

Article

Influence of the Supply Voltage Variation on the Conducted Emission in the Frequency Range up to 150 kHz Injected into the Power Grid by CFL and LED Lamps—Case Study

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Abstract: In normal operating conditions, the mains voltage level provided by low-voltage distribution networks follows time-varying patterns within permissible limits. The statistical characterisation of disturbances inserted into the power grid by nonlinear electrical devices is useful since operators are able to establish power quality limits and assess the residual capacity of networks for new smart installations, which may include a multitude of power electronic devices. Existing standards related to emission tests recommend using a power supply source in the measurement circuit with a nominal voltage parameter. However, the range of permissible variations of relevant supply voltage parameters may have an impact on conducted emissions. It can also be considered that the symptoms of supply voltage variations may manifest themselves differently depending on the equipment's architecture and also the range of frequency observation with reference to harmonics and supraharmonics. The purpose of this study is to measure and analyze non-intentional conducted emissions injected into the power grid by lighting devices, methodically, by numbers of studies under different supply voltage conditions within two frequency bands. The emission is evaluated separately in two ranges: up to 2 kHz and 9–150 kHz. Obtained results show that the level of conducted emission introduced into the low voltage network by modern lighting sources like fluorescent and LED lamps varies with the supply voltage level compared to the emission generated in the nominal voltage level condition. Additionally, in the case of a spectrum of higher frequencies, some trends of shifting of the characteristic frequency bands are recorded. The potential of the obtained results is to complement the knowledge of the emission of modern lighting sources, which can be further used for digital models of these devices and to estimate the impact on the grid under real working conditions.



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1. Introduction

Modern power grids are undergoing constant changes toward more reliable and efficient smart structures, especially in terms of how energy is produced, consumed, and transported. This development presents new and unexpected challenges as well as benefits. An important requirement for future power grids is the provision of a satisfactory quality of power. In normal conditions, the mains voltage level provided by the low-voltage distribution networks follows time-varying patterns within permissible limits. The need to ensure a satisfactory quality of the supplied power has been identified as a key requirement for future power grids [1]. However, power quality can be compromised by new technologies and changing conventional equipment to power-electronic-driven appliances. Low-voltage

distribution networks have been experiencing increasing penetration of distorting loads over the past few decades [2–6]. Modern electrical loads contain electronic power circuits in their topology, which can produce conducted emissions (propagated via power or signal wires into the electromagnetic environment) as they interact with power grid elements, such as loads, cables, transformers, etc. [7–9].

The topic of wide spectra waveform distortions has become challenging, since the emissions introduced into the power grid by electrical equipment may be responsible for severe malfunctioning and loss of efficiency [10–12]. Household devices, industrial-size converters, photovoltaic inverters, electric vehicle chargers, and energy-efficient lighting are examples of devices that can become sources of non-intentional disturbances if electromagnetic compatibility (EMC) requirements are not taken into account during the designing stage [13].

There are guidelines for acceptable levels of harmonic emissions introduced to the grid by electrical loads. Usually, the severity of harmonics in the frequency range up to 2 kHz is determined by the total harmonic distortion (THD) factor. There are two major international standards (sometimes with specific local adaptations): EN50160 [14] and IEEE519 [15]. The standard EN50160 describes a wide range of power quality measurements, including harmonics but also voltage dips, swells, unbalance, interruptions, and flicker severity. The IEEE519 standard focuses only on harmonics and pays particular attention to load currents waveform distortion. Although these standards have some differences, both documents reference the harmonics standards EN61000-4-3 [16], EN61000-4-7 [17], the flicker standard EN61000-4-15 [18] and the standard [19] that describes power quality testing and measurement techniques.

Compared to their low-frequency cousins, the spectral components in the 2–150 kHz range have received far less research. In analogy to the total harmonic distortion factor, the total supraharmonic distortion (TSHD) index is introduced. The normative documents are still imprecise in this regard [20]. The standard EN55015 [21] contains limit values and methods for measuring radioelectric disturbances generated by lighting devices and similar equipment. According to this standard, lighting sources where the active electronic components are placed should be tested before releasing them into the market. Precise normative techniques for monitoring electromagnetic emissions in low voltage networks in the frequency range between 2 and 150 kHz are still lacking. Distribution system operators ought to encourage research in this field and make use of the most recent analysis to take proactive measures to stop degradation and raise the standard of power quality supply [22–25].

The fundamental motivation for this work is the relatively sparse number of research studies concerning the influence of mains voltage level variation on the non-intentional conducted emission in the wide frequency range that electric equipment introduces into the power grid. Several studies, such as those in [26,27], have been developed based on emission observations generated by various electrical devices supplied with nominal voltage. In contrast, low voltage distribution systems typically offer fluctuating mains voltage levels over time as a result of a variety of factors, including changes in the load connected to the system. The standard EN50160 regulates the mains voltage level change in the public distribution system. The minimum allowable voltage level for a nominal voltage of 230 V is 207 V, and the maximum allowed voltage level is 253 V. This means that the mains voltage variation is restricted to $\pm 10\%$ of the nominal voltage. There is a relative gap in methodical investigations showing in a complex way the real impact of mains voltage supply on spectrum components or concentration of characteristic frequency bands.

By examining an experimental scenario of the influence of supply voltage variation within allowed limits on the conducted emission in the frequency range up to 150 kHz delivered into the power grid by certain devices, this research seeks to extend the state-of-the-art of the topic. Section 2 presents our motivation, while Section 3 contains a review of the literature. In Section 4, the methodology for the case study is described. Section 5 consists of two subsections. Section 5.1 summarizes measurement findings in the harmonics

range of frequency (up to 2 kHz). Section 5.2 presents the results in the supraharmonics emissions range (9–150 kHz). This subsection is divided into three case studies, each for different equipment under test (EUT). In the final section of the paper, conclusions are formulated and discussed. For future research, novel directions on this topic are proposed.

2. Problem Description

For many years, the power quality (PQ) field has been focused on waveform distortion problems below 2 kHz. Engineers started to deal with emission problems in the frequency range above 2 kHz relatively recently. The term “supraharmonics” was first introduced during the IEEE Power & Energy Society General Meeting in 2013. It refers to high-frequency harmonics, i.e., from the 40th up to the 3000th. The main causes of concern over the PQ degradation that occurs in the wide frequency range, or from 0–150 kHz, are the increasing number of non-intentional conducted emission sources, such as personal computers (PC), modern lighting devices, power converters, and battery chargers, as well as the popularity of smart grids with power line communication (PLC) systems and the integration of distributed generation (DG) units [28–31].

Light-emitting diode (LED) lamps and fluorescent light sources belong to the category of lighting equipment with electronic modules. Their advantages are low energy consumption, the possibility of flexible shaping of the light beam and smooth change of colour. However, this type of appliance can be a source of electromagnetic disturbances. The electronic power supply systems’ chosen structural solutions determine the level of generated emissions. Most modern lighting devices are powered according to the supply structure which consists of a rectifier bridge with a smoothing capacitor and a controlled pulse width modulation (PWM) converter. For example, modern converters dedicated to supplying LED bulbs work in the frequency range from 20 kHz to 300 kHz, providing energy to the receiver in a pulsed manner. This solution is economically advantageous, and the power supply is more efficient. However, the disadvantage is the generation of electromagnetic disturbances, which may noticeably disturb the operation of other devices supplied from the same power network [32–34].

Considering that the number of energy-saving lighting devices is exceptionally large on a global scale, the article presents the results of the study on the conducted emissions generated by randomly selected compact fluorescent lamps (CFLs) and LED lamps.

Spectrum analysis characterizes the contribution of particular frequency components in points of magnitude or phase. There is a distinction between the approach to harmonics analysis up to 50th harmonic (2.5 kHz for 50 Hz systems, 3.0 kHz for 60 Hz systems) and supraharmonics analysis (up to 150 kHz). Different test and measurement methods are used. In the case of harmonics, it is desirable to find the relation between supply voltage level and particular spectrum components. In supraharmonics analysis, it is more reasonable to examine the influence of the supply voltage on frequency bands rather than on particular spectrum components. While there is a lot of valuable literature presenting the emission of electric equipment, certain evaluations of the impact of specific supply condition patterns have not been collected so far. It might be significant when the digital twin of electrical equipment is considered.

3. Literature Review

Modern lighting appliances such as fluorescent lamps (FLs), CFLs, as well as the most popular nowadays, smart lights, including LED lamps, are sources of conducted emissions that are produced in the frequency range below 2 kHz. Several works have been published about the assessment of harmonic emissions generated by these lighting sources (the selected ones are presented below), but the issue of voltage variation over emissivity is still an open topic.

To save electrical energy, the government has primarily focused on replacing incandescent lamps (ILs) with fluorescent and compact fluorescent lamps. The effects of harmonic current on FLs with different ballasts are studied in [35]. The T5 and T8 fluorescent lamps

with electronic ballasts generate more distorted current waveforms than their older counterparts with electromagnetic ballasts.

3.1. Selected Literature Directly Related to the Characterization of the Influence of Power Supply Conditions on the Emission of Low and High Frequency Disturbances

For typical CFLs tested in [36], the THD in the input current is as high as 75%, while the CFL examined in [37] has a total harmonic current distortion factor (THD_i) equal to 67.7%. Such harmonic pollution is high and may degrade power quality noticeably. The research [38] implies that the harmonic content in the voltage signal is expected to increase as a more distorted current is drawn when connecting subsequent CFLs. The paper [39] evaluates the effect of voltage waveform distortion on the performance of CFLs supplied by constant RMS voltage and constant frequency. The experimental results show that EUT supplied by the nominal voltage with harmonic distortion factor variation up to 8% reduce efficiency of devices. Thus, the results highlight the importance of adjusting the harmonic distortion limits to reduce or prevent the increase in power loss caused by harmonic components.

The LED lamps and another solid-state lighting (SSL) system impact PQ. They are studied, among others, in [40–42]. For these types of lighting, the individual current harmonic components, as well as the THD_i values, often exceed the limits set by the standard IEEE519 [15]. According to [42] the LED and micro-LED lamps show moderated harmonic current emissions under nominal operating conditions (sinusoidal waveform of 230 V RMS and frequency of 50 Hz) as well as under abnormal conditions such as swells, sags, notch or harmonic distortion in the voltage source. As it is indicated in [40], as a greater number of LED lamps are connected to the grid, their performance improves both in terms of power factor and harmonic pollution.

According to the paper [43], the harmonic and supraharmonic current emission of individual CFLs and LEDs is impacted by supply voltage waveform distortion. Among the two types of lamps, there is a significant difference in emissivity, as well as within the same type. Using pure sinusoidal waveforms, the authors describe PQ parameters.

3.2. Selected Literature Covering the Issues of Low- and High-Frequency Disturbance Emissions, Taking into Account the Issues of Concentration of the Devices and Conditions of the Point of the Connection

In addition to lighting CFLs, measurements of other commercial and domestic appliances have been published in the literature. These include TV sets, personal computers, monitors, printers, laptops, chargers and vacuum cleaners with brush motors [4,38,44]. Today, these single-phase loads universally employ switch-mode power supply (SMPS) systems. To achieve a smooth DC output, these systems are usually configured with a rectifier followed by a converter. There is a high degree of nonlinearity in the input current waveform, and it is often presented to the load as short pulses. While the majority of energy-efficient loads based on power electronics consume significantly less energy than their more antiquated counterparts, the authors of [12] emphasize that they are harmonic pollutants and produce relatively high conducted emissions compared with their power demand.

Nonlinear electrical equipment causes an increase in harmonic emission in current, while the range above 2 kHz is relatively little known. Several researchers have begun to characterize the phenomenon of non-intentional conducted emission in the frequency range between 2 and 150 kHz, which is experienced by power system operators. The noise levels measured from CFLs, LED lamps, photovoltaic (PV) inverters, and electric vehicle (EV) chargers are shown in [45–47]. These noises are experienced by the efficiency of the power line communication (PLC) systems, which are considered as intentionally conducted emissions. As the frequency range used in the PLC is from 2 to 148.5 kHz (supraharmonics range), interferences in the communication channel are expected. Thus, as indicated in [48–51] the presence of intentional and non-intentional emissions in low voltage (LV) networks is a growing problem and manifests itself, for example, with a malfunction of smart metering systems based on PLC transmission.

The authors of [52] analyzed the conducted emission in the supraharmonic frequency range for a set of different LED lamps. Evaluating them is relevant because this type of lighting source has been dynamically developing. The researchers drew attention to the research methodology and examined the emissivity of single and parallel-connected selected devices. The results show that selected LED lamps do not meet EMC standards. Both types of peak and average values of emission are related to the permissible limits given in the standard EN55015 [21]. Three tested lamps from one manufacturer exceeded the permissible limits. These results were not repeatable for other manufacturers. In the case of group work of lamps generating significant electromagnetic disturbances, the lamp emitting the highest disturbances has a decisive influence on total emissivity. Hence, in the case of operation of these loads in a group, connecting lamps from different manufacturers in a common circuit gives a favorable (from an economical and radio-electric point of view) reduction of electromagnetic disturbance values up to 10 dB. However, the emissivity depends on the topology of an LED lamp, the converter used and power supply conditions.

The authors of [43] analyze the harmonic and supraharmonic emission of individual LED and CFL lamps in three scenarios: sinusoidal waveform voltage, flat-top shape distorted voltage (total voltage harmonic distortion $THD_u \approx 3\%$) and pointed-top distorted voltage ($THD_u \approx 4\%$). The tests were conducted on a group of 142 lamps manufactured between the years 2009 and 2016 (69 CFL sources and 73 LED sources). These lamps work in various ranges of rated power (CFL range up to 46 W, LED range up to 17 W). For the operation of different, as well as for the same type of these lighting sources, clear differences in the current emission in the band above 2 kHz are noticed. Examining LED lamps supplied by a voltage other than sinusoidal in shape indicates that the level of unintentional emissions injected into the network in the frequency range of 30–95 kHz is greater than the emissivity measured during tests for equipment supplied with nominal voltage sinusoidal in shape.

The research [53] characterizes the level of waveform distortion introduced by the connected step-by-step 1, 10, and 48 identical fluorescent lamps. The result shows that these are some of the most diffuse electrical loads that introduce significant waveform distortions in low-voltage distribution networks. As the number of connected fluorescent lamps increases, the characteristic effect of decreasing emissions in the total current drawn by these devices at low frequencies of 0–2 kHz is observed. The shift in distortion from lower frequency bands to higher (2–150 kHz) is also present. However, increasing the number of fluorescent lamps partially reduces the supraharmonic emission content in the point of common coupling (PCC), but there is a threshold beyond which a further increase in the number of connected devices does not affect the overall supraharmonic emissivity.

The measurement of 191 lamps connected in a single phase is shown by research in [54]. The main interest is the phenomenon of summation and propagation of supraharmonic emission injected into the current drawn by the examined lighting installation. The reference value for an individual lamp is obtained based on its current. The gradual connection of identical LED lamps from the same manufacturer and topology to the LV network affects the summation of supraharmonic components. The findings suggest that the summation of supraharmonic components is influenced by the gradual connection of homogenous LED lamps to the LV network. The non-linear relationship between the number of lamps and the cancellation effect results in a stronger effect as the number of lamps increases. Additionally, as the number of devices increases, there is a subsequent decrease in emitted supraharmonic pollution after reaching the peak point. The secondary emissions and added impedance of the devices contribute to this phenomenon. Therefore, the primary finding is that the highest level of distortion introduced into the grid by LED lighting systems of the same type is influenced by both the device's design and the impedance of the network.

The presented literature review leads to a discussion on the testing conditions for emissivity in the frequency range up to 150 kHz introduced into the power grid by selected electric equipment. Usually, electromagnetic compatibility tests are conducted in laboratory

environments under sinusoidal power conditions. This observation became the motivation to research the influence of supply voltage level on the emissivity generated by electric devices.

The authors of this work attempt to extend the current state-of-the-art by investigating experimental cases of the effect of variations in the supply voltage within permissible levels on unintentional emissions in the frequency range up to 150 kHz introduced into the electrical network by particular devices. Identification of the pattern of the supply voltage conditions and its impact on the frequency spectrum constitutes a certain contribution to the digital twin of electrical equipment.

4. Methodology

In stage 1, the problem description is defined based on the collected knowledge of the topic. A literature review of the topic is provided.

The scope of the study and the relevant aspects are determined in stage 2. The non-intentional emission measurements have been examined under normal operating conditions of the selected individual nonlinear loads with different technical specifications in a laboratory environment located at the Department of Electrical Engineering Fundamentals of Wroclaw University of Science and Technology. The experiment setup includes:

- KIKUSUI PCR 500LA programable generator with regulated voltage level whose task is to supply the equipment under test (EUT) without disturbances coming from the public power system network;
- LISN Rohde & Schwarz HM6050-2 artificial network, whose task is to match the impedance of the supply network and the tested device;
- FLUKE 435 Power Quality Analyzer (possible to analyze signals up to 5 kHz);
- Tektronix RSA306B Real-Time Spectrum Analyzer (possible to analyze signals from 9 kHz to 6.2 GHz);
- Voltmeter to monitor the value of the supply voltage at the terminals of the tested device;
- Lighting fixture in which the tested lamps are placed.

The diagrams of the prepared test setups for the research are shown in Figure 1.

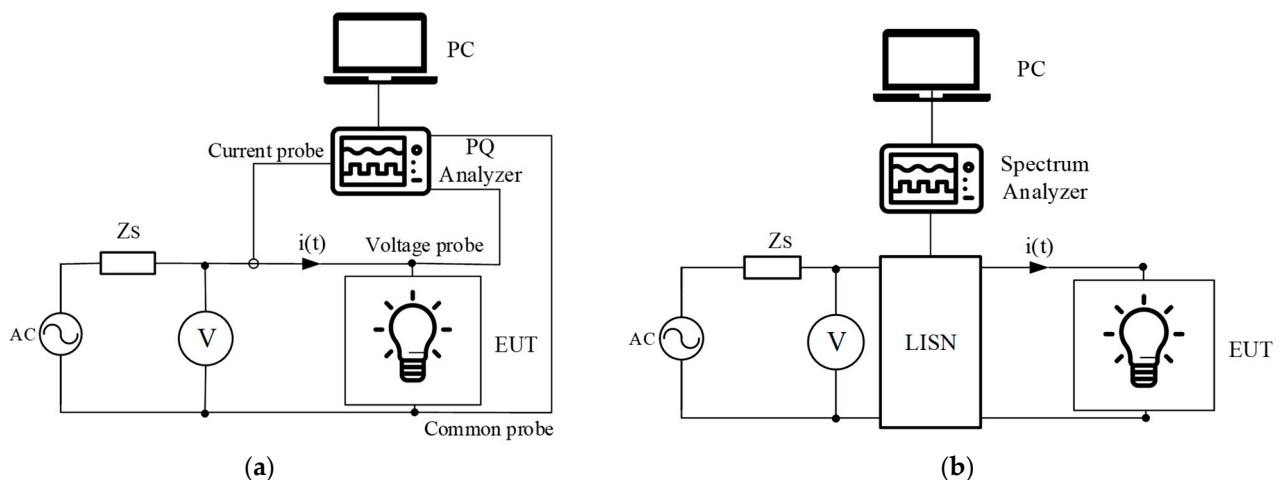


Figure 1. Diagram of the experiment setup: (a) intended for measurements in the frequency range up to 2 kHz; (b) intended for measurements in the frequency range from 9 to 150 kHz.

Table 1 shows the technical specifications, measured power factor (PF), classification, name of the model and manufacturer of the used EUT. According to EN61000-3-2 standard [16] the devices are classified in class C which is dedicated to lighting sources. For Class C equipment the standard allows specification of fundamental current and power factor by the manufacturer. Lighting equipment can broadly be classified into three categories depending on the type of power factor correction (PFC): passive, active and no-PFC

topology. It influences the efficiency of the device. To highlight the features of the passive or active topologies Figure 2 represents a comparison of the current waveform of investigated LED as well as CFL. The real power factor was obtained by measurements. Information about the EUT including detailed specifications, topologies and schematics can be obtained from manufacturers at request. The paper intends to provide data based on measurements in laboratory conditions. Simulation tests using a digital model of the EUT (digital twin) can be used as the augmentation of the research, but they are not included in the scope of the paper.

Table 1. List of equipment under test (EUT).

Lighting Source	Nominal Power [W]	Nominal Voltage [V]	Power Factor [-]	Class According to EN61000-3-2 [16]	Manufacturer/Model
LED	7	220–240	0.85	C	Blitzmann/BLZ-DL01-7W
LED	8	220–240	0.92	C	Blitzmann/BLZ-DL-CC-8W
CFL	20	220–240	0.6	C	Osram/D STICK 20W

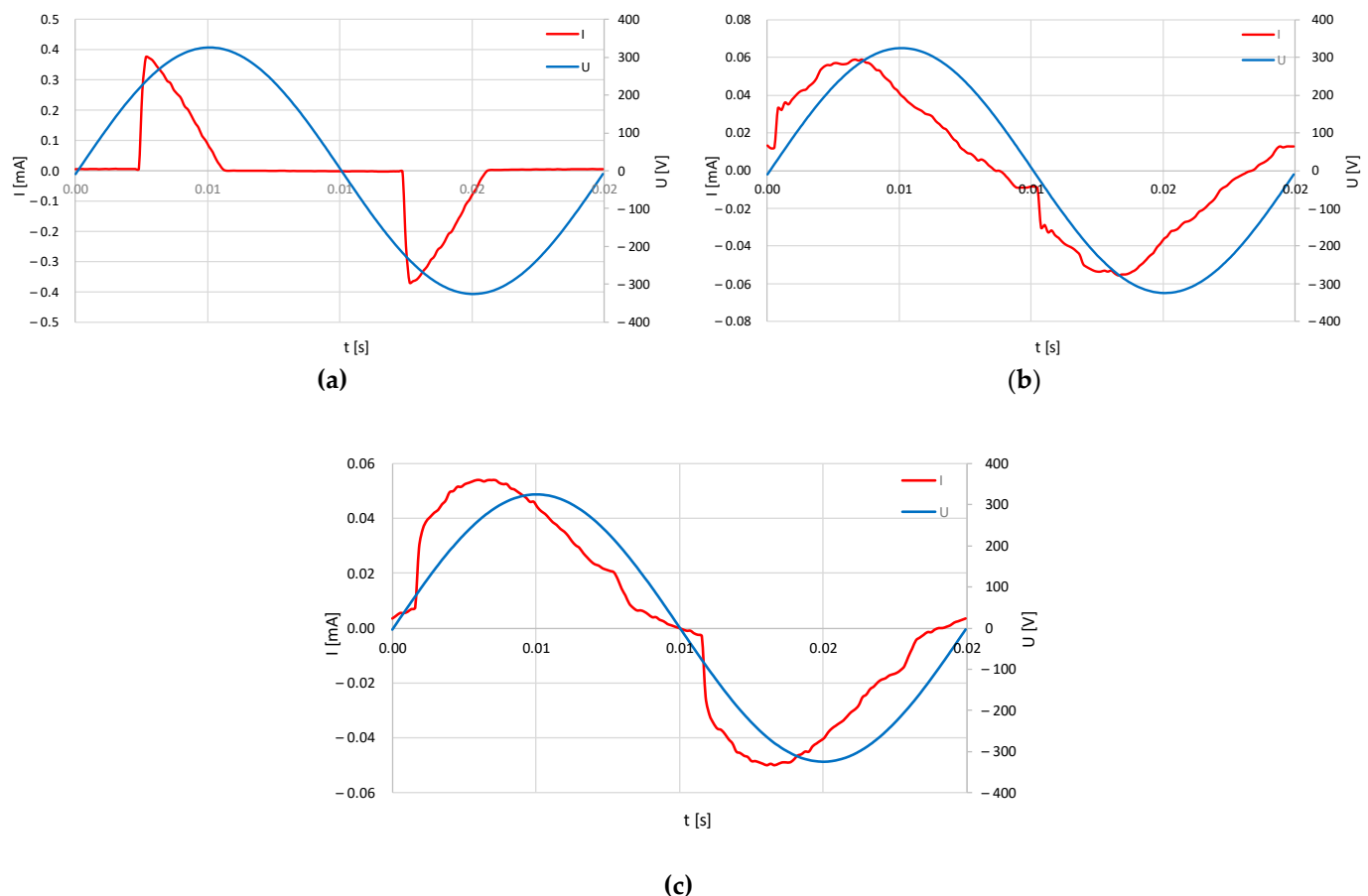


Figure 2. Current waveform (red) under nominal voltage supply (blue) for investigated lighting equipment: (a) CFL 20 W lamp; (b) LED 7 W lamp; (c) LED 8 W lamp.

Each lamp is turned on five minutes before taking measurements to stabilize the thermal conditions of the power supply system in the lamp.

In all cases, the examined object is supplied with sinusoidal voltage from the KIKUSUI PCR 500LA generator. To conduct measurements up to 2 kHz, the class A PQ analyzer FLUKE 435 (with the implemented method of spectrum determination following EN61000-4-7 standard [17]) is used, including the associated equipment such as 5 A precision current

clamps Fluke I5s. The obtained data are analyzed using the manufacturer's PC software (V3.34.1). For sufficient representation of spectra above the harmonic range, EN61000-4-7 standard [17] suggests including a network impedance between the power source and EUT, such as a line impedance stabilizing network (LISN). The measurements at the output terminals of the LISN Rohde & Schwarz HM6050-2 artificial network are made using the Tektronix RSA306B spectrum analyzer. The obtained data are analyzed using specialized software dedicated to the PC, the Tektronix manufactured software SignalVu-PC (V4.1.0022). Detailed information about the spectrum analyzer and dedicated PC software can be found on the manufacturer's website [55].

The value of the disturbance voltage is measured by a quasi-peak detector. To simplify the process of balancing the measured signal level and taking into account losses in the measurement circuit, the results are expressed in dB μ V. Following EN55015 standard [21], the measured disturbance voltage values refer to the permissible quasi-peak value levels in the frequency range from 9 kHz to 150 kHz. The acceptable limits of supraharmonics emission are indicated as the red line in the figures located in the results section.

It should also be pointed out that the frequency range of 2–9 kHz has not been sufficiently investigated in the paper. Generally, it can be emphasized that this range can be considered as omitted, even by standards. The reason may be that most popular power quality analyzers available on the market use a sampling frequency of up to 10,240 kHz, which allows the observed frequency range up to 5120 kHz. On the other hand, spectrum analyzers available on the market dedicated to Power Line Communication transmission are designed to test the band 9–150 kHz. However, considering the development of the power quality analyzers, which increase sampling rates up to 20 kHz and even 300 kHz, there is a justified need to investigate the relatively undiscovered and omitted 2–9 kHz frequency bandwidth in the standards. It is worth considering that extended methodology can consider both exploring the impact of quality of the supply voltage on the emission of disturbances as well as a statistical approach, extending the number of devices under tests to build a representative probe group to form the conclusions, supported by statistical indicators.

5. Results

5.1. Harmonic Emissions

The levels of emission in the harmonic frequency range generated by individual devices supplied with different voltage levels are represented graphically. The measurements are done according to EN61000-3-2 standard [16] supplied voltage does not include background harmonics ($THD_v \approx 0\%$). The various colored bars represent graphically the selected current harmonics in the percent value of the fundamental component 50 Hz systems (in comparison to the fundamental harmonic of 100%).

Figure 3a shows the harmonic spectrum for the CFL 20 W lamp with no-PFC topology ($PF = 0.6$). It consists mainly of third, fifth and seventh harmonics, circa 80%, 50% and 25%, respectively, (in comparison to the fundamental harmonic of 100%). For the lower frequencies (up to 650 Hz), the voltage level variation within the range of 210–250 V with a step of 10 V observable impacts the level of emission. With increasing supply voltage, harmonic current emission becomes more severe. The exception is the 9th harmonic component, for which voltage variation does not influence the amplitude change. The level of successive odd harmonics above 650 Hz (13th harmonic component) decreases to finally reach circa 5% of the fundamental component for the 40th harmonic in 50 Hz systems.

LED bulbs represent nonlinear loads since they contain diodes in their topology. Analysis of the harmonic spectrum for the LED 7 W lamp, equipped with a passive-PFC topology ($PF = 0.85$) and supplied in variable voltage (series of steps from 210 V to 250 V), is shown in Figure 2b. The emission severity of successive odd harmonics up to the 15th is significant. The highest amplitude of disturbance reaches the third harmonic (c. 15% of the fundamental component). For the 5th, 9th, 11th and 13th components, an increase in supply voltage results in an increase in emission level. For the 15th harmonic, in contrast,

the supply voltage gradually increases from 210 V to 250 V and the disturbance marginally decreases. For the 7th and above 17th odd harmonic, the level of disturbances is not sensitive to changes in supply voltage.

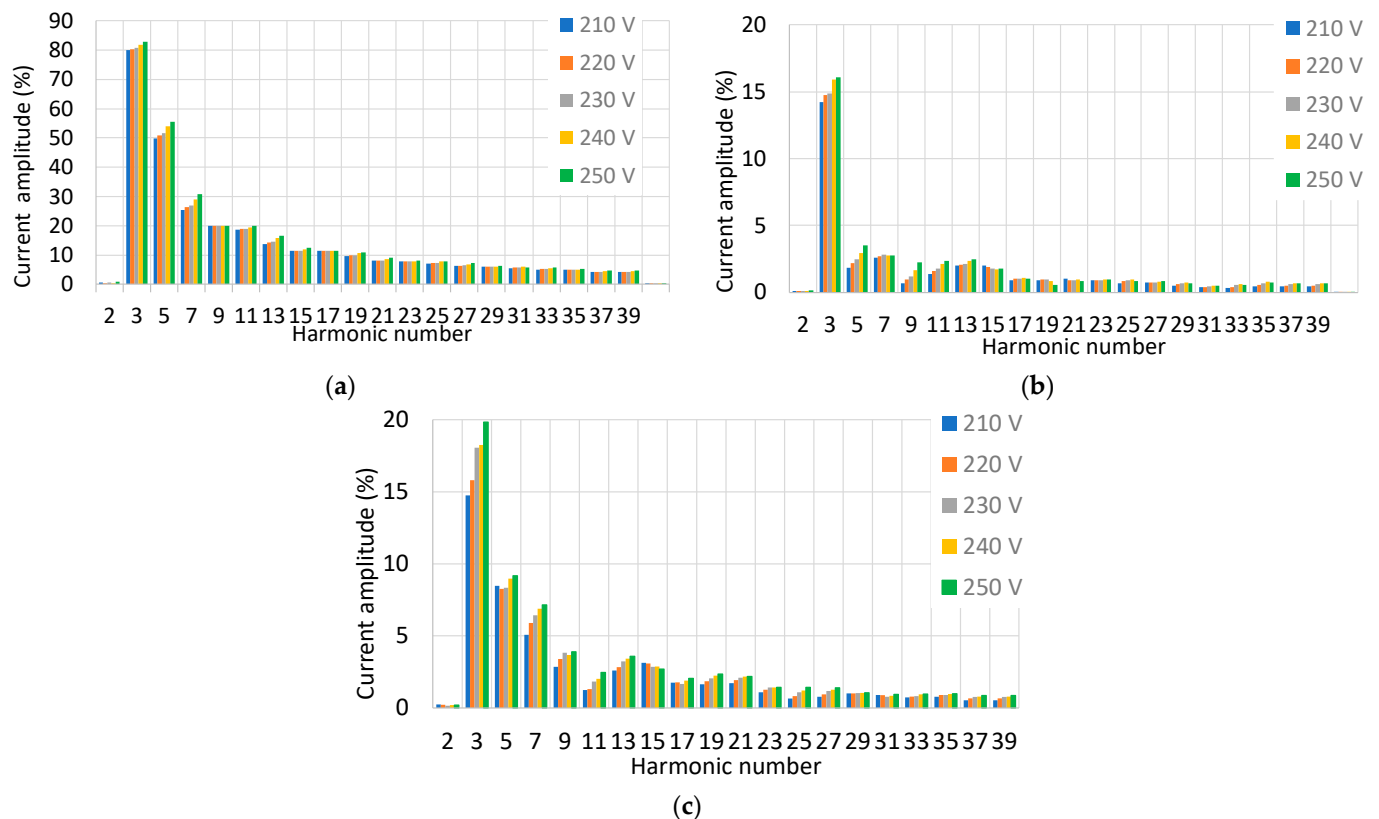


Figure 3. Current harmonic spectrum for various supply voltage values for the: (a) CFL 20 W lamp; (b) LED 7 W lamp; (c) LED 8 W lamp.

Based on different values of the voltage supplied by the LED 8 W lamp equipped with active-PFC topology ($PF = 0.92$), Figure 2c illustrates the distortion level of the input current waveform in the harmonic frequency spectrum. In terms of power factor, this topology has a high efficiency ($PF > 0.9$) [56] but the device has an advanced control power supply circuit with switching devices that shape the input current waveform and insert harmonic pollution. The highest amplitude reaches the third harmonic (c. 18% of the fundamental harmonic component of 100%). The severity of successive odd harmonics is lower and does not decrease proportionally (the 5th harmonic $\approx 9\%$, the 7th harmonic $\approx 6\%$, the 9th harmonic $\approx 4\%$, the 11th harmonic $\approx 2\%$, whereas the 13th and 15th harmonics $\approx 4\%$). Starting with the 15th harmonic current, the severity of the harmonic current does not decrease proportionally.

In the case of the examined LED bulb with active-PFC topology, the influence of supply voltage level variation on the harmonic emission level is significant. The most visible difference is in the third harmonic, the emission severity is a practically linear function of supply voltage. When the voltage is increased from 230 V to 240 V and then 250 V the disturbance also increases by around 2%. Analogically, when the supply voltage is decreased from 230 V to 220 V and then 210 V the amplitude level of the third harmonic decreases by around 3%. The total difference in the severity of this harmonic is 5% between the minimum and maximum levels of supply voltage. For the 7th, 9th, 11th and 13th harmonics, an analogous relation can be observed. The level of the fifth harmonic does not significantly change when the supply voltage is varied. The exception is the 15th harmonic component. The amplitude of this harmonic is highest at a supply voltage equal to 210 V

and decreases as the voltage increases. The severity of the harmonics starting from the 15th one is lower than 3%, and they are more immune to supply voltage variation.

The severity of harmonic disturbances contained in the current signal can be specified collectively by the total current harmonic distortion factor (THD_i), which can be calculated according to the equation:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{40} I_h^2}}{I_1} \cdot 100\% \quad (1)$$

where I_h is RMS current value of the individual harmonic component, e.g., I_1 —RMS current value of the first (fundamental) harmonic.

The value of the total current harmonic distortion factor (THD_i) is mainly determined by odd harmonics, especially those up to the 15th order. Their share in the analyzed spectrum is equal to 99.85%. The value of even harmonics is relatively low (usually below 1‰), therefore it can be neglected.

The numerical indicator (THD_i) of harmonic current emission injected into the power grid by the connected individually lighting devices implies that the overall level of harmonic currents is influenced by a $\pm 10\%$ variation of supply voltage. A small change is noticed for CFL 20 W, the THD varies from -2.9% to 4.1% . For LED 7 W the change is moderate (-6.2% to 8%) and for LED 8 W the change varies between -13.3% and 11.9% which is noticeable. For the selected LED 8 W lamp the maximum relative emission change is higher circa 12% compared to the emission generated by the same device supplied with the nominal voltage level. These statements are illustrated numerically in Table 2, and graphically in Figure 4.

Table 2. Influence of the voltage supply variation on the THD_i factor value.

Supply Voltage [V]	210	220	230 Reference	240	250	Lighting Equipment
THD_i [%]	104.7 (−2.88%)	105.6 (−2.02%)	107.8	110.2 (+2.23%)	112.3 (+4.17%)	CFL 20 W
	15.1 (−6.21%)	15.8 (−1.86%)	16.1	17.1 (+6.21%)	17.4 (+8.01%)	LED 7 W
	18.9 (−13.30%)	20.1 (−7.80%)	21.8	22.8 (+4.59%)	24.4 (+11.93%)	LED 8 W

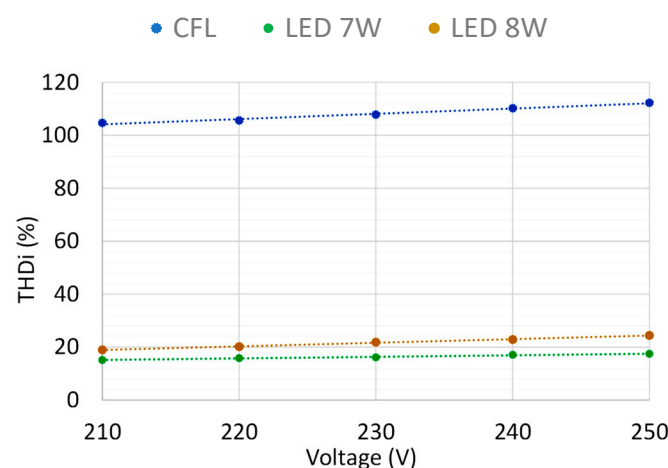


Figure 4. Influence of the voltage supply on the THD_i factor value for selected lighting sources.

The voltage level variation within the permissible tolerance $\pm 10\%$ in the public distribution system according to EN50160 standard [14] may cause such an increase in the THD_i factor that it will affect the assessment of the current harmonic emissivity according to the permissible levels formulated in EN61000-3-2 standard [16].

5.2. Supraharmonics Emission

Nonlinear loads draw non-sinusoidal current even if they are supplied by pure sinusoidal shape voltage with a nominal RMS value. The study [57] indicates that harmonics in the current waveforms strongly deteriorate the quality of the electricity in the frequency range up to 2.5 kHz for 50 Hz systems, 3 kHz for 60 Hz systems.

This section discusses the non-intentional high frequency conducted emission between the 9 and 150 kHz frequency ranges generated by selected individual lighting equipment (Cases 1–3). The supplied voltage does not include background harmonics ($THD_v \approx 0\%$). The results are provided numerically in tables, graphically as broadband emission in frequency representations, and as zoom-ins on dominant emission frequency bands. Thus, it is possible to identify the most severe levels of emission and the corresponding frequency ranges. The obtained data from the spectrum analyzer using PC software (R&S InstrumentView V2.9.0) is saved in dB μ V with a 200 Hz frequency bin step.

5.2.1. Case Study 1—CFL 20 W Lamp

A CFL lamp with a non-PFC topology usually has a power factor of less than 0.6 [56]. Figure 5 shows the spectrum of the CFL 20 W lamp (PF = 0.6) within the frequency range of 9–150 kHz for various supply voltage levels. Each of the curves represents a different voltage supply level varying from 210 V to 250 V with a step of 10 V. The emission produced by EUT shifts slightly towards higher frequency bands as the supply voltage increases from 210 V to the nominal value of 230 V. While, for voltages above the nominal voltage value, the emission shifts noticeably towards lower frequency bands.

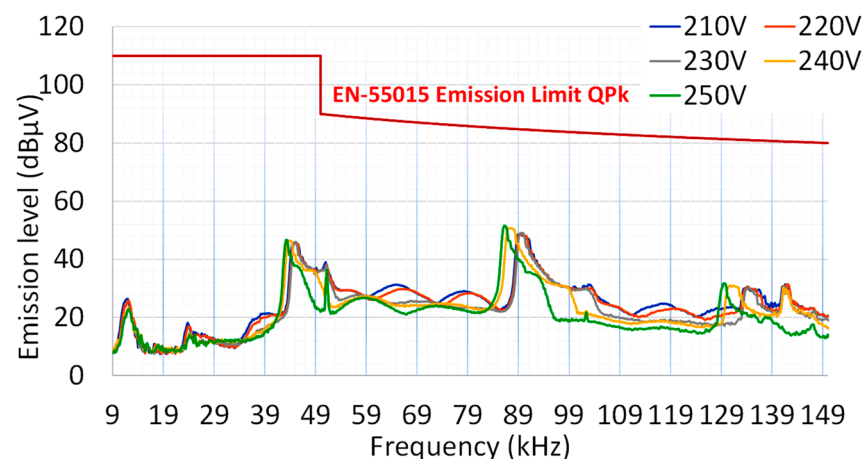


Figure 5. Supraharmonics spectrum of the CFL 20 W lamp for various supply voltage values [21].

Table 3 provides a numerical representation of the effects of voltage variations on frequency shifts and differences in emission levels.

The tested CFL lamp generates the highest emission in the frequency ranges 9–15, 41–48, 83–94 and 126–146 kHz. The zooms for these spectra are shown in Figure 6. A level of emissions in the range of frequency 9–15 kHz (Figure 6a) cannot be attributed to the source of disturbances (EUT). The real source of these disturbances is the programmable power supply device used in the research. The relationship between the supply voltage level and disturbance generated by the device is shown in the frequency range of 83–94 kHz (Figure 6c). In the case when the supply voltage level is higher or lower than nominal, the peak value of emission in both cases is shifted in the frequency band towards lower frequencies (the maximum shift is equal to 3.4 kHz). The maximum value of the signal shift occurs for the signal corresponding to 250 V and 230 V for the dominant emission band between 126 and 146 kHz (Figure 6d) and is equal to 12.2 kHz. The value of supply voltage does not have a significant effect on the amplitude at the peak value of emission, but it can be observed that for most of the dominant emission bands, the amplitude slightly increased

as the supply voltage level decreased. At the nominal voltage supplying condition (230 V), the highest emission level generated by EUT is equal to 49.09 dBV. The obtained results do not exceed the permissible limits specified in EN55015 standard [21].

Table 3. Selected dominant emission bands for the CFL 20 W.

Supply Voltage [V]	210	220	230 Reference	240	250	Dominant Frequency Band
Emission level U [dB μ V]	26.38	25.77	23.45	23.29	22.94	9–15 kHz
Difference in emission level Δ U [dB μ V]	+2.93	+2.32	0	−0.15	−0.51	
Dominant center frequency f [kHz]	12.00	12.00	12.20	12.20	12.20	
Frequency shift level Δ f [kHz]	−0.20	−0.20	0	0	0	
Emission level U [dB μ V]	45.55	45.55	46.00	46.35	46.66	41–48 kHz
Difference in emission level Δ U [dB μ V]	−0.45	−0.45	0	+0.34	+0.66	
Dominant center frequency f [kHz]	45.00	45.00	45.20	43.80	43.20	
Frequency shift level Δ f [kHz]	−0.20	−0.20	0	−1.40	−2.00	
Emission level U [dB μ V]	48.55	48.55	49.09	50.65	51.52	83–94 kHz
Difference in emission level Δ U [dB μ V]	−0.54	−0.54	0	1.56	2.43	
Dominant center frequency f [kHz]	89.20	89.20	89.60	87.40	86.20	
Frequency shift level Δ f [kHz]	−0.40	−0.40	0	−2.20	−3.40	
Emission level U [dB μ V]	31.41	31.41	30.75	30.98	31.70	126–146 kHz
Difference in emission level Δ U [dB μ V]	+0.66	+0.66	0	+0.23	+0.95	
Dominant center frequency f [kHz]	142.20	142.20	141.80	130.60	129.60	
Frequency shift level Δ f [kHz]	+0.40	+0.40	0	−11.20	−12.20	

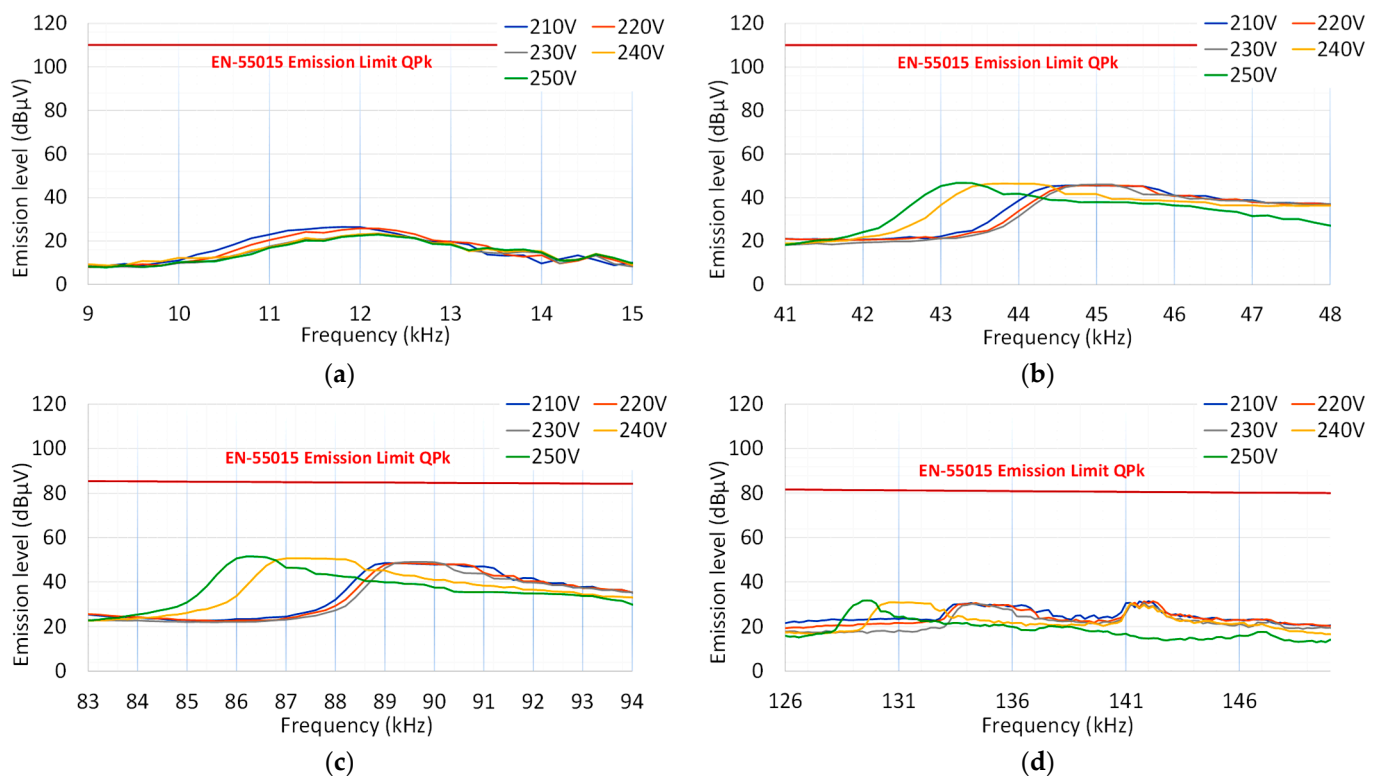


Figure 6. Zoom-ins on the dominant emission band of the CFL 20 W lamp supraharmmonic spectrum for various supply voltage values: (a) frequency range 9–15 kHz, (b) frequency range 41–48 kHz, (c) frequency range 83–94 kHz, (d) frequency range 126–150 kHz [21].

5.2.2. Case Study 2—LED 7 W Lamp

Figure 7 shows the conducted emission in the frequency spectrum within 9–150 kHz generated by the LED 7 W lamp equipped with passive-PFC topology ($PF = 0.85$). This kind of lamp is constructed with a basic energy supply, accompanied by series capacitors or inductors, which are positioned either before or after the bridge diode rectifier, in order to increase the power factor PF (usually falling between $0.6 \leq PF \leq 0.9$) [56].

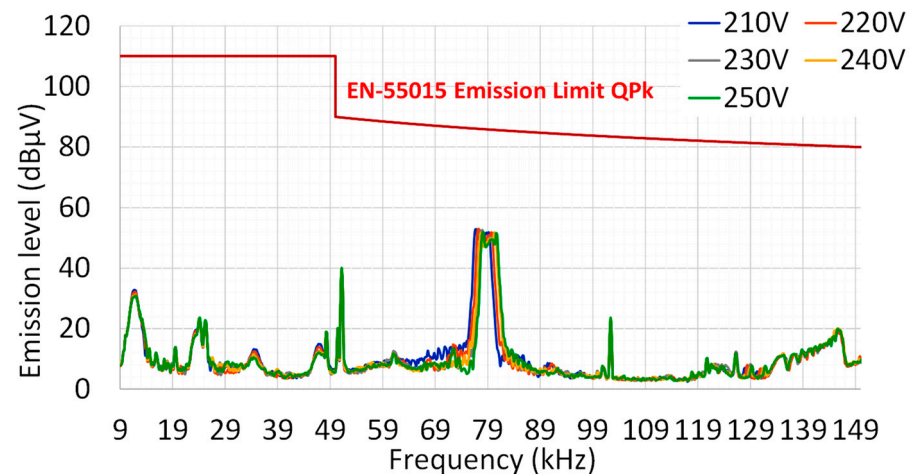


Figure 7. Supraharmonics spectrum of the LED 7 W lamp for various supply voltage values [21].

Table 4 presents the measurement results that indicate that the LED 7 W lamp is characterized by relatively high resistance to blurring (shifting) of the emission characteristics in the frequency domain due to the change in the supply voltage level. Similar to case study 1, a level of emissions in the range of frequency 9–14 kHz cannot be attributed to the source of disturbances (EUT) and the real source of these disturbances is the programmable power supply device used in the research. The maximum observed shift, concerning the frequency for the reference value of nominal voltage level, i.e., 230 V, occurs for the frequency range of 74–84 kHz for the 210 V and is equal to 1.2 kHz.

Table 4. Selected dominant emission bands for the LED 7 W lamp.

Supply Voltage [V]	210	220	230 Reference	240	250	Dominant Frequency Band
Emission level U [dBμV]	32.73	32.10	31.16	31.13	30.85	9–14 kHz
Difference in emission level ΔU [dBμV]	+1.57	+0.94	0	−0.03	−0.31	
Dominant center frequency f [kHz]	11.80	11.80	12.00	12.00	12.00	
Frequency shift level Δf [kHz]	−0.2	−0.20	0	0	0	
Emission level U [dBμV]	52.83	52.97	52.56	51.83	51.77	74–84 kHz
Difference in emission level ΔU [dBμV]	+0.28	+0.42	0	−0.73	−0.79	
Dominant center frequency f [kHz]	76.80	77.20	78.00	78.00	78.20	
Frequency shift level Δf [kHz]	−1.2	−0.8	0	0	+0.20	

Figure 8 zooms in on the dominant bands of the tested LED 7 W lamp. For the EUT, a decrease in the value of the supply voltage causes a shift of the frequency domain band towards lower values. In comparison, an increase in supply voltage causes a shift of the frequency domain band towards higher values (Figure 8b). The highest observed disturbance produced by EUT supplied with 230V equals 52.56 dBμV at 78 kHz bandwidth. The obtained results do not exceed the permissible limits specified in EN55015 standard [21]. The change in the supply voltage level does not significantly affect the emission amplitude change at higher frequencies, i.e., from 84 kHz to 150 kHz.

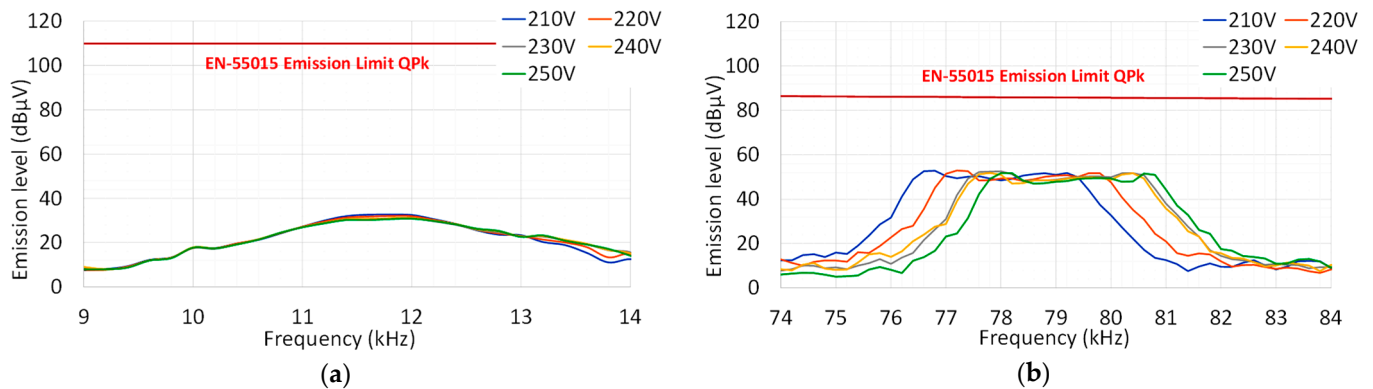


Figure 8. Zoom-ins on the dominant emission band of the LED 7 W lamp supraharmonics spectrum for various supply voltage values: (a) frequency range 9–14 kHz, (b) frequency range 74–84 kHz [21].

5.2.3. Case Study 3—LED 8 W Lamp

Figure 9 shows the conducted emission in the frequency spectrum within 9–150 kHz generated by the LED 8 W lamp equipped with active-PFC topology ($PF = 0.92$). This kind of device has an advanced control power supply circuit that shapes the input current waveform. In this topology, the power factor is the highest ($PF > 0.9$), but the emission occurs in the supraharmonic range due to switching devices.

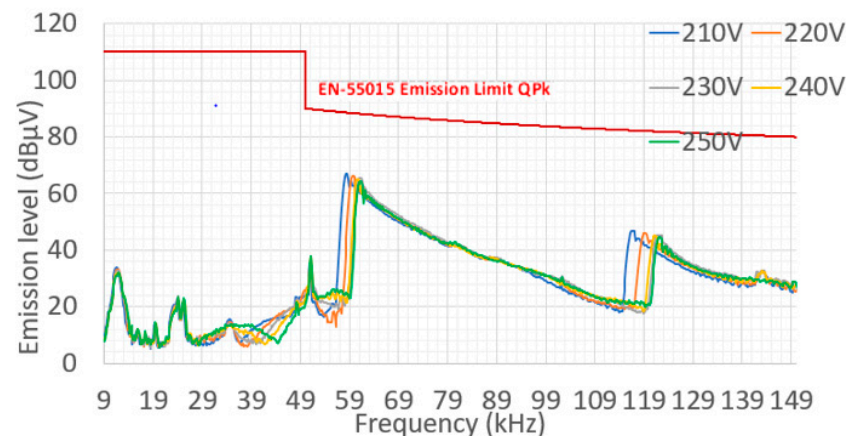


Figure 9. Supraharmonic spectrum of the LED 8 W lamp for various supply voltage values [21].

Figure 10 zooms in on the dominant bands of the tested LED 8 W lamp. The highest disturbances are generated in the frequency ranges within 9–15 kHz, 54–64 kHz and 113–125 kHz. The change in the supply voltage for the EUT has a small effect on the shift in emission characteristics in the frequency domain for the first dominant emission band (9–15 kHz). Based on the previous cases, the programmable power supply device used in the research is the actual cause of these disturbances. A significant shift is presented for the next frequency dominant emission bands, i.e., 54–64 kHz and 113–125 kHz. In the frequency domain, it can be observed that the spectra at supply voltage levels greater than 230 V differ slightly from those at the rated supply voltage level, while the spectra at voltages lower than this rated value shift in the frequency domain towards lower frequency values. The maximum value of the frequency shift occurs for signals corresponding to 210 V and 230 V in the range 113–125 kHz and is equal to 5 kHz (Table 5). The highest emission level generated by EUT at the nominal voltage is 65.37 dBμV at the 61 kHz bandwidth. The obtained results do not exceed the permissible limits specified in EN55015 standard [21].

Compared to the LED 7 W lamp emission levels (Table 4), the general emission amplitude change is greater for the LED 8 W lighting source (Table 5). However, the amplitude at peak values of emission is not significantly sensitive to supply voltage changes.

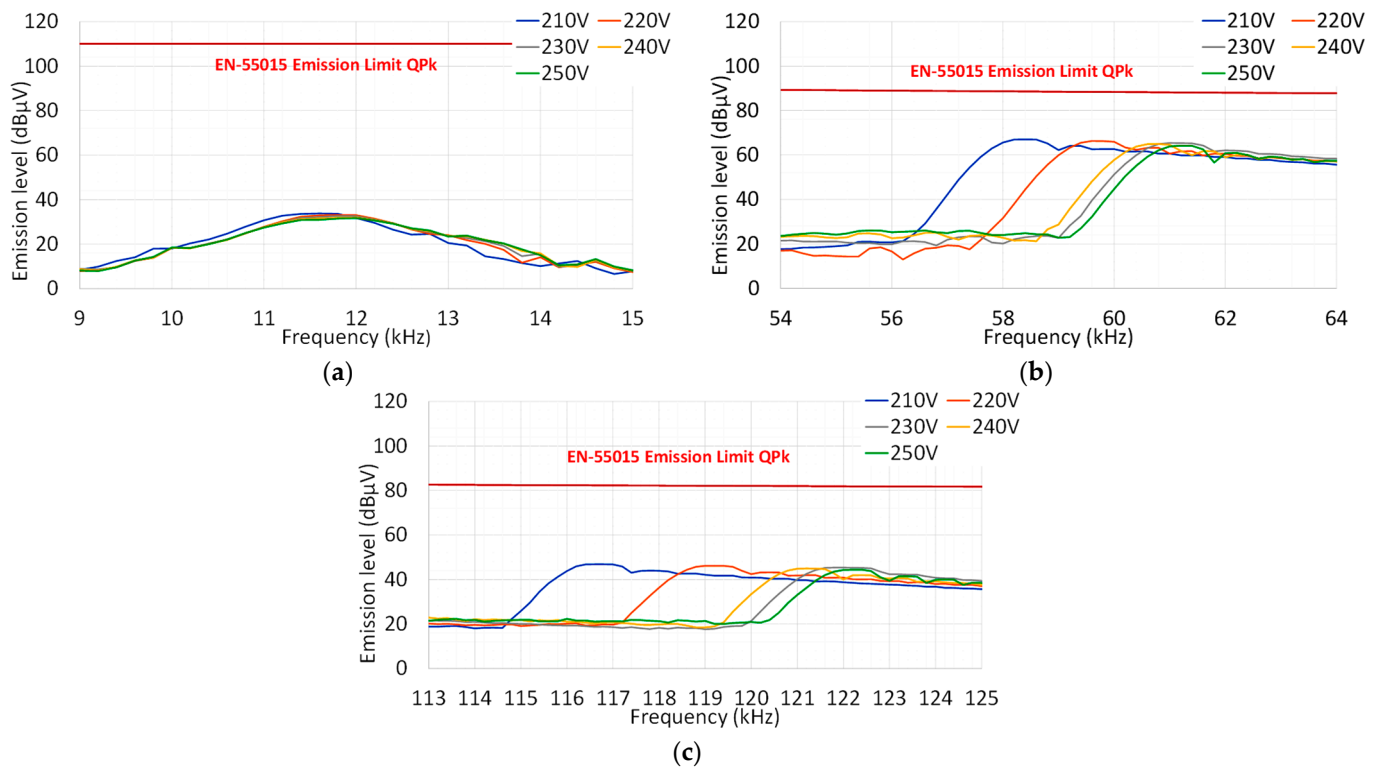


Figure 10. Zoom-ins on the dominant emission band of the LED 8 W lamp supraharmonic spectrum for various supply voltage values: (a) frequency range 9–15 kHz, (b) frequency 54–64 kHz, (c) frequency range 113–125 kHz [21].

Table 5. Selected dominant emission bands for the LED 8 W lamp.

Supply Voltage [V]	210	220	230 Reference	240	250	Dominant Frequency Band
Emission level U [dBμV]	33.79	33.14	32.71	32.01	31.76	9–15 kHz
Difference in emission level ΔU [dBμV]	+1.08	+0.43	0	−0.70	−0.95	
Dominant center frequency f [kHz]	11.80	11.80	11.80	12.00	12.00	
Frequency shift level Δf [kHz]	0	0	0	+0.20	+0.20	
Emission level U [dBμV]	67.04	66.30	65.37	64.95	64.24	54–64 kHz
Difference in emission level ΔU [dBμV]	+1.67	+0.93	0	−0.42	−1.13	
Dominant center frequency f [kHz]	58.60	59.60	61.00	60.80	61.20	
Frequency shift level Δf [kHz]	−2.40	−1.40	0	−0.20	0.20	
Emission level U [dBμV]	46.84	46.14	45.34	44.99	44.41	113–125 kHz
Difference in emission level ΔU [dBμV]	+1.50	+0.80	0	−0.36	−0.93	
Dominant center frequency f [kHz]	116.80	119.00	121.80	121.20	122.20	
Frequency shift level Δf [kHz]	−5.00	−2.80	0	−0.60	+0.40	

For all tested individual lighting devices, the generated emission does not exceed the permissible limits specified in the European standards. The emission spectrum shift in the frequency domain occurs when the supply voltage level is changed within permissible limits. This shift is not linear and depends on the type of load. In most cases, it can be observed that the components of the spectrum, for the selected dominant emission bands, shift towards higher frequencies with the increase in the supply voltage level. It is important to note that the direction of change can change at times, such as for high supply voltage levels compared to the nominal value in CFL lamps (Case 1) or when there is no specific relationship between the change in supply voltage level and the shift in emission characteristics (Case 3). The obtained results will serve for further studies like a deeper

analysis of the topology of the power supply circuits, including filters or power factor correction systems with which electrical loads are equipped.

It is possible to assess the level of supraharmonic components by analyzing the emissions associated with the dominant frequency band. As an analogy to the total harmonic distortion factor, the total supraharmonic distortion factor is used to characterize the overall assessment of emissions across the entire supraharmonic range of 9–150 kHz. It is evaluated according to Equation (2) [20,25]:

$$TSHD = \sqrt{\sum_{B=1}^{705} Y_B^2} \quad (2)$$

where B is the index of the RMS value Y of the 200 Hz frequency bin starting at 9 kHz.

The $TSHD$ factor presents the entire supraharmonic emission in dB μ V emitted by a EUT (Table 6). The tested lighting sources are supplied with varying voltage levels from 210 V to 250 V. The results show that the voltage level variation within the permissible tolerance $\pm 10\%$ according to the standard EN50160 [14] affects the $TSHD$ factor. Contrary to harmonic emissions, the severity of supraharmonic emissions (in examined frequency ranges) increases for all EUT with the decreasing supply voltage level value from 230 V to 210 V. The maximum relative emission change is high circa 9.5% for the CFL lighting source supplied with the voltage 210 V compared to the emission generated by the same device supplied with the nominal voltage level.

Table 6. Influence of the voltage supply variation on the TSHD index value for EUT.

Supply Voltage [V]	210	220	230 Reference	240	250	Lighting Equipment
$TSHD$ [dB μ V]	695.64 (9.46%)	678.22 (6.71%)	635.55	637.30 (0.28%)	582.55 (−8.34%)	CFL 20 W
	346.81 (0.99%)	339.89 (−1.03%)	343.43	341.97 (−0.42%)	337.72 (−1.66%)	LED 7 W
	855.91 (1.88%)	845.49 (0.64%)	840.15	831.59 (−1.02%)	825.89 (−1.70%)	LED 8 W

A decreasing tendency of the $TSHD$ index for the rising supply voltage level value from 230 V to 250 V can be observed numerically on the right side in Table 6 and graphically in Figure 11.

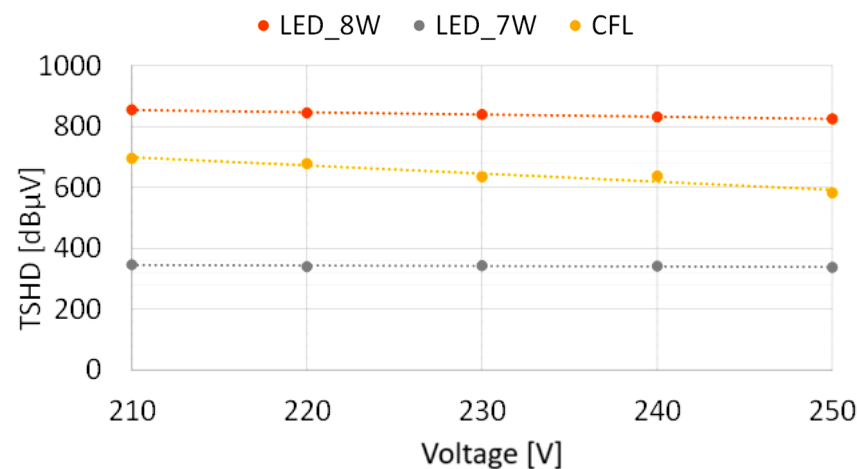


Figure 11. Influence of the voltage supply on the TSHD index value for selected lighting sources.

6. Discussion and Conclusions

Based on the literature review, modern lighting sources used in commercial and residential facilities can emit significant amounts of conducted emissions at frequencies up to

150 kHz. Currently, existing standards refer to emission limits using nominal parameters of supply, i.e., nominal supply voltage and sinusoidal waveform of supply voltage. However, public power grid regulations permit levels of supply voltage in the range $\pm 10\%$ of the rated voltage [14]. It is inclined to propose a discussion-oriented on the new framework of the test conditions, which would consider the impact of voltage supply conditions.

The purpose of this paper is to present a methodical and comparative study on the influence of mains voltage level variation on the conducted emission injected into the power grid by selected electrical equipment. With the use of a programmable power supply, the supply voltage sinusoidal shape is maintained at the frequency of 50 Hz, with the only variable being the mains voltage RMS value level. In public low-voltage networks, voltage changes are assumed to be within the permissible range. The measurements are done in a series of steps of 10 V from 210 V to 250 V, respectively. Tested electrical equipment represents popular energy-saving lighting sources using CFL and LED technologies with active and non-active power factor correction.

The obtained results lead to the general conclusion that there is a relationship between supply voltage level variations and the low and high frequency conducted emissions introduced into the power grid by electrical loads.

In detail, the total harmonic distortion factor increases nearly linearly with an increase in supply voltage in the low-frequency band up to 2 kHz. The increase is mainly influenced by odd harmonics, especially those up to a frequency of approximately 750 Hz (15th harmonic).

In the frequency domain between 9 and 150 kHz, it can be concluded that in the case of LED sources, the amplitude level in the spectra of conducted disturbances is more or less constant at all voltage levels. In contrast, the CFL shows a decrease in the level value of higher frequency conducted disturbances as the supply voltage increases.

In comparison to the emission created at the nominal voltage level for the LV network, the maximum conducted emission change for the supply voltage level variation for the study cases is as follows:

- Higher up to circa 12% in the frequency range 0–2 kHz;
- Higher up to circa 9.5% in the frequency range of 9–150 kHz.

In the frequency domain between 9 and 150 kHz, the dependence between the produced emission and mains voltage level variations is unique for each appliance. For two examined types of lighting sources, CFL and LED, it is observed that a change in the supply voltage level causes a shift in the spectrum in the frequency domain. In most cases, the shift of the dominant spectrum components towards higher frequencies is observed as the supply voltage increases. Occasionally, though, the direction changes, especially at high supply voltages compared to the nominal value (the case with the CFL lamp).

Despite the limited number of tested devices, the presented development leads to further hypotheses that broadband disturbances might be examined throughout the range of permissible voltage supply levels. Current standards ensure the safe use of electrical devices in the power grid environment. Meeting both groups of standards, i.e., emissions and immunity, allows, among other things, to obtain an EU declaration of conformity (DoC). However, there is some divergence between the requirements of the test conditions for immunity and emissions. Emission testing is usually performed under nominal conditions, which in the case of European power networks means 230 V, 50 Hz. At the same time, the statistics of permissible voltage changes in the power grid environment indicate possible voltage changes in the range of $\pm 10\%$ of the rated voltage. Therefore, the immunity tests are performed in conditions even going beyond the $\pm 10\%$ margin. There is a certain gap between the power supply conditions for immunity and emission tests. One of the motivations is that the design process of electrical equipment nowadays is efficient and able to meet the permissible limits formulated in the existing standards. However, at the same time, it can be stated that the spectrum of modern technologies permanently increases as well as the density of electrical equipment in electrical networks. It formulates an assumption for the realistic scenario of the particular equipment or concentrations of

equipment that will not meet the standards when the voltage conditions are not nominal, as already stated in standardized emission tests. The presented results confirmed the influence of power supply conditions on emission levels. Additionally, the presented results support efforts addressed to digital twins of electrical equipment. Described relations between supply voltage level and spectrum of emission can also be useful for designers of filters dedicated to power line communication technologies. Achieved knowledge showing the shift in the dominated bandpass frequencies of non-intentional conducted disturbances emitted by the investigated light sources can be implemented to improve the reliability of intentional transmission.

The intention of the presented investigations is mostly to indicate the gap between the laboratory test conditions and real working conditions and their impact on the emission of electrical devices. The aim is to uncover the trend of emission levels in the function of voltage supply conditions. From this point of view, more crucial is the variety of conditions instead of the number of devices investigated. Once trends are observed, it is planned that future research should expand the approach to include statistical evaluation. More statistically meaningful data should be gathered to obtain significant data as a base for deriving broader conclusions.

Another hypothesis can be related to a mixed load situation when loads of various sizes and power ratings are connected to the same point of common coupling. The emission at the terminal of a device might be higher than that of the whole electrical installation. Thus, it is especially crucial to consider the emission levels at the terminal of the device.

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