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Comparative Analysis of Definitions for the Harmonic Emission Levels

J. Denoël, M. Petit and T.D. Le

Geeps, CNRS UMR 8507 – CentraleSupélec, UPSud and UPMC – Gif-sur-Yvette, France
E-mail: julien.denoel@centralesupelec.fr, marc.petit@centralesupelec.fr, trungdung.le@centralesupelec.fr

Abstract. To keep a high level of power quality, Distribution System Operators (DSOs) must keep harmonic voltage levels under limits specified in standards. These harmonic voltages are due to non-linear equipment connected inside installations, which inject harmonic currents into public networks. In order to apply emission limits per installation, DSOs need to have an accurate and reliable indicator to assess the harmonic emissions of an installation. In this paper, a comparative analysis of two definitions for assessing the harmonic emissions of installations is presented. Their respective advantages and drawbacks are pointed out.

Key words

Harmonic Emission, Disturbing Installation, Power quality, Distribution networks.

1. Introduction

To deliver a high level of power quality to customers, Distribution System Operators (DSO) must meet a number of criteria [1]. Among these, harmonic levels are an important issue. Indeed, for many years, the part of non-linear equipment connected to distribution networks has increased due to the continuous addition of converters. To avoid unacceptable harmonic levels on distribution networks, it is necessary to apply harmonic emission limits, not only to individual pieces of equipment, but also to large installations.

However, today there is no international consensus on the way to assess the contribution of an installation to the global harmonic levels on distribution networks, in order to compare this contribution to harmonic emission limits.

For years, different methods have been suggested in order to solve this problem. The first proposed method is to assess the harmonic currents injected by the equivalent Norton model of the installation into the public network [2]-[3]. Other authors suggest using harmonic active powers as the harmonic emissions of the installation [4]-[5]. In publication IEC 61000-3-6 [6], a new definition is given, based on the impact of the installation on harmonic voltages at its point of common coupling (PCC). As these definitions can sometimes give very different results, a methodology is required to compare their behavior in real situations, including phenomena such as resonances.

In order to compare the different definitions for the harmonic emission levels of an installation, we have used a set of some simplified MV networks. These simplified networks aim at showing harmonic phenomena such as the compensation between multiple harmonic sources, or the resonance between network impedances and compensation capacitors. They also allow knowing if a definition only detects disturbing installations and how the line impedance between the busbar and the installation affects its harmonic contribution.

In the present paper, we will consider the first proposed definition based on a Norton representation of the installation [2]-[3] and the new definition given in technical report IEC 61000-3-6 [6]. In section 2, their respective theoretical expressions will be presented. In section 3, a simplified MV network will be presented. In sections 4 to 6, a comparative analysis of both definitions will be carried out in several configurations of this simplified MV network, in order to point out the advantages and drawbacks of both definitions. In section 7, conclusions and perspectives of this study will be given.

2. Theoretical background on studied definitions

In order to assess the installation harmonic emissions, the first proposed definition was based on a Norton representation of the network and installation at the PCC (Fig. 1).

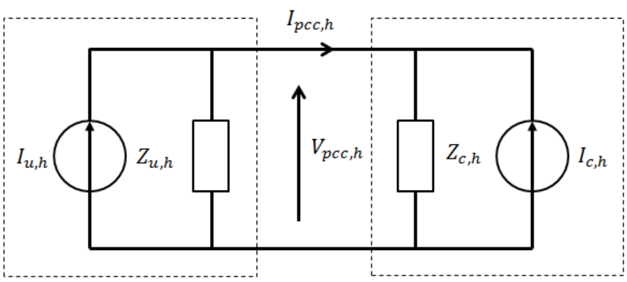

Figure 1. Norton representation of the network and installation at the PCC

$I_{c,h}$ and $I_{u,h}$ are respectively the equivalent harmonic current sources of the installation and the network. $Z_{c,h}$ and $Z_{u,h}$ are respectively the equivalent harmonic impedances of the installation and the network. $V_{pcc,h}$ and $I_{pcc,h}$ are the harmonic voltage and current measured at the PCC of the installation. Subscript h is the harmonic order.

According to the initial definition, the harmonic voltage emission level of the installation is defined by (1).

$$|V_{injected,h}| = \left| I_{c,h} \cdot \frac{Z_{c,h} \cdot Z_{u,h}}{Z_{c,h} + Z_{u,h}} \right| \quad (1)$$

It can be noted that this definition does not consider the harmonic current generated by the network ($\boldsymbol{I_{u,h}}$). Hence, this definition does not take into account the possible compensation with other injected currents.
Physically, this emission level is defined as the maximum increase in the harmonic voltage level that can be produced by the nonlinear loads in the installation at its PCC (i.e. the increase if $\boldsymbol{I_{u,h}}$ and $\boldsymbol{I_{c,h}}$ are in phase).
This definition has two main drawbacks:

- the linear loads are not disturbing, thus it does not take into account the possible resonances created by capacitive loads.
- The existing method to identify the Norton model is able to compute only one side (network or installation) at a given time [7].

In 2008, a new definition was proposed in [6] in order to assess the harmonic emission levels of an installation. This new definition was aimed at considering the effects of linear loads on harmonic voltage levels, particularly in the case of resonances between network impedances and compensation capacitor banks.
The technical report [6] assesses the harmonic emission level as the modulus of the harmonic voltage variation at the PCC when the installation is connecting to the network. This harmonic emission level ($\boldsymbol{\Delta V_{pcc,h}}$) is represented in Fig. 2.
However, according to IEC 61000-3-6, the harmonic emission level is required to be less than the emission limit only when the connection of the installation to the public network leads to an increase in the harmonic voltage level at the PCC. Thus friendly loads, leading to a decrease in harmonic levels, are not considered as disturbing sources.

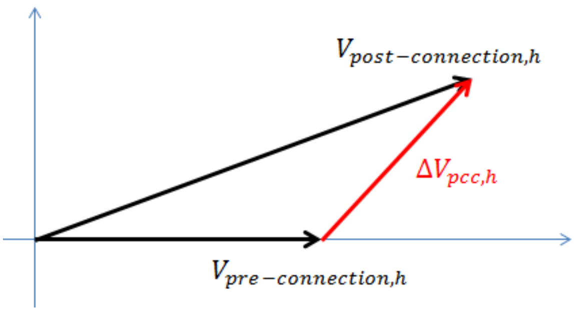

Figure 2. Harmonic voltage variation due to the connection of the installation.

In practice, the harmonic emission is calculated using (2).

$$|\Delta V_{pcc,h}| = |I_{pcc,h} \cdot Z_{u,h}| \quad (2)$$

The harmonic current at the PCC $\boldsymbol{I_{pcc,h}}$ can be directly measured, but the harmonic network impedance $\boldsymbol{Z_{u,h}}$ needs to be known or estimated, which can be difficult without an intrusive method requiring a harmonic current injection or power supply interruption with respect to the installation. In [7] several methods are presented to assess the harmonic network impedance.

3. Presentation of the simplified MV network

All configurations used in this paper are based on the topology represented in Fig. 3. It is a small simplified MV network supplying two large installations modeled by two Norton sources.

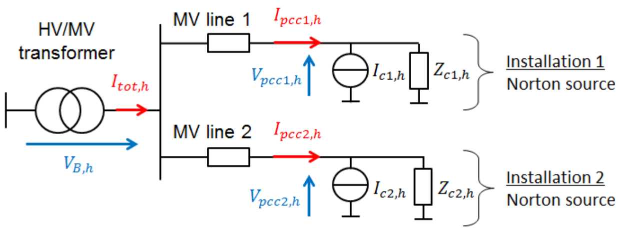

Figure 3. The simplified MV network

The network characteristics that are used in all the configurations studied in sections 4 to 6 are given in Table 1. The lengths of the MV lines and the characteristics of both installations will be given for each case in the corresponding section.

Table 1. Network characteristics.

Power transformer	
Secondary voltage ($\boldsymbol{U_n}$)	20 kV
Nominal power ($\boldsymbol{S_n}$)	20 MVA
Short-circuit voltage ($\boldsymbol{U_{sc}}$)	15%
MV lines	
MV line impedance	Z_l = 0.2+j0.35 (Ω/km)

Even if the topology in Fig. 3 is simple, the configurations used in each case are designed to emphasize the advantages and drawbacks of the studied definitions, by analyzing how they deal with the following situations:

- In case of resonance, how responsibilities are shared between the installation equipped with non-linear devices, and the installation equipped with compensation capacitor banks, creating resonance.
- In case of multiple harmonic current sources, how the definitions share the harmonic emission, considering a possible compensation between harmonic sources.
- In case of the presence of passive loads such as resistors in the installations, how the harmonic currents at the PCCs are shared into disturbing and not disturbing components.

4. Configuration A: resonance.

The characteristics of the installations and the MV lines are reported in Table 2.

Table 2. Configuration A: characteristics

Length of MV lines	
MV line 1	1 km
MV line 2	10 km
Installation 1	
Harmonic source ($I_{c1,h}$)	10 A
Impedance ($Z_{c1,h}$)	None
Installation 2	
Harmonic source ($I_{c2,h}$)	None
Impedance ($Z_{c2,h}$)	RLC parallel load : $Q_C = -1.2 Mvar$ $Q_L = 1.2\ Mvar$ $P = 2.6\ MW$

In this case, the installation 1 generates harmonic voltages due to injection of harmonic currents into the network. The installation 2, when connecting to the network, creates parallel resonance between its compensation capacitor and the network impedance. The resulting harmonic network impedance, viewed from the PCC of installation 1, is represented in Fig. 4.

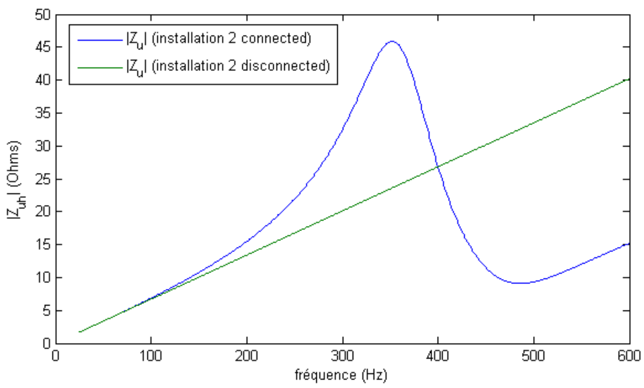

Figure 4. Harmonic network impedance view from PCC of installation 1 (case A).

As shown in Fig. 4, the installation 2 amplifies the network impedance around 350 Hz. Its value is initially 23 Ω without the installation 2. It increases to 46 Ω when the installation 2 is connected to the network. Consequently, the magnitude of harmonic voltages increases. It can be concluded that both installations have a negative impact on the power quality in this case.
With the initial proposed definition, the installations 1 and 2 have harmonic voltage emissions defined in (3) and (4). Their values are given for harmonic order 7.

$$|V_{injected,h,1}| = |I_{pcc1,h} \cdot Z_{u,h,1}| = 460\ V \tag{3}$$

$$|V_{injected,h,2}| = 0\ V \tag{4}$$

where $Z_{u,h,1}$ is the harmonic network impedance viewed from the PCC of the installation 1.

The harmonic emission of the installation 1 represents exactly the magnitude of the harmonic voltage at its PCC. However, a part of this voltage is due to the presence of the installation 2, which has increased the harmonic network impedance.
The harmonic emission of the installation 2 is zero, because the initial definition considers that only nonlinear loads (i.e. harmonic current sources) disturb the network. However, even if the installation 2 has only linear loads, its capacitor bank has a real negative impact on power quality. So, this installation should have a positive harmonic emission. With this definition, the entire harmonic responsibility is allocated to the installation 1. This problematic result was the main reason for proposing the new definition of harmonic emission in [6].
With the new definition, the installations 1 and 2 have harmonic voltage emissions given in (5) and (6).

$$|\Delta V_{pcc,h,1}| = |I_{pcc1,h} \cdot Z_{u,h,1}| = 460\ V \tag{5}$$

$$|\Delta V_{pcc,h,2}| = |I_{pcc2,h} \cdot Z_{u,h,2}| = 1128\ V \tag{6}$$

where $Z_{u,h,1}$ and $Z_{u,h,2}$ are respectively the harmonic network impedance at order h, viewed from the PCC of the installations 1 and 2.
This new definition takes into account the impact of the installation 2, because the entire harmonic current at its PCC is considered as a disturbance source (under hypothesis that the installation would increase the magnitude of harmonic voltage when it is connected to the network). However, the harmonic emission of the installation 1 does not change with this new definition: it is still penalized by the presence of the installation 2.

It can be concluded that the new definition in [6] better takes into account the possible negative effects of linear loads for installations which create the resonance, but not for installations which inject harmonic currents.

5. Configuration B: multiple harmonic current sources.

The characteristics of the installations and the MV lines are reported in Table 3.

Table 3. Configuration B: characteristics

Length of MV lines	
MV line 1	0 km (negligible)
MV line 2	0 km (negligible)
Installation 1	
Harmonic source ($I_{c1,h}$)	20 A $\angle +\theta/2$
Impedance ($Z_{c1,h}$)	None
Installation 2	
Harmonic source ($I_{c2,h}$)	20 A $\angle -\theta/2$
Impedance ($Z_{c2,h}$)	None

In this case, both installations are modelled only with their harmonic current sources (i.e. they have infinite equivalent impedance). This means that the entire harmonic current flowing at the PCC is fully dependent of the installation.
The vectors $I_{pcc1,h}$ $I_{pcc2,h}$ $I_{tot,h}$ and $V_{B,h}$ are represented in Fig. 5.

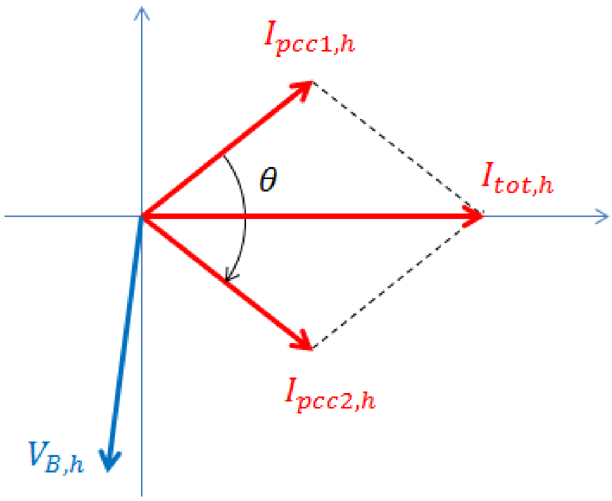

Figure 5. Harmonic currents and voltage (case B).

In Fig. 5, θ is the phase angle between the two injected harmonic currents.
With the initial proposed definition, the installations 1 and 2 have harmonic voltage emissions defined in (7) and (8).

$$\left|V_{injected,h,1}\right| = \left|I_{pcc1,h} \cdot Z_{u,h}\right| = 420\ V \tag{7}$$

$$\left|V_{injected,h,2}\right| = \left|I_{pcc2,h} \cdot Z_{u,h}\right| = 420\ V \tag{8}$$

where $Z_{u,h}$ is the harmonic network impedance at order h, viewed from PCC of installations 1 and 2.
Hence, in this case, the harmonic voltage emission is proportional to the magnitude of injected harmonic current. The network impedances do not depend of installations because they have no harmonic impedance.

With the new definition; in case that both installations increase the magnitude of harmonic voltage when they have been connecting to the network; they have harmonic voltage emissions defined in (9) and (10).

$$\left|\Delta V_{pcc,h,1}\right| = \left|I_{pcc1,h} \cdot Z_{u,h}\right| = 420\ V \tag{9}$$

$$\left|\Delta V_{pcc,h,2}\right| = \left|I_{pcc2,h} \cdot Z_{u,h}\right| = 420\ V \tag{10}$$

Thus, the two definitions give the same result if the two installations increase the harmonic voltage magnitude. Referring to Fig. 1, this magnitude variation is calculated by (11).

$$\Delta\left|V_{pcc,h}\right| = \left|V_{pcc,h}\right| - \left|V_{pcc,h} - I_{pcc,h} \cdot Z_{u,h}\right| \tag{11}$$

This evaluation method can be problematic, because it is possible to have all installations with only negative variation of harmonic voltage magnitude. For example, in the case B, if the following case is considered:

$$|\theta| > 120° \tag{12}$$

It is clear that the total harmonic current $\left|I_{tot,h}\right|$ will be inferior to the individual injected harmonic currents $\left|I_{pcc1,h}\right|$ and $\left|I_{pcc2,h}\right|$. Hence, the harmonic voltage variation will be negative for both installations, and the new definition will allocate them no harmonic contributions. However, (12) does not imply a zero harmonic voltage.
It can be concluded that the method to determine if an installation is considered as a friendly load, proposed in the new definition, is not theoretically justified, and should be revised.

6. Configuration C: multiple Norton sources.

The characteristics of the installations and the MV lines are reported in Table 4.

Table 4. Configuration C: characteristics

Length of MV lines	
MV line 1	3 km
MV line 2	3 km
Installation 1	
Harmonic source ($I_{c1,h}$)	20 A ∠ 0°
Impedance ($Z_{c1,h}$)	Resistive load (4MW)
Installation 2	
Harmonic source ($I_{c2,h}$)	100 A ∠ 0°
Impedance ($Z_{c2,h}$)	Resistive load (4MW)

In this case, both installations have harmonic impedance. This means that the harmonic current at the PCC is not necessarily due to the harmonic source in the installation. This means they are not fully responsible for the harmonic currents flowing at their PCCs. Indeed, this current has two components: one generated by the network, and one generated by the installation. Hence, the presence of harmonic currents at the PCC of an installation does not necessarily mean that this installation has a harmonic impact on the network.
In terms of Norton model (Fig. 1), the harmonic current at the PCC is defined as (13).

$$I_{pcc,h} = -I_{c,h} \cdot \frac{Z_{c,h}}{Z_{c,h} + Z_{u,h}} + I_{u,h} \cdot \frac{Z_{u,h}}{Z_{c,h} + Z_{u,h}} \tag{13}$$

This current has two components. The first one corresponds to the initial definition: it is the harmonic current injected by nonlinear loads in the installation to the network. The second one results of the interaction between the harmonic voltage at the PCC and the linear loads in the installation. If these linear loads are resistive, the harmonic current exists but it is not disturbing. If these linear loads are capacitive, they can create resonance and amplify the harmonic voltage. In this last

case, the harmonic current should be considered as a disturbance.
Hence, as the initial definition does not take into account the negative impact of some linear loads in installations, the new definition could consider some linear loads like resistances as disturbing sources, which can give paradoxical results.
After identification using tables 1 and 4, the following Norton representation of the network and installation 1, viewed from PCC1, is obtained (Fig. 6).

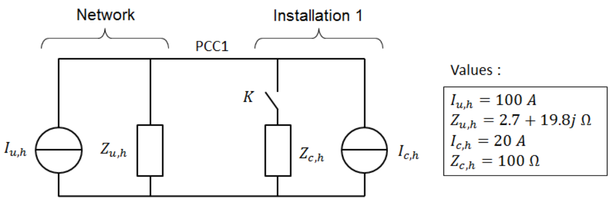

Figure 6. Norton representation of case C from PCC1.$Z_{u,h}$ impedance value is calculated at 250 Hz

In practice, the equivalent harmonic current sources and harmonic impedance of network and installation are supposed to be known or estimated. Their values are given in the chart in Fig. 6. They are obtained for the fifth harmonic order.
First, it is important to emphasize that the equivalent resistive load in the installation 1 decreases the harmonic voltage level. Indeed, both harmonic current sources inject a total current into the equivalent impedance resulting of $Z_{u,h}$ and $Z_{c,h}$ in parallel. As $Z_{u,h}$ is inductive, and $Z_{c,h}$ is resistive, it is clear that $Z_{c,h}$ will decrease the modulus of the equivalent impedance, and consequently the magnitude of harmonic voltage at the PCC. So, in this case, the resistive load in installation 1 has a positive effect to the power quality.
Now, the installation 1 harmonic emission level will be considered when it is connected to the grid in the two following cases: (i) when its resistive load is connected, (ii) and when its resistive load is not considered (disconnected), what means that the installation is a pure nonlinear load. For this analysis, installation 2 have been previously connected.
In both cases (i) and (ii), the installation increases the harmonic voltage magnitude when it is connecting to the network. This increase is lower when the resistance is connected, but remains positive. So, according to the new definition, the installation 1 harmonic emission will be positive, and calculated using (3) with network impedance unchanged between the two cases.
The values of installation 1 emission levels for (i) and (ii) are respectively given in (14) and (15).

$$\left|\Delta V_{pcc1,h}\right|_{(i)} = \left|I_{pcc,h}\right|_{(i)} \cdot \left|Z_{u,h}\right| = 502\ V \qquad (14)$$

$$\left|\Delta V_{pcc1,h}\right|_{(ii)} = \left|I_{pcc,h}\right|_{(ii)} \cdot \left|Z_{u,h}\right| = 400\ V \qquad (15)$$

With the initial definition, the harmonic contribution of installation 1 in both cases is given in (16) and (17).

$$\left|V_{injected,h,1}\right|_{(i)} = \left|I_{c,h}\right| \cdot \left|\frac{Z_{u,h}}{Z_{u,h}+Z_{c,h}}\right| = 382\ V \qquad (16)$$

$$\left|V_{injected,h,1}\right|_{(ii)} = \left|I_{c,h}\right| \cdot \left|Z_{u,h}\right| = 400\ V \qquad (17)$$

It can be noticed that with the new definition, the installation harmonic emission is higher in case (i), when the resistive load is connected. This result is surprising because it was shown above that the resistive load has a positive effect on power quality.
This problem occurs because the connection of the resistance has added a new component to the harmonic current at the PCC, which has increased its magnitude. Although this second component is not disturbing, it has increased the installation harmonic emission by increasing the harmonic current at its PCC.

The problem can also be illustrated by analyzing harmonic voltage phasors in Fig. 7.

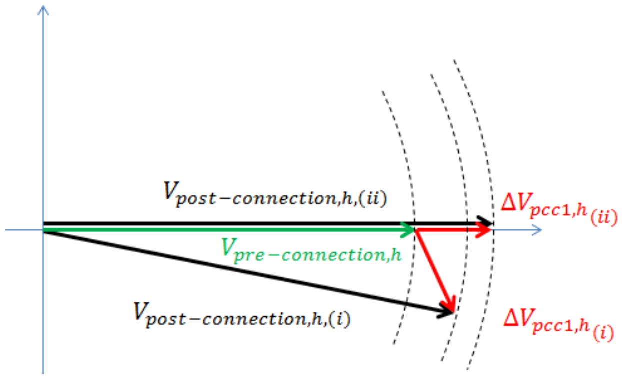

Figure 7. Harmonic voltage vectors when the installation 1 is connecting to the network.

$V_{pre-connection,h}$ is the harmonic voltage at PCC1 produced by installation 2 before connection of the installation 1. $\Delta V_{pcc1,h}{}_{(i)}$ and $\Delta V_{pcc1,h}{}_{(ii)}$ are the harmonic voltage variations in both cases (i) and (ii).
Although the modulus of $\Delta V_{pcc1,h}$ is higher in case (i) when the resistance is connected, it results a lower harmonic voltage than in case (ii). This shows the positive effect of the resistive load to the power quality. However, the new definition uses the modulus of $\Delta V_{pcc1,h}$ as the installation harmonic emission, giving a higher contribution in case (i).
Theoretically, this problem happens when the conditions (18) and (19) are true.

$$X_{u,h} < \sqrt{3} \cdot R_{c,h} \qquad (18)$$

$$I_{u,h} > I_{c,h} \qquad (19)$$

where $X_{u,h}$ is the reactive component of the network impedance, and $R_{c,h}$ the resistive load in the installation.
In this case, the presence of the resistive load results in an increase of the installation harmonic emission calculated from the definition.
This result could be a bit confusing when the DSO tries to assess the impact of an installation, because the harmonic emission given by the new definition is not necessarily representative of the real impact of the installation.

To avoid this problem, the definition of an installation harmonic emission should be revised, with a new method to identify the real disturbing part of the harmonic current at the PCC.

7. Conclusions & Perspectives

This paper deals with the relevance of two definitions for assessing the harmonic emission of an installation. Their efficiencies are discussed through several configurations of a simplified MV network. These cases are designed in order to allow highlighting the advantages and drawbacks of both definitions with respect to some specific configurations of loads.

In the first case, it is shown that the Norton based method [2]-[3], which is the first proposed definition for assessing the installation harmonic emission, is not able to take into account the possible negative effect of compensation capacitor banks on the power quality. The standard [6] partially solves this problem by taking into account the impact of even a linear load.

In the two other cases, the following drawbacks of this new definition are pointed out:

- When there are several harmonic sources connected to the network, the criterion for determining if an installation is considered as a friendly load is not always effective.
- The presence of friendly loads such as resistors in an installation can be seen as an increase of its harmonic contribution whereas the harmonic voltage levels have been decreased.

As these drawbacks can be problematic when we try to assess the contribution of an installation to the global harmonic levels on distribution networks, a proposition of a new definition is needed, in order to assess the real impact of an installation.

Harmonic propagation in an electric power network is a very complex issue due to the coupling between loads (linear and nonlinear ones). Moreover, the harmonic contribution of a load can be reduced or reinforced by the connection of other loads. Then in our goal to propose a criteria (or definition) to estimate the harmonic contribution, it seems not realistic to find THE definition, but more realistic to find the less bad definition.

Up to now, analysis of harmonic contribution definitions is often based on quite simple grid topology. But it is not enough to test their robustness. On-site data are required, and simulations have to be done with test-grids such as the CIGRE network. A statistical or probabilistic approach will probably have to be chosen to analyze the definitions performance.

References

[1] EN 50160 – “Voltage characteristics of electricity supplied by public distribution networks”, English version 2011.

[2] W. Xu, “A method for determining customer and utility harmonic contributions at the point of common coupling”, IEEE Trans. on Power Delivery, vol. 15, no. 2, pp. 804-811, 2000.

[3] Blazic, B. “A modified harmonic current vector method for harmonic contribution determination”, in Power Systems Conference and Exposition, IEEE PES, vol. 3, pp. 1470-1475, Oct. 2004.

[4] Azouaou, “Study of the direction of the harmonic injections in the electrical power systems”, IEEE Universities Power Engineering Conference, 2004.

[5] Grady, “Introduction of the concept of friendliness power to characterize the harmonic emission of non-linear loads”, IEEE Trans. on Electric Ship Technologies Symposium, 2005.

[6] IEC/TR 61000-3-6: Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems. Geneva, 2008.

[7] Gonbeau, O., “Method to determine contribution of the customer and the power system to the harmonic disturbance,” 17th International Conference on Electricity Distribution, May 2003.