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Development and Validation of a LabVIEW-Based Software for Power Quality Analysis in Microgrids

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Abstract. The increasing integration of Distributed Energy Resources in microgrids demands efficient Power Quality monitoring. However, the high cost of commercial analyzers and the complexity of interpreting data from Smart Meters often hinder effective diagnosis. This paper presents a hardware-agnostic, LabVIEW-based software designed for post-processing and automatic PQ diagnosis. The tool processes CSV datasets and translates complex regulatory standards—specifically PRODIST and URSEA—into intuitive compliance indicators, making analysis accessible to non-experts. The system's reliability was validated through an experimental case study in a real microgrid, comparing its performance against a Class A Fluke 1736 analyzer under dynamic loading conditions. Results confirmed the software's robustness, showing negligible errors in RMS voltage, current, and frequency measurements. Additionally, the tool successfully detected regulatory violations, such as Power Factor drops, and accurately analyzed harmonic distortions using FFT algorithms. This solution provides a cost-effective, educational, and technical tool for transforming raw electrical data into actionable diagnostic insights, ensuring compliance and stability in modern power systems.

Key words. Automatic Diagnosis, Smart Meters, Power Quality, LabVIEW, Education.

1. Introduction

According to the Brazilian Legal Framework for Distributed Generation (Law 14.300/2022), a microgrid is defined as the integration of various distributed generation resources, energy storage, and loads within a secondary distribution system, capable of operating either connected to the main grid or in island mode, while controlling electrical parameters and enabling self-healing actions [1]. The growing integration of these systems stems from their ability to incorporate Distributed Energy Resources (DERs), providing greater flexibility. However, this evolution introduces new challenges regarding Power Quality (PQ). The intermittency of renewable sources and the extensive use of power electronics can result in disturbances such as harmonic distortions, voltage imbalances, and frequency fluctuations, which compromise the stability of both the microgrid and the main grid to which they are connected [2, 3]. A typical microgrid architecture illustrating the interaction between these components and the utility grid is shown in Fig. 1.

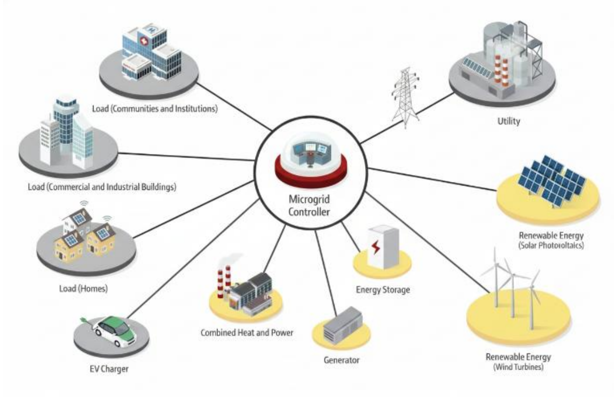

Fig.1. Microgrid scheme [4].

Adequate monitoring of these parameters is essential to ensure compliance with national and international standards, such as IEEE 519 and PRODIST, and to maintain efficient performance. However, precise PQ analysis in microgrids faces significant hurdles. Commercial Class A analyzers, while accurate, are predominantly designed for industrial or transmission systems, making them prohibitively expensive for small-to-medium applications [5]. Furthermore, these devices often operate as "black boxes," requiring deep expert knowledge to interpret the raw data against complex regulations.

This gap is particularly critical in the context of Smart Grids. With the widespread adoption of Smart Meters, vast amounts of electrical data are generated but often remain underutilized due to the lack of accessible analysis tools. While some low-cost solutions have been proposed, they are frequently limited to specific hardware architectures [6]. There is a clear demand for flexible software capable of post-processing data from various sources—ranging from commercial analyzers to utility Smart Meters—and translating them into actionable diagnostics.

This paper presents the development and validation of a LabVIEW-based software designed for the post-processing and automatic diagnosis of PQ parameters. Unlike real-time acquisition systems, this tool is designed to import CSV data from external recorders, making it hardware-agnostic. Its primary innovation lies in the "Automatic Diagnosis" feature, which interprets standards into intuitive indicators for technicians and educational purposes. To validate the proposed tool, an experimental case study was conducted in a microgrid environment under dynamic loading conditions. The software's accuracy in monitoring electrical parameters and detecting regulatory non-compliances.

2. Theoretical Framework

To ensure the reliability of the developed software, the algorithms were designed to be adaptable to various regulatory standards. However, since this work was developed within the Brazilian electrical system, the analysis framework is primarily grounded in the Procedures for Electric Energy Distribution (PRODIST), specifically Module 8 [7]. This choice reflects the local mandatory compliance requirements, although the software architecture allows for the configuration of different limit sets according to other international standards. For parameters where the national code lacks specific definitions—such as harmonic current injection limits for specific consumers—the software adopts the methodology of IEC/TR 61000-3-6 [8].

A. Harmonic Distortion

Harmonic distortions are periodic steady-state distortions of the sine wave caused by non-linear loads. To analyze these distortions, it is necessary to decompose the distorted signal into its constituent frequencies. This is achieved using the Fourier Transform, which represents a periodic function as a sum of sinusoidal components (fundamental and integer multiples frequencies) [9]. In digital processing systems, the Fast Fourier Transform (FFT) algorithm is employed to convert time-domain sampled signals into the frequency domain, allowing for the individual quantification of each harmonic order. Fig. 2 illustrates this decomposition process.

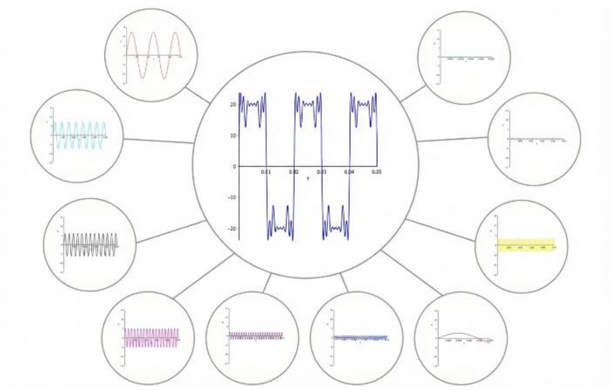

Fig.2. Decomposition of a distorted signal into fundamental and harmonic components.

- Voltage Harmonics ($\boldsymbol{V_h}$): The software evaluates the Total Harmonic Distortion of Voltage $\boldsymbol{DTT_V}$ strictly according to PRODIST limits. For low voltage busbars ($\boldsymbol{V < 1kV}$), the global limit is set at 10%, with specific individual limits for odd and even orders [7].
- Current Harmonics ($\boldsymbol{I_h}$): As PRODIST does not specify limits for harmonic current injection at this voltage level, the assessment follows the IEC/TR 61000-3-6. Specifically, the software references Table 5 ("Indicative values for some odd order harmonic current emission limits relative to the size of a customer installation"). This approach ensures that the microgrid operates within internationally accepted emission levels.

The calculation for THD remains as defined in Eq. (1):

$$\boldsymbol{THD}(\%) = \frac{\sqrt{\sum_{h=2}^{h_{max}} X_h^2}}{X_1}\ \boldsymbol{x\ 100} \quad (1)$$

B. Power Factor (PF)

The Brazilian regulation (PRODIST) mandates a minimum Power Factor of 0.92 (inductive or capacitive) for reference. However, in environments with high harmonic content, the traditional displacement power factor is insufficient as it neglects the distortion power. Therefore, to provide an accurate diagnosis, the software calculates the True Power Factor, defined as the ratio of Active Power ($\boldsymbol{P}$) to Apparent Power ($\boldsymbol{S}$), as shown in Eq. (2):

$$\boldsymbol{PF} = \frac{P}{S} = \frac{V_{RMS} \cdot I_{RMS} \cdot \cos(\theta - \emptyset)}{V_{RMS} \cdot I_{RMS}} = \cos(\boldsymbol{\theta} - \emptyset) \quad (2)$$

C. Frequency Variation

Microgrids operating in island mode are susceptible to frequency instability. Following the strict limits of PRODIST for steady-state conditions, the frequency must remain within $\boldsymbol{60\ Hz\ \pm 0.1\ Hz}$.

As the experimental case study presented in this work utilizes data acquired in Uruguay, the analysis adheres to the Regulation of Distribution Service Quality (RCSDEE) established by URSEA. In this context, the nominal frequency is 50 Hz, with an admissible tolerance range of $\boldsymbol{50\ Hz\ \pm 0.5\ Hz}$ for normal operating conditions [10].

The practical application of these theoretical foundations, particularly the spectral decomposition via FFT and the simultaneous verification of multiple regulatory limits, involves complex data processing. Manual interpretation of such vast datasets is time-consuming and prone to human error. Consequently, the development of a dedicated computational tool becomes essential to automate the calculation and strictly enforce the compliance criteria. The following section details the methodology used to translate these mathematical and regulatory frameworks into a functional software solution.

3. Methodology

The methodology adopted in this work consists of two main stages: the development of the computational tool for power quality analysis and its subsequent validation through experimental tests in a real microgrid environment.

A. Software Development

The software was developed using the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) environment, chosen for its modularity and robust signal processing libraries. The application was designed to be hardware-agnostic, meaning it does not require a direct connection to a specific analog-to-digital converter board during analysis. Instead, it operates in post-processing mode, importing data via CSV (Comma-Separated Values) files generated by various commercial meters or Smart Meters.

The software architecture follows a sequential flow, illustrated in Fig. 3:

- Data Import: The user loads the raw data file (voltage and current waveforms or aggregated logs).
- Processing Engine: The system applies the mathematical formulations described in Section 2 (FFT for harmonics, RMS calculation, and Symmetrical Components).
- Automatic Diagnosis Module: This is the core functionality. The processed values are compared frame-by-frame against the limit curves (PRODIST/IEEE/IEC). If a parameter violates the standard, the software tags the event and calculates the percentage of time the system was non-compliant.
- Visualization & Reporting: Results are displayed in interactive graphs, and a compliance report is generated.

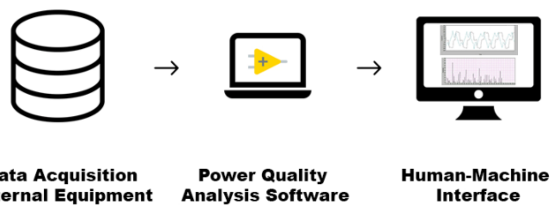

Fig. 3. Flowchart of the developed software architecture.

B. Software Functionalities and User Interface

To ensure usability and efficient data interpretation, the software interface was organized into intuitive modules. The Front Panel, shown in Fig. 4, serves as the main dashboard, providing immediate access to file loading controls and a summary of the system's status. The tool is divided into two primary analytical domains: Electrical Parameters and Power Quality Indicators.

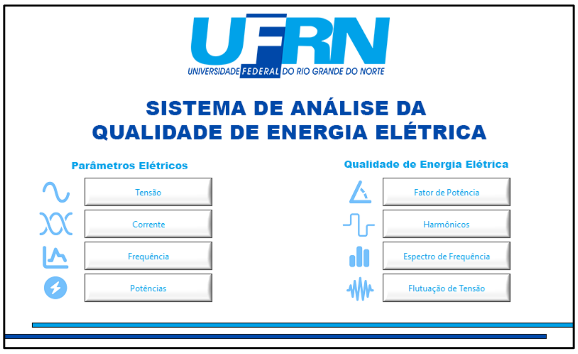

Fig. 4. Software Front Panel showing the main dashboard and control indicators.

1) Electrical Parameters Module

This module focuses on the reconstruction and visualization of the fundamental characteristics of the signal.

- Virtual Oscilloscope: Using the sampled data from the input CSV, the software reconstructs the waveforms for both voltage and current. Fig. 5 illustrates the Voltage Oscilloscope function, which allows the user to visually inspect the signal for sags, swells, or severe waveform distortions before proceeding to deeper mathematical analysis.
- RMS and Frequency: Simultaneous calculation of RMS values and grid frequency monitoring.

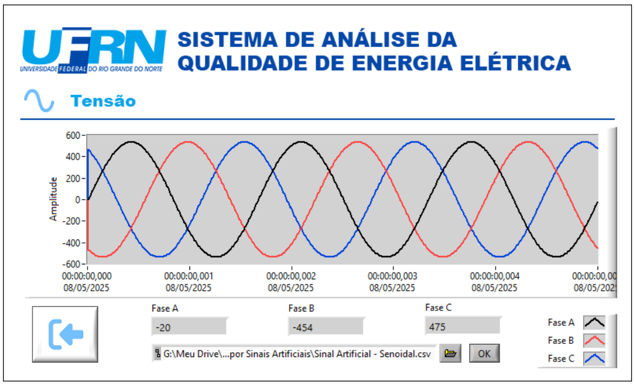

Fig. 5. Virtual Oscilloscope interface displaying reconstructed voltage waveforms.

2) Power Quality Module

This module executes the advanced processing algorithms described in the theoretical framework.

- Harmonic Analysis: Performs the FFT to display the harmonic spectrum up to the 50th order.
- Power Factor Analysis: As detailed in Section 2.2, this specific tool calculates the True Power Factor. As shown in Fig. 6, the interface displays the correlation between Active, Reactive, and Apparent power, explicitly highlighting intervals where the PF falls below the regulatory limit (e.g., 0.92 for Brazil). This allows for a clear distinction between displacement power factor and distortion power factor issues.

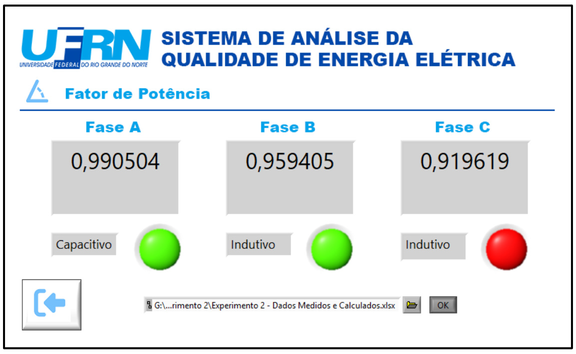

Fig. 6. Power Quality interface focusing on Power Factor analysis and compliance verification.

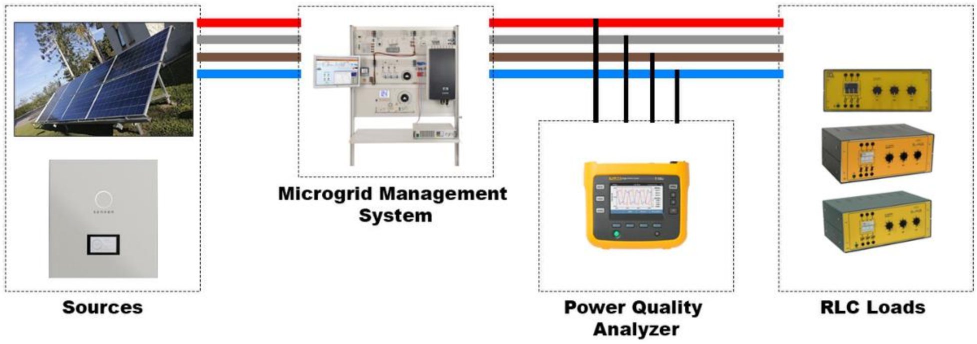

Fig. 7. Experimental microgrid setup used for validation.

C. Experimental Validation Setup

To validate the developed tool, a case study was conducted in a controlled microgrid environment. The experimental setup aims to reproduce real-world conditions of a low-voltage distribution network operating with distributed generation.

1) Microgrid Configuration

The physical system, located in Uruguay (50 Hz grid), is illustrated in Fig. 7. It consists of a hybrid topology connected to a central AC bus, comprising:

- Generation: A real photovoltaic generation system, composed of solar panels with a total installed capacity of 1.65kW, connected to the grid via a commercial inverter.
- Storage: A Battery Energy Storage System (BESS) to regulate bus voltage and frequency.
- Load: Set of electrical loads connected to the bus. These include non-linear equipment essential for generating the harmonic distortions required for the validation of the software's FFT algorithms.

2) Data Acquisition and Reference

To serve as the ground truth for validation, a Fluke 1736 Power Logger (Class A) was installed at the Point of Common Coupling (PCC). This device recorded voltage and current signals simultaneously with the proposed software system. The data logs from the Fluke 1736 were exported and used to verify the accuracy of the calculations performed by the developed LabVIEW tool.

3) Test Scenario

This scenario represents a critical operation condition where the microgrid operates in discharge mode (powered by the BESS and PV) while subjected to a sequence of abrupt load variations designed to stress the Power Factor (PF) diagnostics. The test is divided into three stages:

- Stage 1 (Baseline): Operation with a standard RLC load ($\boldsymbol{R = 1050\Omega, L = 1.84\ H, C = 10\ \mu F}$).
- Stage 2 (Inductive Step): Increase in inductive load ($\boldsymbol{L = 4{,}46\ H}$), intentionally degrading the Power Factor to test the software's non-compliance detection.
- Stage 3 (Compensation): Connection of a capacitive bank to simulate a power factor correction maneuver, verifying if the software correctly identifies the return to compliance.

4. Results and Discussion

The developed software processed the acquired voltage and current signals to assess the microgrid's power quality behavior under dynamic loading conditions, verifying compliance with the PRODIST and URSEA (Uruguay) standards.

A. Frequency Stability Analysis

The software successfully monitored the grid frequency throughout the test duration. As shown in Fig. 8, the fundamental frequency remained stable around the nominal value of 50 Hz. Even during the load switching transients, the instantaneous values tracked by the software showed deviations consistently within the $\boldsymbol{\pm 0.5\ Hz}$ tolerance limit established by the URSEA regulations, confirming the stability of the system.

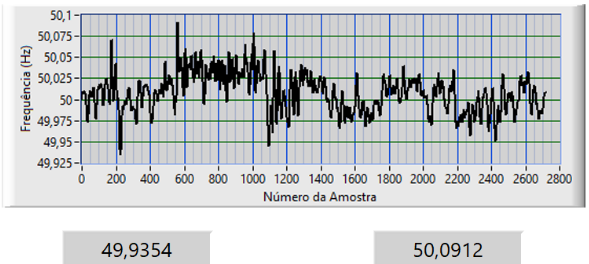

Fig. 8. Frequency stability profile monitored by the developed software.

B. Voltage Profile Analysis

The Voltage RMS profile calculated by the software is presented in Fig. 9. The tool accurately reconstructed the voltage behavior during the test, identifying the voltage sags caused by the connection of the inductive loads and the subsequent recovery. The monitoring module verified that the steady-state voltage levels remained within the adequate operating ranges, providing a clear visualization of the microgrid's regulation capability.

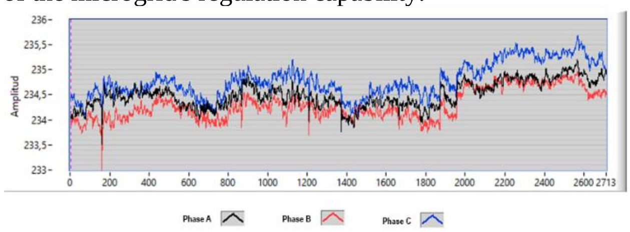

Fig. 9. Voltage RMS profile analyzed by the software during the load variations.

C. Current Profile and Load Transitions

To clearly identify the transition between operating modes, the software monitored the RMS Current profile, as shown in Fig. 10. This parameter proved to be the most sensitive indicator of system dynamics.

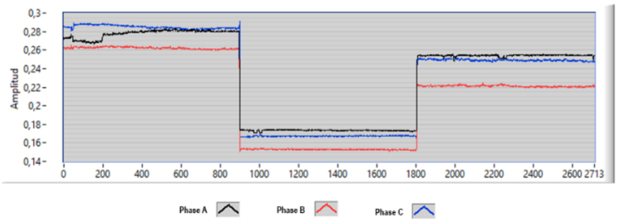

Fig. 10. RMS Current profile highlighting the load transitions and operating modes.

D. Power Factor Dynamics

Following the current analysis, the impact on Power Factor (PF) was evaluated. Fig. 11 illustrates the system's response:

Stage 1: High PF, compliant with regulatory limits.

Stage 2: Correlating with the current surge, the software detects a severe drop in PF to approximately 0.80. The "Automatic Diagnosis" module triggered a non-compliance alert, correctly identifying the violation.

Stage 3: The software captures the reactive power compensation, showing the PF recovering to 0.92.

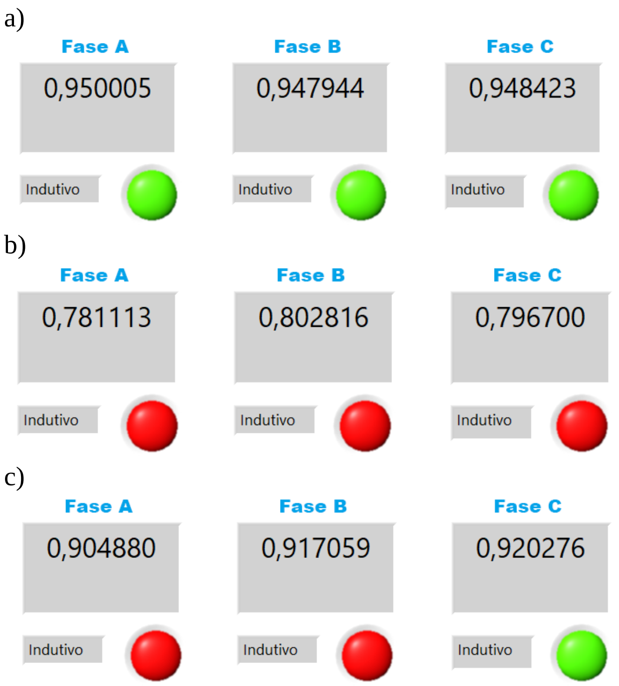

Fig. 11. Power Factor dynamics detected by the software: (a) Baseline operation; (b) Inductive load step; (c) Reactive power compensation.

E. Harmonic Distortion Analysis

The software performed the harmonic analysis. Fig. 12 presents the Total Harmonic Distortion ($\boldsymbol{THD_V}$) profile. The tool identified that, despite the non-linear nature of the load transitions, the distortion levels remained compliant with the URSEA limits ($< \mathbf{8}\%$) and PRODIST standards ($< \mathbf{10}\%$).

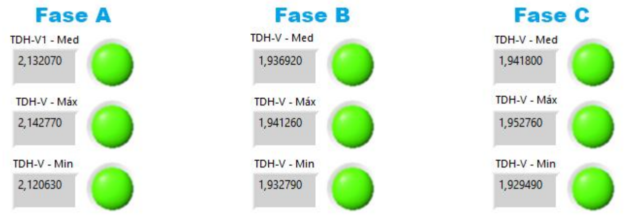

Fig. 12. Total Harmonic Distortion ($\boldsymbol{THD_V}$) analysis.

F. Power Factor Dynamics

To validate the computational accuracy of the developed LabVIEW algorithms, the software's processed outputs were directly compared against the internal calculations of the Class A Fluke 1736 reference analyzer using the same dataset. Table I summarizes the quantitative error statistics, presenting the mean error and maximum deviation for the primary electrical parameters. The analysis confirms that the digital signal processing algorithms do not introduce significant deviations, maintaining a high level of fidelity to the commercial reference equipment.

Table I. - Error statistics relative to the Fluke 1736 analyzer

PARAMETER	MEAN ERROR (%)	MAXIMUM DEVIATION
RMS Voltage (V)	< 0.05	0.02 V
RMS Current (A)	< 0.10	0.05 A
Frequency (Hz)	< 0.01	0.005 Hz
THD Voltage (%)	< 0.20	0.03 %

The results obtained demonstrate the developed software's capability to operate effectively in a dynamic microgrid environment. The cross-analysis between the RMS Current steps and the Power Factor variations confirms that the tool possesses the necessary responsiveness to detect rapid load transitions, correctly distinguishing between the operating regions. This temporal precision is critical for the control and monitoring of low-inertia systems. Furthermore, the experimental validation proved the adaptability of the diagnostic module to specific regulatory frameworks; the system successfully flagged the non-compliance event in the stage 2 while validating the frequency and voltage stability according to URSEA standards, without requiring code modifications. Finally, despite the harmonic content introduced by the PV inverters and non-linear loads, the signal processing algorithms (PLL and FFT) maintained their robustness, ensuring that the generated alerts reflected actual grid events rather than calculation artifacts, thus consolidating the software as a reliable decision-support tool for microgrid operators.

5. Conclusion

This work presented the development and experimental validation of a virtual instrumentation tool designed for Power Quality analysis in microgrids with high renewable penetration. Developed in the LabVIEW environment, the software addressed the challenge of monitoring low-inertia systems with automated diagnostic algorithms adaptable to different grid codes (PRODIST/Brazil and URSEA/Uruguay).

The experimental validation, conducted in a real microgrid environment, demonstrated the system's effectiveness under dynamic operating conditions. The results confirmed that the software is capable of:

- Robust Signal Processing: The PLL and FFT algorithms-maintained stability and accuracy even in the presence of harmonic distortions introduced by PV inverters and non-linear loads.
- Dynamic Event Detection: The tool successfully identified rapid load transitions and correctly diagnosed regulatory violations, specifically the Power Factor drop, triggering instant alerts for the operator.
- Multi-Standard Flexibility: The parametric design allowed for seamless adaptation to the Uruguayan 50 Hz context without code refactoring, validating the proposed modular architecture.

In conclusion, the developed solution provides a cost-effective and flexible alternative to commercial power analyzers, offering not just measurement, but real-time situational awareness. For future works, it is intended to integrate the software with cloud-based platforms (IoT) for remote monitoring and to implement control loops that allow the BESS to automatically compensate for the power quality deviations detected by the system. While the current architecture focuses on hardware-agnostic post-processing to maximize accessibility and ease of use, transitioning the tool to a real-time monitoring system represents a major future upgrade. Future works will aim to integrate the software with National Instruments Data Acquisition (DAQ) hardware and industrial communication protocols to enable real-time capabilities. This would allow the system to trigger immediate self-healing actions within the microgrid.

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During the preparation of this work, the author used Gemini (Google) in order to improve the readability, language, and structure of the manuscript. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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