TYPICAL HARMONIC LEVELS AND SPECTRA WITH LOW-VOLTAGE CUSTOMERS

Math BOLLEN
Luleå University of Technology
Sweden
math.bollen@ltu.se

Sarah RÖNNBERG
Luleå University of Technology
Sweden
sarah.ronnberg@ltu.se

Aurora GIL DE CASTRO
University of Cordoba
Spain
p32rogia@uco.es

ABSTRACT

This paper presents levels of harmonic voltage distortion with low-voltage customers during 2017 and 2018. Measurements were obtained over a period between one hour and one day per location. Results are presented for the harmonics in the phase-to-neutral voltage at 163 locations; the highest 10-minute values per location have been used for presenting the results. For harmonics in the neutral-to-ground voltage, 1-second values at 88 locations have been used. The harmonic levels showed to be well below the limits in EN 50160 and IEC 61000-2-2 for almost all locations and for all harmonics with exception of harmonics 9, 15 and 21. The dominating frequencies at most locations are harmonics 5 and 7.

INTRODUCTION

The majority of sources of harmonics in the electric power system are devices connected to the low-voltage network. Those same devices may also be among the first victims of high harmonic voltage distortion.

Connection of new types of equipment like PV inverters, electric vehicle charging or electric heat pumps, but also more energy-efficient versions of existing types of equipment like variable-speed air conditioning or LED lamps, is expected to have a serious impact on the harmonic voltage distortion in the low-voltage network.

Little is known however about what are typical voltage harmonic levels near the terminals of low-voltage equipment. Such information is among others needed to estimate how much new equipment can be connected before acceptable limits are exceeded (i.e. to determine a "harmonic hosting capacity").

MEASUREMENTS

This paper presents some results from an ad-hoc survey of harmonic levels in low-voltage networks all over the world. All measurements were performed at the wall outlet using a Metrum PQsmart portable power-quality monitor [1]. All measurements took place during 2017 or 2018, for a period between one hour and one day per location. For each location, the highest 10-minute value for each harmonic frequency was obtained. This highest 10-minute value is in the remainder of this paper referred to as the "spectrum" for that location.

The measurement values were obtained over 1-second or 10-second windows in accordance with IEC 61000-4-30 class A. From these values, the 10-minute values were obtained by taking the root-mean-square (rms) of the 1-second or 10-second values. The resulting 10-minute values comply with the Class-A definition in IEC 61000-4-30.

The measurement period, between one hour and one day, is not in accordance with any standard method. The results from this survey are compared with the voltage characteristics in EN 50160. According to EN 50160 and many national regulations, a one-week measurement period is needed. The voltage characteristics in EN 50160 are based on 95% values, whereas in this paper the highest 10-minute values are used. Despite these discrepancies, the authors are of the opinion that the results from the survey still give a good indication of what are typical harmonic levels with low-voltage customers.

Phase-to-neutral voltage

Measurements of the phase-to-neutral voltages have been obtained at 163 locations with low-voltage customers in 17 countries. The 163 measurement locations were distributed over the type of location as follows:

- Domestic customers, apartments and (semi)detached homes: 14 locations,
- Hotel rooms, meeting rooms in smaller hotels: 34 locations
- Office rooms, meeting rooms in office buildings, meetings rooms in hotels with a large conference facility, universities, and congress centres: 28 locations
- Airports, railway stations, hospital, museum, boat terminals: 23 locations
- Restaurants, cafes: 64 locations

The measurement locations were in Brazil (1), Denmark (3), Finland (5), France (3), Germany (1), Hong Kong (4), India (4), Ireland (3), Italy (2), The Netherlands (17), Norway (1), Portugal (9), Slovenia (7), Sweden (94), Switzerland (5), United Kingdom (1), and Zambia (3).

Neutral-to-earth voltage

Next to the phase-to-neutral voltage, which is commonly measured during harmonic studies, the voltage between the neutral and the protective earth was measured at some locations. In all cases, the 1-second values were measured over a period between one and three hours, at 88 locations in 12 countries.

Measurements of the neutral-to-earth voltage were performed in the following countries: Denmark: (1), Finland: (7), France: (4), Hong Kong: (2), Ireland: (2), Italy: (1), The Netherlands: (12), Portugal: (2), Slovenia: (3), Sweden: (50), Switzerland: (1), and Zambia: (3).

Measurements were performed at the following locations:

- Domestic customers, apartments and (semi)detached homes: 7 locations,
- Hotel rooms, meeting rooms in smaller hotels: 21 locations
- Office rooms, meeting rooms in office buildings, meetings rooms in hotels with a large conference facility, universities, and congress centres: 15 locations
- Airports, railway stations, hospital, museum, boat terminals: 11 locations
- Restaurants, cafes: 34 locations

At all these locations, the phase-to-neutral voltages were measured as well.

Boxplot

The results will be presented in the form of boxplot. A boxplot (also known as "box-and-whisker plot" or "box-and-whisker diagram" is a compact way of showing a probability distribution, typically from measurements. An example is shown in Figure 1. The boxplot shows the first, second and third quartile, a "normal range" obtained from the quartiles and outliers that are beyond the normal range.

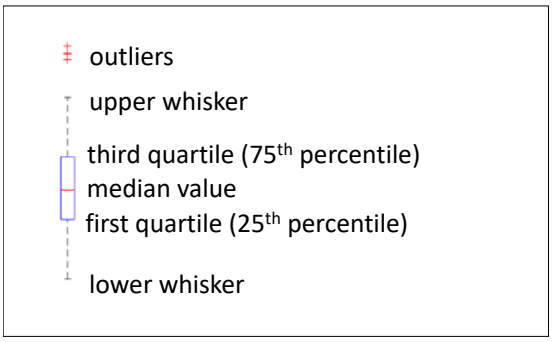

Figure 1. Illustrative example of boxplot.

Different versions of the boxplot use different definitions of the normal range, indicated as the range between the "lower whisker" and the "upper whisker" in the figure. The whiskers indicate "the highest values that are not considered outliers" [2]. Let Q_1 and Q_3 be first and third quartile, respectively. In this paper, the normal data range is considered the range:

$$Q_1 - 1.5(Q_3 - Q_1) < x < Q_1 + 1.5(Q_3 - Q_1)$$

The whiskers indicate the highest and lowest values that are within this normal range. For a Gaussian distribution ("normal distribution") 99.3% of the values will be within this range [2]. Any data points outside of the indicated normal range are marked as outliers.

RESULTS PHASE-TO-NEUTRAL VOLTAGE

Overall results

The boxplot of the spectra for all the 163 locations are shown in Figure 2. The objective values according to EN 50160 (voltage characteristics) and IEC 61000-2-2 (compatibility levels) are indicated in the figure as well. The compatibility levels are used for even harmonics and for harmonics above order 25. The figure shows that the measured values remain well below the limit for most harmonics.

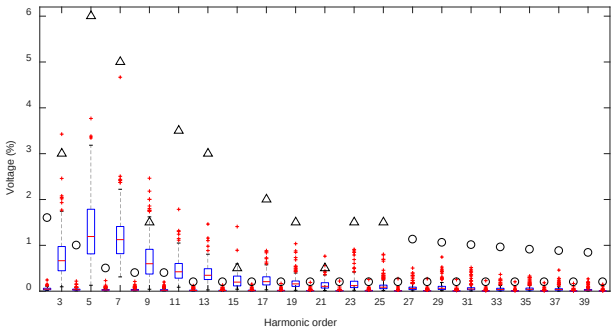

Figure 2. Boxplot of the existing levels of harmonics at all locations. Triangles and circles indicate the limits according to EN 50160 and IEC 61000-2-2, respectively.

The results are presented in an alternative way in Figure 3. The values for each harmonic are divided by the objective value (limit) for that harmonic and the results are presented in percent. The limits used are the same ones as used in Figure 2. The cases for which the limits are exceeded (3, 9, 15, 21 and high-order even harmonics, are discussed below. The figure shows that it is only for harmonics 9 and 15 that the limits are exceeded for more than one or two locations.

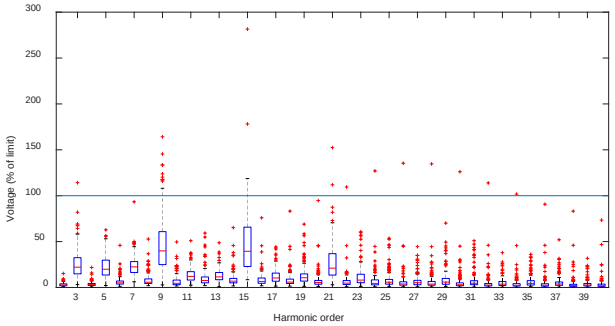

Figure 3. Harmonic levels at all locations as a percentage of the limits

In this figure, the situation is better visible for harmonics with low limits, like even harmonics and high-order odd harmonics. The 75th percentile (upper limit of the box, see Figure 1) is well below the limit (20% or less) for all but a few harmonics (3, 5, 7, 9, 15 and 21). Even harmonics 2 and 4 are well below the limit (less than 25%) at all locations. Al higher orders (with the exception of 5, 7, 9, 15 and 21) show a range of outliers up to about 50% of the limit. The high relative values for high-order even harmonics are all at one location, as will be discussed below.

Harmonic 3

The limit for the third harmonic is exceeded at one location; one additional location shows a value well above the rest. Both are hotels in a mining area in Zambia; their spectra are shown in Figure 4. The limits are again

indicated by circles and triangles, as in Figure 2. For both locations, the third harmonic is the dominating one and both locations show a general decrease in distortion up to about harmonic 15. One of the locations shows increased levels for the odd harmonics in the range 19 to 37.

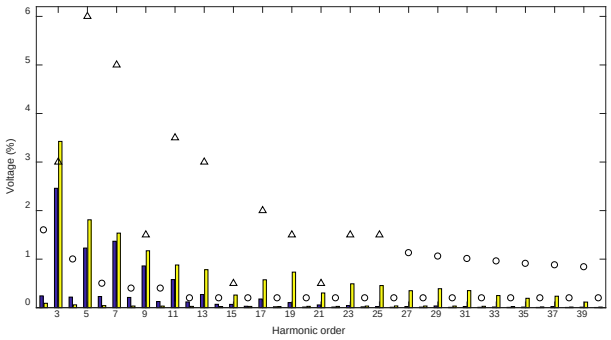

Figure 4. Spectra for the two locations with high third harmonic voltage

Harmonic 5

None of the locations shows a fifth harmonic that exceeds 4%, with the limit being 6%. The fifth harmonic is the one that receives most attention in setting of emission limits and it is good to see that the existing levels remain well below the limit. The four locations with the highest values (above 3%) are, a coffee bar in the centre of Stockholm, an office in Sweden that's supplied from the same HV/MV transformer as a major industrial installation, a hotel in Ljubljana, and a hotel in a city in Northern Sweden. The spectra for these four locations are shown in Figure 5. Because of the way in which these locations were selected, they have the fifth harmonic as the dominant one, and close to each other. For other frequencies, the spectra vary a lot and there does not seem to be any pattern here.

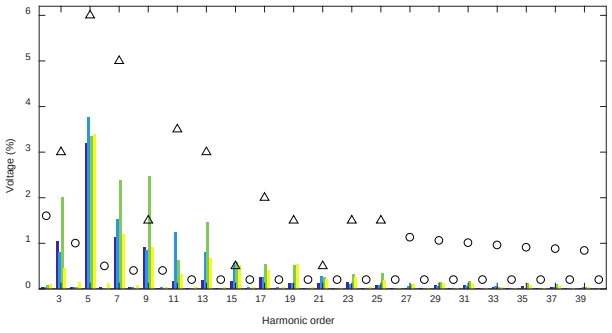

Figure 5. Spectra for the four locations with high fifth harmonic voltage

Harmonic 7

The levels for the seventh harmonic are well below the limit, with the exception of one location, a university building in Finland containing offices and laboratories. The spectrum for this location is shown in Figure 6: the levels for the other frequencies, beyond the seventh harmonic, are all well below the limit at this location.

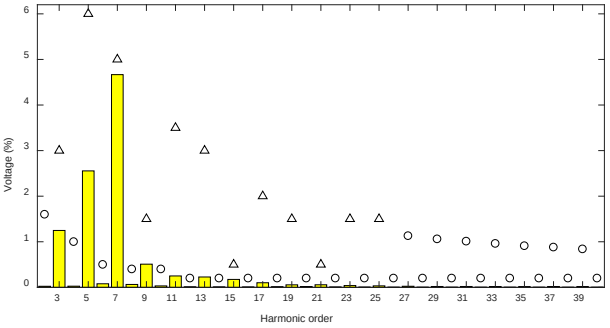

Figure 6. Spectrum for the location with high seventh harmonic voltage

Harmonic 9

The ninth harmonic is the one that exceeds the limit of 1.5% at 12 locations, with three locations exceeding 2%. The latter are two office buildings in Sweden and a restaurant in Ljubljana. The remaining nine locations include a remote hotel in Northern Sweden, an office in a smaller city in Sweden, two offices in Stockholm, a coffee bar and an office in Gothenburg, Sweden, two international airports, and a hotel in Ljubljana. The spectra for all 12 locations with high ninth harmonic are show in Figure 7. Despite the similar values for the ninth harmonic, the values for other harmonics show large differences. The only exception is the third harmonic. More on correlation between harmonics in a later section.

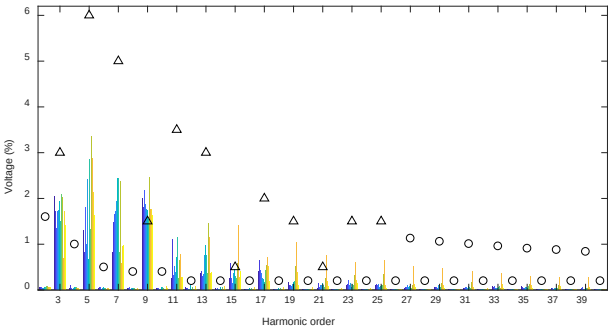

Figure 7. Spectra for the 12 locations with high ninth harmonic voltage

Harmonic 15

The EN 50160 limit for harmonic voltage 15 (0.5%) is exceeded at 12 locations. A proposal for changing the limits in EN 50160 is currently under voting by the national committees [3]; the proposal is to raise the limit for harmonic 15 from 0.5% to 1.0%. Only for one of the measured locations (restaurant in Ljubljana) would even the new limit be exceeded. The second highest level (0.89%) is reached for an office in a city in Northern Sweden. For 10 locations, the 15th harmonic voltage is between 0.5% and 0.6%.

Harmonic 21

The existing limit for the 21st harmonic is exceeded at two locations, a restaurant in Ljubljana and an international airport. An increase of the limit from 0.5% to 0.75% is proposed in [3]. Only at the former location will also the new limit be exceeded. The spectrum for this location is

shown in Figure 8; the limits are exceeded at this location for harmonics 9, 15 and 21. Most the other harmonic voltages are less than half of the limit; the only exception being harmonic 19. The level of this harmonic is the highest level measured for any location. Also, other high-order harmonics have levels that are on the high side.

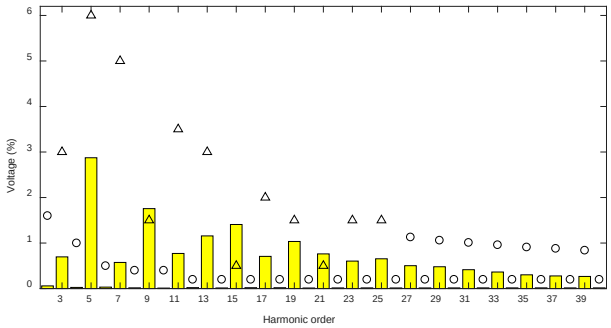

Figure 8. Spectrum of location with high levels of harmonics 9, 15, 19 and 21

Even harmonics

The even harmonics are low at most locations, but there is one location (domestic customer in Brazil) where the limits are exceeded for higher order even harmonics. The spectrum for that location is shown in Figure 9. The shape of the figure clearly indicates a broadband emission with a peak around 1.4 kHz (harmonic 28). The levels of the odd harmonics are within the typical range.

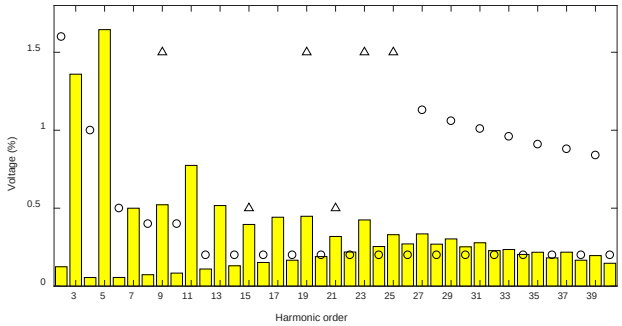

Figure 9: spectrum of location with high even harmonic distortion

Dominating frequencies

The dominating harmonic frequencies are shown in Table 1. The tables gives the number of locations with indicated harmonic orders having highest and highest but one value in the spectrum. For example, at 57 locations, harmonic 5 has the highest and harmonic 7 highest but one.

Table 1. Dominating harmonics (number of locations)

		Highest harmonic but one					
		H3	H5	H7	H9	H11	H13
Highest harmonic	H3		4	6	2		1
	H5	13		57	6	3	
	H7	5	40		7	3	
	H9	3	3	1			
	H11	1	1	5			1
	H23			1			

The lower-order odd harmonics are the dominating ones, with harmonics 5 and 7 being the two highest at about 65% of the locations. Only at eight of the 163 locations is neither harmonic 5 nor harmonic 7 among the two highest ones. For five of those eight locations the first two triplen harmonics (3 and 9) are the dominating ones.

Relations between the harmonic orders

The values for harmonics 3, 5, 7 and 9 are compared in Figure 10. There is a reasonably strong correlation between the third and the ninth harmonic (correlation coefficient 74%); harmonic 3 shows a weak correlation with harmonics 5 and 7 (correlation coefficient 30% and 31%, respectively). The correlation between harmonic 5 and 7 is weak as well (37%). No other low-order odd harmonics shows a correlation above 50% (see Table 2). Correlations are stronger between low-order even harmonics, as shown in Figure 11 and Table 3.

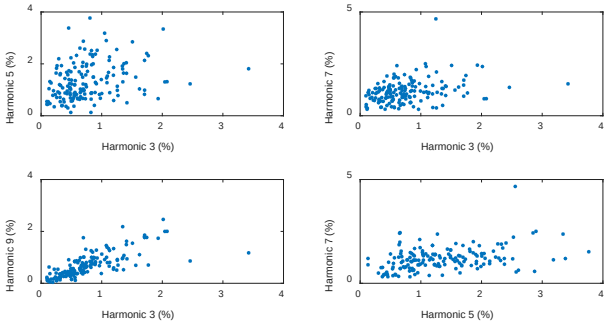

Figure 10. Relations between harmonics 3, 5, 7 and 9

Table 2. Correlation between low-order odd harmonics

	H5	H7	H9	H11	H13
H3	30%	31%	74%	19%	38%
H5	-	37%	38%	-3%	25%
H7		-	37%	3%	30%
H9			-	13%	45%
H11					46%

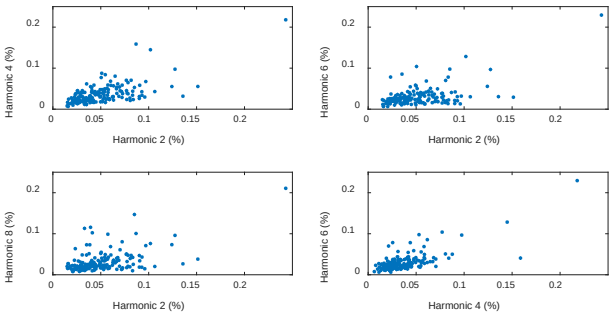

Figure 11. Relations between harmonics 2, 4, 6 and 8

Table 3. Correlation between low-order even harmonics

	H4	H6	H8	H10	H12
H2	64%	56%	52%	43%	56%
H4	-	73%	68%	54%	56%
H6		-	73%	39%	59%
H8			-	69%	57%
H10				-	66%

The correlations between triplen harmonics (3-39) are

shown in Table 4. Correlations above 50% are found between harmonics 3 and 9 as well as between the high-order triplen harmonics.

Table 4. Correlation between triplen harmonics

	H9	H15	H21	H27	H33	H39
H3	74%	35%	14%	16%	17%	7%
H9		47%	16%	11%	12%	3%
H15			61%	50%	44%	44%
H21				80%	70%	68%
H27					87%	81%
H33						89%

The correlations between all harmonics are shown in Figure 12 in the form of a colour map. In the figure, dark red indicates high correlation and dark blue indicates low correlation. High correlation is found for harmonics up to about order 11 and between higher order harmonics. No combinations of low order (below 11) and high order (above 11) show a strong correlation. With increasing frequency, the correlation increases, especially for even harmonics.

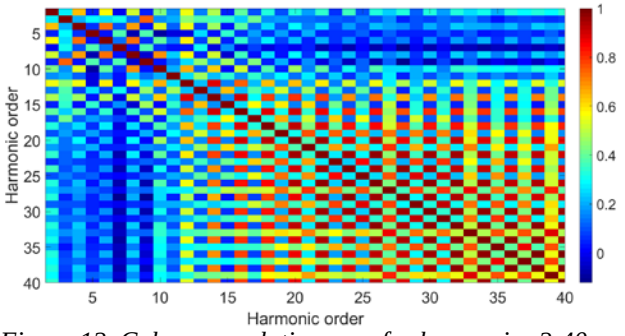

Figure 12. Colour correlation map for harmonics 2-40

NEUTRAL-TO-EARTH VOLTAGE

The boxplot for the harmonics in the neutral-to-earth voltages is shown in Figure 13, based on measurements at 88 locations. Note that the vertical scale is in volt (V), instead of in percent as in the earlier figures. Another difference with the phase-to-neutral measurements is that the highest 1-second value is shown here instead of the highest 10-minute value. There are no standard methods for presenting the harmonics in the neutral-to-earth voltage. There is also no reference (e.g. objective values) for what are high or low values of these harmonics.

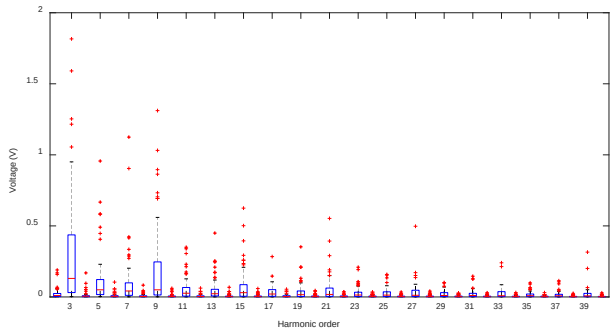

Figure 13. Boxplot of the existing levels of harmonics in the neutral-to-earth voltage at all locations

When considering the third quartile (75th percentile) the highest values are found for harmonics 3 and 9. When considering all values, including the outliers, high values are also found for harmonics 5, 7, 11, 13, 15 and 21. Overall, the values for triplen harmonics are higher than for non-triplen harmonics. The values for even harmonics are lower than for the odd harmonics.

CONCLUSIONS

The measurements presented in this paper clearly show that the harmonic voltage levels in documents like EN 50160 and IEC 61000-2-2 should not be used as typical harmonic levels. The measurements also show that there is a considerable margin between the existing levels and the limits. For most harmonic orders, even the highest levels measured are only around 50% of the limits. For harmonics 3, 21 and higher-order even harmonics, the limits exceeded are for one or two locations. It is only for harmonics 9 and 15 that the limits are exceeded for more than a few locations.

For the non-triplen harmonics, the measured values rarely are above half of the limit.

For the locations with extreme values for one or more of the harmonics, type and country are mentioned. No conclusions should be drawn from this concerning the voltage quality in those countries. The number of locations per country is too small for this.

The proposed new limits for harmonics 15 and 21 would make more margin available at those frequencies to connect new equipment, but it would not solve the challenges with harmonic 9. Even for these harmonics, the levels are below the limits for 95% of the locations.

No attempts were made in this paper to explain any of the observations. Discussions on measures to be taken, like changes in standardization, are also beyond the scope of this paper.

The number of locations remains limited, the selection of the locations was not purely random, and the measurement duration was rather short. Despite these obvious limitations, the general conclusions hold and, for lack of a better survey, the presented results still give typical voltage distortion levels in the low-voltage networks. Some network companies and regulators perform systematic measurements of harmonics in low-voltage networks, in a much more systematic way that the study presented here. Those organisations are encouraged to make their data available to allow comparison with other surveys.

REFERENCES

[1] Metrum PQ Smart, accessed 25 December 2018, https://metrum.se/product/metrum-pq-smart/.
[2] Matlab help function for “boxplot”.
[3] EN 50160/FrpA3:2018, December 2018. Deadline for voting: 2019-02-15.