EMPIRICAL MEASUREMENTS OF POWER QUALITY IN DANISH LOW VOLTAGE SYSTEMS

Henrik Hansen
Danish Energy - Denmark
heh@danskenergi.dk

ABSTRACT

This article examines the general power quality levels in Danish distribution grids, focussing on the rms voltage, flicker and harmonics up to the 25th, based on measurements done over the last decade in various Danish distribution grids.

The level of power quality is in general within the tolerances, however some of the tripplen harmonics are an issue in low voltage grids.

The article also examines the angle of the 5th harmonic voltage to examine the use of the less stringent requirements that are an option to use for larger pieces of equipment.

The angle of the 5th harmonic voltage does not appear to have any definitive conclusion, and whether the less stringent requirements makes sense to allow is highly contingent on the local grid and cannot be taken as a certainty in general.

INTRODUCTION

This paper presents the overall results of a Danish measurement campaign that began in the summer of 2009 and have continued, as well as expanded, since then.

The results presented focus on the voltages, as those are the values that are relevant for the Distribution System Operators (DSOs) when it comes to their obligation to provide a decent quality of supply to the customers. For the same reason, this analysis is limited to the 25th harmonic and below, as those are the ones defined in EN 50160.

The measurement campaign is conducted by Danish Energy, but involve many different Danish DSOs, as the measurement equipment is relocated on a regular basis (usually after measuring for at least one year at a site) aiming to measure at a variety of sites where it is expected to see some interesting results.

The analysis will look at the voltage, flicker levels and harmonics both as the distortion seen alone, but also comparing a few of them to the limits in EN 50160. The analysis will also extend to examining the angle of the 5th harmonic voltage, in order to compare it to the less stringent requirements possible to use in EN/IEC 61000-3-12.

MEASUREMENT DATA

The measurement data is collected in a database, and is measured according to EN/IEC 61000-4-30 Class-A. As such, the focus of the data is the 10-minute mean values.
All data is included, even flagged values, which is why later indicative numbers are using the 99th percentile for determining what the highest levels of distortion are.

Each site generally has measurements for approximately one year, though a few measurements only have a few months, and a few have a couple of years. In total 63 different sites are included and put back-to-back the total amount of data would be equivalent to just over 81 years (~470 days average measurement time per site).

Given the amount of data, duration plots showing all data and 99th percentile indicative values are generally used to present the data.
The sites vary in composition, age, consumer types, distance from transformer, number of consumers etc. to have as large a variety as possible.

The data is used for other means as well, including as input to research projects that look at other aspects of power quality where limited data can be gathered during the project, as well as less research-oriented tasks such as developing more general emission models to be used for taking distortion into account when sizing of low voltage grids.

POWER QUALITY DATA ANALYSIS

The analysis of the Power Quality data is split into subsections, first touching briefly on the rms voltage and flicker, and then into harmonics in general.

Voltage

The grid voltage as experienced by the customers is the first aspect examined, and the aspect that is most well known in general. The voltage should be within +/- 10 % of 230 V, which can be seen in Figure 1.

The green and red dotted lines show the 230 V and +/- 10 % limits, with the black line being all the 10-minute average values.

The blue lines are the measured minimum and maximum voltages, which result in the vertical parts at 0 and 100 % showing dips and swells respectively, as these do occur in the grid and is not filtered out.

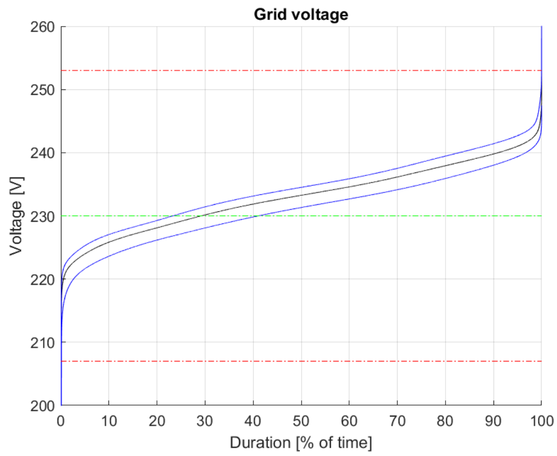

Figure 1: 10-min. mean (black), min. and max (blue) voltages.

Asides from the minimum and maximum values being caused by dips and swells, the voltage in Danish distribution grids is within the allowed range.

In general, the voltage is slightly higher seen over all sites, which corresponds to low voltage grid design before large scale photovoltaic integration, where the voltage was often set 2,5-5 % above 230 V at the transformer, as this allowed more demand to be connected before the voltage became too low at the customer furthest from the transformer.

As distributed production from household photovoltaic units has increased, this is being considered when determining transformer setpoints, moving the average voltage closer to 230 V on average.

The voltage unbalance is not included in this analysis, both due to it being only around 1 % at its worst point, but also as low voltage consumption is not affected by this due to rarely having directly connected 3-phase machines. The effects on the transformers is not included.

Flicker

For flicker, the long-term flicker is shown in Figure 2 (it does not deviate substantially from the short-term flicker when seen across all measurements), with the measurements shown as a black line, and the limit of 1 shown as a dotted green line.

The flicker levels are generally below half the limits, though there are instances of higher flicker which is expected to occur from switching in the grid etc., as well as a limited number of instances of long-term flicker exceeding the limit.

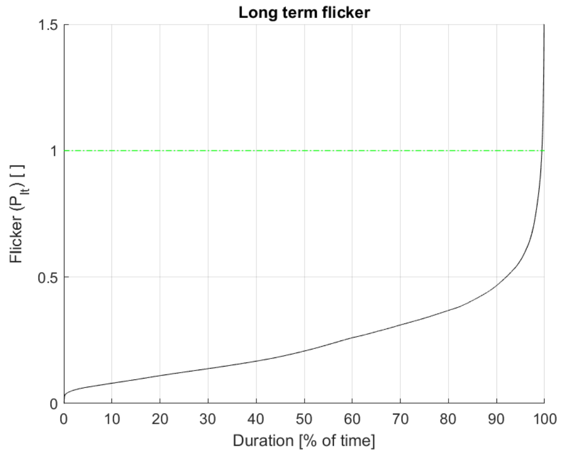

Figure 2: Long term flicker across all sites.

Harmonics

The harmonic distortion is split into 3 bands for this analysis. A lower band showing at the 2nd to 9th harmonic, a middle band showing the 10th to 17th harmonic and a higher band showing the 18th to 25th harmonic.

The levels in each band is shown and briefly described, before the middle band is compared to the limits in EN 50160 currently.

Distortion levels

The lower band is shown in Figure 3 and has the 5th and 7th harmonic as the most distorted, which corresponds well with the many 6-pulse rectifiers in the distribution grid. They are followed by the 3rd and 9th as would be expected in a 4-wire system such as the Danish low voltage grids.

The even harmonics are all very low as expected, due to very few loads causing distortion at these frequencies.

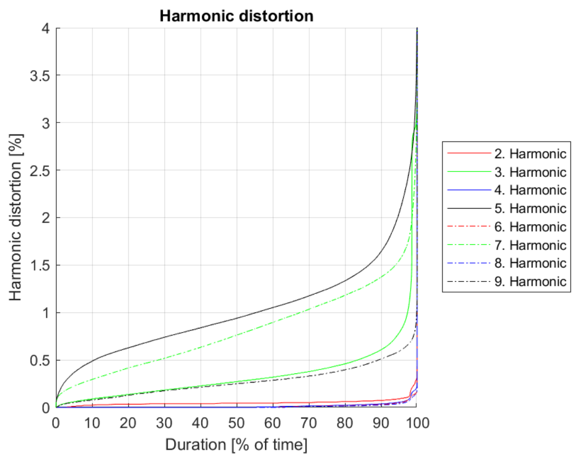

Figure 3: 2nd to 9th harmonic voltage distortion.

Next the middle band is shown in Figure 4 and shows the same tendency as the lower band. The 11th and 13th harmonic is still the highest distorted, again as expected due to the number of 6- and 12-pulse rectifiers.

The 17th harmonic, which would also mainly stem from 6-pulse rectifiers are the same level as the 15th harmonic though, indicating that the noise from single-phase loads in the low voltage system is significant even when compared to the typical distortion patterns from 6-pulse rectifiers.

Again, the even harmonics are generally very low, as expected.

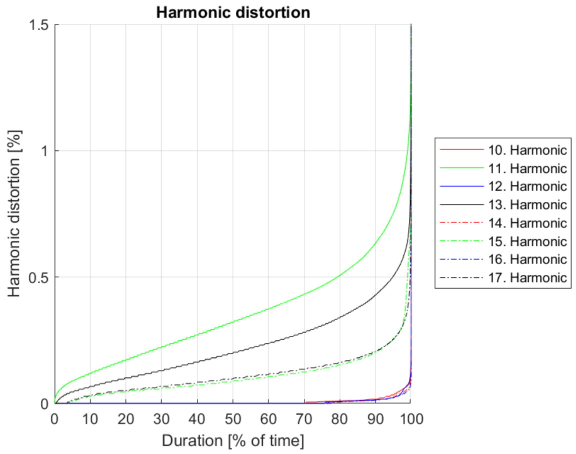

Figure 4: 10th to 17th harmonic voltage distortion.

Lastly the higher band is shown in Figure 5 and begin to show a different result. The distortion here does have the 19th as the highest, but only barely. While the 19th harmonic is above the others for the entire duration, it is by a very narrow margin.

This is also indicated by the sharp changes in the values, as these are getting near the capability of the measurement units' ability to measure without rounding. The discrete changes are in the range of 6-7 % of the uncertainty requirements.

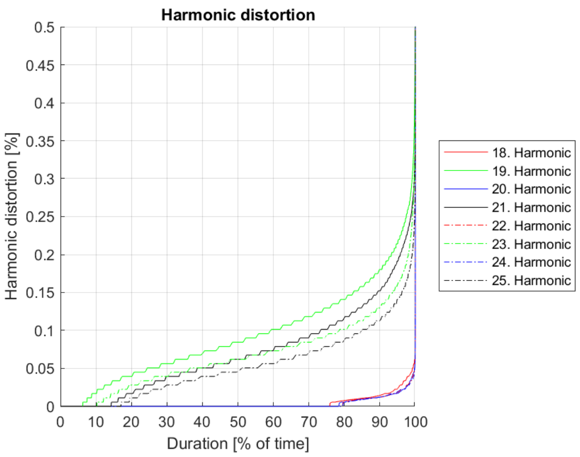

Figure 5: 18th to 25th harmonic voltage distortion.

Ignoring the even harmonics and using the 99th percentile as to define the highest voltage distortion of each site, the lowest, highest and average of these 99th percentiles are shown in Table 1, along with the limits in NE 50160 currently, in order to give an indication of both the highest distortion on average, as well as the deviation, with all values rounded to two decimals.

Harmonic	Min. [%]	Mean [%]	Max. [%]	Limit [%]
3rd	0,10	0,66	3,21	5,00
5th	0,37	1,87	4,10	6,00
7th	0,14	1,39	3,46	5,00
9th	0,01	0,45	1,14	1,50
11th	0,23	0,69	1,32	3,50
13th	0,16	0,49	1,61	3,00
15th	0,00	0,24	0,78	0,50
17th	0,09	0,24	0,85	2,00
19th	0,06	0,21	0,57	1,50
21st	0,00	0,15	0,34	0,50
23rd	0,06	0,16	0,46	1,50
25th	0,03	0,14	0,31	1,50

Table 1: Min. mean and max. 99th percentiles for sites.

The minimum values will often be from measurements in low distortion areas (district-/oil-/gas-heating for example), as well as directly on the low voltage side of the transformer supplying an area.

Similarly, the maximum values will often be from measurements in more distorted areas (heat pumps for heating, distributed photovoltaics, electric vehicles etc.) and will be measured in the cabinet placed at the end of the line furthest from the transformer supplying an area.

Distortion levels utilization of limits

While the actual distortion is interesting, for DSOs it is also important how much of the allowed distortion levels are currently available.

Looking at the 99th percentiles only a single harmonic, the 15th, are above the limits in EN 50160, though others are close as well. In Figure 6 the middle band of the 10th to 17th harmonic is shown and confirms that the 15th indeed does exceed the limits (> 100 % share of limit).

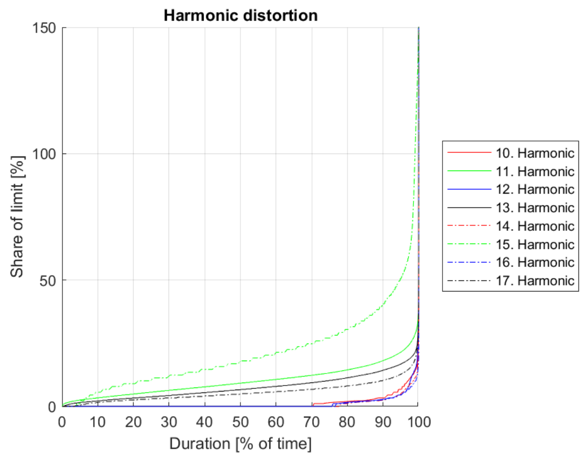

Figure 6: 10th to 17th harmonic distortion part of limits.

While the 15th harmonic is the only one to exceed its limits, the relation between the harmonics change when taking the limits into consideration.

For each band, the most challenged harmonic becomes the 9th, 15th and 21st respectively, clearly indicating that one of the main challenges for DSOs, are the emissions from single-phase loads when looking at issues of power quality in the low voltage grids.

EN 50160 is in the process of amending two of these, the 15th and 21st to 1,0 and 0,75 respectively, but while these amendments will increase these limits, it is still the tripplen harmonics that are the most challenged harmonics even after the new limits.

The even harmonics appear to be higher than the absolute distortion, but this is solely due to them having very low limits in general.

5TH HARMONIC ANGLE

The 5th harmonic angle has an interest due to its use in setting limits for emissions. More specific, EN/IEC 61000-3-12 has options for equipment using alternate limit tables under specific conditions.

These conditions are examined to see if the angle of the 5th harmonic voltage in the low voltage grids are such that added noise from relaxed requirements would not be an issue in general – as these standards are intended for use on all equipment conforming to the requirements of the angle of the 5th harmonic.

Given the changes in equipment over the past decades where more and more electronically based products are used by consumers, and even changing prior resistive loads such as light bulbs and electric heating to electronically based equivalents such as CFL/LED and heat pumps.

IEC background

EN/IEC 61000-3-12 sets requirements for equipment connected to the grid > 16 A, as well as ≤ 75 A per phase.

Use of table 4 and 5 in this standard are dependent on the angle of the 5th harmonic current being within 90-150 and 150-210 degrees respectively, under the assumption that this is an uncommon area for distortion and can thus be given less stringent requirements.

Given the number of measurements, these are examined for the angle of the 5th harmonic voltage to evaluate whether this still makes sense with the changes in modern consumption.

Measured harmonic angles

For ease of analysis, only phase A is included in the evaluation, however the other two phases do follow the same tendency as the shown phase, just shifted 120 degrees each (for positive and negative sequence).

As can be seen from Figure 7 there is a rather large variation in the phase angle of the 5th harmonic. The distortion is mostly placed in the 180-360-degree range, and the magnitude of the distortion is also higher here.

The magnitude is peaking at around 15 V distortion of the 5th harmonic.

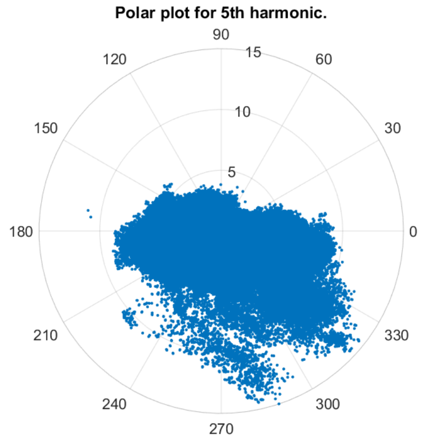

Figure 7: 5th harmonic voltage in phase A across all sites.

As an overall image, this can not give a completely true picture though, as there is great variation. If any initial indication can be given, it should be that the noise levels appear more in the 150-210-degree range than in the 90-150-degree range, making the use of table 4 more desirable for DSOs than the use of table 5.

It would appear initially from Figure 7 that the overall angle would be 310-320 degrees, and opposite the angles required for the use of tables 4 and 5 of EN/IEC 61000-3-12.

Site differentiation

To better gauge the use, the measurements needs to be split up per site and then examine at the various sites individually to see whether this effect is wide-spread, or a result of combining the numerous sites in the measurement campaign as a whole.

Figure 8 shows the measurement site with the ID number 45 – which is a suburban area with heat pumps for heating and photovoltaic production on many houses.

The data shows that the existing voltage distortion here is almost exclusively within the angular areas where 5th harmonic distortion must be placed to use the less stringent requirements. However, this type of area would not often have much equipment falling into the > 16 A per phase range.

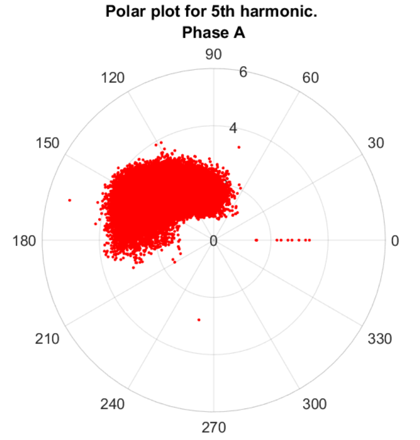

Figure 8: 5th harmonic voltage example within angles.

Figure 9 shows the measurement site with the ID number 78 – which is a typical large discount grocery store in a suburban area.

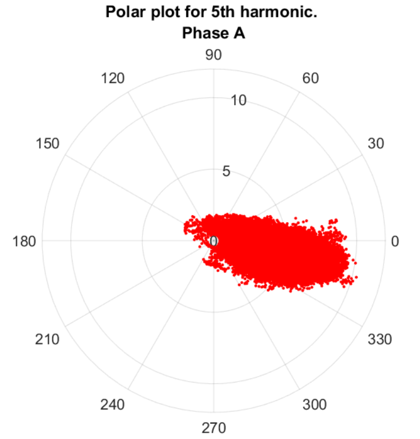

Figure 9: 5th harmonic voltage example outside angles.

Here the existing 5th harmonic distortion is placed almost exactly opposite the angular area allowing for less stringent requirements. This area type would also be one where equipment > 16 A per phase could be connected – typically the cooling systems for the store would fall into this category.

Looking at the various sites, there is a large mix of the angle of the 5th harmonic voltage.

For 23 sites, the existing 5th harmonic voltage is within the angular areas where equipment emissions have less stringent requirements.

For 21 sites, the 5th harmonic voltage varies both within and outside the area.

Only 10 sites are consistently outside the area defined in EN/IEC 61000-3-12 and would thus see an overall benefit for allowing higher emissions from large equipment placing its 5th harmonic distortion within the given angular areas.

Only 54 of the 63 measurement sites have angular information, as a few of the older meters used at several sites does not record the harmonic phase angles.

There is no consistent placement of categories though, and the sites outside are a mix of suburban, urban and commercial areas – just as the mixed category and the category inside the angular areas comprise a mix of all customer groups.

CONCLUSIONS

The harmonic distortion in general in Danish low voltage grids have been examined, as well as the angle of the 5th harmonic voltage in order to compare it to the EN/IEC 61000-3-12.

Distortion levels

The distortion levels present in Danish low voltage grids are generally not an issue, except for the tripplen harmonics. The supply voltage and flicker levels are generally not an issue.

The 15th harmonic is currently exceeding the limits at a few sites, although this will be mitigated when the EN 50160 is amended to double this limit.

Even considering the current amendment the tripplen harmonics are still the ones that are the most challenged regarding limits. Of all harmonics, the 9th and the 15th are the harmonics closest to the limits.

In general, the harmonic distortion is acceptable, but certain frequencies are getting as close as utilizing 80 % of the distortion allowed.

5th harmonic angle and requirements

The 5th harmonic angle does not have a clearly identifiable area across the various measurement sites. Some sites have an angle of the 5th harmonic voltage that support the relaxation in EN/IEC 61000-3-12 tables 4 and 5, while other sites do not.

At the sites measured, only ~20 % support the relaxation, with ~40 % not supporting it and the remaining ~40 % partially supporting it.

The sites can also not be evaluated as certain categories, as all three categories have a similar distribution of regular urban/suburban/rural/commercial customers. The general rule of relaxation therefore does not appear to be valid, as it only is valid for specific grids.