Importance of Studying the quality of energy from distributed generation using renewable energy sources

Thaís Pina Pinto
Universidade Federal do Espírito Santo – Brasil
thaispinapinto@gmail.com

Domingos Sávio Lyrio Simonetti
Universidade Federal do Espírito Santo – Brasil
d.simonetti@ele.ufes.br

ABSTRACT

The growing global concern with the energy generation from renewable sources has resulted in a rapid growth of the distributed generation, mainly using wind or photovoltaic power, which are considerable intermittent energy sources. However, the distribution systems were designed for a unidirectional power flow, from substations to load, and now they have to adapt to this new topology. So, it is of great importance the need for research focused on power quality from distributed renewable energy sources. This article aims to make a comparative analysis of the approaches employed in previous studies, focused on the harmonics penetration from these distributed generators, as a way to quantify the power quality of them. The importance of studying the quality of the energy is verified so that this new generation trend in the electric grid can be properly inserted.

Keywords: *Power Quality; Renewable Sources; Distributed Generation.*

1. INTRODUCTION

The technological development in residential, commercial and industrial environments has become increasingly dependent on electricity. The increase of the consumption in the last few years has demanded a greater use of nonrenewable natural resources, which results in degradations in high scale. It has become necessary to study the use of new ways of generating energy with a greater use of renewable resources. The traditional model of large generators, where the energy is generated and then is transmitted and distributed, is giving place to the process of connection of small units of energy generation, which is called Distributed Generation (DG) (Camargo et al., 2016).

Many renewable energy sources can be used for the purpose of generating electricity, so that there is less degradation to the environment and depletion of non-renewable resources. According to the International Energy Agency (IEA), renewable energy resources are defined as resources that are generally not subject to depletion, such as heat and sunlight, wind power, organic matter (biomass), water fall tidal and geothermal energy.

Technological advances and cost reductions have made renewable energies widely competitive with conventional energy sources, with DG from alternative sources being highlighted. The use of photovoltaic DG connected to the electrical grid is growing up all over the world. Brazil, with a great potential for irradiation, is following this trend, with photovoltaic energy presenting the largest number of connections and generated power, mainly of residences, followed by wind generation, which despite

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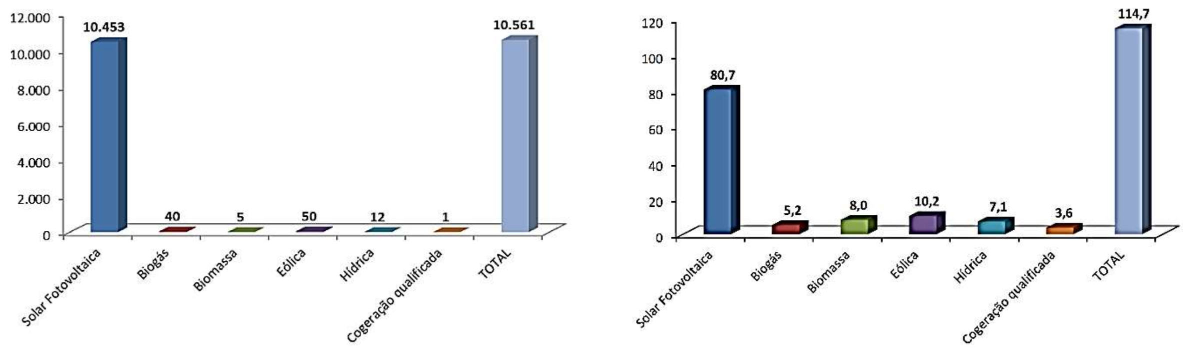
having a smaller number of connections has been having high rates of growth. In the National Energy Report (BEN) of 2017 with base year on 2016 (BEN, 2017), the distributed generation reached 104.1 GWh with an installed capacity of 72.4 MW, especially the solar photovoltaic source, with 53.6 GWh of power generated and 56.9 MW of installed power. In the 2018 BEN with base year on 2017 (BEN, 2018) the distributed generation had a significant increase reaching a generation of 359.1 GWh with an installed power of 246.1 MW, being 53.6 GWh, and 174.5 MW of power generation and installed respectively of photovoltaic generation.

According to the Brazilian Electricity Regulatory Agency (ANEEL) Technical Note 0056/2017, Brazil had a total of 10,561 distributed micro and mini-generation units connected to the grid up to 23/05/2017, of which 10,453 were from photovoltaic power generation installed capacity of 80.7 MW, followed by the wind power source with 50 units and 10.2 MW, as can be observed in **Figure 1**.

Figure 1. Brazil until 2017: a) Micro and mini-generation connections; b) Respective total installed power.



Source: ANEEL.

A subject of increasing importance is the association of built-environment and sustainability. And sustainability encompass, among other aspects, self-generation of electricity. To the electrical system, it is considered a DG source. This integration of DG in the networks results in technical concerns that must be analyzed to ensure that the network can get the quality and safety of the DG.

Thus, this work presents a review regarding the methodologies used in the analysis of the harmonic components' penetration caused by the Distributed Generation as a way of analyzing the quality of the energy coming from them.

2. REGULATION

Studies in the literature (Ackermann, 2001; ANEEL, 2016; Severino, 2008) show that there is no consensus in the definition of distributed generation, without a general definition for the term. According to ANEEL's definition, distributed generation is characterized by the installation of small generators, usually from renewable sources or even using fossil fuels, located near the centers of electric energy consumption.

The insertion of alternative sources of energy began to gain notoriety in Brazil from the years 2011 and 2012. A major contribution was made by the strategic project 013/2011 of ANEEL, entitled "Technical and Commercial Arrangements for the Insertion of Solar Photovoltaic (PV) Generation in the Brazilian Energy Matrix ", that regulated TUSD and TUST discounts, and the Normative Resolution 482/2012, that " Establishes the general conditions for the access of microgeneration and distributed

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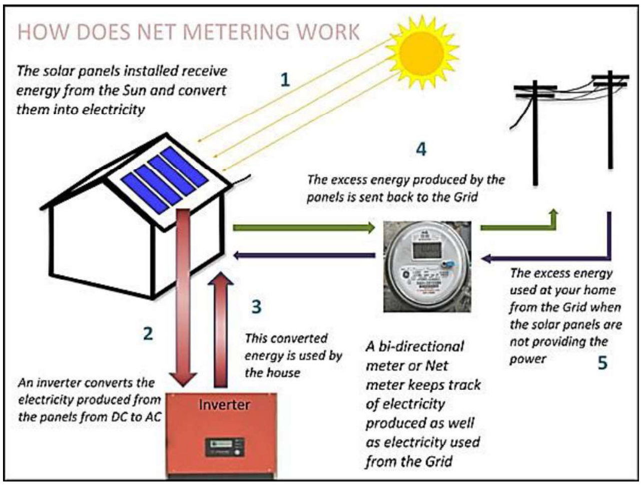
minigeneration to the electric energy distribution systems, the electric energy compensation system, and gives other measures". Nevertheless, the most significant increase came from November 2015 when ANEEL approved improvements in RN 482/2012: with Normative Resolution nº 687/2015, distributed micro-generation was defined as a power generating plant with power equal or less than 75 kW, and mini-generation as a unit with installed power above 75 kW and less than or equal to 5MW, using qualified cogeneration, according to ANEEL regulations, or renewable sources of electric energy, connected to grid facilities through consumer units (ANEEL, 2012; ANEEL, 2015).

If the energy produced is greater than the energy consumed, it generates credit to the consumer unit, also known by the term net metering, defined by the amendment III of article 2 of REN 482/12, according to Normative Resolution nº 517/12 (Bezerra and Araújo 2015; ANEEL, 2012). The **Figure 2** shows how net metering works.

Figure 2. How net metering works



Source: http://nowgosolar.com/nem-2/

Among the improvements, the compensation system that previously could only be done in the same consumer unit that supplied the surplus or another of the same ownership can now also be compensated by means of multi-consumer units, shared generation and remote self-consumption. The period for compensation of the energy ceded to the grid that was previously 36 months became 60 months with the RN 687 (ANEEL, 2012; Melo at. al, 2014; ANEEL, 2012; ANEEL, 2011).

The module 3 of the Procedures for Distribution of Electric Energy in the National Electric System (PRODIST) establishes the conditions for access to the Distribution System, as well as the connection procedures of the electric power concessionaires of each region.

3. POWER QUALITY

Basic characteristics must be satisfied for a power system to be considered adequate to the supply of electricity. In summary, the quality in the supply must meet two main characteristics: continuity of supply and waveform of the supply voltage. Currently a third acquires priority identical to previous ones: the relation with the client. Quality analysis is based on specific regulations by both national and international standards. Electrical equipment applied in the Industrial, Commercial and Residential sectors, are usually fed in alternating current, and it is increasingly sensitive to the poor quality of

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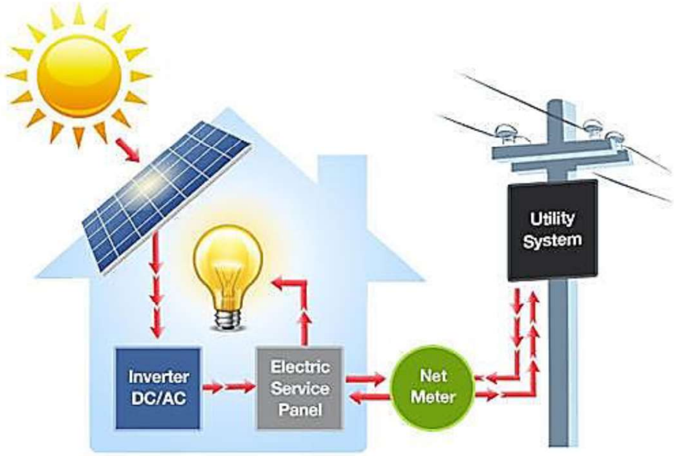
electrical energy, presenting malfunction (Monteiro, 2016) ou (MONTEIRO, 2016).

On the other hand, it is increasingly present in the electrical system, in the three sectors, loads that make use of electronic topologies for its operation. In general, they present rectifier circuits that present non-linear behavior to the grid. The current that is absorbed from the grid is highly distorted, and its analysis requires the decomposition into harmonic components. These fundamental multi-frequency current components cause harmonic voltage drop in the grid and help to distort the voltage at the connection point (Simonetti, 2008).

4. DISTRIBUTED GENERATION

The distributed generation systems connected to the grid with photovoltaic and wind power sources are typically composed of two parts: the one responsible for the production of energy (photovoltaic modules and wind turbines), and the interface between these systems with the grid. The last one is performed by inverters, that by using power electronics can inject harmonic components into the system. The **Figure 3** exemplifies a PV source connected to the grid.

Figure 3. PV source connected to the grid.



Source: https://www.indiamart.com/proddetail/solar-net-metering-projects-15824293630.html

The inverters used in the interface between the distributed generation and the electrical grid generally use Pulse Width Modulation (PWM) control technique to generate the output voltage. The PWM voltage is filtered in order to minimize the switching harmonics. As a result, the generated voltage is practically sinusoidal and approximates the frequency of the grid, but usually presents some harmonic content of low frequency, as for example values of 0.5% of third harmonic and 2% of fifth harmonic (Melo, 2015). All inverters must satisfy international standards regarding the harmonic injection penetration limit in the electrical grid (Oliveira, 2015; Shayani, 2011).

5. HARMONIC DISTORTION

To the electrical system, the harmonic distortions are phenomena associated with deformations in the waveforms of the voltages and currents in relation to the fundamental waveform (PRODIST, 2018). The current flowing through the grid with high harmonic content has the consequence of deterioration of the quality of the supply voltage besides the increase of the losses in the system. To illustrate a voltage

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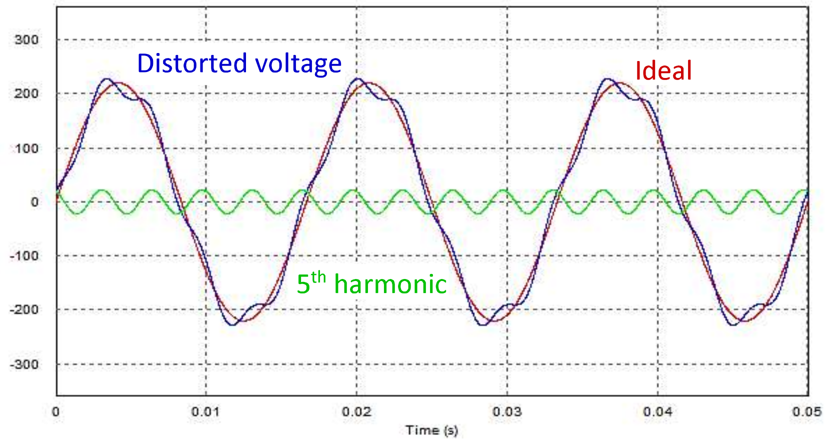
distortion caused by harmonics, **Figure 4** shows the ideal voltage waveform (red line) and the resulted distorted voltage (blue line) if a 10% of 5th harmonic (green line) occurs.

Figure 4. Illustration of a distorted voltage.



Source: Author's own production

The influence of the presence of harmonic components is measured by the indicators Total Harmonic Distortion rate (THD) and the individual harmonic distortion rate, either for current or for voltage at the common coupling point (Oliveira, 2015). Therefore, an ideal harmonic-free voltage and current wave has THD = 0% (pure sinusoidal). Harmonic distortions can be associated with losses as well as with malfunction of some equipment, so it is convenient that the harmonic influence of the distributed generation be minimum. The main Power Quality parameters analyzed in a steady-state or transient condition are (PRODIST, 2018):

1. Steady-state condition: Steady-state voltage; Power factor; Harmonics; Voltage unbalance; Voltage fluctuation; Frequency variation.

2. Transient condition: Short-term voltage variation.

The limits of harmonic distortion are governed by national and international standards. As national Standards it is used the Module 8 of PRODIST - Quality of Electric Energy, and power distribution companies regulations. The main international standards are IEEE Std 519-1992 (Recommended Practices and Requirements for Harmonic Control Electric Power Systems),IEC 61000-3-2 (Harmonic limits for equipment with input currents < 16A per phase), IEC61000-3-4 (Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A per phase), IEC 61000-3-6 (Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems), and IEC61000-3-12 (Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤ 75 A per phase).

The methods of obtaining the harmonics are classified according to the mathematical algorithm involved, basically based on frequency-domain (Fundamental d-q Synchronous Reference Frame, Synchronous Individual Harmonic, Instantaneous power "pq theory" and variants, Generalized integrators and variants) or time-domain analysis (DFT – Discrete Fourier Transform, FFT – Fast Fourier Transform, R-DFT – Recursive Discrete Fourier Transform) (Rocha, 2017).

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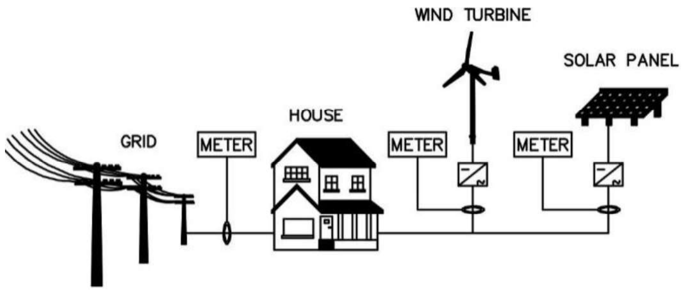
6. POWER QUALITY ANALYSIS METHODS FROM DG

As DG has incremented its presence in built-environments, it is worthy to know which tools are being used to evaluate its influence in the power quality. A comparative analysis of relevant publications approach in the study of harmonic penetration in the period between 2010 to 2018, being most of 2015 onwards, is presented here.

From the sources of generations in question, the photovoltaic generation (Melo at al., 2015; Oliveira, 2015; Rocha, Salvadori and Gehrke, 2017; Bittencourt and Bassaco, 2013; Leite et al., 2018; Fortes et al., 2015; Macêdo and Zilles, 2005; Fortes et al., 2016; Cristes et al., 2012; Souza et al., 2016; Anaurangi, Rodrigo and Jayatunga, 2017) is highlighted due to its higher growth rate as well as the number of connections as mentioned, followed by wind generation (Fortes, 2016; Chen et al., 2017; Reis, Santos and Diniz, 2016). All the DGs are connected to the grid, most of which are three-phase systems connected to the low voltage distribution grids (Melos et al., 2015; Oliveira, 2015; Rocha, Salvadori and Gehrke, 2017; Bittencourt and Bassaco, 2013; Leite et al., 2018; Macêdo and Zilles, 2015; Souza et al., 2016).

Among the methods surveyed, measurements have been made from the connection of power quality analyzers in generation systems in buildings (Melo at al., 2015; Oliveira, 2015; Bittencourt and Bassaco, 2013; Leite et al., 2018; Fortes et al., 2015; Macêdo and Zilles, 2005). These meters were mainly connected at the output of the inverters, due to the possibility of a wide analysis of the power delivered by them, and at the point of connection of the system with the grid, to analyze the bidirectionality of the power flow, thus investigating phenomena of current distortion and voltage. A generic configuration of a DG system with the mentioned methodology is presented in **Figure 5**.

Figure 5. Generic configuration of a DG system with wind and PV generation.



Source: Author's own production.

Comparing the results presented in the publications, the harmonic distortion rates already presented in the PCC (Point of Common Connection) did not show significant changes, with an improvement in the energy quality with a slight decrease in the harmonic distortion rate of the current and the voltage was presented in some cases. These favorable results were observed when the inverter was operating close to the full load, but when the inverter operates with low current demand, with powers lower than 20%, according to present studies, there is an increase of the harmonic distortions (mainly of current), exceeding the values set by both the inverter manufacturer and standards (remembering that the voltage supplied by the grid at the point of delivery has an inherent harmonic content of the grid itself). As these high distortion values occur for powers lower than the nominal power of the inverters, their effects are not relevant. This increase in distortion occurs because the production of harmonic current by the inverter is strongly dependent on the electrical energy supplied by the generator. Total harmonic

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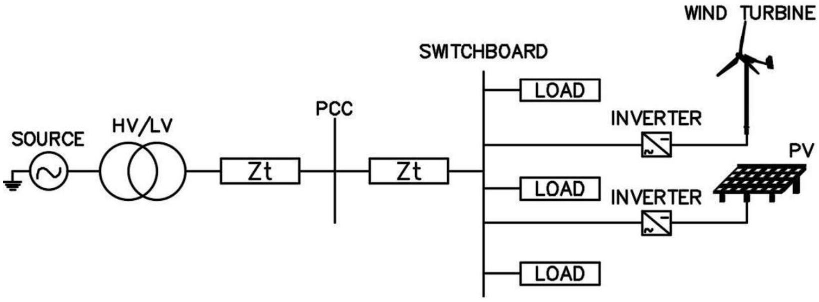
distortion of the current can reach higher values at night or periods of the day where irradiation is temporarily affected by clouds or other physical obstacles. This condition is mainly due to the strategy of controlling the inverters searching for maximum power generation (Fortes et al., 2016).

There is also the case where the measurements were carried out in a feeder that had two connected photovoltaic generations. The measurements taken in each generation show that when the generation is operating closer to the nominal capacity, during the day, the harmonic injection is very low. Considering the measurements made at the feeder, it can be concluded that there was a slight increment of 0.1% in the voltage THD when the whole generation is connected in relation to when it is switched off. The value being small won't have much influence in the limits established by regulation because the DG constitutes a very small portion of the system. It is noted that if there is an increase in the connectivity of the DG, it can result in an increase in the THD (Cristes et al., 2012).

Another way of evaluating harmonic penetration is through computational simulations (Rocha, Salvadori and Gehrke, 2017; Souza et al., 2016; Chen et al., 2017). The system under study is modeled by an equivalent electric circuit as shown in **Figure 6**. "Load" represents the consumer apparatuses, HV/LV is an interface transformer (if needed), and Zt the electrical impedance of cables.

Figure 6. Equivalent circuit of a DG system for simulation analysis.



Source: Author's own production

The circuit is introduced in some circuit simulation program, such as Simulink®, PSIM, ATP or PSCAD, for the studies. As an example (Souza, 2016) presents a study of the impacts on power quality from the distributed generation insertion made through Simulink® software, in which three single-phase generators were introduced progressively, one in each phase, at a low voltage mains. As a result, there is a small increase on the total distortion of all phase currents in the PCC as one generation in the system was inserted. The total voltage distortion, measured on other points in the feeder, had its values slightly altered, but not progressively, where in most cases there was an increase as a generation was inserted in the grid. None of them exceeded the limits established in the standard. In another case (Anaurangi, Rodrigo and Jayatunga, 2017) the PSCAD platform were used, and the harmonic penetration analysis was performed for single-phase and three-phase DG in a grid. Measurements were made both at the inverters output and at various locations in the feeder. It was verified that the percentages of voltage and current THD were lower at the output of the three-phase inverter when compared to the values at the single-phase output. Inverter systems inject high frequency harmonic current due to inverter switching technique and voltage harmonic distortion is mainly dependent on the grid impedance. On the other hand, the effect of the solar irradiation presented considerable influence in the THD, where the low solar irradiance produces high current and voltage THD.

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Some studies use both measurement of magnitudes and evaluation by simulation, in order to extend the analysis of measurement to unmeasured situations (Rocha, Salvadori and Gehrke, 2017; Chen et al. 2017; Reis, Santos and Diniz, 2016). In (Rocha, Salvadori and Gehrke, 2017), before the connection of DG the total hamonic distortion of the mains current (THD) was 25.5% and went to 28.6%, degrading the energy quality even more. In the case of (Chen et al. 2017), when the generation operates far below the maximum power, the THD of the DG output current is much more prominent. According to (Santos and Diniz, 2016) through individual analysis of generating units as well as in the PCC, it was noticed that the current harmonics are present in all harmonic orders studied, and the harmonic distortion of the voltage presented low values, which was justified by the high level local short circuit impedance. In general, in the studies, the practical results corresponded to those previously simulated.

It is worth mentioning that in the literature, simulations are also used to predict host capacity with respect to harmonic distortions, in other words, the maximum amount of DG connected to the grid without exceeding the limits established by the standard (Oliveira, 2015; Rocha, Salvadori and Gehrke, 2017; Chen et al. 2017; Pandi, Zeineldin and Xiao, 2013; Quraan et. al, 2017) as well as measures that seek to mitigate the impacts to the power quality of the system such as the optimal allocation of DGs and the use of power injection control strategies by the inverters.

7. CONCLUSION

With a greater need for the use of renewable resources, one of the alternatives that presents great potential and is growing at an accelerated pace is the use of distributed generation from renewable sources.

This article shows through a range of studies the methodologies used in the analysis of the quality of the energy coming from the DG installed in buildings that use renewable sources. The studies also show the feasibility of having a DG by owners of residential or commercial facilities, industries and buildings, since the prices for the implementation of such systems are increasingly accessible to the consumer allied with the incentives of the Governments such as energy credits making implementation feasible.

It can be concluded that the injection in small quantities of harmonics by the DGs may not have significant variation in the harmonic rates of the electric voltage. If the amount of DG increases as expected, a greater variation in the harmonic distortion rates can occurs, which may exceed the limits established by standards. So, it is of great importance that energy distributors now begin to develop studies so that the distribution network is able to receive the connection of these distributed energy sources without degradation of the power quality.

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