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Power Quality Analysis of Photovoltaic Systems

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Abstract. This research analyses the quality of the electricity produced on photovoltaic systems connected to the power grid in the city of Cuenca (Ecuador). For this, an overview of the literature and the Ecuadorian, American, and European regulations concerning power quality was carried out to determine the regulatory parameters and admissible limits. From the quality records, it is concluded that, in general, there are no power quality problems, except for momentary current imbalances. In one of the cases, violations of voltage parameters, voltage unbalance, current unbalance and flicker were found. The recommended parameters to be included in the Ecuadorian quality standards are individual harmonic distortion and frequency have been registered.

Keywords. Photovoltaic, power quality, grid quality.

1. Introduction

Voltage fluctuations and harmonic distortions are the most common problems in photovoltaic (PV) electrical systems. The occurrence of these anomalies could generate failures in electrical equipment such as luminaires attenuation, disconnection of equipment, loss of data, or other associated problems with electrical protection switches [1].

In Ecuador, some efforts have been made in order to promote renewable energies, particularly photovoltaic energy. The state's constitutional commandments, as well as laws, rules, and regulations, have established provisions intended to impulse clean micro power plants and their development. For several years, the regulated tariff was enforced for several technologies, and preferential prices were established depending on the technology or power. Likewise, National Development Plans, Electrification Master Plans, and several institutional plans have established several axes for the promotion of this type of technology. In Ecuador, Regulation No. ARCERNNR-001/202 (Normative framework for Distributed Generation for self-supply of regulated electric energy consumers) is in force, which establishes the provisions for the process of enabling, connecting, installing, and operating distributed generation systems based on renewable energy sources for power self-supply producers-consumers (SGDA). By January 2023, in the case of Empresa Eléctrica Centrosur, 376.42 kW in small PV systems are in operation. In addition, at least 800 kW in small residential additional systems will be in operation in 2023. This increase in the operation of grid-connected systems brings uncertainty as to how the quality of the power grid can be affected by the insertion of these systems.

This work recollects and performs an analysis of monitored data on the power quality of small residential or institutional PV systems installed in the city of Cuenca (Ecuador) to determine whether the power supply provided by these systems is safe and reliable. It also seeks to compare the monitoring results in accordance with Ecuadorian regulations and international standards, to determine whether the characteristics and limits established in the local regulations are sufficient to reach acceptable power quality of the existing PV system.

2. State of the art

A power-quality study was conducted at Murdoch University (Australia) with the insertion of a PV generation system [3], to this, the information obtained was: voltage and current distortion, voltage offset angle, in addition to the temperature of the equipment used by this university operating with three-phase systems. So, IEC 61000-2-2 [4] and NEMA [5] standards were applied as referential quality for the analysis. A voltage variation within the 2% was determined in concordance with this standard was established. But in the electrical current analysis, it exceeded the 5% described by the IEC and NEMA standards. When performing the transformer temperature study, an overheating effect was observed. The reason for this phenomenon was a consequence of the fact that the third harmonic current is higher than the limit of the IEEE 519 standard [6]. Another cause of this abnormality is the wrong sizing of the power transformer.

Oliva and Balda [7] also performed harmonic measurements of two PV systems located in West Texas in the Davis area (United States). A power quality analysis was performed by applying the IEEE 519 standard [8]. It was found that the even harmonics generated exceeded the limits by up to 25%, with the exception of harmonic 34. The high value of the harmonics cannot be attributed to the insertion of the PV systems, since the harmonic values were maintained under similar conditions even when there was no generation. Then the cause of this phenomenon was the consequence of the high demand for non-linear loads connected to the system.

Then in 2021, some studies were conducted for the interconnection of PV systems to a low or medium-voltage grid in the United States. The objective was to minimize the impact on power quality when implementing small PV systems interconnected. The results of this study show that the interconnection of a PV system can change the power quality parameters of the grid by increasing harmonic distortion and raising voltages by 4 % to 9 %. A possible solution to keep the power quality limits within the established limits is restricting the load so that it does not exceed the power generated by the PV system [9].

Locally, at the Universidad Politécnica Salesiana (Ecuador) [10], a study of the power quality of a grid-connected PV system was carried out t [6], [11] [12]. The study was performed by analyzing the voltage wave and harmonic distortion that occurs when this system is put into operation. The voltage unbalances after the study was carried out and was below the 2% maximum allowed, while the current unbalance exceeds 10%. The cause of this unbalance was a consequence of the higher electricity consumption during the morning hours, while at night when the system does not generate, it behaves as an additional load and introduces disturbances into the power grid. In another study conducted in Ecuador [13], the quality indices of the PV system designed to supply electric vehicle charging stations were evaluated when connected to and disconnected from the grid. In both cases, the measurements were carried out over a 7 days period, as required by the local regulation [11]. The analysis of the parameters showed that none of them exceeded the limits set by Ecuadorian regulations. The conclusion of this analysis was that the PV system does not affect the power quality within the limits of the relevant standards. Although harmonics are introduced into the grid, they were found to be within the limits set by the standard.

A. Reference Standards

National Standards

a. *ARCERNNR 001/2021: Marco normativo de la Generacion Distribuida para autoabastecimiento de consumidores regulados de energía eléctrica*: The purpose of this state guidelines is to regulate consumers who install small size self-consumption systems connected to the grid and distribution companies for net-metering purposes [2].

b. ARCERNNR 002/20: Calidad del servicio de distribución y comercialización de energía eléctrica: Defines the limits on the quality indexes for the commercialization and distribution of electric energy. As well as the registration, measurement, and evaluation processes in concordance with by distribution companies and regulated and non-regulated consumers connected to the grid [2].

B. American Standards

a. IEEE 519: Recommended practice and requirements for harmonic control in electric power systems (2014): This regulation defines the limits of harmonics in voltage and current waveforms limits that allow the power system to operate in acceptable quality and reliable manner. Taking this into account, a certain level of harmonic distortion is acceptable for the utility and the customer [6].

b. IEEE 1159: Recommended practice for monitoring electric power quality (2019): It describes the effects of electromagnetic phenomena occurring in power circuits, as well as the nominal conditions that may appear in the supply, by analyzing equipment that monitors power quality [15].

c. IEEE 1250: Guide for identifying and improving voltage quality in power systems (2018): This regulation assesses the power quality limits and other factors that influence the system performance and the mitigation measures requirements as well for improving the system performance [16].

C. European Standards

a. EN 50160: Voltage characteristics of electricity supplied by public electricity networks (2020): Its purpose is correcting the low-voltage electrical operation installations at a common coupling point. It is applicable in any electrical system including PV systems interconnected with the power grid [17].

b. IEC 61000-2-2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems (2013): This standard provides comprehensive guidance for compatibility levels for each power quality parameter [4].

c. IEC 61000-2-4: Compatibility levels in industrial plants for low-frequency conducted disturbances (2022): The standard is divided into three classes. The first is intended to protect power supplies with high sensitivity for disturbances in power supply, the second class applies to the connection points to the public grid and the last one corresponds to the internal connection of industrial facilities affected by short fluctuating loads [18].

In Table I a comparison of the limits settings is presented with the disturbances allowed for the power quality on an electrical system by each of the standards studied above.

In Tables II, III, and IV a comparison of the harmonic limits in percentage is shown.

Table I. - Comparison of disturbances according to each standard

Disturbance	Standard					
	IEEE 519	IEEE 1250	EN 50160	IEC 61000 2-2	IEC 61000 2-4	ARCERNNR 002/20
THD	8%		8%			8%
Flicker		≤1	≤1			≤1
Frequency		±0.5 Hz	±1 Hz	±1 Hz	±1 Hz	
Voltage		±10%	±10%		±10%	±8%
Voltage unbalance		3%	2%	2%	2%	2%
Current unbalance	20%					20%

Table II. - Comparison of harmonics multiples of 3 according to each regulation

Order	Odd harmonics multiples of 3 according to each regulation			
	IEEE 1250	IEC 61000 2-2	IEC 61000 2-4	EN 50160
3	5%	5%	5%	5%
9	1,5%	1,5%	1,5%	1,5%
15	0,4%	0,4%	0,4%	0,5%
21	0,3%	0,3%	0,3%	0,5%

Table III. - Comparison of odd harmonics not multiples of 3 according to each regulation

Order	Odd harmonics multiples of b3			
	IEEE 1250	IEC 61000 2-2	IEC 61000 2-4	EN 50160
5	6%	6%	6%	6%
7	5%	5%	5%	5%
11	3,5%	3,5%	3,5%	3,5%
13	3%	3%	3%	3%
17	2%	2%	2%	2%
19				1,5%
23				1,5%
25				1,5%
17≤h≤49	2,27×17/h - 0,27			

3. Methodology

The data from five PV systems are used to determine to what extent the power quality in the distribution grid is affected by the PV connection by comparing it with the admissible parameters established in the current regulations.

The current and updated standards and regulations of the electrical sector are taken into account. They are divided into 3 groups: National, American, and European standards. The affection parameters that have the greatest influence on the evaluation and determination of the reliability of the electrical system and its compliance with quality criteria are compiled. The parameters analyzed are voltage level, current level, voltage and current unbalance frequency, flicker, and harmonics.

The five PV systems as case studies are installed and connected to the Cuenca local distribution company (Centrosur). In these cases, the power quality information was not previously available, then, power quality measurement equipment was installed for a one-week period. The quality parameters of the installations were then compared with local, American, and European standards. Table V shows the main characteristics of each system that was evaluated.

Table V. - Characteristics of the evaluated PV systems

Evaluated systems				
Name	Power (kW)	Topology	Consumption (kW)	Plant Factor (%)
Poliéecnica Salesiana University	12,65	Three-phase four-wire	11,38	18,20
Azuay University	69	Three-phase four-wire	30,59	15,96
Cuenca University	15	Three-phase four-wire	0,96	5,23
Residential system 1	2	Two-phase three-wire	0,38	19,11
Residential system 2	1,34	Two-phase three-wire	0,012	10,14

4. Results

The percentages of compliance with the electrical parameters obtained during the measurements in each system analyzed are summarized. In concordance with the ARCERNNR 002/20 standard, if the analyzed parameter exceeds 95% compliance with the recorded data during the measurement instance in each phase, it is considered to be within the quality limits established by each standard. It should be noted that this standard is based on the American standard. The nomenclature used in the summary tables is described below:

N/L The standard does not define this parameter
N/D The parameter was not measured

A. Case I

This PV system has been designed for power feeding to an electrical charging station for electrical vehicles at Politecnica Salesiana University. The results obtained from the PV system are summarized in Table VI. The data were measured using FLUKE 435 equipment.

Table VI. - Characteristics of the evaluated PVsystems ·

Politecnica Salesiana University System Results			
Disturbance	National Standart	American Standart	European Standart
Voltage	99,90%	99,90%	99,90%
Voltage unbalance	99,80%	99,80%	99,80%
Current unbalance	6,51%	6,51%	N/L
Flicker	99,46%	99,46%	99,46%
Individual harmonic distortion	N/L	All comply with the standards	All comply with the standards
Total harmonic	100%	100%	100%

Politecnica Salesiana University System Results			
distortion			
Frequency	N/L	99,80%	100%

The system's voltage levels are 99.90% effective and 99.80% unbalance compliant when. For the electrical current parameter, a greater variation between the minimum and the maximum current is observed, causing 93.49% of the sample current unbalances higher than the 20% established in the [2] and [6] standards. This is due to the unbalance of the loads, short circuits produced in laboratories, or the null generation of the PV system as a consequence of non-irradiation availability. The flicker of the evaluated system has a compliance higher than 99% of the samples, with respect to what is established in the standards [2], [16] and [17]. In the evaluation of the individual harmonic distortion, 100% of the values of the sample were obtained within the limits established in the standards [4], [16], [17] and [18]. In total harmonic distortion, a maximum THD value of 3.45% was obtained, and 100% of the sample complies with the evaluated values of 5% established in the standard [16] and 8% determined by standards [2], [6], and [17]. According to the European standards [4], [17], and [18], 100% compliance is obtained for the evaluated sample for the frequency variation of ±1%. The American standard [16], establishes a variation of ±0.5% in the frequency, obtaining a 99.8% compliance of the sampled values.

B. *Case II*

The system is designed to feed the facilities of the Azuay University. The results obtained from the PV system are summarized in Table VII. The data were measured using the FLUKE 435.

Table VII. – System Results in Case II

Azuay University System Results			
Disturbance	National Standart	American Standart	European Standart
Voltage	99,87%	99,87%	99,87%
Voltage unbalance	99,70%	99,70%	99,80%
Current unbalance	0,99%	0,99%	N/L
Flicker	99,67%	99,46%	99,46%
Individual harmonic distortion	N/L	Harmonic 15, 21 y 27 outside the established limits.	Harmonic 15, 21 y 27 outside the established limits.
Total harmonic distortion	100%	100%	100%
Frequency	N/L	100%	100%

The system's voltage levels have an effectiveness of 99.87% and an unbalance of over 99.70% when evaluated within the limits established in the Ecuadorian standard [2] and international standards [16], [17], and [18]. For the electrical current of the system, a greater variation between the minimum and maximum current is observed. Causing in 99.01% of the sample current unbalances higher than the 20% established in the [2] and [6] standards. The flicker of the evaluated system has 100% of effectiveness, with respect to what is determined in the standards [16] and [17]. In the evaluation of the individual harmonic distortion, 100% of the sample obtained values fall within the limits for the even and odd harmonics not multiples of 3. For the odd harmonics multiples of 3, harmonics 15, 21 and 27 have values higher than the parameters determined in standards [4], [16], [17] and [18]. In total harmonic distortion, a maximum THD value of 7.58% was obtained 100% of the sample complies with the values determined by standards [2], [6] and [17]. The European standards [4], [17] and [18], do establish a variation of ±1% and the American standard [16], establishes a variation of ±0,5% for the frequency. Obtaining 100% of the sample values below these established limits.

C. *Case III*

The system is connected to the utility grid. It is designed solely for the use of the microgrid laboratory belonging to the university. Table VIII, summarizes the results obtained from the PV system that belongs to the Cuenca University. The recorded data were provided by the microgrid laboratory of the university. The equipment used for the measurement was the AEMC 8336 quality analyzer.

Table VIII. – System Results in Case III

Cuenca University PV Facility			
Disturbance	National Standanrt	American Standart	European Standart
Voltage	99,47%	99,73%	99,73
Voltage unbalance	100%	100%	100%
Current unbalance	97,42%	97,42%	N/L
Flicker	99,60%	99,60%	99,60%
Individual harmonic distortion	N/L	Harmonic 6 outside the established limits.	Harmonic 6 outside the established limits.
Total harmonic distortion	100%	100%	100%
Frequency	N/L	100%	100%

The University of Cuenca's PV system complies with electrical power quality standards. The system's voltage levels are 99.47% effective when evaluated within the limits established in Ecuadorian [2] and international [16], [17] y [18] standards. When evaluating the system within the limits established in the Ecuadorian [2] and international [16], [17] and [18] standards, it was determined that the system does not present voltage unbalance. The electrical current of the system does not present large variations between each phase. In 97.42% of the sample, the current unbalance is below the 20% established in the [2] and [6] standards. The flicker of the evaluated system has 100% of effectiveness, with respect to what is determined in the standards [2], [16] and [17].

In the evaluation of the individual harmonic distortion, 100% of the sample obtained values within the limits established in the standards [4], [16], [17] and [18] for the odd harmonic's multiples and non-multiples of 3. The harmonic component 6 has values higher than the parameters determined in the standards. In the total harmonic distortion, a maximum value of 1.60% THD was obtained 100% of the sample complies with the limits determined by standards [2], [6] and [17]. The European standards [4], [17] and [18], establish a variation of ±1%, and the American standard [16], establishes a variation of ±0,5% for frequency. Determining 100% of the sample values below these established limits.

D. Case IV

Table IX summarizes the results obtained from residential PV system 1. The data were provided by Centrosur. The monitoring equipment is the PQBox 100.

Table IX. – System Results in Case IV

Residential System Results			
Disturbance	National Standart	American Standart	European Standart
Voltage	94,35%	96,23%	96,23%
Voltage unbalance	82,94%	90,48%	82,94%
Current unbalance	29,17%	29,17%	N/L
Flicker	88,49%	88,49%	88,49%
Individual harmonic distortion	N/L	N/D	N/D
Total harmonic distortion	100%	100%	100%
Frequency	N/L	N/D	N/D

The tensions have an efficiency of 94.35% in the samples with a variation of ±8% established in [2], and an efficiency of over 96.23% when evaluated with respect to a variation of ±10%, a value established in the standards [16], [17] and [18]. Voltage unbalances are evaluated with respect to the 2% limits established by [4], [17], [18] and [19], while 3% is determined by [16]. This results in non-compliance in the evaluated samples of 17.06% and 9.52% for each limit. For the electrical current parameter of the system, large variations between minimum and maximum current are observed, causing 70.83% of the sample of current unbalances higher than the limit of 20% established in the standards [2] and [6]. The flicker of the evaluated system has a non-compliance of 11.51% of the samples, with respect to the established standards [2], [16] and [17].

The evaluation of the total harmonic distortion obtained a maximum value of 4.18% THD 100% of the sample complies with the evaluated values of 5% established in the [16] standard and 8% determined by the [2], [6] and [17] standards.

E. Case V

Table X summarizes the results obtained from residential PV system 2. The data were provided by Centrosur. The monitoring equipment is the PQBox 100.

Table X. – System Results in Case V

Residential system results 2			
Disturbance	National Standart	American Standart	European Standart
Voltage	99,60%	99,60%	99,60%
Voltage unbalance	100%	100%	100%
Current unbalance	9,03%	9,03%	N/L
Flicker	99,70%	99,70%	99,70%
Individual harmonic distortion	N/L	N/D	N/D
Total harmonic distortion	100%	100%	100%
Frequency	N/L	N/D	N/D

The residential PV system 2 has an efficient power quality. The voltages are 99.60% effective and in unbalances parameters, the compliance of 100% of the sample when evaluated within the limits established in the Ecuadorian [2] and international [16], [17] and [18] standards. For the electrical current of the system, large current variations between phases are observed. Causing in 90.97% of the sample current unbalances higher than the limit of 20% established in the standards [2] and [6]. The flicker of the evaluated system has 100% effectiveness, with respect to that established in the standards [2], [16] and [17]. The evaluation of the total harmonic distortion obtained a maximum THD value of 2.43%, 100% of the sample complies with the evaluated values of 5% established in the standard [16] and 8% determined by the standards [2], [6] and [17].

5. Conclusions

The power quality of an electrical system is concerned with establishing whether the electrical system is reliable and safe. There are several causes of poor power quality, usually due to power line disturbances, voltage variations, service interruptions and harmonic distortions. The results show small variations between the standards studied. However, there are parameters that are not been analyzed in the Ecuadorian standards, such as individual harmonic distortion and frequency. The study of individual harmonics can be of great help when detecting overheating in electrical equipment. As for frequency, although this parameter has always been within the established limits, its analysis could prevent failures in electrical equipment, especially sensible ones or in industrial facilities.

According to the different standards studied and analyzed, voltage and current level, voltage and current unbalance, flicker, harmonic distortion and frequency are the most relevant parameters in the analysis of power quality in photovoltaic systems. By obtaining measurements from different sources, it is observed that there is different equipment that performs data recording. The analysis of each of the PV systems studied shows the non-compliance of the current imbalances with respect to the Ecuadorian and American standards. This non-compliance is due to the fact that during hours of low or no electricity generation, the system behaves as a load that injects current into the distribution network. The size of PV plants does not significantly influence power quality. With reference to the results obtained in case study IV, it is observed that there are non-compliances in most of the parameters studied. These suggest a low efficiency in the electrical equipment connected to the house, which reduces the quality of energy.

Due to the similarity between the limits of the Ecuadorian, American and European standards, there are no major differences between the results when analyzed by each standard. However, there is no consensus on the parameters that should be studied to determine the electrical power quality of a photovoltaic system. The power quality study determines compliance with the limits established for cases I, II, III and V, with the exception of electrical current unbalance. However, case IV presents noncompliance in voltage, voltage unbalance, current and flicker measurements. The system does not comply with 80% of the parameters for which it was evaluated. These problems can be solved by evaluating the loads connected to the system.

It is important to consider that for adequate utilities connection permits of small PV systems, it should request an individual study and design, which includes the certifications of the inverters and equipment. In addition, it should be required to perform the right quality measurements before and after the operation of the system has started, which ensures compliance with regulatory limits.

No significant grid disturbances have been identified in this research in the five cases. The increase of systems and installed capacity in the same location could cause problems in the grid, so a complementary study could analyse the product's quality in areas with several installed projects. Likewise, Ecuadorian regulations allow up to 1 MW of photovoltaic power to be installed per client, so this condition, especially in industrial facilities, could cause the parameters studied could imply significantly outranges in concordance with the standards.

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