Impact of Voltage Harmonics on the Drawn Current and Reactive Power of Appliances

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Abstract: Recent measurements indicate that low-voltage networks are often sources of reactive power, contributing to reverse reactive power flows. These issues are largely influenced by the increasing use of appliances with power electronic components, which typically exhibit capacitive consumption characteristics and supply reactive power to the network. Therefore, this study explores the impact of higher-order voltage harmonic components, focusing on their magnitudes and phase angles, on reactive power variations. Four appliances: a CFL fluorescent lamp, an LED linear tube, and two LCD monitors were tested using a laboratory power supply configured to supply a fundamental harmonic along with selected higher-order harmonics. The investigation evaluates the influence of these appliances on three key parameters: reactive power, active power, and the total harmonic distortion of current (THDI). The findings provide insights into how specific voltage harmonic components and their phase angles affect drawn current and consumed reactive power.

Keywords: power quality; reactive power; power factor; total harmonic distortion; harmonic components

1 Introduction

The degradation of power quality presents a significant risk to the secure and reliable operation of transmission power systems. One of the adverse effects is the undesired transmission of reactive power. In recent years, instances of reverse reactive power flows between transmission and distribution systems have become increasingly evident. This issue has been observed in several European countries, including Slovakia, as noted in references [1-5]. Such reverse flows can cause challenges, particularly voltage rises within the transmission system. Measurements reported in studies [3] and [4] indicate that low-voltage networks act as sources of reactive power, thereby exacerbating the problem of reverse reactive power flow.

The consumption characteristics of users connected to low-voltage networks are largely influenced by appliances that use power electronic components. These devices typically exhibit capacitive consumption nature, leading to the supply of reactive power to the network. This phenomenon is supported by measurements discussed in studies [6-13]. Furthermore, measurements indicate that household appliances frequently demonstrate nonlinear characteristics and draw distorted currents. As a result, the THD_U increases, along with the magnitude and spectrum of higher-order harmonic components in the network. While the fundamental frequency primarily contributes to active power, its magnitude is minimally affected by harmonic distortion. In contrast, harmonic distortion significantly impacts reactive power, with the reactive power of higher-order harmonic components often surpassing that of the fundamental frequency. This contributes to the reverse flow of reactive power between transmission and distribution systems. In simulations conducted by authors in [14], various combinations of household appliances such as LED bulbs, televisions, notebooks, electric showers, and air conditioners were analyzed. The results revealed that certain combinations of these appliances could reduce the THD_I of the drawn current and improve the power factor of their consumption.

A similar effect, as observed with the combination of appliances, can also be induced by higher-order voltage harmonics in the supply network. Certain harmonic orders may mitigate affect of power consumption, while others can exacerbate it. Therefore, this article investigates the influence of voltage harmonics' varying magnitudes and phase angles on the consumption parameters of two types of light sources and LCD monitors.

Based on a review of relevant literature, this specific topic remains largely unexplored by researchers. Most studies in the field focus primarily on the background effects of different types of appliances on power quality at the connection point [15-17]. A similar line of investigation was undertaken by the authors of [18] and [19]; however, their research primarily involved altering the effective value of the supply voltage without considering variations in higher-order voltage components and their phase angles.

In this study, the magnitudes of individual voltage harmonics were configured in compliance with the EN 50160 standard, set at 50% and 100% of the permissible level [20]. Six distinct phase angles were applied for these voltage harmonic magnitudes. The generated harmonics included only odd components up to the 25^{th} order. For each scenario, the consumption parameters of the appliances were recorded, with evaluations focusing on their THD_I, reactive power, and power factor. Based on these measurements, the effects of the appliances on reactive power flow were analyzed. The remainder of this article is structured as follows. Section 2 outlines the measurements conducted on the public low-voltage distribution network. Section 3 describes the appliances and measurement methods used in this study. Section 4 presents the measurement results. Section 5 discusses the findings in detail, and Section 6 concludes the article.

2 Measurement of Public Distribution Low Voltage Network

This measurement evaluated voltage quality within a public low voltage (LV) distribution network. For each phase, odd voltage harmonics' magnitudes (RMS values), phase angles up to the 25th order and the THD_U were measured on a selected feeder supplying the power systems laboratory at the University of Žilina. The measurement results are summarized in Table 1.

Table 1

Voltage harmonics and THD_U measured on the selected feeder

Order *h*	L1			L2			L3		
	U **[V]**	***U*** **[%]**	***φ*** **[°]**	***U*** **[V]**	***U*** **[%]**	***φ*** **[°]**	***U*** **[V]**	***U*** **[%]**	***φ*** **[°]**
1.	234.5	100	0	233.6	100	0	233.6	100	0
3.	2.4	1	-57.9	2.3	1	-81.5	2.3	1	-97.5
5.	8.9	3.8	162.6	9.2	3.9	169.6	9.4	4	178.9
7.	5.3	2.3	32.6	4.1	1.8	40.3	1.8	0.8	78.4
9.	1.9	0.8	-41.1	1.2	0.5	-23.4	0.4	0.2	38
11.	3.3	1.4	131.5	3.3	1.4	100.4	3.3	1.4	-32.6
13.	2.6	1.1	144.1	4.0	1.7	-93.9	4.4	1.9	-31.6
15.	0.9	0.4	172	1.3	0.6	136.6	1.9	2.3	-80.5
17.	1.3	0.6	88.7	2.6	1.1	136.0	2.3	1	119.1
19.	1.1	0.5	55.5	1.3	0.6	108.0	0.9	0.4	136.2
21.	0.3	0.1	-4.5	0.3	0.1	5.9	0.3	0.1	132.3
23.	0.3	0.1	175.2	0.5	0.2	111.5	0.3	0.1	32.8
25.	0.3	0.1	138.4	0.3	0.1	144.5	0.3	0.1	-8.9
***THD*U [%]**	5.058			5.214			5.073		

The percentage values in the Table 1 are referenced to the fundamental harmonic. The phase angle for the fundamental frequency in Table 1 is zero for all phases, as it serves as the reference value for the other harmonics. The phase angles of higher-order harmonics represent the phase shift relative to the fundamental frequency (h = 1). The magnitudes of individual higher-order harmonics and the THD_U in the measured section of the LV network comply with the requirements specified by the technical standard EN 50160 [20]. The voltage waveform contains all odd harmonics up to the 25th order. The highest magnitude is observed in the 5th harmonic, where phase L_3 reaches a value of 4.05% of the fundamental frequency. This remains within the standard's limit of 6%. All higher-order harmonic components exhibit phase shifts relative to the fundamental frequency, with phase angles varying across different harmonic orders and, in some cases, significantly differing between phases for the same harmonic order. For example, for the 11th harmonic, the phase angles in phases L_1 and L_2 are 131 ° and 100 °, respectively, representing a difference of 31°. In phase L_3, the angle is -32 °, which differs by 163 ° compared to phase L_1.

3 Measurement of Appliances

The measurement results presented in Section 2 indicate that the voltage in the public LV distribution network contains higher-order harmonic components with varying magnitudes and phase angles. Similar voltage quality is likely to be observed in other LV networks where many consumers with diverse consumption are connected. These consumers typically use numerous appliances with different consumption characteristics. To investigate this further, four appliances were selected for examination: a compact fluorescent lamp (CFL), an LED linear tube, and two types of LCD monitors, with their respective parameters detailed in the subsequent section.

In each LV network, different combinations of appliances are connected. These appliances can negatively affect voltage quality due to their nonlinear volt-ampere characteristics, which cause them to draw distorted current. As a result, distorted currents interacting with network impedance generate higher-order voltage harmonics. Because of the varying combinations of appliances, different LV networks can produce voltage harmonics with different magnitudes and phase shifts. To investigate this phenomenon, it was necessary to measure scenarios with varying magnitudes and phase shifts of harmonics in the supply voltage for each appliance. In each scenario, the supply voltage included the fundamental harmonic component (which remained constant across all scenarios) and one odd higher-order harmonic component up to the 25^{th} order. The magnitudes of these harmonics were set at 50% and 100% of the limit values specified by the EN 50160 standard [20]. The phase angle was varied from 0° to 360°, in increments of 60°, for each magnitude setting. Given the high number of harmonics and phase shift combinations, 156 scenarios were measured for each appliance. In total, 624 scenarios were measured and evaluated across all appliances.

The 3-phase laboratory source Applied Precision 8325B generated voltage, which contained harmonics as described previously. This source has a nominal power rating of 2 kVA and a voltage generation accuracy class of 0.2%. For this study, generating voltage harmonics with specific phase shifts relative to the fundamental component was essential. The Applied Precision 8325B laboratory source allows for setting the phase shift of higher-order harmonics within a range of 0° to 360° with an accuracy of 0.5°. The ouput voltage on the laboratory source was regulated using the PC application LabVIEW, facilitating remote control for enhanced ease of operation.

The power quality analyzer Dewetron DEWE-571 was used to measure the consumption parameters of each appliance under investigation. This analyzer meets the requirements for Class A power quality measurements as specified by the IEC 61000-4-30 standard [21]. The supply voltage and the current drawn by the appliances were measured directly, without the use of external sensors or transformers. The evaluated consumption parameters included the THD_I, the reactive power of the fundamental harmonic, and the total reactive power. Block diagrams illustrating the measurement setup for lighting sources and LCD monitors are shown in Figure 1.

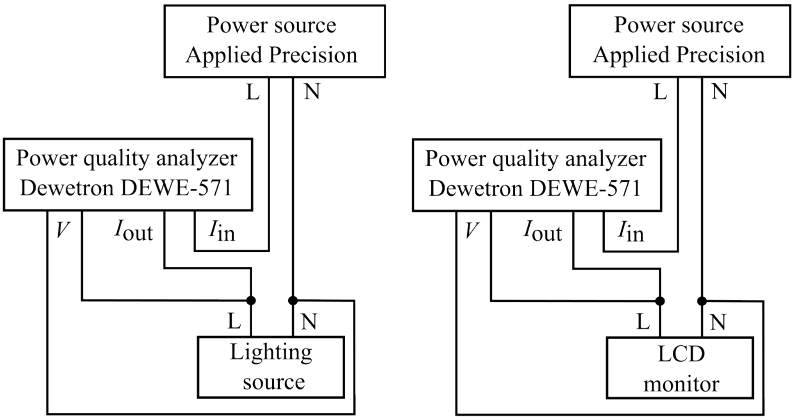

Figure 1
Block diagram of measurement

3.1 Measured Appliances

In total, four appliances were examined, consisting of two types of light sources and two LCD monitors. During the measurement process, the appliances consumed constant active power. For the light sources, this was ensured by maintaining a consistent light intensity, while for the LCD monitors, a static image was displayed on the screen throughout the measurements. The light sources consisted of a CFL and an LED linear tube. The LCD monitors were connected directly to the socket using a modified supply cable, which enabled the connection of the voltage and current sensors of the power quality analyzer. For the measurement of the lighting sources, a test stand was used. This stand, designed as an educational tool, simplifies the measurement of lighting sources. Detailed parameters of the lighting sources are presented in Table 2 and detailed parameters of LCD monitors are provided in Table 3.

Table 2
Parameters of lighting sources

Appliance	***CFL***	***LED linear tube***
Nominal power [W]	23	18
Nominal voltage [V]	220 – 240	220 – 240
Luminous flux [lm]	1520	1700
Color temperature [K]	2700	4000
Energy class	A	A+

Table 3
Parameters of LCD monitors

Appliance	***Monitor 1***	***Monitor 2***
Nominal power [W]	55	45
Resolution	1680 x 1050	1920 x 1080
Luminous intensity [cd/m^2]	250	300

4 Measurement Results

The primary objective of the measurements was to ascertain the influence of individual odd higher-order voltage harmonics on the variations in consumption parameters of the appliances under investigation. Both the magnitude and phase angle of these higher-order voltage components were systematically adjusted. Through the measurements, it became possible to evaluate which harmonic order and angle exerted the most favorable and unfavorable effects on the power quality of consumption.

The subsequent subsections present tables summarizing the THD_I, reactive power of the fundamental harmonic, and total reactive power for each appliance. Each table contains 73 values: one corresponding to a pure sinusoidal supply voltage (base scenario) and 72 representing distorted sinusoidal supply voltages. These distorted waveforms result from combining 12 odd harmonic orders and 6 different phase angles. In each table, a color-coded approach is used to facilitate the interpretation of the data. Specifically:

- Ten values where the harmonic impact was deemed optimal are highlighted in green.
- Ten values indicating the worst impact are highlighted in red.

This approach helps to easily identify the influence of individual harmonics on the consumption parameters. The appliances' active power consumption is not included in these tables due to the negligible impact of harmonics on it. The consumed active power closely approximates the nominal power values provided in Table 2 and Table 3. The reactive power values were directly measured using a power quality analyzer.

4.1 CFL

4.1.1 Results of THD_I, Q and Q_1

Table 4 illustrates the THD_I values for the CFL when individual voltage harmonics reach 100% of the limit set by standard EN 50160 [20]. Cases where the voltage harmonic magnitudes were reduced to 50% of limit value are not included in the table, as the distribution of the 10 best and worst values remained consistent. However, the magnitude of individual consumption parameters was reduced, resulting in a less pronounced influence. The data in Table 4 reveal that certain instances of voltage distortion can reduce the THD_I of the drawn current. The THD_I is notably affected by both the harmonic order and its phase angle. The most adverse effect was observed with the 7th voltage harmonic at a phase angle of -60°, leading to a 33.5% increase in THD_I compared to the base scenario (where no higher-order voltage harmonics were present). In contrast, for the same harmonic order (7th) but with a phase angle of 120°, the THD_I decreased by 10.41% relative to the base scenario.

Table 4

THD_I of CFL

THD_I [%] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
U_1	-	-	-	110.51	-	-
U_1+U_3	121.91	125.73	120.69	101.35	94.61	110.77
U_1+ U_5	127.66	141.63	146.65	120.88	**84.76**	101.66
U_1+ U_7	110.72	133.06	**147.49**	136.99	112.52	99.01
U_1+ U_9	108.17	110.92	115.98	116.83	114.47	110.07
U_1+ U_{11}	126.59	123.32	119.02	123.25	131.88	130.94
U_1+ U_{13}	132.87	132.78	124.36	117.51	119.01	128.01
U_1+ U_{15}	111.68	113.95	113.06	109.83	109.18	109.46
U_1+ U_{17}	116.53	118.55	124.03	124.96	121.37	117.44
U_1+ U_{19}	118.68	114.81	113.84	117.37	120.36	120.03
U_1+ U_{21}	114.37	112.69	110.63	111.12	110.79	112.82
U_1+ U_{23}	120.97	122.45	120.29	117.16	115.54	117.06
U_1+ U_{25}	116.88	119.38	122.71	122.33	119.59	117.99

Table 5

Q_1 of compact fluorescent lamp

Q_1 [var] (voltage harmonics 100% of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
U_1	-	-	-	-9.3	-	-
U_1+U_3	-8.2	-10.3	**-11.8**	-10.5	-7.2	-6.7

***U*₁+ *U*₅**	-7	-9.2	-11.7	-9.5	-6.5	**-5.6**
***U*₁+ *U*₇**	-7.2	-8.5	-10.4	-8.4	-7.2	-6.8
***U*₁+ *U*₉**	-8.9	-9.5	-9.7	-9	-8.6	-8.6
***U*₁+ *U*₁₁**	-8.4	-9.2	-8.8	-7.8	-7.6	-7.9
***U*₁+ *U*₁₃**	-8.5	-9.2	-8.6	-8.1	-7.9	-8.1
***U*₁+ *U*₁₅**	-9.3	-9.4	-9.3	-9.1	-9.1	-9.1
***U*₁+ *U*₁₇**	-9	-9	-8.5	-8.5	-8.5	-8.7
***U*₁+ *U*₁₉**	-9.2	-9	-8.7	-8.6	-8.7	-8.9
***U*₁+ *U*₂₁**	-9.4	-9.2	-9.1	-9.1	-9.1	-9.2
***U*₁+ *U*₂₃**	-9	-8.8	-8.7	-8.7	-8.8	-9
***U*₁+ *U*₂₅**	-9	-8.8	-8.7	-8.7	-8.9	-9

The magnitude of the fundamental harmonic reactive power (Q_1), as shown in Table 5, varies in response to changes in higher-order harmonic components. Q_1 is derived exclusively from the fundamental voltage and current components. The data in Table 5 demonstrate that voltage harmonics influence the phase of the fundamental harmonic current, which, in turn, affects the Q_1 magnitude. The distribution of the 10 best and worst values differs from that observed for THD_I. The difference between the minimum and maximum Q_1 values is 6.2 var. Table 6 provides the total reactive power (Q) measurements for the CFL.

Table 6

Q of compact fluorescent lamp

***Q* [var] (voltage harmonics 100% of standard)**						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
***U*₁**	-	-	-	-28.1	-	-
***U*₁+U₃**	-30.3	-31.3	-30.6	-26.4	-24.6	-27.8
***U*₁+ *U*₅**	-31.6	-35	-36.7	-29.2	**-21.1**	-25.4
***U*₁+ *U*₇**	-27.6	-33.2	**-37**	-32.9	-27	-24.4
***U*₁+ *U*₉**	-27.2	-28.2	-29.5	-29.3	-28.5	-27.6
***U*₁+ *U*₁₁**	-31.2	-30.7	-29.5	-30.1	-32.1	-32
***U*₁+ *U*₁₃**	-32.6	-32.9	-30.7	-28.9	-29.2	-31.4
***U*₁+ *U*₁₅**	-28.3	-28.9	-28.7	-28.1	-27.7	-27.7
***U*₁+ *U*₁₇**	-29.2	-29.6	-30.6	-30.8	-30	-29.3
***U*₁+ *U*₁₉**	-29.7	-28.9	-28.5	-29.2	-29.9	-30
***U*₁+ *U*₂₁**	-28.9	-28.4	-27.9	-27.8	-28	-28.5
***U*₁+ *U*₂₃**	-30.2	-30.4	-29.9	-29.2	-28.9	-29.3
***U*₁+ *U*₂₅**	-29.3	-29.7	-30.4	-30.4	-29.9	-29.6

The distribution of the best and worst values of Q remains consistent compared to THD_I. This consistency is expected since Q is influenced by both the fundamental and all higher-order components of voltage and current and also by THD_I. The difference between the minimum and maximum Q values amounts to 16.6 var. In contrast, this value is lower for Q_1, indicating that higher-order voltage harmonics influence Q more. All measured reactive powers (Q_1 and Q) of CFL exhibit negative values, signifying that the CFL represents a source of reactive power for the network.

4.1.2 Results of Current Harmonics

Based on the THD_I and Q results from Table 4 and Table 6, one best scenario and one worst scenario (for voltage harmonics at 100% of the limit) were selected. The amplitude (I_{MAX}) and phase angle of current harmonics are presented graphically for these selected scenarios and the base scenario in Figure 2 and Figure 3. A color-coded system is used to differentiate the scenarios:

- The base scenario is marked in blue.
- The best scenario is marked in green.
- The worst scenario is marked in red.

For the best scenario, the chosen condition was when the CFL was supplied with voltage containing the fundamental harmonic and the 5th harmonic, with a phase angle of 60° relative to the fundamental. For the worst scenario, the condition selected was when the supply voltage contained the fundamental harmonic and the 7th harmonic, with a phase angle of -60° relative to the fundamental.

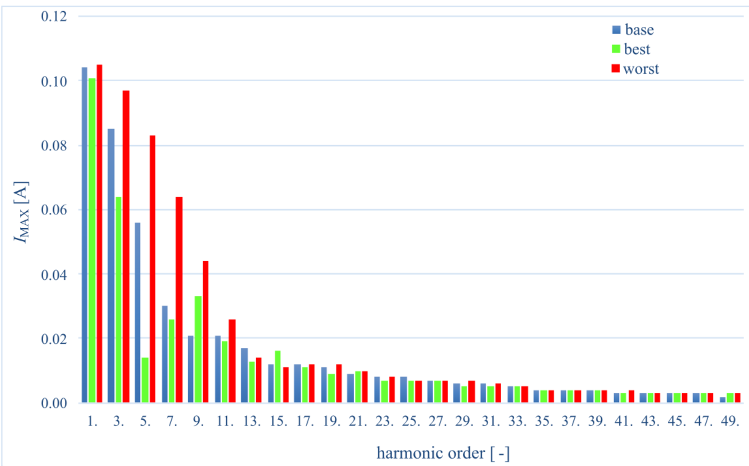

Figure 2

Magnitudes of higher order current harmonics of CFL

Figure 2 illustrates how changes in voltage parameters impact the magnitudes of the CFL current harmonics. Harmonic orders 13 and higher exhibit only minor variations in magnitude, indicating that power quality degradation has a negligible impact on these harmonics compared to the base scenario. This suggests that these higher-order harmonics do not significantly influence the THD_I and Q of the CFL.

Conversely, the first 11 odd harmonics show more significant changes in magnitude. According to the amplitude law, the amplitude of harmonics decreases with increasing harmonic order. Therefore, these lower-order harmonics have a more pronounced impact on THD_I and Q. In most current harmonics, the amplitude decreased during the best scenario compared to the base scenario. The highest decrease, 75%, was observed for the 5th harmonic, where the magnitude dropped from 0.056 A to 0.014 A. During the worst scenario, all harmonic amplitudes increased; the highest increase, 113%, was recorded for the 7th current harmonic, rising from 0.03 A to 0.064 A. The harmonic orders with the most significant changes correspond to the higher-order voltage harmonics added to the supply voltage:

- In the best scenario, the significant change was associated with the 5th voltage harmonic.
- In the worst scenario, the significant change was associated with the 7th voltage harmonic.

The difference between the best and worst scenarios was influenced by the phase angle of the higher-order voltage harmonics. In the best scenario, the phase angle was 60°, while in the worst scenario, it was -60°. This indicates that the order, amplitude, and phase shift of the voltage harmonics relative to the fundamental harmonic all affect the consumption parameters of the CFL. Because the power quality analyzer used in this study can measure the phase angles of current harmonics, these angles were also evaluated for the base, best, and worst scenarios, as shown in Figure 3.

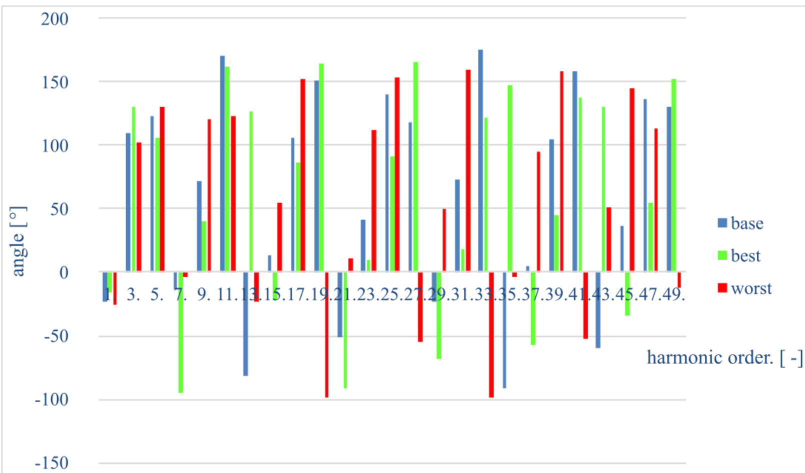

Figure 3
Angels of higher order current harmonics of CFL

Despite the fundamental harmonic of the supply voltage remaining constant across all scenarios, phase angle of fundamental current harmonic varied. In the base scenario, the phase angle was -22.9°, shifting to -16.1° in the best scenario and -25.7° in the worst scenario. These changes in phase angle resulted in variations in the reactive power of the fundamental harmonic, as discussed previously. For the same harmonic order, the phase angle in some cases reversed polarity across different scenarios. This behavior was observed 14 times. For instance, the 13th harmonic exhibited a negative phase angle in both the base and worst scenarios but shifted to a positive value of 126.4° in the best scenario.

4.2 Monitor 1

4.2.1 Results of THD_I, Q and Q_1

Table 7

THD_I of monitor 1

THD_I [%] (voltage harmonics 100% of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
U_1	-	-	-	202.52	-	-
U_1+U_3	218.53	209.95	195.05	178.19	204.91	219.45
U_1+ U_5	240.95	232.16	218.47	**157.59**	235.65	244.89
U_1+ U_7	253.71	246.88	236.54	184.71	253.08	257.17
U_1+ U_9	232.69	229.52	219.14	168.09	202.19	227.19
U_1+ U_{11}	267.48	263.09	256.67	201.38	268.16	270.53
U_1+ U_{13}	271.81	268.04	262.64	205.79	270.92	**273.78**
U_1+ U_{15}	219.43	220.49	212.75	185.19	181.49	206.91
U_1+ U_{17}	267.29	267.55	263.34	205.01	215.76	266.69
U_1+ U_{19}	262.21	262.06	256.61	201.45	189.46	247.57
U_1+ U_{21}	222.16	229.01	220.08	192.68	182.72	199.18
U_1+ U_{23}	265.04	270.83	250.95	210.33	195.39	220.86
U_1+ U_{25}	252.23	272.72	247.75	213.52	198.49	213.44

The measurement methodology and result presentation for both monitors follow the same approach used for the lighting sources. Table 7 outlines the THD_I of monitor 1 when individual voltage harmonics reach a magnitude equal to 100% of the limit specified in the standard. Unlike the lighting sources, the distribution of the 10 best and worst values varies for monitors. The most pronounced adverse effect occurs with the 13th voltage harmonic at a phase angle of -120°, leading to a 35.18% increase in THD_I compared to the base scenario. This result differs from the harmonic order and angle observed for the CFL and LED tube light.

Table 8 and Table 9 depict Q_1 and Q values for monitor 1. The 5th voltage harmonic with a phase angle of 60° decreases the Q1 value close to 0 and mitigates the displacement power factor close to 1. The disparity between the maximal and minimal Q_1 values amounts to 10.1 var.

Unlike lighting sources, the distribution of the best and worst values for THD_I does not align with that of Q for monitor 1. The most significant adverse effect on Q occurs with the 25th voltage harmonic at a phase angle of -120°, differing from the findings for THD_I. The variation between the maximum and minimum Q values is 24.8 var. Both Q_1 and Q exhibit negative values, indicating that monitor 1 supplies reactive power to the network. Due to the high THD_I, there is a substantial difference between Q and Q_1. Notably, in the base scenario, the absolute value of Q exceeds that of Q_1 by 42.7 var.

Table 8

Q_1 of monitor 1

Q_1 [var] (voltage harmonics 100% of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
U_1	-	-	-	-5.6	-	-
U_1+U_3	-5.3	-7.5	-9	-6.4	-2.4	-3.2
U_1+ U_5	-5	-7.6	**-10.2**	-8.3	**-0.1**	-2.4
U_1+ U_7	-4.8	-7.1	-9.3	-7.1	-0.5	-2.6
U_1+ U_9	-5.1	-6.4	-7.6	-6.9	-3.3	-3.9
U_1+ U_{11}	-4.7	-6.3	-8	-6.2	-1.6	-3.2
U_1+ U_{13}	-4.7	-6.1	-7.5	-6	-2	-3.3
U_1+ U_{15}	-5.3	-5.9	-6.4	-6.1	-5.2	-5
U_1+ U_{17}	-4.8	-5.9	-7	-5.8	-4	-3.7
U_1+ U_{19}	-4.9	-5.8	-6.7	-5.8	-4.7	-4.2
U_1+ U_{21}	-5.3	-5.7	-6	-5.8	-5.4	-5.3
U_1+ U_{23}	-4.9	-5.6	-5.9	-5.6	-5.2	-4.9
U_1+ U_{25}	-5.2	-5.5	-5.7	-5.5	-5.3	-5.2

Table 9

Q of monitor 1

Q [var] (voltage harmonics 100% of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
U_1	-	-	-	-48.3	-	-
U_1+U_3	-49.2	-49.6	-49.2	-45.5	-47.8	-49
U_1+ U_5	-53.8	-54.2	-54.6	**-39.7**	-52.1	-53.5
U_1+ U_7	-57.1	-57.6	-58	-43.9	-55.7	-56.8
U_1+ U_9	-54.2	-54.5	-53.3	-41	-46.7	-52.4
U_1+ U_{11}	-61.2	-62.2	-61.9	-45.9	-59.8	-60.8
U_1+ U_{13}	-62.5	-62.9	-63.1	-48.2	-60.8	-62

U_1+ U_{15}	-53.4	-53.9	-52.2	-45.3	-43.7	-49.4
U_1+ U_{17}	-63	-63.8	-63.9	-48.9	-50.2	-61.9
U_1+ U_{19}	-61.7	-62.4	-61.9	-48	-44.5	-57.7
U_1+ U_{21}	-52.7	-54.5	-52.6	-47.3	-43.4	-47.1
U_1+ U_{23}	-61.6	-64.1	-59.6	-49.7	-46	-51.7
U_1+ U_{25}	-59.4	**-64.5**	-58.6	-50.4	-46.8	-50.2

4.2.2 Results of Current Harmonics

For Monitor 1, the distribution of the best and worst values for THD_I differs from that of Q. For graphical representation, the best and worst scenarios were selected based on the THD_I results presented in Table 7. In the best scenario, the supply voltage included the 5th harmonic with a phase shift of 0°, while in the worst scenario, it contained the 13th harmonic with a phase shift of 120°.

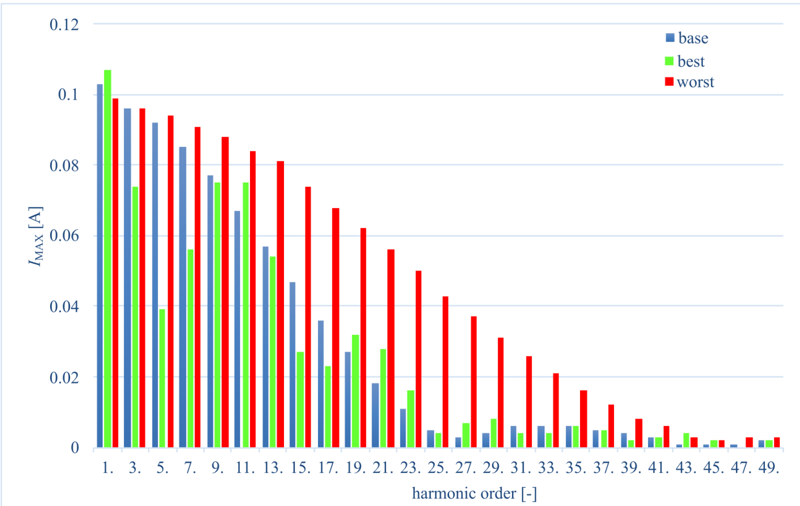

Figure 4

Magnitudes of higher order current harmonics of monitor 1

In the worst scenario, substantial changes in the magnitudes of harmonics were observed in the range from the 9th to the 47th harmonic, compared to the fundamental. The most significant percentage incre ase was recorded for the 27th harmonic, with a rise of 1130%, from 0.003 A to 0.037 A. Despite this large increase, the impact on the consumption parameters of monitor 1 remains minimal, as the magnitude of the 27th current harmonic is approximately 33 times lower than that of the fundamental harmonic. Conversely, the largest decrease in magnitude was observed for the 5th harmonic, with a reduction of 58%, from 0.092 A to 0.039 A. Interestingly, only the harmonic orders with the most significant decreases in the best scenario correspond to the higher-order voltage harmonics (5th harmonic) added to the supply voltage. However, this correlation does not hold for the worst scenario. Figure 5 provides a graphical evaluation of the phase shifts of current harmonics.

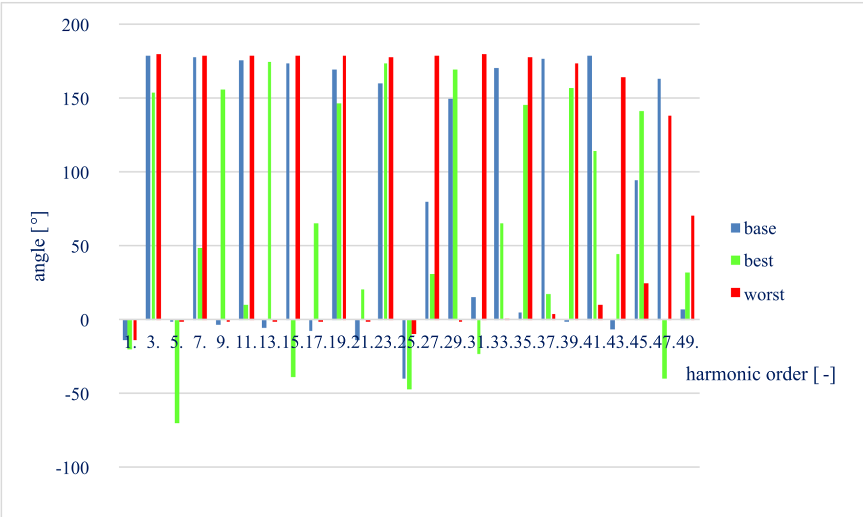

Figure 5
Angels of higher order current harmonics of monitor 1

Similar to the observations for the CFL, in the case of monitor 1, the addition of higher-order voltage harmonics to the supply voltage also influenced the phase angle of the fundamental current harmonic. In the base scenario, the phase angle of the fundamental current harmonic was -13.9°. This shifted to -19.7° in the best scenario and -8.4° in the worst scenario. Additionally, for the same harmonic order, the phase angle reversed polarity across different scenarios 10 times.

5 Discussion

During the measurement procedure, the magnitudes of odd higher-order voltage harmonics, up to the 25th harmonic, were set at two levels corresponding to 50% and 100% of the limits specified by the EN 50160 standard [20]. The phase angles of these harmonics were varied from 0° to 360° in 60° increments. The main goal of these measurements was to analyze the impact of individual odd higher-order voltage harmonics on the power quality of the appliances being tested, focusing on parameters such as THD_I, Q_1, and Q.

The measurements indicate that the distortion in supply voltage can either worsen or improve the power quality of consumption parameters, depending on the harmonic order and phase angle of the specific voltage harmonic. To enhance understanding, the top 10 best and worst values were color-coded (red for worst and green for best), aiding the identification of which harmonics and phase angles influence the power quality of the appliances under observation. The distribution of these values remained consistent across both measurement levels. The scenario corresponding to 100% of the standard had a more significant effect, which is why only data from this scenario are included in the paper.

An intriguing observation is that the same voltage harmonic order can result in consumption parameters falling within both the best and worst value ranges. This implies that a specific harmonic order may either improve or degrade the power quality of appliance consumption parameters, depending on its phase angle. For example, in the case of monitor 1, when the supply voltage includes both the fundamental and the 5th harmonic, the highest and lowest Q_1 values were recorded. The least favorable value occurred at a phase angle of -60°, while the optimal value was observed at a phase angle of 60°.

Table 10

Evaluation of impact on lighting sources

Consumption parameter	**Lightings**			
	Worst interval		***Best interval***	
	har. order	***angle [°]***	***har. order***	***angle [°]***
THD_I	5, 7, 11, 13, 17	-180 - 0	3, 5, 7, 9, 15	60 - 120
Q_1	3, 5, 7, 9, 13, 15, 24, 21	-180 - 0	3, 5, 7, 11	60 - 120
Q	5, 7, 11, 13	-180 - 0	3, 5, 7, 9, 11, 13, 15	60 - 120

Table 10 presents the higher voltage harmonic orders that fall within the best and worst intervals for the consumption of lighting sources. It also includes the phase angles for most of these harmonics within both intervals. The analysis shows that it is not possible to pinpoint specific harmonic orders that consistently have the best or worst effect on the power quality of consumption parameters for the measured lighting sources. A large number of harmonic orders in Table 10 appear in both the best and worst intervals. However, the phase angles within these intervals differ. Specifically, the worst interval contains angles between 240° and 360°, while the best interval includes angles ranging from 60° to 120°.

Table 16 shows the higher voltage harmonic orders and their corresponding phase angles that fall within the best and worst intervals for the consumption of monitors. As with lighting sources, it is not possible to identify specific harmonic orders that consistently have the most favorable or unfavorable effect on the power quality of consumption parameters for the measured monitors. Although the phase angles within these intervals differ, the angle ranges are similar for monitors as they are for lighting sources.

Table 11
Evaluation of impact on monitors

Consumption parameter	Monitors			
	Worst interval		***Best interval***	
	har. order	***angle [°]***	***har. order***	***angle [°]***
THD_I	11, 13, 17, 23	180 - 240	3 - 25	0 - 120
Q_1	3, 5, 7, 9, 11, 13	-180 - 0	3 - 13	60 – 120, 180
Q	11, 13, 17, 19, 23, 25	-180 - 0	3 - 25	0 - 120

Consclusion

This paper presents the measurement results for two LCD monitors, a CFL lamp, and an LED linear tube under different supply voltage conditions. The evaluation focused on their THD_I, Q_1, and Q. All appliances demonstrated nonlinear consumption character with high THD_I, leading to notable differences between Q_1 and Q. Both reactive power values were negative, indicating that these appliances were supplying reactive power to the network.

The study found that the impact of supply voltage distortion on the appliances was influenced by the order and phase angle of higher-order voltage harmonics. The effect of harmonic order appeared to be random, making it challenging to identify which specific order had a more favorable or detrimental effect. However, phase angles of these harmonics between 0° and 120° reduced the negative impact of the appliances on the network. In contrast, phase angles ranging from 180° to 360° worsened the power quality of consumption compared to the base scenario, where the supply voltage contained only the fundamental frequency.

A similar situation could be observed in the public distribution system, where voltage distortion occurs. The presence of higher voltage harmonics and their phase angles in the distribution system are influenced by various factors and can vary across different locations within the same system. As a result, the same appliance may exert a different impact on the distribution system, consequently affecting the flow of reactive power.

In future work, additional appliances will be measured using the same scenarios, harmonic orders, and phase angles of supply voltage as in this study. The measured results will allow for comparisons to determine which harmonic orders and phase angles have similar effects on the consumption parameters as observed in this investigation. Of particular interest will be identifying the phase angles of higher-order voltage harmonics that fall within the best and worst intervals for the newly measured appliances. These findings will then be compared with those from the current study.

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