Dependence of Reactive Power Magnitude Variations on Power Supply Voltage Distortion

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Abstract — **The paper investigates the impact of various higher-order voltage harmonic components' magnitudes and their diverse phase angles on the variations of reactive power. Four appliances (2 monitors, a CFL fluorescent lamp, and a LED tube system) were connected to a laboratory power supply featuring a fundamental harmonic component and simultaneous higher-order harmonic components. The measurement examines the influence of the consumption of each appliance. Three key parameters were prioritized for monitoring, including reactive power, active power, and total harmonic distortion of current.**

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

I. Introduction

The deterioration of power quality poses a threat to the secure and reliable functioning of the transmission power system. Among the negative consequences is the undesired transmission of reactive power. In recent years, the occurrence of reverse flows of reactive power between transmission and distribution systems has become apparent. This phenomenon has been documented in various European nations, including Slovakia, as referenced in [1 - 5]. Such reverse flows can lead to complications related to voltage increases within the transmission system. Findings from measurements cited in [3] and [4] suggest that low voltage networks are sources of reactive power, thereby contributing to the reverse reactive power flow issue.

The consumption patterns of users connected to low voltage networks are predominantly characterized by appliances incorporating power electronic components. These appliances typically exhibit a capacitive character of consumption, resulting in the supply of reactive power to the network. This assertion is corroborated by measurements referenced in papers [6 - 10]. Additionally, measurements reveal that household appliances often exhibit nonlinear characteristics and draw distorted currents. Consequently, the THD_V increases, accompanied by an elevation in the magnitude and spectrum of higher-order harmonic components within the network. While the active power dominant part is created by the fundamental frequency, the impact of harmonic distortion on its magnitude is negligible. Conversely, harmonic distortion can exert a substantial influence on reactive power, where the reactive power magnitude of higher-order harmonic components can be higher than the reactive power of the fundamental frequency. This can contribute to the reverse flow of reactive power between the transmission and distribution systems. Authors in [11] conducted simulations involving various combinations of household appliances (e.g., LED bulbs, television, notebook, electric shower, and air conditioner). These simulations demonstrated that specific combinations of these appliances could mitigate the THD_I of the drawn current and improve the power factor of their consumption.

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. The magnitudes of individual voltage harmonics were set according to standard EN 50160 at 50% and 100% of the compatible level [12]. Six different phase angles of voltage harmonics were applied for these magnitudes. Only odd harmonic components of voltage up to the 25th order were generated. For each scenario, the consumption parameters of the appliances were measured, and their THD_I, reactive power, and power factor were evaluated. Consequently, their effects on reactive power flow were assessed.

The rest of this article is organized as follows: Section 2 discusses the appliances and measurements methods used within this article. Section 3 presents the results of the measurements and Section 4 concludes the article.

II. Measurement

A. *Measurement methode*

The measurements were conducted employing the laboratory source Applied Precision 8325B and the power quality analyzer Dewetron DEWE-571. The block diagram representation of the measurement is depicted in Fig. 1. The supply voltage on the laboratory source was regulated according to the EN 50160 [12] standard utilizing the PC application LabVIEW, facilitating remote control for enhanced ease of operation. In each experimental scenario, the voltage waveform contained the fundamental harmonic component, which remained constant across all scenarios, along with one odd higher-order harmonic component up to the 25th order. The magnitude of the higher harmonic component was varied at two levels, corresponding to 50 % and 100 % of the limit by the EN 50160 standard [12]. For each magnitude, the phase angle was adjusted within the range of 0° to 360°, with increment of 60°. Through this methodology, a total of 156 distinct scenarios were generated for each measured appliance.

The power quality analyzer measured the consumption parameters of each appliance under investigation. Voltage and current were directly measured without using external sensors or transformers. Four appliances were examined in total, comprising two types of light sources and two LCD monitors, with their respective parameters detailed in the subsequent subsection. The evaluated parameters included THD_I, reactive power of the fundamental harmonic, total reactive power.

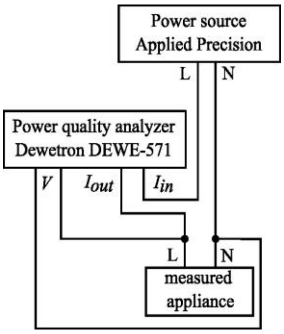

Figure 1. Block diagram of measurement

B. *Measured appliances*

In total, four appliances were examined, encompassing two distinct types of light sources and two LCD monitors. Throughout the measurement process, the appliances maintained a constant power consumption. This was achieved by ensuring consistent light intensity for the light sources and a static image displayed on the screen for the LCD monitors. The light sources consisted of a compact fluorescent lamp (CFL) and an LED linear tube. Detailed parameters of these appliances are provided in Tab. 1.

Table 1. Parameters of light 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+

Detailed parameters of LCD monitors are provided in Tab. 2.

Table 2. 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

III. 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.

Subsequent subsections present tables detailing the THD_I, reactive power of the fundamental harmonic, and total reactive power. The consumed active power of the appliances is not provided from these tables due to the negligible impact of harmonics upon it. Its value closely approximates the nominal power values provided in Tab. 1 and 2. In each table, ten values where the impact was deemed optimal are highlighted in green, while those indicating the worst impact are highlighted in red. This color-coded approach aids in the facile determination of the influence of individual harmonics on consumption parameters.

A. *CFL*

Table 3. THD_I of compact fluorescent lamp

***THD*$_I$ [%] (voltage harmonics 100 % of standard)**						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	110.51	-	-
V_1+V_3	121.91	125.73	120.69	101.35	94.61	110.77
V_1+V_5	127.66	141.63	146.65	120.88	**84.76**	101.66
V_1+V_7	110.72	133.06	**147.49**	136.99	112.52	99.01
V_1+V_9	108.17	110.92	115.98	116.83	114.47	110.07
V_1+V_{11}	126.59	123.32	119.02	123.25	131.88	130.94
V_1+V_{13}	132.87	132.78	124.36	117.51	119.01	128.01
V_1+V_{15}	111.68	113.95	113.06	109.83	109.18	109.46
V_1+V_{17}	116.53	118.55	124.03	124.96	121.37	117.44
V_1+V_{19}	118.68	114.81	113.84	117.37	120.36	120.03
V_1+V_{21}	114.37	112.69	110.63	111.12	110.79	112.82
V_1+V_{23}	120.97	122.45	120.29	117.16	115.54	117.06
V_1+V_{25}	116.88	119.38	122.71	122.33	119.59	117.99

Tab. 3 presents the THD_I for the CFL when individual voltage harmonics reach a magnitude equal to 100 % of the limit specified in standard EN 50160 [12]. Cases, where voltage harmonic magnitudes are at 50 % of the standard, are not depicted in the table, as the distribution of the 10 best and worst values remained unchanged. Only the magnitude of the individual consumption parameters changed, with their influence being smaller. The measured data in Tab. 3 show, that specific instances of voltage distortion can mitigate the THD_I of the drawn current. THD_I is significantly impacted not only by the order of the harmonic but also by its phase angle. The most adverse effect is observed with the 7th voltage harmonic at a phase angle of -60°, resulting in a 33.5 % increase in THD_I compared to the base scenario (without higher-order voltage harmonics). Conversely, for the same harmonic order (7th) but with a phase angle of 120°, THD_I decreased by 10.41 % compared to the base scenario.

Table 4. Q_1 of compact fluorescent lamp

Q_1 [var] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-9,3	-	-
V_1+V_3	-8,2	-10,3	**-11,8**	-10,5	-7,2	-6,7
V_1+V_5	-7	-9,2	-11,7	-9,5	-6,5	**-5,6**
V_1+V_7	-7,2	-8,5	-10,4	-8,4	-7,2	-6,8
V_1+V_9	-8,9	-9,5	-9,7	-9	-8,6	-8,6
V_1+V_{11}	-8,4	-9,2	-8,8	-7,8	-7,6	-7,9
V_1+V_{13}	-8,5	-9,2	-8,6	-8,1	-7,9	-8,1
V_1+V_{15}	-9,3	-9,4	-9,3	-9,1	-9,1	-9,1
V_1+V_{17}	-9	-9	-8,5	-8,5	-8,5	-8,7
V_1+V_{19}	-9,2	-9	-8,7	-8,6	-8,7	-8,9
V_1+V_{21}	-9,4	-9,2	-9,1	-9,1	-9,1	-9,2
V_1+V_{23}	-9	-8,8	-8,7	-8,7	-8,8	-9
V_1+V_{25}	-9	-8,8	-8,7	-8,7	-8,9	-9

The magnitude of the fundamental harmonic reactive power (Q_1), as depicted in Tab. 4, fluctuates in response to variations in the higher-order harmonic components. Q_1 originates solely from the fundamental components of voltage and current. Analysis of the results in Tab. 4 highlights the influence of voltage harmonics on the phase of the fundamental harmonic current, thereby affecting the magnitude of Q_1. 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 amounts to 6,2 var. Tab. 5 presents the total reactive power (Q) of the CFL.

Table 5. Q of compact fluorescent lamp

***Q* [var] (voltage harmonics 100 % of standard)**						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-28,1	-	-
V_1+V_3	-30,3	-31,3	-30,6	-26,4	-24,6	-27,8
V_1+ V_5	-31,6	-35	-36,7	-29,2	**-21,1**	-25,4
V_1+ V_7	-27,6	-33,2	**-37**	-32,9	-27	-24,4
V_1+ V_9	-27,2	-28,2	-29,5	-29,3	-28,5	-27,6
V_1+ V_{11}	-31,2	-30,7	-29,5	-30,1	-32,1	-32
V_1+ V_{13}	-32,6	-32,9	-30,7	-28,9	-29,2	-31,4
V_1+ V_{15}	-28,3	-28,9	-28,7	-28,1	-27,7	-27,7
V_1+ V_{17}	-29,2	-29,6	-30,6	-30,8	-30	-29,3
V_1+ V_{19}	-29,7	-28,9	-28,5	-29,2	-29,9	-30
V_1+ V_{21}	-28,9	-28,4	-27,9	-27,8	-28	-28,5
V_1+ V_{23}	-30,2	-30,4	-29,9	-29,2	-28,9	-29,3
V_1+ V_{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.

B. LED lienear tube

Tab. 6 presents the THD_I for the LED linear tube when individual voltage harmonics reach a magnitude equal to 100 % of the limit. The data in Tab. 6 reveal that similar to the CFL case, specific instances of voltage distortion can mitigate the THD_I of the drawn current for the LED linear tube. The most adverse effect is observed for the 7th voltage harmonic at a phase angle of -60°, resulting in a 35.42 % increase in THD_I compared to the base scenario. This corresponds to the same harmonic order and angle as observed for the CFL. Additionally, the distribution of the 10 best and worst values of THD_I is similar when comparing the LED linear tube and CFL.

Table 6. THD_I of LED linear tube

***THD*$_I$ [%] (voltage harmonics 100 % of standard)**						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	124.34	-	-
V_1+V_3	140.83	140.47	130.75	109.77	108.95	130.34
V_1+ V_5	154.32	161.18	160.08	133.19	**90.25**	131.51
V_1+ V_7	144.92	162.14	**168.39**	155.9	117.53	112.08
V_1+ V_9	117.21	126.05	136.36	135.75	126.09	117.02
V_1+ V_{11}	132.11	130.62	139.35	158.32	156.74	143.24
V_1+ V_{13}	146.52	139.37	136.16	139.24	155.47	154.09
V_1+ V_{15}	127.07	128.53	126.93	123.01	121.85	124.43
V_1+ V_{17}	142.01	147.79	145.68	135.62	130.58	132.37
V_1+ V_{19}	127.85	133.52	140.03	138.05	132.41	127.78
V_1+ V_{21}	124.36	124.52	124.77	126.62	126.92	125.46
V_1+ V_{23}	138.75	135.18	130.49	133.09	141.01	141.41
V_1+ V_{25}	143.71	141.83	135.03	130.18	133.68	141.45

In Tab. 7 and 8, the Q_1 and Q values for the LED linear tube are summarized. These values were obtained under the same measurement conditions as those for THD_I presented in Tab. 6.

Table 7. Q_1 of LED linear tube

Q_1 [var] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-9.7	-	-
V_1+V_3	-8.2	-10.3	**-12.3**	-11.6	-7.8	-6.9
V_1+ V_5	-7	-9.3	-12	-10.7	-6.3	**-5.5**
V_1+ V_7	-6.9	-8.5	-10.6	-9.3	-7.1	-6.2
V_1+ V_9	-8.9	-9.4	-10.3	-9.8	-9	-8.8
V_1+ V_{11}	-8.1	-8.7	-9.6	-8.2	-7.7	-7.7
V_1+ V_{13}	-8.4	-8.9	-9.7	-8.2	-7.8	-7.9
V_1+ V_{15}	-9.5	-9.7	-9.9	-9.5	-9.4	-9.3
V_1+ V_{17}	-8.7	-9.2	-9.4	-8.7	-8.5	-8.5
V_1+ V_{19}	-9.1	-9.4	-9.3	-8.9	-8.8	-8.7
V_1+ V_{21}	-9.5	-9.7	-9.6	-9.4	-9.3	-9.4
V_1+ V_{23}	-9.1	-9.4	-9.2	-8.9	-8.8	-8.9
V_1+ V_{25}	-9.1	-9.4	-9.2	-9	-8.8	-8.9

Table 8. Q of LED linear tube

***Q* [var] (voltage harmonics 100 % of standard)**						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-28.1	-	-
V_1+V_3	-30.3	-31.3	-30.6	-26.4	-24.6	-27.8
V_1+ V_5	-31.6	-35	-36.7	-29.2	**-21.1**	-25.4
V_1+ V_7	-27.6	-33.2	**-37**	-32.9	-27	-24.4
V_1+ V_9	-27.2	-28.2	-29.5	-29.3	-28.5	-27.6
V_1+ V_{11}	-31.2	-30.7	-29.5	-30.1	-32.1	-32
V_1+ V_{13}	-32.6	-32.9	-30.7	-28.9	-29.2	-31.4
V_1+ V_{15}	-28.3	-28.9	-28.7	-28.1	-27.7	-27.7
V_1+ V_{17}	-29.2	-29.6	-30.6	-30.8	-30	-29.3
V_1+ V_{19}	-29.7	-28.9	-28.5	-29.2	-29.9	-30
V_1+ V_{21}	-28.9	-28.4	-27.9	-27.8	-28	-28.5
V_1+ V_{23}	-30.2	-30.4	-29.9	-29.2	-28.9	-29.3
V_1+ V_{25}	-29.3	-29.7	-30.4	-30.4	-29.9	-29.6

The distribution of the best and worst Q and Q_1 values differs, but this distribution is similar for THD_I and Q, to that observed in the case of CFL. Higher-order voltage harmonics exhibit a greater impact on Q. This is evident from the differences between the maximal and minimal values, which amounts to 6.8 var for Q_1 and 15.9 var for Q. Both Q and Q_1 display negative values, indicating that the LED linear tube is a source of reactive power for the network.

C. Monitor 1

Table 9. THD_I of monitor 1

***THD*$_I$ [%] (voltage harmonics 100 % of standard)**						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	202.52	-	-
V_1+V_3	218.53	209.95	195.05	178.19	204.91	219.45
V_1+ V_5	240.95	232.16	218.47	**157.59**	235.65	244.89
V_1+ V_7	253.71	246.88	236.54	184.71	253.08	257.17
V_1+ V_9	232.69	229.52	219.14	168.09	202.19	227.19
V_1+ V_{11}	267.48	263.09	256.67	201.38	268.16	270.53
V_1+ V_{13}	271.81	268.04	262.64	205.79	270.92	**273.78**
V_1+ V_{15}	219.43	220.49	212.75	185.19	181.49	206.91
V_1+ V_{17}	267.29	267.55	263.34	205.01	215.76	266.69
V_1+ V_{19}	262.21	262.06	256.61	201.45	189.46	247.57
V_1+ V_{21}	222.16	229.01	220.08	192.68	182.72	199.18
V_1+ V_{23}	265.04	270.83	250.95	210.33	195.39	220.86
V_1+ V_{25}	252.23	272.72	247.75	213.52	198.49	213.44

The measurement methodology and presentation of results for both monitors use the same approach employed for lighting sources. Tab. 9 displays the THD_I of monitor 1 under conditions where individual voltage harmonics reach a magnitude equal to 100 % of the specified limit in the standard. Unlike lighting sources, the distribution of the 10 best and worst values differs for monitors. The most significant adverse effect is observed for the 13th voltage harmonic at a phase angle of -120°, resulting in a 35.18 % increase in THD_I compared to the base scenario. This does not correspond to the same harmonic order and angle observed for the CFL and LED light tube.

Tab. 10 and 11 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.

In contrast to lighting sources, the distribution of the best and worst values for THD_I differs from that of Q for monitor 1. The most adverse effect on Q is observed for the 25th voltage harmonic at a phase angle of -120°, which is distinct from the findings for THD_I. The difference between the maximal and minimal Q values is 24.8 var.

Both $Q1$ and Q values are negative, indicating that monitor 1 is a source of reactive power for the network. Due to the high value of THD_I, a significant difference between Q and Q_1 is reached. Specifically, for the base scenario, the absolute value of Q is higher by 42.7 var compared to the absolute value of Q_1.

Table 10. Q_1 of monitor 1

Q_1 [var] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-5.6	-	-
V_1+V_3	-5.3	-7.5	-9	-6.4	-2.4	-3.2
V_1+V_5	-5	-7.6	**-10.2**	-8.3	**-0.1**	-2.4
V_1+V_7	-4.8	-7.1	-9.3	-7.1	-0.5	-2.6
V_1+V_9	-5.1	-6.4	-7.6	-6.9	-3.3	-3.9
V_1+V_{11}	-4.7	-6.3	-8	-6.2	-1.6	-3.2
V_1+V_{13}	-4.7	-6.1	-7.5	-6	-2	-3.3
V_1+V_{15}	-5.3	-5.9	-6.4	-6.1	-5.2	-5
V_1+V_{17}	-4.8	-5.9	-7	-5.8	-4	-3.7
V_1+V_{19}	-4.9	-5.8	-6.7	-5.8	-4.7	-4.2
V_1+V_{21}	-5.3	-5.7	-6	-5.8	-5.4	-5.3
V_1+V_{23}	-4.9	-5.6	-5.9	-5.6	-5.2	-4.9
V_1+V_{25}	-5.2	-5.5	-5.7	-5.5	-5.3	-5.2

Table 11. Q of monitor 1

Q [var] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-48.3	-	-
V_1+V_3	-49.2	-49.6	-49.2	-45.5	-47.8	-49
V_1+V_5	-53.8	-54.2	-54.6	**-39.7**	-52.1	-53.5
V_1+V_7	-57.1	-57.6	-58	-43.9	-55.7	-56.8
V_1+V_9	-54.2	-54.5	-53.3	-41	-46.7	-52.4
V_1+V_{11}	-61.2	-62.2	-61.9	-45.9	-59.8	-60.8
V_1+V_{13}	-62.5	-62.9	-63.1	-48.2	-60.8	-62
V_1+V_{15}	-53.4	-53.9	-52.2	-45.3	-43.7	-49.4
V_1+V_{17}	-63	-63.8	-63.9	-48.9	-50.2	-61.9
V_1+V_{19}	-61.7	-62.4	-61.9	-48	-44.5	-57.7
V_1+V_{21}	-52.7	-54.5	-52.6	-47.3	-43.4	-47.1
V_1+V_{23}	-61.6	-64.1	-59.6	-49.7	-46	-51.7
V_1+V_{25}	-59.4	**-64.5**	-58.6	-50.4	-46.8	-50.2

D. *Monitor 2*

Table 12. THD_I of monitor 2

THD_I [%] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	199.88	-	-
V_1+V_3	216.35	214.39	202.14	176.41	191.37	209.85
V_1+V_5	237.59	238.31	231.75	179.73	211.79	232.19
V_1+V_7	249.79	251.23	248.09	202.71	230.07	244.77
V_1+V_9	228.07	230.62	226.28	191.47	**172.28**	212.77
V_1+V_{11}	261.14	264.66	264.13	220.41	245.52	257.71
V_1+V_{13}	265.98	268.68	**268.82**	225.21	220.91	255.29
V_1+V_{15}	210.94	218.34	218.12	198.69	177.49	188.27
V_1+V_{17}	259.11	264.47	266.13	226.07	188.26	219.75
V_1+V_{19}	235.62	254.73	259.16	223.97	181.22	187.48
V_1+V_{21}	196.65	213.51	221.64	205.97	187.16	184.31
V_1+V_{23}	204.52	238.22	256.73	229.39	197.34	188.74
V_1+V_{25}	200.52	223.07	249.25	230.67	203.84	192.61

Tab. 12 presents the THD_I for monitor 2. The distribution of the 10 best and worst values differs for monitor 2 compared to monitor 1. Similar to monitor 1, the most significant adverse effect is observed for the 13th voltage harmonic, but with a different phase angle of -60°. In this instance, a 34.49 % increase in THD_I compared to the base scenario was recorded.

Tab.13 and 14 illustrate the Q_1 and Q values for monitor 1. The 17th and 19th voltage harmonics, with phase angles of 60° and -180° respectively, reduce the Q_1 value to 0 var and adjust the displacement power factor to 1. The range between the maximal and minimal Q_1 values is 20.1 var. Across all measured appliances, the Q_1 values were consistently negative. However, for monitor 2, in the base scenario, while Q_1 remains negative, certain voltage harmonics alter its flow direction. The nature of consumption (inductive or capacitive) of monitor 2 is influenced by the harmonic order and phase angle of voltage harmonics. As a result, the color-coded marking of the 10 best and worst Q_1 values is determined based on absolute values.

The distribution of the best and worst values for Q is similar to that of THD_I in the case of monitor 2. The most significant adverse effect on Q is observed for the 17th voltage harmonic with a phase angle of -60°. The difference between the maximal and minimal Q values is 43.3 var. Voltage harmonics do not influence the flow direction of Q, its value remains negative for any examined harmonic order, indicating a capacitive power factor.

Table 13. Q_1 of monitor 2

Q_1 [var] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-2.3	-	-
V_1+V_3	-1	-5.6	-9.1	-5	3.9	3.1
V_1+V_5	0.2	-5.2	**-10.7**	-9.1	9.4	5.2
V_1+V_7	0.6	-3.9	-8.6	-6.7	8.9	4.9
V_1+V_9	-0.4	-3	-5.5	-5.7	1.3	1.6
V_1+V_{11}	0.9	-2.3	-5.6	-4.3	7	4.1
V_1+V_{13}	1	-1.8	-4.7	-3.6	4.2	3.7
V_1+V_{15}	-1.4	-2.3	-3.3	-3.3	-1.9	-1.1
V_1+V_{17}	0.6	-1.4	-3.5	-2.8	**0**	1.4
V_1+V_{19}	**0**	-1.4	-3.1	-2.6	-1.2	-0.4
V_1+V_{21}	-1.9	-2.2	-2.7	-2.5	-2.1	-1.8
V_1+V_{23}	-1.4	-1.6	-2.2	-1.9	-1.5	-1.3
V_1+V_{25}	-1.8	-2.1	-1.8	-1.6	-1.5	-1.6

Table 14. Q of monitor 2

Q [var] (voltage harmonics 100 % of standard)						
Angle	***-180°***	***-120°***	***-60°***	***0°***	***60°***	***120°***
V_1	-	-	-	-91.7	-	-
V_1+V_3	-93.5	-94.7	-94.7	-86.6	-89.6	-92.7
V_1+V_5	-102.2	-104	-105.8	-84.5	-96.5	-101.3
V_1+V_7	-108.9	-110.5	-112.2	-91.6	-103.7	-107.5
V_1+V_9	-103	-104.6	-103.8	-88.7	**-78.7**	-96.4
V_1+V_{11}	-116.3	-118.2	-119.5	-99.1	-110.7	-115
V_1+V_{13}	-119	-120.6	-121.9	-101.5	-99.2	-116.4
V_1+V_{15}	-97.3	-100.5	-100.7	-91.7	-81.6	-86.4
V_1+V_{17}	-117.6	-120.7	**-122**	-103.2	-85.3	-99.9
V_1+V_{19}	-107.5	-116.5	-118.9	-102.3	-82.5	-85.4
V_1+V_{21}	-90.1	-97.9	-101.7	-94.4	-85.6	-84.3
V_1+V_{23}	-93.4	-109	-116.3	-104.7	-89.9	-86
V_1+V_{25}	-91.5	-102.1	-114	-105.2	-92.7	-87.8

IV. Discussion

For the measurement procedure, the magnitude of the odd higher voltage harmonic component up to the 25th harmonic was adjusted at two levels, corresponding to 50 % and 100 % of the limit by the EN 50160 standard [12], with phase angles ranging from 0° to 360° in increments of 60°. The primary objective of these measurements was to examine the influence of individual odd higher-order voltage harmonics on the power quality of consumption parameters (specifically THD_I, Q_1, and Q) of the appliances under examination.

The measurements reveal that the distortion of the supply voltage can either deteriorate or mitigate the power quality of consumption parameters, depending upon the order and phase angle of the specific voltage harmonic. To better clarity, the 10 best and worst values were color-coded (using red and green), facilitating the evaluation of which voltage harmonic and phase angle can either mitigate or deteriorate the power quality of consumption for the measured appliances. The distribution of the best and worst values remained consistent for both levels. The level corresponding to 100 % of the standard exhibited a more substantial impact, hence only data from this measurement scenario are presented in the paper.

An interesting finding is that the same order of voltage harmonic can lead to the consumption parameters falling within both the interval of the 10 best and worst values. This suggests that a specific voltage harmonic order can either deteriorate or mitigate the power quality of consumption parameters of appliances, depending on its phase angle. For instance, in the case of monitor 1, when the supply voltage contains the fundamental and the 5th harmonic, both the maximal and minimal values of Q_1 were recorded. The most adverse value was observed with a phase angle of -60°, while the best value was recorded with a phase angle of 60°.

Table 15. 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 <	3, 5, 7, 9, 15	60 - 120
Q_1	3, 5, 7, 9, 13, 15, 24, 21	180 <	3, 5, 7, 11	60 - 120
Q	5, 7, 11, 13	180 <	3, 5, 7, 9, 11, 13, 15	60 - 120

Tab. 15 displays the voltage higher harmonic orders that fall within the best and worst intervals for the consumption of lighting sources. Additionally, the table includes phase angles for the majority of these voltage harmonics falling within both the worst and best intervals. Evaluation reveals that it is not possible to determine specific harmonic orders that have the best or worst impact on the power quality of consumption parameters of the measured lighting sources. A significant part of the harmonic orders listed in Tab. 15 fall within both the best and worst intervals. However, in contrast, the phase angles within these intervals differ. Specifically, angles ranging from 240° to 360° are present in the worst interval, while angles ranging from 60° to 120° are present in the best interval.

Table 16. 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 <	3 - 13	60 – 120, 180
Q	11, 13, 17, 19, 23, 25	180 <	3 - 25	0 - 120

Tab. 16 exhibits the voltage higher harmonic orders and corresponding phase angles that fall within the best and worst intervals for the consumption of monitors. Similar to the case of lighting sources, it is not posible to determine specific harmonic orders that exert the best or worst impact on the power quality of consumption parameters for the measured monitors. The phase angles within these intervals differ. However, the intervals of angles are similar for monitors compared to lighting sources.

V. Consclusion

The paper presents the results of measurements conducted on two LCD monitors, a CFL lamp, and an LED linear tube under varying levels of supply voltage distortion. The focus of the evaluation was primarily on their THD_I, reactive power of the fundamental harmonic (Q_1), and total reactive power (Q). All appliances exhibited nonlinear consumption characteristics with high THD_I, resulting in significant differences between Q_1 and Q. Both reactive powers exhibited negative values, indicating that these appliances supplied power to the network, contributing to the reverse flow of reactive power between the transmission and distribution systems.

The study found that the extent of their influence is influenced by the supply voltage distortion, specifically by the order and phase angle of higher-order voltage harmonics. The influence of harmonic order was found to be random, making it difficult to determine which order had a better or worse effect. However, voltage angles of these harmonics ranging from 0° to 120° mitigated the impact of the measurement appliances on the network. Conversely, angles in the range from 180° to 360° deteriorated the power quality of consumption compared to the base scenario, where the supply voltage contained only the fundamental frequency.

Similar behavior could occur in the public distribution system where voltage is distorted. The content of higher voltage harmonics and their angles in the distribution system are influenced by many factors and can vary within the same system based on location. Consequently, the same appliance may have a different impact on the distribution system, and thus on reactive power flow.

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