



SOURCES OF HARMONIC DISTORTION IN CONSUMER POWER SUPPLY CIRCUITS AND THEIR IMPACT ON POWER QUALITY IN LOW-VOLTAGE SMART GRIDS

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Abstract

This paper presents an analysis of the impact of modern nonlinear loads on power quality in low-voltage networks supplying residential installations and local smart-grid systems. Particular attention is devoted to total harmonic distortion of input current (THDI) and power factor, treated as diagnostic indicators of the operating condition of low-voltage networks. The study is based on the assumption that rectifier-based input stages and switch-mode power supplies commonly used in electronic devices constitute major sources of power-quality disturbances.

The research methodology consisted of two complementary stages. In the first stage, numerical modeling of simplified rectifier and switch-mode converter topologies was performed in the LTspice environment in order to analyze the mechanisms of harmonic generation and their influence on THDI and power factor. In the second stage, experimental measurements were conducted on selected consumer devices, including LED lamps, a fluorescent lamp, a charger, and a switch-mode power supply, operating under real network conditions characterized by distorted supply voltage.

The results showed good qualitative agreement between numerical simulations and experimental measurements. Strongly impulsive input current waveforms and high THDI values were observed for loads equipped with rectifier-capacitor and switch-mode input stages. The measurements also confirmed that significant differences between devices were associated mainly with the topology of the input stage, while no simple monotonic relation with rated power was observed within the investigated set of loads. The obtained results indicate that THDI and power factor can be treated as useful diagnostic indicators of power-quality threats in contemporary low-voltage power systems.

Keywords: power quality, THDI/THDv, power factor, nonlinear loads, switch-mode power supplies, smart grids, DC networks

1. INTRODUCTION

Modern low-voltage power networks, including installations supplying residential installations and local smart-grid systems, undergo significant changes due to the growing share of power-electronic loads. Devices such as switch-mode power supplies, LED lighting, chargers, electronic equipment, and systems cooperating with photovoltaic sources and energy storage draw current in a highly nonlinear manner, leading to distortion of current and voltage waveforms in the network [1], [2].

Classical power systems were designed assuming voltage and current waveforms close to sinusoidal. Under such conditions, power quality assessment was mainly based on phase displacement between voltage and current and the associated reactive power. Contemporary installations,

however, are dominated by nonlinear loads, for which low power factor results largely from current waveform distortion rather than classical displacement reactive power [11].

The presence of harmonics in load currents leads to increased thermal losses in conductors and transformers, overheating of infrastructure components, degraded performance of protection devices, and reduced accuracy of electricity metering [1], [11], [12]. In smart grids that integrate distributed sources, inverters, energy storage systems, and electric vehicle charging infrastructure, power quality problems are additionally linked to stability and security of supply [3]–[5].

While the literature extensively discusses harmonics generated by large-scale power converters, photovoltaic installations, and EV charging stations [1], [2], [5], far less attention has been devoted to the massive, distributed generation

of disturbances by small household loads, despite the fact that they currently represent the most numerous group of devices connected to low-voltage networks. Their combined effect may be cumulative and may affect the system as a whole.

Particularly problematic are rectifier circuits operating with input capacitors and switch-mode power supplies without active power factor correction. These loads generate highly impulsive current consumption, resulting in high total harmonic distortion (THDI) and degraded power factor [6], [11]. Such effects occur even for low-power devices, challenging the intuitive assumption that power quality threats are associated only with large industrial loads.

In response to the increasing complexity of power quality problems, fast harmonic monitoring techniques and automatic interpretation methods have been developed for diagnostic systems [7], [8]. At the same time, attempts are made to mitigate disturbances using passive and active filters, advanced converter control strategies, and concepts of hybrid or local DC networks [2], [3], [9], [10]. However, these approaches do not remove the fundamental cause of the problem—the repeated AC/DC conversion performed by numerous end-use devices.

The research hypothesis adopted in this study is that, within the investigated group of consumer low-power devices, rectifier circuits and switch-mode input stages are the principal sources of current harmonic distortion (THDI) and power factor degradation. It is further assumed that the physical mechanisms responsible for these effects can be reproduced using simplified LTspice models and qualitatively confirmed by measurements of real devices.

The obtained results indicate that parameters such as THDI and the power factor can be treated as diagnostic measures of power quality threats, relevant for assessing the operating state of modern power networks with a growing share of power-electronic loads.

2. LITERATURE REVIEW

2.1. Significance of THDI and power factor in power quality assessment

In the literature, harmonic distortion of current and voltage is widely recognized as a major factor deteriorating power quality. Classical studies indicate that for nonlinear loads the power factor cannot be identified solely with phase displacement between fundamental components, since current waveform distortion plays a significant role [11]. Consequently, a low power factor may occur even when displacement reactive power is not dominant.

Later studies extend this concept by treating THDI not only as a waveform quality indicator but also as a measure of additional losses and stresses imposed on power system components. Abdel Aleem et al. proposed harmonic-adjusted THDI, accounting for frequency-dependent effects of

harmonics on thermal losses and loading of conductors and transformers [12]. From a practical perspective, increased THDI can therefore be regarded as an early indicator of deteriorating operating conditions.

Numerous investigations confirm that harmonics cause increased losses, overheating, maloperation of protection systems, and reduced metering accuracy [8], [11], [12]. Hence, parameters such as THDI and power factor acquire not only quality-related but also diagnostic significance.

2.2. Nonlinear loads as sources of harmonic disturbances

Modern distribution networks are characterized by a growing share of nonlinear loads, including both industrial devices and mass-produced household equipment such as switch-mode power supplies, LED lighting, and chargers [1], [2], [11]. A common feature of these loads is the presence of rectifiers and energy storage capacitors, which leads to impulsive current draw.

A review of harmonic mitigation methods in microgrids presented by Adineh et al. shows that primary sources of disturbances include converter switching processes, resonances with grid impedance, and nonlinear loads [2]. Although these studies mainly address AC microgrids, the underlying physical mechanisms are directly relevant to residential supply circuits.

In the context of smart grids, photovoltaic systems, and EV charging infrastructure, inverters and chargers have been shown to significantly increase harmonic levels [1], [5]. While passive and active filtering can reduce some effects, they do not eliminate the root cause—impulsive current consumption.

Power factor correction (PFC) circuits represent another important research area. As demonstrated in [6], conventional PFC solutions improve the local power factor of individual devices but do not necessarily lead to a global improvement in network power quality, indicating the need for adaptive control strategies based on real distortion levels.

2.3. THDI as an indicator of network stability threats

In modern power systems, power quality issues are increasingly analyzed in the context of stability and supply security. Studies on hybrid AC/DC microgrids show that the growing share of distributed sources and converters increases system sensitivity to harmonics, voltage asymmetry, and fluctuations [3], [4].

Particularly important are investigations demonstrating that increased THDI can cause incorrect operation of protection and control systems. Alasali et al. showed that harmonic disturbances in PV-rich networks may lead to increased losses and protection malfunctions [5], indicating that THDI should be treated as a predictor of decreased safe operating margins.

2.4. Harmonic monitoring and power quality diagnostics

For THDI to serve as a diagnostic indicator, fast and reliable estimation methods are required. Muzi and Barbati demonstrated that classical FFT algorithms using long observation windows are insufficient for smart grids with short time constants, proposing second-order generalized integrator frequency-locked loop (SOGI-FLL) methods capable of real-time harmonic estimation [7].

Parallel efforts focus on automated interpretation of measurement results. Nolasco et al. proposed a system based on recursive Fourier transform and fuzzy logic to diagnose power quality conditions online [8], underlining the growing role of harmonic parameters as inputs for diagnostic and decision systems.

2.5. Harmonic mitigation and the concept of DC networks

The literature describes numerous harmonic mitigation methods in AC networks, including passive and active filters and advanced converter control strategies [2]–[4]. However, these solutions are increasingly complex and do not remove the fundamental cause of repeated AC/DC conversion.

Consequently, local DC networks are increasingly considered to supply devices that are inherently DC-based. Studies on DC microgrid power quality show that such architectures can reduce conversion stages and some AC-related harmonic phenomena [3], [9], [10]. At the same time, power quality issues do not disappear but change their nature, appearing as ripple and switching disturbances.

The research direction adopted in this work was additionally inspired by methods used in concordance analysis and prospective technology assessment [13]–[15].

2.6. Research gap

The literature review shows that power quality, harmonics, and mitigation methods are well recognized at industrial and network levels. However, the issue of distributed, large-scale generation of high THDI by small household loads, particularly rectifier and switch-mode power supplies, has been addressed to a much lesser extent.

Furthermore, the impact of such loads on power factor, metering accuracy, and low-voltage network operation under already distorted supply conditions remains insufficiently studied. This research gap constitutes the direct motivation for the modeling and experimental investigations presented in this paper.

3. MODELING OF HARMONIC DISTURBANCE SOURCES IN RECTIFIER AND SWITCHING CIRCUITS

Numerical modeling constitutes an essential stage of the research, enabling the identification of fundamental mechanisms responsible for current

waveform distortion and deterioration of the power factor in supply circuits. In real nonlinear loads, phenomena related to voltage rectification, energy storage, switching of active components, and interaction with network impedance occur simultaneously, which makes direct interpretation of measurement results difficult.

The objective of the modeling was not to accurately reproduce a specific commercial power supply, but rather to capture the physical mechanisms of harmonic generation characteristic of commonly used rectifier and switch-mode circuits. Such an approach allows the simulation results to be directly related to the experimental observations presented later in the paper [16].

3.1. Research assumptions and scope of modeling

The analysis began with a classical linear load, for which the current drawn from the grid has a sinusoidal waveform and the power factor is close to unity. Subsequently, nonlinear elements typical of electronic power supply input stages were gradually introduced into the model, including rectifier diodes, a Graetz bridge, filtering capacitors, inductive components, and a transistor operating as a switching element.

The main hypothesis adopted at the modeling stage assumed that the dominant factor shaping the harmonic spectrum and the value of current THDI is the method of AC voltage rectification and the impulsive nature of charging the input capacitors, rather than the load power or the characteristics of the output stage.

Accordingly, a sequential development of the model was adopted, including:

- a half-wave rectifier with a diode, capacitor, and resistive load,
- a full-wave rectifier using a Graetz bridge,
- a bridge rectifier with an input LC filter,
- a rectifier with additional inductive elements on the DC side,
- a simplified model of a switch-mode power supply with a switching transistor.

This approach made it possible to examine how individual elements of the input topology influence:

- the shape of the grid current,
- the harmonic spectrum,
- the value of total harmonic distortion (THDI),
- the power factor (PF) and the nature of its degradation,
- the overall energy efficiency of the system.

3.2. Description of numerical experiments

The numerical experiment was conducted in the LTspice environment using time-domain transient analysis. All modeled circuit variants were supplied by an ideal sinusoidal voltage source with a frequency of 50 Hz and an amplitude corresponding to nominal low-voltage network conditions. The analysis focused on waveforms observed at the input side, as seen from the grid side.

For each circuit topology, simulations were carried out until steady-state conditions were reached. The initial transient interval associated with capacitor charging and circuit startup was excluded from the analysis. The observation window was selected to include an integer number of supply voltage periods.

In models incorporating switching elements or fast transient phenomena related to capacitor charging, the maximum integration time step was limited to ensure accurate representation of both the fundamental 50 Hz component and higher-order harmonics. Simulation parameters were selected to guarantee numerical stability and comparability of results among the different variants.

The output-side load was adjusted so that the average power level remained similar across the analyzed configurations. This procedure enabled a direct comparison of the impact of input-side topology on power quality independently of the load magnitude.

Voltage and current waveforms at the input side were recorded, and average and RMS values required for further power quality analysis were calculated. The adopted procedure allows the numerical experiment to be reproduced and the obtained results to be unambiguously interpreted.

3.3. Simulation methodology and determination of power quality parameters

In this paper, THDI denotes total harmonic distortion of input current (1), while THDV refers to total harmonic distortion of supply voltage; the generic term THD is used only when referring to harmonic distortion in a general sense.

The evaluation of the influence of individual rectifier and switching topologies on power quality required clear definitions of the parameters used to describe both current distortion and the energetic performance of the system. The following quantities were analyzed: total harmonic distortion of the input current (THDI), power factor (PF), $\tan \varphi$ of the fundamental component of the fundamental component, and system efficiency. THDI was determined from the harmonic spectrum of the input current recorded at the supply side of the analyzed circuit. In the numerical procedure, the THDI value was calculated on the basis of harmonics from the 2nd to the 32nd order, with the fundamental component taken as the reference value.

Simulations were performed in LTspice 24.1.10, focusing on steady-state conditions after transient effects had decayed. The observation window covered an integer number of 50 Hz supply voltage periods.

Total harmonic distortion of the input current was determined using FFT analysis according to the classical definition:

$$THDI = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \quad (1)$$

where I_1 denotes the RMS value of the fundamental current component, and I_h is the RMS value of the h -th harmonic component. This definition makes it possible to distinguish the effect of waveform distortion from the effect of phase displacement of the fundamental component. As a result, THDI was treated in this study as the principal measure of nonsinusoidal current consumption generated by the analyzed input-stage topology.

The power factor was calculated as the ratio of active power drawn from the grid to apparent power:

$$PF = \frac{P}{S} = \frac{P}{U_{rms} \cdot I_{rms}} \quad (2)$$

where P is the active power and S is the apparent power at the system input. This approach accounts for both phase displacement and waveform distortion, which is essential in the analysis of nonlinear loads.

To separate the influence of classical displacement reactive power from harmonic distortion effects, only the fundamental components of voltage and current were additionally analyzed. Based on these, the phase displacement angle and the value of $\tan \varphi$ were determined.

In LTspice, active power was calculated as the average value of instantaneous power:

$$p(t) = u_{in}(t) i_{in}(t), P = \frac{1}{T} \int_{t_0}^{t_0+T} u_{in}(t) i_{in}(t) dt$$

using built-in .meas directives.

Energy efficiency was determined as the ratio of output power delivered to the load to input power drawn from the grid:

$$\eta = \frac{P_{out}}{P_{in}} \quad (4)$$

with identical time intervals used for calculating input and output powers. The adopted methodology ensures consistency of comparisons among successive model variants and is consistent with approaches used in related numerical investigations [17]–[20].

3.4. Results of numerical modeling

Model 1 – Single-diode rectifier with resistive load

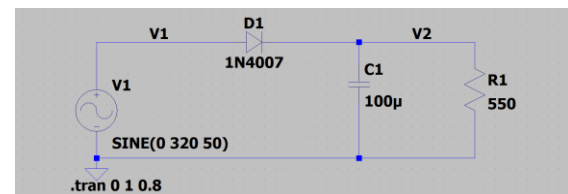


Fig. 1. Simulation schematic of Model 1

The first numerical experiment considered the simplest half-wave rectifier model. This configuration allows the basic mechanism of distortion formation to be analyzed. The capacitor is charged only when the source voltage exceeds the capacitor voltage increased by the diode forward voltage drop. Consequently, the input current is discontinuous and takes the form of short capacitor charging pulses.

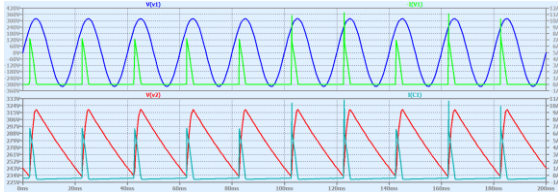


Fig. 2. Time-domain waveforms for Model 1

Model 2 – Full-wave rectifier with Graetz bridge

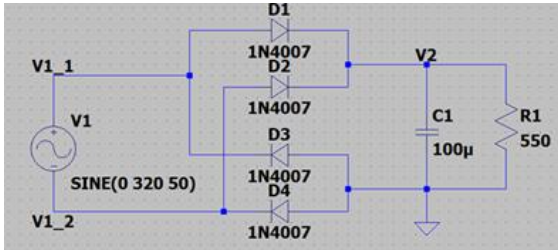


Fig. 3. Simulation schematic of Model 2

In the second experiment, the model was extended to a full-wave bridge rectifier. Replacing the single diode with a Graetz bridge improves the conditions on the DC side and reduces output voltage ripple, but it does not eliminate the impulsive nature of the grid current. On the contrary, the nonlinear load behavior seen from the grid remains pronounced.

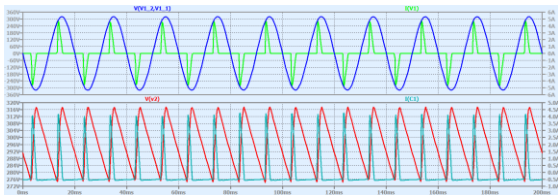


Fig. 4. Time-domain waveforms for Model 2

Model 3 – Bridge rectifier with LC input filter

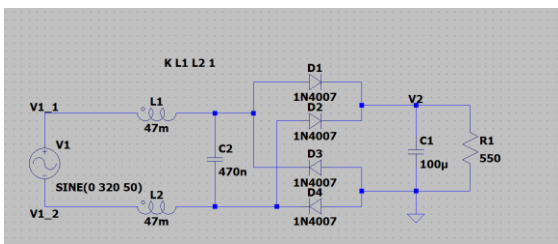


Fig. 5. Simulation schematic of Model 3

In the third variant, an input LC (EMI) filter was added. Its purpose is to limit rapidly changing current components drawn from the grid and partially smooth the input current waveform. The influence of inductive and capacitive elements on input current shape, harmonic reduction, power factor, phase angle, and efficiency was analyzed.

The results show that classical input filtering reduces high-frequency components but does not remove the fundamental mechanism of capacitor charging. More significant THDI reduction was achieved by introducing inductive elements on the

DC side, which directly limit current dynamics during energy transfer.

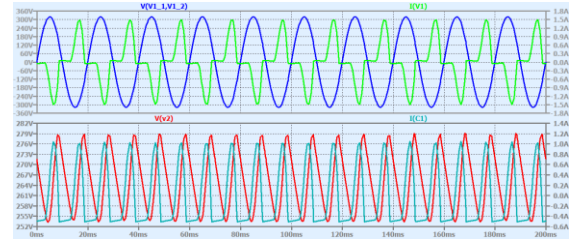


Fig. 6. Time-domain waveforms for Model 3

Model 4 – Rectifier with switching transistor

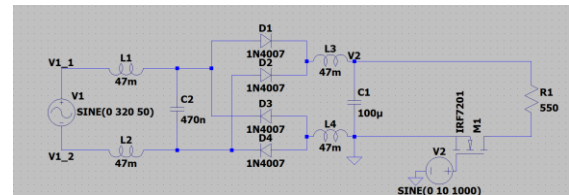


Fig. 7. Simulation schematic of Model 4

In the final modeling stage, a transistor operating as a switching element at a frequency of 1 kHz was added. This configuration represents a simplified input stage of a switch-mode power supply. In this case, the input current spectrum includes both harmonics related to AC rectification and additional components resulting from switching operation. Consequently, the load becomes a source of both low-frequency harmonic distortion and potential electromagnetic interference.

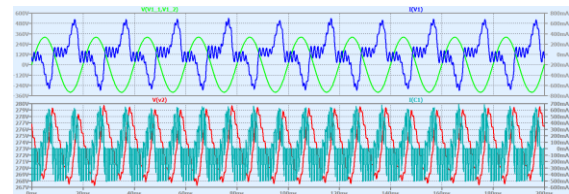


Fig. 8. Time-domain waveforms for Model 4

3.5. Relation of the numerical models to real consumer devices

The numerical models developed in this study were not intended to reproduce specific commercial devices in a one-to-one manner. Their purpose was to isolate the dominant physical mechanisms responsible for current distortion, power factor degradation, and changes in the energy transfer process at the input stage of nonlinear loads. For this reason, the models should be interpreted as representative classes of input-stage topologies commonly found in consumer devices.

Model 1 should be treated as a reference mechanism illustrating the basic effect of half-wave rectification, capacitor charging, and discontinuous current consumption. It is not considered a direct representation of a typical modern consumer product, but rather a simplified baseline case

showing how current distortion appears already at the most elementary rectifier level.

Model 2 corresponds to a simple bridge-rectifier input with a smoothing capacitor. This structure is representative of many low-cost consumer devices, including basic LED drivers, low-power chargers, and simple electronic power supplies without active current shaping. In such devices, the capacitor is charged only near the peaks of the supply voltage, which results in strongly impulsive input current and high THDI.

Model 3 represents a rectifier input stage equipped with passive filtering elements. This case can be related to consumer devices that include basic EMI suppression or passive line-conditioning components. The model makes it possible to assess to what extent passive filtering reduces higher harmonic content and improves the input current waveform, while not eliminating the nonlinear nature of the load.

Model 4 represents a simplified front-end of a switch-mode power supply. In this case, the input behavior is shaped not only by rectification and capacitor charging, but also by high-frequency switching. This model is therefore associated with a broad class of modern consumer devices, such as switch-mode chargers, electronic adapters, compact LED power supplies, and other low-power supplies using active switching elements.

This classification provides the framework for interpreting for the measurement results presented in the next section. The measured devices are not expected to reproduce the simulation results exactly, because commercial products differ in component values, control strategies, and operating conditions. Nevertheless, their measured waveforms, THDI values, and power factor characteristics should remain consistent with the mechanisms predicted by the corresponding model class. In this sense, the simulation results are used as a causal framework for interpreting the behavior of real consumer loads.

3.6. Conclusions from numerical modeling

The numerical modeling confirms that the primary cause of high current THDI values in supply circuits is not the nature of the final load, but rather the topology of the input power stage. The more effectively the filtering capacitor smooths the DC voltage, the more impulsive the grid current becomes.

The simulation results show that the highest THDI was obtained for Model 2, i.e. the full-wave bridge rectifier with a smoothing capacitor, which confirms that this topology produces the most strongly impulsive input current among the analyzed cases. At the same time, the lowest power factor was observed for Model 1, whereas the introduction of passive filtering in Model 3 led to a clear improvement in PF and a substantial reduction in THDI compared with the simple rectifier-capacitor configurations. The switching-stage topology represented by Model 4 did not eliminate current

distortion; instead, it increased the spectral complexity of the input current due to the combined effect of rectification, energy storage, and high-frequency switching.

Table 1. Summary of numerical simulation results

MODEL	$U_{in,rms}$ [V]	$I_{in,rms}$ [A]	P_{in} [W]	S_{in} [VA]
1	225.43	1.580	139.69	356.12
2	225.71	1.350	163.06	304.69
3	225.71	0.735	131.57	165.84
4	226.27	0.317	56.65	71.81

MODEL	$PF = P/S$	P_{out}	$\eta = P_{out}/P_{in}$	THDI[%]
1	0.392	139.06	0.996	44.18
2	0.535	160.27	0.983	148.31
3	0.793	127.60	0.970	61.57
4	0.789	56.06	0.990	71.65

Classical AC-side filtering methods can only partially mitigate the effects of this phenomenon. Effective improvement in power quality requires modifications to the energy transfer mechanism after rectification, such as DC-side inductors or active power factor correction circuits.

The modeling results provide direct justification for the experimental investigations presented in the next section and enable the observed THDI levels in real devices to be interpreted in terms of fundamental physical mechanisms.

4. MEASUREMENTS OF REAL ELECTRICAL LOADS

The objective of the experimental investigations was to verify whether the mechanisms of harmonic disturbance generation identified in numerical modeling also occur in real electrical loads commonly used in consumer installations. Particular attention was given to loads equipped with rectifiers and switch-mode power supplies, which – according to the literature review and modeling results – should exhibit a high level of current distortion.

The measured devices were interpreted with reference to the model classes introduced in Section 3. In particular, LED lamps and simple low-power supplies were compared mainly with Model 2 or Model 3, whereas switch-mode chargers and electronic adapters were interpreted primarily in the context of Model 4. The purpose of this comparison was not to demonstrate exact numerical equivalence, but to verify whether the measured current waveforms and power-quality indices remain consistent with the physical mechanisms predicted by the corresponding model topology.

The measurements were carried out under real operating conditions in a low-voltage network characterized by a noticeable but stable level of supply voltage distortion. This approach enabled the assessment of the actual impact of nonlinear loads on power quality without the use of artificially idealized supply sources.

4.1. Relation of measured devices to the model classes

In order to link the experimental results with the numerical analysis, the measured devices were interpreted in relation to the model classes introduced in Section 3. Devices with strongly simplified rectifier-capacitor input stages were associated mainly with Model 2. Devices equipped with additional passive input filtering were interpreted as being closer to Model 3. Consumer loads based on switch-mode conversion, such as chargers and electronic power supplies, were associated primarily with Model 4. Model 1 was not treated as a direct representation of a commercial device, but rather as a reference mechanism illustrating the origin of strongly discontinuous current in rectifier-fed circuits.

Therefore, the purpose of the measurement section is not to identify exact numerical agreement between a particular device and a particular simulation case, but to verify whether the measured current waveforms, THDI values and power-factor characteristics remain consistent with the physical mechanisms predicted by the corresponding model topology.

4.2. Measurement methodology and conditions

Measurements were conducted at the supply point of single-phase loads operated at a nominal voltage of 230 V and a frequency of 50 Hz. Voltage and current waveforms were recorded in the time domain and subsequently analyzed in the frequency domain to determine their harmonic content. All analyses were performed under steady-state conditions after the stabilization of RMS values of voltage and current.

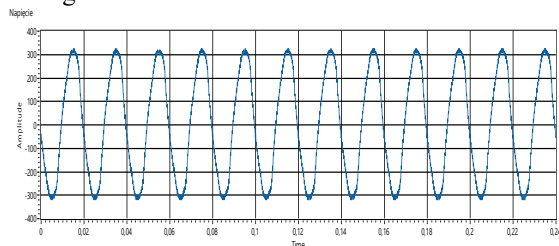


Fig. 9. Measured waveform of the supply voltage

An important methodological observation was that the supply voltage at the measurement point was not ideally sinusoidal. Throughout the entire measurement series, the total harmonic distortion of voltage (THDV) ranged approximately from 9.5% to 10.5%. This distortion level remained relatively constant and independent of the type of connected load, enabling a meaningful comparison of current distortion results among different devices.

The recorded current waveforms were subjected to harmonic analysis to determine the total harmonic distortion of current (THDI). In addition, RMS values of voltage and current as well as time-domain waveforms were analyzed, allowing an assessment of the energy consumption characteristics.

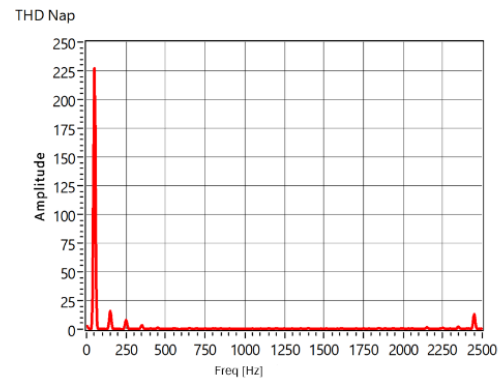


Fig. 10. Total harmonic distortion (THDV) of the measured supply voltage

4.3. Groups of tested loads

The experimental study included several representative groups of loads commonly found in residential environments:

- a reference load of nearly linear character (halogen lamp),
- LED light sources with different rated powers and internal designs,
- a fluorescent lamp,
- a high-power switch-mode charger (67 W),
- a low-power switch-mode power supply (15.3 W).

The selection of devices was intended to compare loads with similar end-use functions but different input-stage topologies.

4.4. Measurement results

For the reference load—the halogen lamp—a low level of current distortion (THDI below 10%) was obtained, which confirmed its quasi-resistive behavior. The input current waveform remained close to a sinusoid despite the presence of distorted supply voltage.

A clearly different behavior was observed for nonlinear consumer loads equipped with rectifier-capacitor or switch-mode input stages. In these cases, the input current waveform became strongly deformed, and the THDI values increased substantially. The recorded results showed that the decisive differences between the tested devices were associated mainly with current distortion rather than with changes in the supply-voltage distortion level.

The tested LED lamp exhibited a relatively low THDI compared with the other nonlinear loads, which suggests that its input stage provided a more favorable current waveform than the fluorescent lamp and the analyzed electronic power supplies. By contrast, the fluorescent lamp produced significantly higher current distortion, indicating a much more impulsive current draw.

Particularly high THDI values were recorded for the high-power switch-mode charger and the low-power switch-mode power supply. In both cases, the measured distortion level was very high, and in the most extreme case exceeded 200%. These results confirm that even low-power devices may generate

strongly distorted input current if their topology includes rectification, capacitive smoothing, and no effective active power-factor correction.

To facilitate the interpretation of the archived measurement cards, the most important quantitative results obtained for the selected representative consumer devices are summarized in Table 2. The table does not replace the detailed waveform records and software-generated measurement sheets, but provides a compact comparison of the key power-quality indicators, namely THDI, THDV, rated power, and the auxiliary parameter reported by the measurement software as the linear ratio. Such a synthetic presentation makes it easier to compare the tested loads and to relate their measured behavior to the model classes introduced in Section 3.

4.5. Comparative analysis and reference to modeling results

A comparison of experimental results with numerical modeling outcomes reveals very good qualitative agreement. The impulsive nature of current draw observed in simulations of capacitor-input rectifiers was also present in real LED lamps, chargers, and switch-mode power supplies.

The high THDI values measured experimentally correspond to those topologies that, in numerical modeling, exhibited the most significant degradation of power factor and a pronounced contribution of low-order harmonics. This confirms that simplified circuit models correctly capture the main physical mechanisms responsible for harmonic generation.

An important conclusion is also that the experiments were conducted under already distorted supply voltage conditions. This confirms that nonlinear loads not only generate their own

disturbances but also operate in an environment that may further amplify current distortion effects.

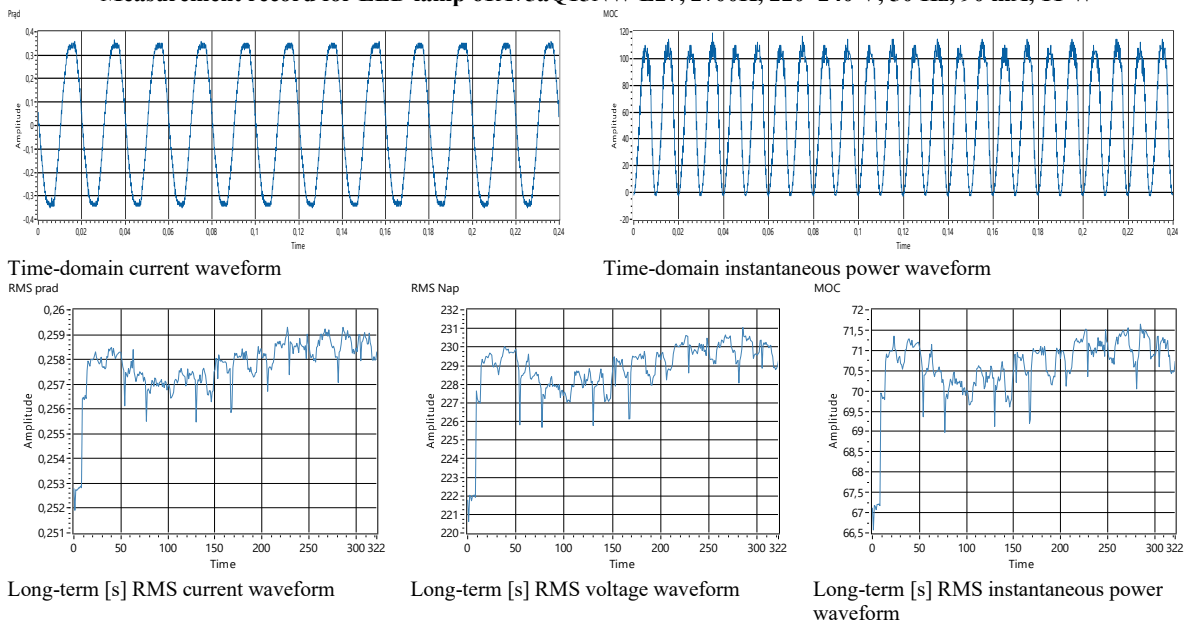
4.6. Conclusions from experimental measurements

The experimental measurements clearly confirm that the dominant sources of high current THDI in residential supply circuits are loads equipped with rectifiers and switch-mode power supplies. LED lighting, chargers, and small electronic power supplies generate significantly higher distortion than loads with nearly linear characteristics.

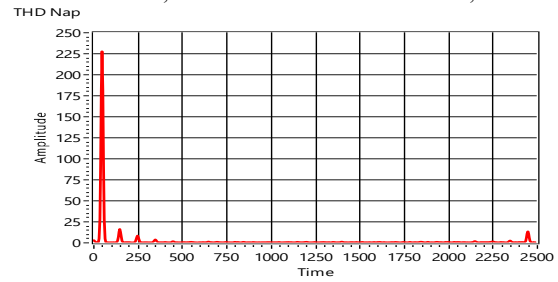
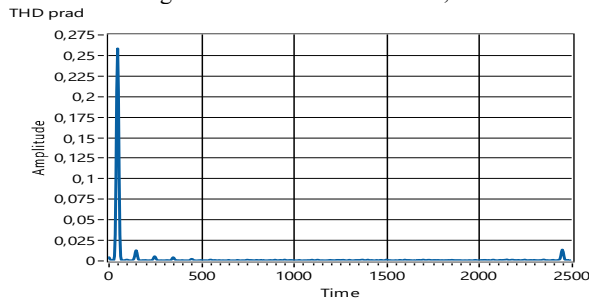
The obtained results indicate that power quality problems in low-voltage networks have a distributed and potentially cumulative nature. A single low-power device does not pose a system-level threat; however, the mass deployment of such devices leads to a substantial deterioration of power quality parameters. These observations directly justify further analysis of the influence of harmonics on energy metering accuracy and the search for methods to limit the scale of this phenomenon.

Table 2 condenses the most important measurement results obtained for selected representative consumer loads. The data show that the supply-voltage distortion level remained relatively stable throughout the measurement series, whereas the decisive differences concerned THDI generated by individual devices. The lowest distortion was observed for the reference load and for the tested LED lamp, while very high THDI values were recorded for the fluorescent lamp and especially for the switch-mode power supplies. This synthetic comparison confirms that the dominant factor differentiating the measured devices was the topology of the input stage rather than the end-use function of the load.

Measurement record for LED lamp 61A75aQ15NW E27, 2700K, 220–240 V, 50 Hz, 90 mA, 11 W



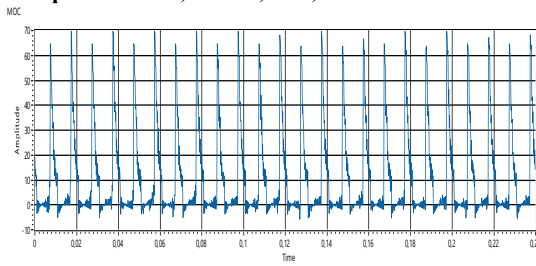
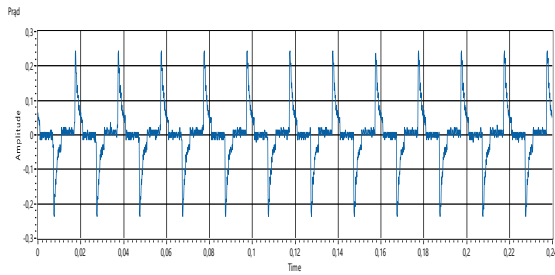
THD		dB	%	Linear ratio
	Current	-22,14	7,80	0,08
	Voltage	-20,31	9,98	0,10



THDV of the supply voltage

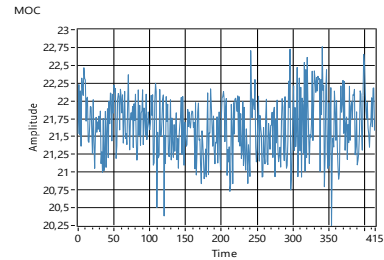
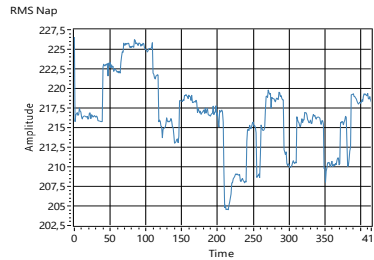
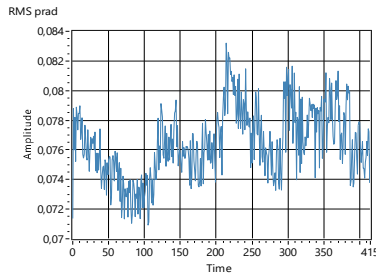
THDI of the supply current

Measurement record for fluorescent lamp NNSHR32, 2700K, E27, 35 W



Time-domain current waveform

Time-domain instantaneous power waveform

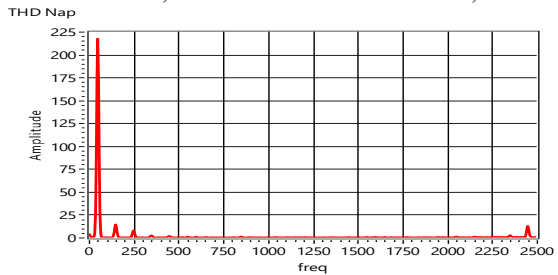
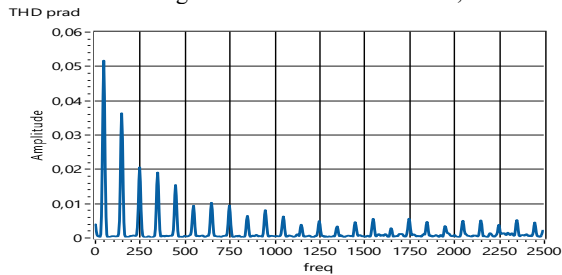


Long-term [s] RMS current waveform

Long-term [s] RMS voltage waveform

Long-term [s] RMS instantaneous power waveform

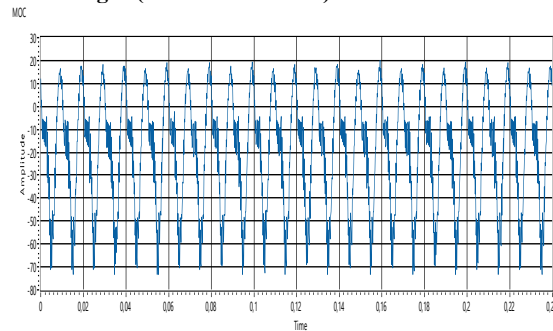
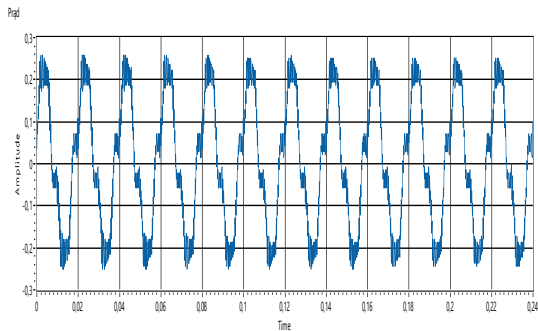
THD		dB	%	Linear ratio
	Current	0,36	106,44	1,05
	Voltage	-20,04	9,87	0,10



THDI of the supply current

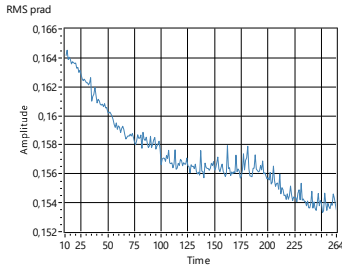
THDV of the supply voltage

Measurement record for 67 W Xiaomi charger (no-load condition)

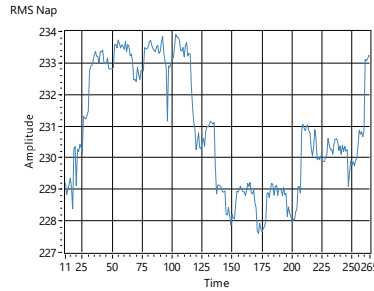


Time-domain current waveform

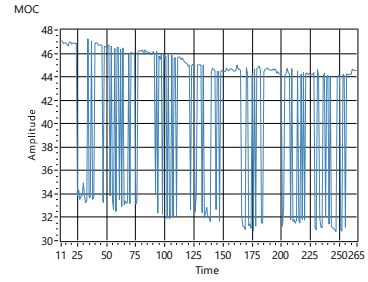
Time-domain instantaneous power waveform



Long-term [s] RMS current waveform

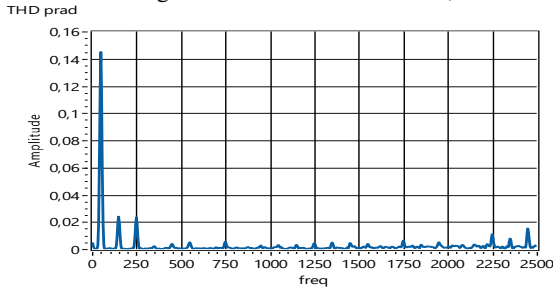


Long-term [s] RMS voltage waveform

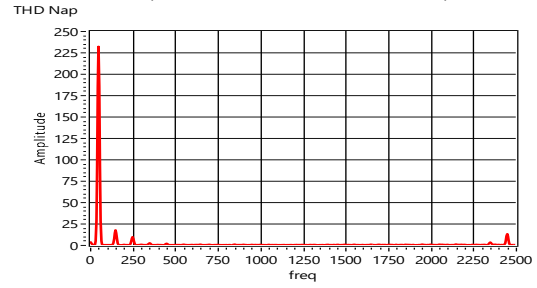


Long-term [s] RMS instantaneous power waveform

THD		dB	%	Linear ratio
Current		-11,08	28,18	0,28
Voltage		-19,73	10,47	0,10

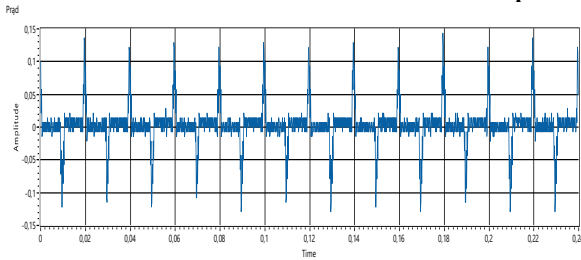


THDI of the supply current

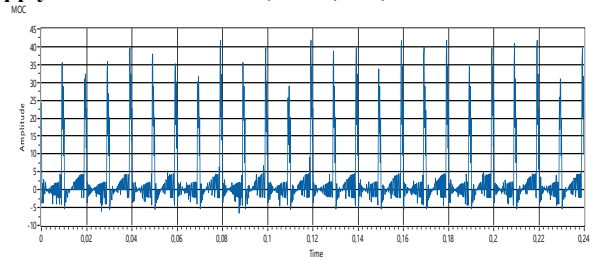


THDV of the supply voltage

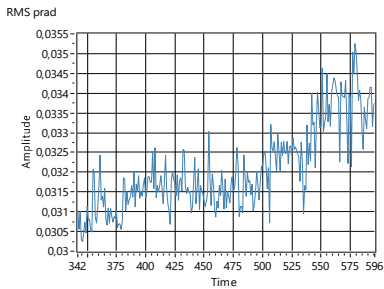
Measurement record for switch-mode power supply KSA-15E-051300HE, 5.1 V, 3 A, 15.3 W



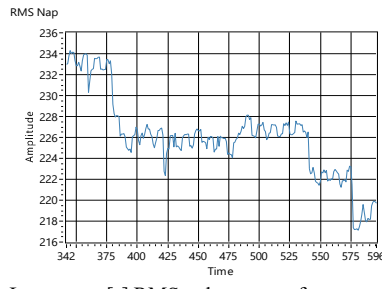
Time-domain current waveform



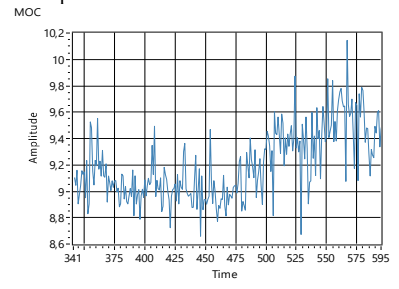
Time-domain instantaneous power waveform



Long-term [s] RMS current waveform

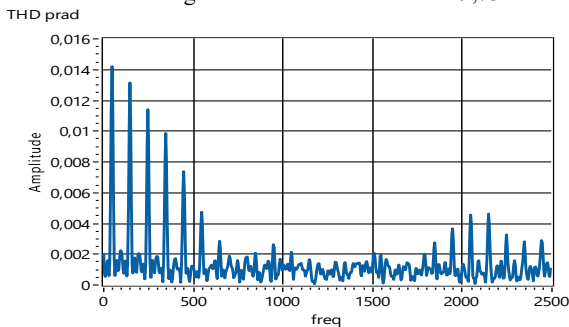


Long-term [s] RMS voltage waveform

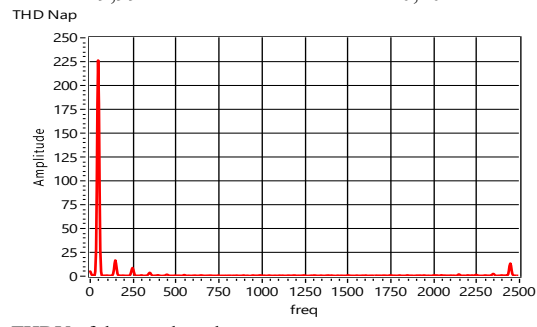


Long-term [s] RMS instantaneous power waveform

THD		dB	%	Linear ratio
Current		5,23	205,56	1,83
Voltage		-19,73	9,99	0,10



THDI of the supply current



THDV of the supply voltage

Table 2. Summary of measured power-quality parameters of selected consumer loads

Device	Rated power [W]	THDI [%]	THDV [%]	Linear ratio	Interpreted device class / closest model
Halogen lamp (reference load)	—	< 10	9.5–10.5*	—	Nearly linear reference load
LED lamp 61A75aQ15NW E27	11.0	7.80	9.98	0.08	LED driver with relatively mild distortion, closest to Model 3
Fluorescent lamp NHR32 E27	35.0	106.44	9.87	1.05	Strongly distorted rectifier-fed load, closest to Model 2
Xiaomi charger (no-load condition)	67.0	28.18	10.47	0.28	Switch-mode charger, closest to Model 4
KSA-15E-051300HE switch-mode power supply	15.3	205.56	9.99	1.83	Strongly distorted switch-mode power supply, closest to Model 4

* THDV of the supply voltage remained approximately constant during the measurement series and typically ranged from about 9.5% to 10.5%. For the halogen lamp, only the low-distortion character of the input current (THDI below 10%) was used as the reference criterion.

5. DISCUSSION OF RESULTS

The conducted numerical and experimental investigations provide a coherent and consistent picture of the mechanisms responsible for the deterioration of power quality in circuits supplying residential loads and elements of local intelligent power systems. Both simulation results and measurements of real devices clearly indicate that rectifier circuits operating with input capacitors and switch-mode power supplies constitute the dominant sources of current harmonic distortion.

Numerical modeling made it possible to identify the fundamental physical mechanism responsible for harmonic generation. The impulsive nature of current consumption, resulting from short conduction intervals of rectifier diodes during capacitor charging, appeared already in the simplest rectifier topologies. Transition to more complex configurations, such as full-wave rectifiers or switch-mode power supplies with a switching transistor, does not eliminate this phenomenon but instead increases the spectral complexity of the input current. This indicates that within the investigated set of devices, the structure of the input power stage appeared more decisive than rated power alone within the investigated set of devices.

The measured waveform of the LED lamp is consistent with the behavior predicted by Model 2, i.e. a bridge rectifier with capacitive smoothing and strongly impulsive input current. The charger exhibited features characteristic of Model 4, where rectification is combined with switch-mode conversion, resulting in high THDI and reduced power factor.

Measurements of real electrical loads strongly corroborate the conclusions drawn from numerical modeling. The reference load with nearly linear characteristics exhibited low current THDI despite the fact that the supply voltage was already distorted. In contrast, the use of loads equipped with switch-mode power supplies resulted in a rapid increase of THDI, frequently exceeding 100% and, in extreme cases, reaching values above 200%. These results demonstrate that harmonics generated by contemporary electronic devices may have RMS amplitudes comparable to or even greater than those of the fundamental current component.

A particularly important observation is that the highest distortion levels were recorded not only for high-power devices but also for small chargers and low-power power supplies. This finding challenges the intuitive assumption that power quality threats are mainly associated with single, large industrial loads. Instead, the results confirm that the problem has a distributed and potentially cumulative nature: individual low-power devices may be negligible from a system perspective, but the simultaneous operation of a large number of similar nonlinear loads leads to significant qualitative overloading of low-voltage networks.

Special attention should also be paid to the fact that the experimental measurements were carried out under real supply conditions characterized by a noticeable level of voltage distortion. This means that nonlinear loads do not operate in isolation but in an environment that is already harmonically degraded. In such conditions, a mutual reinforcement effect occurs: distorted voltage contributes to further distortion of the drawn current, while nonlinear current consumption aggravates voltage waveform deformation. This mechanism is particularly important from the standpoint of the stability and operational safety of local power networks and should be taken into account in their technical assessment.

The analysis of the power factor enables an important distinction between the underlying causes of its degradation. In both numerical simulations and experimental measurements, cases were observed where a low power factor coincided with a relatively small phase displacement angle of the fundamental current component. This indicates that power factor deterioration was caused mainly by current waveform distortion rather than by classical displacement reactive power. This result has significant diagnostic implications, as it shows that traditional reactive power compensation methods are insufficient for improving power quality under present conditions dominated by nonlinear loads.

From a system-level perspective, the obtained results suggest that parameters such as THDI and the power factor should be treated as indicators of the operating condition of the network, rather than merely as characteristics of individual loads. High THDI values imply increased losses, qualitative

overloading of network infrastructure, and a higher likelihood of malfunctioning protection and metering systems. In this sense, harmonic analysis becomes an integral part of technical diagnostics of low-voltage power networks.

The study also highlights the limitations of classical mitigation approaches based solely on passive filtering on the AC side. While such filters may suppress selected frequency components, they do not eliminate the root cause of the problem, namely impulsive energy transfer to input capacitors. More effective solutions involve direct intervention in the post-rectification energy transfer mechanism, such as DC-side inductors or active power factor correction. The measured device showed partial similarity to Model 3, suggesting the presence of passive filtering elements that smooth the input current but do not eliminate harmonic distortion.

In this context, alternative power supply architectures, particularly local DC networks, deserve further consideration. Although DC systems do not completely eliminate power quality problems, they may reduce the number of AC/DC conversion stages and limit the scale of harmonic phenomena associated with the mass deployment of switch-mode power supplies. The presented results confirm that this direction represents a justified and promising area for further research, especially in local prosumer installations and microgrids.

In summary, the discussion of results shows that the observed phenomena are universal and systemic in nature. Harmonics generated by contemporary electronic loads are not marginal effects but constitute an important factor influencing the reliability, safety, and correct operation of modern power infrastructure. Consequently, their analysis should form an essential element of diagnostics in low-voltage power networks.

6. FINAL CONCLUSIONS

Based on the performed literature review, numerical modeling, and experimental investigations of real electrical loads, the following final conclusions can be drawn:

1. The adopted hypothesis has been confirmed, indicating that the dominant sources of high values of total harmonic distortion of current (THDI) in circuits supplying residential installations and local intelligent power systems are rectifier circuits operating with input capacitors and switch-mode power supplies. Within the investigated set of loads, the decisive factor was the topology of the input power stage rather than the rated power of the load.
2. Numerical modeling demonstrated that impulsive current draw from the grid occurs already in the simplest rectifier circuits, while the transition to more complex topologies only increases the spectral complexity of harmonic components. This indicates that the generation of current harmonic distortion is inherent to the topology of the input stage and constitutes a direct consequence of AC voltage rectification and capacitive energy transfer.
3. Measurements of real electrical loads confirmed the simulation results. Loads with nearly linear characteristics exhibited low current distortion, whereas LED light sources, chargers, and switch-mode power supplies reached very high THDI values, often exceeding 100% and, in extreme cases, exceeding 200%.
4. Analysis of the power factor showed that its deterioration in the examined systems resulted mainly from current waveform distortion rather than from classical phase displacement between the fundamental voltage and current components. This indicates that conventional reactive power compensation methods, although effective in linear systems, are not sufficient to ensure satisfactory power quality in networks dominated by modern nonlinear loads.
5. An important methodological conclusion is that the experimental investigations were conducted under conditions of actually distorted supply voltage. This means that nonlinear loads operate in an environment that is already harmonically degraded, which may lead to mutual reinforcement of adverse phenomena.
6. Parameters such as THDI and the power factor should therefore be treated as useful diagnostic indicators of network operating conditions, rather than solely as quality parameters of individual loads. High THDI values may constitute an early warning signal of deterioration of network operating conditions due to cumulative distortion of the power supply system and potential malfunctions of protection and metering systems.
7. Classical mitigation measures based exclusively on passive AC-side filtering allow only partial reduction of the observed effects. Effective improvement of power quality requires intervention in the post-rectification energy transfer mechanism, for example through the use of DC-side inductors or active power factor correction circuits.
8. The presented results justify the need for further research on the influence of harmonics on the accuracy of electricity metering and on alternative power supply architectures, particularly local DC networks, which may limit problems resulting from the mass rectification of AC voltage by end-use devices.

In summary, harmonic disturbances and power factor degradation should be regarded as significant diagnostic challenges with a direct impact on the reliability, safety, and stability of modern low-voltage power networks. With the continuing increase in the number of power-electronic loads, the importance of this problem will continue to grow.

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Data availability: The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Declaration of competing interest: The author declares no conflict of interest.

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