Comparative Analysis of the Contribution of Harmonic Injection by PV Systems in Microgrids

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Abstract: This work has as main objective to identify and to evaluate the contribution of harmonic injection and power distortion of two residential Consumers (C1 and C2). It was considered that Consumers are inserted in a microgrid represented by a system based on a modified 13-bar IEEE model. Currently, the injection of a Consumer's harmonics cannot be accurately measured, leading to penalizing other Consumers. Therefore, this issue is extremely important, since more non-linear loads and sources are inserted in the system. The amount of harmonics injected into the system and the Consumer's distortion power are calculated individually according to the IEEE 1459-2010 standard. The harmonic distortion index proposed by Anu and Fernandez (2020) is extrapolated and used to determine the contribution of harmonic injection by PV generation systems. Simulations using MATLAB/Simulink$^{\text{TM}}$ validated the methodology adopted, regarding the determination of the responsibility of each Consumer over the harmonics injected into the network.

Keywords: Harmonics; PV System; Power Quality; Harmonic Distortion Index; Microgrid.

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1. INTRODUCTION

With the growth of the insertion of distributed energy resources (DERs), in the electric grid, in the last years, the study and analysis of the electrical power quality (EPQ) has become one of the main objectives of researchers of the area. One of the parameters analyzed when dealing with EPQ is total harmonic distortion (THD) and its respective individual harmonic components (Nömm et al. (2018)). The latter are caused by the presence of non-linear loads and sources in the distribution system (DS).

The increasing use of power electronics devices to drive industrial, commercial and residential loads has significantly increased harmonics in the electrical grid. Grid harmonics have destructive impacts on the grid components, including distribution transformers. The projected increase in the use of solid-state devices for the control of power devices and systems has exceeded expectations and accentuated the harmonic problems inside and outside the power system.

Harmonic currents increase the RMS current in electrical systems and deteriorate the quality of the supply voltage. In addition, they overload the electrical network and can damage the equipment, and can also interrupt the operation of the devices and increase operating costs. Symptoms that harmonic levels are high include overheating of transformers, motors and cables, thermal triggering of protective devices and logic failures of digital devices. In addition, the service life of many devices is reduced by high operating temperatures. Capacitors are especially sensitive to harmonic components of the supply voltage due to the fact that the capacitive reactance decreases as the frequency increases. In practice, this means that a relatively small percentage of harmonic voltage can cause significant current to flow through the capacitor circuit.

The effects of the harmonic components are more problematic in microgrid (MG) or, in general, in distribution systems. This is due to the number of non-linear loads that are generally high in the distribution systems. A MG is a type of distribution system consisting of local loads and DERs and that can also operate in isolated mode.

We have found several methods of harmonic detection in the literature that are referred to in terms of extraction accuracy, speed, effect of the filter on stability, etc. There are different classifications for harmonic extraction methods. A very common way is to classify them as methods in the frequency domain and in the time domain. According to Kuyumcu and Karabacak (2020), frequency domain methods consist of a discrete Fourier transform (DFT), fast Fourier transform (FFT) and discrete recursive Fourier transform (RDFT). In addition, methods in the time domain consist of methods based on synchronous references (Rodriguez et al. (2007)), methods based on the theory of instantaneous power (p-q) and methods based on the generalized integrator (Rodríguez et al. (2006)).

The methods for detecting harmonic sources can be classified into single-point and distributed measurement methods (Cataliotti et al. (2008)). Distributed measurement methods provide accurate information about the harmonic state of the power system, but are difficult to implement, as they require complex and expensive measuring instrumentation. Single point measurement techniques are best suited to estimate the harmonic contribution at the

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customer's site due to easy implementation and low cost (Anu and Fernandez (2020)).

Anu and Fernandez (2020), proposed a new harmonic distortion index (i_{HN}) to identify the harmonic contribution of non-linear loads. The detection method used was a single point, and the i_{HN} was used to determine the contribution of harmonic injection into the DS of each consumer under analysis in relation to other consumers.

In this work, the methodology presented by Emanuel (2012) for the calculation of powers, under non-sinusoidal voltage and current conditions, and the harmonic distortion index (i_{HN}) proposed by Anu and Fernandez (2020) are extrapolated and used to determine the contribution of harmonic injection by PV generation systems and the effects on other consumers located in the same microgrid.

2. HARMONICS - THEORETICAL BACKGROUND

Harmonics are continuous phenomena and should not be confused with short-time phenomena, such as sinking, rising or interrupting voltage lasting less than or equal to three seconds, which only last a few cycles.

We can consider the EPQ from a dual analysis where the quality of the supply voltage has an influence on current profile circulating in the installation and voltage profile can be impacted by the nature of the load (current). The degree of harmonic tolerance in a power system is closely related to the susceptibility of the load or the power supply. For those devices where the shape of wave is irrelevant, for example resistive loads for heating, the sensitivity is lower. The most sensitive are those that, in their design, assume the existence of a sinusoidal supply, such as communication and data processing equipment. However, even for low susceptibility loads, the presence of harmonics (voltage or current) can be harmful, producing greater stress on components and insulators.

The direct effect of non-linear systems on the EPQ is the distortion in the current, and the indirect, the distortion in the voltage. The distortion in the voltage is propagated, as well as the harmonic currents that will circulate through linear loads fed by such voltages. Some of the problems that harmonics can cause include overheating and equipment failure, false load firing, incorrect operation of protection relays and interference in the communication circuit.

2.1 Total Harmonic Distortion

The THD is the deformation of the voltage and current waveforms that result in deviations from the pure sine waveform (Ajeigbe et al. (2018)). According to Santoso et al. (2012), harmonic distortion is caused by non-linear devices (loads or sources) in the power system and, considered by many experts in the field, it is still the most significant problem of EPQ.

Traditional parameters of the power system, such as: powers (reactive, active and apparent), power factor and phase sequences are defined for the fundamental frequency context in a pure sinusoidal condition. In the presence of harmonic distortion, the power system no longer operates in a sinusoidal condition and, as a result, many of the simplifications that power engineers use for fundamental frequency analysis no longer apply.

To measure the THD of a circuit, we need to check the amplitude of each harmonic generated in relation to the fundamental of the input signal. This calculation is an average of the voltage levels in relation to the input (see Equation 1), where X represents a generic variable, which can indicate voltage or current and h represents the order of the harmonic component.

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} X_h^2}}{X_1} \tag{1}$$

2.2 Harmonic Detection Methods

Some harmonic detection methods have been proposed in several studies, such as: Anu and Fernandez (2020), Wilsun Xu et al. (2004), Aiello et al. (2005) e Cristaldi et al. (2002). According to Chang-Song Li et al. (2016), these methods can be classified according to the number of measurement points of the electrical quantities in: multi-point and single point. The first, which is based on distributed measurement and synchronous data collection, can result in complete and accurate information about harmonics, however, in practice, its implementation is difficult because of the high costs of installation and operation. The single point methods are simple and convenient for application in engineering, but generating less accurate results.

2.3 Harmonic Distortion Index

The IEEE 1459-2010 standard (Emanuel et al. (2012)) deals with standard definitions for measuring parameters of the electrical system under sinusoidal, non-sinusoidal, balanced and unbalanced conditions. Mathematical expressions that have been used in the past, as well as new expressions, are listed in this standard as well as explanations of the characteristics of new definitions are presented. The apparent power for non-sinusoidal conditions can be defined as:

$$S^2 = S_1^2 + D_I^2 + D_V^2 + S_H^2 \tag{2}$$

Partitioning Equation 2, we initially present the expression for the calculation of the fundamental apparent power (S_1^2), obtained from the following relation:

$$S_1^2 = P_1^2 + Q_1^2 \tag{3}$$

where, (P_1) is fundamental active power ($= V_1 I_1 cos\Theta$); and, (Q_1) is the fundamental reactive power ($= V_1 I_1 sen\Theta$).

Also from Equation 2, we will have, respectively, current distortion power (D_I), voltage distortion power (D_V), apparent harmonic power (S_H), harmonic distortion power (D_H), and, the total power distortion (TPD) expressed by:

$$D_I = V_1 + I_H \tag{4}$$

$$D_V = I_1 + V_H \tag{5}$$

$$S_H = V_H I_H = \sqrt{P_H^2 + D_H^2} \tag{6}$$

$$D_H = \sqrt{S_H^2 - P_H^2} \tag{7}$$

$$TPD = \sqrt{D_I^2 + D_V^2 + D_H^2} \tag{8}$$

We can assign the responsibility for harmonic injection to the utility or the customer by comparing the voltage and current waveform at the customer's coupling point (Fernandez and Chandramohanan Nair (2013)). The physical nature of the distortion powers has its bases in the process of generating current harmonics and not must be confused with reactive power, but monitored separately (Emanuel (2012)). According to Anu and Fernandez (2020), harmonic injection at the Consumer's location can be quantified by a term known as harmonic distortion index (i_{HN}) which consists of the relationship between the total contribution of harmonic current (i_h) at the Consumer connection point and the fundamental current (I_1) of the consumer.

$$i_{HN} = \frac{i_h}{I_1} \tag{9}$$

3. DESCRIPTION OF THE SYSTEM IN ANALYSIS

In order to carry out the simulation, obtain the data and make the necessary analyzes, a modified IEEE system with 13 bars was used, since this system adequately represents a microgrid (see Figure 1). The system consists of a substation, linear and non-linear loads, consumers, impedances and a PV source.

The substation, located in bar 1, has a RMS phase-to-phase voltage of 69kV with a frequency of 60Hz. Transformer 1 - 69kV/13.8kV (Δ/Y connection). Transformers 2 - 5 are 13.8kV/380V (Y/Y connection). Bars 2, 3, 4, 6, 7, 9, 10, 12 and 13 are powered by a voltage of 13.8kV. Bars 5, 8 and 11 are powered by 380V. As can be seen in Figure 1, Consumers C1 and C2 are located at bar 13, after a transformer (T5), powered by a voltage of 380kV. In both Consumers, there are linear loads connected with active power of 25kW and reactive power of 2kVAr. The PV array has 100 kW and is connected to the DS via a DC-DC boost converter and a three-phase three-level voltage source converter.

4. SIMULATIONS RESULTS

Three scenarios were simulated in order to determine the i_{HN} and to assess the influence that each Consumer (C_X) has in relation to the injection of harmonics into the network. For this, MATLAB/Simulink^{TM} was used for simulation purposes. The evaluated scenarios were as follows: Scenario - #1: C1 and C2 operating only with linear loads; #2: C1 with PV source and C2 with linear loads; #3: C1 and C2 with PV sources. Simulations were carried out to obtain data to analyze the behavior, in terms of harmonics insertion, of the PV generation systems connected to the DS. The results obtained are shown in Table 1.

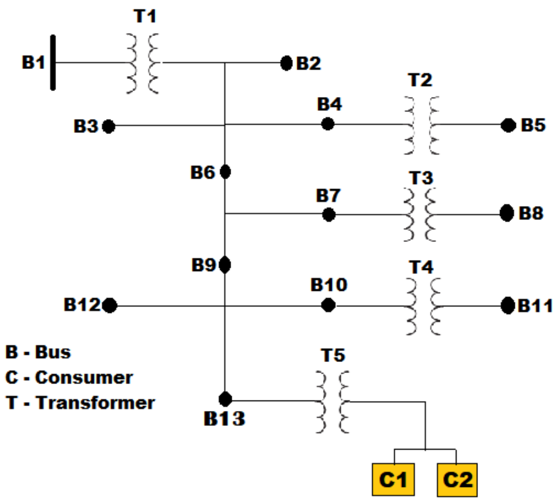

Figure 1. Single-line representative diagram of the microgrid.

Scenario #1: THD_V and THD_i are zero and of the i_{HN} is close to zero, indicating that Consumers contribute little to the harmonic insertion in the DS. The voltage and current waveforms, for both Consumers, behave very close to an ideal sine wave, therefore, as expected, as there are no non-linear loads or sources in this evaluated scenario.

Scenario #2: THD_V and THD_i and i_{HN} for C1 were significantly increased, indicating that this Consumer contributes to the injection of harmonics into the DS. In the case of C2, the i_{HN} remained relatively low, indicating that this Consumer, as in scenario #1, has no responsibility for the harmonics present in the system (see Figures 2, 3, 4 and 5).

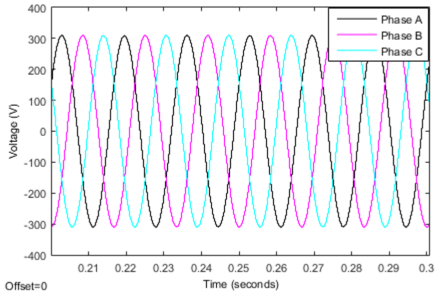

Figure 2. Voltage waveform of Consumer 1 at Scenario #2

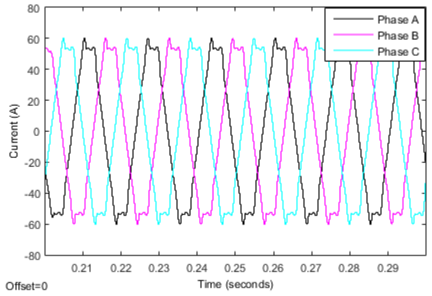

Figure 3. Current waveform of Consumer 1 at Scenario #2

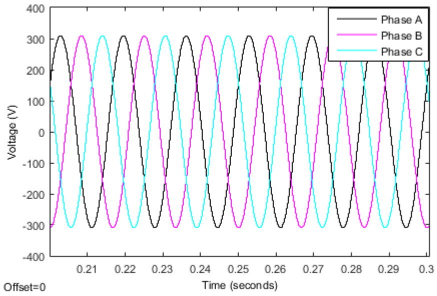

Figure 4. Voltage waveform of Consumer 2 at Scenario #2

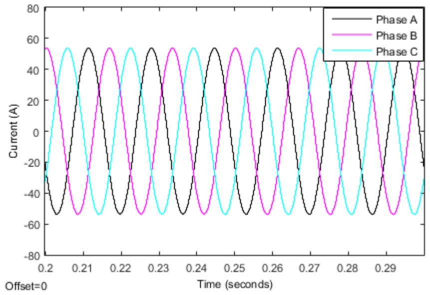

Figure 5. Current waveform of Consumer 2 at Scenario #2

Scenario #3: THD_V and THD_i and the i_{HN} for C1 remained high, while for C2, the parameters that were previously lows were added significantly as well. With that, it can be verified that both consumers are responsible for the harmonic pollution contained in the electric network. The Consumer voltage and current are shown in Figures 6, 7, 8 and 9.

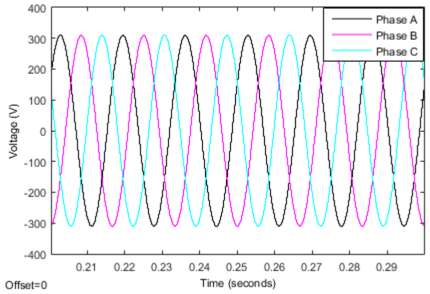

Figure 6. Voltage waveform of Consumer 1 at Scenario #3

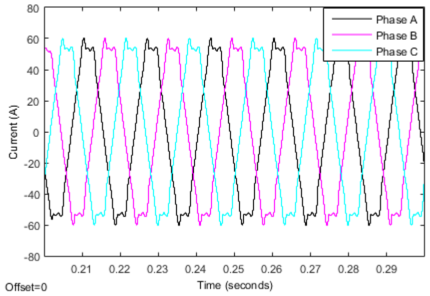

Figure 7. Current waveform of Consumer 1 at Scenario #3

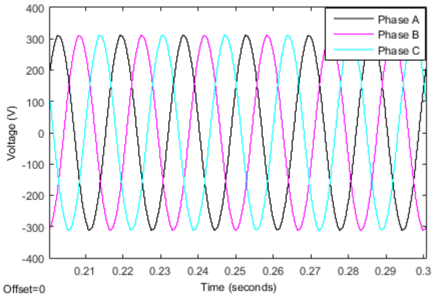

Figure 8. Voltage waveform of Consumer 2 at Scenario #3

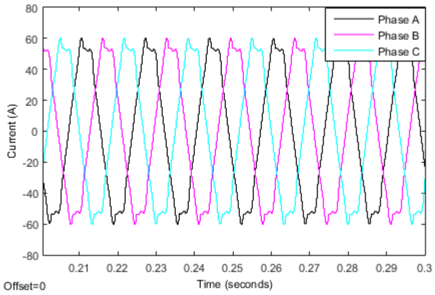

Figure 9. Current waveform of Consumer 2 at Scenario #3

Table 1. Parameter values obtained

	Consumer #1			Consumer #2		
	Scenarios					
	#1	#2	#3	#1	#2	#3
THD_V	$2.50\text{x}10^{-4}$	$1.09\text{x}10^{-2}$	$2.00\text{x}10^{-1}$	$3.74\text{x}10^{-4}$	$1.05\text{x}10^{-2}$	$2.03\text{x}10^{-2}$
THD_I	$4.30\text{x}10^{-4}$	$4.37\text{x}10^{-1}$	$4.42\text{x}10^{-1}$	$4.30\text{x}10^{-4}$	$8.05\text{x}10^{-3}$	$4.58\text{x}10^{-1}$
i_{HN}	$1.00\text{x}10^{-2}$	$2.30\text{x}10^{-1}$	$2.50\text{x}10^{-1}$	$1.00\text{x}10^{-2}$	$2.00\text{x}10^{-2}$	$2.60\text{x}10^{-1}$
D_I	$0.00\text{x}10^{0}$	$6.21\text{x}10^{2}$	$6.56\text{x}10^{2}$	$0.00\text{x}10^{0}$	$3.20\text{x}10^{1}$	$6.68\text{x}10^{2}$
D_V	$0.00\text{x}10^{0}$	$3.10\text{x}10^{2}$	$3.24\text{x}10^{2}$	$0.00\text{x}10^{0}$	$2.10\text{x}10^{2}$	$3.35\text{x}10^{2}$
D_H	$0.00\text{x}10^{0}$	$5.20\text{x}10^{1}$	$7.00\text{x}10^{1}$	$0.00\text{x}10^{0}$	$5.00\text{x}10^{0}$	$7.10\text{x}10^{1}$
TPD	$0.00\text{x}10^{0}$	$6.96\text{x}10^{2}$	$7.35\text{x}10^{2}$	$0.00\text{x}10^{0}$	$2.12\text{x}10^{2}$	$7.51\text{x}10^{2}$

5. PRELIMINARY CONCLUSION AND FUTURE WORK

In this paper, the Harmonic Distortion Index is used to evaluate the harmonic injection by Consumers with photovoltaic sources in their system. It was verified that, with the insertion of photovoltaic sources in the distribution system by Consumer 1 or Consumer 2, the Harmonic Distortion Index and the total power distortions were significantly increased when compared to scenarios that do not have non-linear loads or sources in the system. This index can also be used as a reference when assigning responsibility for harmonic pollution in the power grid. Future studies can be done comparing this index presented with other methods of identification and analysis of harmonic distortion in a microgrid, in order to identify the advantages and disadvantages that each method has and its reliability.

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