Evaluation and Updating of Harmonic Voltage Limits

J.F.G. Cobben
Dept. of Electrical Engineering
Eindhoven University of Technology
P.O. Box 513, 5600MB
Eindhoven (NL)
J.F.G.Cobben@tue.nl

D.A.M. Geldtmeijer
Dept. of Asset Management
Enexis B.V.
P.O. Box 856, 5201AW
’s-Hertogenbosch(NL)
Danny.Geldtmeijer@enexis.nl

A.F.J Almering
Dept. of Standardization
Philips Intellectual Property&Stnds
P.O. Box 220, 5600AE
Eindhoven(NL)
Ton.Almering@philips.com

J.B.M. van Waes
Energy
Movares
P.O. Box 2855, 3500GW
Utrecht(NL)
Jeroen.van.Waes@Movares.nl

***Abstract*— Characteristics of the current emission for new developed devices are changing resulting in lower low order harmonics and an increase in high order harmonics. For the low voltage network this results in an increase in high order harmonic voltages, violating more often the limits for the harmonic voltages at the 15th and 21th order harmonic. To improve this situation harmonic current could be reduced, network impedance could be decreased or the harmonic voltage limits could be increased. Since there are no complaints regarding these higher harmonic voltages, this paper presents an alternative approach to update these harmonic voltage limits.**

***Index Terms*-- harmonic standards, regulation, network impedance, harmonic voltages, harmonic emission.**

I. INTRODUCTION

The Dutch network operators continuously measure the power quality of their grids and present the results in an annual report[1]. As part of this program harmonic voltages are measured. The Dutch grid code refers to standard EN50160[2]. This standard includes the harmonic voltage limits as shown in Table 1.

TABLE I: HARMONIC VOLTAGE LIMITS

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
h	Relative voltage	h	Relative voltage	h	Relative voltage
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,5	6...24	0,5
13	3	21	0,5		
17	2				
19	1,5				
23	1,5				
25	1.5				

Apart from these harmonic limits for the individual harmonic voltages, also a limit for the total harmonic distortion (THD_U) is defined. The limit for the THD_U is set to 8%.

As is given in Table 1 the limits for the 15^{th} and 21^{th} harmonic voltage are relatively low compared to most of the other harmonics (even of harmonic voltages with higher order). In recent years there were a number of cases for which the measured 15^{th} harmonic voltages exceeded the given limit. This violation of the grid code is not acceptable. It needs to be analyzed and proper measures shall be taken.

The network operators also keep track of customer complaints. So far, no customer complaints can be related to this topic.

The aim of this paper is to provide insight in the backgrounds and to introduce an alternative approach for the current standards. It presents:

- An historical overview of the standards;
- A summary of measurement results;
- An identification of possible risks;
- A summary of measures to meet standards.

The paper concludes with an alternative approach for the current standard. The proposal aims to achieve limits giving the economic optimum by taking into account the interest of customers, manufacturers and network operators

The focus of the paper is on the low voltage grid as multi-triple harmonics only have only influence at this voltage level.

II. STANDARDS

The combination harmonic currents from various sources and the network impedance at the point of connection (POC) result in harmonic voltages. Regarding to harmonics there are:

- Equipment standards which provide emission (e.g. IEC61000-3-2[3] and IEC61000-3-12[4]) and immunity (e.g. [5], [6] and [7]) levels for *individual equipment*;
- Standards for network operators for harmonic voltages, e.g. [2] and [8].

The emission standards of currents and the acceptable harmonic voltage are related.

A. *Emision standards for Equipment*

The main equipment connected to the low voltage network shall comply with the EN 61000-3-2[3]. This standard is applicable for manufacturers. In this standard the harmonic *current limits* are set, depending on the type of device, the usage and density and taken into account the harmonic voltage limits and the network impedance. During tests the impedance of the power supply must be low enough to reduce the influence of the harmonic voltage distortion on the test result. As example in Table 2 the current limits are given for class A equipment which is defined as:

- balanced three-phase equipment;
- most of the household appliances;
- tools, excluding portable tools;
- dimmers for incandescent lamps;
- audio equipment.

TABLE II: HARMONIC CURRENT LIMITS CLASS A EQUIPMENT [3]

Harmonic order n	Maximum permissible harmonic current A
Odd harmonics	
3	2,30
5	1,14
7	0,77
9	0,40
11	0,33
13	0,21
$15 \le n \le 39$	$0{,}15\frac{15}{n}$
Even harmonics	
2	1,08
4	0,43
6	0,30
$8 \le n \le 40$	$0{,}23\frac{8}{n}$

Modern devices have a tendency to generate harmonic currents with a higher frequency compared to older equipment. As the total harmonic current distortion is often decreasing (more and more devices with active power factor correction), the influence of the higher order harmonics are increasing. This trend in harmonic currents is illustrated in figure 1.

B. *Standards for Harmonic Voltages*

The standard EN 50160[2] provides limits on harmonic voltages and is applicable for European network operators. Harmonic currents in a network will result in the harmonic voltages at the POC's. This summation of harmonic currents will differ per location and in time depending on the different type of applications used, and the harmonic order of the harmonics.

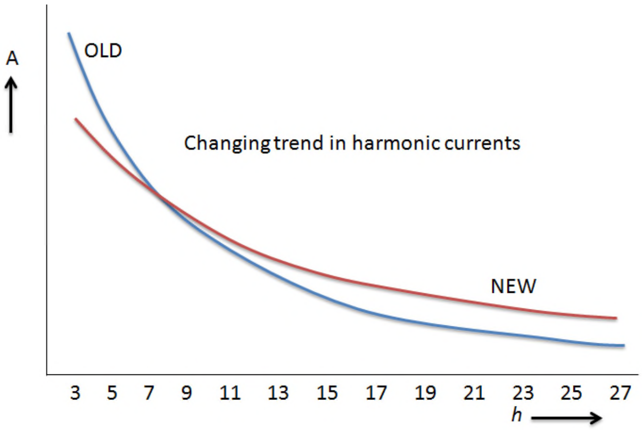

Figure 1: Trend in harmonic currents of devices

Increasingly higher harmonic currents, combined with the low limits for especially the 15th and 21th harmonic voltages, more often result in a violating of these harmonic voltage limits.

The harmonic voltages in the network also depend on the harmonic impedance of the network and the loads connected to the network.

- Due to the skin effect and the inductivity of the network, the *network impedance* $Z_{network}$ *increases* for higher frequencies;
- At higher frequencies the *load impedances* Z_{POC} *decrease* (and mostly all the capacitors connected at the entrance of many devices) which will influence the impedance at each point of connection of the installation.

This results in an impedance-frequency plot which is depicted in figure 2.

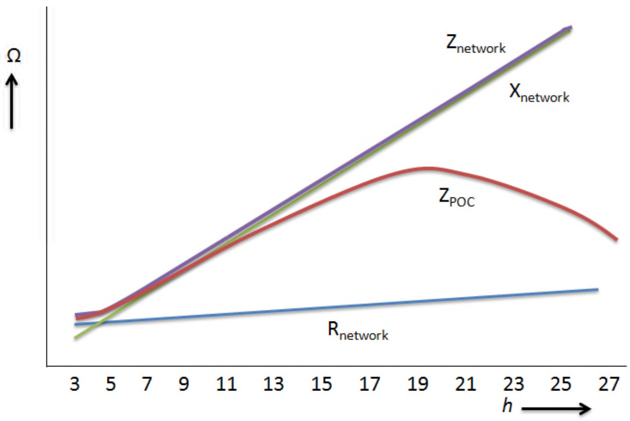

Figure 2: Indication of impedance on POC's

C. Immunity standards for equipment

The standards IEC61000-2-2[5], IEC61000-2-4[6] and IEC61000-2-12[7] give manufacturers of electric equipment a reference on what to expect when a device is connected to a low voltage installation anywhere in the world. These standards provide worldwide accepted harmonic voltage levels for devices, which they should be able to withstand.

D. Discussion

One can make a number of comments regarding these various standards:

1) Differences between immunity standards and EN50160: As expected the immunity standards and the standard for network operator are related, i.e. individual levels for harmonic voltages are given as a 10 minute average value. However their limits differ for these 10 minute averages, and the immunity standards also include short-term limits which can be higher(and still lead to the same 10 minute values).

2) Although a network operator is compliant with his standards, the immunity levels related to very short-term effects may be exceeded.

3) Summation of harmonic currents: As described the sum of the individual harmonic sources must be known to determine the contribution to the total harmonic voltages at the POC. The contribution will differ for the different harmonic orders of the current. The summation factor for low order harmonics is often higher than for the higher harmonic orders. Currently regulation lacks clear levels for harmonic currents at the POC. Which would be the counterpart of the regulated harmonic voltage levels. From time to time this gap leads to complicated discussions between network operators and their individual customers.

4) Rationale behind harmonic voltage limits: The origin of the harmonic voltage limits in standards and regulation are likely a set of measurements in various electricity networks. The closest the authors of this paper came to the original data used is at that time is a CIGRE paper published in 1981[9]. The original data has not been recovered, but this trail leads to measurements carried out in the late 70s – early 80s. From there the IEC and CENELEC somewhat parted in deriving limits for their respective standards.

The world has changed since the 70s, also from an electricity/power quality/harmonics point of view. The question that rises is: *Is it time for an update of harmonic voltage limits based on more recent measurement data?*

III. MEASUREMENTS IN DUTCH GRIDS

In the years 2009-2014 on site measurements throughout the Netherlands were carried out by the project 'Power Quality in the Netherlands'. During the years 2009-2013 the measurement campaign for LV grids consisted of approx. 60 measurements for a week at random locations. As from 2014 the number of locations has increased to 250[1]. Per measurement location:

- The average voltage per harmonic frequency was determined during 10 minutes;
- Per frequency the voltage is evaluated. The relative amplitude (in %) is determined. This is the harmonic voltage related to the fundamental voltage.
- For each frequency the 95%-value is determined per location. This is the 10-minute value which has occurred in 95% of these time intervals as a maximum, for 5% of the time intervals the measured value is higher.
  (Occasional peaks are therefore not included in the 95% value)
- The voltages are measured and assessed per phase. The network operators must comply with the Dutch Grid Code. This document refers to [2] which provides limits per frequency. For each measurement the previously determined 95% value is compared to this limit. The limit for the 15th harmonic is 0.5%.

Figure 3a presents distribution of all 95%-values over measurement intervals (2014). For example 22% of the measured 95%-values are within the range of 0.1-0.2%. The limit is 0.5%.

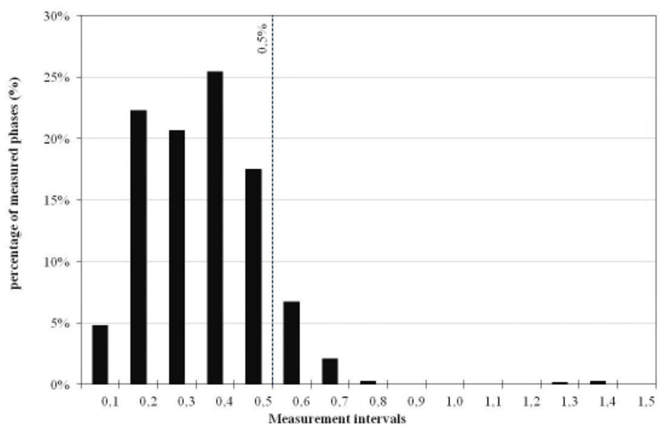

Figure 3a: Distribution 95%-values 15th harmonic over measurement intervals (2014).

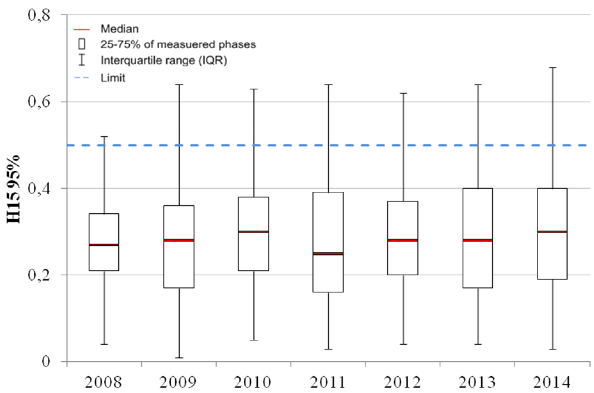

Figure 3b: Measured 95%-values over the years: 25%-75% of the results are within the range op the boxes. Example: in 2014 25% of the 95-values were>0.4%.

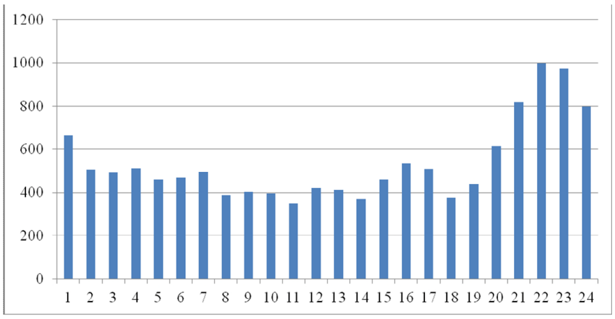

Figure 3c: Total per clock hour of 10 minute readings that exceed limit. (15th harmonic, phase measurements, 2014).

Over the years only the limits of the 15th and 21st harmonic are exceeded for a significant number of measurement locations. Table III lists the percentage of measurement locations which meets the 15th Harmonic limit.

TABLE III: PERCENTAGE OF MEASUREMENT LOCATIONS WHICH MEETS THE 15TH HARMONIC LIMIT.

2010	2011	2012	2013	2014
88%	88%	88%	78%	84%

On the basis of a first impression, it seems that:

- there is no upward trend in the number of sites that do not meet the limit. The 2013 results are a negative exception(Table III);
- In addition to a frequently mentioned cause "increased inverter-based equipment" there is no obvious cause or correlation observed with location of measurement sites or the season during which the measurements were carried out;
- The degree of urbanization also seems to have minor influence on the result;
- From the analysis it follows that there is a slight increase in the evenings, when the load decreases (Figure 3c). The influence of solar panels is difficult to determine.

Since 2014 the number of measurement sites has been increased, so that the (statistic) results in the coming years will be even more reliable.

There is also inquired by the Dutch participants in international working groups. The Dutch measurement program is relatively extensive compared to some other countries. Elsewhere limits seem to be exceeded as well, but reports on this and information on any measures fail.

IV. IDENTIFIED RISKS VS. CUSTOMER COMPLAINTS

Revision of existing compatibility levels shall have no negative impact on electric appliances. This is part of the scope of working group IEC SC77A/WG8. There are some general potential risks identified regarding harmonic voltages:

- Induction motors: From a general point of view, only the lowest harmonic orders seem to be a problem for induction motors;
- Transformers: the most critical phenomenon is eddy loss in the windings due to harmonic currents, especially for higher harmonic orders. Further assessment is needed to evaluate the relative impact of each harmonic order on transformers and the consequences on admissible harmonic voltage levels;
- Capacitor banks: identified potential risks are increased losses and heating due to the current flowing through the capacitor and the reduction of insulation life caused by the partial discharge effect due to the peak voltage experienced by the capacitor;
- Cables: increased losses and heating and the reduction of insulation life caused by the partial discharge effect;
- Interferences on telecom systems and stray voltages.

All these risks are not specific to the 15th harmonic. There are few to no studies with numerical justifications for these risks for this frequency. No complaints about the network operators such distortions are known. The connected products have in principle no problem with a small increased limit because they already take into account 1.5% of odd neighbors.

V. MEASURES

As the violation of the grid code is unacceptable on the long term measures are required. These options are considered:

- Reduction of the harmonic voltage by reduction of the harmonic currents (which leads to an increasing effort for the manufacturer);
- Reduction of the network impedance to reduce the harmonic voltages (effort for the network operator);
- Changing the harmonic limits of the EN 50160.

Because there are no customer complaints regarding the 15th or 21th harmonic voltages the last option is preferred. This option provides the lowest cost to society.

VI. ALTERNATIVE APPROACH FOR VOLTAGE LIMITS

In this section, a proposal for new harmonic voltage limits is given. The harmonic voltages will be calculated using the network impedances and the limits for the harmonic currents, as defined in the standard IEN61000-3-2[3] for class A devices (Table II). By using this approach there is a direct relation between the harmonic current as already defined in the mentioned standard and the proposed update of the harmonic voltages. No update of equipment standards is required to apply this proposal.

In figure 4 the result of calculating the possible harmonic voltage in relation with the network impedance is given. For the network impedance the 50 Hz value of 0.4+j0.25[2] is used and extrapolated to the specific harmonic frequency.

These values are relative (percentile) values, because the absolute value will depend on more aspects as the amount of devices, the connection of customers along the network cable and the summation of harmonic currents.

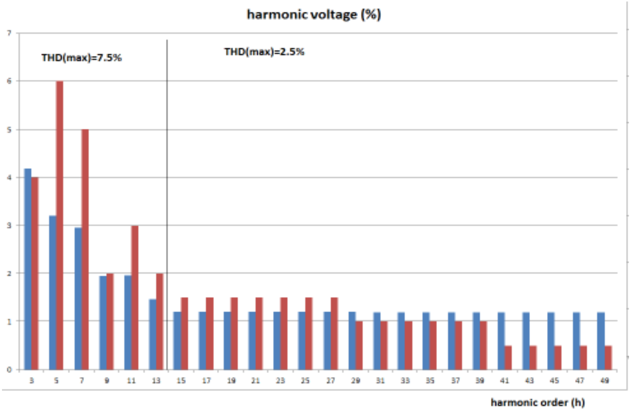

Figure 4: Proposal for harmonic voltage limit(red) vs. the calculated voltages(blue).

In blue the calculated voltages are given. In red the proposal for the new limits are presented. The 5th, 7th, 11th and 13rd harmonic voltages increased considering the influence of 6 and 12-pulse bridges often used in industrial installations. Furthermore scaling to integers or 1 decimal place is done. Also there should be a limitation to the existents of harmonics with very high frequencies. This could be arranged by limiting harmonic voltages with frequencies above 41th order and limiting the total harmonic distortion in two different areas.

The first areas is the area where also a lot of industrial devices will operate, until the 13rd harmonic. The THD could have a limit of 7.5%. For the higher harmonic orders a separate limit is set to 2.5%. This solution will result in a less stricter limit for the individual harmonics but a stricter THD limit for the higher harmonic orders on the THD.

VII. CONSIDERATIONS

Violating the harmonic limits without further actions is not an option. The harmonic limits must be reconsidered or other appropriate measures shall be taken. Important future works for the next stage to improve the European standard on the characteristics of the supply voltage are:

- To do additional measurements to network impedances (including all connected loads);
- To discuss the update of harmonic limits within the several committees of CENELEC or IEC regarding the maximum harmonic voltages and currents;
- Study the existing harmonic background voltage from medium voltage networks and the propagation of harmonic currents and voltages in the network.

ACKNOWLEDGMENTS

Many people have contributed to the PQM projects in recent years. Our colleagues from other companies associated in Netbeheer Nederland have been closely involved. Their contribution is gratefully acknowledged.

The authors would like to thank the project manager Rik Luiten and Hans Wolse for the analysis of the measurements and the significant contribution to the input for this paper.

REFERENCES

[1] Luuk Derksen “Spanningskwaliteit in Nederland, resultaten 2014”, Netbeheer Nederland/Movares, April 2015(to be published).

[2] *Voltage characteristics of electricity supplied by public electricity networks.* EN50160 (2010).

[3] *Electromagnetic compatibility (EMC): Limits for the harmonic current emissions (equipment input current ≤ 16 A per phase)* EN 61000-3-2 (2014)

[4] Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤ 75 A per phase, IEC61000-3-12(2011).

[5] *Electromagnetic compatibility (EMC) - Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems,* IEC61000-2-2(2002).

[6] *Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances,* IEC61000-2-4 (2002).

[7] *Electromagnetic compatibility (EMC) - Part 2-12: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems,* IEC61000-2-12 (2003).

[8] *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.* IEEE Std 519(2014).

[9] Pesonen, M.A., “Harmonics, characteristic parameters, methods of study, estimates of existing values in the network”. *Electra, 77: pp 35-56.* 1981.