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Analysis of Power Quality in Photovoltaic Solar Microgeneration Systems - A Case Study from Uruguay

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Abstract. Photovoltaic microgeneration is a key opportunity to diversify the energy matrix, enhance electricity supply sustainability, and contribute to renewable energy. However, its grid integration can cause power quality issues, such as voltage fluctuations, low power factor, and harmonic distortion. This study compares power quality in On-Grid, Off-Grid, and Hybrid photovoltaic systems under different load conditions in single-phase configurations. Experimental measurements were conducted on a photovoltaic system at the Technological University of Uruguay (ITRCS) using a network analyzer to assess power factor and total harmonic distortion. Results were compared with national and international standards. On-Grid systems exhibited better power quality, with lower harmonic distortion and a more stable power factor. In contrast, Hybrid and Off-Grid systems showed greater harmonic distortions and power factor fluctuations. The Hybrid system, in particular, presented critical values, with a power factor between 0.61 and 0.63 and a harmonic distortion of 19.85%, demonstrating the need for compensation and filtering strategies. This study underscores the importance of implementing harmonic mitigation and power factor correction techniques, such as active and hybrid filters and inverter control optimization. It also highlights the need for stricter power quality regulations for microgeneration due to national regulatory gaps.

Key words. Photovoltaic microgeneration, power quality, voltage harmonics, current harmonic distortion, power factor.

1. Introduction

In recent years, renewable energies have gained prominence due to the need to mitigate the impact of global warming and reduce dependence on fossil fuels. Technologies such as photovoltaic solar and wind energy have become more competitive thanks to cost reductions, gradually displacing coal and gas usage. Distributed generation and microgeneration are fundamental concepts in today's energy landscape, especially with the growing interest in renewable and sustainable sources. Both terms refer to the production of electricity near the consumption point, in contrast to large power plants requiring an extensive distribution network. Distributed generation encompasses small- to medium-scale power systems connected to the distribution grid, allowing users not only to consume but also to generate their own energy. Microgeneration refers to small-scale power generation typically designed to meet the energy needs of a household or small business.

In Uruguay, microgeneration is regulated by Decree N°. 173/010, which allows users connected to low voltage to generate their own energy from renewable sources and inject surpluses into the National Administration of Power Plants and Electric Transmission (UTE) grid. This decree made Uruguay one of the first countries in Latin America to establish a regulatory framework for distributed generation, promoting the adoption of small-scale solar and wind technologies.

However, challenges arise with the integration of photovoltaic technologies into the grid. Photovoltaic generation itself does not create harmonics; however, the problem mainly arises from the inverters, which, by converting direct current to alternating current, can introduce harmonics into the system. These harmonics can negatively affect power quality, causing overheating of equipment, malfunctioning of electronic devices, and, in extreme cases, damage to installations. The mass integration of photovoltaic systems into power generation has increased the presence of harmonics in distribution systems, which affects power quality. This phenomenon can lead to equipment malfunctions and higher costs related to corrective maintenance.

To better understand the levels of harmonic distortion that can occur in the network, Table I shows the total current harmonic distortion (THD-C) adapted by

Schneider [1] from the IEC 61000-3-6 standard based on the item 8.2.1, considering the types of equipment connected and their impact on the electrical network.

Table I. - Total Current Harmonic Distortion adapted from IEC 61000-3-6. [1]

THD-C	Comments
THD-C < 10%	Weak harmonic currents, low risk of disturbances
10% < THD-C < 50%	Significant harmonic currents, risk of heating and the need to oversize power supplies
50% < THD-C	Very high harmonic currents, almost certain risk of disturbances, dangerous degradation and heating unless the installation is carefully calculated and sized with these restrictions in mind

2. Methodology

For all the systems, the same set of photovoltaic panels located outside the LSU was used, connected in series with six panels. They have a total power of 1650 W, a total voltage of 187.8 V, and a total current of 8.8 A. A photograph of the photovoltaic system used in this work.

Fig. 1. Photovoltaic Array.

Design and Implementation of the Panels/Boards

Due to the lack of specific boards for monophase Off-Grid and Hybrid systems, an exhaustive inspection of the materials available at the ITR was carried out. During this process, various components available in the Electronics and Electrotechnology Laboratory were identified, including batteries, an inverter, and a charge controller from the Victron brand. Additionally, an inverter from the Fronius brand designed to operate in grid-connected (On-Grid) systems available. Both pieces of equipment are part of a kit that has the potential to be configured as a hybrid system.

On the other hand, at the LSU an inverter from the Atersa brand (model Tauro BC-1524), capable of operating in standalone mode (Off-Grid), was found along with a charge controller and the corresponding fuses. This equipment comes from a standalone system that previously operated at the institution but has since ceased functioning. Therefore, it was decided to reuse these components to develop a didactic board intended for use in educational activities and laboratory practices. Table I presents a comparison of the main characteristics of the inverters used in this work.

Table II. - Technical Characteristics of the Inverters Used

Equipment	MultiPlus-II GX 48/3000/35-32	Fronius primo 3.0-1	Steca StecaGrid 1511
Max. Input Voltage	38 – 66 V	1000 V	450 V
Max. Input Current	32 A	12 A	13 A
Max. Input Power (DC)	2400 W	4500 W	1540 W
Nominal Output Voltage (AC)	230 V	180 V - 270 V	230 V
Nominal Output Power (AC)	3000 W	3000 W	1500 W

Selection of Loads

In this section, the loads to be used in the monophase solar system are specified, which will be able to simulate different operating conditions in the selected systems. For this configuration, an inductive load and a resistive load were used. A motor corresponding to a hydroelectric pump from the UTEC Fluid Mechanics Laboratory was selected as the inductive load, and an electric stove was chosen as the resistive load. Moreover, the electric stove was selected based on its power, ensuring it was approximately equal to that of the motor. This allowed for maintaining similar operating conditions.

Table III. - Characteristics of the Loads for the Monophase Systems.

Equipment	Power (W)
Inductive Load	600
Resisitive Load	750

Measurements in Monophase Systems

The measurements in the On-Grid system began using the Fluke brand network analyzer, which was employed in all the measurements. For the monophase systems, 12 continuous hours of measurements were carried out, from 6 AM to 6 PM, starting with the inductive load, i.e., the motor. The period from 6 PM to 6 AM was left for the equipment to measure without any load connected, and then the resistive load was connected from 6 AM to 6 PM. The time was selected to cover the full spectrum of possible photovoltaic generation.

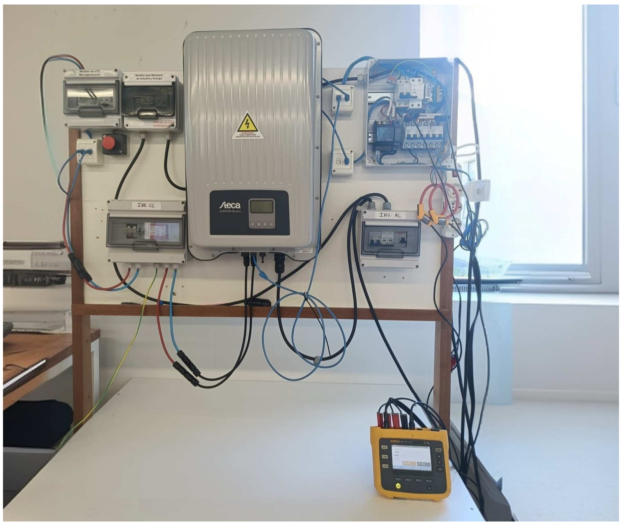

Fig. 2. Board used in the On-Grid system.

Hybrid System Measurements

The previously mentioned equipment was used for the hybrid system. Since the system's batteries are not in optimal condition, it was decided to perform one-hour measurements for each type of load, with the aim of preventing overloading the system and ensuring its proper functioning.

The first measurement was carried out starting at 10:00 AM, beginning with the resistive load and then the inductive load. A one-hour rest interval was left between the two measurements, designed to avoid overexerting the batteries and ensure system stability during the tests. This was necessary because the batteries were previously fully discharged.

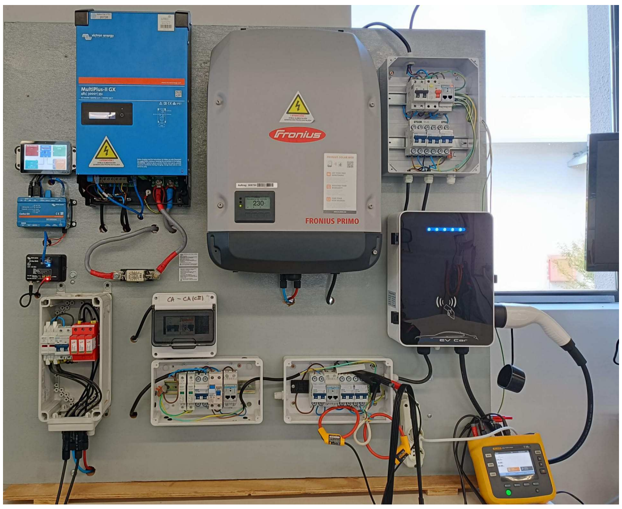

Fig. 3. The board employed in the experimental tests for the Hybrid system.

Off-Grid System Measurements

The same measurement time as for the hybrid system was used for the Off-Grid system, that is, one hour of measurement starting at 10:00. Afterward, a one-hour rest interval was made to allow the batteries to charge, and then the measurement was resumed with the inductive load.

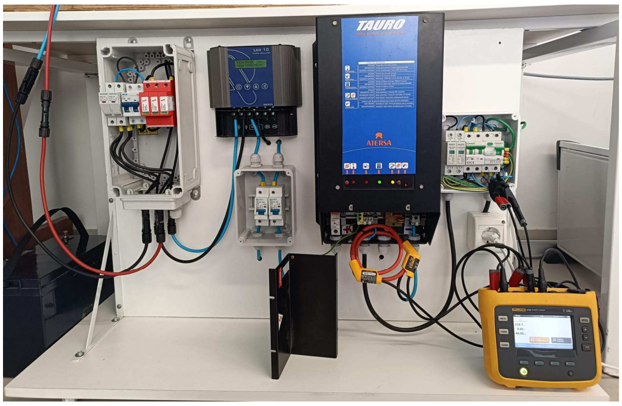

Fig. 4. Photograph of the Off-Grid board.

3. Results and Discussion

On-Grid

The graph generated from the data obtained using the network analyzer shows that the most predominant harmonics correspond to the fifth (n=5), seventh (n=7), and eleventh (n=11) orders. This is characteristic of electrical systems operating with inverters or electronic devices. These devices, functioning as nonlinear loads, generate harmonic distortion in the electrical grid. The harmonics observed are primarily generated by the inverter, and their magnitude varies depending on the type of load connected to the system.

According to [3], the increasing use of nonlinear loads from power electronics has led to a higher presence of harmonics in electrical systems. This can cause overheating of cables, transformers, and motors, as well as excessive currents in the neutral and resonance phenomena. As observed, none of these harmonics exceed 1.4%, indicating that the system complies with the limits established by international standards such as IEEE 519, which is widely adopted, especially in Brazil, and by the Low Voltage Regulations of UTE. [4][7]

As previously mentioned, low-order harmonics tend to have the highest values. This behavior aligns with the study by [8] who analyzed harmonics generated in an On-Grid photovoltaic system. Their research highlighted that the first odd harmonics, particularly those of orders 3, 5, 7, and 9, are the main contributors to harmonic distortion levels.

According to IEEE 519 and the Brazilian PRODIST standard [6], low-order harmonics such as 3rd, 5th, 7th, and 9th should remain below 4%. In comparison, Uruguayan regulations established in the URSEA

Distribution Service Quality Regulations specify that the 9th-order harmonic must not exceed 1.5%.

For a detailed analysis was used [9], presenting the URSEA limits for each harmonic order. The comparison of results confirmed that all analyzed harmonics remain below the maximum allowed values, ensuring that the system complies with both national and international power quality standards.

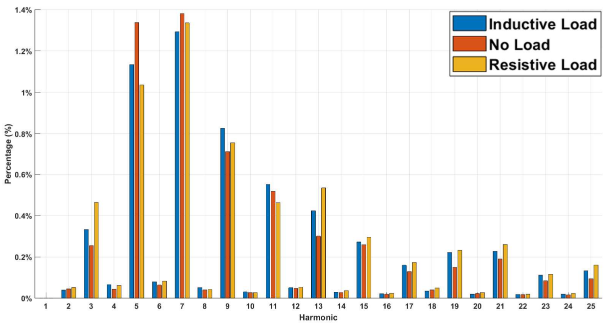

Fig. 5. Voltage Harmonics in the On-Grid Monophase System.

Hybrid

As observed in Fig. 7, although no values exceed the URSEA limits for voltage harmonics, the most significant harmonics are found at orders 5, 7, 9, and 13, with values exceeding 1% in some cases. In particular, the 7th harmonic presents the highest value, reaching approximately 1.41% in the presence of the inductive load (motor-pump coupling working with constant fluid flow).

In general, inductive loads tend to generate higher harmonic levels compared to resistive loads, especially in odd harmonics such as 3, 5, 7, and 13. This aligns with the typical behavior of inductive loads, which can introduce additional distortions in the voltage waveform. The inductive load used in this study is a hydroelectric bomb, where water circulates inside, and this characteristic ensures the generation of harmonics.

In an electrical power quality analysis of a grid-connected photovoltaic system with energy storage (SAEB), concluded that when analyzing individual and total voltage harmonics, a significant presence of the 5th harmonic was found in both photovoltaic subsystems. This harmonic exceeded the IEEE 519 and IEC 61000 limits during the early morning and late afternoon hours. The study determined that this harmonic injection was not caused by the photovoltaic systems but was associated with loads connected to the substation's connection point.[10]

Furthermore, when the energy storage system was connected at the node where the North and South parking photovoltaic subsystems were located, a reduction in both individual and total harmonic distortion was observed, albeit slight. This finding suggests that these storage systems help mitigate the negative effects of harmonics. [4][5]

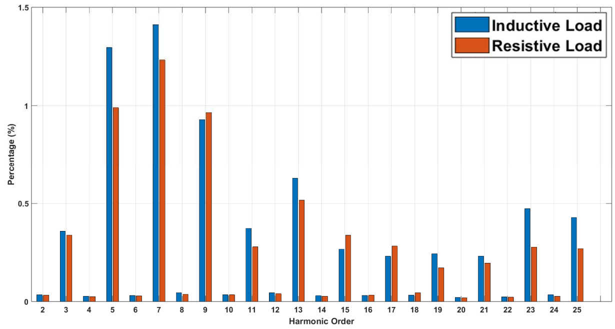

Fig. 6. Voltage Harmonics in the Hybrid Monophase System.

Off-Grid

The third harmonic stands out as the most significant in both types of loads, with a greater predominance in the inductive load, as observed in Fig. 8. Additionally, the harmonics of orders 5, 7, 9, and 11 show considerable values, being more pronounced in the resistive load. The presence of these harmonics indicates a distortion in the voltage waveform, suggesting a possible source of generation within the system.

In isolated (Off-Grid) systems, inverters can be one of the main sources of harmonics, especially when powering nonlinear loads. If the inverter does not produce a pure sine wave but an approximation, such as a modified sine wave, additional harmonics can be generated, affecting the quality of the supplied energy. As shown in Figure 7, a significant presence of voltage harmonics is detected even in the resistive load. Although isolated solar systems use resistive loads, voltage harmonics may still appear due to the nature of the inverters used. The inverters, responsible for converting the direct current generated by solar panels into alternating current, can introduce harmonic distortions in the output signal. These distortions are caused by the electronic switching processes within the inverter, which generate harmonic components in the voltage waveform. Even when the connected loads are purely resistive, the voltage wave quality can be affected by these distortions.

[11] analyzes how photovoltaic inverters can generate harmonics that are injected into the electrical grid. Although the main focus of his study is on grid-connected systems, the principles are equally applicable to isolated systems, as the source of harmonics is the inverter itself. The electronic nature of photovoltaic inverters facilitates the introduction of harmonics into the electrical system, affecting the quality of the supplied energy even when resistive loads are used. Previous studies have analyzed the presence of harmonics in isolated photovoltaic systems.

[12] observed that for voltage harmonics, the values remained below the 5% limit established by regulations, with the third harmonic being the highest at 1.44%. In comparison, in the present study, the third harmonic presents a value of 2.28%, indicating greater voltage distortion. According to the Uruguayan standards, the maximum permissible value for the third harmonic is 5%, which suggests that if a variation in the operation of the

load (modification of the fluid in flow or contamination by ferromagnetic materials [14]) could lead to conditions outside those established by the regulations, due to the proximity of the current limit. However, to maintain the third harmonic within acceptable levels for longer usage, a more powerful battery bank would be required.

On the other hand, [13] concluded that the total harmonic distortion (THD) in an isolated photovoltaic system was adequate and met power quality standards. This suggests that isolated photovoltaic systems can operate efficiently without causing significant power quality issues, such as excessive harmonics.

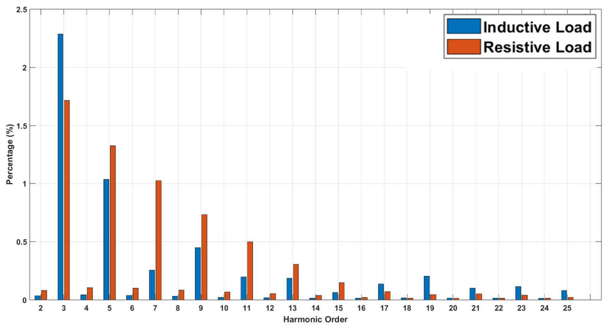

Fig. 7. Voltage Harmonics in the Off-Grid Monophase System.

Comparison Between Monophase Systems

The Table IV shows the maximum values of the voltage harmonics for each system and type of load, along with the THD-C and the power factor, which provides a clearer visual comparison.

Table IV. - Characteristics of the Loads for the Monophase Systems.

System	Load Type	Power Factor	THD-C	Max. Voltage Harmonic
On-Grid	Inductive	0.95 -0.93	13.9%	1.29%
	Resistive	0.93 – 1	2.35 %	1.33 %
Hybrid	Inductive	0.61 - 0.63	19.8 %	1.4 %
	Resistive	1	2.2 %	1.2 %
Off-Grid	Inductive	0.64 - 0.66	17.3 %	2.28 %
	Resistive	1	2.8 %	1.7 %

When comparing the On-Grid, Hybrid, and Off-Grid systems, it is observed that the On-Grid system presents the lowest values of voltage harmonics, while the Off-Grid system has the highest values. In particular, the third-order component in the Off-Grid system exceeds 2%, which is significant.

Regarding the Total Harmonic Distortion of current (THD-C), the Off-Grid system also shows the highest value, although the differences between systems are smaller. In the case of the resistive load, the system presents a higher THD-C, but always within the allowed limits (below 10%), as defined in Table I. However, for systems using batteries, the THD-C approaches 20%, indicating a tendency for higher harmonics in these systems. For the On-Grid system, during the 12-hour measurements, the THD-C was approximately 14%. In comparison, the battery-based systems had shorter measurement durations: 15 minutes for the hybrid system and 1 hour for the isolated system. This suggests that systems with batteries tend to generate more harmonics compared to the On-Grid system.

The limits for THD-C in these systems were determined using the values from Table I, which are based on the IEC 61000 standard. Although there is no specific national regulation for these limits in Uruguay, the regulatory body responsible for monitoring power quality recommends using these IEC 61000 values, up to the 50th harmonic, for all three systems mentioned.

Regarding the fifth, seventh, and ninth-order voltage harmonics, no significant values were observed in the isolated system, but they were present in the hybrid and On-Grid systems. This suggests a possible direct relation with the UTEC electrical grid, where the systems were connected, which then communicates with UTE's electrical grid. For the seventh-order harmonic, both in the hybrid and On-Grid systems, the value is around 1.4%. Lastly, it is important to highlight that for the isolated system, the increase in voltage harmonics is a concerning factor, as the value is close to half of the maximum allowed limit, which could cause issues in a residential environment.

Fig. 9, presents different graphs of the power factor for the three monophase systems studied. Regarding the power factor (PF) of the On-Grid system, it is within the limits set by UTE. However, in both the hybrid and isolated systems, under inductive load, the PF is lower than the 0.92 limit established by UTE's current tariff document.

When comparing both systems, it is observed that the PF is lower in the hybrid system, which could be related to the battery condition, as discussed in the corresponding section. Although the hybrid system has access to the electrical grid, which should improve its stability and efficiency, the battery condition seems to limit its performance, negatively affecting the power factor. On the other hand, the isolated system, which depends entirely on the batteries, shows a higher PF than expected. Theoretically, one would expect a better power factor in the hybrid system, as the grid provides a more stable voltage and frequency reference, allowing the inverter to operate under more controlled conditions and reducing output signal fluctuations compared to the isolated system. However, the suboptimal state of the batteries in the hybrid system could be affecting its efficiency, resulting in performance below expectations.

Regarding voltage variations over time, greater fluctuations are observed in the isolated system, with some jumps in the hybrid system, although of smaller magnitude, and the smallest jumps are present in the On-Grid system. These voltage variation behaviors could be linked to the battery condition, which influences the voltage stability in the different systems.

From the analysis, it is concluded that the On-Grid monophase system presents the best energy quality, with the lowest values of voltage and current harmonic distortion, as well as maintaining a power factor within the limits set by UTE. In contrast, battery-based systems (Hybrid and Off-Grid) show a higher presence of harmonics and a lower power factor, especially in the hybrid system, where the battery condition appears to negatively influence the system's performance. The Off-Grid system is the one that shows the greatest voltage fluctuations and higher harmonic content, which could cause issues in residential applications.

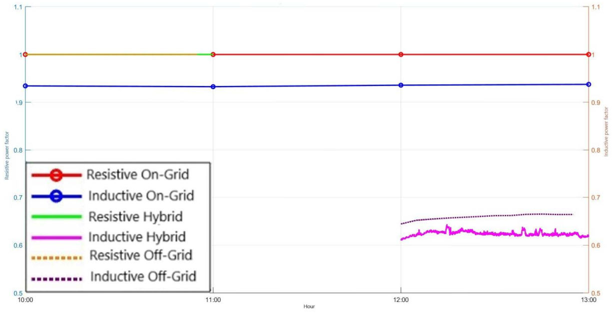

Fig. 8. Comparison of Power Factor (PF) for Different Single-Phase Systems.

4. Conclusions

Based on the results obtained, it is concluded that the single-phase On-Grid system provides the best power quality, standing out for its low levels of voltage and current harmonic distortion while maintaining a power factor within the limits established by UTE. In contrast, battery-based systems, such as Hybrid and Off-Grid, exhibit a higher presence of harmonics and a lower power factor, which could lead to penalties. The hybrid system, in particular, is more affected, possibly due to the state of the batteries, negatively impacting its performance. This highlights the importance of proper battery maintenance to ensure safe and stable operation. The Off-Grid system, on the other hand, showed greater voltage fluctuations and higher harmonic content, which could pose a risk for residential applications, especially when considering larger loads and prolonged energy use. However, no significant issues were observed with resistive loads. This issue could be mitigated by using multilevel inverters, which would also improve power quality. Filters can also be used to address these issues. Passive filters can be effective in mitigating harmonic distortions in Off-Grid and Hybrid systems, particularly when harmonics are significant. However, passive filters have limitations in correcting high-frequency harmonics and do not improve the power factor. Hybrid filters, by combining the advantages of passive and active filters, offer a more flexible solution, making them suitable for improving both harmonics and power factor in Hybrid and Off-Grid systems. Finally, active filters represent the most advanced solution, as they can dynamically mitigate harmonics and correct the power factor.

Microgeneration does not significantly affect grid stability when on-grid systems are used. However, when hybrid systems are employed, meaning those with batteries, distortions are observed, which indicates that battery maintenance is a relevant issue to be considered in these systems.

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