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Unified Platform for Automated Tests of Inverter-Based Resources with Harware-in-the-loop

Luiz F. R. Menegazzo[1], **Anderson L. N. Severo**[1], **Lucas Bisêlo Piton**[1]; **Catherine Marquioro de Freitas**[1]; **Ricardo J. F. Bortolini**[1], **Lucas Vizzotto Bellinaso**[1], **Leandro Michels**[1], **Fernanda de Morais Carnielutti**[1]

[1]Federal University of Santa Maria, Power Electronics and Control Group, Santa Maria, RS, Brazil.

e-mail: luizmenegazzo@inriufsm.com.br; anderson@inriufsm.com.br; lucasbpiton@gmail.com; catherine.mfreitas@gmail.com; rjochann@gmail.com; lucas@gepoc.ufsm.br; michels@gepoc.ufsm.br; fernanda.carnielutti@gmail.com.

ABSTRACT Testing of inverter-based resources (IBRs) faces challenges in establishing standardized procedures across all product development stages. Most of the testing approaches use Hardware-in-the-Loop (HIL) during the early stages independently from the final product testing, which can lead to discrepant results. To solve these issues, this paper proposes a unified platform for automatically testing IBRs. It can be used during all product development stages, from pure simulation to Controller Hardware-in-the-Loop (CHIL) and finally on the complete commercial product, ensuring uniform test procedures with different test setups. A case study describing compliance tests of grid-connection codes of photovoltaic (PV) inverters are presented to demonstrate the proposed approach. Experimental tests were performed in accordance to Brazilian grid-connection codes in an ISO/IEC 17025 accredited laboratory. The results obtained with the proposed platform in CHIL and full-hardware showed high similarity with the ones obtained with the accredited laboratory, validating the proposed approach. In addition, the platform can be used to perform tests not specified in standards and to verify the performance of IBRs in operating conditions that are often difficult to be tested in laboratory. Ensuring consistent test procedures, the platform facilitates comparable results along all the testing stages, reducing the product development cycle.

KEYWORDS CHIL, Inverter-based Resources, Hardware-in-the-loop, Photovoltaic Inverter, Test automation, Test Platform.

I. INTRODUCTION

The development of increasingly sophisticated power electronics, such as inverter-based resources (IBR), requires comprehensive testing to ensure product safety, quality and reliability. Conventional testing approaches consider the utilization of different platforms during each stage of product development. Usually, the conformity evaluation with the required standards is only performed in laboratory during the final development stage, when the complete prototype is built. This procedure can lead to conformity problems, demanding design retrofits and resulting in increased costs and longer product development cycle.

In the context of testing and validation of IBRs, Hardware-in-the-Loop (HIL) and real-time simulations emerge as promising tools to facilitate the product development cycle. These approaches enable the replication of real-world conditions and the performance of controlled experiments in the laboratory, providing more reliable results. The use of automated test benches, both real and HIL-based, allows for more efficient and standardized compliance testing, ensuring the safety and adequate performance of IBRs connected to the electrical grid. Additionally, this approach offers greater flexibility in performing the tests.

HIL testing is extensively used in industries such as robotics [1], [2], aerospace [3], [4], naval [5] and machines/engines [6], [7] to test controllers and firmware without the necessity for complete hardware integration. HIL has also been widely applied in the field of renewable energy, enabling real-time development, testing and validation of systems. In the wind energy sector, studies explore the use of HIL for the control and analysis of wind farms [8]–[10]. Similarly, in the field of electric vehicles (EV), HIL is used in the development and validation of EV control systems [11], [12]. Particularly in power electronics and power systems, HIL technologies have been widely used as a robust method for testing and validation [13]–[16]. One of the primary uses of HIL testing is the real-time simulation of hardware connected with the converter controller, that runs the actual firmware. This process is known as Controller Hardware-in-the-Loop (CHIL). Table 1 highlights the differences between CHIL testing and traditional laboratory testing methods, showing the division of the Equipment Under Test (EUT) into firmware and hardware components.

Some papers were published discussing the application of CHIL testing in power electronics. In [18], [19], a review of methods used for EUT certification with HIL and real-

TABLE 1. Comparison of CHIL and Laboratory Testing Approaches (adapted from [17])

Approach	Test Equipments	Measurement Instruments	EUT firmware	EUT hardware
CHIL	simulated	simulated	real	simulated
Laboratory	real	real	real	real

time simulation is provided. In [20], [21] the use of HIL to test complete distributed generation systems is shown. Papers such as [22], [23] use HIL to verify the efficiency and reliability of islanding detection under various operating conditions. In [16], [24], [25], HIL is used to test the integration and stability of IBRs. Finally, [26]–[28] present testing platforms for PV inverters and their grid connection and safety functions. These papers use HIL to simulate, test and validate inverters, ensuring compliance with interconnection standards and considering aspects such as voltage regulation, frequency control and system protection. Furthermore, [28]–[30] presents a Power HIL (PHIL), where the EUT is connected to power sources that emulate the dynamics of the electric power system in real-time.

These papers address the development of testing platforms for EUTs aiming to enhance their integration and interoperability with the electrical grid. They explore different approaches, such as CHIL and PHIL test benches, and highlight the benefits of these techniques in terms of efficiency, cost, and validation of grid support functions. However, a major challenge for HIL-based certification is the absence of standardized and automated procedures that can be consistently applied across all development stages, from initial pure simulation, passing through CHIL or PHIL testing, and finishing with laboratory testing of the complete EUT, including product certification in the laboratory. This lack of uniform, validated and automated processes can result in uncertainties and ambiguities during testing. The referenced papers do not directly address these issues.

One can observe that most IBRs must comply with different grid codes or standards. These standards may have international coverage such as IEEE 1547 [31], IEEE 2800 [32], and new IEC 63409-1/7 (under development), regional coverage such as EN 50549-1/2 [33], or even national coverage such as ABNT NBR 16149 [34], ABNT NBR 16150 [35], and INMETRO ordinance No. 140 [36] which are only applicable in Brazil. Papers addressing automatic test benches and specific laboratory automation software to perform these test have been published. Figueira et al. [37] focuses on automating a laboratory to perform tests of the old Brazilian grid connection standard, while [38] focuses on automating tests of the Chinese standard.

The objective of this paper is to address the limitations of previous works and to introduce an automated testing platform for IBRs. The proposed platform extends and generalizes the concept introduced in [17] to work in different environments, including pure simulation, CHIL, and real laboratory. The Typhoon HIL® TyphoonTest platform was chosen as it allows to write Applications Programming Interface (APIs) in the Python programming language, interacting with HIL devices and Typhoon HIL software tools during runtime. This approach provides flexibility and adaptability for both research and product development needs. Users can select the testing mode that best fits the current phase of development, and the reports with the test results are automatically generated. The platform can evaluate multiple operational conditions, helping in the identification of issues for various scenarios. By maintaining consistent test procedures across all test environments, the platform ensures that the results are comparable to those from accredited laboratories. This significantly reduces the time required to transition from initial product development to final certification.

The main contributions of this paper are:

- Detailed description of the developed platform for automated testing of IBRs;
- Demonstration of the platform capability to perform tests in different environments;
- Demonstration of the platform ability to perform multiple tests by changing test parameters;
- Validation of the proposed platform through comparison of CHIL results with the real laboratory.

The main differences compared to [17] are:

- An extended literature review;
- A more detailed description of the platform structure, operation and test environments;
- New comparative results between CHIL and real laboratory;
- Results from tests changing the grid impedance.

In section V this paper presents experimental results of a case study that compares the performance of the proposed platform with that of the accredited laboratory at the Smart Grid Institute (INRI), Federal University of Santa Maria (UFSM). Additional CHIL tests were also performed for other conditions, such as variations in the grid impedance. The tests were performed using a commercial single-phase inverter with a nominal power of 1.5kW. The specific tests included undervoltage disconnection time, overfrequency disconnection level, direct current component measurement and total harmonic distorction (THD) measurement.

II. PLATFORM ENVIRONMENTS

The platform was developed with a layered architecture, where the test procedures are performed in the same way regardless of the test environment. This ensures consistency and repeatability of the tests being performed. Three distinct test environments are presented: fully virtual, fully physical and hybrid, implemented as a CHIL setup.

A. Virtual-Hardware-in-the-Loop (VHIL)

The virtual environment is fully simulated in the Virtual HIL (VHIL). The software used for the simulation of the electrical and electronic elements is the Typhoon HIL Control Center (THCC) and the inverter control is implemented in a C block within the schematic. As it is a pure simulation, this test environment has lower fidelity compared to a real environment, but it is a fast, safe and low-cost way of performing initial tests, making it easier to test the inverter firmware in the early development stages. The VHIL testbench schematic is seen in Figure 1.

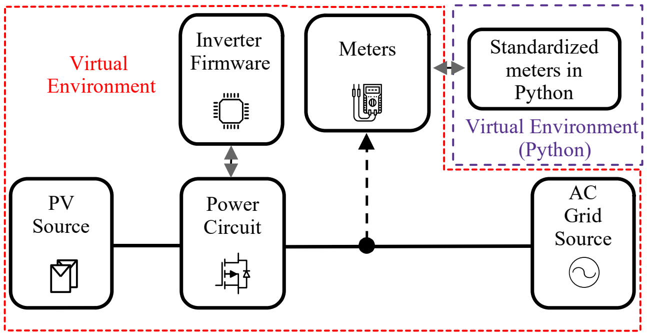


FIGURE 1. VHIL testbench schematic.

B. Controller-Hardware-in-the-Loop (CHIL)

The hybrid test environment, implemented as CHIL, is a combination of simulated and real components. In this setup, the power schematic of the inverter, sources and measurement instruments are simulated, while the inverter firmware is real. The connection between these elements is done through interface boards that connect the real firmware to a real-time simulation device using both analog and digital inputs and outputs. In this case, the device is the HIL 604, which can be seen in Figure 2 along with an example of the CHIL setup. The CHIL testbench schematic is seen in Figure 3. The analog and digital I/Os of the HIL equipment are interfaced with the A/Ds and PWMs of the microcontroller via an interface board. These signals are conditioned to interact with the analog input pins of the microcontroller, emulating the inputs from the actual inverter hardware. The inverter firmware controls the simulated hardware by sending PWM signals to the HIL digital inputs. This configuration allows testing of the inverter control system prior to its integration with the physical hardware.

C. Real Laboratory

The real test environment comprises a laboratory equipped with sources and measurement instruments to perform the tests of IBRs such as commercial PV inverters (considered here as the EUT). In this environment, the test procedure is performed using real laboratory equipment, controlling the sources and receiving data from the measuring instruments. All components are real, yielding more reliable results. However, this comes at the expense of reduced safety and significantly higher costs. The real testbench schematic is seen in Figure 4.

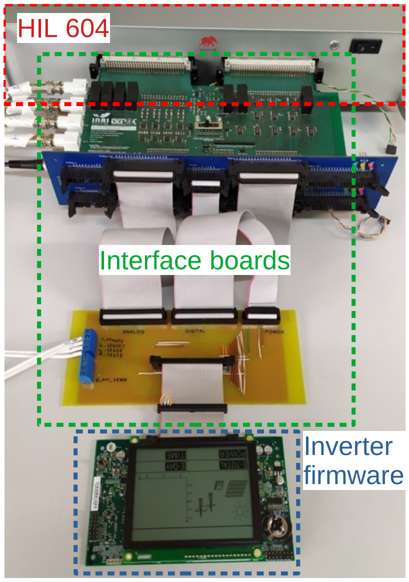


FIGURE 2. Example of connection board between HIL simulator and controller for CHIL testing (adapted from [17]) .

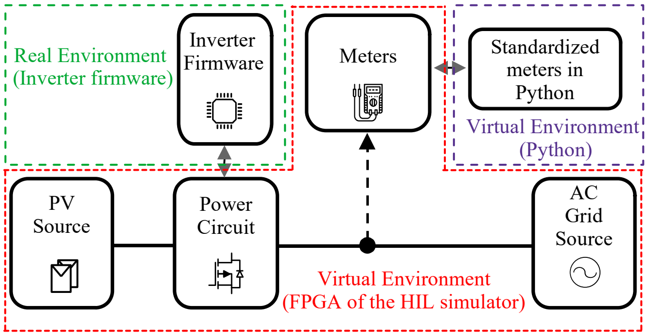


FIGURE 3. CHIL testbench schematic.

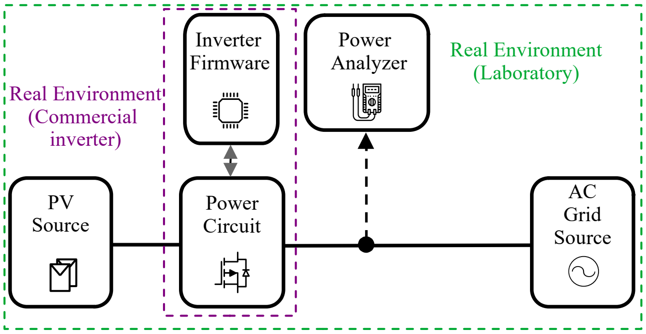


FIGURE 4. Real testbench schematic.

III. PLATFORM STRUCTURE

The platform is programmed in Python and was designed using object-oriented programming with multiple layers. The main Python library used was TyphoonTest, which is a test automation library from Typhoon HIL. This architecture allows for the inclusion or modification of tests without the need to modify other programming layers, ensuring that the same test scripts can be used with different environments. The platform also supports automated and customizable testing, enabling the inclusion of different parameterizations for the same test and the execution of predefined sets of tests. This automation significantly reduces the time required to perform the tests compared to manual testing. The platform is divided into three layers:

A. Higher layer - Test files

The higher programming layer is where the test procedure files are located. In each file, the step-by-step procedure of a specific test is implemented. These tests are ”blind” in relation to the environment, this is because of the test files calls some functions to perform the test procedure, for example: ”Set equipment to nominal conditions,” ”Increase grid voltage by 1 Volt,” ”Start data capture,” among others. These functions are defined in lower layers of the platform. As a result, adding a new test to the platform or modifying existing ones is simple.

The basic structure of a test follows nine steps:

1) **Step 1**: Performs the initial test setup, such as compiling a schematic or loading libraries.
2) **Step 2**: Initializes the test elements, whether simulation or communication with real equipment.
3) **Step 3**: Waits until the EUT reaches steady-state.
4) **Step 4**: Configures and starts data capture for the test.
5) **Step 5**: Performs all steps for the test procedure.
6) **Step 6**: Finalizes data capture and collects the data.
7) **Step 7**: Post-processes the collected data according to the test requirements.
8) **Step 8**: Checks if the EUT passed or failed the test.
9) **Step 9**: Generates the final report presenting the results and other relevant information.

In this layer, there are also configuration files for each test procedure. The role of the configuration file is to set up and parameterize the test, for example, selecting which signals are captured, defining the capture times and specifying test conditions.

B. Middle layer - Driver files

The middle programming layer contains the driver files of the platform, that define the functions used in the tests. For example, if a test includes a function ”increase the grid voltage by x Volts,” the driver defines how this function will be performed. Each environment has its own drivers, for example the driver for a simulated environment sends a command to increase the grid voltage for the simulated grid source. In a real environment, the driver sends the command to a real grid emulator according to the communication protocol established by the manufacturer. There are three different types of drivers, each consisting of two files: one defines the driver parameters, and the other defines the functions used by the tests. The drivers are:

1) **Test environment driver**: defines the parameters of the test environment, such as whether it is a simulated or real environment, the voltage limits of the sources, the communication protocols, etc. It is also where the functions used by the tests are defined, such as functions for changing grid voltage or frequency, adjusting the power of the PV source, etc.
2) **EUT driver**: defines the parameters of the EUT, such as nominal voltage and power. It also defines functions related to the EUT, such as limiting the power of the equipment or turning off the EUT.
3) **Capture driver**: defines the functions for data capture during tests. If it is a real environment, it involves communication with a commercial power analyzer. If it is a virtual environment, it uses the standardized functions developed for the platform, explained below.

In the capture driver, to meet the requirements of accreditation laboratories and to replicate the functionalities of certified and calibrated power analyzers used in certification testing laboratories, post-processed functions for the calculation of electrical quantities were developed in Python. These functions were developed to comply with specific standards, including IEC 61000-4-30 [39], IEC 61000-4-7 [40], IEC 61000-4-15 [41], and IEC TR 61000-1-7 [42]. They process raw data collected during tests and provide the necessary measured values for test analysis. The use of these standardized functions in Python enhances the accuracy and reliability of the tests, ensuring compliance with the standards. These functions were developed using specific algorithms to ensure consistent results that comply with the mentioned standards, and were validated using the following procedures:

1) **Direct comparison with standardized meter:** Here, identical waveforms were injected into both the developed functions and a calibrated energy analyzer, in this case the LMG670 energy analyzer. By comparing the outputs, the relative error between the signals was calculated. The results from all these tests indicated that the relative error was consistently less than 0.5%.
2) **Comparison with pre-established signals:** In this alternative method, a signal with fully known characteristics (such as RMS value, active and reactive power, harmonics, etc.) was generated. This signal was then fed into the functions, and the relative error between the known signal and the calculated result was analysed. In the results of all tests, the relative error consistently remained below 0.5%.

C. Lower layer - Platform configuration file

This layer is the platform configuration file, that specifies which drivers are used, including those for test environment, EUT driver and data capture driver. This configuration file determines whether the environment is virtual (VHIL), hybrid (CHIL) or real (laboratory). This layer and the object-oriented programming facilitates a structured and scalable code framework. This approach enhances flexibility in modifying test procedures by focusing changes on the relevant driver files, without modifying other components, thereby optimizing development efficiency and reducing overall effort to test the equipment.

The proposed structure, based on programming layers, allows for the inclusion of new grid connection tests for IBRs with minimal effort. When additional tests use the same setup, it is only necessary to include new parameters or procedures in the files of the upper layer, using the functions already created. For example, the IEEE 1547 [31] standard contains several tests that follow the same procedures but require different parameters. On the other hand, if the test setup differs from those already implemented, a new one can be added to the drivers of the middle layer and used for tests already developed in the upper layer. For example, by changing the middle layer, the platform is able to perform tests on single-phase or multi-phase inverters.

IV. CASE STUDIES

In this section, two case studies that were used to validate the proposed platform will be presented. The first case study is to validate the platform by reproducing standardized grid connection tests for PV inverters, obtaining comparative results between the same equipment being tested using the platform in CHIL and in a real laboratory, in addition to comparing them with results obtained from tests in an accredited laboratory. The second case study is to validate the platform capability to perform the same test several times, but changing parameters. In this way, tests were performed by changing the grid impedance and evaluating the impact on the EUT.

A. CASE STUDY 1: EVALUATION OF GRID-CODE COMPLIANCE OF PV INVERTERS

Certification standards for PV inverters are constantly updated to improve the safety and reliability of these devices, reflecting the increasing demand for grid-connected systems and the need to safeguard electrical infrastructure. In Brazil, the certification tests for PV inverters are currently defined by INMETRO Ordinance No. 140 [36]. According to it, the typical test setup for PV inverter certification includes a PV source connected to the DC side of the inverter, a grid simulator connected to the AC side, a standardized energy analyzer for measurements and a computer equipped with laboratory automation software to control the testing procedures. All sources and equipment must comply with minimum quality standards. Figure 4 illustrates an example of a PV testing schematic.

Some of the tests described in [36] include flicker, measurements of DC current injection, THD and power factor, voltage and frequency trip level and trip time, active power control in response to frequency variations, reconnection tests, immunity to transient faults, anti-islanding, etc. In this paper, results for four tests will be presented: overfrequency and undervoltage disconnection time, as well as THD and DC current measurements, that are briefly explained below:

1) **Overfrequency Disconnection Level:** The inverter is required to disconnect at a frequency of 62.0±0.1Hz;
2) **Undervoltage Disconnection Time:** The inverter must disconnect from the grid within 400ms when the grid voltage drops below 80% of the nominal voltage;
3) **DC Component:** The DC current injected or absorbed by the inverter must be less than 0.5% of the inverter nominal AC current;
4) **THD:** The current THD must be less than 5% when the inverter operates at nominal power.

B. CASE STUDY 2: EVALUATION OF IMPACT OF GRID IMPEDANCE VARIATION ON PV INVERTERS

One of the advantages of the modular design of the platform is the possibility to automate tests for operating conditions different from those specified in the standards. This includes performing the same standardized tests while varying parameters such as grid connection voltage, grid harmonics, and grid impedance. Such tests, which would otherwise require significant time and manual adjustments of the parameters, can be efficiently performed using CHIL testing and automation. To perform these tests, specific impedance values need to be defined to evaluate the performance of the EUT in different grid situations, where its impedance is not ideal.

For the definition of the grid impedances, the worst-case impedance for a real-world scenario is considered, where the equivalent grid impedance is the sum of the low-voltage cable impedance Z_{LV} and the transformer impedance Z_{TR} between medium and low voltage line, as illustrated Figure 5. The medium-voltage impedance Z_{MV} is not considered. These particular impedance values are defined for the 1.5 kW inverter that will be considered in the experimental results.

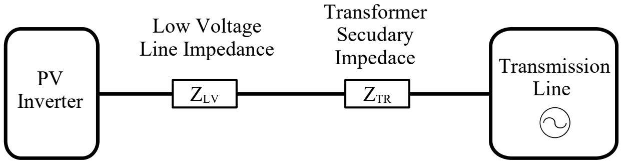


FIGURE 5. **Definition of the equivalent grid impedance.**

To calculate Z_{LV}, a distance of 100 meters was considered with a cable cross-sectional area of 2.5 mm^2. Using manufacturer data, the cable resistivity is approximately 8.87 mΩ/m and the reactance is approximately 0.4 mΩ/m. Thus, Z_{LV} can be defined as:

$$Z_{LV} = 8.87\times10^{-3}\times100\times2+(0.41\times10^{-3}\times100\times2)i; \quad (1)$$

$$Z_{LV} = 1.774 + 0.082i\,\Omega. \quad (2)$$

For the transformer impedance Z_{TR}, a transformer with a base voltage of 220 V, nominal power of 5 kW, typical impedance of 3%, and an X/R ratio of 3.5 was considered. The reflected impedance to the secondary side is:

$$Z_{LV(Secondary)} = \frac{(220)^2}{5 \times 3} \times \frac{1}{100} = 0.2904\,\Omega. \quad (3)$$

With the secondary impedance and an X/R ratio of 3.5, the transformer impedance Z_{TR} was calculated as $0.08 + 0.279i\,\Omega$.

Finally, to determine the total worst-case impedance for the inverter, the three impedances were summed:

$$Z_{total} = Z_{LV} + Z_{TR} \approx 1.8 + 0.4i\,\Omega. \quad (4)$$

For the tests, six different impedances were defined:

1) No impedance;
2) $0.5Z = 0.9 + 0.2i\Omega$;
3) $0.8Z = 1.44 + 0.32i\Omega$;
4) $0.9Z = 1.62 + 0.36i\Omega$;
5) $Z = 1.8 + 0.4i\Omega$;
6) $1.1Z = 1.98 + 0.44i\Omega$.

V. EXPERIMENTAL RESULTS

In this section, results will be presented regarding the two case studies presented in the previous section. All tests were performed using a single-phase PV inverter with a nominal active power of 1.5kW and nominal voltage of 220V. All testing procedures followed the guidelines of [36].

First referring to case study 1, overfrequency disconnection level and undervoltage disconnection time tests provide comparative results for the same EUT tested in CHIL and real laboratory using Tytest (this is how the platform presented in the paper was named in the results figures), in addition to the results obtained with the platform, the test result is also presented with the test performed in the accredited laboratory of the Smart Grid Institute - INRI, Federal University of Santa Maria - UFSM, using the laboratory's own automation system. Other comparative results were presented in [17].

In addition, referring to case study 2, THD and DC component measurement tests were performed by changing the grid impedance.

A. TESTS ACCORDING TO THE BRAZILIAN STANDARD

The overfrequency disconnection level and undervoltage disconnection time tests were performed with the same EUT in three different environments: In the accredited laboratory using its own automation and with the developed platform using both CHIL and the real equipment.

For the overfrequency disconnection level test, the grid frequency is incremented, and the frequency in which the EUT disconnects is recorded. Figure 6 illustrates the comparison of the overfrequency trip level test, where the lines representing CHIL, accredited laboratory, and the real bench using the platform show overlapping results. The test results demonstrated that the inverter disconnected at 62Hz in all environments, indicating consistent behavior for different testing conditions.

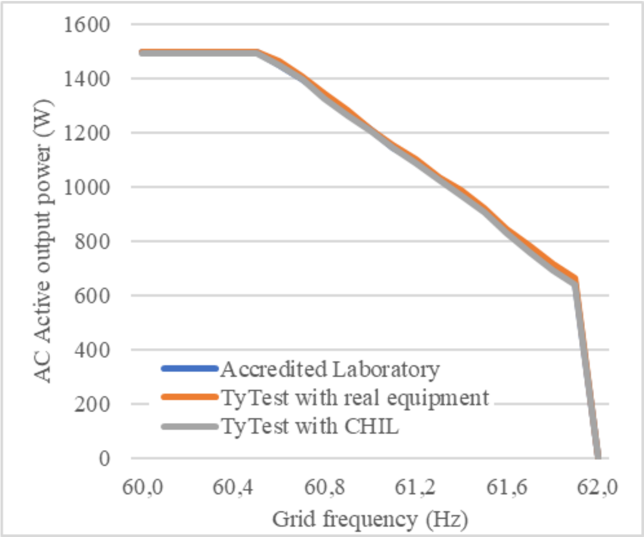


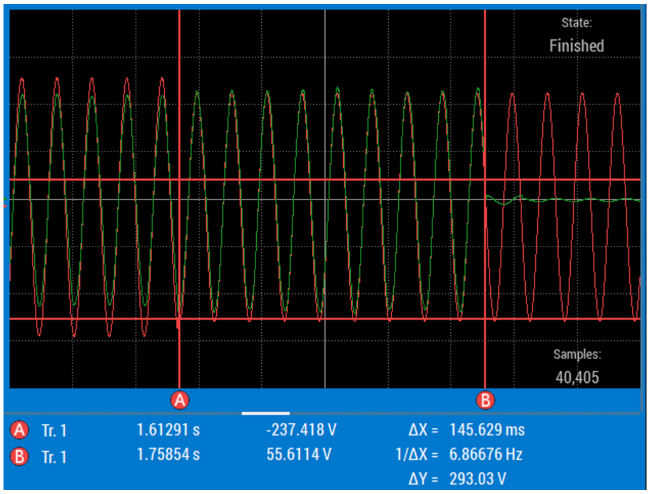
FIGURE 6. Comparative results for overfrequency level disconnection test .

For the undervoltage disconnection time test, an undervoltage step is applied to the grid, and the time at which the EUT disconnects is recorded. Figure 7 illustrates the results from the undervoltage trip time test performed at the INRI accredited laboratory without the proposed platform, showing a disconnection time of 145.63ms. Figure 8 depicts the same test using the proposed platform on a real bench, with measured disconnection time of 147.29ms. Finally, Figure 9 shows the test results performed using the proposed platform with CHIL, recording a disconnection time of 146.86ms. Comparison among these results reveals minimal variation, with a maximum difference of 1.66ms. This highlights the platform high fidelity to real-world conditions, even with CHIL testing.

The presented tests are important to ensure the stability and quality of energy generated by IBRs when integrated in the electrical grid. Each test, in accordance to current standards and platform specifications, analyze the assurance of energy safety, stability, and quality across diverse operating conditions. Experimental results from platform testing, including those performed in CHIL environments, are very similar to results from accredited laboratory tests. The consistency of the results, facilitated by identical Python-scripted procedures in both CHIL and lab settings, indicated that any discrepancies were not attributable to scripting or firmware. Rather, differences likely resulted from calibration inaccuracies, variations between real-time simulation models and the characteristics of laboratory equipment and EUTs.

B. Tests changing grid impedance

The impedance variation was performed for THD and DC current injection tests. In these tests, the EUT is connected



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A Tr. 1    1.61291 s    -237.418 V     ΔX = 145.629 ms
B Tr. 1    1.75854 s    55.6114 V    1/ΔX = 6.86676 Hz
                                       ΔY = 293.03 V
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FIGURE 7. Comparative results for undervoltage time disconnection test in accredited laboratory (voltage in red and current in green).

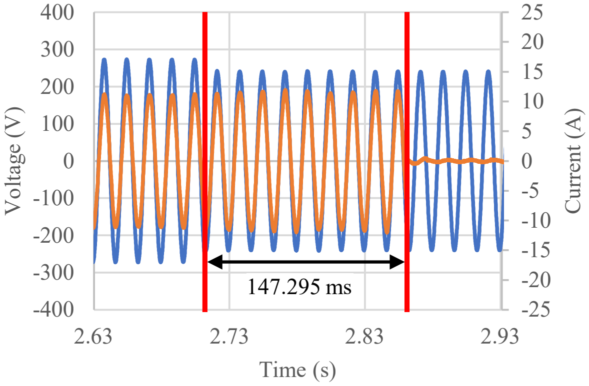

FIGURE 8. Comparative results for undervoltage time disconnection test using proposed platform in real laboratory (voltage in blue and current in orange).

to the grid, and these indexes are measured when the equipment reaches steady-state at nominal power. Each test was performed six times, varying the impedance according to the values defined in section B. The results show each test for the inverter nominal power with each impedance condition.

Impedances between 1% and 80% of Z did not significantly affect the control of the inverter. The selected values are not much greater than Z to ensure that the inverter does not disconnect due to overvoltage. The inverter exhibits robust control, unaffected by low impedances. It can be observed from tests that, as the grid impedance increases, the levels of direct current component (Figure 10) and THD (Figure 11) also increase. This phenomenon is attributed to the influence of grid impedance on the inverter control. The control exhibited robustness, as, even with different results, the inverter did not fail the test.

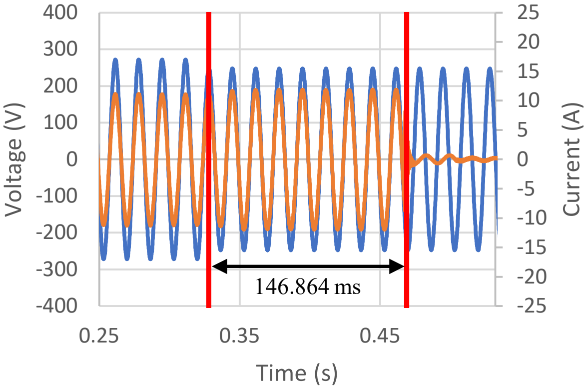

FIGURE 9. Comparative results for undervoltage time disconnection test using proposed platform with CHIL (voltage in blue and current in orange).

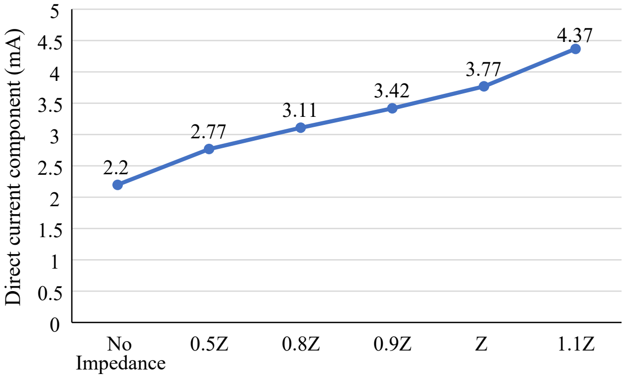

FIGURE 10. Comparison of DC component test varying the grid impedance

VI. CONCLUSION

This paper addresses the challenges of implementing consistent test procedures for various stages of PV inverter development, from early stages to certification. Previous efforts in this area have largely focused on automating laboratory or HIL testing, but lacked a unified solution covering the entire development cycle. To overcome these challenges, this paper proposed an automated testing plat-

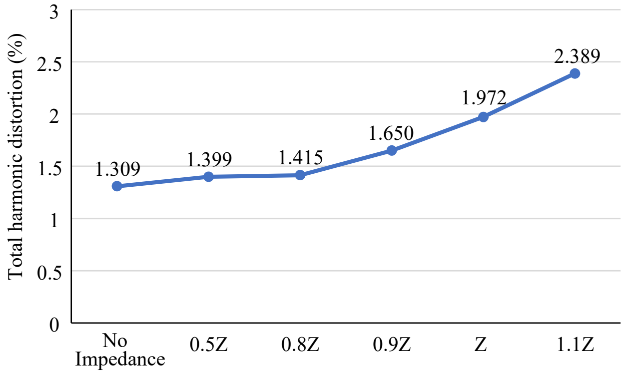

FIGURE 11. Comparison of THD test varying the grid impedance

form developed in Python. This platform performs automated test procedures in VHIL, CHIL and traditional laboratory setups. As a case study, a PV inverter was tested according to the Brazilian standard for certification of PV inverters. The results demonstrate significant benefits for the energy industry, such as the possibility of perform tests in CHIL with results similar to real tests. By enabling automated, rapid and simplified set of tests with parameter variations, this platform streamlines the development and validation of new products. This approach reduces time and costs associated with traditional testing methods. Future works aim to expand the platform to standards such as IEEE 1547 [31], IEEE 2800 [32] and the new IEC 63409 standards that are currently under development and which tend to standardize the requirements for connecting IBRs to grid.

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AUTHOR'S CONTRIBUTIONS

MENEGAZZO, L. F. R.: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. **SEVERO, A. L. N.**: Data Curation, Investigation, Methodology, Software, Validation. **PITON, L. B.**: Investigation, Methodology, Software, Validation, **DE FREITAS, C. M.**: Investigation, Writing – Original Draft. **BORTOLINI, R. J. F.**: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Resources, Validation, Visualization, Writing – Review & Editing. **BELLINASO, L. V.**: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Supervision, Visualization, Writing – Review & Editing. **MICHELS, L.**: Conceptualization, Funding Acquisition, Methodology, Project Administration, Resources, Supervision, Writing – Review & Editing. **CARNIELUTTI, F. M.**: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Supervision, Visualization, Writing – Review & Editing.

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BIOGRAPHIES

Luiz Fernando Rissotto Menegazzo received his B.S. degree in Electrical Engineering in 2021, followed by his M.Sc. degree in Electrical Engineering from the Federal University of Santa Maria (UFSM), Santa Maria, Brazil, in 2023. He has been a researcher with the Power Electronics and Control Group (GEPOC) since 2018. His research interests include hardware-in-the-loop, test automation, photovoltaic systems, and power electronics. Additionally, he is a member of the technical standards committees ABNT/CB-003/CE 003 082 and IEC/TC 82.

Anderson Luis do Nascimento Severo graduated in control and automation engineering in 2021 from the Federal University of Santa Maria (UFSM), Santa Maria, Brazil, where he obtained a master's degree in electrical engineering in 2024. He is currently Technical Manager of the Photovoltaic Testing Laboratory at Federal University of Santa Maria and Researcher at the Power and Control Electronics Research Group (GEPOC) at UFSM. His research interests include measurement algorithms for test certification, uncertainty analysis, photovoltaic inverters and power electronics for renewable energy.

Lucas Bisêlo Piton received the bachelor's degree in electrical engineering in 2024 from the Federal University of Santa Maria (UFSM), Santa Maria, Brazil. He currently works at WEG SA in the commercial engine research and development sector, Jaraguá do Sul, Brazil.

Catherine Marquioro de Freitas obtained her bachelor's degree in electrical engineering in 2020 from the Universidade Regional do Noroeste do Estado do Rio Grande do Sul (UNIJUÍ), Ijuí, Brazil. She received her master's degree in electrical engineering in 2023 from the Federal University of Santa Maria (UFSM), Santa Maria, Brazil. She currently works at the Integrated Operations Center of the energy distributor CEEE-D Equatorial, Porto Alegre, Brazil.

Ricardo Jochann Franceschi Bortolini , received the B.Sc. in Control and Automation Engineering by Federal University of Santa Maria (UFSM) in 2015, M. Sc. and Dr. in Electrical Engineering from Federal University of Santa Maria (UFSM) in 2018 and 2023 respectively. He worked as Technical Manager at the Photovoltaic Inverters Testing Laboratory in the Smart Grids Institute (INRI-UFSM), from 2017 to 2023. Since 2023, he is R&D&I Project Manager at the INRI-UFSM Embrapii unit (Brazilian Company of Research and Industrial Innovation). Besides, he is a researcher at GEPOC and a member of SOBRAEP and IEC. Your main research interests include renewable energy, power electronics, system testing and validation and hardware-in-the-loop.

Lucas Vizzotto Bellinaso received his B.S. and M.S. degrees in electrical engineering in 2012, followed by his M.Sc. and Ph.D. degrees in electrical engineering from the Federal University of Santa Maria (UFSM), Santa Maria, Brazil, in 2014 and 2017, respectively. Since 2015, he has been with the Power Electronics and Control Group (GEPOC) at the same university, where he is currently Professor. His research interests include PV systems, power electronics and control applied to renewable energy systems, and safety of PV systems. Additionally, he is currently National Secretary of ABNT/CB-003/CE 003 082, the Brazilian mirror committee of IEC TC 82.

Leandro Michels (S'97 M'08) received the B.S and Ph.D. degrees from the Federal University of Santa Maria (UFSM), Brazil, in 2002 and 2006, respectively, both in electrical engineering. Since 2009 he has been with the Power Electronics and Control Research Group (GEPOC) at UFSM, where he is currently an Associate Professor. He was director of Smart Grids Institute (INRI/UFSM) and of the Unit on Energy and Mobility of Brazilian Company of Research and Industrial Innovation (Embrapii). Dr. Michels is Research Productivity Grant level DT-1A of Brazilian National Council for Scientific and Technological Development (CNPq). He has works in the field of photovoltaic systems as manager of the laboratory of PV inverters, in working groups to develop of IEC and Brazilian photovoltaic standards, as well as in R&D projects with industry. His current research interests include photovoltaic systems, modeling and control of static converters and standards compliance.

Fernanda de Morais Carnielutti received the bachelor's degree in electrical engineering in 2010 from the Federal University of Santa Maria (UFSM), Santa Maria, Brazil, where she received the master's and doctoral degrees in electrical engineering in 2012 and 2015, respectively. From 2016 to 2018, she was a Professor with the Federal University of Santa Maria, campus Cachoeira do Sul. She is currently a Professor with the Federal University of Santa Maria, campus Santa Maria and a Researcher with the Power Electronics and Control Research Group (GEPOC), UFSM. Her research interests include control and modulation of static power converters, multilevel converters, power electronics for renewable energies, microgrids and model predictive control. Dr. Carnielutti is a member of the IEEE Power Electronics Society, IEEE Industrial Electronics Society, and IEEE Industry Applications Society.