HARMONICS: HARMONIZING A SHARED RESPONSIBILITY

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ABSTRACT

Non linear loads change the sinusoidal nature of the AC power current and as a consequence the AC voltage. This results in the flow of harmonic currents in the networks and a harmonic distortion of the supply voltage at the Point of Connection (POC). Utilities are responsible for the harmonic contents of the voltage at the POC even when the harmonic voltages are exclusively caused by the harmonic currents produced by the connected customers.

In order to guard the limits of the harmonic voltages, utilities must be able to set limits to the harmonic currents. Customers, however, may reverse charges by claiming that the harmonic currents are caused by the harmonic voltages. In this "chicken or egg" discussion, knowledge about the interaction of the harmonic background voltage and the produced harmonic currents is crucial.

Based on several measurements of harmonic interaction of household equipment, the authors of this paper have set up new approach to model the interaction between harmonic voltages and harmonic currents on the POC using harmonic fingerprints of connected devices. The harmonic fingerprint model is used in network analysis for determining harmonic limits and liabilities.

INTRODUCTION

The limits for harmonic currents that are found in international standards serve the purpose of avoiding excessive harmonic voltages. It is very difficult to define such limits other than for a "clean" supply with a pure sinusoidal voltage. However, in trying to share out the available room for harmonic pollution among the connected equipment, the effects of harmonic voltages on the harmonic current emission is very relevant and has to be taken into account.

The most evident effect of harmonic voltages is the response of a "linear" ohmic load to harmonic voltages. Basically, an ohmic load will cause x% harmonic current if x% harmonic voltage is present. Although this is trivial, it is often not accounted for in harmonic calculations. In most harmonic models, the loads are represented as current sources, which simply inject the harmonic currents into the network model that were measured in a lab with a clean voltage. However, the "linear" harmonic currents due to the harmonic voltages may be higher than the measured "non-linear" harmonic currents due to the fundamental voltage.

The total harmonic current, *I(f)*, at frequency *f*, at a specific measuring point, may consist of harmonic current when U(f)=0, harmonic current due to a harmonic background voltage U(f) with frequency f, and harmonic current due to a harmonic background voltage with other frequencies. None of these terms can be simply neglected. The question is how to regard all these terms. A straight forward method is presented here, that enables the direct use of measured harmonic behavior in network analyses. This method uses the harmonic fingerprint.

THE HARMONIC FINGERPRINT

The harmonic fingerprint is a dataset that contains a large set of harmonic measurements for a single device. To establish a fingerprint, the device under test is first connected to an undistorted voltage. The harmonic current emission of the device is then measured. Subsequently, a 3^{rd} harmonic voltage is added to the supply voltage with the amplitude and phase shift stepwise increasing, from 0.5% to 5% for example and from 0° to 360°.

The harmonic currents are measured, both amplitude and phase, for each combination. This procedure is carried out automatically for each harmonic voltage. A thus measured harmonic fingerprint results in 121 currents for each harmonic number. In addition, the crosstalk interference is measured and stored. This crosstalk interference means that for example a 5^{th} harmonic voltage can (and mostly will) result not only in 5^{th} harmonic currents but also in currents with other frequencies. All measured data is stored in a fixed format which is the harmonic fingerprint for the device under test.

A part of a harmonic fingerprint is shown in figure 1 and 2. These are the 3^{rd} and 25^{th} harmonic currents for a modern PC. PC's are found in almost every household nowadays and office buildings may have tens or even hundreds of PC's on a single feeder. This makes the PC an interesting object of study.

The figures show a number of dots, where each dot is a single measurement for the 3^{rd} or 25^{th} harmonic currents. The star-dots are measured at a voltage phase shift of zero degrees, relative to the fundamental voltage.

More information about the harmonic fingerprint can be found in [1].

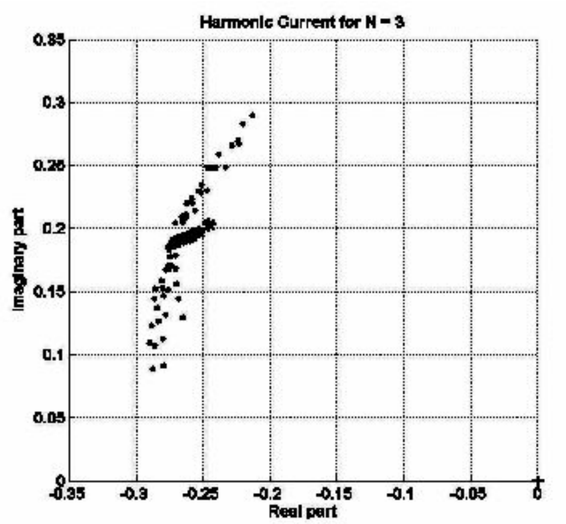

Figure 1: Harmonic fingerprint for a PC for 3rd harmonic voltages

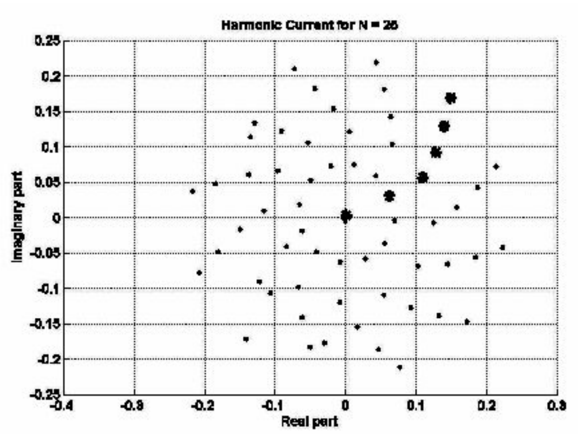

Figure 2: Harmonic fingerprint for a PC for 25th harmonic voltages

HARMONIC CURRENTS AT THE POC

A grid operator is responsible for the harmonic voltage distortion. In order to safeguard the power quality, he needs to know whether a certain device may be connected to the grid or not. This is important for industrial customers, but also for commercial and domestic customers.

For smaller devices, standard compliance tests are used to make sure that these devices will never cause excessive voltage distortions. For larger devices, new acceptance test have to be developed. Figure 3 shows a flowchart which could be used for connecting devices to the grid.

Devices with a nominal current smaller than 16 A should be tested conform the IEC 61000-3-2 [2]. If the nominal current exceeds 16 A or when the device does not comply with IEC 61000-3-2, and the nominal current is smaller than 75 A, the device must comply with IEC 61000-3-12 [3]. If the device complies and the short circuit ratio is above 33, connecting should be allowed.

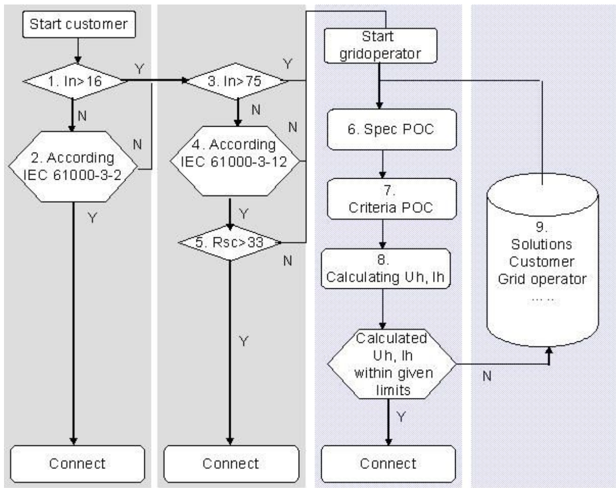

Figure 3: Flowchart for connecting installation/device to grid

In all other cases, an assessment of the expected harmonic currents and voltages has to be made. The grid operator will look in these cases to the POC, where additional criteria should be made for the maximum allowed harmonic distortion of the current.

The IEEE 519 intends to state such harmonic limits for a whole installation. The standard gives current distortion limits as a function of the short circuit current (Isc) at the POC as shown in table 1.

Isc/Il	h<11	11<h<17	17<h<23	23<h<35	h≥35	TDD
<20	4	2	1.5	0.6	0.3	5
20..50	7	3.5	2.5	1	0.5	8
50..100	10	4.5	4	1.5	0.7	12
100.1000	12	5.5	5	2	1	15
≥ 1000	15	7	6	2.5	1.4	20

Table 1: limits for harmonic current (%In) according to IEEE 519

Another approach to find limits for the harmonic current distortion is to determine the global contribution to voltage distortion caused by the LV system under consideration. This method is explained here for the 5th harmonic voltage.

First of all a planning level for the several voltage levels has to be established. Figure 4 shows the 5th harmonic level in the Dutch HV-, MV- and LV-grid, as measured in 2005. Acceptable planning levels for the 5th harmonic voltage are taken from these measurements and shown in table 2. The harmonic voltage at the LV feeder is also caused by the MV distortion. By using the planning levels L and the transfer factor T, the maximum harmonic voltage that can be allocated to the total of loads at the considered LV system is given by:

$$G_{U5,LV} = \sqrt[\alpha]{L_{U5,LV}^{\alpha} - T_{U5,MV\rightarrow LV}^{\alpha} \cdot L_{U5,MV}^{\alpha}} \quad (1)$$

$$= \sqrt[1.4]{0.55^{1.4} - 1\cdot(0.45)^{1.4}} = 2\%$$

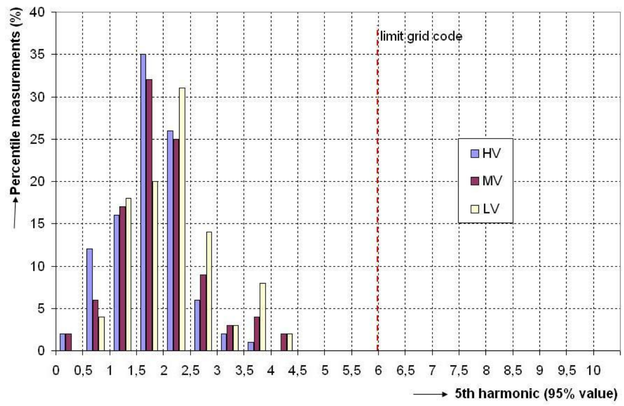

Figure 4: Measured 5th harmonic voltage in 2005

Planning level for 95% percentile of 5th harmonic voltage		
HV	MV	LV
3.5	4.5	5.5

Table 2: acceptable planning levels

This is the maximum tolerable additional voltage distortion at the LV grid. This amount is used to establish current distortion levels for the connected customers, by first establishing the maximum contribution to the 5th voltage distortion for each customer, ΔUh5. The maximum grid impedance should be related to the nominal current of the protection device (Ipr) on the POC. These types of connection and the related grid impedances are given in table 3.

Connection type	Amperage (Ipr)	Maximum Zg (mΩ)	Isc/Ipr
1 phase+neutral	40 A (35 A)	326 (373)	30
3 phases+neutral	25 A	523	30
3 phases+neutral	40 A (35 A)	326 (373)	30
3 phases+neutral	50 A	261	30
3 phases+neutral	63 A	207	30
3 phases+neutral	80 A	163	30

Table 3: Grid impedances related to maximum current POC

Figure 5 shows a small low voltage grid, using typical Dutch data for the components. Domestic customers may be combined with small industrial or commercial customers in such grids. The loads in this grid are placed such that their network impedance is according to table 3.

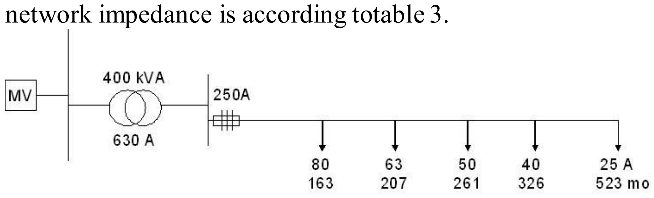

Figure 5: One low voltage feeder with all typical low voltage loads

Due to the low simultaneously use of 0.1 it will be sufficient to calculate the ΔUh5 on the POC, with taking into account only 2 disturbing customers at the same time. The limit so calculated for the ΔUh5 on the POC equals:

$$\Delta U_{h5} = \sqrt[1.4]{\frac{2^{1.4}}{2}} = 1.22\% \qquad (2)$$

The maximum harmonic current injected for the several points of the grid can now be estimated by using

$$\Delta U_{h5} = I_5 \cdot Z_{g,5} \qquad (3)$$

The results are shown in table 4

Amperage (Ipr)	Zg_5 (mΩ)	I_5 (A)	I_5 (%)
25 A	1110	2,5	10
40 A (35 A)	730	3,8	9.5
50 A	590	4,7	9.4
63 A	470	6,0	9.5
80 A	380	7.4	9.3

Table 4: Calculated maximum 5th harmonic current

The conclusion from these calculations is that limiting the 5th harmonic current on the POC to 10% of the fundamental current is a suitable solution. These kinds of calculations can be done for all harmonics and the total demand distortion to achieve some percentage for each separate harmonic. If the result of the calculations is positive (harmonic currents and voltages are within given limits) then connecting is acceptable, otherwise other solutions have to be found. Proper calculations of harmonic voltages can however only are made using the harmonic fingerprint of the connected devices.

CALCULATING WITH FINGERPRINTS

In order to use the harmonic fingerprint in a harmonic load flow calculation, we need to change the load model that is normally used in these calculations. The network analysis software "PowerFactory" was used for this. For load flow calculations at the fundamental frequency, this software models the load as a voltage dependent current source, as is depicted in figure 6. By selecting the kind of dependency, the load model is given the characteristics of a fixed impedance, a pure current source, a fixed P-Q load or any other characteristic.

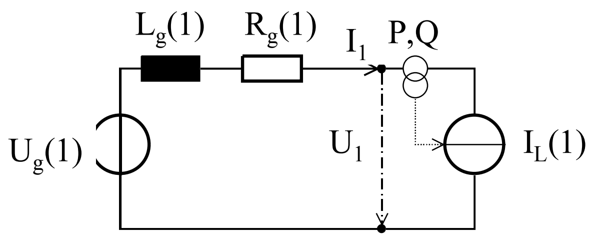

Figure 6: load model at fundamental frequency

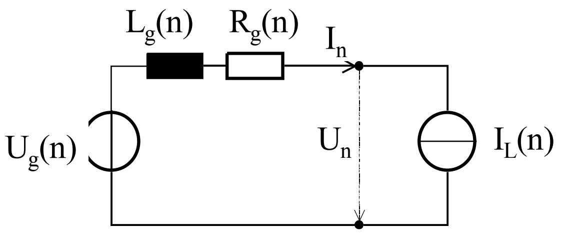

Figure 7: load model for n^{th} harmonic

The load model for the harmonic load flow calculations is about the same, except that a fixed harmonic current will be injected at each calculated frequency. The harmonic currents are defined as effective values and angles for each phase, for each frequency. The effective values (in pu.) and the current angles are given as relative to the fundamental current vector.

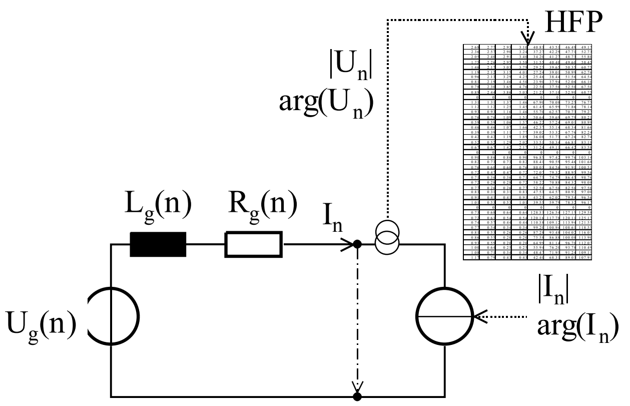

Figure 8: load model for n^{th} harmonic with HFP lookup table.

The basic change for incorporating the harmonic fingerprint is to use the controlled current source for harmonic calculations also. In stead of a simple P,Q-dependency on voltage magnitude, we need a controller that will take the calculated voltage magnitude and phase angle to look up the corresponding harmonic current magnitude and phase angle in the harmonic fingerprint matrix as is depicted in figure 5. The harmonic current that is to be injected becomes the new set point for the harmonic load flow calculation. This calculation has to be repeated iteratively, as depicted in figure 9, until convergence is reached.

The harmonic load flow calculations were implemented in the PowerFactory software with the help of the DPL scripting language. Two-dimensional interpolation was used for the voltage magnitude and angle in order to get the corresponding harmonic currents.

Precise evaluation of the harmonic voltages can be made this way. When these are found to be lower than the allowed limits, connection is possible. Otherwise, mitigation measures have to be taken. In assessing the effects of these measures, the harmonic fingerprint calculations will be of use again.

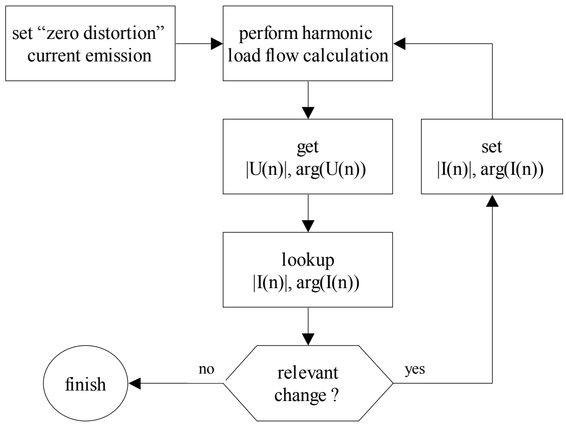

Figure 9: flow diagram for harmonic load flow calculations

CONCLUSIONS

Working with the above outlined methodology makes responsibilities more clear. The customer has to limit the current at the POC, where maximum values are given. The harmonic background voltage is the responsibility of the grid operator. Together they have to determine if a special device can be connected to the grid on a certain place, or not. The harmonic fingerprint offers an accurate method for calculating harmonic voltages in situations were harmonic emission is influenced by the background harmonic voltages. When accurate calculations are needed to find the harmonic currents at the POC, the harmonic fingerprints of all relevant connected devices should be available. Future research may be targeted towards establishing harmonic fingerprint data from on-line measurements under various conditions. At the same time, a database of typical harmonic fingerprints will be created by the ongoing research in the PQ labs that are able to measure harmonic fingerprints. This will enable the connection of problematic equipment in even the hardest conditions without jeopardizing the harmonic voltage quality.

REFERENCES

[1] J.F.G. Cobben, W.L. Kling, J.M.A. Myrzik; The making and purpose of a harmonic fingerprint, CIRED 2007

[2] IEC 61000-3-2, Limits for harmonic currents emissions (equipment input current ≤ 16 A per phase), Edition 2:2000 consolidated with amendment 1:2001; IEC, Geneva Switzerland

[3] IEC 61000-3-12: 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 IEC, Geneva Switzerland