variable operating states. Therefore, the second step of the measurement procedure is introduced to assess the reproducibility of the results. It implies the additional exposure of the test appliances with variable operating states to selected test signals during the entire operating cycle. The duration of the operating cycle is either predefined or configurable. The only appliance with a predefined operating state is the washing machine (14 minutes). The operating cycle is set to one minute for other appliances with variable operating states.

Additional thermal stress of the DC link capacitor of the selected LED lamp is estimated as the difference in the operating temperature ($\Delta\vartheta$) between the test scenarios with harmonic or interharmonic distortion and the reference scenario (c.f., Table 1). The measurement procedure begins with a thermal stabilization of the operating temperature and the determination of the thermal time constant as described in [28], followed by the subsequent permanent application of the test signals. In the latter step, the operating temperature is measured at constant intervals of one minute for a total time of three time constants, corresponding to the 95 % of expected temperature increase. The final value of the expected temperature increase is obtained using a curve fitting approach based on the method of least squares [28].

4) REPRODUCIBILITY OF RESULTS

As a result of the second step of the measurement procedure, fundamental and nonfundamental active power is calculated for each measurement interval recorded during the entire operating cycle. The variation of measurement values is evaluated based on the median and the interquartile range (IQR), which measures the statistical dispersion of values around the median.

Similar conclusions can be drawn for all test appliances with variable operating states. While a considerable IQR and difference in median indicate a substantial variation of nonfundamental active power, its relationship to fundamental active power remains reasonably constant during the entire operating cycle of appliances. As shown in Fig. 3 for the washing machine, a nearly linear dependency is typically observed between fundamental and nonfundamental active power variations over time. Consequently, the results of both steps of the measurement procedure reveal a strong correlation in relative nonfundamental active power, which confirms the validity of the first step of the measurement procedure for the analysis of the test appliances with variable operating states.

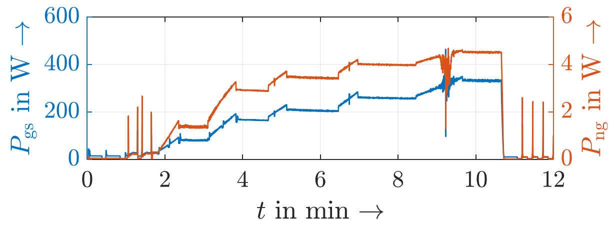


FIGURE 3. Active power of washing machine (blue – fundamental active power, red – nonfundamental active power).

IV. RESULTS

Perceptible short-term impacts are reported as discrete events, while the adverse long-term impact is evaluated based on the nonfundamental active power of test appliances when supply voltage distortion is applied. The nonfundamental active power is considered significant if the value exceeds twice the uncertainty of its calculation. It should be noted that the nonfundamental active power can be either positive or negative. The negative values imply a reduction of the operating temperature of the DC link capacitor and are not reported.

The following subsection presents the results for an 11 W LED lamp in detail and serves as a reference for discussing of the results for all appliances in aggregated form.

A. DETAILED RESULTS FOR LED LAMP

1) HARMONICS

a: SHORT-TERM IMPACT

The LED lamp is not affected by individual harmonics and harmonic mixes

b: LONG-TERM IMPACT

The LED lamp has a considerable nonfundamental active power consumption when exposed to supply voltage distortion, as seen in Fig. 4. Significant nonfundamental active power is obtained primarily with test signals containing individual odd non-triplen harmonics. The highest value reaches 6.2 % at the 7th harmonic.

The results of tests with individual odd non-triplen harmonics are identical for scenarios *Hi 1* and *Hi 2*, as the test levels for odd non-triplen harmonics remain constant. At the same time, the values depend on the applied harmonic phase angle, which affects the input current waveform and, consequently, the active power of a test appliance. For example, for the 3rd and 5th harmonics, the nonfundamental active power tends to be higher at phase angles of 180°, while for the 7th harmonic, the same applies to the phase angle of 0°.

The results of tests with individual even and odd triplen harmonics are different for scenarios *Hi 1* and *Hi 2*. In this case, the nonfundamental active power consumption increases with the test levels. While the values are at most 0.1 % for scenario *Hi 1*, they reach 1.1 % at the 20th and 22nd harmonics for scenario *Hi 2*.

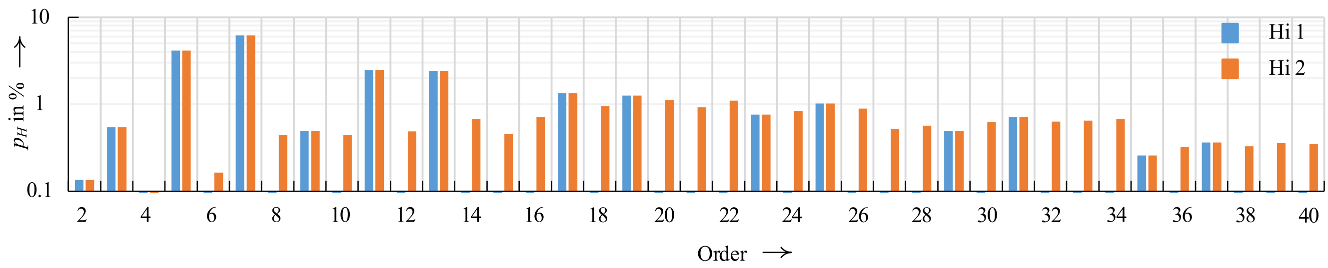


FIGURE 4. **Highest relative nonfundamental active power of LED lamp caused by individual harmonics.**

TABLE 5. **Relative nonfundamental active power of the led lamp caused by harmonic mixes.**

Test	Distortion	Phase angle variation		
		all 0°	*0°-180° flat-top*	*0°-180° pointed-top*
Hm 1a	Odd non-triplen	3.3 %	8.9 %	7.2 %
Hm 1b	Even, odd triplen	-	-	5,0 %
Hm 2a	Odd non-triplen	same as for Hm 1a		
Hm 2b	Even, odd triplen	1,0 %	1.9 %	9.9 %

Dash indicates insignificant or negative value of nonfundamental active power

TABLE 6. **Additional thermal stress ($\Delta\vartheta$) of the DC link capacitor of the LED lamp.**

Scenario	Distortion	Test level (THD_U) / %	p_H / %	$\Delta\vartheta$ / K
Hi 1	22nd	0.5	0	0
	25th	2.0	1.0	2.4
Hi 2	22nd	2.5	1.1	2.6
	25th	same as for Hi 1		
Hm 1	Even, odd triplen (mix *b*)	5.9	5.0	6.9
Hm 2		8.0	9.9	12.4

Table 5 summarizes the results of tests with harmonic mixes. For scenario *Hm 1,* the mix of odd non-triplen harmonics causes higher nonfundamental active power compared to the mix of even and odd triplen harmonics. The increase of test levels for even and odd triplen harmonics in scenario *Hm 2* partly compensates for this difference and can even lead to opposite results for a pointed-top waveform.

Similarly to the results of tests with individual harmonics, phase angle variation also affects the nonfundamental active power caused by harmonic mixes. Thus, the mix of odd non-triplen harmonics has the highest nonfundamental active power with a flat-top waveform (low crest factor). In contrast, a worst-case scenario for the mix of even and odd triplen harmonics is represented by a pointed-top waveform (high crest factor).

The additional thermal stress induced by the test signals mentioned above is presented in Table 6. The measurement results confirm the correlation between the nonfundamental active power and the increase in the operating temperature of the DC link capacitor. Similarly to the values of nonfundamental active power, the additional thermal stress caused by even and odd triplen harmonics increases considerably with the test levels. A systematic difference in the impact of odd and even harmonics, as found by [29], has not been observed.

Comparing the results for the mix of even and triplen harmonics shows that the nonfundamental active power has almost doubled for scenario *Hm 2*. At the same time, the increase in THD_U amounts to only 36 % (c.f., Table 6). Given that the increase in test levels mainly relates to the higher harmonic orders (above the 14th), a higher nonfundamental active power and additional thermal stress are expected for appliances with a capacitive input impedance characteristic.

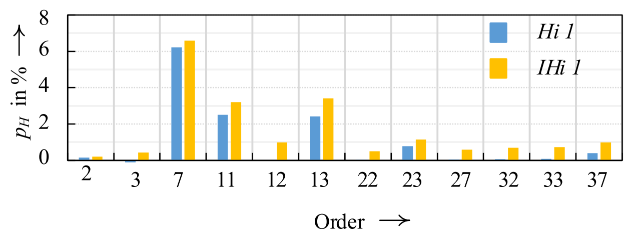


FIGURE 5. **Relative nonfundamental active power of LED lamp caused by test signals without (*Hi 1*) and with closely located interharmonics (*IHi 1*).**

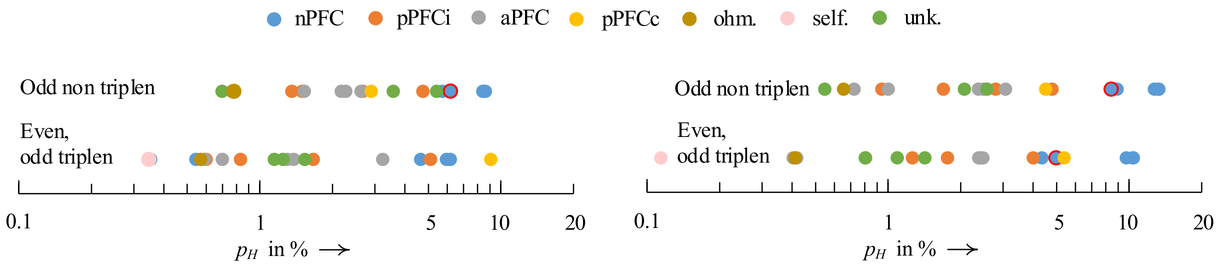
2) INTERHARMONICS

a: SHORT-TERM IMPACT

The LED lamp produces distinct light flicker when exposed to interharmonics in scenario *IHi 1*. It is observed with test signals containing interharmonics around the 2nd, 3rd, 7th, 11th, 12th, and 13th harmonics. In contrast, their location (close or distant to the respective harmonic) does not affect the results from the observer's point of view. The light flicker is not perceived at test levels according to scenario *IHi 2*.

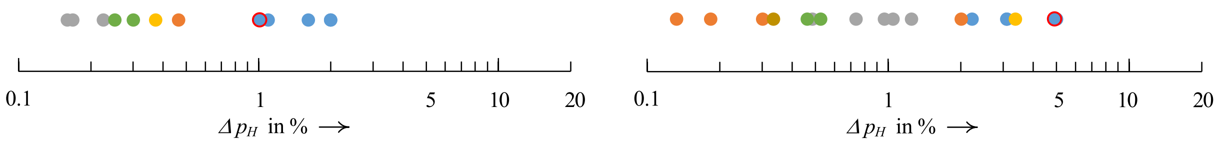
b: LONG-TERM IMPACT

Since test signals are defined as a combination of interharmonics and individual harmonics, the impact of the former is evaluated in comparison with the results of tests for scenario *Hi 1* (c.f., section V.A.1.b). Fig. 5 shows the nonfundamental active power for test signals without (scenario *Hi 1*) and with closely located interharmonics (scenario *IHi 1*). An increase in the nonfundamental active power in the latter case is observed in most cases and reaches 1.1 % at the 12th harmonic order.



(a) Individual harmonics (scenario *Hi 1*) (a) Harmonic mixes (scenario *Hm 1*)

FIGURE 6. Highest relative nonfundamental active power of test appliances.



(a) Comparison of scenarios *Hi 2* and *Hi 1* (a) Comparison of scenarios *Hm 2* and *Hm 1*

FIGURE 7. Increase in the highest relative nonfundamental active power of test appliances.

The differences between the results for test signals with closely and distantly located interharmonics are negligible. The nonfundamental active power decreases with the magnitude of interharmonics and does not exceed 0.1 % for scenario *IHi 2*.

B. AGGREGATED RESULTS FOR ALL TEST APPLIANCES

The color codes in Fig. 6 and 7 refer to the classification of appliances according to the topology of the electronic circuit (c.f., Table 2). Blue dots with a red outline indicate the 11 W LED lamp results discussed in the previous section.

1) HARMONICS

a: SHORT-TERM IMPACT

The appliances are not affected by individual harmonics or harmonic mixes. The only exception is the air conditioner, which produces audible noise when exposed to the individual odd non-triplen harmonics of the 5^{th} to 13^{th} order or harmonic mixes containing these harmonics. It should be noted that test levels for odd non-triplen harmonics remain constant for scenarios based on existing (*Hi 1*, *Hm 1*) and proposed (*Hi 2*, *Hm 2*) compatibility levels. Consequently, this interference case does not relate to the modification of compatibility levels.

b: LONG-TERM IMPACT

When exposed to supply voltage distortion, most appliances have a considerable nonfundamental active power consumption.

Fig. 6a summarizes the results of tests with individual harmonics for scenario *Hi 1*. The chart shows the highest relative nonfundamental active power observed among all tests with individual harmonics for each appliance. Again, it is seen that the highest values are usual for appliances with "pPFCc" and "nPFC" circuit topologies.

A closer look at the results of individual tests reveals the dominant impact of lower harmonics (below the 14^{th} order). The highest nonfundamental active power value occurs at the 3^{rd}, 5^{th}, and 7^{th} harmonics, and the values are strongly affected by the harmonic phase angle. For half of the appliances, the impact becomes more pronounced with the phase angle of 180°.

Fig. 7a shows the increase in the highest relative nonfundamental active power with test signals for scenario *Hi 2* compared to scenario *Hi 1*. Since the test levels for odd non-triplen harmonics remain constant in both cases, the results changed only for even and odd triplen harmonics. The highest increase reaches 2 % and relates to the 15^{th}, 16^{th}, 20^{th}, and 21^{st} orders. Given the above, the impact of even and odd triplen harmonics becomes comparable to that of odd non-triplen harmonics.

Fig. 6b summarizes the results of tests with harmonic mixes for scenario *Hm 1*. Again, the chart shows the highest relative nonfundamental active power among all tests with harmonic mixes for each appliance. It is seen that the highest values are usual for appliances with "nPFC" circuit topologies.

In line with the results of the LED lamps, phase angle variation also affects the nonfundamental active power caused by other test appliances. For instance, harmonic mixes with a flat-top waveform tend to have a less pronounced impact than those with a pointed-top waveform. The latter is a worst-case scenario for most appliances, except for some with "aPFC" and "pPFCc" circuit topologies.

Fig. 7b shows the increase in the highest relative nonfundamental active power with test signals for scenario *Hm 2* compared to scenario *Hm 1*. Since the test levels for odd non-triplen harmonics remain constant in both cases, differences are seen only for the mix of even and odd triplen harmonics. The highest increase reaches 5 % and, similar to the results of tests with individual harmonics, is usual for appliances with "nPFC" circuit topology.

2) INTERHARMONICS

a: SHORT-TERM IMPACT

In line with the results of the previous subsection, the air conditioner produces audible noise when exposed to test signals containing the 7th, 11th, and 13th harmonics.

Three of five LED lamps produce distinct light flicker with test signals containing interharmonics at test levels according to scenario *IHi 1*. While lamps with "pPFCc" and "nPFC" circuit topologies are sensitive to interharmonics around the 2nd, 3rd, 7th, 11th, 12th, and 13th harmonics, the sensitivity of the lamp with an "aPFC" circuit topology is limited to interharmonics around the 3rd harmonic. The differences between the effects of closely and distantly located interharmonics are negligible from the observer's point of view. Moreover, the light flicker is not perceived at test levels according to scenario *IHi 2*.

b: LONG-TERM IMPACT

Fig. 8 summarizes the results of tests with individual interharmonics for scenario *IHi 1*. The chart shows the change in relative nonfundamental active power induced by closely located interharmonics.

The change in the nonfundamental active power can either be positive (i.e., an increase) or negative (i.e., a decrease) compared to the results of tests with individual harmonics (scenario *Hi 1*). This behavior can be traced back to the resulting crest factor of a test signal. For instance, an interharmonic in combination with the 3rd harmonic at the phase angle of 0° causes decreased values for most appliances. Conversely, the same combination with the phase angle of 180° leads to the opposite result (i.e., increased values).

For most test signals, except those containing the 3rd harmonic, an increase in the resulting nonfundamental active power is observed. The highest increase reaches 5 % and is usual for appliances with "nPFC" circuit topology. The contribution of interharmonics is especially pronounced for test signals containing even and odd triplen harmonic orders, which do not cause significant nonfundamental active power at test levels according to *Hi 1*.

The differences between the results of test signals containing closely and distantly located interharmonics

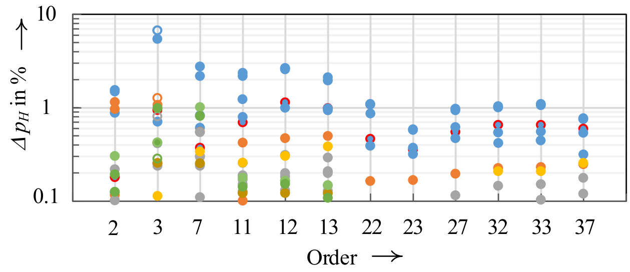


FIGURE 8. Change in relative nonfundamental active power caused by interharmonics (scenario *IHi 1*) (filled marker – increase, unfilled marker - decrease).

are negligible. The contribution of interharmonics to nonfundamental active power decreases with the magnitude of interharmonics and does not exceed 0.4 % in scenario *IHi 2*.

V. CONCLUSION

The article summarizes the results of the immunity assessment of twenty representative mass-market electrical appliances. A set of twenty single-phase electrical appliances with high penetration in public LV networks is examined with test signals containing individual harmonics, harmonic mixes, and individual interharmonics. Following the ongoing revision of compatibility levels, the test levels consider existing and proposed levels for harmonics and interharmonics.

The evaluation framework distinguishes between perceptible malfunctions and adverse long-term impacts, which implies the additional thermal stress of built-in components, especially the DC link capacitor. Furthermore, based on the experimental results, a correlation between the additional thermal stress and the nonfundamental active power of appliances is established, which serves as a measure for the long-term impact.

Unlike perceptible malfunctions, the long-term impact concerns all electrical appliances. It is shown that both harmonics and interharmonics led to a significant increase in nonfundamental active power regardless of harmonic order (odd/even, triplen/non-triplen).

Concerning the immunity to harmonics, the modification of the compatibility level for even and odd triplen harmonics does not increase the number of interference cases for the test appliances. Still, it might cause increased aging of electrical appliances due to the additional thermal stress of the DC link capacitor. In particular, it can affect compact electrical appliances with simple circuit topologies, such as LED lamps, battery chargers, and power supplies without active cooling.

Concerning the immunity to interharmonics, the existing test levels based on the levels for mains signaling in the LV network pose an excessive challenge for electrical appliances. Besides the perceptible light flicker observed for three of five

LED lamps, electrical appliances experience a considerable increase in nonfundamental active power. In that light, the levels limited by 0.5 % of the magnitude of the supply voltage are better reflective of the actual immunity of modern electrical appliances to interharmonics.

In the next step, more attention is given to electrical appliances with modern, energy-efficient circuit topologies. A further area for future work is research on the suitability of integral values (e.g., partially weighted harmonic distortion) for reflecting, e.g., the long-term impact and immunity of network components and protection devices.

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VICTOR KHOKHLOV (Student Member, IEEE) received the B.Sc. degree in electrical power engineering from the Moscow Power Engineering Institute, Moscow, Russia, in 2014, and the M.Sc. degree in electrical power engineering from the Ilmenau University of Technology, Ilmenau, Germany, in 2017. He is currently pursuing the Ph.D. degree in electrical power engineering with the Institute of Electrical Power Systems and High Voltage Engineering, Technische Universität Dresden, Germany. His research interests include different aspects of network disturbances above 2 kHz, especially their impact on functionality and lifetime of modern electrical appliances.

FRIEDEMANN MÖLLER received the Dipl.-Ing. degree in electrical power engineering from Technische Universität Dresden, Dresden, Germany, in 2012. He was a member of the Scientific Staff at the Institute of Electrical Power Systems and High Voltage Engineering, Technische Universität Dresden. He is currently with the Ingenieurgesellschaft für Energie-und Kraftwerkstechnik mbH, Cottbus, Germany, as a Project Manager of energy systems. His main research interests include the impact of electrical vehicles and distributed generation on the current and voltage quality in low voltage grids.

JAN MEYER (Senior Member, IEEE) received the Dipl.-Ing. and Ph.D. degrees in electrical power engineering and the Ph.D. degree in power quality from Technische Universität Dresden, Dresden, Germany, in 1994, 2004, and 2018, respectively. He is currently with Technische Universität Dresden, as a Senior Lecturer and a Team Leader at the Power Quality Research Group. His research interests include network disturbances and their assessment, especially distortion below and above 2 kHz, all aspects related to the uncertainty in power quality measurements and the efficient and automated analysis of large data amounts from power quality measurement campaigns.

PETER SCHEGNER (Senior Member, IEEE) received the Dipl.-Ing. degree in electrical power engineering from the Darmstadt University of Technology, Darmstadt, Germany, in 1980, and the Ph.D. degree from Saarland University, Saarbrücken, Germany, in 1989, with a dissertation on the earth-fault distance protection. He was a System Engineer in the field of power system control and became a member of the Scientific Staff at Saarland University. Then, he worked as the Head of the Development Department of Protection Systems, AEG, Frankfurt A. M., Germany. Later, he became a Full Professor and the Head of the Institute of Electrical Power Systems and High Voltage Engineering, Technische Universität Dresden, Dresden, Germany.