Harmonic current interaction at a low voltage customer's installations

Citation for published version (APA):

Bhattacharyya, S., Myrzik, J. M. A., Kling, W. L., Cobben, J. F. G., & Casteren, van, J. (2009). Harmonic current interaction at a low voltage customer's installations. In *Proceedings of the 10th International Conference on Power Quality and Utilization (EPQU 2009), Lodz, Poland* (pp. 1-6). EPQU.
<https://doi.org/10.1109/EPQU.2009.5318859>

DOI:

[10.1109/EPQU.2009.5318859](https://doi.org/10.1109/EPQU.2009.5318859)

Document status and date:

Published: 01/01/2009

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Harmonic Current Interaction at a Low Voltage Customer's Installation

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Abstract— The increased use of power electronics and switching devices in the electricity network have changed the operational environment of the power system. These devices have non-linear voltage-current characteristics and produce harmonic currents, and consequently distort the voltage waveform. A low voltage domestic customer can have mixed loads that consist of linear and non-linear loads such as home appliances and lighting devices. In the PQ laboratory of TU/Eindhoven, the harmonic fingerprints of various household devices are measured. A LV household customer's installation, consisting of various home appliances, is simulated in the network analysis tool 'Power Factory'. The measured harmonic fingerprints of the connected devices are fed in to this software to perform harmonic simulations. The simulation results give the total harmonic current distortion level at the installation and the combined harmonic current interaction effects of different household devices. Furthermore, a case study is done to evaluate the total current harmonic distortion level at a customer's installation when the grid voltage is polluted with a specific order of harmonic (such as the 5th harmonic). This is expected to be a typical futuristic scenario when many non-linear devices would be connected in the network and would distort the supply voltage.

Keywords- *harmonic simulation; harmonic current pollution; harmonic fingerprint; home appliance; harmonic interaction*

I. INTRODUCTION

The conventional ac electric power systems are designed to operate with sinusoidal 50 or 60Hz voltage and current. The increased use of power electronic and switching devices in the network influences this sinusoidal voltage. These devices have non-linear voltage-current characteristics and distort the steady state ac voltage and current waveforms. The periodically distorted waveforms can be analyzed using 'Fourier analysis' by examining harmonic components of the waveforms. Harmonics can be defined as sinusoidal

components of a periodic waveform having a frequency that is an integer multiple of a fundamental frequency (50 or 60Hz). The knowledge of power system harmonics is important to determine and to avoid dangerous resonant conditions in the network. When harmonic currents propagate along the networks, they can result in increased losses and possible aging of grid components. They can interfere with control, communication and protective equipment too. The voltage or current quality is determined by the various harmonics present in the power system and their respective amplitudes and phase angles.

The propagation of harmonic currents in a power system and the resulting voltage distortion depends on the characteristics of harmonic sources and the frequency response of system components. Therefore, models of various harmonic generating loads and system components are developed to determine the propagation of harmonics throughout the power system. In the low voltage (LV) network, a household customer can have mixed loads that consist of linear and non-linear components. Devices that generate harmonic currents are generally modeled as a current source with fixed harmonic currents. In the harmonic fingerprint approach, the interaction between non-linear devices is also modeled. A harmonic fingerprint gives the complete behavior (both the magnitude and phase angle) of a device for different harmonic orders even when the supply voltage is distorted with a specific type of harmonic. However, it is often difficult to obtain an average harmonic load model of a LV customer because of the variation of usage and dynamic nature. It is observed that the net harmonic current produced by various harmonic loads at a customer's installation is usually significantly smaller than the algebraic sum of harmonic currents produced by individual non-linear loads, mainly because of mutual phase cancellation.

Harmonic current fingerprints for various home appliances are measured in the PQ laboratory of TU/Eindhoven. Also, a typical customer's installation along with various home appliances and lighting devices are implemented in the network analysis tool 'Power Factory' (developed by DIGSILENT, Germany). The measured harmonic fingerprints are fed in to the model and simulation is done. In this paper, harmonic simulation results are analyzed for various combinations of customer's devices and the total harmonic current pollution at a typical customer's installation is calculated for a clean grid as well as under polluted grid voltage conditions.

II. HARMONIC MODELING CONCEPTS

The following important information is found about harmonic analysis from various literature surveys:

- System harmonic impedance is sensitive to network parameters, topology and actual load composition
- Load composition is an important parameter in harmonic study and affects damping of harmonics
- Linear loads are a significant component of the system harmonic impedance which is sensitive to load size and composition
- Non-linear loads produce harmonics even when the voltage is sinusoidal, and a different spectrum of harmonics when the supply voltage is distorted
- Harmonic currents may cancel or enhance each other partially because of the differences in phase angles at respective harmonic frequencies
- Some devices such as transformers and induction machines can attenuate harmonic currents.

A. Indices used for harmonic measurement

The most commonly used measure of deviation of a periodic waveform from a sine wave is expressed by the total harmonic distortion (THD). The THD can be measured in reference to fundamental component (F_1) or rms value (F_{rms}). In this paper, the THD is calculated with respect to rms value as shown in (1).

$$THD_{rms} = \frac{\sqrt{\sum_{n>1}^{\infty} (F_n)^2}}{F_{rms}} \quad (1)$$

Where, $F_n = n^{th}$ component of the waveform.

Furthermore, the power system harmonics cause an additional power flow in the network, identified as distortion volt-amperes. Thus, total apparent power flows (S) in the presence of network harmonics are the combination of active power (P), reactive power (Q) and distortion power (D) as shown in (2).

$$S^2 = P^2 + Q^2 + D^2 \quad (2)$$

Presence of large harmonic components changes the power factor (PF) of the system to a lower value as shown in

(3) and increase the demand of apparent power in the network.

$$PF = \frac{DisplacementPowerFactor(DPF)}{\sqrt{1+(TotalHarmonicCurrentDistortion)^2}} \quad (3)$$

Displacement Power factor (DPF) is defined as the ratio of active power (P) and apparent power (S) for the fundamental component. When there is no harmonic present in the network (which means total harmonic current distortion is zero), DPF and PF of the system will be same. Equation (3) is valid if total harmonic voltage distortion is less than 10% and the power loss in the network due to harmonics is small compared to the fundamental component of active power.

B. Analysis methods

There are different methods to analyze the harmonic propagation in an electric network. The methods for harmonic analysis can generally be in the frequency and time domains.

The frequency domain calculation imposes a steady-state condition, described by a limited number of frequency components. The difficulty is the representation of non-linear devices that cause interactions between the different frequency components. This method uses a phasor representation for various harmonic sources and system impedances. Therefore, this method is more effective for the network with rigid (constant) harmonic sources and linear impedances.

Time domain methods for the analysis of electrical systems are generally more accurate than frequency domain techniques. On the other hand, they are more complex to implement and time consuming. This method uses a time representation of the system elements and harmonic sources. Generally for harmonic propagation study, time domain method is more accurate.

Most harmonic flow analysis on the power system is performed using steady-state, linear circuit solution techniques. The propagation of harmonic current in a power system and the resulting voltage distortion depends on the characteristics of harmonic sources as well as the frequency response of system components. The non-linear devices that generate harmonic currents can be modeled by using a simple current source model [1]. When the voltage distortion at the customer's bus is low (less than 5 percent), the current distortion for many non-linear devices are considered to be a constant current source and independent of the distortion in the supply voltage. In the current source model, the magnitudes of harmonic currents and the phase angles for respective harmonic orders have to be set. With several harmonic producing current sources, depending on their phase angles, the effects of the harmonic producing sources at a particular bus can either addition or cancellation.

In this paper, the network analysis tool 'Power Factory' is used for simulation purposes. When starting the harmonic simulation, it carries out a three phase load flow to determine the steady state conditions of the voltage, current magnitudes

and phase angles at each network terminal and each network branch. The in-built programming language has been used to add the analysis for harmonic fingerprint models. It has the feature to calculate harmonic voltage and current distributions based on user defined harmonic sources and grid characteristics.

C. Standards used

The existing international EMC standards dealing with limits for harmonics by LV appliances are product standards. The standard IEC 61000-2-2 [2] specifies the compatibility levels for individual harmonic voltages in LV networks, up to the 50th order. Whereas IEC 61000-3-2 [3] provides individual harmonic current limits for appliances with a rated current ≤ 16 A per phase, while IEC 61000-3-12 [4] deals with all equipment having a rated input current > 16 A and ≤ 75 A per phase. Moreover, the device manufacturer should also specify the minimum short circuit ratio for the device for connecting it at a customer's installation. The connection of disturbing loads in the network will change the total distorted harmonics voltage at the point of connection (POC). Thus, the change of distorted harmonics voltage ($\Delta THDU$) is a function of load currents (I), total harmonics current distortion (THDI) and system impedance (Z) at the customer's POC [5] as shown in (4).

$$\Delta THDU = f(I, THDI, Z) \quad (4)$$

Hence, when a customer asks for a connection, the utility should check the change of harmonic distortion voltage level at the POC as per EN 50160 and can suggest the customer for required connection requirements.

Another standard IEEE 519 [6] specifies harmonic current distortion limit as a function of short circuit current (I_{sc}) at the customer's point of connection. The various limits given in the standards are for clean sinusoidal voltage conditions. When the supply voltage is distorted because of harmonic pollutions, the devices produce different harmonic current emissions, sometimes significantly larger than that for the clean grid voltage. Even for the linear loads, a distorted supply voltage will influence their current emissions behaviors. No presently available standard specifies harmonic current emission limit at a customer's POC for the polluted grid condition. Therefore, in this paper a brief analysis is done to find out the harmonic current emission levels when the grid supply voltage is distorted with a specific order of harmonics.

D. Attenuation and diversity effects

The most common model for harmonic sources is in the form of a harmonic current source, specified by its magnitude and phase spectrum. The phase is usually defined with respect to the fundamental component of the terminal voltage. The data can be obtained from an idealized theoretical model or from actual measurements. The net harmonic currents injected by large numbers of single phase electronic loads are significantly affected by both the attenuation and diversity.

Attenuation, which refers to the injection of voltage and current distortion, is primarily due to the shared transformer impedance. When the non-linear loads are represented by a fixed harmonic current source, there will be an error on the voltage THD when compared to the simulation where the currents are dependent on the node voltage. The attenuation factor is represented by the ratio of the resultant current (I_h^N) for harmonic h for N units to the total harmonic current for h harmonics injected by N sources ($N \cdot I_h$). I_h is the harmonic current injected by each non-linear device.

When a system contains a single dominant source of harmonics, phase spectrum is not important. However, phase angles should be taken into consideration when multiple harmonic current sources are present. The distortion of an aggregate waveform might be limited because of the 'diversity effect'. This effect is due to the possible harmonic cancellations among the non-linear loads because of the dispersion in harmonic current phase angles. A possible origin can be found in the variation of line impedance or the different X/R ratios of line impedance and the variation in load parameters. In order to quantify the effect of the phase angle dispersion, the following current harmonics diversity factor as shown in (5) has been defined.

$$\text{Diversity factor} = DF_h = \left| \frac{\sum_{i=1}^N I_h^i}{\sum_{i=1}^N |I_h^i|} \right| \quad (5)$$

Where,

N = number of non-linear loads, $I_h^i = |I_h^i| \angle \theta_h^i$ is harmonic current of order h injected by i^{th} load

The attenuation effect of the harmonic propagation is related to short circuit ratio (SCR), while the diversity factor is less sensitive to the variation of SCR [7].

III. HARMONIC FINGERPRINT MEASUREMENTS

The electricity consumers in different sectors (industrial, commercial and residential) use various types of loads that are typically a mix of linear and non-linear loads. In the LV networks, household consumers are the biggest group of electricity users and use mixed type of loads. Examples of linear loads are incandescent lamps, motors, heaters, conventional ovens and air-conditioner; whereas non-linear loads include compact fluorescent lamps (CFL), converters, computers, etc and other home appliances, such as television sets, video players, refrigerator, vacuum cleaner, etc. The non-linear loads are characterized by highly distorted load currents (THDI of 80-130%) [7]. However, the THDI at a typical LV customer's installation generally does not exceed 20%. This happens because of mutual attenuation and diversity effects among different loads.

A. Development of a harmonic fingerprint

A harmonic fingerprint is a database that contains a large set of harmonic measurements for a single device. In the PQ laboratory of TU/Eindhoven, various household appliances and lighting devices are chosen for measurement as shown in TABLE I. First, each device is tested for a clean sinusoidal voltage condition and its harmonic spectrum, total harmonic

current distortion, true power factor, displacement power factor, fundamental current component and total rms current value are recorded. Figure 1 shows the harmonic spectrum of a PC under clean grid condition. Subsequently, the supply voltage is polluted with various odd harmonics (from 3rd harmonic up to 25th harmonic), having an amplitude variation of 1% to 10% (with a step of 1%) and also a phase shift of 0° to 360° (with a step of 30°) and respective harmonic currents are measured. So, for each device two matrices (each of 12x10 dimensions) are formed with new harmonic current amplitude and new phase angle data respectively, for different harmonic pollution conditions. The developed matrix for each device can be plotted, as shown in Figure 2. References [8] and [9] give more information on the harmonic fingerprint development method.

Figure 1: Harmonic spectrum of a PC under clean grid condition

Figure 2: Harmonic fingerprint plot for a PC (for h=3 and h=25)

In the measurements, it is assumed that even harmonics are significantly lower than odd harmonics and therefore, even harmonics measurements are not included yet in the present analysis. Also, it is found that the effects of harmonics for household devices are more prominent up to 25th harmonics. Thus, the harmonic fingerprints for various devices are measured from 3rd to 25th harmonic only.

B. Devices considered for measurement

The devices that are considered for harmonic fingerprint measurements in the PQ laboratory are listed in TABLE I with their specifications. As the harmonic fingerprint can vary for the same device from different manufacturers, therefore such information of the measured devices is also given in TABLE II. The purpose of harmonic fingerprint measurement is not to get accurate current emission of a single device, but to estimate an approximate harmonic pollution level in the network when similar types of devices are connected in large numbers.

TABLE I: Technical details of devices (as measured by PQ meter in the laboratory)

Device in operation	Cosφ	DPF	I _{rms} (A)	I ₁ (A)	THD (%)	
					w.r.t I ₁	w.r.t I _{rms}
Compact fluorescent lamp (CFL)	0.555	0.903	0.092	0.058	107.	67.4
Refrigerator	0.596	0.593	0.751	0.727	10.2	9.9
LCD TV	0.758	0.994	0.775	0.599	83.4	64.4
PC + Monitor	0.486	0.975	0.881	0.427	170.	82.4

Note: THD values measured by PQ meter are based on fundamental current. So, they are recalculated for rms current component too.

TABLE II: General specification of devices taken for measurement

Devices	Specifications		
	Manufacturer	Type	Technical data
CFL	Philips	GENIE 11W	220-240V, 50-60 Hz
Refrigerator	Whirlpool	ARC 5754/2	Energy consumption 2700kWh/year
TV	Philips	32PFL5403D/12	81cm LCD, 130W
PC	Retailer (Aragorn)+Dell	Monitor: 1703FPt	N/A

C. Interface between measurement and simulation

In the PQ laboratory, a typical domestic installation is set up with various devices connected together as shown in Figure 3. The total harmonic distortion and harmonic spectrum is noted for a clean grid and some specific polluted grid conditions (such as 5th harmonic voltage with 2.5% amplitude and 180° phase shift). Also, the individual device harmonic spectrum is measured and the harmonic fingerprint matrix is developed in Excel format. The network analysis tool 'Power Factory' is used to simulate the model network of a household (shown in Figure 3) with various devices connected at its terminal. The harmonic fingerprint matrices for different devices are fed to respective devices' database of the modeled network. Also, the cable data along with its harmonic spectrum (obtained from field measurement [10]) is included in the model. Then, a harmonic analysis is done to find out the total harmonic current distortion (THDI) at different parts of the simulated network.

D. Model network used for simulation

Figure 3 shows the model network that is used for simulation. The point of common coupling (PCC) is a LV bus where different LV customers are connected. The short circuit capacity at this point is taken as 0.5MVA. A LV cable (150mm², Al conductor and XLPE insulation) of 500m length and a small connection cable of 10m length are used to connect the nodes between PCC and POC. At the POC, three typical household customers are connected in each phase. Each of them is assumed to have similar single phase devices such as TV, PC, refrigerator, CFL and other loads (like cooking element, incandescent lamps, etc). First, it is assumed that the external grid supplies a clean sinusoidal voltage at the POC. Next, a polluted grid condition is taken (for example 5th harmonic voltage pollution) for simulation, shown as 'harmonic voltage source' in Figure 3.

Figure 3: Simulated network

IV. SIMULATION RESULTS

The simulations are done with the linear and non-linear loads on the model network as shown in Figure 3. Two main study cases are considered:

- Clean grid condition (with sinusoidal supply voltage)
- Polluted grid condition (5th harmonic voltage pollution with 2.5% amplitude and 180° phase shift)

The cases considered for simulation are also verified with practical measurement in the PQ laboratory. Both the simulation and measurement results are found comparable.

A. Clean grid condition

For the clean grid condition, it is assumed that the supply voltage is sinusoidal. Five loads, as shown in Figure 4, are connected at the POC of the installation. Among them four loads generate harmonics as indicated in TABLE I and their harmonic fingerprint data are fed into the database of 'Power Factory'. The THDI values found from the simulation at different devices terminals and lines are shown in Figure 4. The THDV value at terminals PCC and POC are found quite small (approximately 1%). The total current harmonics distortion produced by the combined load at the installation is 14.7%, compared to a single device's (such as PC) current

harmonics distortion of 90%. This is because of the presence of linear load and also the diversity and attenuation effects of non-linear loads at the POC.

Figure 4: Harmonic simulation results for clean grid condition

It is to be noted that while measuring the harmonic fingerprint for TV, the normal operation of TV was disturbed for various amplitudes signals of 23rd and 25th voltage harmonic pollutions. The TV under test was switching off frequently during the measurements. The recorded data for 23rd and 25th harmonics were found wrong and therefore for TV, the harmonic fingerprint up to 21st order of harmonics is taken in the simulation. Hence, THDI value found for TV in the simulation is relatively smaller than the measurement results of TABLE I. This disparity will be investigated in detail during the next phase of the research.

Another simulation was done to check the influence of linear loads in the network. Therefore, the linear load of Figure 4 is switched off and the simulation is repeated. THDV values at POC and PCC are found bit smaller than in the previous case, while THDI in the line is high (35%), compared to 14% for the clean grid condition. However, the total values of harmonic currents for both the cases do not vary much as shown in TABLE III.

TABLE III: Influence of linear loads on harmonic currents

Load condition	I_{rms} (A)	THDI (%)	Total harmonic current (A)
Linear +Non-linear loads	6.3	14.7	0.95
Non-linear loads only	2.6	35.2	0.86

Note: Total harmonic current value = $I_{rms} * THDI / \sqrt{1 + THDI^2}$

B. Polluted grid condition

The simulation is also done on the model network for a polluted grid condition with a harmonic voltage source in the network. A 5th harmonic pollution of 2.5% amplitude and 180° phase shift is injected and the simulation is repeated. Results are shown in Figure 5.

Figure 5: Harmonic simulation results for polluted grid condition

Figure 5 shows that under the polluted grid voltage conditions. The total harmonic current pollution (0.92A) as well as the THDI (14.9%) at the POC remains almost the same as the previous case; while THDI in the network increases (58%). Also, THDI for different devices have changed slightly depending on their respective phase angle attenuation. If Figure 4 and Figure 5 are compared, it can be noticed that THDI of CFL remains almost unchanged; THDI of PC is reduced slightly, whereas that of TV and fridge are increased for the polluted grid condition. Simulation results show that the linear load is consuming a harmonic current which is linearly proportional to the harmonic voltage at its terminal.

The harmonic current spectrums of different devices also change to some extent when the grid voltage is polluted. Under this situation, the harmonic fingerprint data for different devices will be useful as they give information on the new values of harmonic current emissions. In extreme situations, some specific order of harmonic current for a device may increase significantly for a polluted grid condition and can exceed the standard limit of IEEE 519.

All the simulation results are verified by performing real measurements on the specified devices in the PQ laboratory of TU/Eindhoven. The simulation results and measurements are found comparable.

V. CONCLUSION

The analysis of this paper shows that the use of non-linear loads in the household activities has significant influence on the network's harmonic current pollution level. The combined effects of various non-linear LV devices (home appliances, etc) attenuate the total harmonic current distortion in the network mainly because of phase cancellation and diversity effects. In this study, it is found that the total current harmonic distortion level at the customer's installation is around 14% when the customer has mixed loads. Harmonic fingerprint measurements for non-linear devices are important to know and also the behavior of them under polluted grid conditions, which will be common

in the future electricity infrastructure as more non-linear devices will be present in the network. It can happen that some specific order harmonic currents increase significantly in the network under the polluted grid condition, exceeding the limits given by the standard IEEE 519. This study gives an idea about the total harmonic current pollution levels under clean and polluted grid conditions. Also, the influence of linear loads on harmonic current pollution levels is discussed.

In the next phase of this research more harmonic fingerprints for other commonly used devices (such as solar inverter, LED lamps) will be done and further simulations will be performed to get an overview of the variation of harmonic current emission levels at LV customer's installation and their impacts on the network. This in order to analyze if the limits of the standard IEEE 519 are required to be modified; or a restriction on harmonic current emission is needed at a customer's installation or a stricter standard is needed for customer's devices.

ACKNOWLEDGEMENT

Special thanks go to Glenn van Wolk and Yan Li for helping to perform harmonic fingerprint measurements in the PQ laboratory of TU/Eindhoven.

REFERENCES

- [1] Gary W.Chang, Wilsun Xu, Paulo F.Ribeiro, "Modeling of harmonic sources –power electronic converters", a tutorial: <http://www.powerit.vt.edu/AA/chapters/pdf/c3pdf.pdf>
- [2] IEC 61000-2-2- "Compatibility levels for low-frequency conducted disturbances and signaling in public medium-voltage power supply systems", First edition 2003-04, IEC, Geneva, Switzerland, 2003.
- [3] IEC 61000-3-2 – "Limits for harmonic currents emissions (equipment input current ≤ 16A per phase (2000)), IEC, Geneva, Switzerland.
- [4] IEC 61000-3-12- "Limits for harmonic currents produced by equipment connected to public low voltage systems with input current > 16A and < 75A per phase (2005)", IEC, Geneva, Switzerland.
- [5] Marinko Stojkov, Krno Trupinic, Darko Poleto, "Determination of specific electricity consumers' which have great impact on harmonic distortion of voltage waveform", 19th International conference on electricity distribution (CIRED), Vienna, 2007.
- [6] IEEE 519-1992: "Recommended practices and requirements for harmonic control in electrical power systems", IEEE, 1992.
- [7] Mau Teng, Jovica V. Milanović, "Development of stochastic aggregate harmonic load model based on field measurements", IEEE transactions on power delivery, vol.-22, no.-1, January 2007.
- [8] Sjeff Cobben, Wil Kling, Johanna Myrzik, "The making and purpose of harmonic fingerprints", proceeding of 19th International Conference on Electricity Distribution (CIRED 2007), Vienna, 2007.
- [9] Jasper van Casteren and Sjeff Cobben, "Harmonics: harmonizing a shared responsibility", proceeding of 19th International Conference on Electricity Distribution (CIRED 2007), Vienna, 2007.
- [10] Sjeff Cobben, "Power Quality- implications at the point of connection", PhD dissertation, TU/Eindhoven 2007.