

Article

Disturbances Generated by Lighting Systems with LED Lamps and the Reduction in Their Impacts

Łukasz Putz ^{*}, Karol Bednarek ^{*} and Ryszard Nawrowski

Poznan University of Technology, Faculty of Electrical Engineering, 3A Piotrowo Street, 60-965 Poznan, Poland; Ryszard.Nawrowski@put.poznan.pl

^{*} Correspondence: lukasz.putz@put.poznan.pl (Ł.P.); karol.bednarek@put.poznan.pl (K.B.)

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Featured Application: The article materials can be used in modernization works of lighting systems in commercial facilities.

Abstract: The paper deals with electromagnetic disturbances in the form of current higher harmonics, which are generated by LED lighting elements. It presents the problems related to the formation and impact of higher harmonics in the electrical systems of commercial facilities. The results of tests and analyses of current distortions for two different LED lamps are included, and these are in reference to the parameters set out in the normal applicable standards. A system was then proposed to improve the quality of energy in the mains of commercial facilities in the form of a two-stage power supply. Tests of the systems with the aforementioned LED lamps were conducted and commented upon after introduction of the two-stage power supply. The final part of the paper contains a summary of the obtained test results.

Keywords: LED lamp; lighting system; current and voltage distortion; higher harmonics; total harmonic distortion (THD); electromagnetic compatibility; power factor correction (PFC); two-stage power supply

1. Introduction

Electrical and electronic devices used and manufactured nowadays are very often technically advanced. Most frequently, they are characterised by the pulse consumption of energy. Non-linear elements are commonly used in them. This causes the distortion of the temporal waveforms of currents drawn by them and the voltages processed by them (despite being powered by sinusoidal voltage). Thus, during their operation, there are problems with the impact of higher harmonics. These issues are strictly related to the quality of the energy in the electrical power systems, and consequently, also to the reliability and correct operation of the electrical equipment and its energy efficiency. Therefore, they are key elements for the functioning of commercial facilities and in everyday life [1–12].

In commercial and industrial buildings as well as in residential buildings (in private life, e.g., houses or apartments), in order to ensure the appropriate working, living, and rest conditions for humans, and also for the purpose of making different facilities visible or exposed, lighting systems where different artificial light sources are used are commonly applied. In view of their very low luminous efficiency, the use of traditional bulbs has been abandoned almost completely. Instead, discharge light sources were introduced, thus improving the luminous and energy efficiency of the lighting systems. Luminaires that use light-emitting diodes (LED) are characterised by even more advantageous parameters in this respect. LED lamps produce a lot of light with relatively low electricity consumption. The use of such light sources is also economically advantageous—the long life means lower investment costs, and the low active power consumption translates into lower operational costs.

Despite many advantages, the electroluminescent light sources have one major drawback—they cause strong distortions in the current [13–24].

This article focuses on the issue of the generation of current higher harmonics by LED lighting elements. The results of the measurements of electricity quality parameters for various light sources based on LED technology will be presented and analysed. A system that allows for the adjustment of the content of current higher harmonics in large electrical installations (e.g., lighting systems comprising LED lamps) will be presented. Also, the results of the measurements will be presented after introducing such a system into installations using the previously tested lighting elements.

2. The Impact of Higher Harmonics in Electrical Circuits

Each non-linear element incorporated into the system most frequently causes the non-linearity of that system (the distortions of currents and voltages which occur in it) and thus, the occurrence of problems connected to the impact of higher harmonics. Very frequently, the consequences of the impact of higher harmonics are severe for other devices operating in the surrounding environment, and thus also for their users [2–10].

A high level of distortion of the current or voltage signal is related to [4]:

- The instability of the power supply system,
- Increased reactive power consumption,
- Increased active power losses,
- A reduction in the efficiency and durability of devices.

The level of the impact of higher harmonics on electrical devices depends on the sensitivity and resistance of these devices. Loads that are similar to resistance loads in nature, and that are mainly used for heating purposes (e.g., resistance furnaces) demonstrate the highest resistance. On the other hand, small electronic devices designed to be powered by a sinusoidal signal with the mains frequency, such as the automated control equipment of an intelligent building, are characterised by the highest sensitivity to the impact of higher harmonics. The impact consequences of higher harmonics can vary depending on the group of devices [2–6,9,10,12,25]:

- In motors and generators, they cause an increase in the losses in the winding and the magnetic circuits, which leads to an increase in the operating temperature of the devices and contributes to the faster ageing of winding insulations; thus, their operation time is shortened; in three-phase induction motors, negative sequence components (e.g., h_5 or h_{11}) generate a rotating field in the opposite direction to the rotation of the rotor; thus, they generate a braking torque, and as a result of this, they are an additional load for the motor;
- In transformers, the distorted current causes an increase in the losses both in the winding and the core; the higher losses mean the generation of a higher amount of heat, and in order to maintain the rated operating temperature, it is necessary to reduce the maximum transformer load in which the distorted currents and voltages occur; in three-phase four-wire systems, in the neutral wire, the zero sequence harmonics are aggregated (especially the third one and the ninth one), causing an increase in current in the neutral wire, which may, as a consequence, result in damage to the neutral wire;
- In capacitors, they are manifested in the form of current and voltage overloads; this may cause local discharges in the dielectric, which consequently lead to short circuits in the plates and permanent damage to the capacitor;
- In switches, contactors, or relays, their proper operation may be disturbed, the switch moment may be completely different from that for which they were designed (the devices may switch off in an apparently unjustified manner, and as a consequence of this, there may be downtimes in the operation of active auxiliary electrical equipment); with the THD exceeding 20%, this is a typically stochastic process;

- In electronic devices, interferences in their operation may occur (due to a different total value of the supply voltage containing higher harmonics), or the devices may be subject to damage (the current higher harmonics cause additional heat losses that significantly increase the operating temperature, which, most frequently, is already extreme under normal conditions); furthermore, at high peak factors, damage to semi-conductor sub-assemblies is also possible;
- In electrical light sources, symptoms may vary depending on the type of the light source, but generally, a change in the lighting intensity is noticeable; also, the temperature of the lamps increases, which results in a speeding up of the ageing processes.

Problems related to signal distortions become more and more complicated, as the above-mentioned technically advanced devices (e.g., LED lamps), on the one hand, are a source of higher harmonics, and on the other hand, on many occasions, they are systems which are strongly sensitive to the impacts of voltage and current higher harmonics.

Electroluminescent light sources are capacitive loads, and they draw current in which the signal is significantly distorted from the sinusoid. The nature of the load and the current waveform are significantly affected by control and supply systems built using DC-DC converters. As a consequence of this, the power factor declines, high reactive power is consumed, and higher harmonics of current are generated affecting voltage distortion in the power mains. This follows from the fact that LEDs, which are the main components of LED lamps, are non-linear elements. The systems that manage their operation (drivers) are also characterised by strong nonlinearities. Each non-linear element incorporated in the electrical circuit causes current waveform distortion in the system. In analyses of distorted signals, using the Fourier transform, this translates into the occurrence of a frequency spectrum in which, in addition to the fundamental frequency (compliant with the distorted signal frequency), intensive components with frequencies that are a multiple of the fundamental frequency appear, i.e., higher harmonics [26–32].

In driver circuits, power factor correction (PFC) circuits, which work to reduce current distortions, i.e., to reduce the occurrence of higher harmonics, are integrated. The degree of reduction in the impact of the harmonics depends on the quality and technical advancement of these circuits. However, this is related to the price of these circuits. In the market economy, the price of products is often the factor that has a decisive impact on the choice of structural solutions for products. Therefore, cheap elements with disadvantageous technical parameters, which are not directly important for the user, appear on the market. The results of their application, however, are the irrational management of energy and an adverse impact on other devices that operate in the same electrical system.

The issue of the deterioration of the electrical parameters in lighting systems is particularly important in the case of connecting compact LED luminaires, which are substitutes for traditional light sources in the already existing installations of facilities. Because of the limited dimensions of such lamps, the application of extended current distortion correction circuits inside them is difficult. The negative aspects of the use of electroluminescent light sources have been discussed on many occasions by the authors of this article in numerous publications and during conferences [20–23,28–30].

This is, by no means, just a local or national problem. It concerns all countries because electrical lighting is commonly used everywhere. Complex lighting systems may consist of hundreds or even thousands of light sources. If the number of LED lamps connected to electrical systems constitutes a significant part of all of the electrical light sources in a facility, then, because of the level of power consumed, problems with the impact of higher harmonics in such mains occur. In many scientific centres from all over the world, research related to the quality of the electricity in the power systems of LED lamps is conducted [13–32]. At the same time, different solutions aimed at the improvement of the electricity quality parameters in these systems are proposed [33–46].

The problem may turn out to be very serious in a very near future. The number of LED lamps connected to the electricity network is increasing rapidly. They are widely used in domestic and office lighting, in public utility places, as street and industrial lighting, and in recent years, even as lighting

in cars [47]. In the not so distant future, this type of lamp may drive all other light sources used so far out of the market.

The importance of the discussed issue is intensified by provisions included in Directive 2005/32/EC of the European Parliament, which prohibit any further manufacture and marketing of incandescent light sources within the EU (excluding special applications where their use is indispensable) [48]. At the same time, the Directive orders a switch to energy-saving lighting (LED lamps or compact fluorescent lamps). The schedule for the gradual withdrawal of bulbs was included in regulation No. 244 of the European Commission from the year 2009 [49].

The limitation of the impact of higher harmonics in electrical systems in large facilities may consist of the appropriate separation of loads, that is, the application of separate power lines for loads that generate higher harmonics and for loads that are sensitive to the impact of higher harmonics. It may also involve the installation of separation transformers. In order to eliminate the impacts of higher harmonics on other electrical circuits, it is recommended, above all, to use filters. In practice, passive filters are often used for this purpose (mainly in systems where the frequency characteristics of the current drawn do not change)—solutions that are simple but at the same time cheap. In systems where there are more circuits and devices that generate higher harmonics with a different spectral distribution of the introduced harmonics, activated stochastically (not systematically), it is recommended to use active filters, which are more effective and eliminate the harmonic impacts with greater precision. However, they are more complex and much more expensive (an economic justification for their implementation is also required for them).

A reduction in the impacts of higher harmonics in large systems (e.g., lighting systems) may be achieved through the use of a two-stage power supply. The mains voltage is rectified at the input of the power supply and then supplied to the inverter system via a DC line, where sinusoidal voltage with more advantageous parameters than those of the mains voltage is generated. Because of the two-stage operation (the occurrence of a DC section), disturbances generated in the circuit switched on at the output of the power supply are transferred to a limited extent to its input, i.e., the power mains. The introduction of such solutions is not planned if single LED lamps or lighting systems with a very small number of such lamps (with low total power) are implemented. Above all, in such a case, there will be no economic justification for the application of such a technical solution, and furthermore, distorted signals with extremely lower power hardly affect the power mains. Therefore, the introduction of systems to limit the impacts of higher harmonics in systems where distorted currents will have high values (high distortion powers will be present) is more important. In such a situation, two-stage power supplies would be economically justified.

In particular cases, when there is a need in the given power mains for guaranteed level of power supply, it is possible to use the two-stage power supply (UPS) system, which, in the VFI (Voltage Frequency Independent) topology, contains the two-stage power supply within its structure, and in addition to the provision of an uninterrupted power supply, will simultaneously limit the impact of higher harmonics on the remaining part of the mains. In a properly selected two-stage power supply, in addition to the elimination of the impacts of higher harmonics (distortion power), the consumption of reactive power (related to the phase shift between the basic harmonics of current and voltage) is also limited. The limitation of the reactive power consumption is also linked to a reduction in the costs of drawing energy from the mains for institutional recipients, which would be an additional justification for the introduction of such a two-stage power supply. An example where this issue was solved this way involves the UPS EVER Powerline Green power supplies, which, as well as an uninterrupted power supply and absorption of harmonic impacts, allow for compensation of the reactive power of other devices connected to the joint power supply network through the appropriate management of the current drawn from the network (at a level of 25% of apparent power of the UPS)—this functionality is undergoing the patenting procedure at the moment. Owing to the use of the two-stage power supply (UPS), an improvement in the quality of the power supplied to the loads by it is also achieved.

In this paper, the authors globally dealt with issues related to the elimination of impacts of higher harmonics on the power mains—through the application of two-stage power supplies (UPS VFI) in electrical lighting systems that comprise a large number of LED lamps.

3. Tests of Selected LED Lamps

LED lamps, just like any electrical device, should meet the requirements for the emission of higher harmonic currents. These requirements were stipulated in IEC 61000-3-2:2019 [50]. According to the quoted standard, electrical devices were divided into four groups: A, B, C, and D. LED light sources, as lighting equipment, were qualified into group C. In this group, the lighting equipment is divided into subgroups, and the active power consumed by the device was assumed as the criterion of the division. Loads whose power exceeds 25 W belong to one group and the second group comprises loads with a power of up to 25 W, inclusively. The active power is determined on the basis of a certain measurement. If the measured power is within the limits, ranging between 90% and 110%, of the rated power of the device, the power declared by the manufacturer must be selected. If, on the other hand, the value of the measurement exceeds the specified limits, the measured power is taken into account.

The tests presented in this article refer to LED lamps up to 25 W. For this reason, only the requirements of IEC 61000-3-2:2019 [50] for tested light sources are described.

Two sets of requirements were presented in IEC 61000-3-2:2019 [50] for lighting devices with an active power less than or equal to 25 W; however, it was clearly emphasised that it was enough to fulfil only one set (any and at the same time more advantageous) to meet the requirements of the standard:

1. The respective harmonic currents of loads converted into one watt of the input active power, should not exceed the permissible levels presented in Table 1.
2. The third and fifth harmonic currents expressed as a percentage of the fundamental component of load current should not exceed 86% and 61%, respectively, and at the same time, the pattern of the temporal current waveform should meet specific parameters. The threshold value at a level of 5% of the current amplitude during growth should be achieved before or at 60° of the shift in relation to the supply voltage signal, and 100% of the amplitude before or at 65°. The 5% threshold during the current signal fall should be achieved at or after 90° [50].

Table 1. Permissible values of current harmonics for lighting devices (class C) with an input active power less than or equal to 25 W (according to [50]).



Harmonic Order h	Maximum Permissible Harmonic Current Recalculated on a LED Lamp with One-Watt Active Power Input I_h [mA/W]
3	3.4
5	1.9
7	1.0
9	0.5
11	0.35
13, 15, ..., 39	$3.85/h$

Two types of LED lamps were subjected to testing.

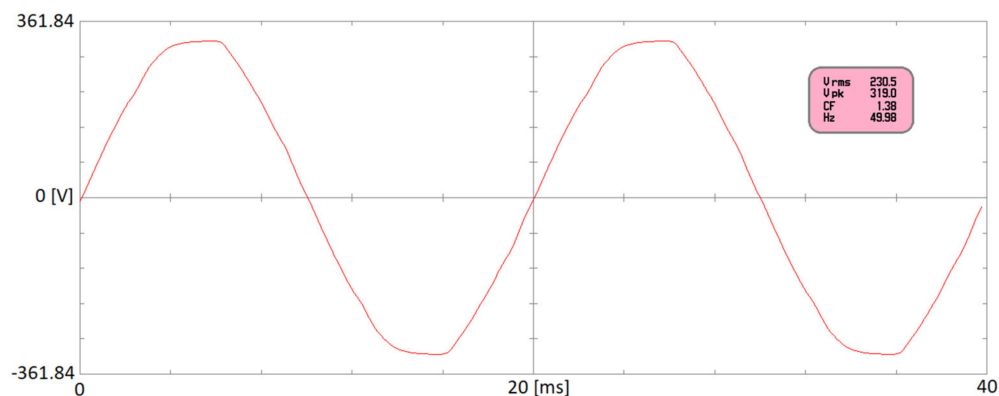
1. LED lamps with the E27 base with a power of 8 W, including 8 COG diodes, which can be substitutes for traditional bulbs, most frequently used in households;
2. 25 W LED linear luminaires, including 36 diodes, type SMD5050, which may be a substitute for luminaires with linear fluorescent lamps, often used in schools or offices.

The most important rated parameters of the tested semiconductor light sources are listed in Table 2.

Table 2. Rated parameters of tested light sources.

	LED Lamp 1	LED Lamp 2
		
Nominal Power P_N	8 W	25 W
Nominal Voltage U_N	220–240 V	230 V
Frequency of Supply	50/60 Hz	50 Hz
Voltage f_N		
Type of LED	COG	SMD5050
Number of LEDs	8	36
Luminous Flux Φ	1055 lm	3350 lm
Color Temperature T_C	3000 K (warm)	4000 K (neutral)

The tested lamps were powered with mains voltage with the effective value $U_{rms} = 230.5$ V and frequency $f = 49.98$ Hz. The supply voltage waveform was slightly distorted from the sinusoid, as is visible in Figure 1. Thus, higher harmonics are present in the voltage signal (Figure 2). The total harmonic distortion value in voltage THD_U was 2.2%; on the other hand, the voltage crest factor CF_U was 1.38. In accordance with the requirements of [50], the measured voltage parameters are within the permissible limits and can be used to power electroluminescent light sources. In order to perform the tests, the system was deliberately powered in this way, as in this case, it was necessary to create the real operating conditions of the LED lamps in facilities. Tests were conducted using a professional energy quality analyser—FLUKE 434/PWR. Current and voltage waveforms were studied using the Fluke View software.

**Figure 1.** Oscillogram of the waveform of the voltage powering the tested LED lamps.

The results of the performed measurements of electrical parameters for both lamps (Table 3) were compliant with the values declared by manufacturers. The active power of LED lamp 1 was 8.3 W, and for LED lamp 2, it was 25.2 W. The values of the current crest factor CF_I , amounting to 3.09 and 1.97 mean significant distortions of the current waveform, especially in the case of LED lamp 1. Figures 3 and 4 show oscillograms of the current and the supply voltage waveform obtained for the tested lamps.

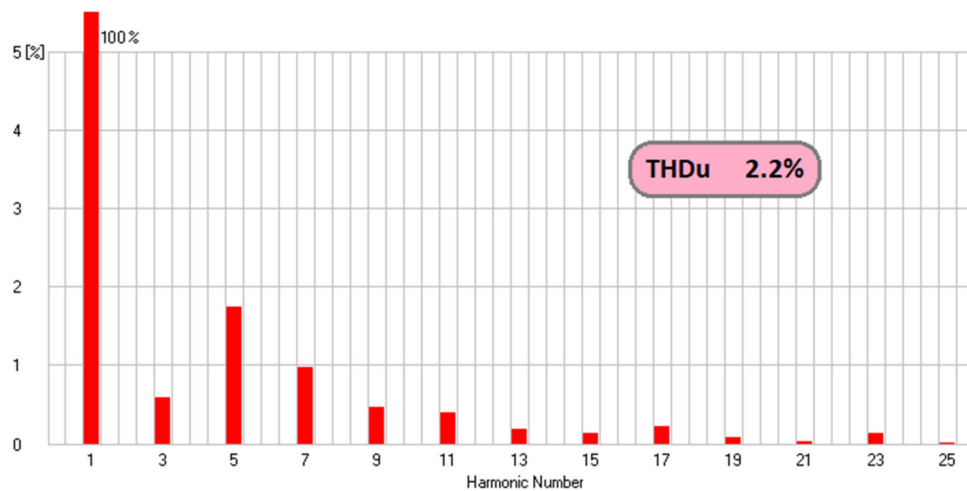


Figure 2. Spectral characteristic of higher harmonics of voltage supplying the tested LED lamps.

Table 3. Results of measurements of electrical parameters for the tested LED lamps.

	LED Lamp 1	LED Lamp 2
RMS Current I_{rms}	40 mA	119 mA
Amplitude of Current I_m	124 mA	237 mA
Current Crest Factor CF_I	3.09	1.97
Active Power P	8.3 W	25.2 W
Reactive Power Q	3.8 var	9.7 var
Apparent Power S	9.1 VA	27.1 VA
Power Factor $\cos \varphi$	0.91	0.93
Power Factor PF	0.63	0.88
Total Harmonic Distortion Ratio THD_I	121.2%	54.1%
3rd Current Harmonic Level h_3	88.5%	46.4%
5th Current Harmonic Level h_5	60.4%	11.0%
7th Current Harmonic Level h_7	38.7%	15.2%
9th Current Harmonic Level h_9	36.3%	6.1%
11th Current Harmonic Level h_{11}	30.5%	9.7%
13th Current Harmonic Level h_{13}	23.4%	8.6%
15th Current Harmonic Level h_{15}	16.8%	6.1%

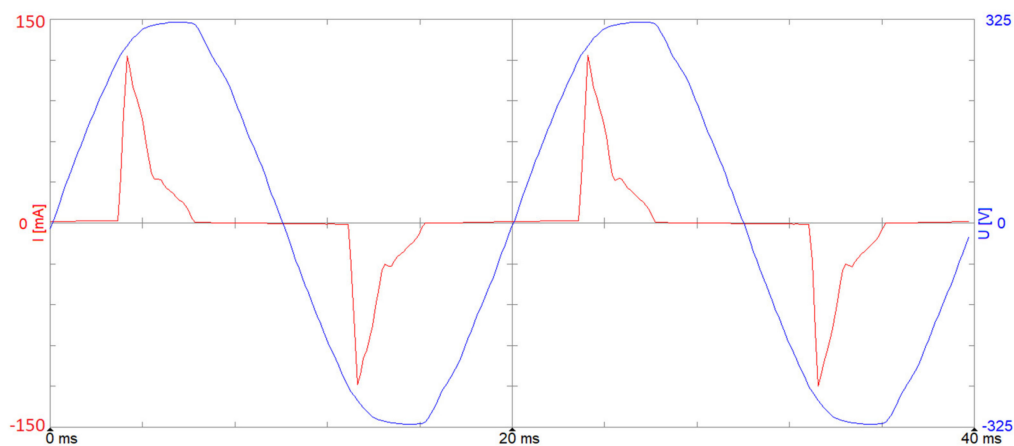


Figure 3. Oscillogram of the waveform of voltage and current flowing through LED lamp 1.

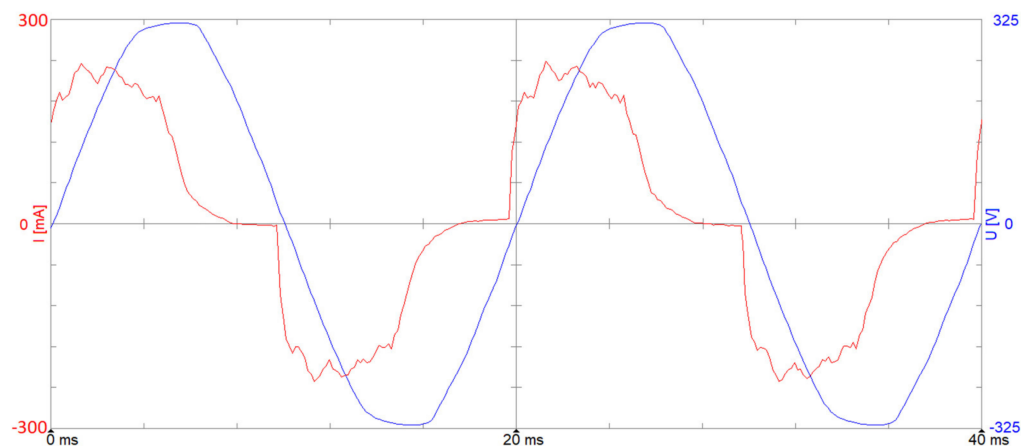


Figure 4. Oscillogram of the waveform of voltage and current flowing through LED lamp 2.

Measurements of the current higher harmonics for the tested LED lamps confirmed the suppositions resulting from the observation of the oscillograms. LED lamp 1 generates high initial levels of uneven current higher harmonics $h3$, $h5$, and $h7$, which have the strongest impact on the current waveform distortions, these were at the following values: 88.5%, 60.4%, and 38.7%, respectively. The level of the third harmonic exceeds the permissible limit determined in [50]; therefore, the use of the lamp on the European market should not be allowed. In the case of the second tested lamp, the results of the measurement of the current higher harmonics are clearly lower and are within the limits of normatively permissible values ($h3 = 46.4\%$, $h5 = 11\%$, and $h7 = 15.2\%$). These are, however, still very high values of current harmonics, which may have a negative effect on supply voltage distortions or the safety of the electrical system and other loads.

The total harmonic distortions in current THD_I for the tested lamps amounted to 121.2% (LED lamp 1) and 54.1% (LED lamp 2). Consequently, the second light source clearly affects deterioration in the power quality parameters to a lesser extent. The presence of higher harmonics is also proven by the lower value of the power factor PF (which takes into account higher harmonics) in relation to the power factor $\cos \varphi$ (only for basic components). Also, in the case of these measurements, the results for the first lamp proved to be worse than in the case of the second lamp; for LED lamp 1, $PF = 0.63$ (at $\cos \varphi = 0.91$), and for LED lamp 2, obtained $PF = 0.88$ (where $\cos \varphi = 0.93$).

Figures 5 and 6 present the values of the currents of the respective harmonics converted into one watt of the input active power of the tested LED lamp. The comparison was made with the values permissible in accordance with the aforementioned standard [50]. The percentage content of harmonics $h3$ and $h5$, as well as the total harmonic distortions in the current THD_I for the tested light sources, are also provided.

While analysing charts from Figures 5 and 6 and referring to the provisions of IEC 61000-3-2 [50], it can be concluded that the first light source exceeds the permissible values in each of the two provided sets of requirements. In the case of the second light source, the shape of the current temporal waveform and the share of current harmonics $h3$ and $h5$ are within the specified permissible values. On the other hand, the hypothesis, which refers to the levels of the respective uneven current harmonics, is not confirmed.

If single LED light sources are used, their power is small in comparison to other electrical loads and would not exert a significant impact on the deterioration of the power quality in power mains. However, if the total power of electroluminescent light sources was to be taken into account, for example, in schools, office buildings, shopping centres or manufacturing halls, it might turn out that these would be the main electrical loads in the given facility, and then their significant share in the deterioration of the power quality parameters must be considered. In such cases, it is globally advisable (for a given facility) to use devices which limit the penetration of current higher harmonics generated by the LED lighting into the power mains. A two-stage power supply may be one such device.

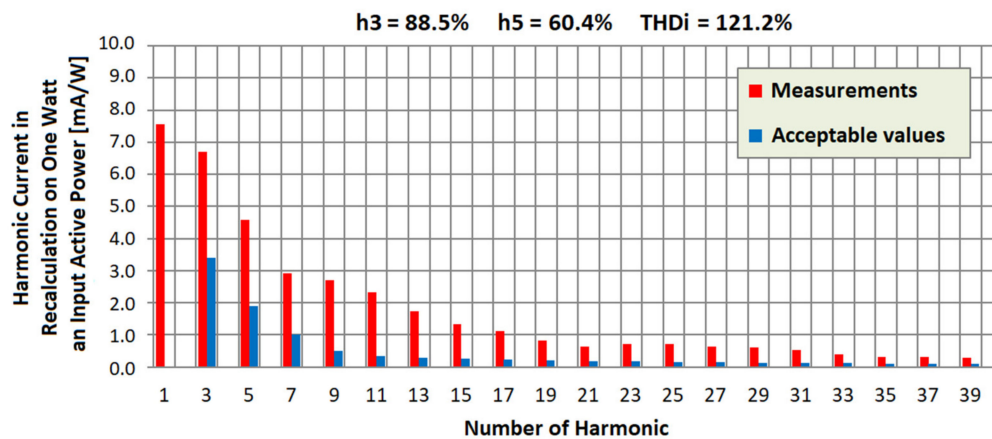


Figure 5. Spectral characteristic of current higher harmonics flowing through LED lamp 1 in reference to the permissible values according to [50].

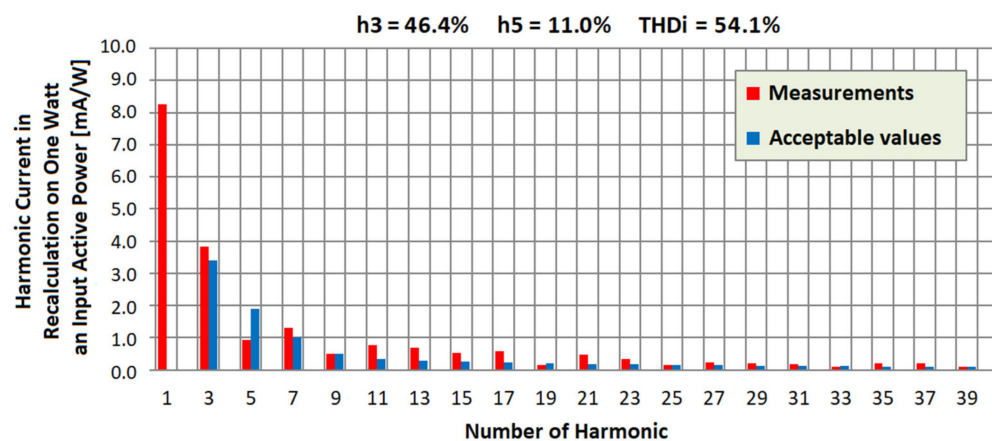


Figure 6. Spectral characteristic of current higher harmonics flowing through LED lamp 2 in reference to the permissible values according to [50].

4. Two-Stage Power Supply (with a Double Conversion)

In the case of the connection of power supply circuits to loads with strong non-linearities, which draw strongly distorted currents (with a high content of higher harmonics), it is necessary to apply circuits that reduce the occurrence of current and voltage higher harmonics. Recipients with a significant grouping of such loads are commercial facilities, where a lot of computer hardware (containing switching power supplies), electronic regulators of the consumed power (e.g., in ventilation systems, air-conditioning systems, industrial systems), or energy-saving lighting (discharge lamps or LED lamps) are in use. Besides the production sphere, other facilities may also include shopping centres, banks, office buildings, educational, medical and service facilities as well as other business units and residential buildings.

One device that significantly limits the occurrence of current higher harmonics in the power grid is a two-stage power supply. The double conversion of electricity takes place in it: the sinusoidal voltage of the power supply system is rectified in the rectifier block at the power supply input and is then supplied to the inverter through the DC-DC bus where it is converted into sinusoidal voltage with much more advantageous parameters. In this circuit, an improvement in the quality of the supply voltage parameters (values, frequencies, shape) is obtained. The energy separation of loads and the network takes place, and at the same time, a significant limitation in the impact of the current higher harmonics of non-linear loads on the power mains is achieved.

In practice, such power supplies are the main component of the uninterrupted power supply (UPS), operating in the VFI (Voltage Frequency Independent) topology, i.e., on-line. A block diagram of

this system is presented in Figure 7. The use of a battery pack additionally allows for the uninterrupted supply of loads in the event of a power failure or improper parameters of the supply voltage (until the energy collected in energy storages is exhausted) [4,5].

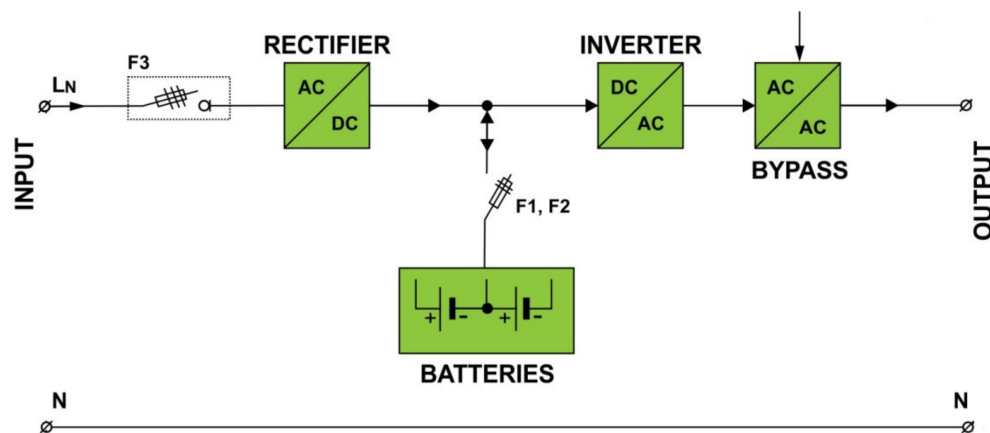


Figure 7. Block diagram of the two-stage power supply in the VFI two-stage power supply (UPS).

In view of the properties of the two-stage power supply and its common use in UPS VFI, this chapter of the article presents the results of testing of a three-phase, non-linearly loaded UPS for the purposes of quantitative and qualitative representation of this problem. The tests were performed using the UPS EVER Powerline Green 33/Lite series.

Figure 8 includes oscillograms of the distorted current with which the power supply output was loaded and the voltage at the UPS output, generated by its inverter circuit. The waveforms were vertically shifted in relation to each other, in order to make them clearly legible. The results of the testing of the higher harmonics and the total harmonic distortions (THD) of these signals are depicted in Figure 9.

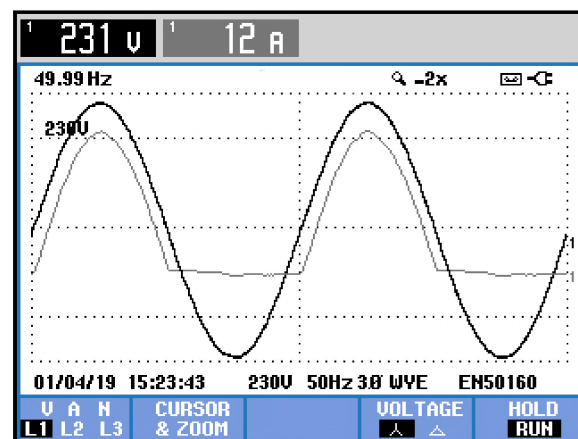


Figure 8. Oscilloscope waveforms of load current and voltage at the UPS output.

For research purposes, the waveform of the load current is intentionally shaped in a non-linear and non-symmetric manner by the specialist electronic circuit. Its THD_I is 41.6%. In the frequency spectrum, there are mainly even harmonics, which is the consequence of the lack of symmetry of the load (the current is drawn in a single wave). Voltage generated at the UPS output (supplied to loads) is sinusoidal, with a small THD_U , which is equal to 0.7%.

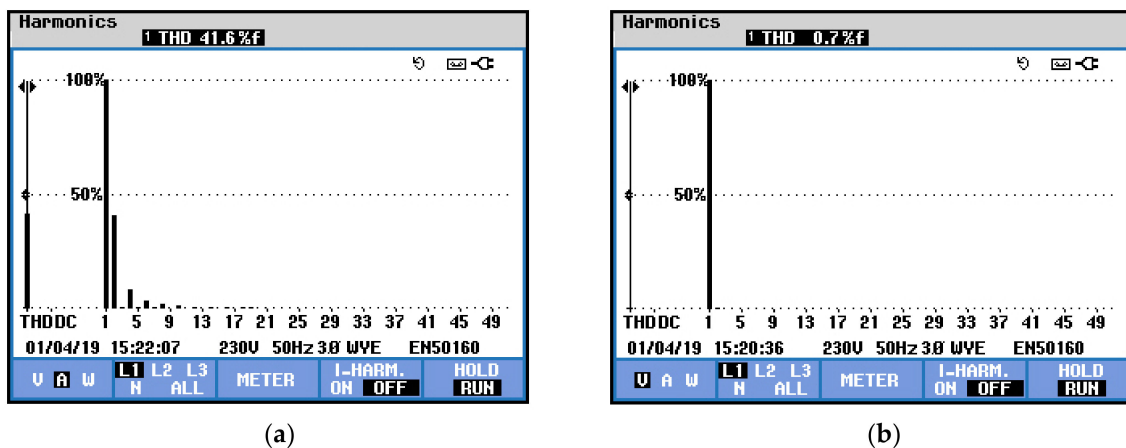


Figure 9. Frequency spectrum of the higher harmonics and THD for: (a) UPS load current, (b) voltage at the power supply output. The oscilloscope waveforms of the mains voltage supplied to the power supply input and of the current drawn by the UPS from the mains are presented in Figure 10, and the results of tests of the higher harmonics and THD for these signals can be seen in Figure 11.

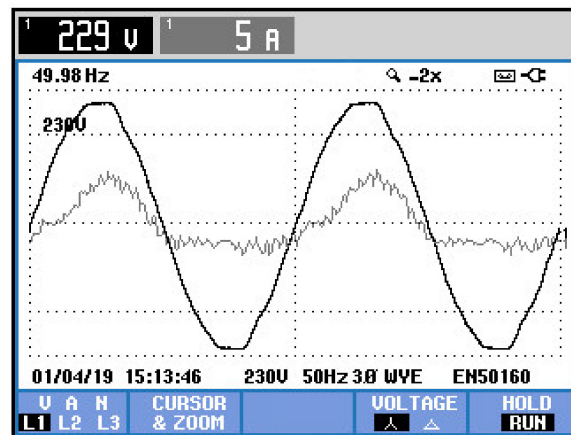


Figure 10. Oscilloscope waveforms of the current drawn by the UPS from the mains and of the mains voltage at the power supply input.

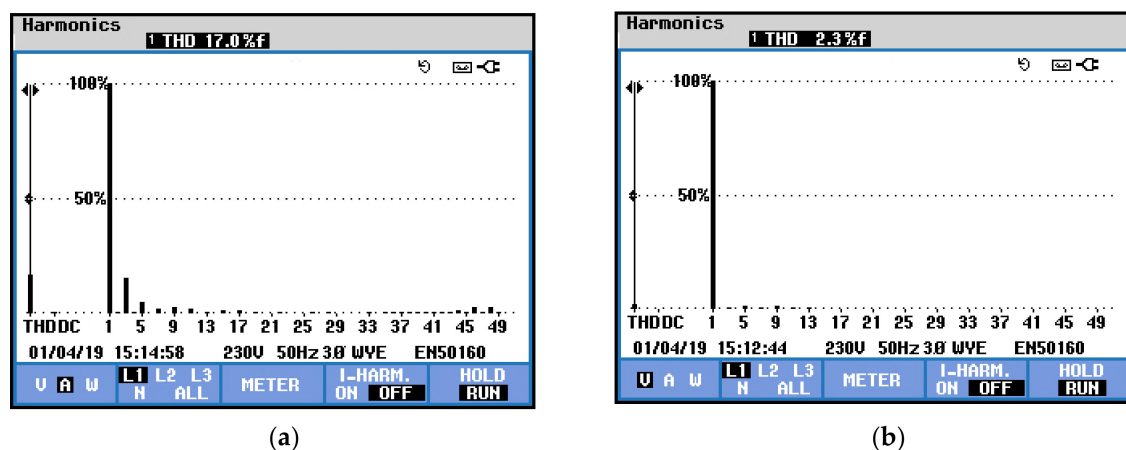


Figure 11. Frequency spectrum of higher harmonics and THD for: (a) current drawn by the UPS from the mains, (b) mains voltage at the power supply input.

The current drawn from the mains by the UPS, loaded non-linearly and non-symmetrically, has the THD_I at the level of 17%, and thus about 2.5 times lower than the THD of the power supply load current. Furthermore, mainly uneven harmonics are present in it; thus, the power supply performed

symmetrisation of the current waveform. The mains voltage during the performed tests had THD_U at a level of 2.3%. So, it can be stated that the UPS reduced the distortion of voltage supplied to loads by more than three times. In similar UPS operating systems with double energy conversion, even more advantageous results regarding improvements in the electricity quality were obtained, and these were presented in the papers of [2–6]. At non-linear symmetrical UPS load current waveforms, the obtained distortions of the current (THD_I) drawn from the mains were even seven times lower in relation to the non-linear load current of the UPS.

In the case of commercial facilities with strongly non-linear load characteristics and consumption of high amounts of power, in order to improve the power quality, it is possible to use three-phase uninterrupted power supplies (similar to the one tested) or, if necessary, power supplies adapted to higher powers. In specific cases, a few units operating in parallel can be used. For less powerful non-linear loads, it suffices to apply two-stage one-phase power supplies, as was the case with the single LED lamps analysed in the paper.

5. Tests of LED Lamps with an Attached Two-Stage Power Supply

Another stage of the tests was the repeated performance of measurements for the same LED lamps (described earlier), but this time, the lighting systems were modified with the introduction of a two-stage power supply. For this purpose, the UPS EVER Powerline RT 1000 was used. The results turned out to be very interesting. Their specifications are presented in Table 4.

Table 4. Results of measurements of the electrical parameters in the two-stage power supply circuit with LED lamp 1 and LED lamp 2, respectively.

	LED Lamp 1	LED Lamp 2
RMS Current I_{rms}	56 mA	145 mA
Amplitude of Current I_m	104 mA	215 mA
Current Crest Factor CF_I	1.85	1.48
Active Power P	11.7 W	31.1 W
Reactive Power Q	5.4 var	12.1 var
Apparent Power S	12.9 VA	33.4 VA
Power Factor $\cos \varphi$	0.91	0.93
Power Factor PF	0.86	0.91
Total Harmonic Distortion Ratio THD_I	32.0%	19.7%
3rd Current Harmonic Level $h3$	18.8%	10.4%
5th Current Harmonic Level $h5$	21.8%	14.2%
7th Current Harmonic Level $h7$	4.3%	3.2%
9th Current Harmonic Level $h9$	2.7%	3.7%
11th Current Harmonic Level $h11$	3.1%	0.8%
13th Current Harmonic Level $h13$	3.8%	1.5%
15th Current Harmonic Level $h15$	5.9%	2.3%

Current distortions were significantly reduced. The total harmonic distortion of current THD_I for LED lamp 1 was reduced to 32% (i.e., almost four times), and in the case of LED lamp 2, THD_I was reduced almost three times down to 19.7%. The initial uneven harmonic components $h3$ and $h5$ were significantly reduced from 88.5% and 60.4%, respectively, to 18.8% and 21.8% for the first light source. In the case of the second light source, the value of the $h3$ component was significantly reduced from 46.4% to 10.4%, while the value of $h5$ component increased slightly from 11% to 14.2%.

Figures 12 and 13 present charts of the levels of the current higher harmonics in the system with analysed LED light sources and the two-stage power supply (marked in red). For the sake of comparison, the levels of the harmonics of the lighting system without a power supply (marked in grey) and the values permissible according to [50] (marked in blue) were added. On top of this, the percentage values of $h3$ and $h5$ components and the level of the THD_I were provided.

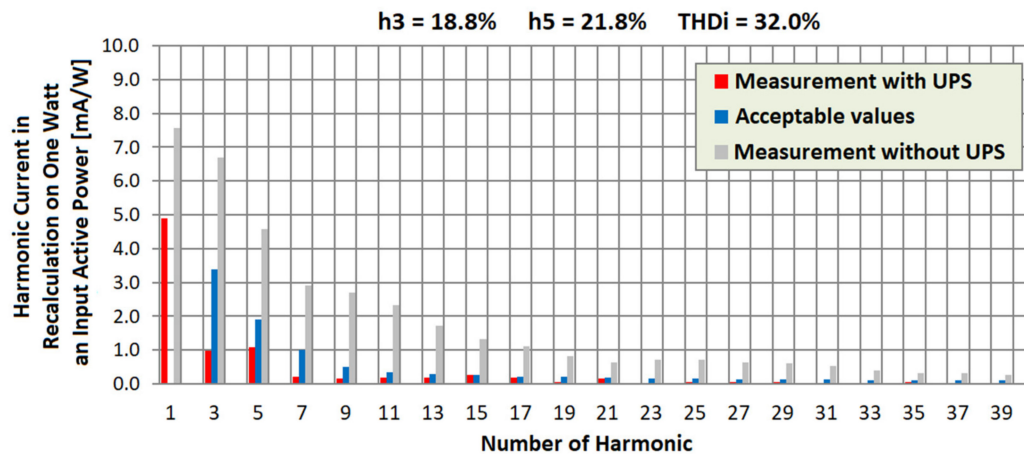


Figure 12. Spectrum of the higher harmonics of the current drawn from the mains by the power supply with a double conversion and flowing through LED lamp 1 (at the power supply output) in reference to the permissible values according to [50].

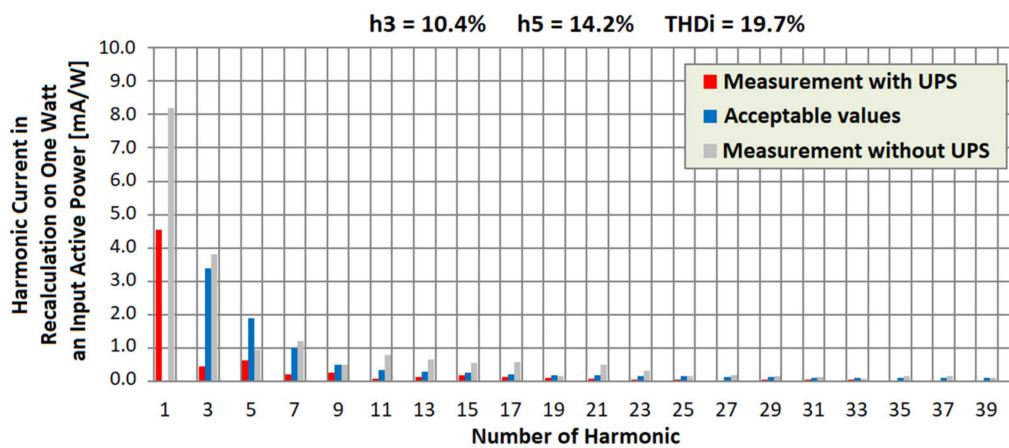


Figure 13. Spectrum of the higher harmonics of the current drawn from the mains by the power supply with a double conversion and flowing through LED lamp 2 (at the power supply output) in reference to the permissible values according to [50].

The current crest factor CF_I in the system comprising a two-stage power supply circuit and LED lamp 1 was 1.85 and was improved in relation to the circuit without the correction circuit, where it amounted to 3.09. For the system that includes LED lamp 2, the value of CF_I improved from 1.97 to 1.48. Such values indicate a change in the pattern of the current signal, which can be observed by comparing Figure 3 with Figures 4 and 14 with Figure 15. The current waveforms presented in Figures 14 and 15 are distorted from the sinusoidal waveform to a lesser extent.

The introduction of the two-stage power supply into the tested circuits also contributed to an improvement in the power factor PF from 0.63 to 0.86 (LED lamp 1) and from 0.88 to 0.91 (LED lamp 2). On the other hand, the power factor of the fundamental component $\cos \varphi$ did not change and amounted to 0.91 for the first light source, and 0.93 for the second one.

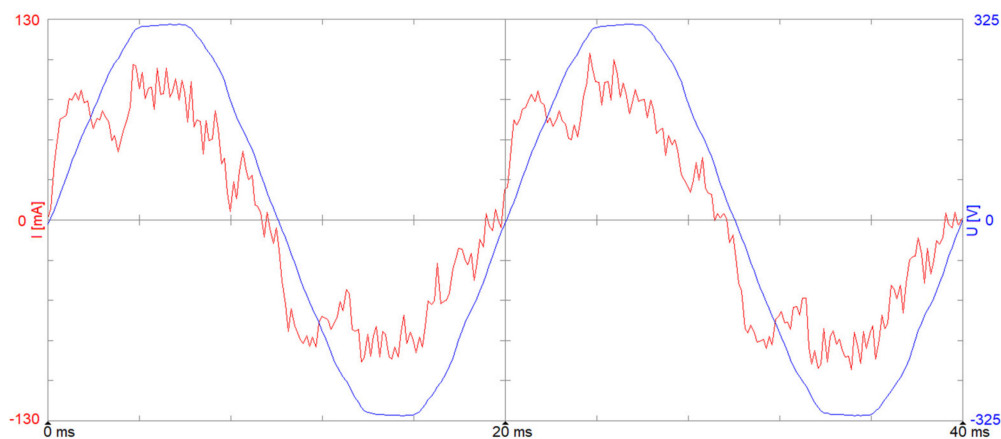


Figure 14. Oscillogram of the waveform of the current drawn by the system comprising a power supply with a double conversion, including LED lamp 1 attached at the output.

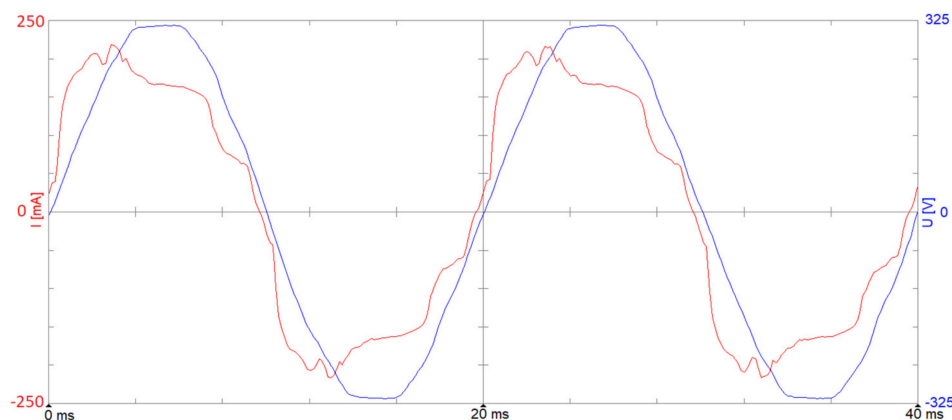


Figure 15. Oscillogram of the waveform of the current drawn by the system comprising a power supply circuit with a double conversion, including LED lamp 2 attached at the output.

By comparing the results of the conducted measurements with the requirements of IEC 61000-3-2 [50], it is possible to conclude that the application of a power supply circuit with a double conversion resulted in a reduction in the levels of the higher harmonics to permissible values. The patterns of current waveforms, just like the levels of the $h3$ and $h5$ components, are compliant with the standard guidelines [50]. Also, the values of all the uneven current harmonics from $h3$ to $h39$ expressed in mA per 1 W of active power of the load do not exceed the permissible values.

The results of the measurements of lighting systems with the two-stage power supply attached could be even more advantageous if the power supply was loaded at the level of 80–90% of its rated power. The test results described above were obtained under conditions where the power of the installed LED lamps was lower than 20% of the rated load of the power supply with double conversion.

6. Remarks and Conclusions

The quality of the energy in power mains and the limitation of the impacts of electromagnetic interference as well as proper energy management are absolutely vital in the functioning of all facilities that supply, process, and use electricity. These issues have the highest priority as they are related to the proper and reliable operation of devices and electrical, electronic, and IT systems along with the fulfilment of the functions designed for them by their constructors and users, as well as the economics and ecology of energy usage.

Based on the conducted measurements and considerations, as well as analyses presented by authors in other publications [20–23,28–30], it is possible to conclude, unambiguously, that the electrical lighting systems that use lamps operating with LED technology, introduce strong distortions of the

drawn current (the impact of harmonics), and at the same time, they put a strain on power supply systems with reactive capacitive power (in addition to the active power). With the high cumulation of such loads, irregularities in the operation of the surrounding auxiliary equipment, sensitive to the impacts of higher harmonics, may appear. Another severe effect for the recipients is an increase in costs for the utilisation of electricity, resulting from the additional energy losses related to the impact of harmonics, and the drawing of the reactive capacitive energy from the mains (much more expensive than the active energy).

An improvement in the operation of the facilities and their mains, in terms of impacts of higher harmonics (generated, among others, by lighting systems with LED lamps), can be achieved by using two-stage power supplies. They are commonly used in uninterrupted power supplies (UPS). In view of the energy separation of loads from the power mains (VFI topology), their use helps to achieve the elimination of the impact of mains interferences on loads (an improvement in the quality of the power supply for sensitive devices), as well as a significant reduction in the impact of the higher harmonics of current drawn by them on the power mains. In the case of UPS, an additional benefit from their use is the uninterrupted powering of loads during power failures until the discharge of the installed electricity storages. This allows for the safe completion of processes by the connected loads.

Owing to the decrease in the content of higher harmonics (current and voltage distortions) in the mains of commercial facilities, a reduction in the energy drawn from the power grid is obtained (through the elimination of the distortion power consumption). Furthermore, energy losses occurring in devices related to the production and transmission of energy as a result of the current flowing through them effectively decreased by the current resulting from distortion (i.e., the presence of higher harmonics), are also limited. Because of this, the energy efficiency of the entire system is improved (economic and technical benefits), and the heat emissions from the elements of that system into the surrounding environment are also reduced (ecological benefits). Another important factor is the improvement in the transmission capacities of the existing power infrastructure owing to the reduction in the distortion power consumptions (benefits for electricity providers).

In circuits with LED lighting, in addition to the need for the elimination of the impacts of higher harmonics, there is a demand for reactive capacitive power compensation. This function is additionally fulfilled by certain uninterrupted power supply solutions (e.g., UPS EVER from the Powerline series). Proper determination of the specifics of the loads and relevant identification of the problems in different facilities related to human activity enable suitable adaptation of technical remedial measures to limit the impact of interferences, and at the same time, the introduction of rational energy management.

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