FEDERAL UNIVERSITY OF SANTA MARIA
CENTER OF TECHNOLOGY
POSTGRADUATE PROGRAM ON ELECTRICAL ENGINEERING

Ricardo Jochann Franceschi Bortolini

CONTRIBUTIONS FOR COMPLIANCE TESTING OF INVERTER-BASED RESOURCES USING HARDWARE IN-THE-LOOP

Santa Maria, RS
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Doctoral exam presented to the Postgraduate Program in Electrical Engineering, from the Federal University of Santa Maria (UFSM, RS, Brazil), as a requirement to obtain the title of **Doctor in Electrical Engineering.**

Advisor: Prof. Dr. Leandro Michels

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Bortolini, Ricardo
CONTRIBUTIONS FOR COMPLIANCE TESTING OF INVERTER BASED RESOURCES USING HARDWARE IN-THE-LOOP / Ricardo Bortolini.- 2023.
185 p.; 30 cm

Orientador: Leandro Michels
Tese (doutorado) - Universidade Federal de Santa Maria, Centro de Tecnologia, Programa de Pós-Graduação em Engenharia Elétrica, RS, 2023

1. Inverter based resources 2. Hardware-in-the-loop 3. Real-time Simulation I. Michels, Leandro II. Título.

Sistema de geração automática de ficha catalográfica da UFSM. Dados fornecidos pelo autor(a). Sob supervisão da Direção da Divisão de Processos Técnicos da Biblioteca Central. Bibliotecária responsável Paula Schoenfeldt Patta CRB 10/1728.

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Santa Maria, RS
2023

I dedicate this work to my family, especially my parents Anilton and Clea, for all the support they have always given me throughout my journey. I also dedicate this to my girlfriend, Ana Paula, for her love and companionship at all times.

ACKNOWLEDGEMENT

This work was only possible thanks to the collaboration of several people, whom I would like to thank.

To God, for being the greatest force in the universe and without whom nothing would be possible.

To my family, which is the basis of everything in my life, especially to my parents, Anilton and Clea, who have always supported and accompanied me throughout my journey, thank you very much.

To my girlfriend, Ana Paula, for always being attentive and companionable, even in difficult moments, when things didn't seem to work, or the results weren't achieved.

To all my friends for the moments of leisure and relaxation, which serve to recharge our strength and move forward.

To my friend and advisor, Prof. Leandro Michels, for the opportunities made available, for the excellent guidance, since the graduation days, and for the friendship maintained throughout these years.

To the other professors who directly or indirectly participated in this work. Professors Fernanda de Morais Carnielutti, Lucas V. Bellinaso, Rafael Beltrame, and all other GEPOC professors and researchers.

To my colleagues and friends in the laboratory for their help in the development of the project, and for all the support provided during all this time, which made this project a reality. And a special thanks to the ones that directly helped in this project through opinions, comments, figures, codes, among other things, Alisson Mazzorani, Anderson Severo, Lucas Piton, Luiz Fernando, Miréli Vendrusculo, Paulo Roberto.

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES/PROEX) - Financing Code 001.

The author thanks INCTGD, CAPES, CNPq and FAPERGS for the financial support received for the development of this work. This work was carried out with the support of the INCT and its funding agencies (CNPq process 465640/2014-1, CAPES process No. 23038.000776/2017-54 and FAPERGS 17/2551-0000517-1).

“It’s a dangerous business, Frodo, going out your door. You step onto the road, and if you don’t keep your feet, there’s no knowing where you might be swept off to.”

Frodo

ABSTRACT

CONTRIBUTIONS FOR COMPLIANCE TESTING OF INVERTER-BASED RESOURCES USING HARDWARE IN-THE-LOOP

AUTHOR: Ricardo Jochann Franceschi Bortolini
ADVISOR: Prof. Dr. Leandro Michels

Renewable generation through inverter-based resources (IBR), such as solar photovoltaic (PV) and wind power, is the fastest-growing energy source worldwide. Many utility-scale PV and wind farms have been built using multi-megawatt size inverters, which are directly connected to the bulk power system (BPS). This application demands detailed system studies to evaluate the impact of those IBR operating into the power grid, as well as compliance testing of the inverters for assurance of their security and performance. Nowadays, the compliance testing of those equipment is performed using fully assembled inverters in an accredited laboratory. However, there are only a few laboratories worldwide qualified to test this kind of equipment, since the testing setup for multi-MW size inverters is large and expensive. Due to this, many efforts are being performed to the development of hardware in-the-loop (HIL) for compliance testing of IBR. In this approach, HIL is being used for real-time simulation of power converters and power system, allowing the testing of control and protections performance at any power range. This work presents a contribution in the classification of HIL and power HIL (PHIL) testing, as well as proposes complementary requirements for compliance testing using hardware in-the-loop (THIL) to obtain results with similar confidence with full-power equipment testing in conventional certification laboratories.

Keywords: Inverter based resources, Hardware-in-the-loop, Real-time Simulation.

RESUMO

CONTRIBUIÇÕES PARA TESTES DE CONFORMIDADE DE RECURSOS BASEADOS EM INVERSORES UTILIZANDO HARDWARE-IN-THE-LOOP

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ORIENTADOR: Prof. Dr. Leandro Michels

A geração renovável através de recursos baseados em inversores (RBI), como energia solar fotovoltaica (FV) e energia eólica é a fonte de energia com crescimento mais rápido em todo o mundo. Muitos parques fotovoltaicos e eólicos foram construídos usando inversores com potência de vários megawatts e estão diretamente conectados ao sistema de energia. Esta aplicação exige estudos detalhados do sistema para avaliação do impacto dos RBI operando na rede elétrica, bem como testes de conformidade dos inversores para garantia de seu desempenho e segurança. Atualmente, os testes de conformidade desses equipamentos são feitos com inversores totalmente montados em laboratório certificado. No entanto, existem apenas alguns laboratórios em todo o mundo qualificados para testar estes equipamentos, uma vez que a estrutura para testes de inversores de vários megawatts de potência é grande e cara. Devido a isso, muitos esforços estão sendo feitos para desenvolver testes de conformidade de RBI utilizando hardware-in-the-loop (HIL). Nesta abordagem, os equipamentos HIL estão sendo utilizados para simulação em tempo real de conversores de potência e sistemas de potência, permitindo testar o desempenho das proteções e sistemas de controle em qualquer faixa de potência. Este trabalho apresenta uma contribuição para a classificação de HIL e power hardware-in-the-loop (PHIL), bem como propõe requisitos complementares para testes de conformidade utilizando hardware-in-the-loop (THIL) para obter resultados com nível de confiança semelhantes aos resultados obtidos com testes em escala real realizados em laboratórios de certificação convencionais.

Palavras-chave: Recursos baseados em inversores, Hardware-in-the-loop, Simulação em tempo real.

INDEX OF FIGURES

INDEX OF TABLES

ACRONYMS AND ABBREVIATIONS

ABS	Anti-lock braking system
AC	Alternating Current
ADS	Automated driving system
AIT	Austrian Institute of Technology
ANVISA	Brazilian Health Regulatory Agency
BESS	Battery Energy Storage Sytem
CHIL	Controller Hardware-in-the-loop
DC	Direct Current
DER	Distributed energy resources
DG	Distributed generation
ECS	Electronic stability control
ECU	Engine control units
ENIAC	Electronic Numerical Integrator and Calculator
EPO	European Patent Office
EUT	Equipment under test
HIL	Hardware-in-the-loop
IBR	Inverter-based Resources
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
Inmetro	National Institute of Metrology, Standardization and Industrial Quality
INRI	Smart Grid Institute
IREC	Interstate Renewable Energy Council
JPO	Japanese Patent Office
LCRG	Linear congruential random-number generator
LVRT	Low voltage fault ride through
NASA	National Aeronautics and Space Administration
NE	Normalized Error
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
NRTL	Nationally Recognized Testing Laboratories
ONS	National Power System Operator
PEI	power electronics interface
PF	Power Factor
PHIL	Power Hardware-in-the-loop
PV	Photovoltaic
RCI	Research Center Imarat
SAE	Society of Automotive Engineers
SHIL	Software-in-the-loop
SIRFN	Smart Grid International Research Facility Network
SNL	Sandia National Laboratories
SPLs	Simulation programming languages
SVP	System Validation Platform

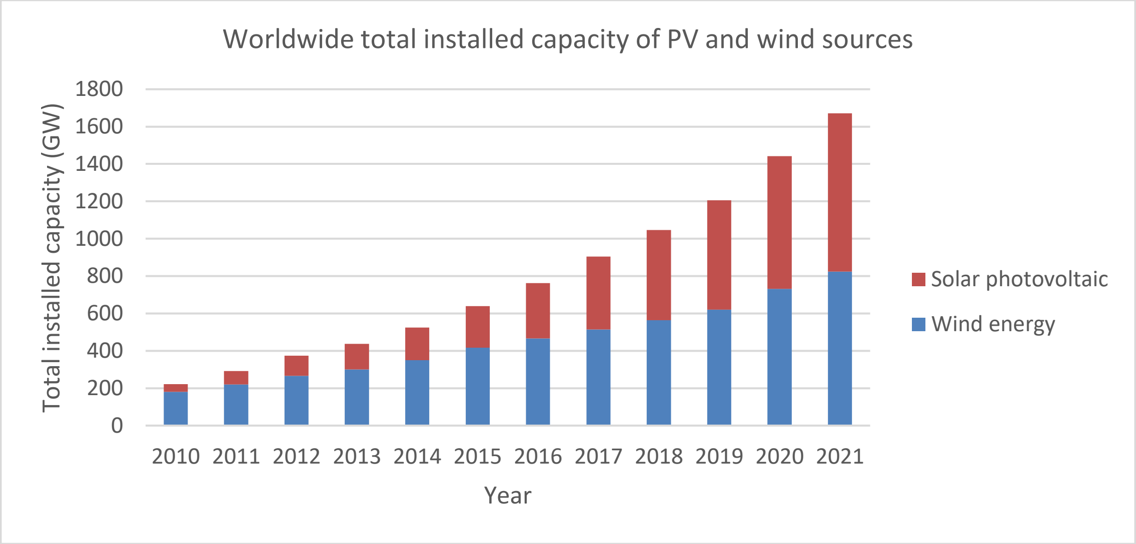
THD	Total Harmonic Distortion
UL	Underwriters Laboratories
USPTO	US Patent Office
VeHIL	Vehicle-in-the-loop
WIPO	World Intellectual Property Organization

SUMMARY

1 INTRODUCTION

In the last years, the growing concern about environment and energy security lead to an exponential growth on the number of installations and installed capacity of photovoltaic (PV) and wind systems around the world, as shown in Figure 1-1.

Figure 1-1 - Worldwide total installed capacity of solar photovoltaic and wind energy



Source: adapted from (INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA), 2022).

Wind and solar generation differ from conventional generation in that there is no mass rotating in synchronism with the system electrical frequency. The voltages and currents produced interact with a decoupling DC bus and must be converted to AC for grid interconnection. Solar photovoltaic and newer wind turbines utilize power electronic converters for connecting to the electric grid. These converter interfaces are constructed at the wind turbine or solar PV array to convert the generated variables, i.e., voltage, current, power, etc., to 50 or 60 Hz AC power frequency values (BOWMAN et al., 2019). One of the most important problems of renewable energy is its intermittent characteristic and, to reduce this, companies are also developing battery energy storage systems (BESS) that also utilizes power converters to store the exceeding energy (especially from renewable sources) in large batteries to support the grid when needed, i.e., using the stored energy to supply the grid during a demand peak or supporting the grid through reactive power compensation. All those systems are now fitted in a new research area called inverter-based resources (IBR). Despite the power converters and its uses being no novelty to the electrical area, the increasing penetration of IBRs on the power grid, driven by the renewable energies, is leading to new grid conditions and situations that were not addressed until now and requires a deeper study to assure a safe integration to the power grid.

The most important equipment for grid connection of IBRs is the inverter, which performs the interface between the energy resources (PV modules, batteries, etc.) generating power in direct current, and the grid, which operates in alternating current. In addition to converting DC to AC, the inverters can also support the grid through a series of features like frequency, reactive power, and voltage control. As an example, a study from (KARIMI et al., 2016) shows that:

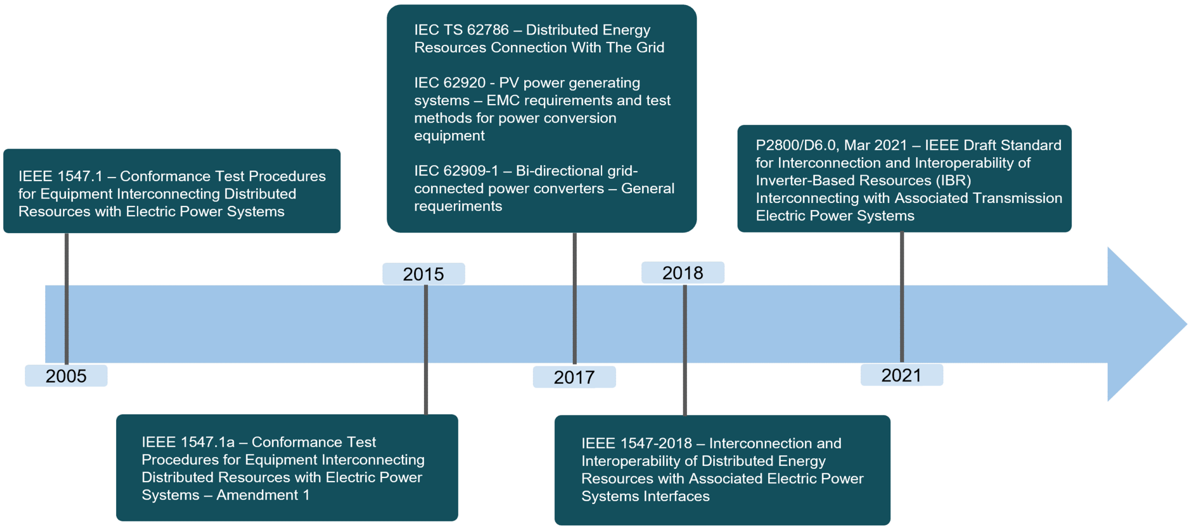
- At medium PV penetration (10%), inverter voltage support can help to reduce the size of conventional voltage support capacitors by nearly 40%.
- At high PV penetration levels (30-50%), PV inverters might be sufficient to provide all the feeder voltage support.

The inverters can also be used to provide protection features like under/over voltage/frequency support, low voltage fault ride through, ground fault and residual current protection among other features.

To ensure the safety and reliability, of the inverters and the grid itself, the regulatory bodies around the world have defined operation and grid connection standards for inverters in their respective grid codes, this is the case of "California's Rule 21", "IEEE 1547", "IEC 62909 series", "EN 50549", among others. It is necessary to assess the compliance of the inverters with the grid codes of the systems where they will be connected. The compliance assessment is made through a series of tests, in the case of PV inverters, in a controlled environment with simulated grid and solar panels, as described in the standards.

Despite the importance of grid codes to the overall safety and quality of the electrical systems, they impose some challenges and concerns to inverter manufacturers. As shown in Figure 1-2, the standards are constantly being changed and updated. From 2005 to 2021, IEEE and IEC alone published 6 standards/amendments (IEEE 1547.1, IEEE 1547.1a, IEEE 1547-2018, IEC 62920, IEC 62909-1, IEC TS 62786) and a new one is already on draft. It means that the requirements are constantly evolving, and new tests are necessary to assure the compliance of the inverter to the new requirements. The tests are carried out as one of the last stages of the development process and need a prototype to be performed, meaning that early firmware tests cannot be performed because, in order to work, the prototype needs that all the ancillary systems, and at least some of the security ones, to be completely implemented and tested. In addition to the prototype, manufacturers still need to have, or to rent, a large structure of equipment like power analyzers, PV simulators, grid simulators and specialized personnel that are familiarized with the standards and how the tests are performed on the certified/accredited laboratories.

Figure 1-2 - Timeline of IBR related standards from IEC and IEEE since 2005.



Source: Author

As an alternative, the utilization of hardware-in-the-loop (HIL) simulations allow the development and testing of independent controllers without the need of all the ancillary systems. This technique is widely used by industries like aerospace, defense, naval, among others, to accelerate the development process and test system integration and controls design before the implementation of the prototype (DAMEN SHIPYARDS, 2018).

In addition to simulations, HIL can also be used to test and certify products and components. Companies like Bureau Veritas are using HIL testing for ships and offshore unit certification since 2016. HIL testing purpose, in this case, is to check proper working of control systems according to specifications in a simulated environment and can be used to certify any embedded system in a ship or offshore unit. The tests are not mandatory, but companies can perform the tests in a voluntary way. (BUREAU VERITAS, 2016).

In the last years, the electricity grids are becoming smarter and more complex with increased use of software-driven digital electronics and creating a realistic power system for testing purposes would be prohibitively expensive. In this direction, some companies like DNV GL are already offering services of HIL testing for electronic components and converters (DNV GL, [s.d.]).

Hardware-in-the-loop technology is growing every day and will change how products can be developed and tested, even allowing the two stages to occur simultaneously in many cases. The laboratories and manufactures will need to adapt to this new kind of test procedures, and the limits of what can be done, or how trustful the results of the HIL tests can be, still needs to be evaluated. Also, new methodologies and procedures to standardize how the tests or simulations are performed also needs to be developed and tested.

1.1 MOTIVATION

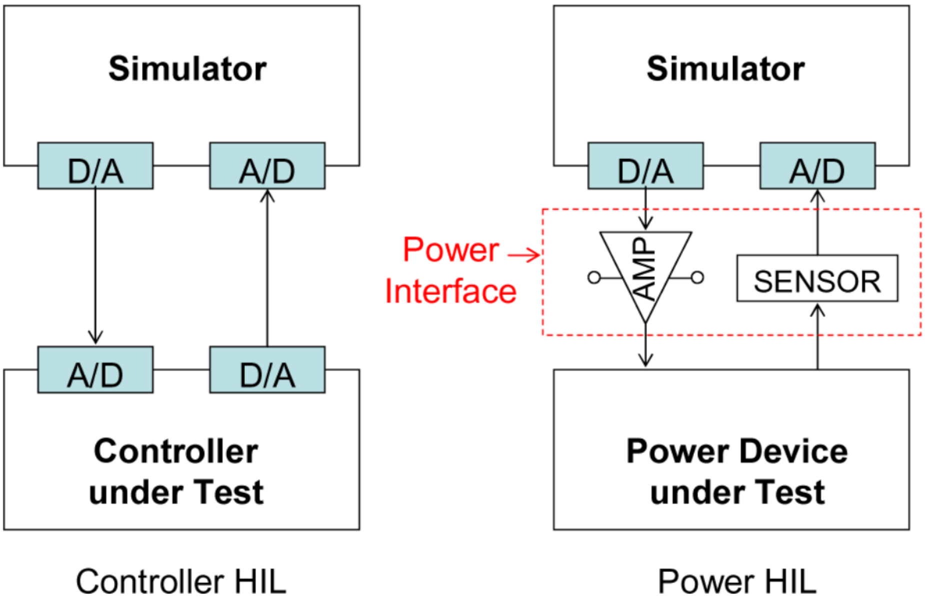
Despite HIL testing being widely used in some industries and its increasing popularity in power electronics, there is no official classification for HIL testing. There is only a commonsense classification of what is being tested, i.e., in case of power electronics, control or power systems. As the HIL simulation advances to other areas, new categories are created for new products being tested, as Software-in-the-loop, Vehicle-in-the-loop, among others. So, a better classification method, specifically for IBR can be better understood. Actually, in power electronics, almost every HIL testing is classified in one of the two categories, according to IEEE Taskforce on Interfacing Techniques for Simulation Tools (REN et al., 2011):

- Power hardware-in-the-loop (PHIL); in a PHIL simulation, the hardware under test involves actual power devices that require significant power flow between the hardware and the simulation system. In these conditions, especially designed power amplifiers and actuators become necessary to establish the interface. Examples of PHIL simulation are propulsion motor testing on a simulated electric ship system, operation of a real motor drive circuit on various simulated motors, and a distributed generator connecting to a simulated utility grid. Certification laboratories use this kind of test bench, using an AC grid simulator instead of the real grid and solar panels simulators in case of PV inverters, for example.
- Controller hardware-in-the-loop (CHIL); in a CHIL simulation, the hardware under test is a controller, which exchanges signals with the simulated system at a low power level. Examples of CHIL simulation include protection relay

testing under simulated fault scenarios, power electronics controllers operating with simulated motor drives, and an electronic engine control unit reacting to an automobile engine simulation.

Figure 1-3 shows the main differences between the hardware used in each category. These two categories are wide and do not allow a standardization of HIL testing. Considering, for example, the CHIL category, it is possible to have different kinds of "controller testing". It is possible to simulate the control laws using a virtual hardware where all signals are simulated and there is no interface with the real world. It is also possible to have the entire control board assembled, with sensors, actuators, and signal conditioning units and simulate just the power circuit or environmental conditions like the AC grid or PV panels. Both of those extreme situations can be considered CHIL but are far from each other in terms of accuracy and representation of the real-world application. Therefore, there is a gap in the literature about how systematically addressing this issue.

Figure 1-3 - Controller HIL simulation versus power HIL simulation



Source: (REN et al., 2011)

Due to the potential of the IBR to support and assist on grid regulation, the number of features that are being requested by the standards is also increasing each time they are updated. Most standards already require reactive power control, low voltage fault ride through, among other features. An example is the Brazilian standard ABNT NBR 16149 from 2013 that already demands those features from PV inverters sold on Brazilian market (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2013a). As the number of features needed to comply with the standards increases, the complexity of the firmware inside the inverters and the test routines also increase, sometimes demanding complex and expensive measurement equipment and time-consuming routines, leading to increased development and testing cost and time.

Another point is the fact that testing one equipment alone is not a guarantee that several units of the same equipment will work well when connected to the grid. As a result, especially for high power equipment, it is necessary to test them considering a realistic grid model, with grid impedance and considering possible interactions with other equipment. An example of it is the anti-islanding test proposed by (HOKE et al., 2018) with multiple inverters connected to multiple points of a realistic grid model instead of a single unit in an ideal grid simulator.

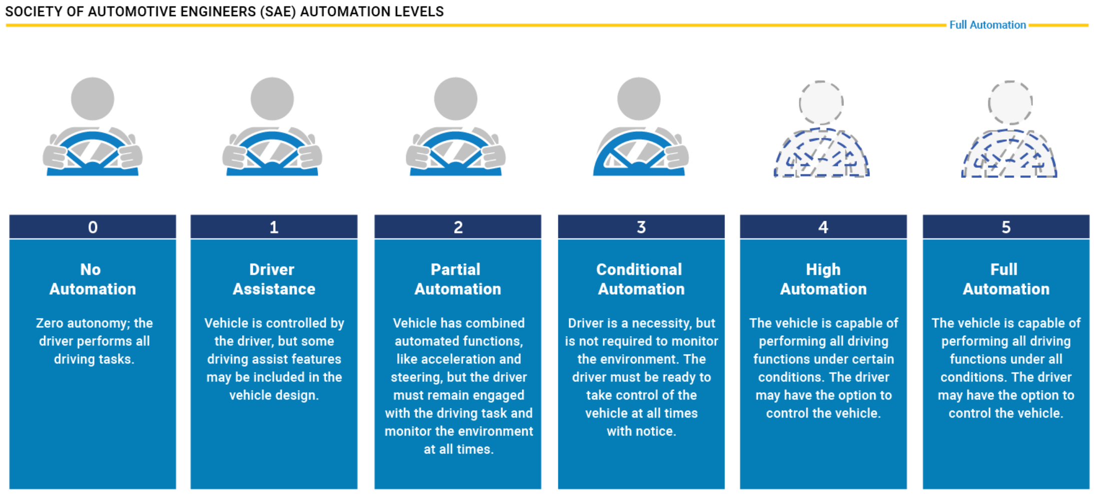
Building certification laboratories is complex and most of the needed equipment is expensive and sometimes sensitive. So, even if the laboratories have the necessary structure to test all kinds of situations, some of them, especially the most critical conditions, may not be worth testing due to the possibility of equipment damage.

The use of HIL in equipment certification may be a solution to almost all the mentioned problems costing just a fraction of a conventional certification laboratory. However, despite being promising, this is still an open area that needs to be better evaluated. Most of the literature is still concerned about the fidelity of the HIL simulation to the real equipment, but it is already possible to start analyzing if the results of a HIL test, considering a standard compliance scenario, are acceptable in terms of uncertainties and metrological analysis to assure that a test made using just HIL simulations will have the same “value” of a test performed in a conventional certification laboratory and what is the fidelity level of the tests, so the manufacturers can have an idea of how close to the reality the HIL results are.

1.2 RELEVANCE

Standardized classification is a basic condition for dissemination of a given technology. For instance, when vehicles started to have autonomous or automated functions, all companies stated that their cars were autonomous. However, there is significant difference between a car with cruise control, that only keeps the speed constant and disable the function once the driver uses the brake, and a car that can find its own way through GPS and drive to the destination alone, without human interference. To solve this problem and standardize what autonomous driving is, in 2016, the Society of Automotive Engineers (SAE) developed the standard “J3016 – SURFACE VEHICLE RECOMMENDED PRACTICE” and introduced the “Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles” (SAE INTERNATIONAL, 2018a), where six levels of driving automation were defined, as shown in Figure 1-4.

Figure 1-4 - SAE Autonomous Driving Level classification



0	1	2	3	4	5
No Automation	**Driver Assistance**	**Partial Automation**	**Conditional Automation**	**High Automation**	**Full Automation**
Zero autonomy; the driver performs all driving tasks.	Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.	Vehicle has combined automated functions, like acceleration and steering, but the driver must remain engaged with the driving task and monitor the environment at all times.	Driver is a necessity, but is not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.	The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option to control the vehicle.	The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

Source: (SAE INTERNATIONAL, 2018b) redesigned by “National Highway Traffic Safety Administration (NHTSA)”

Classifications from standard associations are normally based on scientific studies that systematize the topic. Considering HIL scenario, there is a lack of a systematic approach about testing levels that can help the community to clearly understand the extension of its application.

Despite the lack of a systematic classification, most worldwide relevant international laboratories are providing HIL services to market. In 2020 a review endorsed by most of the world's leading laboratories such as Fraunhofer, DERLab, Sandia National Laboratories, National Institute of Advanced Industrial Science and Technology, TU-Sofia, Austrian Institute of Technology, among others has been published (MONTOYA et al., 2020). Recent standards revisions have acknowledged the use of HIL as a method for test compliance. The IEEE Std. 2030.8-2018 accepts testing environments ranging from fully simulated testbeds to field installed equipment ("IEEE Std 2030.8-2018 IEEE Standard for the Testing of Microgrid Controllers", 2018). Similarly, the forthcoming IEEE Std. 1547.1 also accepts HIL approach to test compliance (IEEE P1547.1/D9.9, 2020).

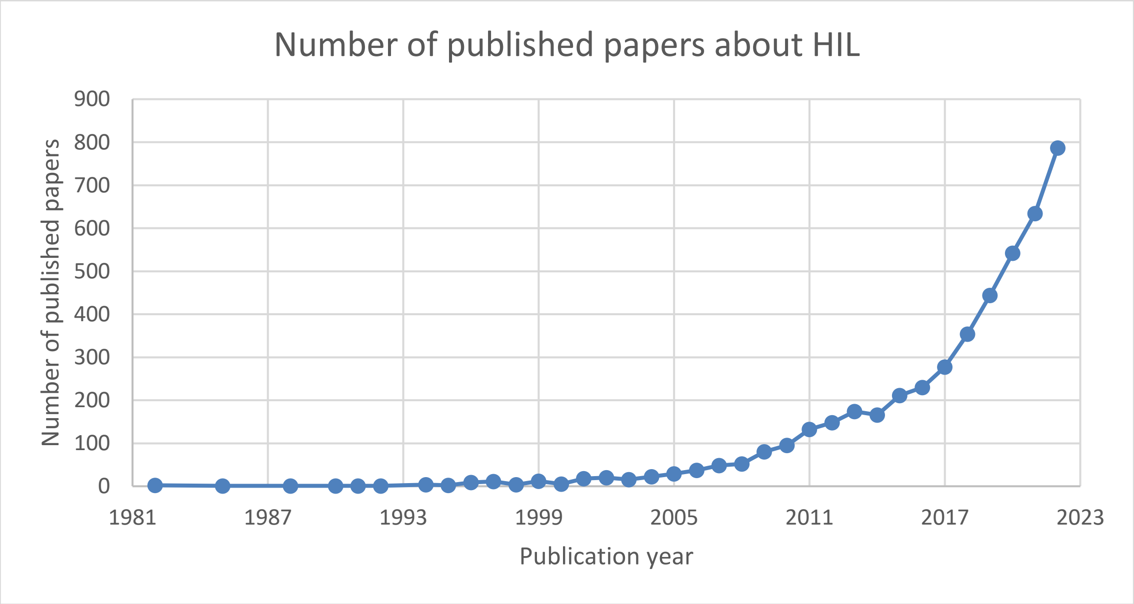
Research community and market keep performing efforts on development of platforms for validation according to grid codes and pre-certification of units, definition of procedures for compliance testing and acceptance tests (MONTOYA et al., 2020). However, it has not been found scientific studies addressing the impact of measurement methods and measurement uncertainties on results, when considering the HIL approach for power electronics.

1.3 LITERATURE REVIEW

A systematic literature review was carried out using the Scopus database from Elsevier (ELSEVIER B.V, [s.d.]). Scopus is a source-neutral abstract and citation database curated by independent experts. It covers more than 25,100 titles from more than 5,000 international publishers including all the most relevant ones like IEEE, SAE Technical Papers, Elsevier, MDPI among others. In addition to papers, it also covers more than 43.7 million patent records derived from five patent offices: World Intellectual Property Organization (WIPO), European Patent Office (EPO), US Patent Office (USPTO), Japanese Patent Office (JPO) and UK Intellectual Property Office (IPO.GOV.UK) (ELSEVIER, 2020).

The searched keywords were ((“hardware-in-the-loop” OR “hardware-in-loop”) AND “electronic”) limited to English or Portuguese languages and subareas of engineering and energy. This was intended to find all papers in Scopus base that had at least a mention of hardware-in-the-loop used in the electronic area, which also includes power electronics. The search returned a total of 9076 papers, from which 4625 are papers published on journals. Figure 1-5 shows the number of papers published in each year, demonstrating that HIL is a recent and fast-growing topic.

Figure 1-5 - Number of published papers about HIL on SCOPUS database



Source: Author

In the second stage, all journal papers were classified, through their titles and abstracts, in two categories. The first category is composed of papers that uses HIL testing or developing platform to test or prove concepts, architectures, control laws, etc. but with HIL being a secondary part of the paper or just a tool to prove the concepts. On the second category were classified all papers where HIL is the main part of the paper, with development of HIL testing benches, methods, algorithms, etc., where the main intention of the authors is to propose a standardized way to test or prove concepts using a predefined HIL platform or algorithm.

On the third stage of the literature review, all papers from category 2 were further classified as applied to inverters or static converters or applied to other forms of electronics, like avionics or embedded car systems. After the third stage of literature review and paper classification, a total of 103 papers were considered relevant to this work but, 42 of them were not used due to being similar or using the same concepts as the other 61 papers. In the next sections a brief review of modeling, simulation, and hardware-in-the-loop history as well as the current state of the art will be presented.

1.3.1 MODELING

Modeling is the mathematical representation of a physical phenomenon. Simulation is the numerical representation of such models on a computing machine. Accurate fast modeling and analysis environments are required for design optimization, dynamic characterization, controller design, and transient stability assessment of electric systems, machines, or converters. (MOJLISH et al., 2017).

In the beginning of the modeling history, the Monte Carlo method is generally considered to have originated with the Buffon "needle experiment" in 1777. The experiment is to "throw" needles onto a plane with equally spaced parallel lines to estimate the value of π. Since Buffon's published solution contained an error that was corrected by Laplace in 1812, the terminology Buffon-Laplace needle problem is also used.

About a century after Laplace's contribution, is the perhaps surprising role played by simulation in one of the most important development on applied statistics. These results were published in 1908 with a paper formulating what is now known as Student's t-distribution. This inaugural application of simulation to the field of industrial process control is a remarkable example of the synergy of simulation-based experimentation and analytic techniques in the discovery of the exact solution of what is arguably a classical industrial-engineering problem. (GOLDSMAN; NANCE; WILSON, 2009).

In the mid-1940s two major developments set the stage for the rapid growth of the field of simulation: The construction of the first general-purpose electronic computer such as the Electronic Numerical Integrator And Calculator (ENIAC) and the work of Stanislaw Ulam, John Von Neumann, Nicholas Metropolis, and others to use the Monte Carlo method on electronic computers in order to solve certain problems in neutron diffusion that arose in the design of the hydrogen bomb (COOPER; ECKHARDT; SHERA, 1989).

Ulam's fondness for card games and his attempts to find an easier way to estimate the probabilities of certain events in those card games apparently led him to the idea that a "Monte Carlo" approach to the problems of mathematical physics might be effective. An important complement to the work on the Monte Carlo method in the 1940s was the introduction of linear congruential random-number generators (LCRGs) by Lehmer. The increasing availability of general-purpose electronic computers in the 1950s allowed for the rapid proliferation of simulation techniques and applications in other disciplines (GOLDSMAN; NANCE; WILSON, 2010).

The development of the general-purpose electronic computers also started the development of programming languages, first known as general-purpose languages. The first one was used in the ENIAC and is known as "ENIAC coding system", developed in 1943 and refined until 1955, when the ENIAC ended its operations. The ENIAC coding system was also the base for several new programming languages during the ENIAC lifetime and even after its shut down. After the ENIAC and the development of other computers, a series of programming languages were also developed and started to diverge from the "original" ENIAC coding system. It is important to note that ENIAC was not the first computer developed, but the first programmable electronic general-purpose computer. Before it, several other specific purpose computers or calculating machines and their specific operating languages already existed (FRIEDMAN, 1992).

Even though a simulation routine or simulation program could be written in general-purpose programming language, a series of new specific languages were created with focus on simulation routines. Those languages are called simulation programming languages (SPLs) and its development progressed with the conviction that model complexity could be better accommodated, and modeling conveniences better provided with a language reflecting the problem-solving domain. By 1981 a total of 137 SPLs had been created, as shown in Figure 1-6 (NANCE, 1995). Those SPLs can be organized in 3 categories (LACKNER, 1964):

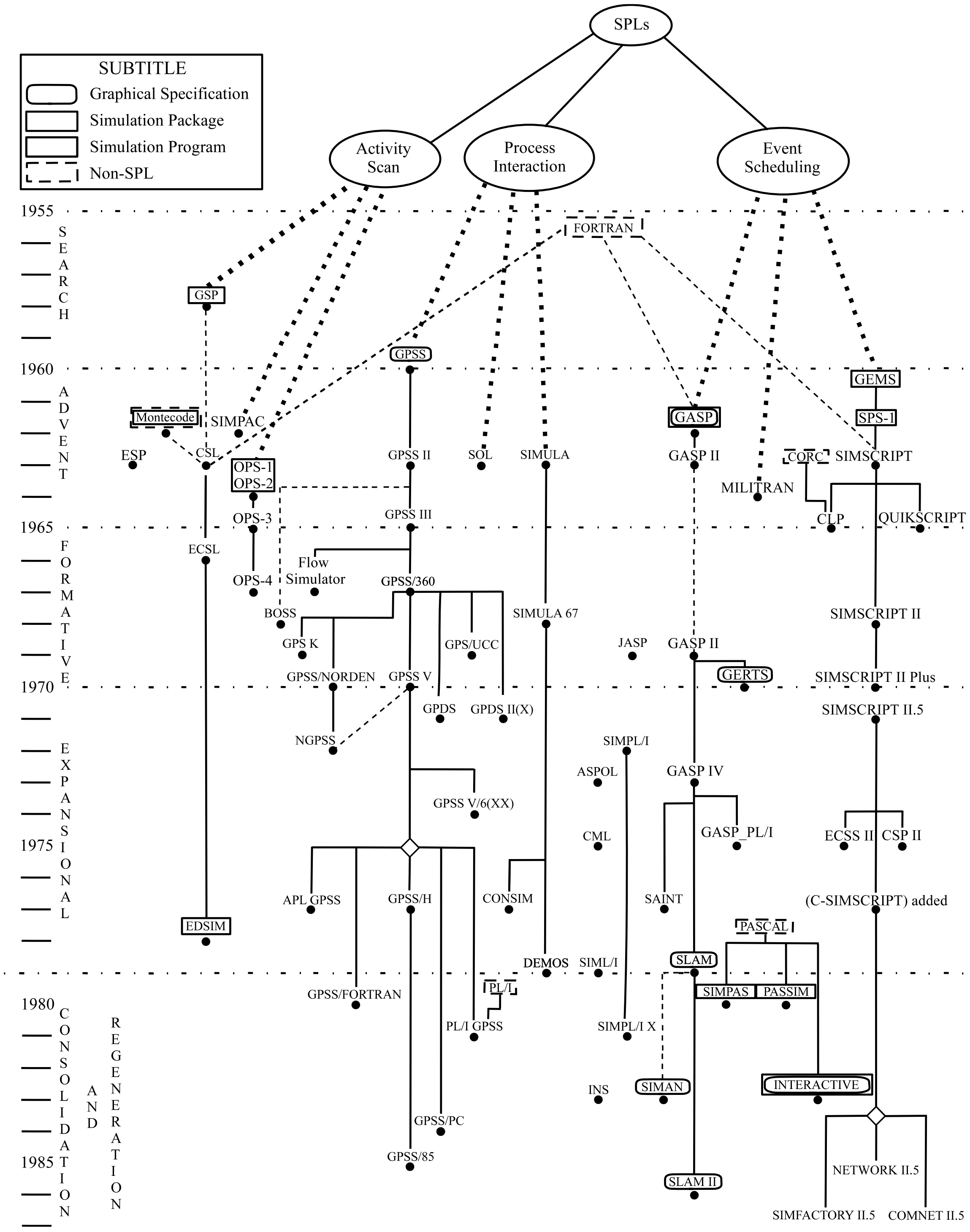
- **Event scheduling**: each event routine describes related actions that may all occur in a single instant.
- **Activity scanning**: each activity routine describes all actions that must occur because a particular model state is reached.
- **Process interaction**: each process routine describes the entire action sequence of a particular model object.

The evolution of computer simulation software until the mid-1980's can be summarized in the description of the history of simulation programming languages. Since that time, the entire complexion of simulation model design, development, execution, and sustainment has undergone a radical transition. The transition to a large degree stems from technology advances in hardware and software coupled with the increasing expectations of simulation modelers and end users (NANCE; OVERSTREET, 2017).

Beginning in the late 1970's, a succession of major hardware advances creates an almost illogical situation wherein the:

- Physical size of basic logic and storage units is decreased by orders of magnitude.
- Cost of the elements is reduced in a similar fashion.
- Central processing unit, memory access, and disk access speeds of these elements are increased accordingly.
- Graphics devices costs are likewise reduced.
- Computer networking costs and performance render less expensive.

Figure 1-6 - The genealogical tree for simulation programming languages until 1985



Source: (NANCE, 1995), remade by the author.

A well-documented review of the history of computer simulation software post 1970 can be found in (NANCE; OVERSTREET, 2017) as the authors explain and describe the transition from simulation programming languages to modeling and simulation (M&S) software, a more advanced and complex environment to run simulations. Examples of those software are the well-known in electronic industry, Ansys® (1970), Simulink® (1984) and PSIM® (1994). While the focus of SPLs was on solving generic mathematical problems, commonly found in all kinds of simulations, the M&S are focused on specific environments, like mechanical, fluids, electronics, etc. The main advantage is a more simple and friendly interface and the possibility to use premade models of components, where the final user does not need to know the equations behind the components, and still be able to choose among different models, focused on simulation speed, result fidelity or any other aspect that matters to the project.

By far, the early work in simulation and that which has been dominant in management science and operations research over the history is system analysis, where the intent is to mimic behavior to understand or improve system performance. A second objective is education and training, where the former addresses the broader understanding of concepts and the latter, more specific behavior in the application of concepts. A third objective is acquisition and system acceptance, where the simulation model is intended to answer questions related to "Does the system meet the requirement?" or, "Does a subsystem contribute significantly to the improvement of the larger system performance?" A fourth objective relates to research which can involve the creation of an artificial environment. In such environment, system components can be tested or the behaviors of an individual or groups can be compared, contrasted, or categorized (NANCE; SARGENT, 2002).

1.3.2 REAL TIME SIMULATIONS

A simulation is a representation of the behavior or characteristics of one system using another system, especially a computer program designed for a specific purpose. A simulation model can be discrete or continuous. Real world phenomena are continuous by nature, it means that the variables change in a continuous way, without abrupt changes from one state to another, or in other words, they have an infinite number of states. In a discrete model the state variables change only at specific moments in time, with a finite number of states. A computer is digital by nature, it only solves equations and perform operations when a clock signal is switched and thus does not have information of what happens between the two points in time.

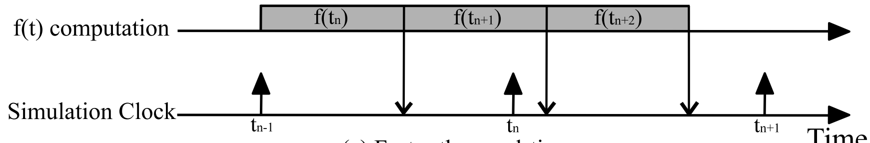
Considering just the discrete-time simulations, the difference in time from one point to another, also known as “time step”, can be equally spaced, with a constant time step, or variable, where the time step varies according to the simulation point. For real time simulations it will be considered only the discrete-time simulation with fixed (constant) time step. There are other solving techniques that use variable time-steps for solving high frequency dynamics and non-linear systems, but they are unsuitable for real-time simulation. During a discrete-time simulation, the amount of real time needed to compute all equations and functions representing a system during a given time-step may be shorter or longer than the duration of the simulation time-step. When the real time needed is smaller than the time-step, the simulation “runs faster” than the real time and is known as “faster than real-time” simulation. When the real time needed is longer than the time step, the simulation takes more time to be concluded than it represents in real time and is known as “slower than real-time” simulation. These situations are considered offline simulations and, in both cases, the moment at which a result becomes available is irrelevant (BÉLANGER; VENNE; PAQUIN, 2010).

For the last half-century, offline simulation was the major tool in design verification and testing before hardware prototyping and field deployment. Once the system models grew in complexity, even for a moderately sized system, the software overhead associated with offline simulation made them a less attractive option. Alternatively, in a real-time simulation environment, the model waveforms are reproduced within the same time interval as they would have been in real world time. A real-time emulated system model, therefore, allows engineers to evaluate the controller, system, or driver performance under a wide range of contingencies and extreme conditions in a nondestructive environment before field deployment (MOJLISH et al., 2017).

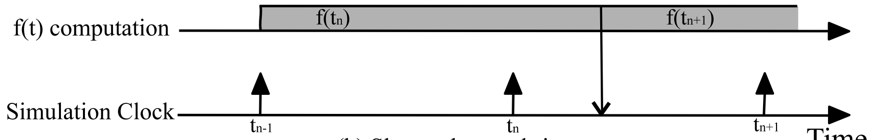
During a real-time simulation, the accuracy of computations not only rely upon precise dynamic representation of the system, but also on the length of time used to produce the results and the synchronization between the calculation results and the time step. To ensure a proper real time simulation, the simulator needs to solve the equations faster than the real-time, but then, it needs to wait until the next time step to start solving the equations again. This contrasts with the offline faster than real-time simulation where it starts solving the next set of equations as soon as it finishes the last one, this comparison is shown in

Figure 1-7. If the system cannot solve the equations within the time window and a new clock cycle starts while the system is still computing, the results will be compromised as the simulation will lack results and time synchronization. This is called a simulation overrun, shown in Figure 1-8, and when it happens it means that some adjustments need to be performed. The most common adjustments are the increase of the time step, reduction of simulation model complexity or increasing the available computing power (FARUQUE et al., 2015).

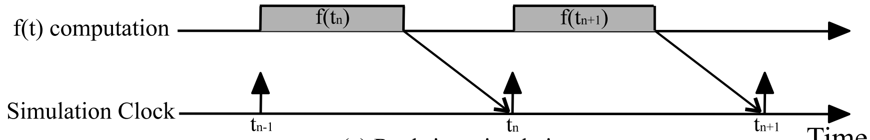
Figure 1-7 - Comparison of real time and offline simulations



(a) Faster then real-time



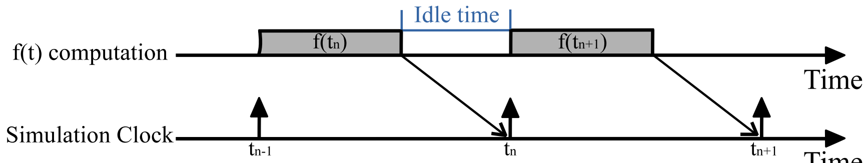
(b) Slower then real-time



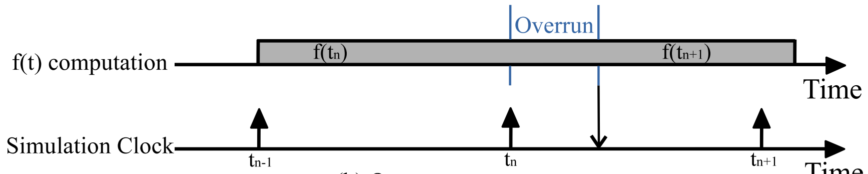
(c) Real-time simulation

Source: Adapted from (BÉLANGER; VENNE; PAQUIN, 2010)

Figure 1-8 - Illustration of simulation overrun



(a) Normal simulation



(b) Overrun occurrence

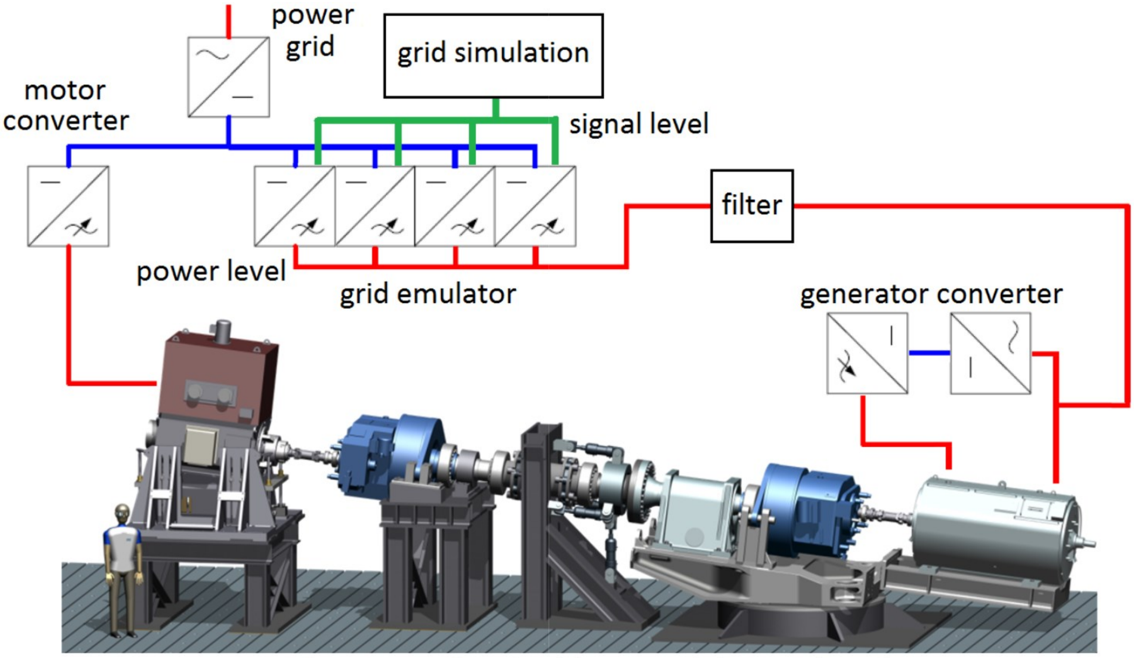
Source: Adapted from (FARUQUE et al., 2015)

1.3.3 HARDWARE-IN-THE-LOOP

Hardware-in-the-loop (HIL) is a technique where a controller is connected to a test system that simulates the signals that the controller would receive from the real system. This way the controller "thinks" that it is assembled in the real product, and it is possible to test and iterate with the test setup as if it would in the real-world scenario. An example of a HIL test bench used to evaluate and test wind turbines is shown in Figure 1-9. In this setup, an electrical engine is used to move the shaft, simulating the wind, and a grid simulator is used to simulate different grid conditions. This way it is possible to test the power converter or control systems of wind turbines without the need of the whole wind turbine (tower, blades, auxiliary systems, etc.) and still being able to test the controller or converter in situations that would be very difficult to test relying on specific climatic or grid conditions.

HIL tests can be assembled in various ways, not necessarily using the real controller or power hardware, as it is possible to simulate both using other devices, like a computer or a digital real-time simulator, or even a dedicated equipment (like the old structure of an airplane to simulate the real one).

Figure 1-9 - Example of HIL test bench for wind turbines



Source: (HELMEDAG et al., 2013)

The history of the first HIL solutions is not well documented, in part due to the non-formalized and non-academic form that this approach had and the highly industrial “in the kitchen” application. However, the first known example of hardware-in-the-loop system is a flight simulator. It could be considered as a HIL system with a physical control system (a pilot) placed in a physical sub environment (a real airplane mounted on the ground with a face towards the wind) and experiences the behavior of a virtual simulation of the environment. It was created in 1910 by the “Sanders Teacher” to protect both human’s life and machine. In this case, the virtual part of the HIL system is the wind, which of course cannot be controlled. This is the reason why the system was not very useful. Later, in 1917, a more functional simulator was presented, which included controllable body which is used to represent different responses and the feeling of speed (BRAYANOV; STOYNOVA, 2019).

It is known that the HIL technology has been widely used in defense and aerospace industries as early as the 1950s. Those industries took advantage of HIL systems mainly due to the risk of human life involved and the extremely expensive prototype systems under test. At that moment, the low complexity of the systems developed by other industries like energy, automotive, construction, etc. and the high cost of assembling HIL systems, that were built for very specific situations or equipment, restricted the use of those systems to just a few kinds of industries and applications (NABI et al., 2004). The National Aeronautics and Space Administration (NASA) reported in 1968 that HIL simulation of the control and stabilization systems of the spacecrafts was a key factor for the success of the Apollo project (CARROL; SPENNY, 1968). In 1997 a paper revealed the HIL system used by the Research Center Imarat (RCI) to test missile guidance and control systems, in activity as early as the 1980s (CHADHURI; VENKATACHALAM; RABHAKAR, 1997).

Automotive industry was the next one to take advantage of the HIL simulations once the car projects continuously grew in complexity, with the development of the engine control units (ECU), anti-lock braking system (ABS) and electronic stability control (ECS). All those systems require embedded control systems that needs special adjustments for each kind of vehicle they are used. All those adjustments can be made without the need of a real car prototype, allowing for reduced project-to-product time and production costs (TUMASOV et al., 2019).

1.3.4 HARDWARE-IN-THE-LOOP IN THE ELECTRICAL AND RENEWABLE ENERGY INDUSTRY

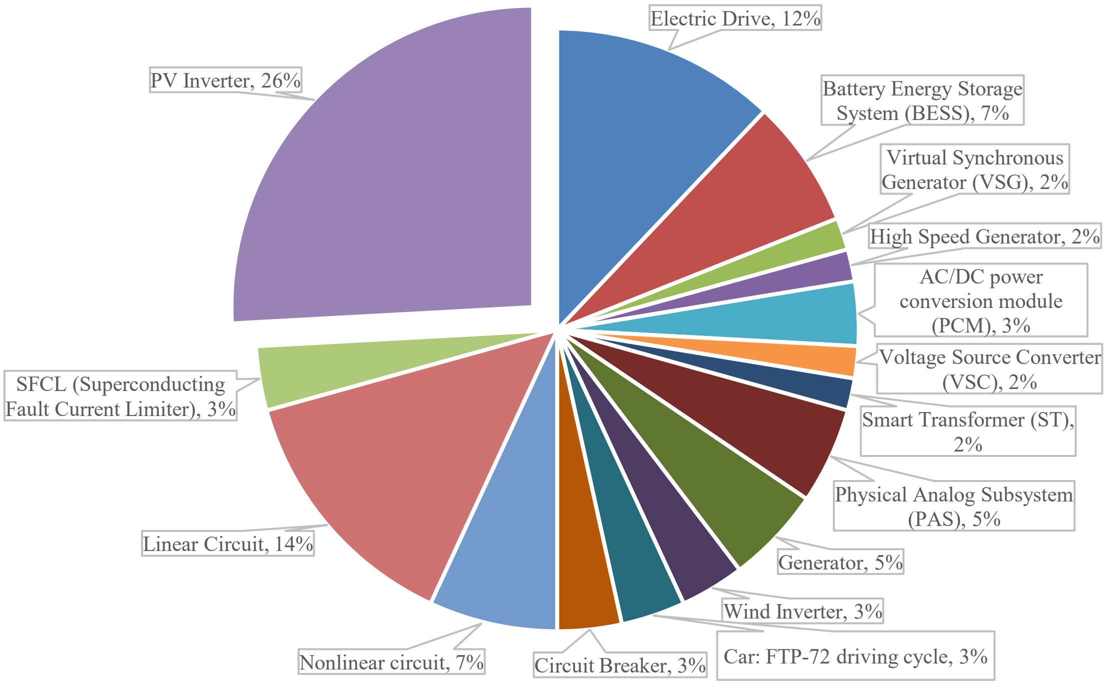
Modeling and simulation of power and power-electronic-based systems are essential steps that enable design and verifications of numerous electrical energy systems including modern electric grid and its components, distributed energy resources, as well as electrical systems of ships, aircraft, vehicles, industrial automation, etc. (CHINIFOROOSH et al., 2010).

In (DUKE, 1989) is found the first publication related to hardware-in-the-loop simulation in journals or magazines in the SCOPUS database. This paper describes a verification and validation (V & V) process to assure the safety of flight control systems, carried out by the National Aeronautics and Space Administration’s Ames Research Center. From 1989 to 1997 a half dozen of papers have been published, also regarding the HIL testing of embedded electronics and control systems on the aerospace industry. In 1997 an IEEE review showed the potential, benefits, and challenges of HIL simulation on several industries. The key point of this paper is the use of HIL simulation to develop the servomotors control for the Gemini Telescope Program, showing how HIL simulations could be used in power electronics (MACLAY, 1997). From 1997 to 2004, 18 more papers regarding servomotors control, embedded flight controls and electric engines for automotive industry were published.

Only in 2004 was published the first paper regarding microgrids and distributed generation. In this paper it is shown how HIL was used to validate and measure the performance of a controller for multi-bus microgrid system. The controller was designed to be used in each distributed generation system (DG) inside a microgrid and contains voltage and current loops for regulating the grid-interfacing inverters. It also provides external real and reactive power control and synchronization algorithm to ensure smooth and safe reconnection in case of an islanding event, which are almost the same functions that PV inverters need to have today (LI; VILATHGAMUWA; LOH, 2004). After 2004 the number of papers published in this field grew in a linear trend until 2017, where it started to grow exponentially.

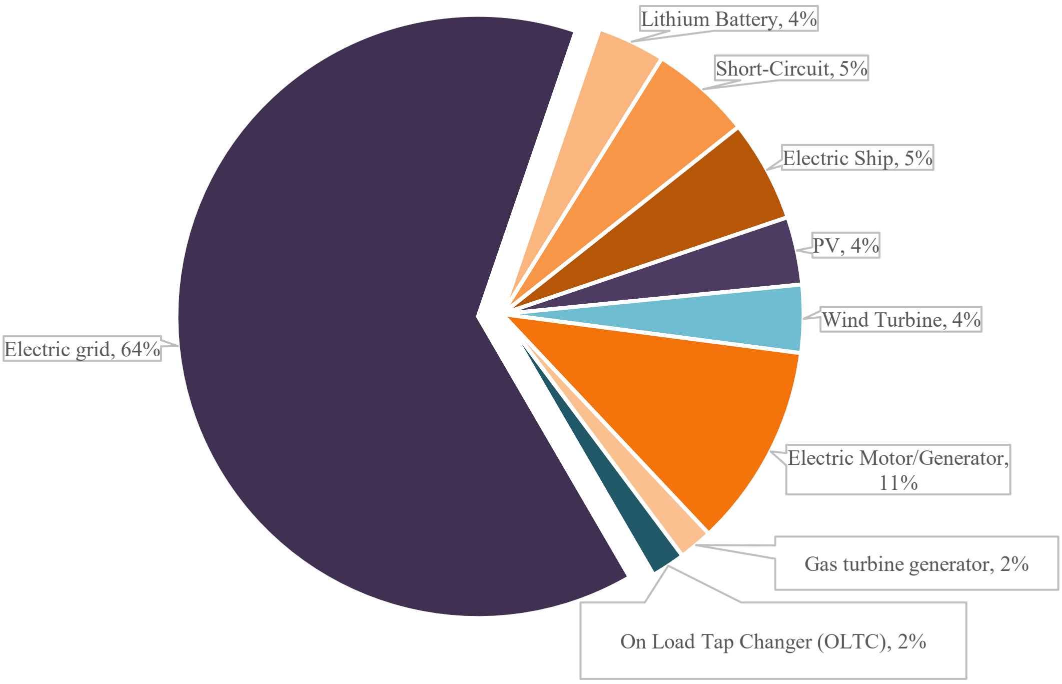
(GARCÍA-MARTÍNEZ et al., 2020) describes the creation of an open worldwide database about HIL testing with more than 50 papers. The authors first built a database with the available papers and then made it public and free, allowing any researchers interested in HIL simulation or testing to contribute with their own experiments or divulgating the results, equipment used, methods, etc. Nowadays, the database has papers from several laboratories that are pioneers on this topic, like National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), Austrian Institute of Technology (AIT), University of Montreal, among others. The paper also shows the distribution of equipment tested and the systems simulated as shown in Figure 1-10 and Figure 1-11. Among the tested equipment, the PV inverters are the most tested one, with 26% of all papers in the database related to HIL testing of PV inverters. Also, battery energy storage systems (BESS) that can be related to PV inverters appear with 7% of all papers. Considering the systems simulated using the HIL technology, 64 % of all papers use HIL to simulate electric grids and the connection of different kinds of equipment connected to the grids. The importance of this paper is to show; i) how the renewable energy and power electronic industries can be benefited with the fast expansion of the HIL real time simulation technology ii) the relevance of this issue; iii) how it can change the way that the certification laboratories will evaluate the products in a near future.

Figure 1-10 - Percentage of equipment under tests simulated in database.



Source: Adapted from (GARCÍA-MARTÍNEZ et al., 2020)

Figure 1-11 - Percentage of systems simulated in database.



Source: Adapted from (GARCÍA-MARTÍNEZ et al., 2020)

Some of the laboratories that are ahead of this topic are the Austrian Institute of Technology (AIT), National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). The AIT published a paper in 2012 where it shows the difficulties and challenges of the HIL technology on power electronics simulation and solutions to the problems found (LEHFUSS; LAUSS; STRASSER, 2012). In 2013 the SNL published a paper where it proposes a way to evaluate anti-islanding algorithms on grids with multiple inverters, which proved to be limited due to the great variety of topologies and possible configurations in the distribution networks (NEELY et al., 2013). This problem was further solved by the NREL. NREL developed a laboratory using power hardware-in-the-loop (PHIL) to perform the tests that SNL proposed, with the advantage of being able to simulate any kind of electrical network only changing the mathematical model of the simulation, without the need for construction of real electrical networks, thus, proposing a new way to perform tests on inverters (HOKE et al., 2018).

In addition to the work being done by national laboratories around the world, in 2017 the Institute of Electrical and Electronics Engineers (IEEE), the world's largest technical professional organization, created a committee, named "Hardware-in-the-loop (HIL)

Simulation based Testing of Electric Power Apparatus and Controls” to standardize and guide the utilization of HIL technology in electronics testing (IEEE, 2017).

In 2018 the IEEE showed the Global Real-Time Superlaboratory (Global RT Superlab) initiative, to create a “super laboratory” of digital real-time simulators connecting, through a virtual interconnection, the equipment from eight laboratories distributed in United States and Europe to test the integration of distributed energy resources (DER) with the power systems and the effects of the growing amount of electronic and switched generators into the grid (MONTI et al., 2018).

In 2020 a survey from some of the biggest renewable energy and HIL testing laboratories in the world showed the state-of-the-art in RT and HIL technologies and that some standards (IEEE Std. 2030.8-2018 and IEEE Std. 1547.1) are already accepting HIL testing as a way to test compliance and that this is inevitable for the future of the equipment and compliance testing (MONTOYA et al., 2020).

1.3.5 HARDWARE-IN-THE-LOOP IN PRODUCT CERTIFICATION

The use of hardware-in-the-loop tools for product development and validation, as shown in the previous sections, is widely used, and a natural way is to also try to use HIL for product certification. This possibility raises several questions that are also part of this thesis to be further investigated.

1 - Can HIL be used for product certification?

2 - How good are the results of HIL testing compared to testing the real equipment?

3 - How the different testing setups (CHIL, PHIL, SHIL, etc.) affect the results compared to the real equipment?

4 – If an equipment is considered in compliance with a standard in a HIL testing scenario, what is the confidence level that the final product will also be complying?

5 – Can HIL, in some way, be used to certify products in standards that were developed to test products in the “traditional way”?

6 – If not for full compliance test, can HIL be used in other ways like product maintenance or recertification, where the same product is tested again to keep its registry?

Those questions arose with the development of the hardware-in-the-loop technology itself but become even more important during the last years. As the technical and scientific community better understand the possible benefits of smart inverters to provide ancillary and auxiliar services to the grid, the grid codes, standards, and consequently the requirements that PV inverters must comply with increases. With more requirements to be tested, the test time also increases, which can lead to a situation where product certification time can become a bottleneck to product and technology development.

A specific case where this become apparent is due to the California Electric Rule 21 and the standard UL 1741 updates. In 2015 the California Public Utilities Commission updated the California Electric Rule 21 (CA Rule 21) to include grid-support requirements. One year later, the Underwriters Laboratories (UL) published an updated version of the UL 1741 certification protocol that included pass/fail criteria for the new grid support functions (UNDERWRITERS LABORATORIES, 2016). Then, the CA Rule 21 stated that all PV inverters installed on investor-owned utility systems should be compliant with UL 1741 within one year. It resulted in a surge of certification testing at the Nationally Recognized Testing Laboratories (NRTL) (JOHNSON et al., 2018).

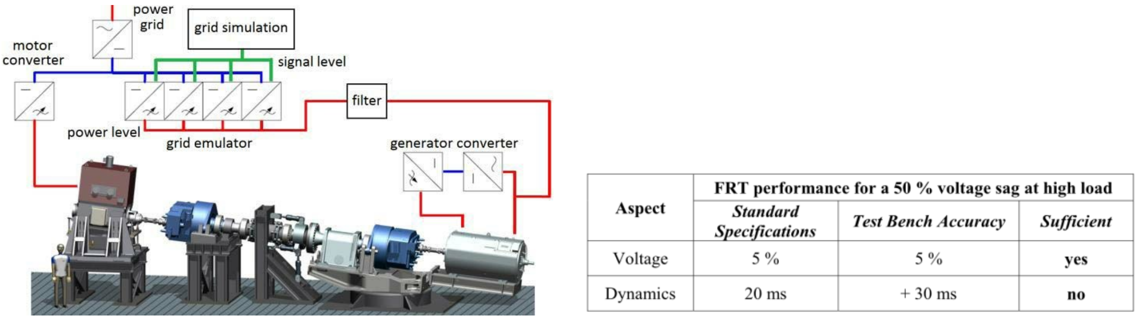
According to a study from the Interstate Renewable Energy Council (IREC), a handful of states already require new distributed resource installations to use smart inverters that meet a standard known as IEEE 1547-2018. As more devices that meet the standard become available, more states are evaluating such a requirement. The SunSpec Alliance expects that more than 30 states will set smart inverter requirements by April 2023. In this same study, IREC stated that the duration of each test is between nine and twelve weeks and considering the number of NRTL, and that no inverter would reprove in the tests, it would need between 54 to 72 weeks to test 155 models from 30 manufacturers that answered the IREC questionary (PV MAGAZINE, 2022).

This kind of situation is happening all around the world as new requirements are adopted and need to be tested. In Brazil, the Inmetro ordinance n°140/2022 imposed grid supportability and grid support requirements that are different from the old ordinance n° 004/2012. It also increased the range of inverters that need to be certified from 10 kW to 75 kW and set a deadline of 1-3 years depending on the inverter nominal power (INSTITUTO NACIONAL DE METROLOGIA, 2022). By January 2023 there are only 2 accredited laboratories in Brazil that can perform the tests and a few more temporary designated laboratories that can also perform the tests to help reduce the “certification stress” caused by the new ordinance. Manufacturers also think that certification time will be a bottleneck to the development and deployment of new products.

Considering the problem described and the alternatives to mitigate or even solve it, HIL testing is a promising alternative. Certification bodies, universities, and the industry itself is working to use HIL as a certification tool while trying to answer the questions raised above.

The first HIL testbeds to test and certify IBR started as early as 2010. A good example is the wind turbine simulator based on PHIL shown in (HELMEDAG; ISERMANN; MONTI, 2014). In this paper it is proposed a way to certify the fault ride through capabilities of wind inverters. Figure 1-12 (a) shows the testbench schematic while Figure 1-12 (b) shows a result comparison between the minimum voltage and dynamic accuracy requirement and the testbench results. As can be seen, in this first prototype it was not possible to fully comply with the standard in some cases, but it still has a lot of advantages compared to the traditional testing system, as shown in Figure 1-13.

Figure 1-12 – (a) Proposed PHIL solution for wind inverter certification, (b) Comparison between the testbench accuracy and the minimum accuracy required by the standard.

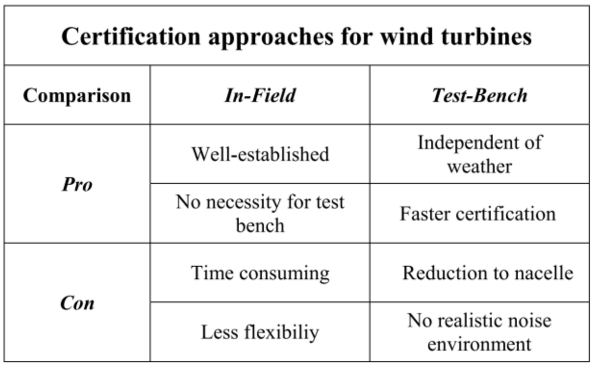


Aspect	FRT performance for a 50 % voltage sag at high load		
	Standard Specifications	*Test Bench Accuracy*	*Sufficient*
Voltage	5 %	5 %	**yes**
Dynamics	20 ms	+ 30 ms	**no**

(a) (b)

SOURCE: (HELMEDAG; ISERMANN; MONTI, 2014)

Figure 1-13 - Pros and cons of the PHIL wind turbine certification testbench

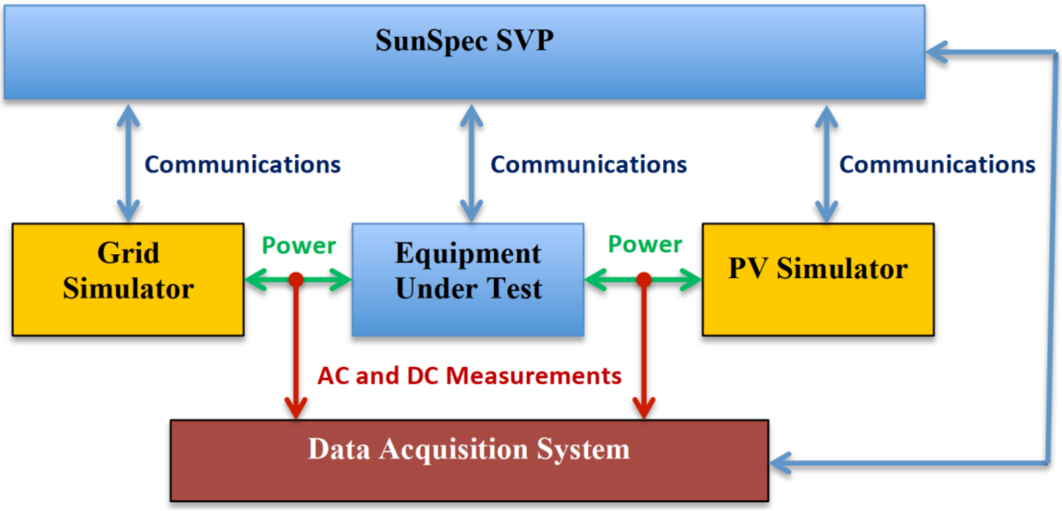


Certification approaches for wind turbines		
Comparison	***In-Field***	***Test-Bench***
Pro	Well-established	Independent of weather
	No necessity for test bench	Faster certification
Con	Time consuming	Reduction to nacelle
	Less flexibiliy	No realistic noise environment

SOURCE: (HELMEDAG; ISERMANN; MONTI, 2014)

The SunSpec Alliance, a trade alliance of more than 100 solar and storage distributed energy industry participants (SUNSPEC ALLIANCE, [s.d.]), developed the SunSpec System Validation Platform (SVP) to provide a framework for testing and validating SunSpec compliant devices. The general approach in the SunSpec SVP is to provide an environment that can manage and execute test scripts that utilize libraries that provide access to all the necessary components in the system. This approach allows for the same test logic to be applied in testing scenarios that may be using different physical components to implement any particular functional block in the test system (SUNSPEC ALLIANCE, 2011). The objective of the SVP is to automatize the testing protocols, independent of the power equipment to assure that any laboratory, accredited or company owned, can perform the tests in the same way. An example of how the SunSpec SVP is implemented in a laboratory is show in Figure 1-14. In the beginning, it was not designed as a HIL platform, but as a way to integrate and control a series of equipment like power supply, power analyzer, among others to replicate a given test protocol in any laboratory. The idea worked well, and a series of test protocols and standards were added to SunSpec SVP along the time, in a series of partnerships between industry, national laboratories and academy to create the Smart Grid International Research Facility Network (SIRFN).

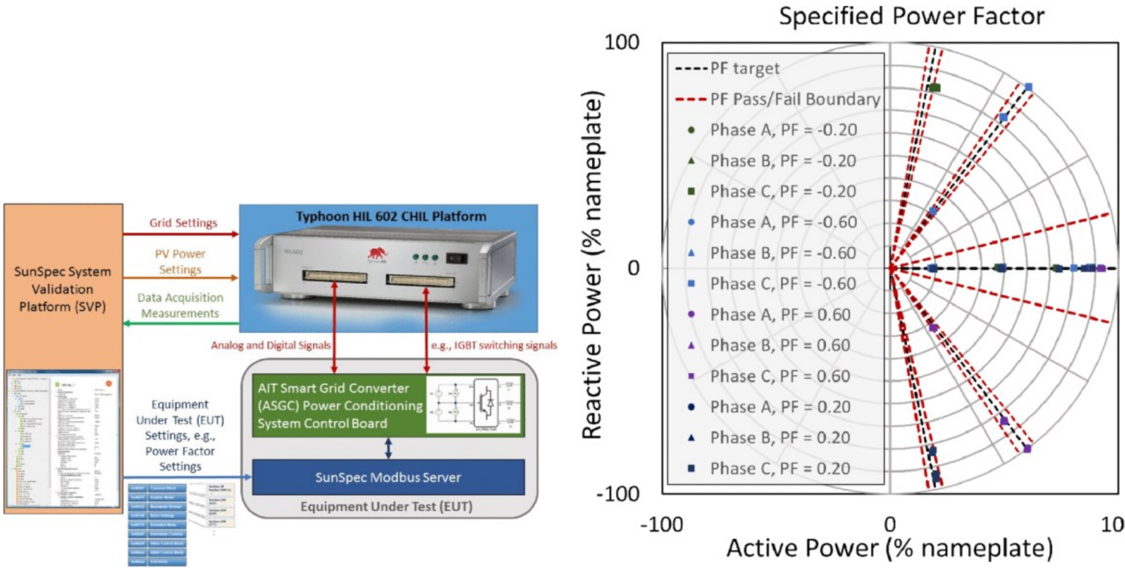
Figure 1-14 - Example of SunSpec SVP implementation for a Distributed Energy Resource inverter



Source: (SUNSPEC ALLIANCE, 2011)

Despite the SunSpec Alliance SVP great success in standardizing test protocols, simplifying the certification procedure and thus reducing the certification time, it still needs full power testing in a fully implemented prototype which, especially for high power inverters, may be time and resource demanding for both the manufacturer and the laboratory. In 2017 (JOHNSON et al., 2017) and 2018 (JOHNSON et al., 2018), as an effort to find a better way to test equipment compliance, the Austrian Institute of Technology (AIT) and the Sandia National Laboratories (SNL), working with the SIRFN, developed a test platform integrating a Controller Hardware-in-the-loop with the SunSpec SVP, creating what they called the CHIL-SVP (JOHNSON et al., 2018). The platform was designed to reproduce the UL 1741 test procedures, already implemented in the SunSpec SVP, without the full power testing, just with the inverter's controller. Figure 1-15 (a) shows the CHIL test configuration implemented by the AIT and Figure 1-15 (b) shows the results for one of the CHIL tests, the power factor control, presented by the AIT.

Figure 1-15 - (a) CHIL test configuration implemented by AIT, (b) Power factor test results for CHIL.



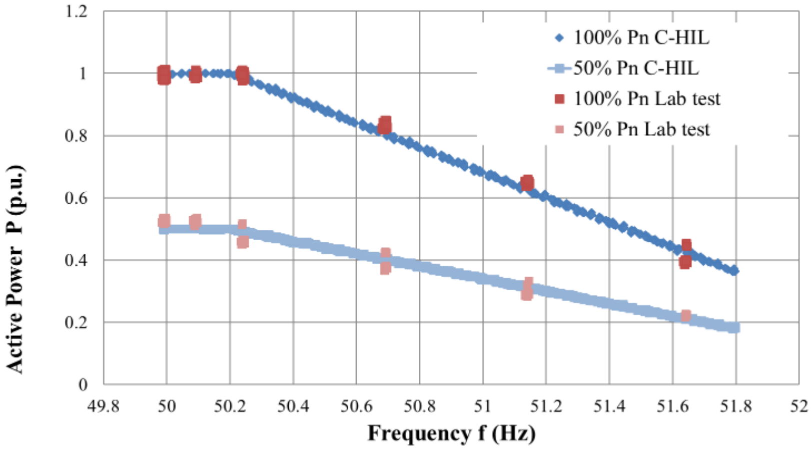
(a) (b)

Source: (JOHNSON et al., 2018)

Later in 2018, the AIT and SNL laboratories published another paper showing a platform to perform "pre-certifications" on solar photovoltaic inverters using a CHIL testbench that they called "C-HIL Pre-Certification Toolbox". The authors claims that the C-HIL pre-certification toolbox developed by AIT provides a complete implementation of widely used test procedures in Europe and allows fully automated testing of the basic characteristics and capabilities, grid support and protective functions of grid-connected converters. The comparison of the results from C-HIL based testing with those obtained from traditional laboratory testing highlights the suitability of the C-HIL approach as alternative up to the final pre-certification phase. They also affirm that to ensure an appropriate representation of the real unit in the C-HIL environment it is necessary to fully understand the behavior of the individual components and ensure they are properly modelled in the simulated environment (BRÜNDLINGER et al., 2018). Figure 1-16 (a) shows the inverter's control board connected to the CHIL testbench and Figure 1-16 (b) shows a test result comparison for active power control, between the CHIL and the real inverter, with the same control board.

Figure 1-16 - (a) PV inverter used to compare CHIL and real testing results, (b) Result comparison for active power control.

(a)

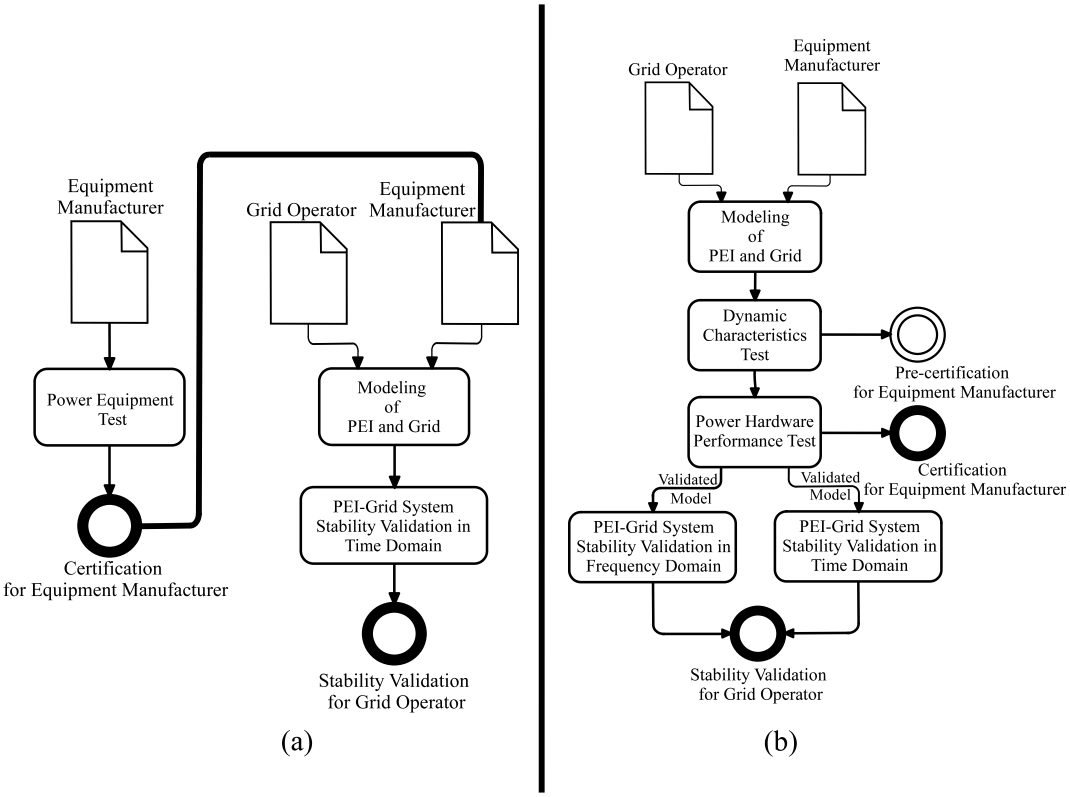


(b)

Source: (BRÜNDLINGER et al., 2018)

In 2019, (ZHANG et al., 2019) proposed a new method to test and validate the grid compatibility of inverters, which are called power electronics interface (PEI) in the paper, using hardware-in-the-loop. In the proposed method, the PEI would first be fully modeled by the manufacturer, and a control board with the final control algorithm would be sent to the testing laboratory to be used in a pre-certification of only the control system, using CHIL. During the pre-certification phase, the manufacturer can interact with the laboratory and fix the algorithm as needed to comply with the desired standard, receiving a pre-certification approval at the end of the process. After the pre-certification phase, the power system performance is also certified, through a PHIL testbed. After the two distinct phases, the equipment is considered certified, and the models are also used for further model calibration and validation. Figure 1-17 (a) and (b) show a comparison between the conventional and the new proposed test and validation method.

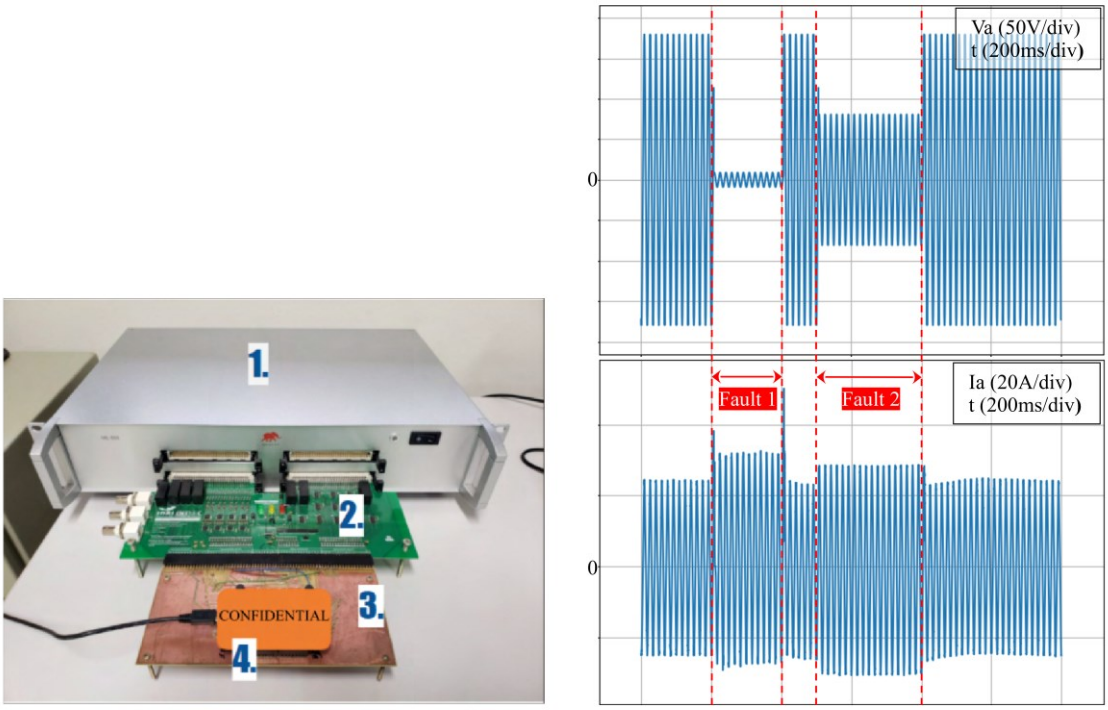
Figure 1-17 - (a) Conventional test and validation method, (b) proposed test and validation method.



Source: (ZHANG et al., 2019)

In 2020 (FERNANDO RISSOTTO MENEGAZZO et al., 2020) and 2021 (MENEGAZZO et al., 2021) the Power Electronics and Control Group (GEPOC) and the Smart Grid Institute (INRI) from the Federal University of Santa Maria (UFSM) published two papers, describing the possibility to test commercial photovoltaic inverters, according to the Brazilian standards, using a CHIL testbench. The test setup and the result for a low voltage fault ride through test are show in Figure 1-18. Similar to the work published by SunSpec, Sandia and IAT, the authors showed promising results in modeling and testing a commercial photovoltaic inverter, implementing the test algorithm, and running pre-certification tests according to the Brazilian Inmetro ordinance n°004/2011. The platform is now used by NRI as a product development and pre-certification tool to help manufacturers better understand the Brazilian requirements and test the inverters prior to the certification, reducing the cost with reproved products for the manufacturers and the time needed to certify products.

Figure 1-18 - (a) Implemented CHIL testbed, (b) test result for low voltage fault ride through

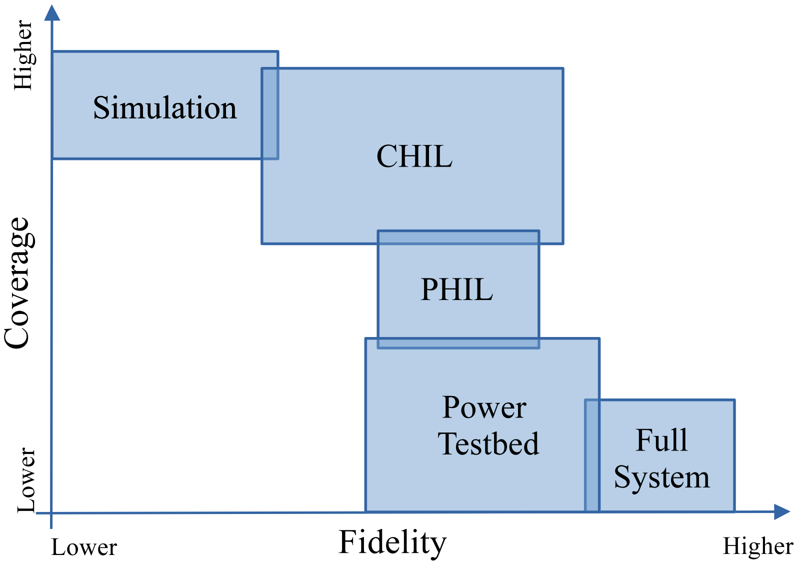


(a) (b)

Source: (MENEGAZZO et al., 2021)

Still in 2021, Typhoon HIL published a paper showing the advantages, challenges and outlooks about HIL-based certification (MAGNAGO et al., 2021). This paper highlights a series of successful cases utilizing hardware-in-the-loop as a pre-certification and development tool, comparing some of the results with the final product or between simulation and testbench results. Regarding the challenges pointed in the paper, the validation of the product model is the biggest concern, as the credibility of the test results is dependent on the fidelity between the model and the real product. It also highlights that the model must be certified as well and the fact that in current development state, there is a need to compare the model and the real product to validate the model and thus, it is still necessary to build a prototype. Also, even considering the best simulations, the fidelity of a HIL testing may be not as accurate as a full system test, but it is a new technology and improvements are being made every day. Figure 1-19 shows a comparison between test coverage (number of conditions and scenarios that can be tested) and test results fidelity with the real product that each kind of HIL test can achieve.

Figure 1-19 - Test coverage vs fidelity from different test methods

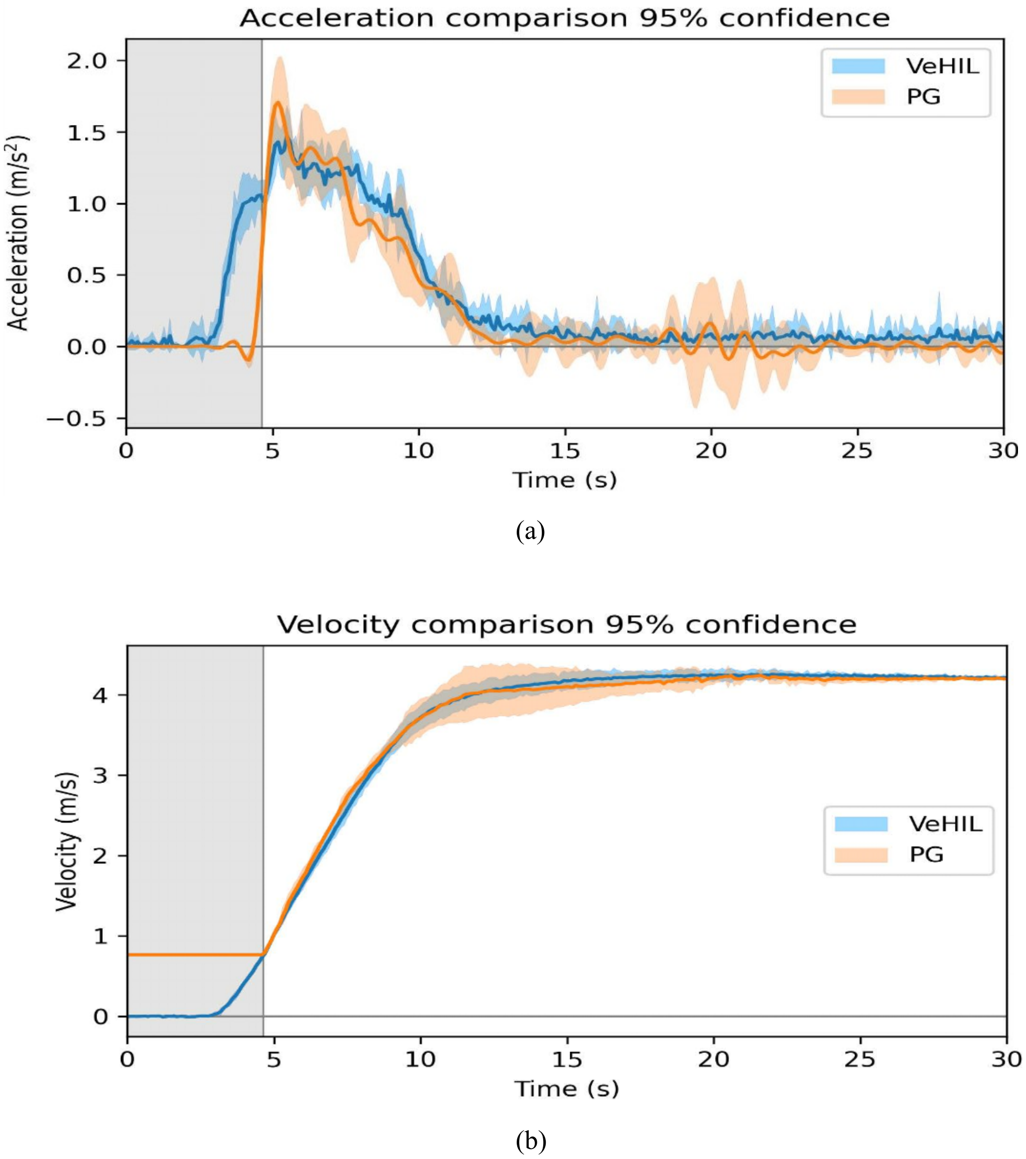


Source: (MAGNAGO et al., 2021)

The possibility to use HIL as a certification tool is a research subject not only to the power electronics industry. Several studies in different areas are also being performed, almost all of them with the same objective, trying to improve the product certification process using HIL testing. An example is shown in (DONA et al., 2022) where a vehicle-in-the-loop (VeHIL) testbench is used to evaluate the performance of an automated driving system (ADS) used to steer autonomous vehicles. ADS testing can be even more difficult to perform than power converters, as it needs to be assembled in a vehicle and the vehicle must drive in a specific circuit, which limits the test coverage to a very specific scenario. If not in a closed circuit, the test coverage is greatly improved, but test repeatability is compromised as the system will probably not run in the same conditions every time.

The HIL platform can create several test conditions to increase test coverage while keeping the test repeatability. Figure 1-20 shows that the results between the real circuit or, as it is called in the paper, proving ground (PG) and the vehicle-in-the-loop (VeHIL), are consistent for a simple circuit with simple maneuvers, but there is still room for improvement and to test more complex driving scenarios, with obstacles and unpredictable situations.

Figure 1-20 - Comparison between VeHIL and the proving ground (PG), (a) acceleration, (b) velocity



(a)

(b)

Source: (DONA et al., 2022)

1.4 CONTRIBUTIONS

This thesis will provide diverse contributions to the field of IBR certification. The theme is relevant because, in addition to other industry segments, mainly aerospace and defense, the energy and power systems area can benefit from the use of HIL systems to reduce product development, testing and certification costs and time while increasing the test coverage of the products.

The use of HIL platform for product certification is already discussed by several agents, both in industry and academia, as it allows a drastic reduction in the certification time of complex products, allowing even the evaluation and certification of independent parts of larger systems without the need to build prototypes. In addition, as it is a recent technology, there are still many opportunities for novel research on the area, ranging from converter models and simulations to solving problems in simulations of specific phenomena. Therefore, this work investigates the topic in a wide view, proposing what can be used as a basis for classification as well as determining the fidelity level of tests carried out in a HIL platform compared to the ones performed in accredited laboratories.

The main contributions of this thesis are:

- A more objective classification of the different test scenarios that can be performed within the HIL environment based on the completeness level of system or prototype under test.
- A quantified estimate of the fidelity level that can be achieved in each type of simulation using HIL, (CHIL, PHIL, EHIL, THIL, etc.) comparing the results obtained at each level of the proposed classification with the actual results, measured in the final prototype, tested in an accredited laboratory. It will allow designers to have a better idea of how trustful the results obtained in each simulation level is.
- Propose a validation procedure for conformity assessment methods within HIL simulator that can be generalized to other areas or types of tests.
- The development of a HIL testbench to perform testing in all levels of the proposed classification and to allow testing using the same test conditions in all stages of the product development process. The platform will also be used as a basis for future HIL related research in the university.

Other contributions will be proposed to achieve the main ones, as follows:

- Development of measuring instruments models on Python/C, considering international standards, to be used in various HIL simulations, replicating the way that real instruments perform measurements like harmonics, total harmonic distortion, flicker, voltage, power, power factor, etc.
- Development of test routines replicating the ones used in an accredited laboratory to be used to test PV inverters inside HIL environment.
- Development of a case study with routines that replicate the standards ABNT NBR 16149 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2013a), ABNT NBR 16150 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2013b) and ABNT NBR IEC 62116 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2012) and the Inmetro ordinance n° 140/2022
- Comparative analysis between the results of an accredited laboratory and HIL compliance testing considering Brazilian standards for on-grid PV inverters.

1.5 ORGANIZATION

The organization of this thesis is as follow. The second chapter presents a classification proposal for HIL testing, considering the aspects of the product and the environment in which it will be tested. Chapter 3 shows the implementation and validation of an IBR testbench with all the measurement algorithms and test protocols. In the fourth chapter it is demonstrated a practical application of the proposed classification and the IBR testbench running a series of tests in a commercial PV inverter, using the testbench in different modes (PHIL and CHIL) and comparing to results from an accredited laboratory for the same inverter. In the fifth chapter the results of the comparison are analyzed and compared through a statistical method used to compare laboratories in interlaboratory activities, to validate and numerically verify how close the HIL results are from the accredited laboratory. In the last chapter it will be presented the conclusion of the process, the papers published during the doctoral period and the proposed future works.

2 CLASSIFICATION PROPOSAL OF HARDWARE-IN-THE-LOOP SIMULATIONS FOR THE CERTIFICATION PROCESS OF INVERTER-BASED RESOURCES

This chapter proposes a level-based classification for HIL simulations applied to IBR. As mentioned in the first chapter, since the beginning of the HIL usage in electronics, the classification of the tests is made considering just what is tested, CHIL when the hardware under test is just the control system and PHIL when the hardware under test is the power circuit. Those two test categories are very generic as they are tied only to the product itself and do not consider the environment where the product is operating. HIL can test a wide range of situations, from the product itself (product environment), where just the behavior of specific parts of the product is important, to entire scenarios of grid characteristics and how a product will perform in different conditions or scenarios. So, even a finished product, as a solar or wind inverter, can be part of a bigger HIL assembly, to test a microgrid for example.

During a certification test, the product is tested using a standardized test scenario, and its performance in a specific, standardized, condition is evaluated. This scenario, that will be called “external environment”, can be created using power simulators (grid simulator, PV simulator, among others), HIL simulators, the real equipment (real PV cells, real power grid) or any other way to reproduce the desired conditions. Despite the quality of the equipment, there are still differences between a real grid and a grid simulator. There is a wide range of equipment and manufacturers, from the most affordable to the most accurate ones, from switched to linear power amplifiers, and so the response from a specific inverter, connected to different grid simulators, can also be very different. Considering a certification purpose, it is necessary to standardize and create categories considering the external environment where the equipment will be tested.

Still in the external environment, it can be divided into two parts, the first, as already mentioned, is based on the equipment scenario, to evaluate the use of different methods to simulate the grid, wind or PV cells. The second scenario, inside the external environment, is related to the equipment under test (EUT) management. Considering modern grids and the future tendency of smart grids and system integration, it is also important to determine how the management of the inverters will be performed and how to test it. So, inside the external environment a subcategory will evaluate the communication and management of the inverters, from fully isolated inverters, where no parameters can be changed and without any kind of communication, to fully integrated and remote-controlled equipment, that can have their parameters and characteristics remotely changed by grid operators, for example.

Beyond the product and external environments, there is still one more environment that needs to be considered, the “testing environment”, where issues related to the certification process are addressed. Standardized measurement methods, test protocols and algorithms are necessary to assure the repeatability and reliability of the tests, as well as the measurement uncertainties and other issues that can influence the test results.

The idea of this new classification is to create standardized categories, based on how close to the final application the product under test is and separate tests performed at the beginning of the development process from those performed just before the final product is deployed on market. This is important, especially from a commercial point of view as, in the exact same way that happened with the autonomous vehicles, when laboratories start selling their products (certification or development tests) it may cause confusion to the companies about the extension of the tests that their products will be submitted. Having standardized categories of tests allows for a further development of standardized test routines that need to be performed to fit inside a category. For example, a hybrid inverter, used to connect PV and BESS to the grid, that have multiple power converters inside it, may test only one converter at a time or all converters operating simultaneously at the same time. Both types of tests can be classified as “PHIL” even having a big difference on complexity and “reality” level of the tests, so it is possible to define, i.e., a PHIL level 1 category, to test just individual circuits, PHIL level 2 to test individual converters and a PHIL level 3 to test all the power converters operating at once.

The definitions of CHIL and PHIL are not wrong, they are used until the present day and can well separate what is being tested in each type of test, but they can be further expanded to better define what will be tested, how and at what level of confidence. This is why this thesis proposes that the concept of CHIL and PHIL will be kept the same as used by the IEEE taskforce (REN et al., 2011), however they will be subdivided in 3 sublevels according to the integration level in relation to the final product and two new categories, that will be called “environments”, also divided in sublevels, will be created to deal with the external environment (EHIL) and the testing environment (THIL). So, the final definitions, are:

- Product environment – It is the environment where the product itself will be tested. Inside the product environment, the two conventional categories of PHIL and CHIL are tested to validate the behavior of specific parts or the product as a whole.

- External environment (EHIL) – In the external environment, the main concern is the scenario or “environment” where the equipment is being tested. So, in this environment it is important to standardize how the testing scenario will be created. For example, different levels of EHIL are used to determine if the product is tested using a simulation of a PV panel, a common DC power supply, a DC power supply with solar array simulator (SAS) or a real PV panel. It will also test how the equipment management (MHIL) system will work, considering the level of management that the product has, for example, if it can be remotely controlled by a grid operator or if it is needed to have local access to the equipment to perform any kind of configuration or parametrization via USB cable or any other local method.

- Testing environment (THIL) – The testing environment is used to standardize how the compliance tests will be performed. If the variables are measured using standardized measurement methods, if the testing algorithm is standardized and if the measurement uncertainties are considered in the testing or not.

2.1 PRODUCT ENVIRONMENT

In the product environment, the objective is to test the behavior of individual parts or the product itself, usually for development purposes. It is normally the first part of a development product testing, where the main objective is to check if the control or power hardware is properly working, in its most basic functions, before advancing to more complex testing scenarios.

The product environment usually can be divided in two parts, the control hardware, and the power hardware, that can also be a vehicle or airplane or any other kind of plant. Both parts can have distinct and independent development levels so, they need to be divided in separated categories to ensure a proper classification.

Inside this environment, the conventional CHIL and PHIL categories will be kept, considering what is being tested, the control or the power hardware. However, due to the necessity to better standardize the different complexity levels of product testing, 4 levels will be considered, with clearly defined objectives separating each level. Figure 2-1 shows a diagram of the product environment with two separated levels for CHIL and PHIL testing.

The levels will be used to define the complexity of the hardware being tested, and there is no need to follow a specific order. For example, it is not needed to start at CHIL 0 and then scale up to CHIL 3. A test can be performed in any level desired by the designer, and there is no need to match the CHIL with PHIL. It is possible, for example, to have a CHIL 3 and PHIL 0 test, where the controller is tested as a final product while the power hardware is entirely simulated.

Figure 2-1 - Product environment diagram

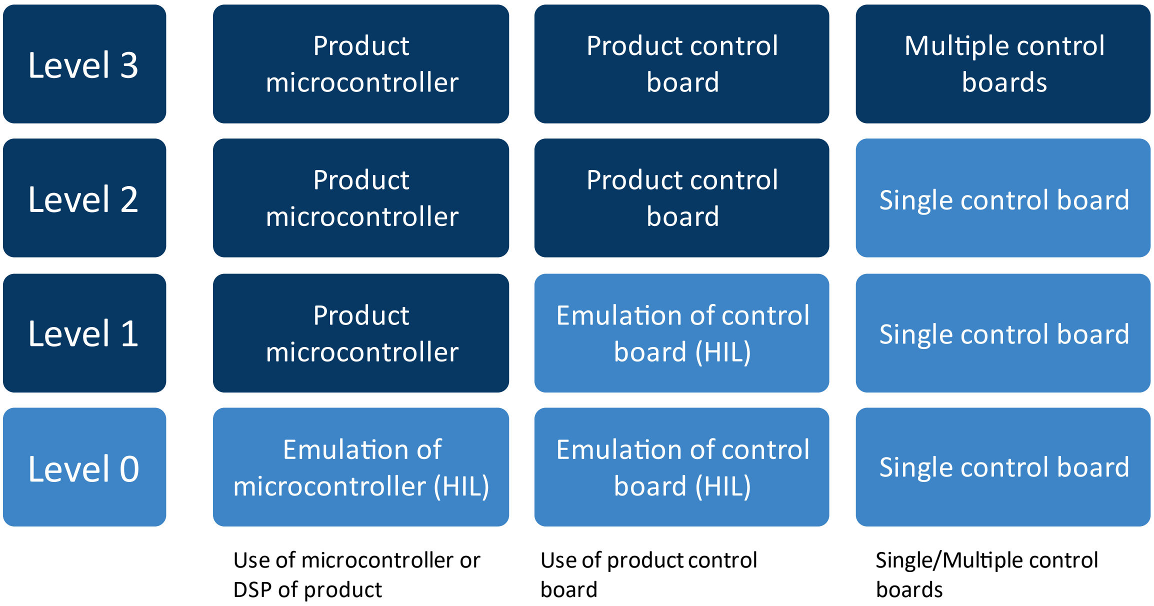
Source: Author

2.1.1 CHIL CLASSIFICATION

The CHIL classification focuses only on the control board, and goes from level 0, where everything is simulated, to level 3, where the hardware tested is the complete control hardware (processor, control board, signal conditioning units, etc.) composed of two or more control boards operating together, when applicable.

There are 3 key factors that determine the level transition, as shown in Figure 2-2, the use of a real microcontroller, a real product board and if there is one or more control boards working in parallel in the same product. All finished products will fit in CHIL 2 or CHIL 3. As will be better explained in the follow sections, the reason to have a level for multiple controllers is due to the complexity added when interactions between the multiple controllers can interfere on test results and the fact that a single controller operating alone may work well, but there is no guarantee that multiple units of this same controller, operating in parallel, will have the same results, so a CHIL 3 assures that the control system was tested and is able to operate in parallel with other units.

Figure 2-2 - CHIL Classification diagram



Level 3	Product microcontroller	Product control board	Multiple control boards
Level 2	Product microcontroller	Product control board	Single control board
Level 1	Product microcontroller	Emulation of control board (HIL)	Single control board
Level 0	Emulation of microcontroller (HIL)	Emulation of control board (HIL)	Single control board
	Use of microcontroller or DSP of product	Use of product control board	Single/Multiple control boards

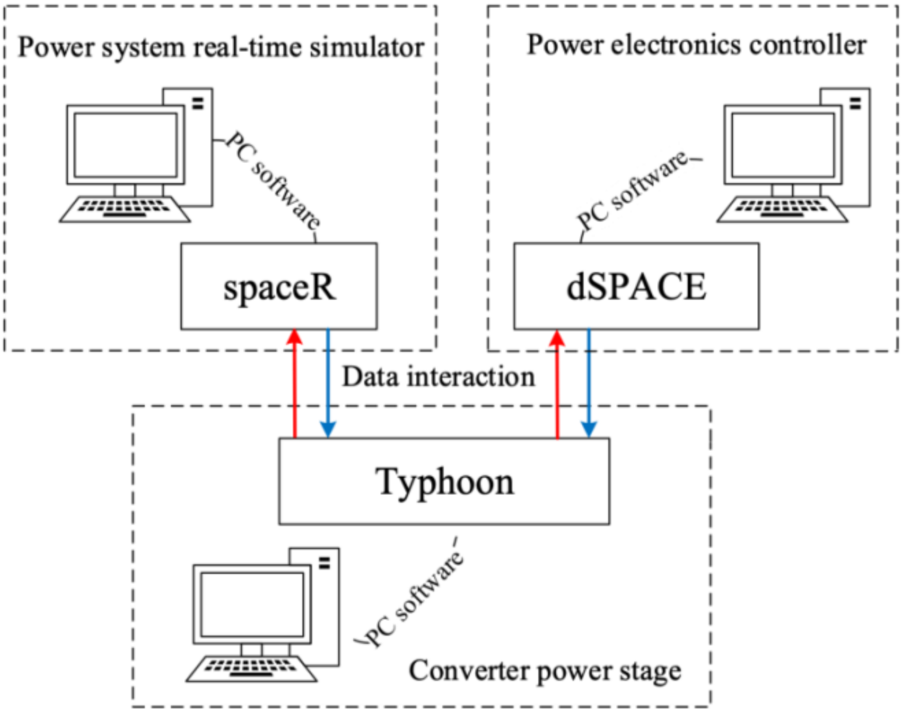
Source: Author

2.1.2 CHIL LEVEL 0

In CHIL level 0 (CHIL 0), the entire control system is simulated, it can be implemented in any computer or HIL simulator but does not use a dedicated processor or control board that will be part of the final product. This kind of test is usually performed in research areas to validate or explore the behavior of newly proposed control strategies, without a specific product in mind. During a product development or certification process, this level of CHIL test is used to evaluate if the control algorithm is enough to satisfy all the necessary requirements of a standard or certification process. Also, when the manufacturer wants to optimize the control hardware, first developing a code that will make its product work as intended and then, knowing the code size and processing requirements, choose the best processor to run the code.

The main objective of a CHIL 0 certification is to assure that the control laws and required functions, for a specific standard, are programmed and implemented in the code. It also allows designers to build and test a specific set of functions, to comply with some standard, before even defining the control hardware to be used in the final product. An example of a CHIL 0 is shown in Figure 2-3.

Figure 2-3 - Example of CHIL 0 simulation



Source: (PAN et al., 2022)

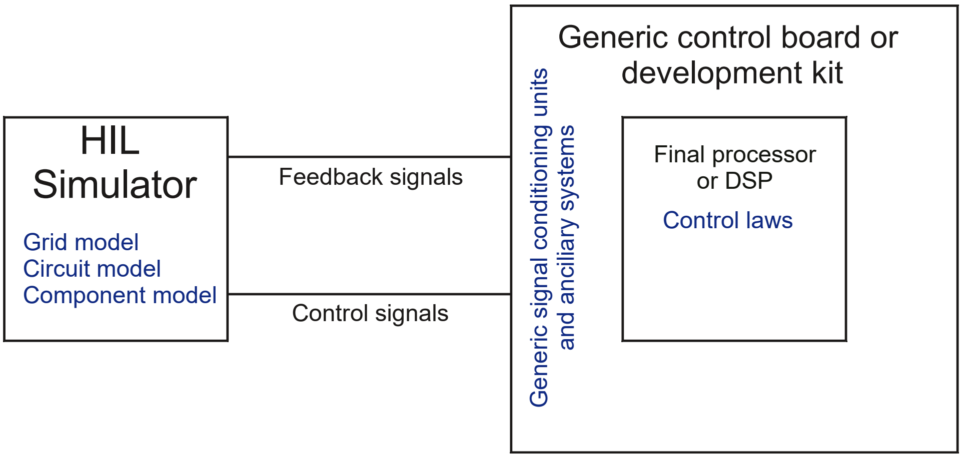
2.1.3 CHIL LEVEL 1

In the CHIL 1, the controller used in the tests is the same used in the final product. The rest of the system is simulated on HIL (sensors, power circuit, grid, solar panels). It is one step ahead from the CHIL 0, as using the real controller, in a generic control board or development kit, as shown in Figure 2-4, allow for identification of problems related to code generation or implementation, control law processing time and other microprocessor related problems like:

- Processor architecture bit width (8 bits, 16 bits, or more).
- Computer number format (fixed-point or floating-point).
- Analog-to-digital (ADC) or digital-to-analog (DAC) converter resolution.
- ADC and DAC linearity.
- ADC and DAC processing time.
- Clock speed.
- Signal levels.

The main objective of a CHIL 1 certification is to assure that the control laws and functions, programmed and implemented in the final processing unit, are working as intended. This stage is important to assure that in ideal conditions, i.e., with a well-designed and already extensively tested generic control board, the control system will comply with design requirements.

Figure 2-4 - Example of a CHIL Level 1 test with the real DSP assembled in a generic development kit



Source: Author

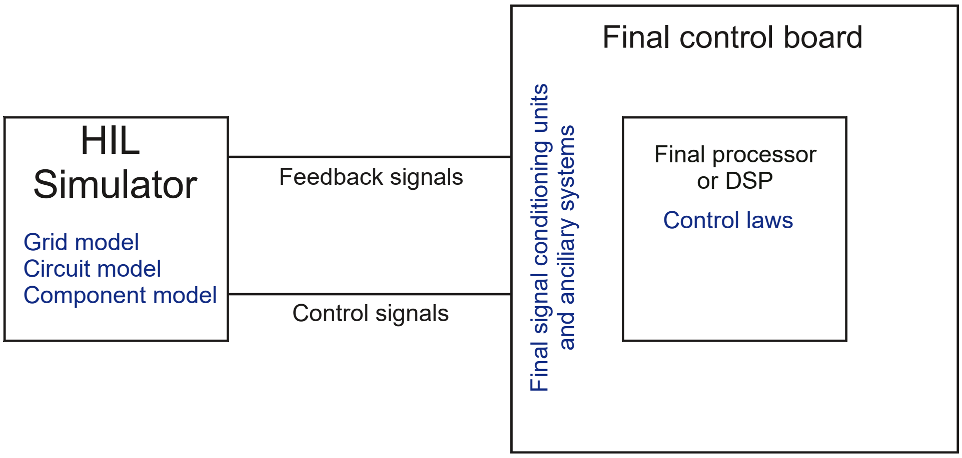
2.1.4 CHIL LEVEL 2

In the CHIL 2, the controller and the control board used in the tests are the same used in the final product, the rest of the system is simulated on HIL, as shown in Figure 2-5. Using the real controller and control board allows for identification of more problems and failure conditions related to the board and auxiliary circuits.

The control board components and layouts will interface with the controller and may generate situations not previewed when just the controller is tested in a generic, and well tested, control board. Several companies like NI, Texas, among others, offers a generic “development kit”, where it is possible to assemble a fully operational inverter and test it. But, in some cases, the final product will use the same processor used in the development kit, but not the same board, as it is usually cheaper to develop a specific board to the final product. In these cases, it is necessary to test again the control system with the new control board. In other cases, the development board can be part of the final product, and in those situations, it is still considered a CHIL 2 and the CHIL 1 can be avoided.

The main objective of a CHIL 2 certification is to assure that the complete control system, composed of the controller and the control board, is properly working. This is the final level of CHIL for most of the commercial inverters as it is a common practice to only have one control board controlling the entire equipment.

Figure 2-5 - Example of a CHIL Level 2 test with the real equipment control board.



Source: Author

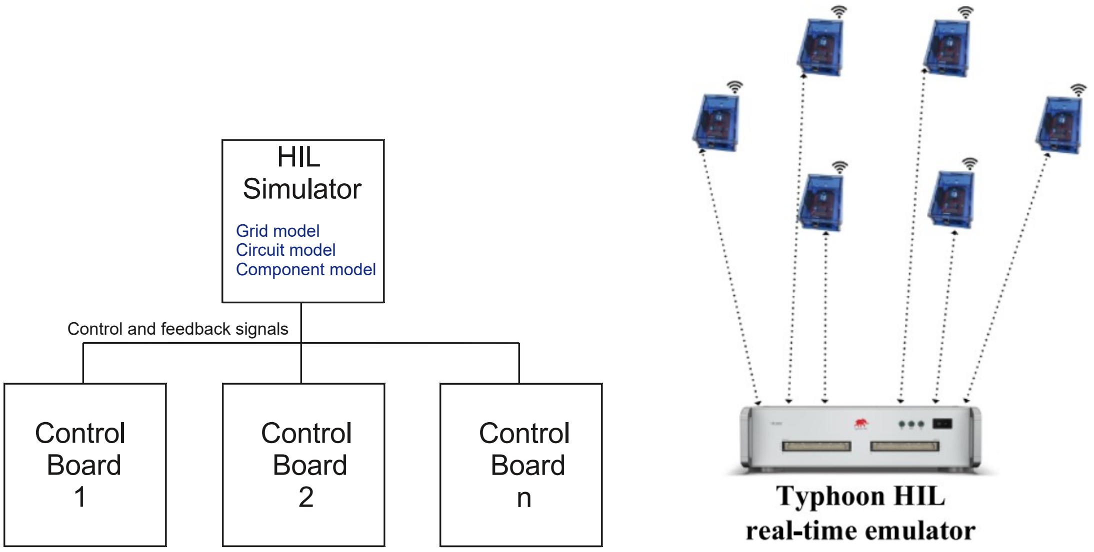
2.1.5 CHIL LEVEL 3

For CHIL 3 tests, the entire control system, with multiple control units in parallel, are used in the final product, as show in Figure 2-6. This test is applicable for systems composed of multiple controllers that need to work together in a parallel (one controller for each part of the system like a two-stage inverter with a boost-inverter configuration for example) or master-slave configuration (one main controller needs to operate a series of smaller controllers, like in a micro inverter setup where many panel-sized inverters need to operate in series to synthesize the desired current or voltage waveform). The problems and failure conditions that can be identified in this test are related to system communication and integration between the controller and ancillary systems like:

- Communication delay and interference or loss of communication.
- Ancillary system malfunction.
- Master/slave controller malfunction.
- Parallel controller malfunction.

The main objective of a CHIL 3 certification is to assure that multiple units of the controller, operating in parallel, will work according to design specifications.

Figure 2-6 - Example of CHIL-3 tests where multiple controllers are tested togheter to evaluate distributed control capability (a) generic schematic, (b) pratical application



(a) (b)

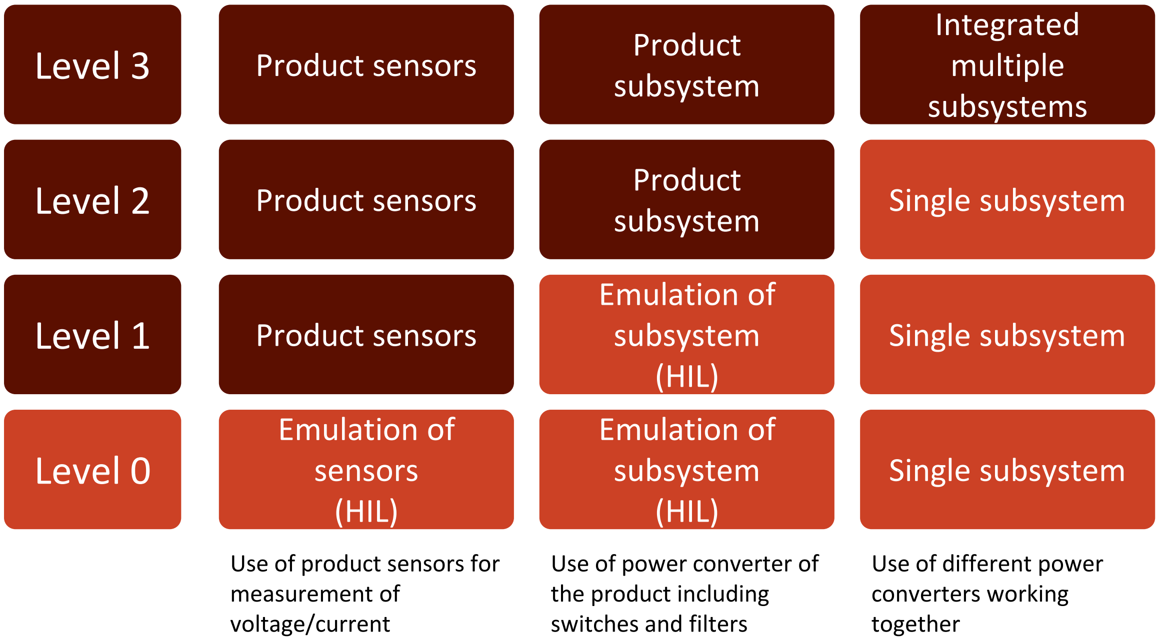
Source: Author and (NIGAM et al., 2021)

2.1.6 PHIL CLASSIFICATION

The PHIL classification focus on the plant or, considering power converters, the power circuit. Like the CHIL classification, it goes from level 0, where everything is simulated, to level 3, where the hardware tested is the complete power hardware composed of two or more power converters operating together, when applicable.

There are also three key factors that determine the level transition, as shown in Figure 2-7, the use of real sensors, the actual power hardware and if there is one or more power converters working in parallel in the same product. All finished products will fit in PHIL 2 or PHIL 3 categories. Also, the reason to have a level for multiple converters is due to the complexity added when interactions between the multiple converters can interfere on product behavior and/or test results. A single converter operating alone may work well, but there is no guarantee that multiple units of this same converter, or even other converters (i.e., boost + inverter configuration), will have the same results, so a PHIL 3 assures that the power circuit was tested and is able to operate with other units.

Figure 2-7 - PHIL Classification diagram



Level 3	Product sensors	Product subsystem	Integrated multiple subsystems
Level 2	Product sensors	Product subsystem	Single subsystem
Level 1	Product sensors	Emulation of subsystem (HIL)	Single subsystem
Level 0	Emulation of sensors (HIL)	Emulation of subsystem (HIL)	Single subsystem
	Use of product sensors for measurement of voltage/current	Use of power converter of the product including switches and filters	Use of different power converters working together

Source: Author

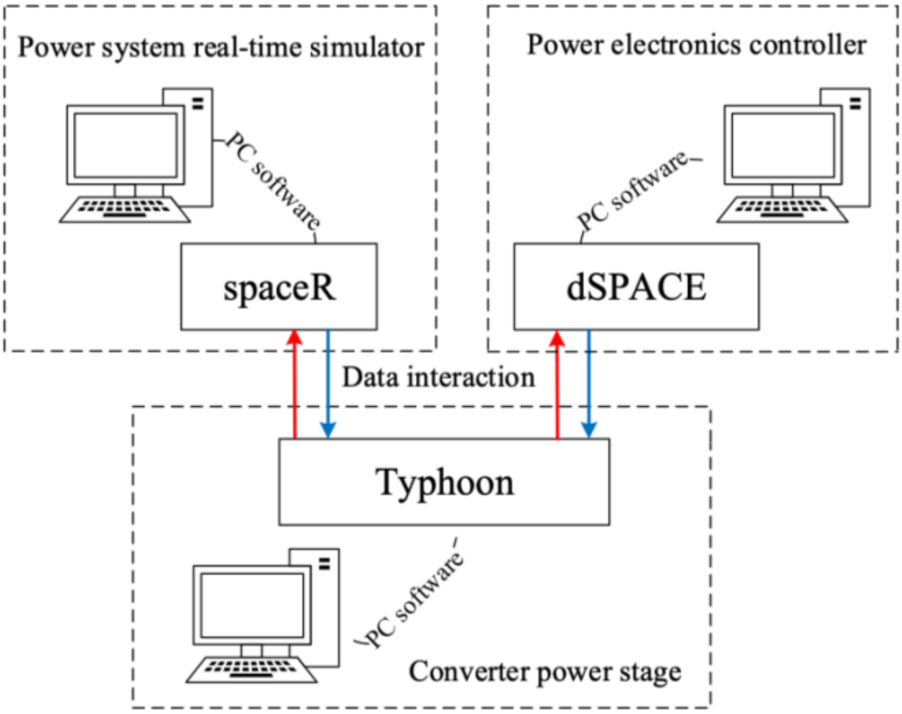
2.1.7 PHIL LEVEL 0

In PHIL level 0 (PHIL 0), the entire power system is simulated, it can be implemented in any computer or HIL simulator and does not use any part of the final product. CHIL 0 and PHIL 0 are usually tied to each other in a specific case called "simulation in the loop", used to recreate specific products or scenarios in a completely virtual environment, as shown in Figure 2-8.

Another example of PHIL 0, with varying levels of CHIL, is to validate if a specific control system can operate with different plant models, and so the models are implemented and simulated while the controller is real.

In product certification, PHIL 0 can be used to test extreme conditions in a safe environment. It can be used, for example, to estimate the short circuit current, or the voltage and current behavior in specific components during a fault. In product development, PHIL 0 is also useful to test the efficiency and impact of protection routines/systems and to evaluate some project details, like determining the best converter topology for a specific application, simulating the desired scenario with different alternatives.

Figure 2-8 - Example of PHIL 0 application



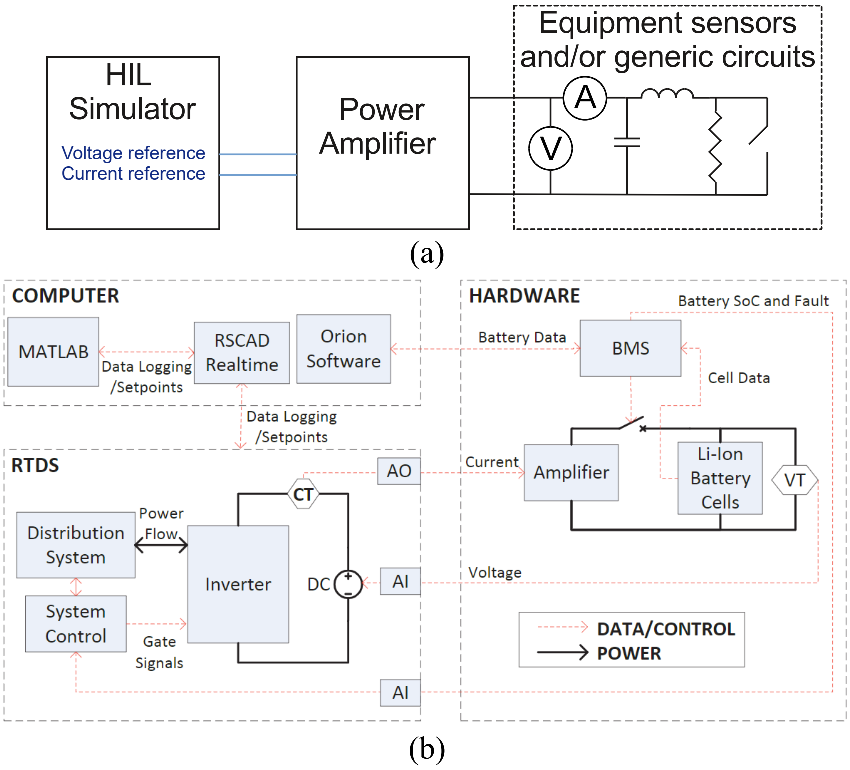
Source: (PAN et al., 2022)

2.1.8 PHIL LEVEL 1

PHIL level 1 (PHIL 1) tests the equipment sensors and/or a specific circuit. It can be used prior to energizing the converter for the first time to assure that everything is working. For example, PHIL 1 can be used to test if protection circuits will work at the desired levels of voltage and current and what will be the behavior of the PWMs and switches during a specific event, without risking equipment damage. In product certification, PHIL 1 does not provide enough information about a product behavior to assure the compliance with standards but can be used in specific situations to at least verify if the components will have the desired behavior during test conditions or to test specific components that will be part of the inverter and needs to have its own compliance testing certificate.

The main objective of PHIL 1 is to assure that the hardware complies with the minimum requirements prior to converter first power-up, checking if the sensor gains, polarity, etc. are correct. Also checking if other important parts are working as intended, like if circuit protections are actuating among others features. An example of a PHIL 1 application is shown in Figure 2-9.

Figure 2-9 - Example of PHIL-1 testbed (a) generic schematic, (b) practical application for battery cell testing



(a)

(b)

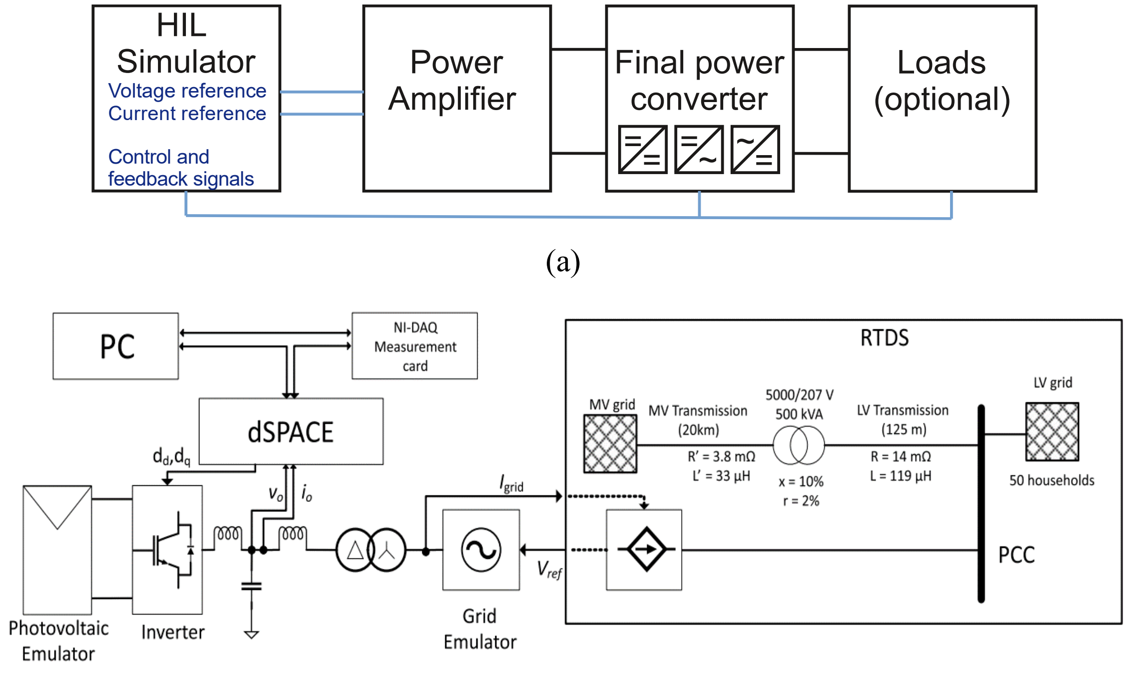
Source: (TAYLOR; AKHAVAN-HEJAZI; MOHSENIAN-RAD, 2017)

2.1.9 PHIL LEVEL 2

In PHIL level 2 (PHIL 2) a fully assembled power converter is tested, as shown in Figure 2-10. This is the final level for most inverters that are composed of a single power converter, like microinverters or high-power central inverters. PHIL 2 can also be used to individually test power converters composed of various modules or with multiple units operating in parallel, like a boost-inverter setup using a constant voltage source to test just the inverter or using a load to test the boost capabilities, or even individual parts of larger inverters composed of multiple modules.

The main objective of PHIL 2 is to assure that a single power converter is properly working and complies with standards. This is also the most well-known example of PHIL that can be found in literature.

Figure 2-10 - Example of PHIL 2 (a) generic schematic, (b) practical application to test photovoltaic inverters into specific grid models and online identification of complex power grid.



(a)

(b)

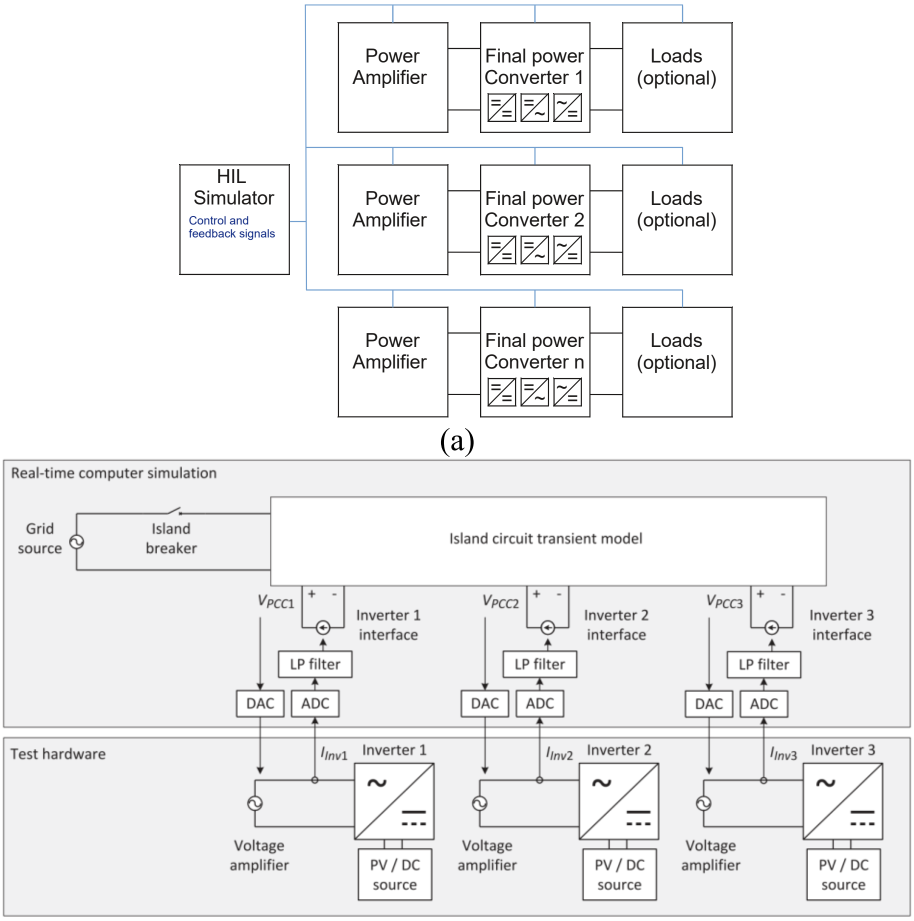
Source: author and (REINIKKA et al., 2018)

2.1.10 PHIL LEVEL 3

In PHIL level 3 (PHIL 3), the entire power hardware, composed of multiple converters used in the tests is the same that will be assembled in the final product. It is common to have large inverters that use multiple modules in parallel to achieve high power output. It is also common to have utility scale inverters composed of a boost converter in series with an inverter, and one converter can interfere in the operation of the other(s). Even if all power converters were individually tested in PHIL 2 and are correctly operating, there is no guarantee that, when assembled together, they will still comply with the standards. As a result, it is necessary to have a PHIL level to evaluate the behavior of multiple power converters. Figure 2-11 shows an example of a PHIL testbench for multiple power converters to test the impact of the interaction between them in island detection algorithms.

The main objective of the PHIL 3 tests is to assure that a complete setup of multiple power converters operating together still comply with the standards.

Figure 2-11 - Example of PHIL 3; (a) general schematic, (b) practical application



(a)

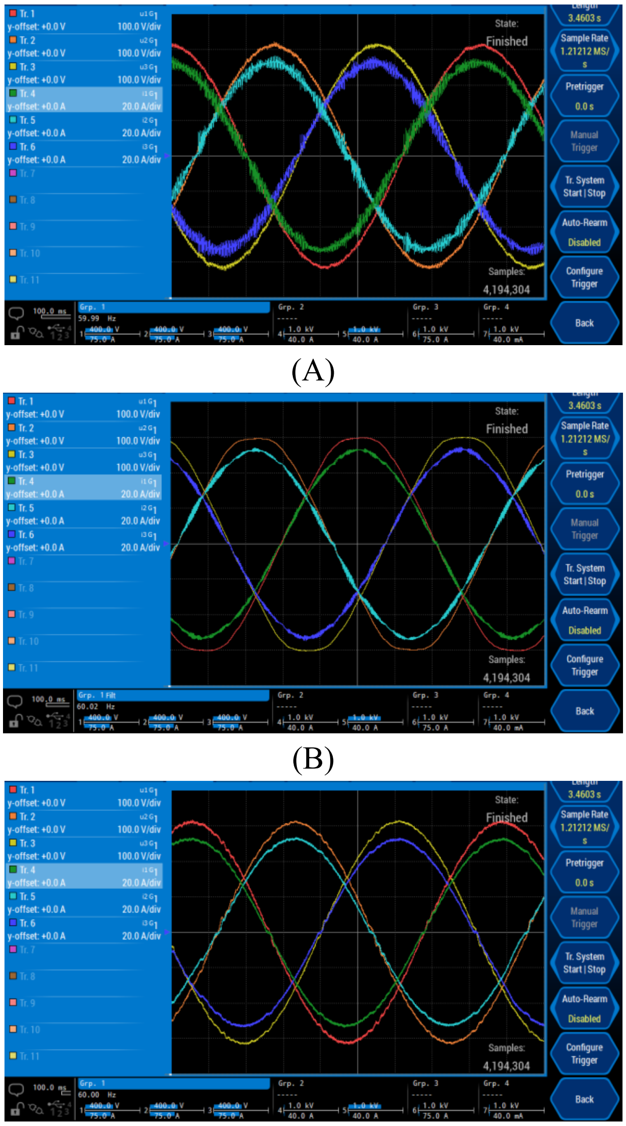
(b)

Source: (HOKE et al., 2018)

2.2 EXTERNAL ENVIRONMENT

The external environment is where all environmental conditions that are not dependent on the inverter itself are tested. For example, an inverter can be tested with multiple kinds of grid or PV array simulators, resulting in different behaviors and test results. The classic example of how the ambient can influence test results is the use of an ideal grid simulator, without impedance between the inverter and the power simulator, or the use of such impedance, as shown in Figure 2-12, that shows three different current waveforms for the same inverter connected to three distinct grid models.

Figure 2-12 - Different current waveform for the same inverter connected to different grid models (A) ideal grid, (B) real laboratory grid, (C) ideal grid with IEC61000-3-3 flicker impedance.



(A)

(B)

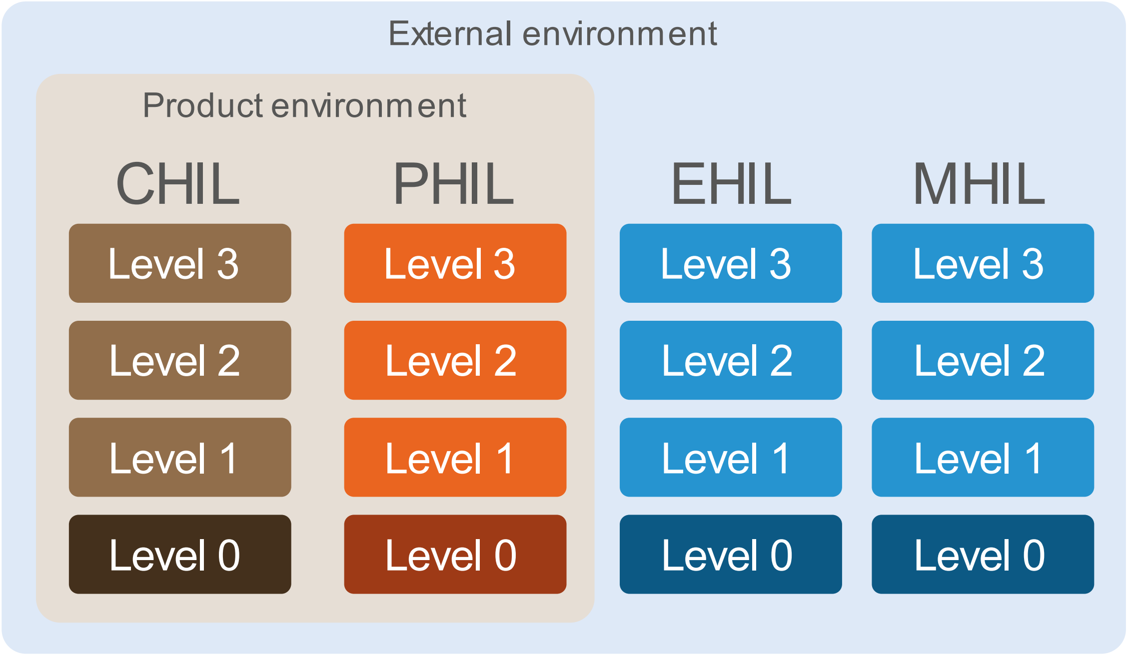
(C)

Source: Author

Another common problem related to the environment, and that is considered in this proposition, is the equipment management. Considering the new concepts of smart grids and the fact that system regulators are observing the benefits that inverters can bring to the power system, as voltage, frequency and reactive power control, the possibility to remotely manage the parameters of an inverter is an important topic. From a fully isolated inverter, where no parameter can be changed, to fully connected inverters that can be remotely controlled via internet or other protocol, those capabilities need to be evaluated.

To better organize and standardize the environment where an equipment will be tested, considering everything outside the equipment itself, two subcategories are proposed as shown in Figure 2-13, "environment (EHIL)" to define the conditions of the power systems that will be connected to the EUT during the tests (AC and DC sources, grid simulators, among others) and the "management (MHIL)" to define how the inverter management will be performed and how it will respond to such commands, for example, running all standard tests simulating that the commands to change parameters are coming from a specific system, defined by the grid operator, or are being locally changed.

Figure 2-13 - External environment diagram



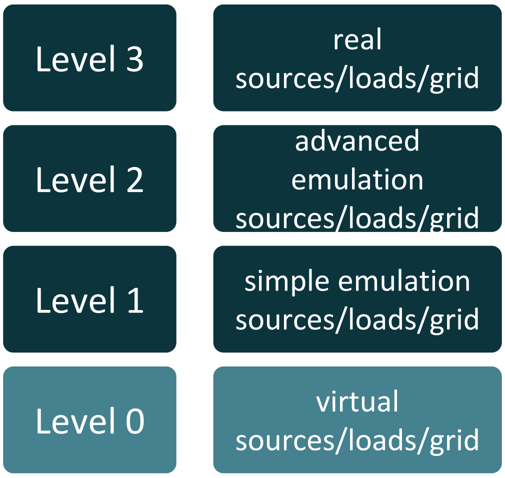
Source: Author

2.2.1 EHIL CLASSIFICATION

The objective of the EHIL classification is to define in which kind of environment the inverter is tested. Starting at level 0, inside a HIL simulator, where everything is simulated, to level 3, which uses the real sources and/or loads. The use of different testing conditions can significantly change the test results, and an environment to define it is necessary. So, the EHIL testing environment is used to measure how close to the “real world scenario” the equipment is tested.

The key factor that determines the transition between levels is the equivalence of the utilized model/equipment to the real environment where the equipment will operate. A real equipment, operating at field, will be a level 3 situation, but it is not possible to always test the equipment in such case, so, most of the tests performed in laboratories are between level 1 or 2 of the diagram shown in Figure 2-14. A few exceptions can be found, especially when the loads are simple. It is possible, for example, to test an inverter designed to start an electrical motor, utilizing the real electrical motor. It is also possible to simulate the current and voltage waveforms of the motor using an electronic load, as it is the case of the Inmetro ordinance n°140/2022 that allows both kind of tests, using a real motor or a simulated one, to certify off grid and/or hybrid PV inverters.

Figure 2-14 - EHIL Classification diagram



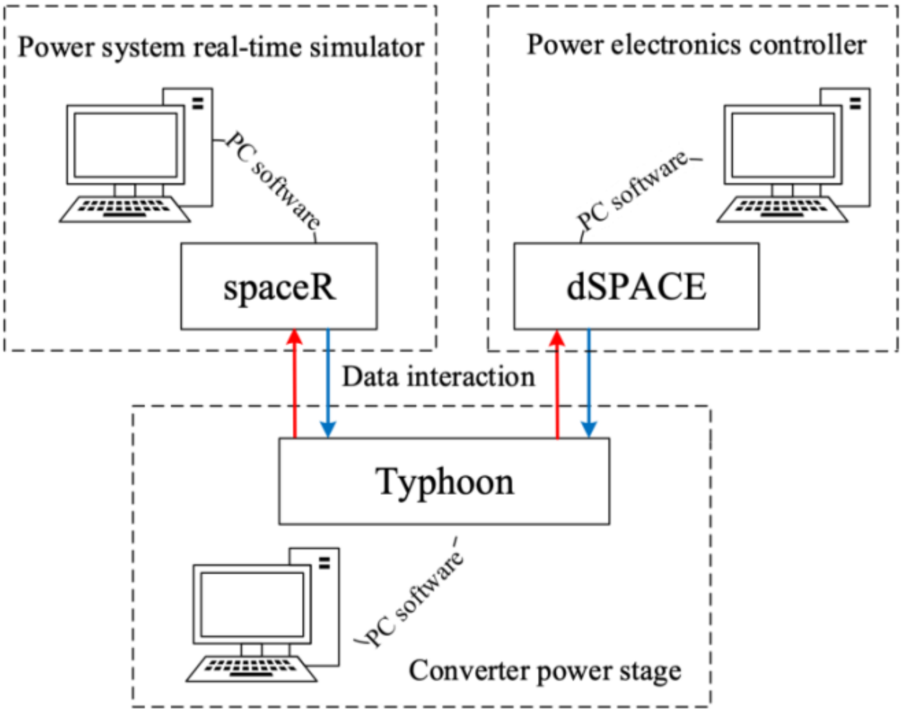
Source: Author

2.2.2 EHIL LEVEL 0

The EHIL Level 0, as in the CHIL 0 and PHIL 0, is a specific case where everything is simulated, and so, the same image can be used to demonstrate all of them. In this case, there is no real parts being tested, just circuit models and control algorithms, as well as load and grid models. When everything is simulated (CHIL 0, EHIL 0 and PHIL 0) it is also a very specific situation, that some authors and companies call a "Simulation in-the-loop", as there are no real parts, demonstrated in Figure 2-15.

EHIL 0 can be used with CHIL level 0-3, as it is possible to test real controllers using simulated environments, but it is not possible to test EHIL 0 with PHIL 1-3, just with PHIL 0. To test power equipment, it is needed a power source or load, and so, it will fall in EHIL 1-3 categories, as will be better explained in the following sections.

Figure 2-15 - EHIL Level 0 demonstration



Source: (PAN et al., 2022)

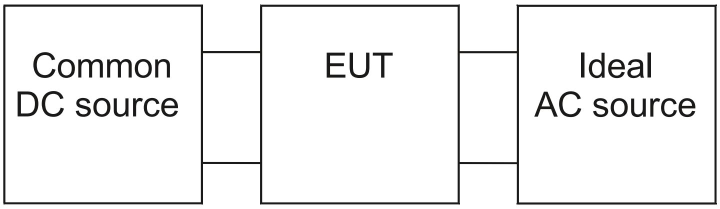
2.2.3 EHIL LEVEL 1

In EHIL Level 1 (EHIL 1), the environment is created through the use of simple simulations of the loads and sources. An example of a simple simulation is the use of a DC source to simulate a PV panel or battery. Another case, usually utilized by certification laboratories, is the use of a simple grid simulator that only replicates grid voltage and frequency, as an ideal grid, as shown in Figure 2-16. This is the case of the Inmetro ordinances 004/2011 and 140/2022. In the specific case of Brazilian certification process, all tests are performed considering an ideal grid simulator of 127V or 220V (220V/380V) 60 Hz. The only test that uses a more complex system is the flicker test, that uses a grid impedance, defined by IEC 61000-3-3, to simulate a weak grid.

Despite being a possible way to simulate the environment, such kind of testing conditions are not very representative of the real-world scenario, especially regarding the grid simulators. There is not a simple grid model that is representative of the conditions that the inverter may face when installed in the field and so, even a certified product, tested in ideal conditions, may have problems when operating with a distorted or high impedance real grid.

The main objective of EHIL 1 certification is to assure that, in ideal conditions, the equipment will comply with the standard tests. Despite this stage being important, and in some cases, the most utilized in test laboratories, it is not the most representative in terms of “real world scenario”.

Figure 2-16 - Simple environment simulation with a DC source simulating PV array and AC Source to simulate the grid.



Source: Author

2.2.4 EHIL LEVEL 2

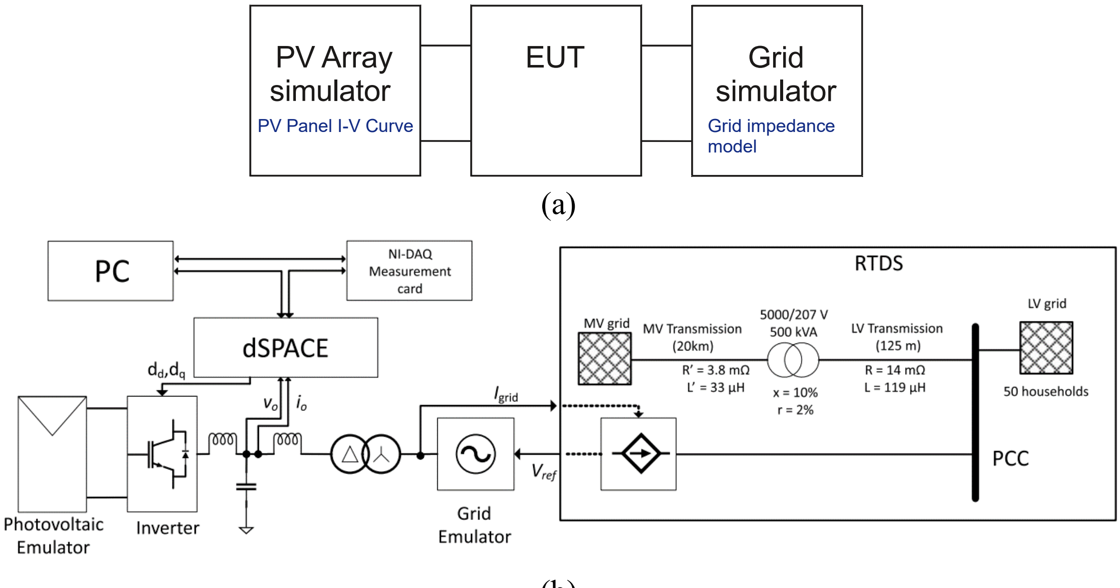
In EHIL Level 2 (EHIL 2), the loads and sources are simulated using complex and more representative models, such as a PV array simulator instead of a simple DC source, a grid simulator instead of a simple AC source and, when applicable, grid impedance models, that can be externally assembled, or internally programmed in the grid simulator.

A good example of a EHIL 2 implementation is the figure used to represent the PHIL 2 situation. The schematic in Figure 2-17 represents a solar inverter being tested with a complex grid model, running in a HIL simulator, that represents the transmission and low voltage grids as well as transformer and other elements of the grid. This kind of model is more representative than the simple AC sources used in EHIL 1.

There is not a model that represents the exact environment that an inverter will face when operating, but it is possible to determine some of the worst-case scenarios. Despite not being a fully representative test, it is still more representative than the EHIL 1.

The main objective of the EHIL Level 2 certification is to verify the compliance of the EUT to the desired standards, considering non ideal conditions. Those conditions can be determined by each regulatory body around the world, as the representative grid models are different in each country. It would assure that the equipment, especially the imported ones, developed considering different grid models, will still work in the new scenario.

Figure 2-17 - EHIL 2 representation (a) general schematic, (b) practical application with grid impedance model for PV inverter testing



Source: (REINIKKA et al., 2018)

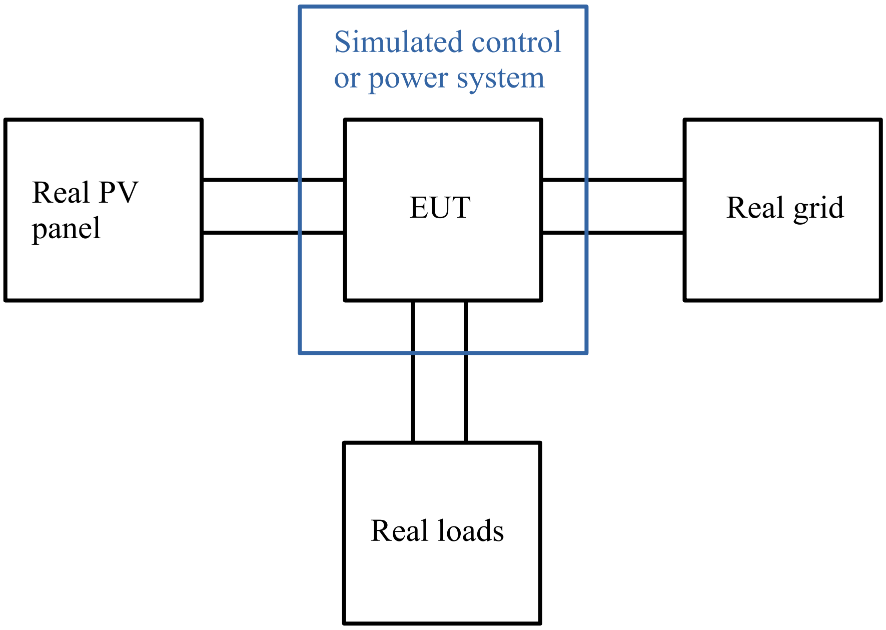
2.2.5 EHIL LEVEL 3

In EHIL Level 3 (EHIL 3), the real loads or sources are used during inverter testing, as shown in Figure 2-18. This is the highest level in terms of realty and fidelity as it is the real scenario where the equipment will operate. Unfortunately, it is difficult to implement this kind of testing in laboratory, as some real-world scenarios are really difficult to reproduce due to complexity, cost, or safety concerns.

Most of the laboratories will still use the EHIL level 1 and 2 scenarios, but in some cases, it will be possible to reproduce real world conditions inside laboratories. It is necessary to create this category to embrace the specific cases where real loads or sources will be used, as it may be the case of small inverters.

The main objective of the EHIL 3 is to assure that the equipment is fully tested in the most complex and close to reality scenario, when it is possible and applicable. This is the highest level of reality that a test can have and complying with standards within this scenario is a really good indicative that the equipment will have the same behavior in field.

Figure 2-18 – Schematic of a EHIL 3 simulation with simulated parts of the EUT and real grid, loads or PV panel.



Source: Author

2.2.6 MHIL CLASSIFICATION

The MHIL classification is based on the communication and management interface of the inverter. As already mentioned, inverter management is a matter of increasing importance on modern electrical power systems. The benefits that inverters can bring to power system, helping to regulate voltage and reactive power is an important topic. Papers like (BASU et al., 2020) show a gain in stability and resilience in grids with high PV penetration, if they operate in a smart way to support the grid.

However, other papers like (WANG et al., 2022) show that even with the actual grid support functionalities, demanded by grid interconnection standards like UL 1741, they may still become instable under some circumstances, when operating in weak distribution grids with high PV penetration for example.

Considering the exposed problems and the fact that grid support provided by IBR are still being investigated, it is probable that the grid support functionalities will keep improving and changing along the coming years. Inverters already installed will also need to be updated to comply with the new requirements, and a way to do this must be evaluated. Also, some of the new features being proposed in literature may need a direct control of the inverters from a central grid operator.

Considering the entire situation, it is necessary to have a specific test environment to evaluate the management characteristics of the IBR, shown in Figure 2-19, classifying them according to the management level and testing how they will operate when such commands are sent to them.

Figure 2-19 - MHIL Classification diagram

Source: Author

2.2.7 MHIL LEVEL 0

In MHIL Level 0 (MHIL 0), the equipment under test has no management system or is not using it during the tests. This is the case of very simple power converters that are programmed to operate at a defined point, and it is not possible to change any kind of parameter or specification. The inverter is installed and will operate in the same way during its lifetime.

2.2.8 MHIL LEVEL 1

In MHIL Level 1 (MHIL 1), the equipment under test has a simple offline management system, usually through external buttons, commands, or displays, when applicable. This kind of inverter allows modification of parameters or configurations, but only if a technician can go to the inverter physical location and change such parameters. Despite having a management system, it still operates in almost the same way as a MHIL 0 situation, as a grid operator cannot remotely configure the equipment to provide any kind of ancillary or auxiliary services.

2.2.9 MHIL LEVEL 2

In MHIL Level 2 (MHIL 2), the equipment under test can be accessed and controlled through a local network or a peer-to-peer (P2P) system. In this situation the equipment can be directly connected to a phone, through a specific app, for example, that allows parameters or configuration changes without being physically near the inverter. However, it is still not possible to connect the equipment to a regional control system, as a grid operator, for example, and so, its functions are also limited.

There is the case where the equipment can also be connected to the internet and be remotely controlled, but only by the manufacturer own system, which allows for a change that can affect all the installed equipment. In this case it is still considered a MHIL 2 classification, as a grid operator would only have an indirect control of the system, needing to ask manufacturers to perform all the desired tasks involving the inverter configuration.

2.2.10 MHIL LEVEL 3

In MHIL Level 3 (MHIL 3), the equipment under test has a management system in such a way that it is possible to remotely control the operation parameters and other configurations. The management system can be integrated with standard management systems operated by grid operators and all inverters can be directly controlled by the grid operators.

This is a level that is currently unachieved by most countries, as is the case of the Brasil itself. In Brasil, the National Power System Operator (ONS) does not have a system that can control the inverters connected to the grid and still can not use them to support the power system. So, even considering that the Inmetro ordinances and Brazilian standards demand that the inverters connected to the grid must have a series of specific commands to change the operating parameters, like power factor, active and reactive power, among others, there is no system that can be used to it, and so, just MHIL level 0-2 can be tested for Brazilian certification.

2.2.11 Considerations about EHIL and MHIL testing

The external environment is a very complex environment to be standardized. An equipment can be connected through a series of different component at the same time, such as DC power sources, grid simulators, battery simulators and load simulators. All of them may have their own simulation models, that can vary from EHIL 0-3 in each equipment. This is the case of inverter testing considering the Inmetro ordinances, where a PV array simulator (EHIL 2) is used with a simple grid simulator (EHIL 1) at the same time to test a PV inverter. In this case, a confusion may happen when defining in which EHIL level this test should be considered. To solve this kind of problem, when considering the external environment, the EHIL level used should be the one the component that most impact the results. For example, if the standard being used during the tests is related to grid interface, then the grid simulator EHIL level should be used, despite other equipment with different EHIL levels connected to the inverter during the tests.

This also applies to MHIL testing. The same inverter can be tested considering MHIL level 3, in places that have statewide management systems for inverters, or level 2 in countries that do not have this kind of system or operate with different communication protocols that the inverter does not have.

2.3 TESTING ENVIRONMENT

Any laboratory, that wants to certify or test compliance of products, must follow the standard “ISO/IEC 17025 – General requirements for the competence of testing and calibration laboratories.” The main objective of this standard is to assure that all laboratories will use, when possible, the same measurement and testing methods. Also, when not possible, the standard guides the creation or adaptation of new methods. The guidelines for method development are:

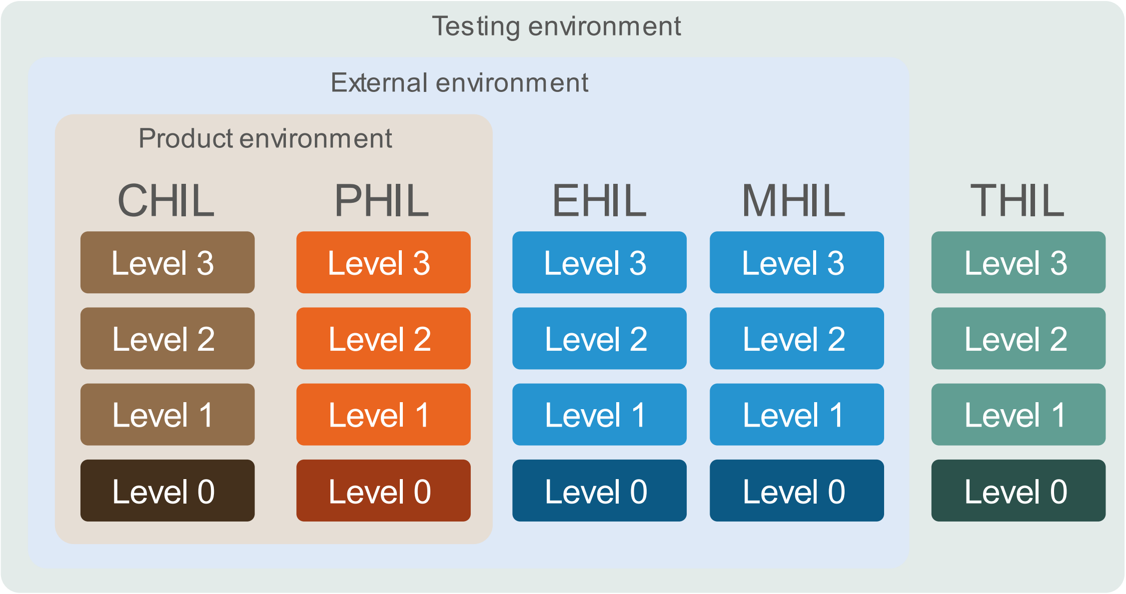
Reproducibility – The method must be developed in a way that, knowing all the necessary data, it can be reproduced by different laboratories.

Reliability – The results obtained by any laboratory, following the same methods, must be convergent, considering the confidence level.

Robustness – When possible, methods must be developed in a way that minimizes the impact of parameter variation and external influence. For example, using simulators from distinct manufacturers should not cause relevant differences in test results.

To have a reference of the compliance level of the measurement and testing methods with the ISO/IEC 17025 requirements, the testing environment (THIL) is created, it is the “widest” environment that embraces all the previous ones, as shown in Figure 2-20.

Figure 2-20 - Testing environment diagram



Source: Author

2.3.1 METHOD SELECTION, VERIFICATION AND VALIDATION

Item “7 Process Requirements” of the ISO/IEC 17025:2017 (ISO/IEC, 2017) defines the requirements to assure the validity of the test results, and among all points, some are crucial to the testing environment and will be used to divide it in 4 levels, from none of the requirements fulfilled to complete compliance of HIL testing with ISO/IEC 17025 requirements.

“7.2.1.1 The laboratory must use adequate methods and procedures to all the laboratory activities and, when appropriated, to the measurement uncertainty analysis, in addition to statistical techniques to data analysis.”

“7.2.1.6 When it is required to develop a method, it must be a planned activity which must be assigned to competent personnel and equipped with appropriate resources. As the method development advances, periodical critical analysis must be made to assure that the costumer necessities keep being satisfied. Any modifications in the development plan must be approved and authorized.”

“7.2.2.1 The laboratory must validate not standardized methods, methods developed by the laboratory and normalized methods modified or used outside its original scope. The validation must be too embracing as necessary to satisfy the necessities of a specific application or application field. The validation techniques may be one of the following or a combination of them.

a) Calibration or precision and trend analysis using standards or reference materials.
b) Systematic assessment of factors that influence the results.
c) Method robustness test by varying controlled parameters, such as incubation temperature or volume dispensed.
d) Comparison with results acquired through other validated methods.
e) Interlaboratory comparison.
f) Results measurement uncertainty assessment through the comprehension about the method theorical principles and the practical expertise about the method performance.

2.3.2 MEASUREMENT UNCERTAINTY ASSESSMENT.

The standard also defines requirements regarding the measurement uncertainty assessment, which is an obligation to all accredited testing laboratories.

“7.6.1 The laboratory must identify the contributions to measurement uncertainty. When assessing the measurement uncertainty, all the significative contributions, including the ones from sampling process, must be considered using appropriated methods.”

“7.6.3 A laboratory that realizes tests must assess the measurement uncertainty. When the test method makes it impossible to assess a rigorous uncertainty analysis, an estimative must be made based on method theorical principles and the practical expertise about the method performance.”

2.3.3 ENSURING THE VALIDITY OF RESULTS.

Regarding the validity of test results, to assure that the laboratories are measuring things in a correct and valid way, the standard also defines requirements.

“7.7.1 The laboratory must monitor the validity of the results. The resulting data must be registered so that trends can be detected and, when applicable, statistical methods for critical analysis of the results must be applied. This monitoring must be planned and critically analyzed and must include, when appropriated, but not limited to:”

a) Utilization of reference materials or materials for quality control.
b) Utilization of alternative instrumentation to get traceable results.
c) Functional checks of measurement and test equipment.
d) Use of checking standards or working standards with control charts, when applicable.
e) Intermediary checking of measurement equipment.
f) Replicated tests or calibrations, using the same methods or different methods.
g) Retesting or recalibration of retained items.
h) Results relationship of different characteristics of an item.
i) Critical analysis of the results.
j) Intralaboratory comparison.
k) Testing of blind items.

“7.7.2 The laboratory must monitor its performance through results comparison with other laboratories, when available and appropriated. The monitoring must be planned and critically analyzed and must include, but not limited to, one of the following alternatives:

a) Participating of proficiency tests.
b) Participating of interlaboratory comparisons distinct from proficiency tests.

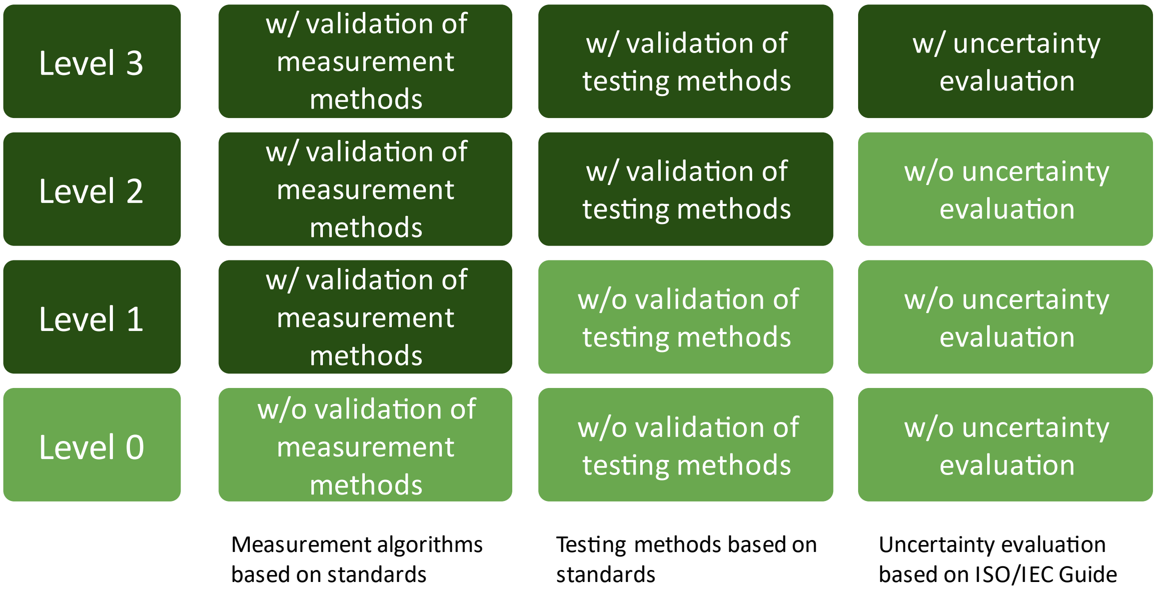
2.3.4 THIL CLASSIFICATION

Testing Hardware-in-the-loop (THIL) focus on the measurement and testing process, it goes from level 0, where no validated method is used, to level 3 where measurement and testing methods are validated, and uncertainties are evaluated and considered.

As in the previous classifications, there are three key factors that determine the level transition, shown in Figure 2-21 that is, utilization of validated measurement methods, utilization of validated testing methods and uncertainty evaluation.

A conventional laboratory, performing product certification without the use of hardware-in-the-loop, already operates at an equivalent to THIL 3. For product development, any of the THIL levels are allowed and, actually, most part of HIL testing can be classified at THIL 0, as they use proprietary measurement and testing methods without properly standardization. A few companies already have standardized measurement algorithms and/or testing methods that can be classified in THIL 1 or 2, but almost no company has a solution that effectively implements THIL 3. It is important to mention that the process classified as THIL 0, 1 or 2 is not wrong or should not be used, as they are developed usually for product development, where there is no standardized testing method for specific situations. But for product certification, only THIL 3 is allowed as the inferior levels do not entirely fulfill the ISO/IEC 17025 requirements.

Figure 2-21 - THIL Classification diagram



Level 3	w/ validation of measurement methods	w/ validation of testing methods	w/ uncertainty evaluation
Level 2	w/ validation of measurement methods	w/ validation of testing methods	w/o uncertainty evaluation
Level 1	w/ validation of measurement methods	w/o validation of testing methods	w/o uncertainty evaluation
Level 0	w/o validation of measurement methods	w/o validation of testing methods	w/o uncertainty evaluation
	Measurement algorithms based on standards	Testing methods based on standards	Uncertainty evaluation based on ISO/IEC Guide

Source: Author

2.3.5 THIL LEVEL 0

In THIL level 0 (THIL 0) the measurement system and method used to perform the tests and evaluate the data is the one developed and used by each HIL manufacturer or, in other words, a non-standardized method or measurement system. Also, there is no evaluation of measurement or test uncertainty. Considering a “metrology level”, this is the lowest confident scenario, as all measurements are performed without a standardized method and without measurement uncertainty analysis or method validation and, this way, do not satisfy the requirements of the ISO/IEC 17025 to be used as a compliance test.

This level of testing can be used as a precertification option as it is the less expensive in terms of cost and time and the most versatile way to test power converters. The versatility comes from the fact that, as there are no restrictions to the measurement system or the testing method, it allows for rapid changes on the system without the need of recalibration or uncertainties recalculation. Also, in this level of THIL, there is no need to follow specific methods, and so the manufacturer or the laboratory can create or adapt any kind of method to measure or check the equipment behavior in very specific scenarios, like equipment debugging for example.

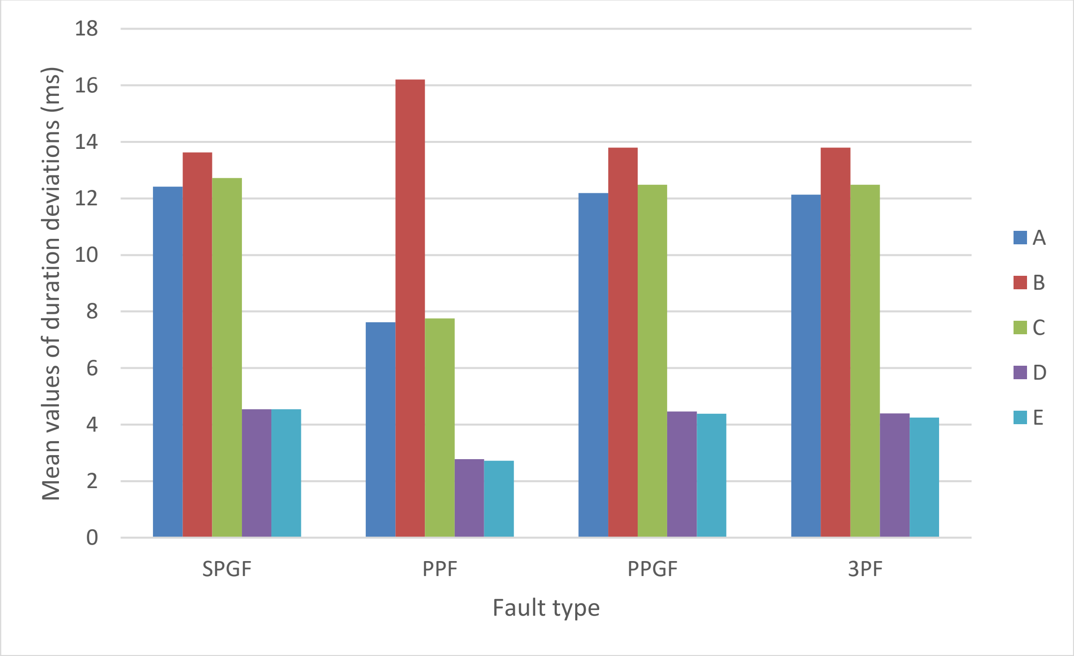
Despite this type of testing being useful for product development and precertification tests, the results have no value to compliance assessment as they do not comply with the ISO/IEC 17025, and more elaborated test and measurement methods need to be further used.

2.3.6 THIL LEVEL 1

In THIL 1 the measurement system and method used to perform the tests and evaluate the data is standardized, based on worldwide accepted standards, i.e., the IEC 61000-4-30 for power quality parameters (INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC), 2015). At metrology level, this is the middle term scenario, as all measurements are performed with a standardized method but still without measurement uncertainty analysis or testing method validation and standardization.

This level of testing can also be used as a precertification option with a better confidence level than the THIL 0, especially when the test is performed in different HIL hardware that could have distinct measurement techniques. It requires more effort (time and money) to implement standardized measurement methods by the manufacturers and, ideally, a definition of a common method to be used by all manufacturers. But once it is implemented it can easily come as a default standard on all HIL systems and substitute THIL 0 testing with the same cost and better confidence level. Figure 2-22 shows an example of how different measurement methods can have different results when measuring the same event.

Figure 2-22 – Mean values of dip duration deviation comparison for different RMS measurement methods during grid faults. (SPGF = single-phase to ground fault, PPF = phase-to-phase fault, PPGF = Two phases to ground fault, 3PF = Three phases fault)



Source: Adapted by the author from (YE et al., 2014)

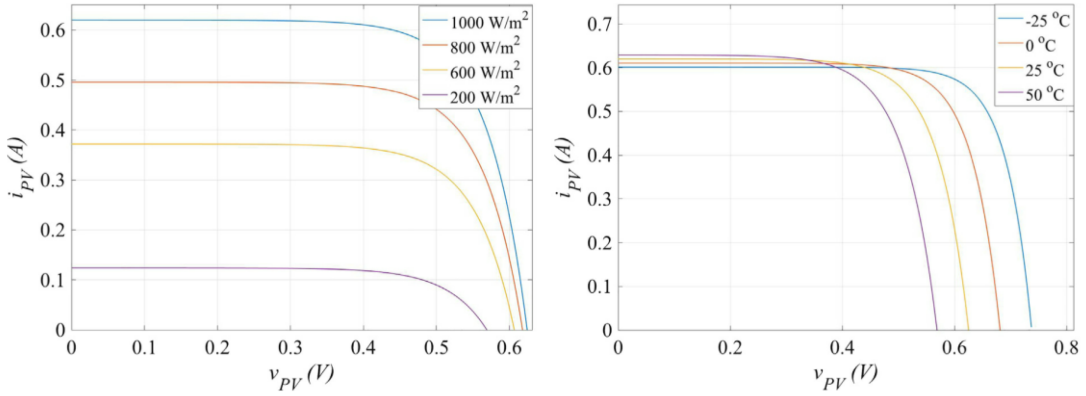
2.3.7 THIL LEVEL 2

In THIL 2 the measurement and testing methods used to perform the tests and evaluate the data are standardized, based on worldwide accepted standards. At metrology level, this is the second highest confidence level scenario.

The validation and standardization are important because, while the measurement method standardization assures that everyone is measuring the same variable in the same way, the testing method standardization assures that everyone is measuring a specific variable or behavior in the same conditions and through the same procedure. A common example of how different testing methods, especially with different parameters, can return very different results is shown in Figure 2-23, where the I-V curve of a generic solar panel is measured in diverse conditions, resulting in very different values of short-circuit current, open circuit voltage and maximum power point power. To solve this problem, the standards define that all solar panels must be tested at standard test conditions (STC). But even if the parameters are standardized, different ways to measure still may results in unmatching results, like using I-V trackers with different topologies, resolution, or acquisition rate and consequently, even at STC, they can return different I-V curves for the same panel.

Despite THIL 2 results being representative and robust, they still do not completely fulfill the ISO/IEC 17025 and still cannot be used for product certification.

Figure 2-23 - I-V curve for the same panel measured through different parameters (a) constant temperature and varying irradiance, (b) constant irradiance and varying temperature.



(a) (b)

Source: (ZHU; XIAO, 2020)

2.3.8 THIL LEVEL 3

In THIL level 3 (THIL 3) the measurement and testing methods used to perform the tests and evaluate the data are standardized, based on worldwide accepted standards and measurement/test uncertainties are accounted for.

This level of testing is almost exclusive to accredited laboratories and certification processes, as in order to calculate the measurement uncertainties the equipment needs to be calibrated and all issues that can possibly interfere on results need to be accounted. To achieve this level of confidence all parts between the HIL simulator and the control board, i.e., interface boards, need to be carefully planned and analyzed and kept the same among all tested equipment, as changing something will imply in the recalculation of the uncertainties.

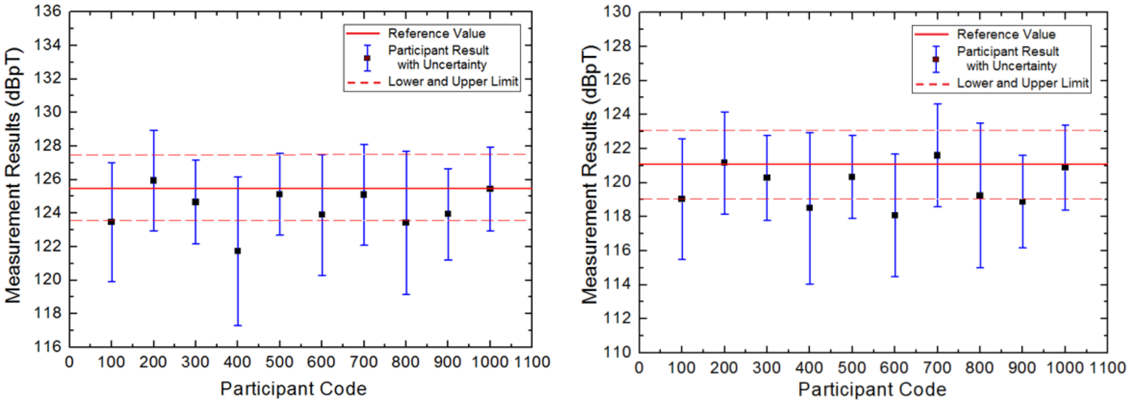
At this level, all the requirements of the ISO/IEC 17025 about validity of test results can be accomplished, and the HIL testing could be used as a compliance certification method.

Uncertainty calculation is important as no measurement equipment is perfect and shows the measured variable with 100% certainty. Considering digital equipment, with finite ADC resolution, the value will always be rounded to a predefined value based on the resolution, and so, any information between two ADC levels is lost. For example, if every level of the ADC corresponds to a multiple of 1 V (1V, 2V, 3V) and it always round to the nearest number, a measurement of 1,3 V will be shown as 1 V by the equipment and so, in this case, the equipment has 0,5 V of uncertainty and the correct reading would be "the real voltage is in the range of 1 V ± 0,5V".

Measurement uncertainty does not appear only on ADC converters, but almost any physical part of measurement equipment, like the resistors that compose the voltage divider circuit that may vary their resistance due to temperature, humidity, or due to aging, for example. Even the simplest instruments, like a simple ruler, has measurement uncertainty due to temperature (material dilatation), aging (material degradation), or utilization (being dropped from the table may change the ruler size).

This way, assessing the uncertainty of measurement equipment and the process as a whole is important because, even measuring the same variable, with the same equipment, in the same conditions, may return different vales, but considering the uncertainty range the values may be convergent. Ideally it is desirable that instruments have the smallest uncertainty range as possible; this is usually the difference between a "good" and a "bad" instrument, but even the best ones still have uncertainty ranges and will show different values when measuring the same thing. Figure 2-24 show a series of measurements, performed in the same conditions and in the same reference material, used in an interlaboratory comparison, where it is possible to see that even if all labs are showing slightly different values, all of them are still convergent and show "the same results" considering the uncertainty range, and thus all of them are considered able to perform the EMI measurements according to the specific standard.

Figure 2-24 – EMI testing interlaboratory measurement comparison with uncertainty range



(a) (b)

Source: (OEN et al., 2022)

2.4 ANALYZES OF THE REQUIREMENTS TO ASSURE THE VALIDITY OF TEST RESULTS

As already mentioned in the beginning of the THIL classification the item “7 Process Requirements” of the ISO/IEC 17025:2017 defines all the requirements that a testing or certification laboratory needs to comply to assure the validity of the test results. A small overview of the points will be shown and how different parts, involved on product certification chain, can act to achieve the goal of using HIL for product certification. The main points to validate a testing method are:

- **Standardization and reproducibility of the testing method**: The method must be reproducible by other accredited laboratories and the results from all laboratories must be compatible, considering the measurement uncertainty range.
- **Measurement uncertainty analysis of the method**: The measurement uncertainty associated with the method must be assessed by the laboratories to define the confidence level and allow further comparison with other accredited laboratories.
- **Method validation**: The laboratory must validate non standardized methods or methods developed by the laboratory. Among several ways to validate a method, a comparison of results between a standardized method and the newly developed one is acceptable.

To comply with the mentioned points, a series of measures are needed among all involved parts, standards development bodies, HIL equipment manufacturers and the certification laboratories.

- **Standardization and reproducibility of the testing method:** This point can be divided in two parts, measurement method and testing method. The first part, related to HIL manufacturers, is to implement in their equipment standardized measurement methods, i.e., using the IEC 61000-4-30 to measure power quality parameters instead of their own algorithms or routines. This allows for compatible results even in different HIL hardware. The second point, related to standard definition bodies (ABNT, IEEE, IEC, ISO, etc), is the definition of how a specific test is performed, i.e., using the method described in the ABNT NBR 16150 to measure the voltage level at which the inverters disconnect. These two points assure that all laboratories are measuring the same thing in the same way and are following the same steps to achieve the results, and despite being a common procedure outside the HIL environment, it must be extended to such environment too.

- **Measurement uncertainty analysis of the method:** This point relates mainly to certification laboratories. The main action that all laboratories must do is to calibrate their HIL hardware i.e., to assure that when an analog output sends 5 V, it is really sending 5 V. As there is information exchange between the HIL hardware and the control board, it is necessary to assure that this information is correct. When interface boards or other components that can contribute to measurement uncertainties are used between the HIL and the control board, their influence in the measurement uncertainty needs to also be accounted for. As a last point, all HIL manufacturers need to calculate and clearly inform the measurement uncertainty of their equipment, in the same way that power analyzers or other measurement equipment already do.
- **Method validation:** As the final step to assure the validity of the results, further investigations, i.e., comparing the results of a HIL testing with the results of a conventional test performed in the same equipment are needed. This part also mainly relates to the laboratories to test as many equipment as possible to collect enough data to assure that the results from HIL testing match the results of the conventional tests. There is also a need for model validation, to assure that the model sent to the laboratory is really representative of the product that will be tested, but this part needs to be better discussed, as it involves not only technical concerns but also a mechanism to assure that companies with "bad intentions" are not sending good models to certification while selling bad products, not represented by the models.

2.5 SUMMARY

In this chapter it was proposed a new classification of HIL testing, keeping the already known and accepted definitions used by IEEE taskforce but expanding it with subclasses to better understand the extension of the tests performed. The new subclasses are based on how close to the final product the hardware under test is. For example, a CHIL 1 test is used to test only if the final processor (assembled in a generic control board) will work as intended, while in CHIL 2 the board tested needs to be the same used in the final product. With the expanded CHIL and PHIL, defined as the product environment, the proposal creates two other environments to consider aspects that just the CHIL and PHIL classification would not englobe.

In the external environment, the aspects related with the environment where the equipment will operate and its fidelity to the real scenario are considered. Its 4 levels define the “realism” level of the loads, sources, grid, among other external components, to which the inverter will be connected. Also, the management interface and how the equipment can send or receive commands, can be evaluated in the management subclass of the external environment.

The last environment proposed is the “Testing environment”, to deal with matters relative to how a conventional certification laboratory works, how measurements are performed, uncertainties analysis and calculation are performed, and how an inverter can be considered compliant or not with standards.

3 DEVELOPMENT OF A TESTBENCH FOR INVERTER-BASE RESOURCES

In this chapter the testbench proposed to perform development and compliance testing on photovoltaic inverters will be detailed, as well as the applicable ordinances, standards, procedures, measured variables, among other issues related to inverter certification tests. As already explained, this methodology can be used in any kind of IBR testing or certification process. In this work, it will be applied to photovoltaic inverters because the Smart Grid Institute (INRI) has the largest accredited PV inverter certification laboratory in Brazil and has all the equipment necessary to comply with ISO IEC 17025, including validated testing methods according to the Brazilian Inmetro ordinances n° 004/2011 and n° 140/2022 that will be used to compare and validate the proposed testing methods.

3.1 PROPOSED TESTBENCH FOR INVERTER-BASED RESOURCES

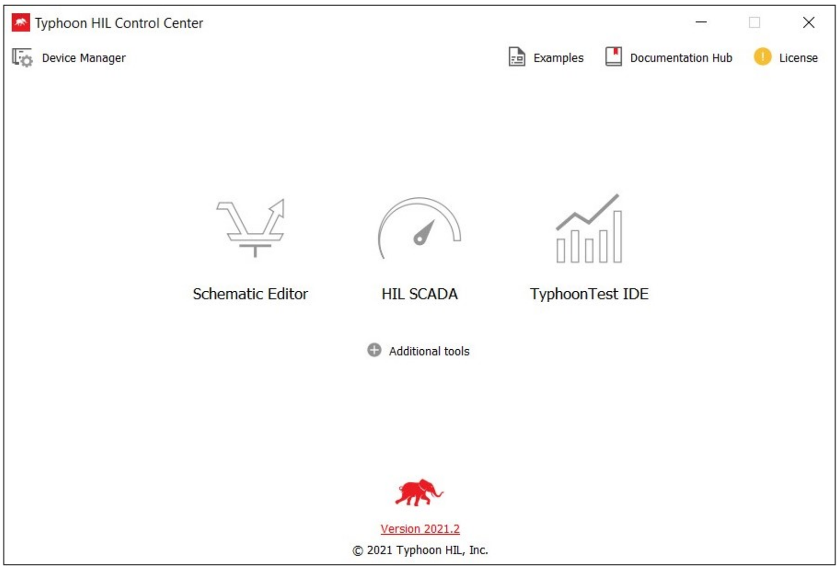
The main objective of the testbench is to perform development and certification test protocols in various kinds of IBR and in all levels of the classification proposed in chapter 2, considering all the applicable environments, PHIL, CHIL, EHIL, MHIL and THIL. This way, test protocols must be the same among all the platforms, as well as the measurement system.

The testbench needs to integrate a HIL simulation platform with the actual laboratory infrastructure meeting the following requirements:

- Open programming language, allowing the development of custom-made codes to integrate all the laboratory equipment with the HIL platform.
- Open communication protocols to let the testbench be integrated with power or measuring equipment.
- Possibility to perform all the necessary tests following the same protocol in all levels of the proposed classification, from a fully simulated to fully powered tests.
- Possibility to develop its own measurement algorithms to replicate the laboratory measuring instruments, to assure the standardization between all test levels and environments.
- Modular structure programming, to allow the system to build each test sequence considering the desired environment or test level using common blocks.

The system that best suits all the requirements, and the laboratory already uses, is the Typhoon HIL Control Center platform, from Typhoon HIL (Figure 3-1). Inside the Typhoon Control Center there are a series of tools that allow the creation of standardized tests, measurement algorithms, communication scripts, among other things necessary to the IBR testbench.

Figure 3-1 - Typhoon control center interface

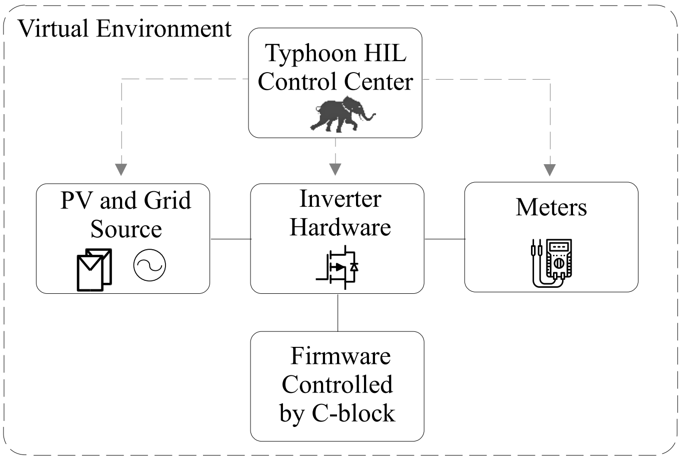


Source: https://www.typhoon-hil.com/documentation/typhoon-hil-software-manual/concepts/typhoon_hil_control_center.html

In the Typhoon system itself, it is already possible to perform HIL testing considering the pure virtual and the CHIL environments. In the “Schematic Editor” the power converter electrical circuit is designed and compiled. In the HIL SCADA it is possible to “run” the power converter, in a CHIL or pure simulated environment. Once everything is working as intended, the inverter can be tested at TyphoonTest IDE, where all the developed measurement and automated test algorithms are implemented.

Figure 3-2 shows the schematic of a fully virtual test. The Typhoon HIL Control Center is responsible for simulating the inverter power circuitry, PV and AC sources and the meters, while the inverters control system is implemented via a C-block inside the HIL604. This kind of test allows the initial development of the power converter and to test if the concept will work before building the prototype. Moreover, with the implemented testbench, it is already possible to perform certification tests with the fully simulated system, to verify if the control logic complies with the standards, for example.

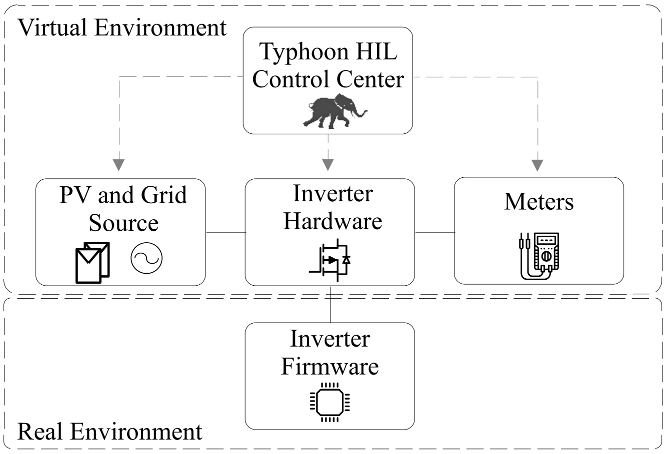
Figure 3-2 - Fully virtual test schematic, where all components are simulated inside HIL604.



Source: Author

A CHIL test schematic is shown in Figure 3-3. In this kind of test, the control system runs in a separated, dedicated control board, while the Typhoon HIL Control Center simulates all the input and output signals, based on the power schematic designed in the "Schematic Editor", and implement the models of the power supplies and the meters, developed in this project, to simulate a certification test "inside" the HIL604.

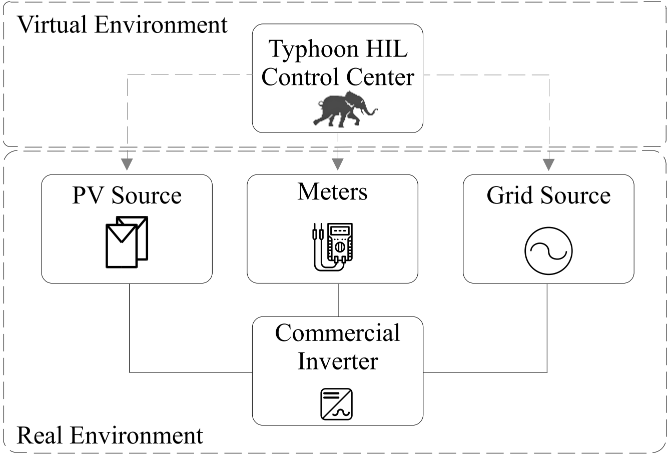
Figure 3-3 – CHIL test schematic, real control board and simulated power circuitry.



Source: Author

In the real testbench, shown in Figure 3-4, the equipment under test is the final, completely assembled commercial inverter. Typhoon HIL Control Center only controls the laboratory equipment to set the desired test conditions to power supplies (voltage, power, current, etc.) and acquires the measurement data from the laboratory instruments through direct communication. This is the final step and the closest, in terms of fidelity, to the normal laboratory testing that the INRIFV is accredited to perform on photovoltaic inverters.

Figure 3-4 - Real test schematic, real equipment, meters and power supply.



Source: Author

As for the equipment used in the real laboratory, and that are controlled by the Typhoon HIL Control Center, the laboratory has two LMG670 from Zimmer (Figure 3-5), that are the main equipment and responsible for all electrical measurements. With 7 channels it is possible to test three phase inverters with up to 4 MPPTs with up to 1000 V_{rms} and 200 A_{rms} in each channel.

The AC source simulators are from two different brands, a Supplier FCAT 10000-48-15-PFC55450 (Figure 3-7) three phase grid simulator with up to 100 kVA and 250 V_{AC} and two ITECH IT7900 (Figure 3-6) with 120 kVA and 150 kVA, both up to 350 V_{AC}.

For the DC sources, the laboratory has six Keysight PV Array simulators model N8957APV (Figure 3-8) with 1500 V_{DC} and 30 A_{DC}.

The measurement algorithms of all the laboratory equipment are modeled and simulated inside Typhoon HIL Control Center platform through python scripts and the system can generate any kind of test with the same test protocol, choosing the appropriated simulated or real power/measurement equipment to perform the certification test.

Figure 3-5 - LMG670 Precision power analyzer (A) Frontal view, (B) Back view

(A) (B)

Source: https://www.zes.com/en/Products/Precision-Power-Analyzers/LMG670

Figure 3-6 - IT7900 Regenerative Grid Simulator (A) Frontal view, (B) Back view

(A) (B)

Source: https://www.itechate.com/en/product/ac-power-supply/IT7900.html

Figure 3-7 - FCAT 10000-48-15-PFC55450 AC grid simulator

Source: http://www.supplier.ind.br/produtos_img/fcat_10000-48-15-pfc55450_05082022170339.pdf

Figure 3-8 - N8957APV Photovoltaic Array Simulator (A) Frontal view, (B) Back view

(A) (B)

Source: https://www.keysight.com/us/en/support/N8957APV/photovoltaic-array-simulator-1500vdc-400vac.html#

3.2 INMETRO ORDINANCE N° 140/2022

The National Institute of Metrology, Standardization, and Industrial Quality (Inmetro) is the body responsible for product regulation, when there is no other specific body, like the Brazilian Health Regulatory Agency (ANVISA), responsible for food, medicament, and other health related products for example. In 2011 the Inmetro started to regulate the commercialization of photovoltaic inverters, through the Inmetro ordinance n° 004/2011, which sets the minimum requirements regarding performance and user safety that PV inverters must meet to be sold on Brazilian market.

Due to technology development, a series of studies regarding the impact of a high renewable penetration on power systems, new functions that PV inverters can perform and the emergence of new kinds of PV inverters, in 2022 the Inmetro published the ordinance n° 140/2022 (INSTITUTO NACIONAL DE METROLOGIA, 2022) that will gradually replace the old requirements from the ordinance n° 004/2011. Table 3-I and Table 3-II show all the tests required by the new ordinance and the variables to be measured in each test, respectively.

Ordinance n° 140/2022 will only completely replace the old one in 2026, but for smaller inverters, with nominal power inferior to 10 kW the deadline is may/2024. INRI is the first accredited laboratory in Brazil to perform those tests and the testbench can perform the tests both in conventional way, as an accredited service, and through HIL as a non-accredited service that can be used to evaluate the equipment prior to the certification.

Table 3-I - Inmetro ordinance n°140/2022 test list

Test	Standard	Item
1 - Visual inspection	Specific Annex D	3.1
2 - Overload supportability on PV inputs	Specific Annex D	3.2
3 - Polarity reversal on PV inputs	Specific Annex D	3.3
4 - Out of phase automatic reconnection	ABNT NRB 16150	6.1
5 - Detection and interruption of isolation failure on PV inputs	IEC 62109-2	4.8
6 - Detection and interruption of excessive leakage current on PV inputs	IEC 62109-2	4.8
7 - DC injection on AC output	Specific Annex D	3.4
8 - Current harmonics and waveform distortion on AC output	ABNT NRB 16150	6.3
9 - Fixed power factor on AC output	ABNT NRB 16150	6.4.1
10 - Power factor with PF curve on AC output	ABNT NRB 16150	6.4.2
11 - Injection/demand of reactive power on AC output	ABNT NRB 16150	6.2
12 - Over/under voltage on AC output	Specific Annex D	3.5
13 - Over/under frequency on AC output	Specific Annex D	3.6
14 - Flicker on AC output	ABNT NRB 16150	6.1
15 - Anti-islanding	ABNT NBR IEC 62116	Entire
16 - Immunity against active power variation during underfrequency on AC output	Specific Annex D	3.6
17 - Active power control during overfrequency on AC output	Specific Annex D	3.9
18 - Immunity against over/under frequency transients and ROCOF	Specific Annex D	3.8
19 - Immunity against over/under voltage transients	Specific Annex D	3.1
20 - Connection and reconnection on AC output	Specific Annex D	3.11
21 - Active power limitation on AC output	ABNT NRB 16150	6.11
22 - Reactive power control on AC output	ABNT NRB 16150	6.12
23 - Grid disconnection on AC output	ABNT NRB 16150	6.13
24 - Conversion efficiency	Specific Annex D	3.12

Source: Translated from (INSTITUTO NACIONAL DE METROLOGIA, 2022)

Table 3-II - Inmetro ordinance n°140/2022 measured variables

Test	Measured variable	Unit
1 - Visual inspection	------------	-----
2 - Overload supportability on PV inputs	Active power	W
3 - Polarity reversal on PV inputs	------------	-----
4 - Out of phase automatic reconnection	------------	-----
5 - Detection and interruption of isolation failure on PV inputs	Resistance	Ω
6 - Detection and interruption of excessive leakage current on PV inputs	Current	mA
7 - DC injection on AC output	Current	mA
8 - Current harmonics and waveform distortion on AC output	Current THD	mA -----
9 - Fixed power factor on AC output	Power Factor	-----
10 - Power factor with PF curve on AC output	Power Factor	-----
11 - Injection/demand of reactive power on AC output	Reactive Power	Var
12 - Over/under voltage on AC output	Voltage	V
13 - Over/under frequency on AC output	Frequency	Hz
14 - Flicker on AC output	Pst, Plt, dmax, Tmax	-----
15 - Anti-islanding	Time	ms
16 - Immunity against active power variation during underfrequency on AC output	Active power Frequency	W Hz
17 - Active power control during overfrequency on AC output	Active power Frequency	W Hz
18 - Immunity against over/under frequency transients and ROCOF	Active power Frequency	W Hz
19 - Immunity against over/under voltage transients	Active power Voltage	W V
20 - Connection and reconnection on AC output	Active power Time	W s
21 - Active power limitation on AC output	Active power	W
22 - Reactive power control on AC output	Reactive power	Var
23 - Grid disconnection on AC output	Active power	W
24 - Conversion efficiency	Active power	W

Source: Author

3.3 MEASUREMENTS OF ELECTRICAL VARIABLES AND RELATED STANDARDS

To standardize the measurement of the main variables used on power industry, the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) developed a series of standards regarding electrical variables measurement. Table 3-III shows the respective standard to measure each of the variables from the tests in Table 3-II. Most of the standards come from IEC, as they consider generic, single-phase signals, that can be replicated for multi-phase signals. The IEEE standards, in this case, also apply to three phase signals, as they were developed to simplify the calculation considering the characteristics of three phase signals instead of performing three independent single-phase measurements. Also, IEC is considered the most relevant standardization body for electrical area and so, if there is an IEC standard applicable, it should be used. Only if there is no standard from IEC, the local standardization bodies can be used (IEEE, EN, ABNT, among others.)

Table 3-III - Electrical variable and respective standard

Variable	N° of phases	Standard
Active power	Mono	IEC TR 61000-1-7
	Three	IEEE Std 1459-2010
Reactive power	Mono	IEC TR 61000-1-7
	Three	IEEE Std 1459-2010
Apparent power	Mono	IEC TR 61000-1-7
	Three	IEEE Std 1459-2010
Power factor	Mono	IEC TR 61000-1-7
	Three	IEEE Std 1459-2010
Voltage (RMS)	Any	IEC 61000-4-30
Current (RMS)	Any	IEC 61000-4-30
Frequency	Any	IEC 61000-4-30
Harmonics and THD	Any	IEC 61000-4-7
Flicker	Any	IEC 61000-3-3 (Limits)
	Any	IEC 61000-3-11 (Limits)
	Any	IEC 61000-3-5 (Limits)
	Any	IEC 61000-4-15 (Specifications)

Source: Author

3.3.1 IEC 61000-4-30

The “IEC 61000-4-30: Testing and measurement techniques – Power quality measurements” is a standard that specifies the measurement methods and instrumentation requirements for power quality parameters in electrical power systems (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2015). Some of the key points of this standard are:

- **Power quality parameters:** The standard defines various power quality parameters such as voltage, current, frequency, harmonics, interharmonics, flicker and voltage dips, among others.
- **Measurement classification:** The standard classifies the measurements in 3 classes, A, S and B. Class A measurement equipment is used where precise measurements are necessary, for example, verifying compliance with standards. Class S equipment uses equivalent intervals of measurement as class A, but the processing and uncertainty requirements are less restrictive. Class B measurement methods have old requirements and should not be employed for new instruments, but they may be relevant for legacy instruments still in use.
- **Measurement methods and uncertainty:** The standard provides guidelines for measuring power quality parameters and the minimum uncertainty requirements, for each measurement class. An equipment must comply with both requirements (method and uncertainty) to be classified in a measurement class.

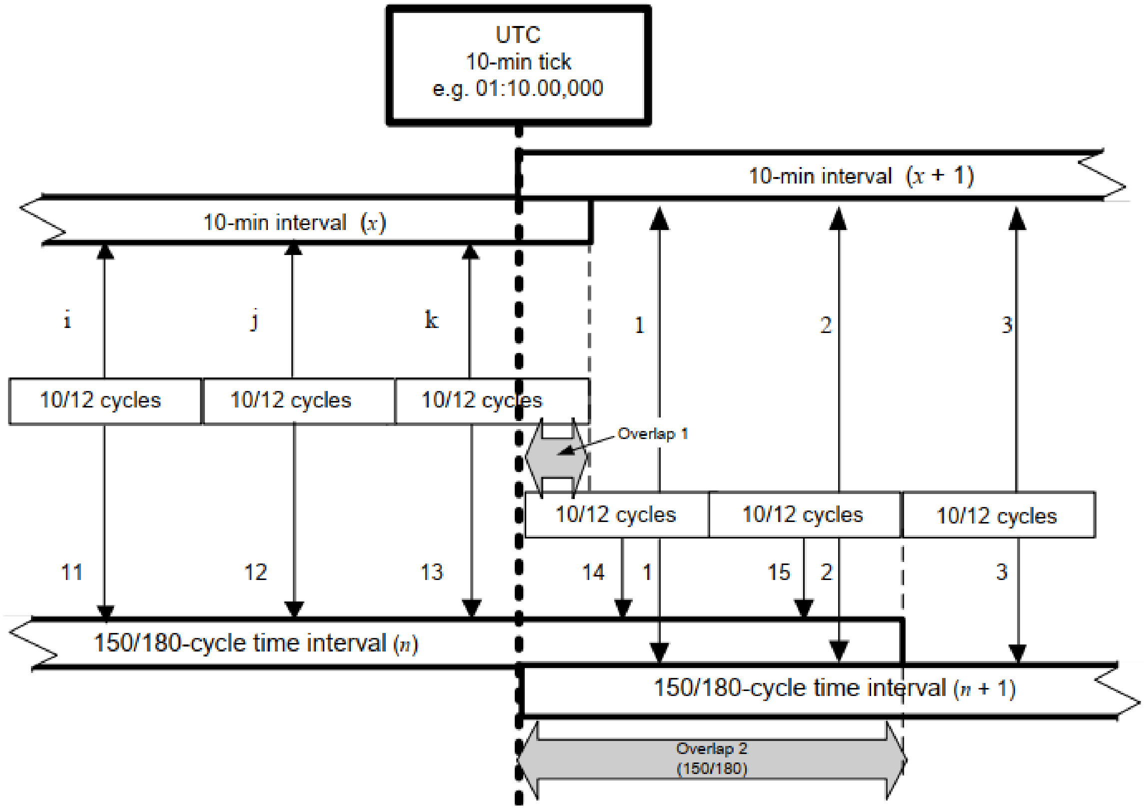
Among the points highlighted, the most important one is the measurement aggregation over time intervals. The standard defines that all steady state measurements (voltage, current, power, etc.) must be performed over a 10/12 cycles (10 cycles for 50 Hz and 12 cycles for 60 Hz power systems) and not over a specific time step. The measurements may be further aggregated in 150/180-cycle interval, 10-min interval and 2-hour interval as follows:

- 150/180-cycle interval shall be aggregated without gap from fifteen 10/12-cycle time intervals for class A measurements. For class S it is permitted to have gaps for harmonics, interhamornics, mains signaling voltage and unbalance.
- 10-min aggregation shall be aggregated from 150/180-cycle and the 10-min aggregation value shall be tagged with the UTC time (for example 01H10.00,00)

- 2-hour aggregation shall be performed from twelve 10-min intervals. The 2-hour interval shall be gapless and not overlapping.

This measurement aggregation is carried out to other standards, that use the same measurement intervals and aggregation method to measure other variables. Besides the aggregation algorithm, it also defines how the cycles are divided to create the 10/12 cycle windows, considering the zero crossing, and always considering only complete cycles. As the 10-min and 2-hour integration are based in time, and the 10/12 and 150/180-cycles are based in cycles, it may create overlaps at the end of a 10-min cycle and so, the last 10/12 cycle window shall be aggregated with the previous 10-min interval, as show in Figure 3-9. Overall, the standard aims to ensure that power quality parameters are measured consistently and accurately.

Figure 3-9 - Example of 10-min aggregation with overlaps



Source: (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2015)

3.3.2 IEC TR 61000-1-7

"IEC TR 61000-1-7 Power factor in single-phase systems under non-sinusoidal conditions" is a technical report that provides guidance on single phase power quality measurement (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2016). Despite the title emphasizing "under non-sinusoidal conditions" the standard guides power related measurements (active, reactive and apparent power, power factor, among others) on three conditions; the general case, where both voltage and current are distorted; the specific case where just the current is distorted; and the specific case where both voltage and current are pure sinusoidal waveforms.

The main points of the standard are the definitions of fundamental and non-fundamental variables where the fundamental ones are related only to the fundamental component of the signal while the non-fundamental ones are related to the harmonics and interhamonics components. Then, the power factor, for example, is defined as:

- Power factor: Is defined as the ratio of the absolute value of the active power to the apparent power, or the product of fundamental and non-fundamental power factor.
- Fundamental power factor: Is defined as the ratio of the absolute value of the fundamental active power to the fundamental apparent power. In other words, what determines the fundamental power factor is only the displacement between the voltage and current.
- Non-fundamental power factor: Is defined as the ratio of the power factor to the fundamental power factor. The non-fundamental power factor only referrers to non-fundamental variables like DC component, harmonic and interharmonic components.

3.3.3 IEEE Std 1459-2010

The "IEEE Standard definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions" is similar to the IEC 61000-1-7 in defining power measurements. In this case, for three-phase systems, it is possible to use the definitions of IEC 61000-1-7 considering each phase as an individual single-phase system, but for direct measurement of three phase systems, the IEC is not applicable, while the IEEE provides standardized ways to measure the power quantities

(IEEE POWER & ENERGY SOCIETY, 2010). Comparing both standards, the IEC and IEEE are equivalent when defining the single-phase measurements, the main difference is the fact that IEEE also provides ways to directly measure three phase systems while the IEC only focuses on single phase systems.

3.3.4 IEC 61000-4-7

The "IEC 61000-4-7 Electromagnetic compatibility (EMC): Testing and measurement techniques – General guide on harmonics and interhamonics measurements and instrumentation, for power supply system and equipment connected thereto." Is the part of IEC 61000 applicable to instrumentation intended for measuring spectral components in the frequency range up to 9 kHz which are superimposed on the fundamental of the power supply systems at 50 Hz and/or 60 Hz (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2020).

The main points of the IEC 61000-4-7 are the definitions of the measurement instrumentation intended for testing individual items of equipment in accordance with emission limits, given in other standards. It also defines the procedure to perform the measurements, specifying filters, time window, minimal accuracy requirements and measurement protocol, as show in Figure 3-10.

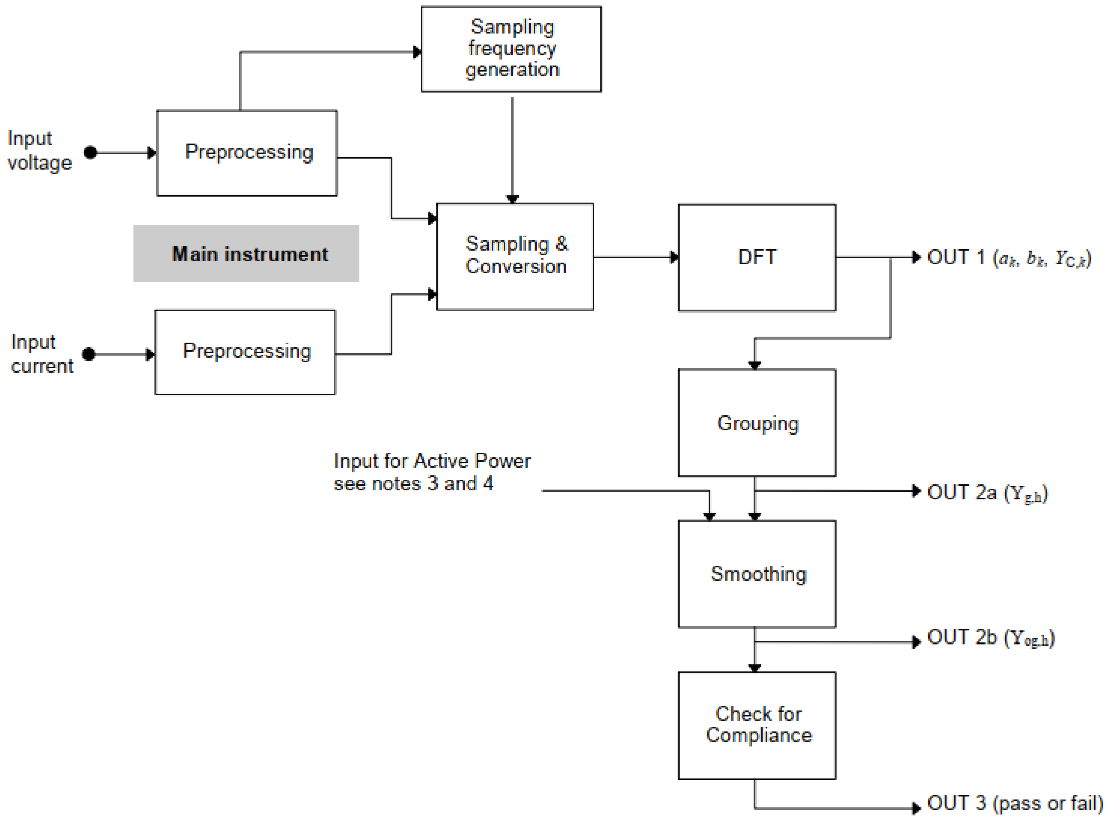
3.3.5 IEC 61000-4-15, IEC 61000-3-3, IEC 61000-3-11, and IEC 61000-3-5

The standard IEC 61000-4-15 "Testing and measurement techniques – Flickermeter – Functional and design specifications" is the IEC that gives a functional and design specification for flicker measuring apparatus intended to indicate the correct flicker perception level for all practical voltage fluctuation waveforms, considering 120 V or 230 V and 50 Hz or 60 Hz inputs (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2010). It also defines measuring equipment classes for different kinds of measurement (laboratory, in field, etc.) in a way similar to the IEC 61000-4-30.

The other three flicker related standards define the limits according to specific current levels and kinds of equipment:

IEC 61000-3-3 defines limits of voltage changes in electrical and electronic equipment having an input current equal to or less than 16 A per phase, intended to be connected to public low-voltage distribution system and not subject to conditional connection (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2009a).

Figure 3-10 - General structure of harmonic and interharmonic measuring instrument.



Source: (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2020)

- IEC 61000-3-11 defines limits of voltage changes in electrical and electronic equipment having an input current from 16 A up to and including 75 A per phase and is intended to be connected to a public low-voltage distribution system, and which is subject to conditional connection (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2017).
- IEC 61000-3-5 defines limits of voltage changes in electrical and electronic equipment having an input current exceeding 75 A per phase and is intended to be connected to a public low-voltage AC distribution system (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2009b).

3.4 IMPLEMENTATION OF THE MEASUREMENT ALGORITHMS

To achieve the standardized measurement algorithms, required for Testing Hardware-in-the-loop (THIL) 1, 2 and 3, all parameters evaluated during the tests performed in the proposed IBR testbed will be measured using algorithms developed by the project team to comply with the standards described in the last section.

The main objective of the testbench is to perform all certification tests at any level of the proposed classification of chapter 2, and it is necessary to run the tests in different environments, from everything simulated, inside a HIL platform, to everything real, utilizing the measuring equipment from the real laboratory. This way, the measuring equipment functions were replicated inside the HIL environment, to replicate the measurement algorithms utilized by the LMG670. As already shown in the testbench introduction, the measuring algorithms were implemented in Python language and as a separated module to be integrated in the main test structure. The user can choose between the “virtual instruments” or the “real instrument” to perform the tests using the real LMG670 or its virtual measuring algorithms.

An important issue about the implemented measuring algorithms is that they can operate with generic drivers. The LMG670 was chosen because it is the equipment that the real INRI laboratory uses to perform the PV inverter testing. But it is possible to develop drivers to any other equipment. The functions have standardized inputs and outputs, and, for example, the test will demand the “AC RMS Voltage” as an input to calculate the results and the driver will call the respective variable from the virtual drivers. The data than can come from the real equipment, importing through a communication algorithm, or from the virtual equipment, using the implemented algorithms to perform the measurement. Any of those drivers can be altered or even replaced to communicate or to replicate the measuring algorithms from other equipment, as long as they provide an output variable named “AC RMS Voltage” to be exported to the main test algorithm.

The other reason to replicate the measurement algorithms is to facilitate the validation. As the LMG670 is already validated to perform all the measurements in the real laboratory, it is possible to validate the developed algorithms by measuring the same waveform using the LMG670 and the algorithms and compare the results for different test conditions. A list of all measurement methods implemented is shown in Table 3-IV.

Table 3-IV - List of implemented measurement algorithms.

Single phase (generic)	RMS voltage and current
	Frequency
	Flicker (PST, PLT, dc_{max}, d_{max}, T_{max})
	Voltage and current harmonics and THD
	Voltage and current interharmonics
	Total apparent power
	Total active power
	Total reactive power
	Total power factor
	Fundamental apparent power
	Fundamental active power
	Fundamental reactive power
	Fundamental power factor
	Non fundamental apparent power
	Non fundamental active power
	Non fundamental reactive power
	Non fundamental power factor
Three phase	Total apparent power
	Total active power
	Total non active power
	Total power factor
	Fundamental positive sequence active power
	Fundamental apparent power
	Fundamental unbalance power
	Fundamental positive sequence apparent power
	Positive sequence reactive power
	Fundamental positive power factor
	Load unbalance
	Non fundamental apparent power
	Harmonic apparent power
	Non fundamental active power
	Harmonic pollution factor

Source: Author

3.5 VALIDATION OF THE MEASUREMENT ALGORITHMS

According to ISO/IEC 17025, “the laboratory must validate not standardized methods, methods developed by the laboratory and normalized methods modified or used outside its original scope. The validation must be too embracing as necessary to satisfy the necessities of a specific application or application field. The validation techniques may be one of the following or a combination of them.” (ISO/IEC, 2017). One of the techniques recommended by the standard is the “Comparison with results acquired through other validated methods”. This way, all the measurement algorithms were validated through a direct comparison between the implemented algorithm and the measurements performed by the LMG670 which is an equipment that utilizes validated methods. To perform this comparison, a series of waveforms were acquired using the LMG670 and the datapoints were exported in CSV format to be used in the algorithms, assuring that the measurements of the LMG670 and the algorithms were performed using the same data.

It is important to mention that the comparisons were performed using a series of different waveforms, all of them with the same results, showing that the implemented algorithms have the same performance as the original equipment. The results of this comparison were summarized and just a part of it will be shown in the text as this is not the main objective of the thesis.

3.5.1 Current and voltage RMS

The voltage and current RMS algorithms are implemented according to the standard IEC 61000-4-30 and were validated using sinusoidal waveforms of 127 V_{rms} and 220 V_{rms} for voltage and 5-6.5 A_{rms} for current. They were also validated using distorted waveforms with harmonic content and with inductive, capacitive, and resistive loads. Some of the results are shown in Table 3-V for voltage measurements and Table 3-VI for current ones. The voltage and current measurements were performed at the same time as the “split window” function, necessary to separate the waveform in 10/12 cycle windows, uses the voltage waveform as a reference and having a current signal with 90° phase difference is one of the problems that may appear when measuring non unit power factor signals.

Table 3-V - RMS Voltage comparison results

Sample	Load	Python script (V)	LMG670 (V)	Absolute Difference (V)
1	Inductive	219.651	219.650	0.001
2	Inductive	220.118	220.118	0.000
3	Inductive	220.116	220.117	0.000
4	Inductive	220.116	220.116	0.000
1	Resistive	219.676	219.676	0.000
2	Resistive	220.102	220.102	0.000
3	Resistive	220.107	220.107	0.000
4	Resistive	220.099	220.099	0.000
1	Capacitive	219.702	219.709	0.006
2	Capacitive	219.973	219.974	0.000
3	Capacitive	219.977	219.978	0.000
4	Capacitive	219.973	219.974	0.000

Source: Author

Table 3-VI - RMS Current comparison results

Sample	Load	Python script (A)	LMG670 (A)	Absolute Difference (A)
1	Inductive	6.5398	6.5400	0.0002
2	Inductive	6.5251	6.5250	0.0001
3	Inductive	6.5246	6.5250	0.0004
4	Inductive	6.5249	6.5250	0.0001
1	Resistive	5.4972	5.4970	0.0002
2	Resistive	5.5082	5.5080	0.0002
3	Resistive	5.5082	5.5080	0.0002
4	Resistive	5.5081	5.5080	0.0001
1	Capacitive	6.0161	6.0160	0.0001
2	Capacitive	6.0083	6.0080	0.0003
3	Capacitive	6.0078	6.0080	0.0002
4	Capacitive	6.0084	6.0080	0.0004

Source: Author

3.5.1 Power meters

The power meter algorithms are based on IEC 61000-1-7 and IEEE1459 standards, they were also validated through a direct comparison with LMG670 for fundamental and non-fundamental power factor, active, non-active and apparent power using resistive, inductive, and capacitive loads. Table 3-VII to Table 3-X shows the comparison results for active power, fundamental apparent power, power factor and fundamental reactive power.

Table 3-VII - Active power comparison results

Sample	Load	Python script (W)	LMG670 (W)	Absolute Difference (W)
1	Inductive	70.62	70.59	0.03
2	Inductive	70.56	70.47	0.09
3	Inductive	70.63	70.62	0.02
1	Resistive	1921.59	1921.59	0.00
2	Resistive	1921.61	1921.62	0.01
3	Resistive	1921.30	1921.30	0.00
1	Capacitive	20.47	20.46	0.01
2	Capacitive	20.53	20.50	0.03
3	Capacitive	20.50	20.49	0.01

Source: Author

Table 3-VIII - Fundamental apparent power comparison results

Sample	Load	Python script (VA)	LMG670 (VA)	Absolute Difference (VA)
1	Inductive	1396.29	1396.29	0.00
2	Inductive	1396.19	1396.24	0.05
3	Inductive	1396.42	1396.37	0.05
1	Resistive	1928.91	1928.91	0.00
2	Resistive	1928.93	1928.93	0.00
3	Resistive	1928.59	1928.59	0.00
1	Capacitive	1136.93	1136.92	0.01
2	Capacitive	1136.89	1137.01	0.12
3	Capacitive	1136.96	1136.92	0.04

Source: Author

Table 3-IX – Power factor comparison results

Sample	Load	Python script	LMG670	Absolute Difference
1	Inductive	0.051	0.051	0.00
2	Inductive	0.050	0.050	0.00
3	Inductive	0.051	0.051	0.00
1	Resistive	0.996	0.996	0.00
2	Resistive	0.996	0.996	0.00
3	Resistive	0.996	0.996	0.00
1	Capacitive	0.018	0.018	0.00
2	Capacitive	0.018	0.018	0.00
3	Capacitive	0.018	0.018	0.00

Source: Author

Table 3-X - Fundamental reactive power comparison results

Sample	Load	Python script (VAr)	LMG670 (VAr)	Absolute Difference (VAr)
1	Inductive	1394.50	1394.50	0.00
2	Inductive	1394.41	1394.46	0.05
3	Inductive	1394.63	1394.59	0.04
1	Resistive	168.75	168.75	0.00
2	Resistive	168.72	168.76	0.04
3	Resistive	168.41	168.35	0.06
1	Capacitive	1136.75	1136.73	0.01
2	Capacitive	1136.70	1136.82	0.12
3	Capacitive	1136.78	1136.92	0.04

Source: Author

3.5.1 Frequency, harmonics, interharmonics and THD

The frequency, harmonics, interharmonics and total harmonic distortion (THD) meters were implemented according to IEC 61000-4-7 and their validation was performed also through direct comparison with LMG670 measurements. In this case, the waveforms used were square, triangular and sinusoidal with amplitude ranging from $5V_{rms}$ to $220\ V_{rms}$ as shown in Table 3-XI and Table 3-XII.

Table 3-XI - Harmonic absolute amplitude and THD comparison for 5V, 60Hz square waveform

Harmonic order	Python script (V)	LMG670 (V)	Absolute Difference (V)
1	1.806	1.806	0.000
2	0.000	0.000	0.000
3	0.602	0.602	0.000
4	0.000	0.000	0.000
5	0.361	0.361	0.000
6	0.000	0.000	0.000
7	0.258	0.258	0.000
8	0.000	0.000	0.000
9	0.201	0.201	0.000
10	0.000	0.000	0.000
11	0.164	0.164	0.000
12	0.000	0.000	0.000
13	0.139	0.139	0.000
14	0.000	0.000	0.000
15	0.120	0.120	0.000
16	0.000	0.000	0.000
17	0.106	0.106	0.000
18	0.000	0.000	0.000
19	0.095	0.095	0.000
20	0.000	0.000	0.000
21	0.086	0.086	0.000
22	0.000	0.000	0.000
23	0.078	0.078	0.000
24	0.000	0.000	0.000
25	0.072	0.072	0.000
26	0.000	0.000	0.000
27	0.067	0.067	0.000
28	0.000	0.000	0.000
29	0.062	0.062	0.000
30	0.000	0.000	0.000
31	0.058	0.058	0.000
32	0.000	0.000	0.000
33	0.054	0.054	0.000
THD	46.779%	46.778%	0.001%

Source: Author

Table 3-XII – Frequency and harmonic absolute amplitude comparison for 127V, 60,5Hz sinusoidal waveform with forced 3rd and 10th order harmonic injection.

Harmonic order	Python script (Hz)	LMG670 (Hz)	Absolute Difference (Hz)	Python script (V)	LMG670 (V)	Absolute Difference (V)
0	0.000	0.000	0.000	0.106	0.106	0.000
1	60.501	60.501	0.000	127.044	127.042	0.002
2	121.002	121.002	0.000	0.018	0.021	0.004
3	181.504	181.504	0.000	12.724	12.721	0.003
4	242.005	242.005	0.000	0.027	0.028	0.001
5	302.506	302.506	0.000	0.301	0.303	0.002
6	363.007	363.007	0.000	0.012	0.013	0.001
7	423.508	423.508	0.000	0.190	0.191	0.001
8	484.010	484.010	0.000	0.016	0.017	0.000
9	544.511	544.511	0.000	0.077	0.077	0.000
10	605.012	605.012	0.000	2.578	2.577	0.001
11	665.513	665.513	0.000	0.052	0.053	0.001
12	726.014	726.014	0.000	0.027	0.027	0.000
13	786.515	786.516	0.001	0.090	0.090	0.000
14	847.017	847.017	0.000	0.016	0.017	0.001
15	907.518	907.518	0.000	0.129	0.129	0.000
16	968.019	968.019	0.000	0.018	0.018	0.001
17	1028.520	1028.520	0.000	0.133	0.133	0.000
18	1089.021	1089.020	0.001	0.013	0.013	0.000
19	1149.523	1149.520	0.003	0.111	0.110	0.000
20	1210.024	1210.020	0.004	0.010	0.010	0.001
21	1270.525	1270.530	0.005	0.085	0.085	0.000
22	1331.026	1331.030	0.004	0.016	0.015	0.001
23	1391.527	1391.530	0.003	0.054	0.054	0.000
24	1452.029	1452.030	0.001	0.022	0.021	0.001
25	1512.530	1512.530	0.000	0.022	0.022	0.000
26	1573.031	1573.030	0.001	0.024	0.023	0.001
27	1633.532	1633.530	0.002	0.030	0.030	0.000
28	1694.033	1694.030	0.003	0.025	0.024	0.001
29	1754.535	1754.530	0.005	0.035	0.036	0.001
30	1815.036	1815.040	0.004	0.019	0.018	0.000
31	1875.537	1875.540	0.003	0.034	0.035	0.000
32	1936.038	1936.040	0.002	0.014	0.014	0.000
33	1996.539	1996.540	0.001	0.032	0.033	0.000

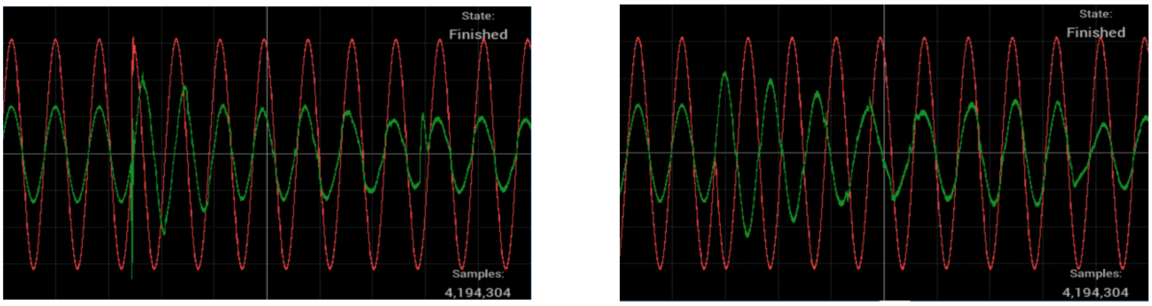
Source: Author

3.6 IMPLEMENTATION OF THE TEST ALGORITHMS

The test algorithms implemented are shown in Table 3-XIII. Some of the algorithms were not implemented as they are not relevant for the thesis or cannot be simulated through HIL simulators. Some of the tests are also potentially destructive tests, where the approval criterion is that the inverter cannot be damaged during it, and so, also not possible to simulate on HIL.

One example of the potentially destructive tests is the number 4, “out of phase automatic reconnection”, where the equipment is connected to the grid, at nominal power, and, at distinct moments, two voltage phase jumps are applied, as shown in Figure 3-11, one with a 90° variation and the other with 180° variation. This causes a current disturbance in the inverter, that may cause a damage, and the inverter must withstand it. In HIL simulation it is possible to apply the voltage phase jump and analyze the controller reaction to it, measuring the peak current; however it is not possible to see if it will damage the inverter or not. This way, when running in HIL, the approval criteria is to compare if the measured peak current is smaller than the inverter maximum allowed current.

Figure 3-11 - Voltage phase jump examples, (a) 90°, (b) 180°, red = voltage, green = current



(a) (b)

Source: Author

Another example of a test that is not relevant to this thesis is the “Visual inspection”, where the approval criterion is to check if the inverter has the minimum markings, in its body and the user manual, that the standard demands. It also checks if the equipment arrived at the laboratory without damage and with all necessary accessories as well as to check if it has an eletromechanical switch that disconnects it from the grid. All those things cannot be simulated in HIL and so were not implemented.

Table 3-XIII - List of implemented test algorithms for virtual, control and power testing

Test	Virtual	Control	Power
1 - Visual inspection	X	X	X
2 - Overload supportability on PV inputs	✓	✓	✓
3 - Polarity reversal on PV inputs	X	X	X
4 - Out of phase automatic reconnection	✓	✓	✓
5 - Detection and interruption of isolation failure on PV inputs	X	X	X
6 - Detection and interruption of excessive leakage current on PV inputs	X	X	X
7 - DC injection on AC output	✓	✓	✓
8 - Current harmonics and waveform distortion on AC output	✓	✓	✓
9 - Fixed power factor on AC output	✓	✓	✓
10 - Power factor with PF curve on AC output	✓	✓	✓
11 - Injection/demand of reactive power on AC output	✓	✓	✓
12 - Over/under voltage on AC output	✓	✓	✓
13 - Over/under frequency on AC output	✓	✓	✓
14 - Flicker on AC output	✓	✓	X
15 - Anti-islanding	✓	✓	X
16 - Immunity against active power variation during underfrequency on AC output	✓	✓	✓
17 - Active power control during overfrequency on AC output	✓	✓	✓
18 - Immunity against over/under frequency transients and ROCOF	✓	✓	✓
19 - Immunity against over/under voltage transients	✓	✓	✓
20 - Connection and reconnection on AC output	✓	✓	✓
21 - Active power limitation on AC output	✓	✓	✓
22 - Reactive power control on AC output	✓	✓	✓
23 - Grid disconnection on AC output	✓	✓	✓
24 - Conversion efficiency	X	X	X

Source: Author

3.7 VALIDATION OF THE TEST ALGORITHMS

Still according to ISO/IEC 17025, the laboratory must validate its testing methods and algorithms. In the same way that the measurement algorithms were validated through a direct comparison between the ones running on LMG670, the testing algorithms are validated through a direct comparison between the INRIFV accredited testing protocols, and the ones implemented in the IBR testbench, using the same parameters and inverter. The inverter used is a PHB-1500SS, a model that the laboratory owns and is known to be relatively stable and already used during inter and intra laboratorial activities. More details about the tests and the equipment will be shown in the next chapter. Again, as this is not the main objective of the thesis, just a few examples will be shown to demonstrate how the comparisons were performed and that the results are compliant.

3.7.1 Fixed power factor on AC output

In the fixed power factor test, the inverter is set to operate with a specific, fixed, power factor (PF). It starts with PF = 1, while the PV sources are set to provide enough power to force the inverter to operate at 10% of its nominal AC power. The power factor is measured, and the process is repeated to evaluate the power factor with the inverter operating at 20%, 30%, 50%, 75% and 100% of its nominal active power. For inverters with nominal power higher than 6 kW, the test is also repeated with the inverter set to operate at PF = 0.9 capacitive and inductive.

The comparison of the results is shown in Table 3-XIV. As the inverter has a nominal active AC power of 1500 W, it does not need to have the option to change the operating power factor and so, even in the part of the test where it should be set to operate at PF = 0.9, it keeps operating at PF = 1. However, as the important comparisons are the measurement results during all parts of the test, this does not change the comparative analysis. Even if the inverter cannot be set to operate at different power factors, if the measured PF is the same, in the laboratory protocol and the IBR testbench, the results are compliant. Also, there are small differences between some measurements, for example, at 75% nominal power the laboratory measured 0.986 while the testbed measured 0.989. This is due to the equipment natural active behavior, where the controller may oscillate during its operation and the inverter will never have exactly the same operating values, which also is not a problem for the comparison purpose.

Table 3-XIV - Fixed power factor on AC output test result comparison

	IBR Testbench			INRIFV Protocol		
EUT relative AC power	**PF = 1**	**PF = 0.9c**	**PF = 0.9i**	**PF = 1**	**PF = 0.9c**	**PF = 0.9i**
10%	0.774	0.756	0.774	0.776	0.776	0.776
20%	0.966	0.966	0.966	0.968	0.968	0.968
30%	0.987	0.987	0.987	0.990	0.990	0.990
50%	0.989	0.989	0.989	0.991	0.991	0.991
75%	0.985	0.986	0.986	0.989	0.989	0.989
100%	0.992	0.992	0.992	0.993	0.993	0.993

Source: Author

3.7.2 Current harmonics and waveform distortion on AC output

In the current harmonics and waveform distortion on AC output test, the inverter is set to operate at 10%, 20%, 30%, 50%, 75% and 100% of its nominal active AC power. The individual harmonic distortion, up to the 33rd order, as well as the total harmonic distortion, are measured. The measurement time is set to 30 seconds for each power level and the system aggregates the values to compute the results, reducing the effect of value oscillation due to normal equipment operation.

The Table 3-XV shows the individual harmonic current comparison for the PHB1500SS inverter operating at 100% of its nominal AC power (1500 W). Table 3-XVI shows the total harmonic distortion comparison for the six measured power levels for the same inverter. The results shows that, when considering the measurement uncertainty, the differences between the values measured by the accredited laboratory system and the IBR testbench system, are not statistically significant, validating the developed test procedure.

Despite the differences that appear in some values on the tables, it is important to note that the inverter itself is an equipment with an active behavior and it is difficult, even using the same methods and measuring equipment, to have the exact same values between two tests. That is why it is important to consider the measurement equipment and the inverter uncertainty when performing such comparisons.

Table 3-XV – Individual current harmonic distortion comparison for 100% of the inverter nominal AC power

Order	Testbench value (%)	INRIFV value (%)	Order	Testbench value (%)	INRIFV value (%)
3	0.34	0.38	**2**	0.51	0.51
5	0.12	0.11	**4**	0.10	0.90
7	0.11	0.11	**6**	0.03	0.03
9	0.26	0.23	**8**	0.12	0.15
11	0.35	0.30	**10**	0.14	0.20
13	0.44	0.45	**12**	0.15	0.20
15	0.40	0.42	**14**	0.13	0.14
17	0.37	0.32	**16**	0.05	0.07
19	0.39	0.42	**18**	0.07	0.08
21	0.29	0.20	**20**	0.05	0.06
23	0.32	0.15	**22**	0.14	0.07
25	0.31	0.40	**24**	0.16	0.07
27	0.29	0.32	**26**	0.11	0.10
29	0.23	0.25	**28**	0.18	0.06
31	0.24	0.26	**30**	0.12	0.10
33	0.24	0.20	**32**	0.03	0.08

Source: Author

Table 3-XVI – Total harmonic distortion comparison

Relative AC power (%)	Testbench THD value (%)	INRIFV THD value (%)
10	16.36	16.37
20	9.42	9.40
30	5.49	5.48
50	2.57	2.59
75	2.02	2.00
100	1.41	1.43

Source: Author

3.8 SUMMARY

This chapter shows the proposed inverter-based resources testbench, implemented during the project duration and used to evaluate the different testing scenarios from the proposed classification. The platform is programed as an open-source code that can be adapted to any other standards, in addition to the Inmetro ordinance n°140/2022 that is already implemented.

All test comparisons show that the IBR testbench can reproduce the same tests, with the same reliability, that the accredited laboratory can perform. Due to the amount of data collected to test and compare the platforms, and as this is not the main objective of the thesis, just a part of the data is shown, to exemplify how the comparison was performed and that the results are compliant.

4 PRACTICAL IMPLEMENTATION

A practical implementation, through a case study, will be detailed in this chapter. The objective is to verify the feasibility of HIL testing on commercial equipment and the proposed classification. To perform this verification, a commercial photovoltaic inverter, model PHB1500SS from PHB, was modeled and simulated using a HIL604 from Typhoon HIL. The inverter was submitted to 5 test sequences in the accredited laboratory, the PHIL testbench and CHIL testbench, both on TyTest, to statistically verify the results compliance.

4.1 EQUIPMENT UNDER TEST

The equipment under test (EUT) is a 1500W photovoltaic inverter, model PHB1500SS from PHB (Figure 4-1). As already mentioned, this equipment is used for interlaboratory comparisons between the INRIFV and other laboratories as it is stable through different test setups and easy to test. PHB kindly provided the equipment electrical schematic and authorized its use, the schematic however cannot be published due to confidential agreement. The EUT is divided into two parts, the power board and the instrumentation and control board.

Figure 4-1 – PHB1500SS photovoltaic inverter

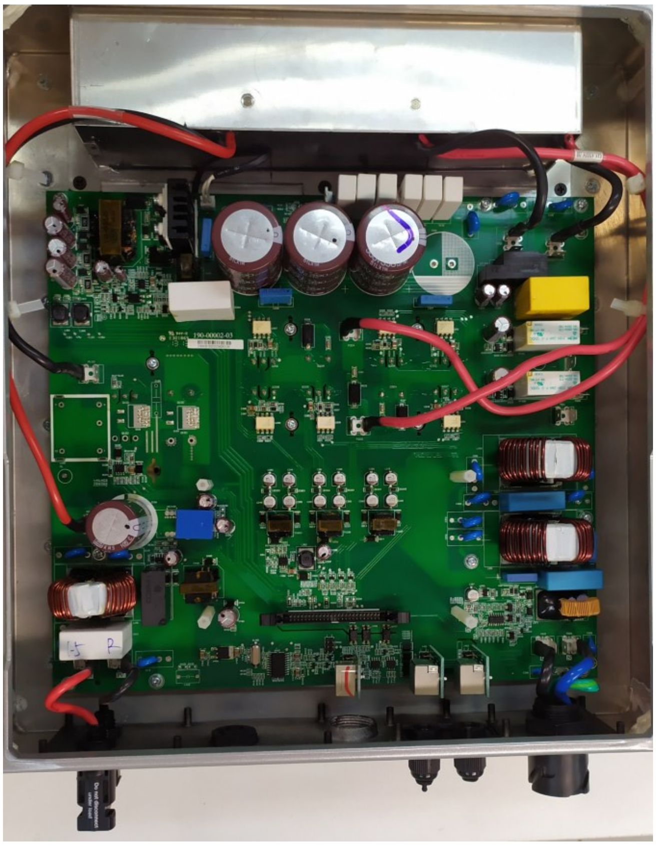
Source: Image from internet

4.1.1 Power circuit board

The power circuit board, shown in Figure 4-2, is where all the power components are mounted. The inverter has a two-stage configuration, consisting of a boost converter, for a single MPPT input, and an H6 single-phase inverter. The voltage, current, isolation and leakage current sensors are also installed in the power circuit board, but their outputs are directly sent to the instrumentation and control board to be conditioned and processed.

The voltage sensors are composed of resistive dividers directly connected between the power wires and the instrumentation board, where they are conditioned. They measure the grid voltage in 3 points, the PV and DC link voltage are also measured. The current sensors measure the PV input and grid output currents. In addition to the voltage and current sensors, there are also an isolation sensor in the PV input, a case temperature, and a leakage current sensor. At the inverter grid output there is also an EMI filter.

Figure 4-2 - PHB1500SS power circuit board



Source: Author

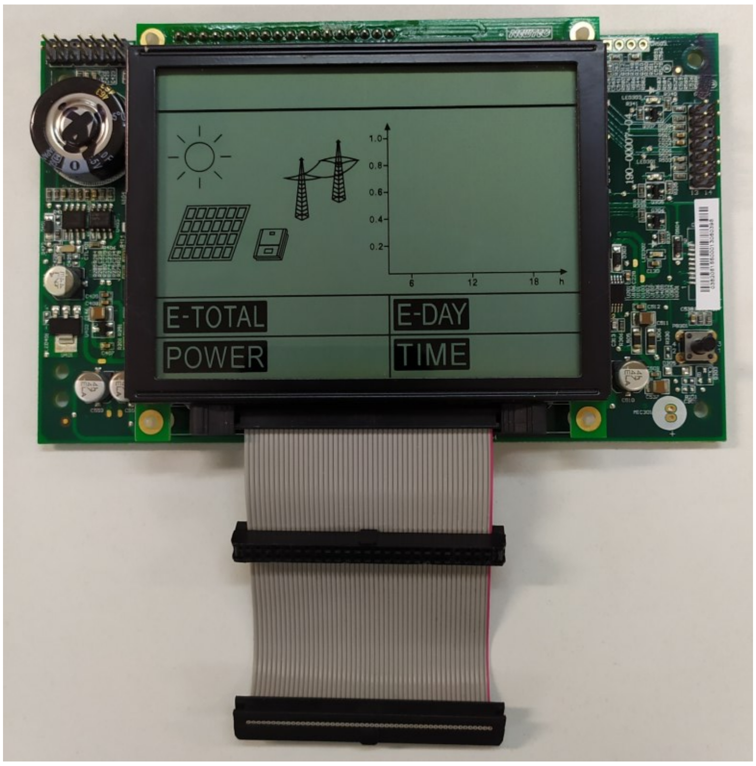
4.1.2 Instrumentation and control board

The instrumentation and control board (Figure 4-3) is where all the signal conditioning circuits are mounted, in addition to the two DSPs that control the equipment. The communication with the power board is performed through a 50-pin flat cable that feeds the control board with 5V and ±15V power lines, the sensors output and send the PWM and relay signals to the power board.

This inverter uses the same control board for a family of equipment, with different power levels and input ports, so, not all the features are used in the 1500W model. Inputs related to models with more MPPTs and some auxiliary circuits, like the “baby boost” are disabled and the pins not connected in this model.

The communication with the inverter can be performed through a direct connection via USB port, or through RS485. Both are mounted on the power board.

Figure 4-3 - PHB1500SS Instrumentation and control board

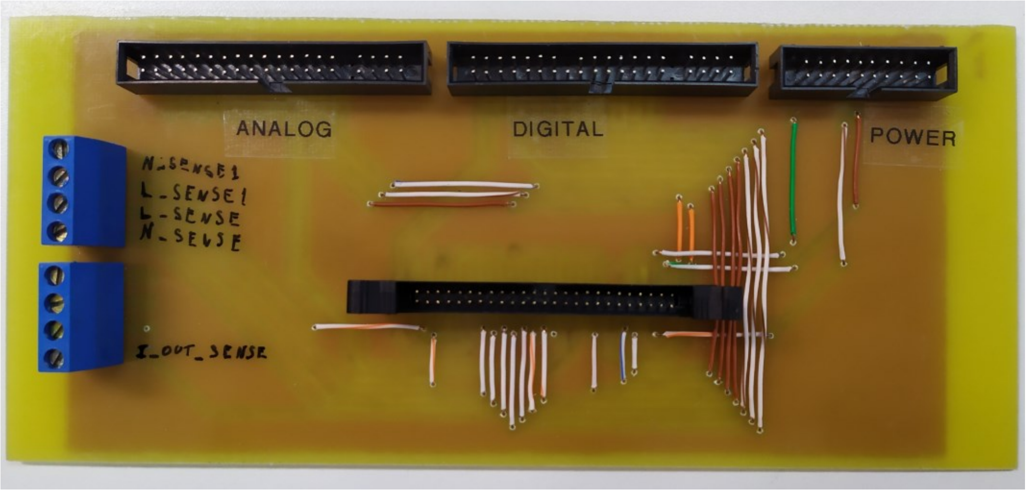


Source: Author

4.1.3 HIL interface board

To connect the inverter control board to a HIL simulator, it is necessary to build an interface board, shown in Figure 4-4. This is a step that needs to be performed for every control board that will be tested. The main function of this interface is to connect the HIL digital and analog I/Os to the DSP or sensors I/Os in the prototype. The board may also provide adequacy between the voltage levels, as well as impedance matching, between HIL and the DSP/Control board. Table 4-I shows the voltage level comparison between the PHB1500-SS control board and the HIL604.

Figure 4-4 - HIL interface board



Source: Author

Table 4-I - HIL604 and control board voltage level comparison

Sensor/actuator	Control board range	HIL604 range
CA Voltage	±25 V	±10 V
CA Current	±5 V	±10 V
PV voltage	0 – 3.3 V	±10 V
PV current	0 – 3.3 V	±10 V
DC Bus voltage	0 – 3.3 V	±10 V
PWM and relays	5 V	5 V

Source: Author

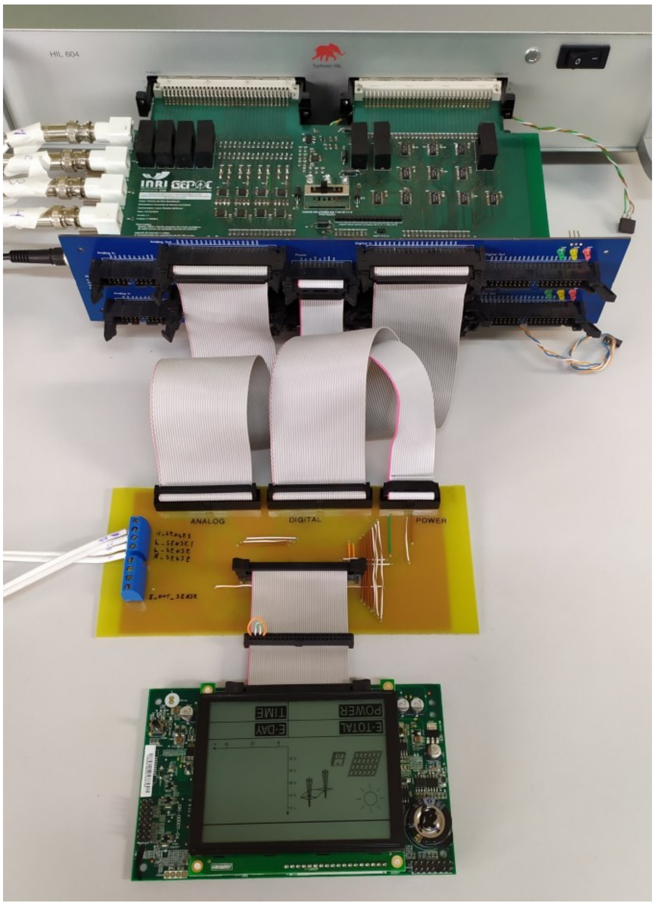
4.1.4 Complete simulation setup

Figure 4-5 shows the complete CHIL test setup, with the instrumentation and control board connected to the interface board, that is connected to the Typhoon HIL604 protection board. The HIL604 protection board can regulate the voltage levels to protect a DSP, preventing negative voltages or voltages above a specific threshold that can be defined through a multi position switch as 3V, 3.3V, 5V or 10V.

The circuit that is simulated inside HIL604 is shown in Figure 4-6, representing the PV panel, the input boost converter, the H6 single-phase converter and the output filter. It is not necessary to simulate each switch independently, as the Typhoon schematic editor have specific models to implement various types of converter topologies, to reduce the simulation computational burden.

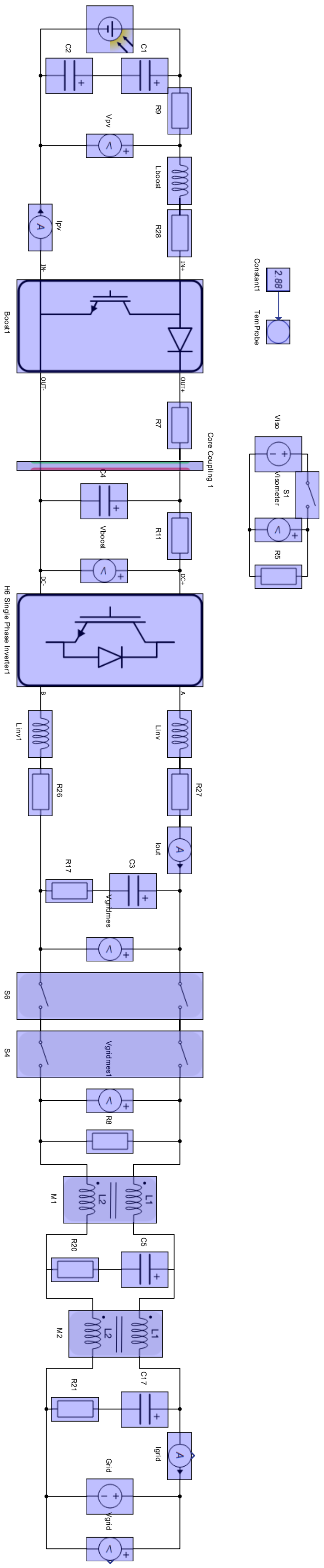
Figure 4-7 and Figure 4-8 show a comparison of the simulated and the real voltage and current waveforms for six different power levels.

Figure 4-5 - Complete CHIL test setup



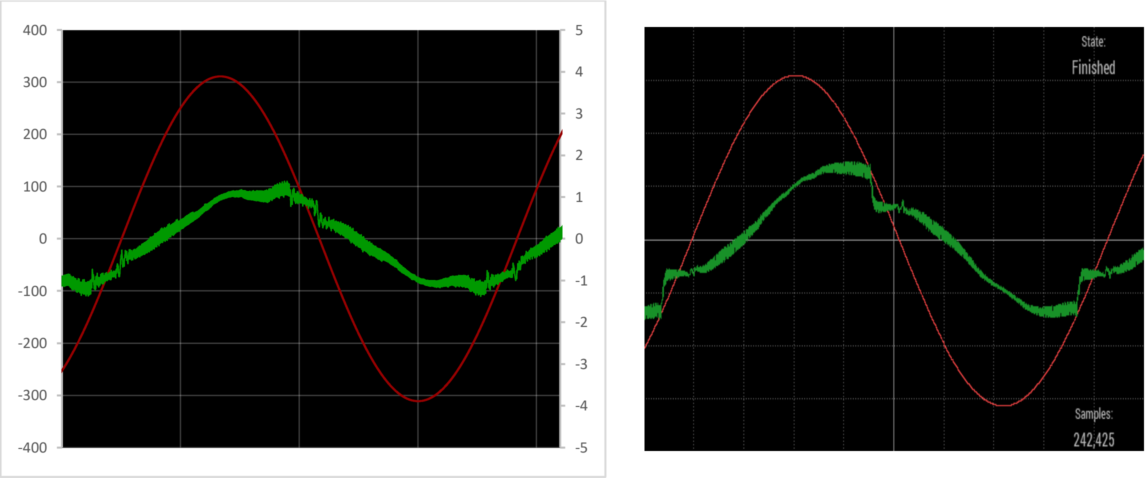
Source: Author

Figure 4-6 - PHB1500SS CHIL model

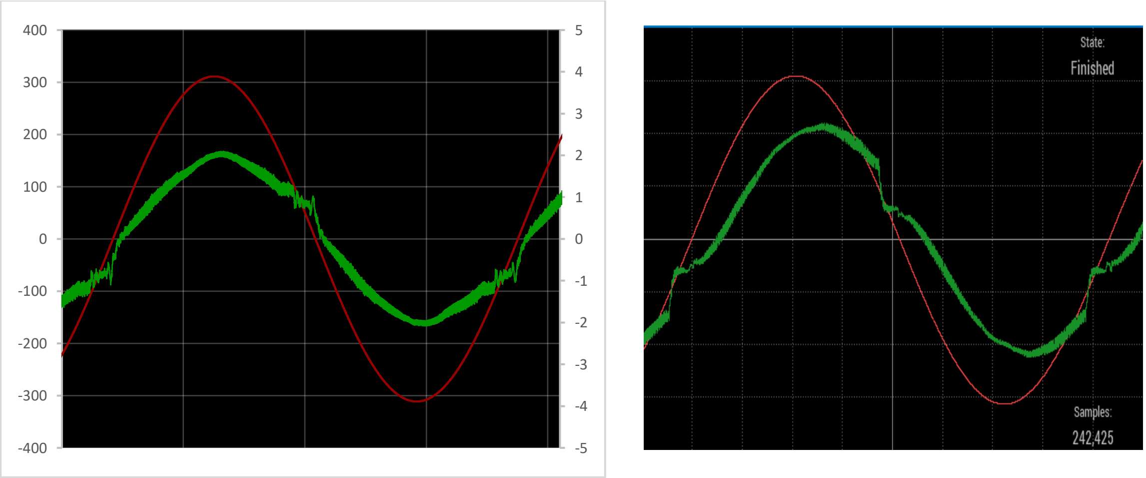


Source: Author

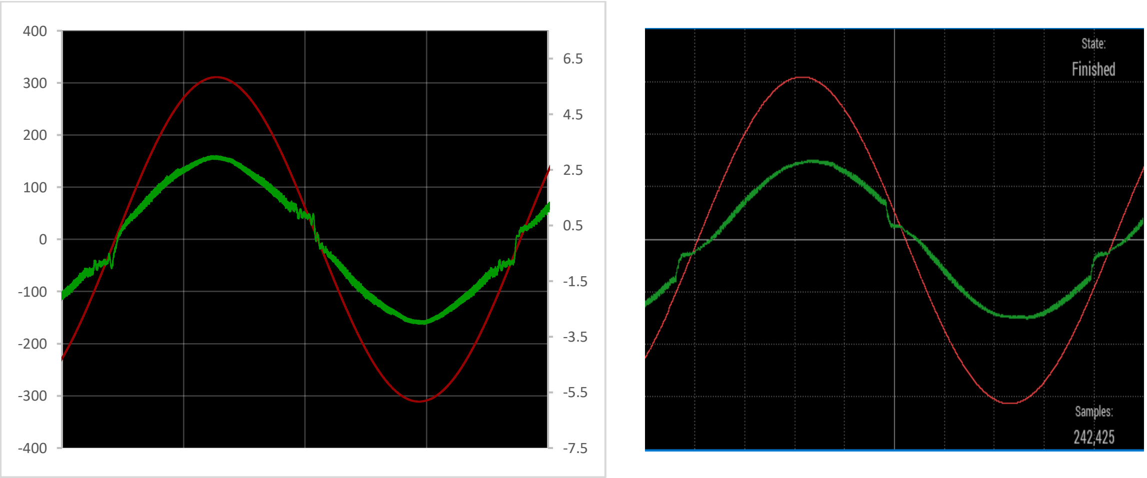
Figure 4-7 - Waveform comparison between CHIL (left) and the real equipment (right)



10% nominal power



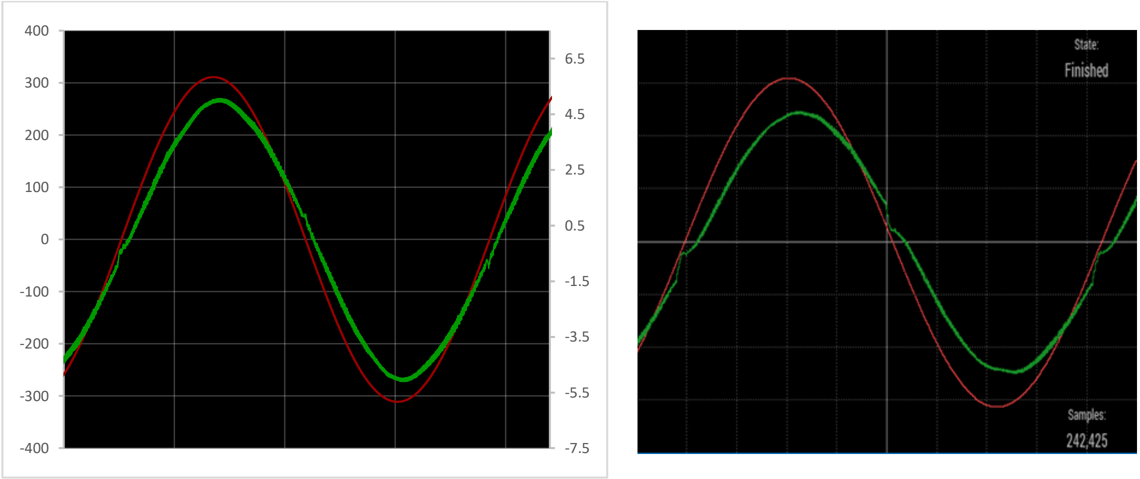
20% nominal power



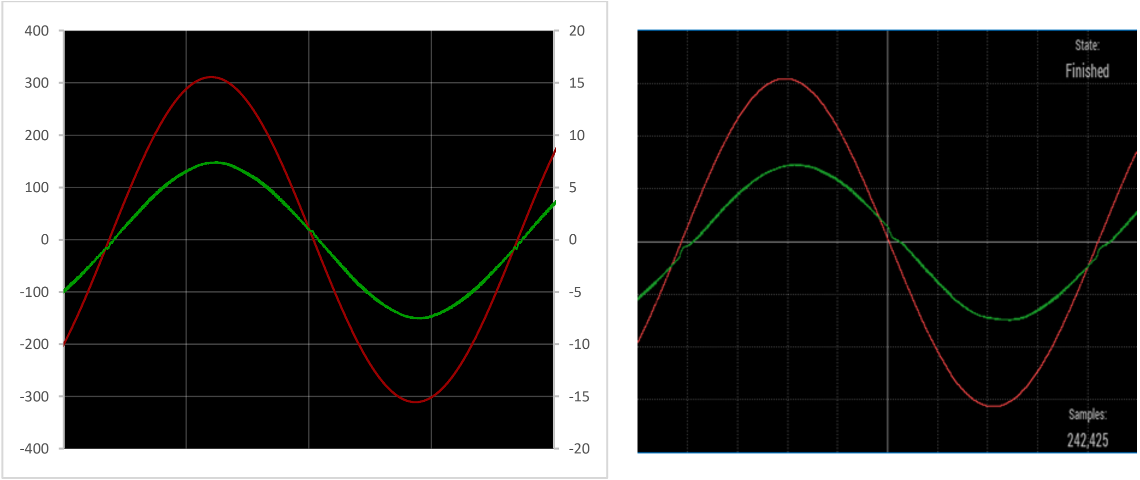
30% nominal power

Source: Author

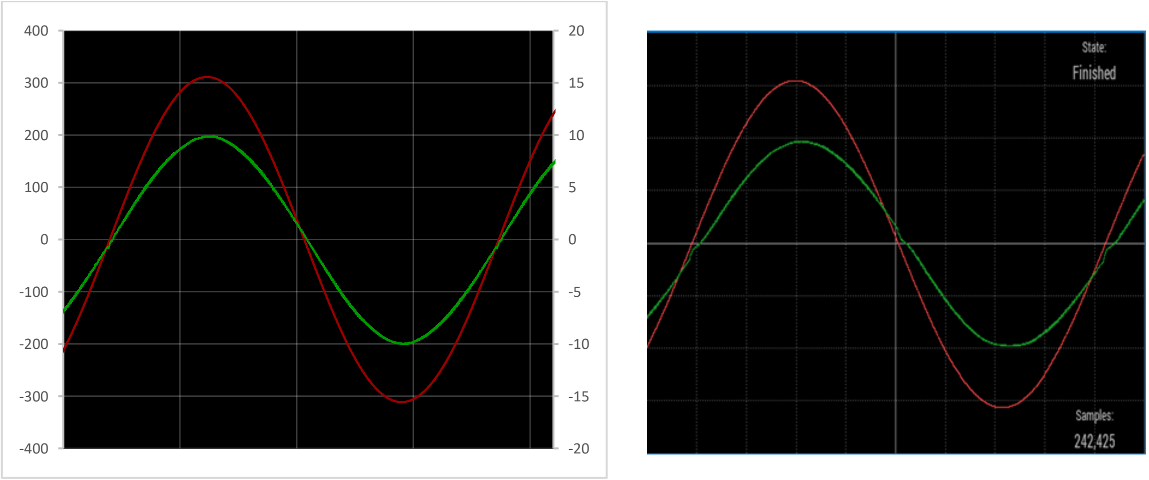
Figure 4-8 - Waveform comparison between CHIL (left) and the real equipment (right)



50% nominal power



75% nominal power



100% nominal power

Source: Author

4.1.5 Tests classification in the proposed classification

Considering the tests classification proposed on chapter 2, the tests on this inverter have two different classifications, based on what part of the testbench will be used. The test results that will be shown in the next section consider the equipment being tested in its final stage, both in CHIL and PHIL so, the classification is shown in Table 4-II.

Table 4-II - Tests level classification in the proposed classification

	CHIL	PHIL	EHIL	MHIL	THIL
TyTest with CHIL	2	0	1	1	3
TyTest with real equipment	2	3	1	1	3
Accredited laboratory	2	3	1	1	3

Source: Author

When using the IBR testbench as CHIL, it can work considering any level of CHIL, as already explained; however, for this specific case the EUT has a single controller board, with integrated instrumentation. As a result, it is classified as CHIL 2 in all tests.

For PHIL testing, the EUT has a two-stage topology, with a boost converter and an H6 single-phase inverter. Considering that this is a final product, the converters cannot be disassembled and tested independently, so this equipment is classified as PHIL 3 for tests that involves power. For the CHIL testing, the PHIL is classified as PHIL 0 because all the power electronics are simulated in a HIL simulator and there is no real power circuit.

For the EHIL classification, despite being possible to work with more elaborated models, especially the grid ones, the accredited laboratory utilizes a common AC grid simulator that is “seen” by the inverter as an ideal source, with no impedance or variable behaviors, only a stable 220V@60Hz grid. To match the accredited laboratory results the same simple model was used in all tests and so the EHIL classification is 1 in all tests.

The MHIL classification is defined as level 1 in all tests because the equipment has an offline management system, where it is possible to change some values using a direct USB cable connected to the inverter.

For the THIL classification, as the comparison is performed with an accredited laboratory, tests were performed at THIL 3 level, where all uncertainties are calculated, and the testing and measurement protocols and algorithms are validated and standardized.

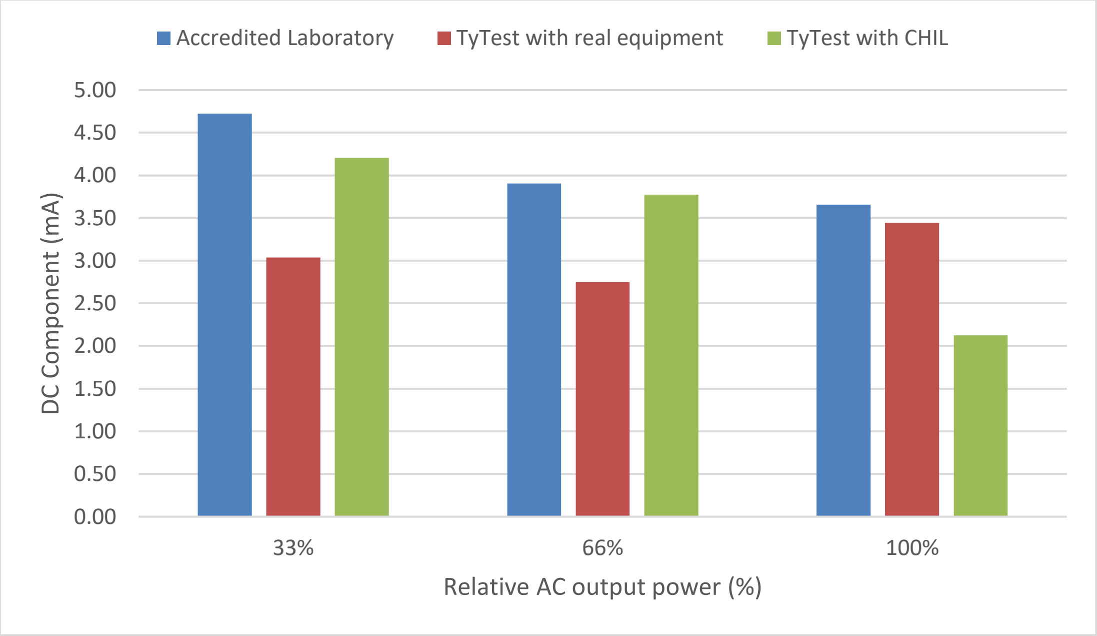
4.2 TEST RESULTS

As previously stated, the EUT was submitted to 5 test sequences in the accredited laboratory, in the TyTest using the real laboratory equipment, but controlled by the HIL simulator (PHIL) and the TyTest running in CHIL. All the results and graphs below are the mean values from the 5 tests in each category. One important thing to consider is that the inverter used in the tests is older than the Inmetro ordinance n°140/2022 and so it does not have some functionalities that are demanded in this new ordinance. However, the main point of this comparison is not to say if the inverter passes or fail in any of the tests, but to compare the inverter behavior and check if the tests results are compliant among the accredited laboratory and the TyTest PHIL and CHIL testbench.

4.2.1 DC component injection on AC current.

The DC component injection test verifies how much DC component the inverter is injecting in its AC output, which can cause problems like transformer saturation. The maximum allowed DC injection is 0.5% of the inverter nominal output AC current, in this case, the output DC current must be smaller than 34 mA (6,81 A of nominal AC current). Figure 4-9 shows the test results comparison.

Figure 4-9 - DC component injection on AC current test results



Source: Author

4.2.2 Harmonics and total harmonic distortion

In the harmonics and THD testing, the inverter must have a current THD smaller than 5%, and each individual harmonic distortion must be smaller than the threshold values shown in Table 4-III. All values are measured in six different output power levels, 10%, 20%, 30%, 50%, 75% and 100% of the inverter AC output nominal power. However, only the values measure at 100% nominal power are considered for compliance purposes.

Table 4-III - Individual harmonic distortion threshold

Odd harmonics index	**Distortion threshold**
3º to 9º	< 4.0%
11º to 15º	< 2.0%
17º to 21º	< 1.5%
23º to 23º	< 0.6%
Even harmonics index	**Distortion threshold**
2º to 8º	< 1.0%
10º to 32º	< 0.5%

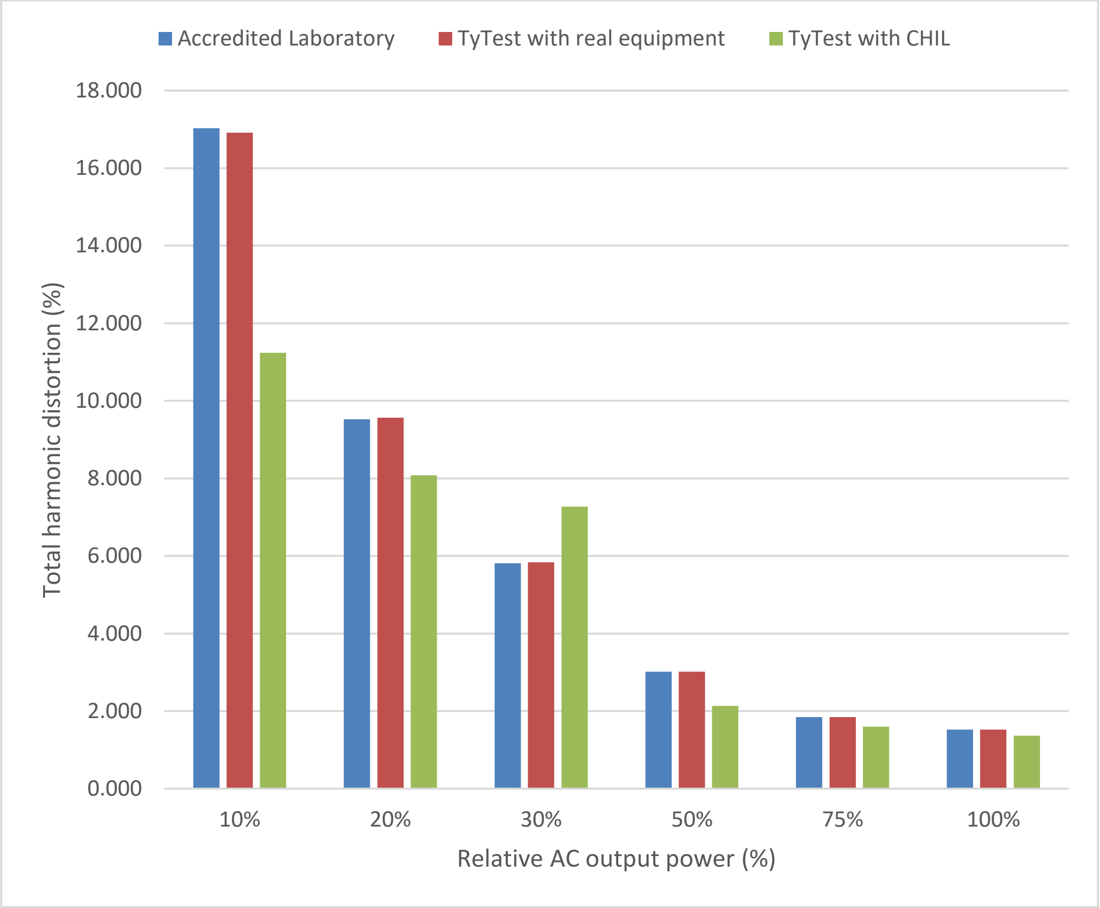
Source: Author

Figure 4-10 shows the total harmonic distortion for each power level. An interesting thing to note is that at high power levels, the results have a smaller difference between the 3 types of tests, however, as the power level is reduced, the difference increases, for example, at 100% power level the THD from accredited laboratory and PHIL are 1.52% while the CHIL is 1.37%, a difference of less than 10% between the simulated and real equipment. But at 10% nominal power, the real equipment has a THD of 17.03% while the CHIL shows 11.24%, a difference of 34% between the two platforms.

The reason of this difference will be better investigated in the following chapter of results analysis and discussions. But it is related to some non-idealities between the simulated model and the real converter, especially regarding the switches and gate driver specifications like dead time, rise and fall time values and minimal duty cycle.

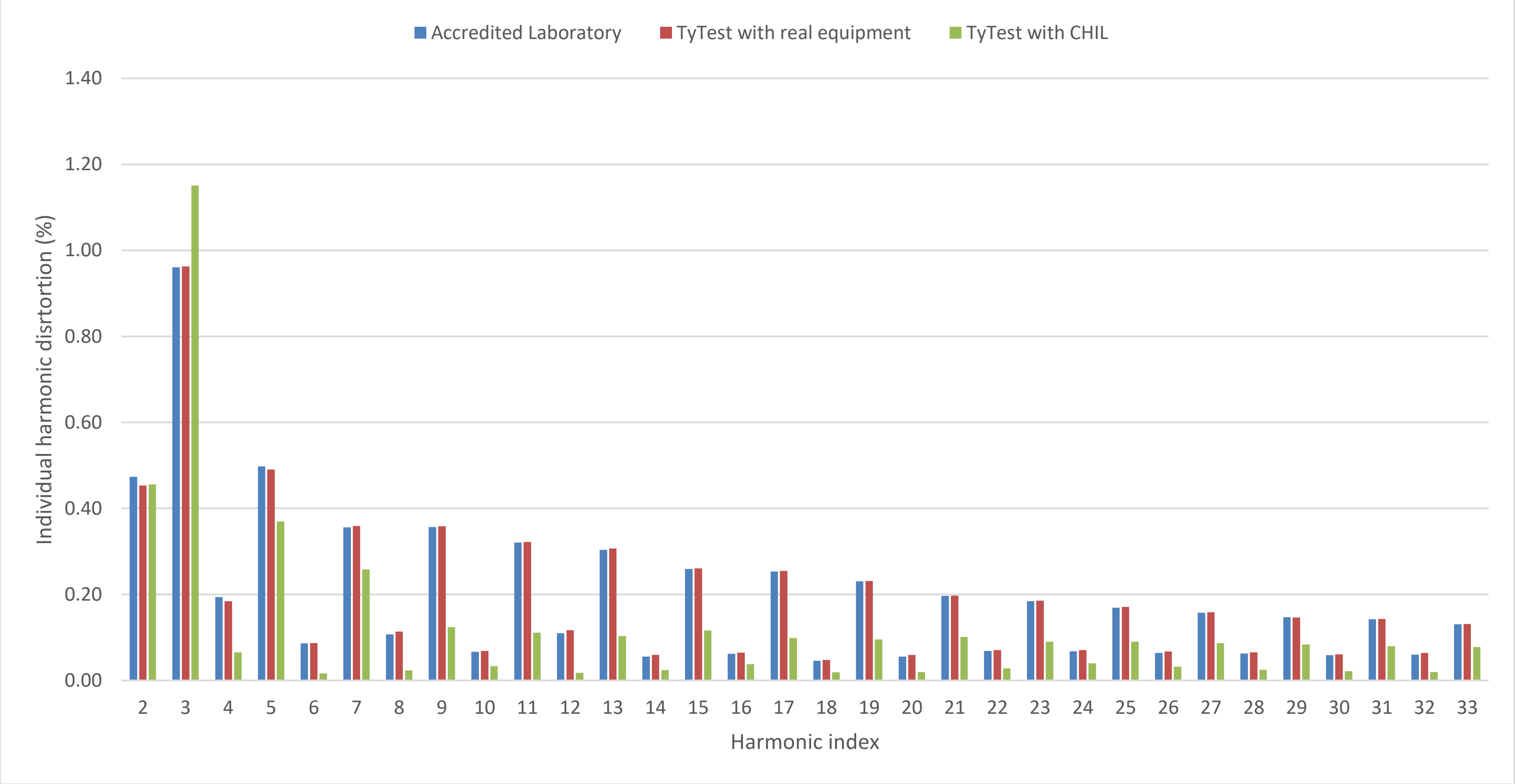
Figure 4-11 shows the individual harmonic distortion results at 100% nominal power, where the same effect can be observed, causing a considerable difference between the real equipment and the CHIL testing.

Figure 4-10 - THD results comparison



Source: Author

Figure 4-11- Individual harmonic distortion at 100% nominal output power



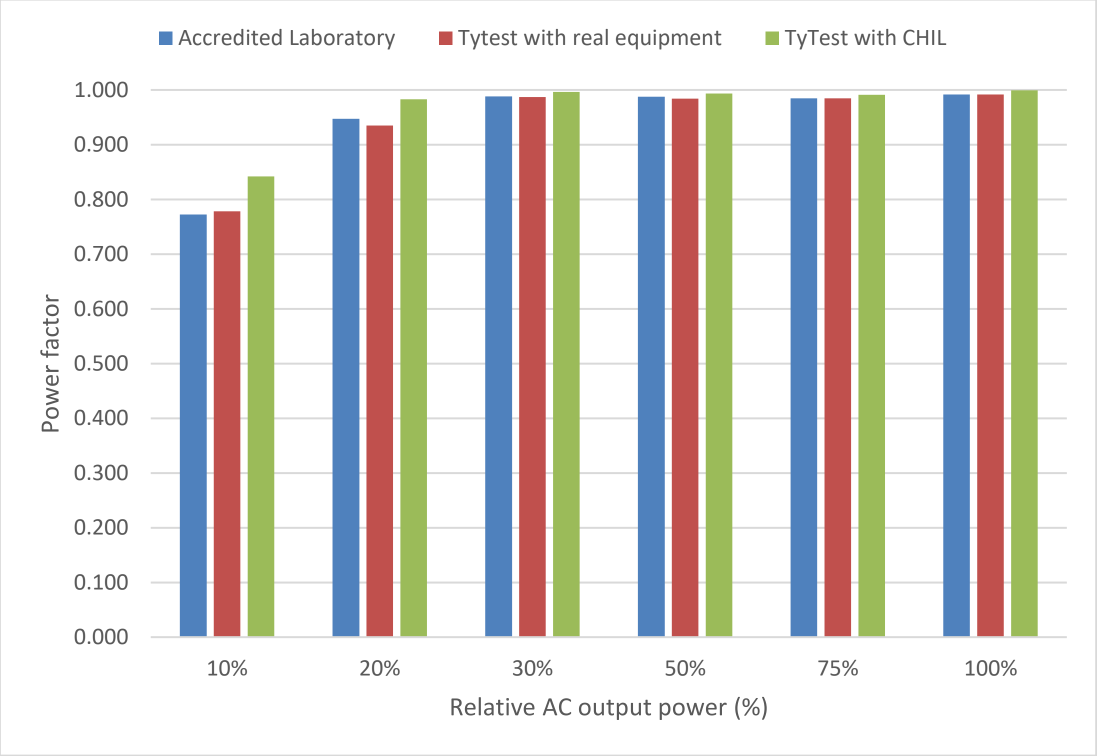
Source: Author

4.2.3 Fixed power factor

In the fixed power factor (PF) test, the equipment is set to operate at unit PF, the tolerance for this test is ± 0.025 and so, the inverter must keep a PF between 0.975 and 1 while the output power is higher than 20% of its nominal power. For inverters with a nominal power higher than 6 kW, the test is repeated two more times with the equipment set to operate with PF = 0.9 capacitive and 0.9 inductive, respectively.

Considering that the nominal power of the EUT is 1500 W, it only needs to perform the test at PF = 1. Figure 4-12 shows the test results for all the six measured power levels. As already observed in the THD and harmonics test, the results are close at higher power levels but a difference of 8,4% appears at 10% nominal power, for the same reasons commented at the THD test.

Figure 4-12 – Fixed power factor results comparison.

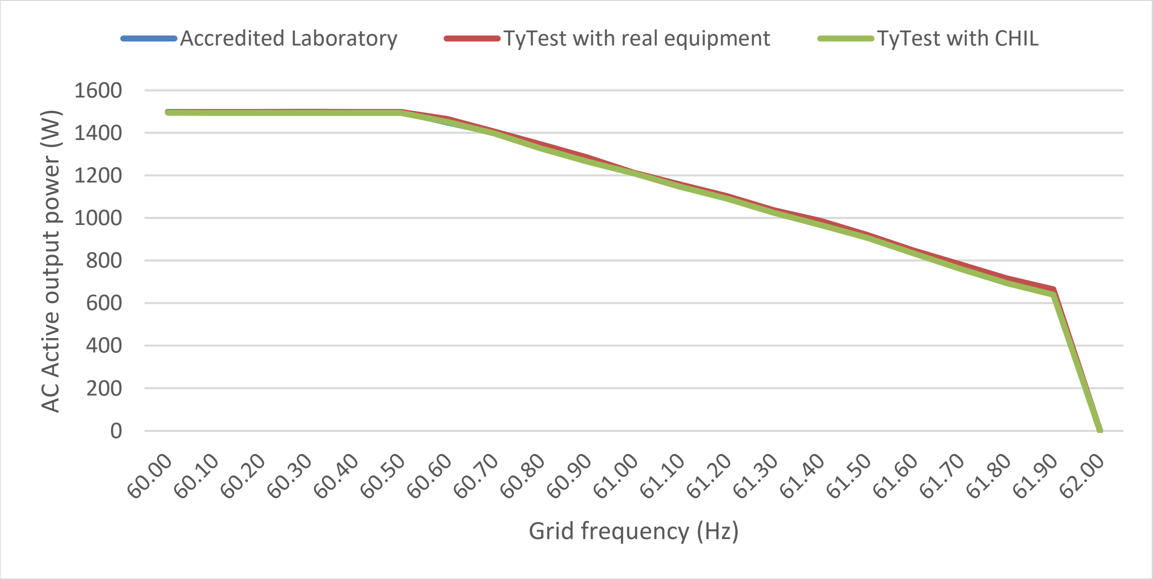


Source: Author

4.2.4 Frequency level for overfrequency disconnection

The frequency level for overfrequency disconnection test measures the frequency level that triggers the protection. As set in the old Inmetro ordinance n°004/2011, the frequency threshold is 62 Hz, for the new ordinance n°140/2022, this value has been changed to 62.6 Hz. The test procedure is the same in the two ordinances, so there is no problem in testing an older inverter. In all cases the inverter disconnected at 62 Hz, as expected due to the older configuration. The power reduction as the frequency increases is due to the "active power control on overfrequency" functionality that the inverters must have.

Figure 4-13 – Frequency level for overfrequency disconnection results comparison

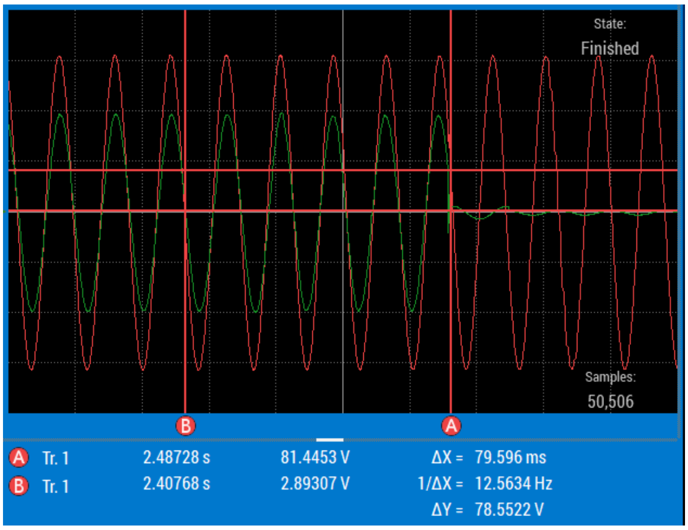


Source: Author

4.2.5 Disconnection time for overfrequency disconnection

In addition to the frequency threshold that triggers the overfrequency protection, the time needed for the inverter to disconnect from the grid is measured. The disconnection time, not considering the supportability time, must be smaller than 200 ms. Figure 4-14 shows the disconnection time for all tested situations. In this case it is not possible to have a graph with the mean value, but all disconnection times, in all cases, oscillate between 76 and 79 ms.

Figure 4-14 - Disconnection time for overfrequency results comparison

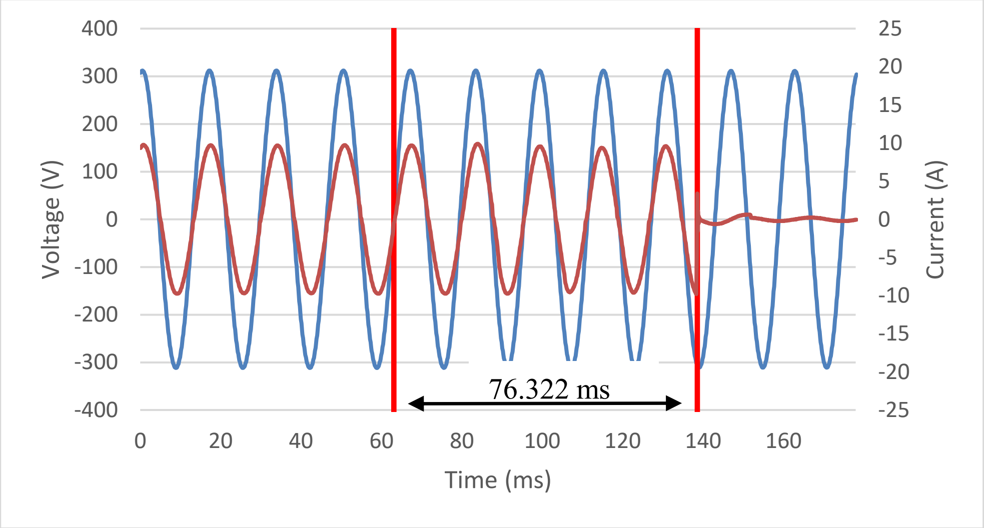


State: Finished

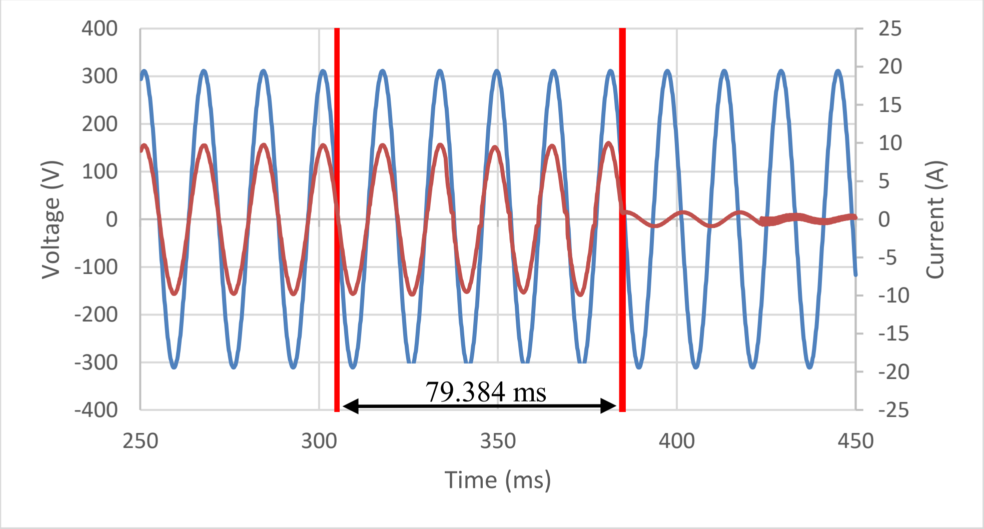
Samples: 50,506

A	Tr. 1	2.48728 s	81.4453 V	ΔX = 79.596 ms
B	Tr. 1	2.40768 s	2.89307 V	1/ΔX = 12.5634 Hz
				ΔY = 78.5522 V

Accredited laboratory



TyTest with real equipment



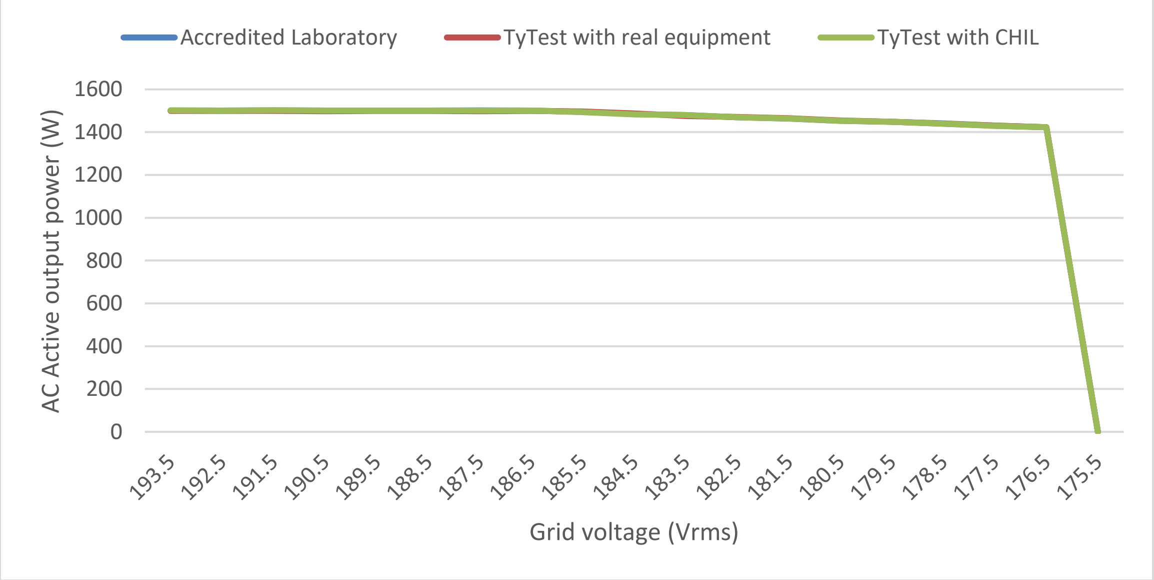
TyTest with CHIL

Source: Author

4.2.6 Voltage level for undervoltage disconnection

The voltage level for undervoltage disconnection test measures the voltage that triggers the low voltage protection, disconnecting the inverter from the grid. In both ordinances (004/2011 and 140/2022) this limit is 80% of the nominal voltage or 176 Vrms in this case. The new ordinance however creates 3 layers of disconnection time depending on the voltage level, demanding faster disconnection times the smaller the voltage is. Figure 4-15 shows the test results comparison, with a good match between the platform in both modes and the accredited laboratory.

Figure 4-15 - Voltage level for undervoltage disconnection results comparison

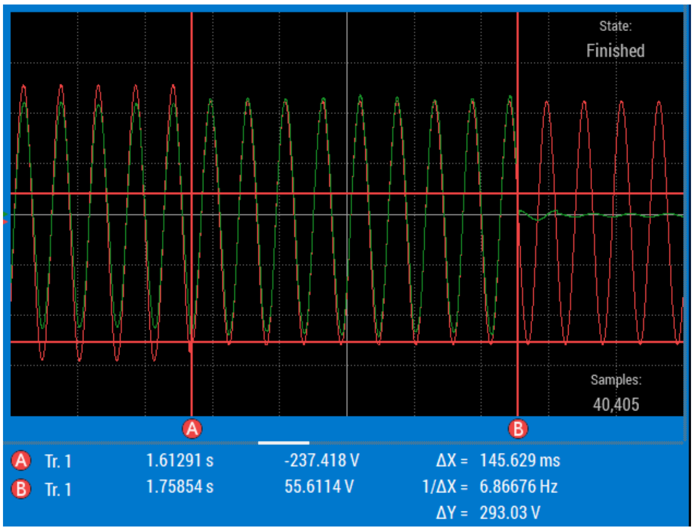


Source: Author

4.2.7 Disconnection time for undervoltage disconnection

The disconnection time for undervoltage is also measured for the first layer of protection. When the grid voltage goes below 80% but keeps above 50% of the nominal voltage, the inverter must wait 2.5 seconds and then disconnect in less than 200 ms. This creates a disconnection window between 2.5 and 2.7 seconds. As the old ordinance do not demand this supportability time, the inverter immediately disconnects from the grid in less than 200 ms, as shown in Figure 4-16, with almost the same disconnection time between both platforms and the accredited laboratory.

Figure 4-16 - Disconnection time for undervoltage results comparison

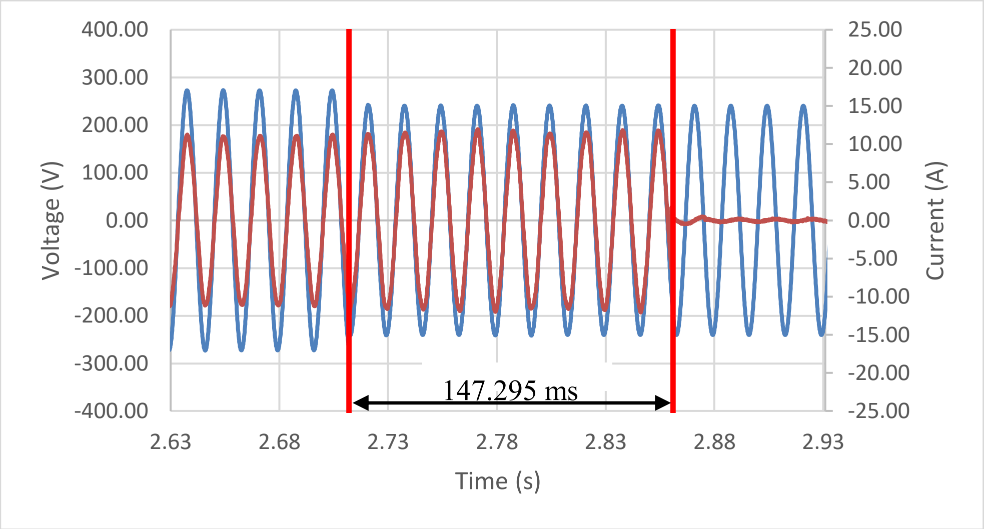


State: Finished

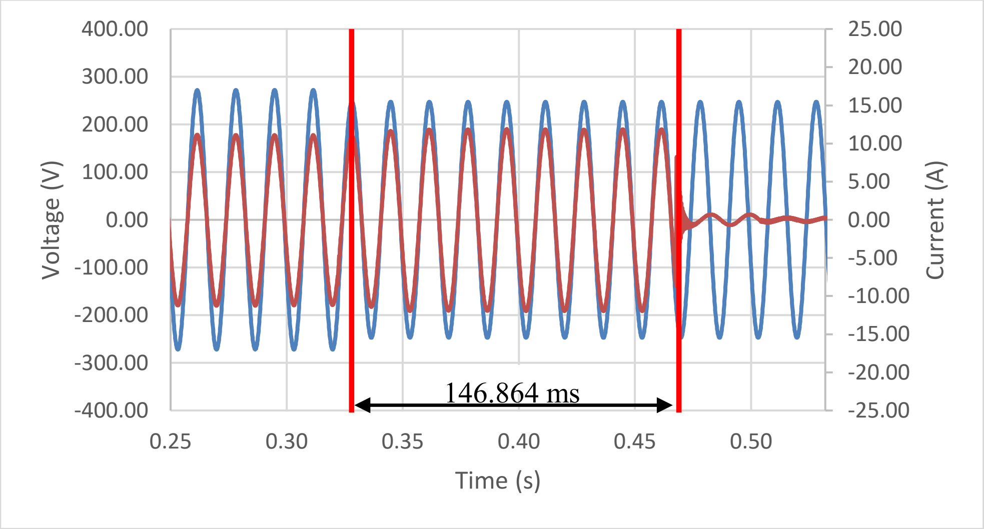
Samples: 40,405

```
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
```

Accredited laboratory



TyTest with real equipment



TyTest with CHIL

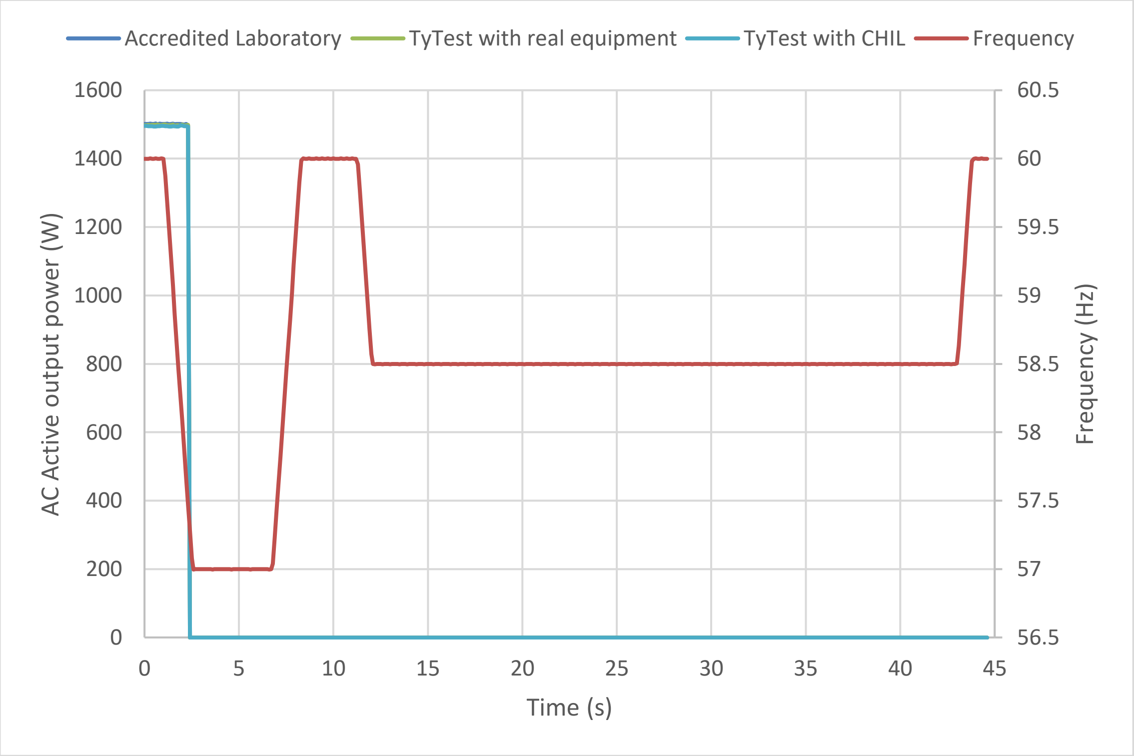
Source: Author

4.2.8 Rate of change of frequency supportability

The rate of change of frequency (RoCoF) supportability test does not exist in the older ordinance and is introduced in the new Inmetro ordinance n°140/2022. In this test, the inverter must support a frequency variation rate of, at least, 2.1 Hz/s. This test has been added to the ordinance because some inverters that are installed in Brazil were disconnecting from the grid due to frequency protections even when the grid frequency was inside the "normal operating range", and it was observed that those inverters had implemented another frequency protection feature that disconnects the inverter when a frequency transient happens.

Figure 4-17 shows the test results comparison, where the inverter disconnected from the grid in all situations when the grid frequency reached 57.5 Hz. It is important to mention that the inverter does not have a RoCoF protection, the disconnection occurred due to the frequency level itself, as expected for an inverter that complies with the Inmetro ordinance n°004/2011 older frequency threshold values. But in all situations the disconnection occurred at the same point.

Figure 4-17 – Rate of change of frequency supportability test results.



Source: Author

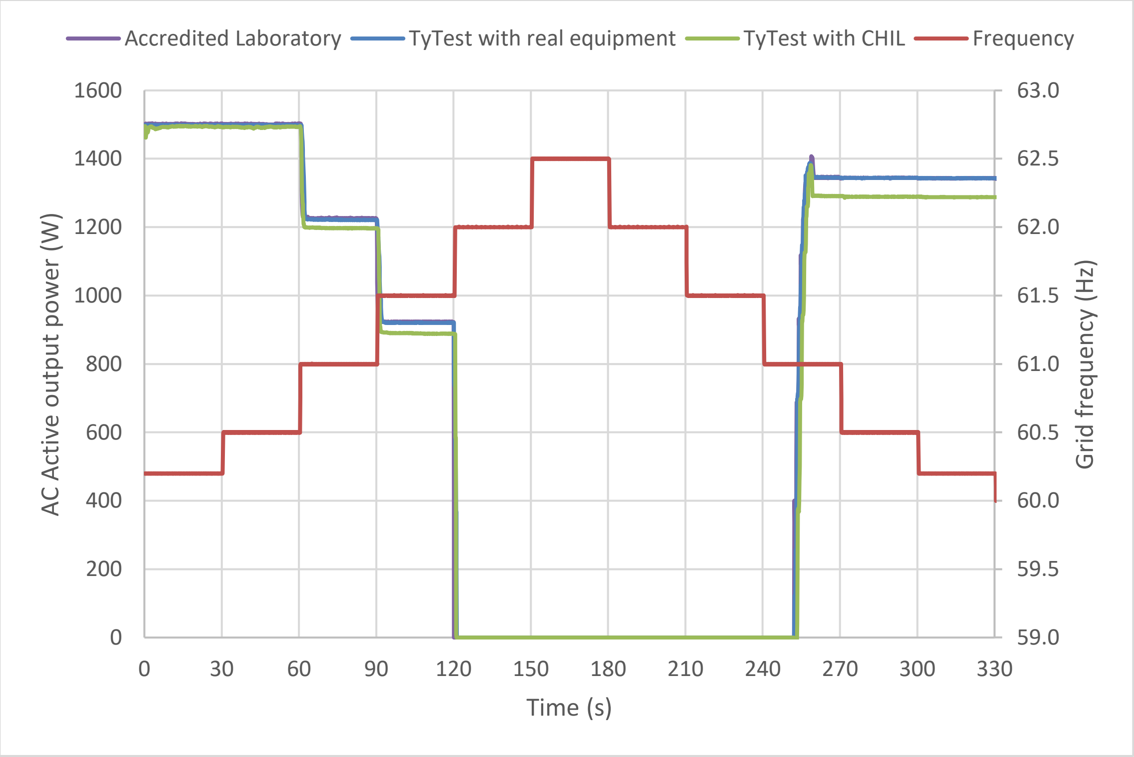
4.2.9 Active power control in overfrequency

The active power control in overfrequency is a function to support the grid, where inverters must reduce their injected active power if the grid frequency rises above a threshold. In the ordinance n° 004/2011 this threshold is 60.5 Hz while in the new 140/2022 ordinance this value has been changed to 60.2 Hz.

Figure 4-18 shows the test results. The inverter, as it is still configured to ordinance 004/2011, disconnected when grid frequency reached 62 Hz, but till that point the power reduction is correctly.

There is a 20-30 W difference between the CHIL result and the real laboratories after the second frequency degree. Despite being a difference of about 2%, it will be further investigated in the next chapter, especially considering that in the frequency level for overfrequency test, where smaller degrees are applied, this difference does not appear.

Figure 4-18 - Active power control in overfrequency test results



Source: Author

4.3 SUMMARY

This chapter showed the practical implementation and the tests results for a 1500 W PHB1500-SS photovoltaic inverter, comparing the IBR testbench operating in PHIL (TyTest with real equipment) and CHIL (TyTest with CHIL) simulations with the actual accredited laboratory.

At a first, the current waveforms are not exactly equal between CHIL and PHIL, especially at low power levels, due to the non-idealities that cannot be modeled in the current HIL software, like the switch rise and fall times, dead time, among other things. For simpler inverter topologies those parameters can be set inside the Typhoon specific models, but for the H6 converter that is used in this project, those options are not available.

By only graphically comparing the results, the power quality ones have a higher difference, especially the harmonics and THD, which is a consequence of the waveform difference between the simulation and the real equipment. But the protection and utility/function test results have a good match between both platform modes and the real laboratory.

5 STATISTICAL ANALYSIS AND DISCUSSION OF THE RESULTS

In this chapter it will be presented a statistical analysis to evaluate how close the results of the testing platform are in comparison with the values measured by the accredited laboratory. The tests will also be thoroughly analyzed and the differences between the results will be further investigated, to determine the causes of the differences.

5.1 A BRIEF REVIEW ABOUT MEASUREMENT UNCERTAINTY AND ITS RELEVANCE TO RESULTS COMPARISON

In 1993 the International Organization for Standardization (ISO) published the "Guide to Expression of Uncertainty in Measurement" (GUM), a universal method for estimating measurement uncertainty that become the worldwide reference for uncertainty measurement (DA SILVA HACK; SCHWENGBER TEN CATEN, 2012). By definition, any quantitative measurement has two parts:

- A numerical value that gives the best estimate of the quantity being measured
- An uncertainty value associated with this estimated value, which represents the statistical dispersion of the values attributed to a measured quantity. It can also be called an indicative of the "quality" of the measurement.

Even though the terms "error" and "uncertainty" are being used somewhat interchangeably in daily routines, they have different definitions according to the GUM. Error is the difference between the true value and the measured value, uncertainty is the dispersion around the estimated value of the measurand, that is caused by the interplay of errors and so, the smaller the dispersion, the smaller is the uncertainty. The ± symbol that often follows the reported value of a measurand indicate the uncertainty associated with the particular measurand and not the error (FARRANCE; FRENKEL, 2012).

The dispersion around the measurement, or just uncertainty, may appear due to a lot of factors, including the measurement equipment resolution, calibration, environmental effects, among others. But it can also appear due to the subject being measured. Especially talking about non-static subjects, that is the case of inverters, they may have varying responses to the same situation and between multiple measurements of the same condition. A classical case that is experienced in photovoltaic inverters certification is the anti-islanding test, where the equipment needs to disconnect from the grid in less than 2 seconds when it detects an island event.

Along with the anti-island algorithm, the inverters may also have other features that impact the disconnection time, like the low voltage fault ride through (LVRT) feature that requires the inverter to not disconnect from the grid for a determined amount of time during a voltage sag. An island event may be detected by many techniques and conditions, including ones that causes a low voltage condition. In this situation the inverter control may interpret it in two ways, directly as an islanding condition, and then the inverter immediately disconnect from the grid, or just as a low voltage fault, where the control enters in LVRT mode and keeps connected for a determined amount of time before disconnecting.

A practical example is shown in Table 5-I, where the inverter is tested in the same condition 5 times and the disconnection times vary between 138.22 ms and 520.71 ms. In this case the "disconnection time measurement" is 293.51±235.94. Which means that the measured value, for new tests, may be between 57.57 ms and 529.45 ms. This is an example of a poor-quality measurement as the dispersion around the mean value is high, but it is not an error or incorrectly measurement, it is the subject that can have different responses to the same situation, and a 150 ms or 500 ms are two possible results for the same measurement.

Table 5-I – Anti-island test results for a 20 kW PV inverter. Values are in ms.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.
100%	143.38	513.25	520.71	138.22	151.98	293.51	204.07	235.94

Source: Author

To correctly compare the results of the tests performed using the developed IBR testbench, the measurement uncertainties need to be considered. For the accredited laboratory this is a normal procedure that is also required by international standard, as already detailed in chapter 2 and an example of how those values are calculated is shown in the Appendix. For the TyTest with real equipment, considering that the procedure is equal to the accredited laboratory, and the measurement equipment is also the same, the measurement uncertainties can be considered the same as the accredited laboratory. For the CHIL uncertainties, there is still no official method to calculate them, unless the GUM, that uses generic procedures that must be adapted to each specific case. Sometimes those methods are very hard to elaborate and implement or even impractical, as a deeply knowledge about the HIL simulator hardware and software is needed, as well as calibrating all the I/Os that would be used to represent the simulated values. And those would only be the uncertainties from “translating” the virtual values to real world values, the uncertainties of the simulation itself are even more difficult to determine.

As a rule of thumb, in this case, only the standard deviation of the results, obtained from the 5 measurements will be considered as the CHIL uncertainty. This is an underestimation of the CHIL uncertainty, as the expanded uncertainty is the sum of all uncertainty sources, and the standard deviation is just one of them. However, for the method that will be utilized, the normalized error (NE), this will not be a problem.

5.1.1 Normalized error

According to the ISO/IEC 17043, the normalized error (E_n) is a conventional score utilized in proficiency testing for calibration laboratories, when measurement uncertainties are considered (ISO/IEC, 2010). Despite being a technique widely used for interlaboratory comparison, the normalized error can be extended to any situation where two or more measurements need to be compared. It can be used to determine if different methods to measure the same quantity have matching results, for example. This is how it will be applied to the tests, using the same inverter, the same control board and the same laboratory equipment and protocols, in different platforms, to verify the compliance between the tests. The normalized error is calculated using the equation:

$$E_n = \left| \frac{x_{Mea} - X_{Ref}}{\sqrt{U_{Mea}^2 + U_{Ref}^2}} \right|$$

Where,

X_{Mea} = measurement result

X_{Ref} = reference measurement result

U_{Mea} = Expanded Uncertainty of measurement

U_{Ref} = Expanded Uncertainty of reference measurement

Considering a reference measurement, in this case the accredited laboratory, all other measurements are compared to the reference and if the normalized error is smaller than 1 the results are compliant. For values higher than 1, the results are considered not compliant.

Also, as the uncertainties appear as a divider, the higher the measurement uncertainty, the easier it becomes to reach values below 1. So, in this case, the underestimation of the CHIL uncertainty will have the impact of CHIL needing to have results closer to the mean value measured by the reference, than it would need with a higher uncertainty. This also is the downside of the normalized error analysis, as measurements with high uncertainty may generate questionable results.

5.2 RESULTS COMPARISON AND ANALYSIS

Utilizing the normalized error analysis, the results of each test will be analyzed.

5.2.1 DC component injection on AC current.

As shown in Tables 5-II to 5-IV, the normalized error calculated for the DC component test is smaller than 1 in all tests, meaning that there is an equivalence in the results between the TyTest, in both PHIL and CHIL modes, and the accredited laboratory.

An interesting thing to observe in the tables is that the DC component injection is so small that in most measurements, the measured value is smaller than the uncertainty. So even if there is a relatively big difference between two values (3.19 mA and 6.83 mA, a 114% difference in two measurements on the same point) they are still compliant, due to the uncertainty level being bigger than the measurements themselves.

Table 5-II - Accredited laboratory (reference) normalized error analysis for DC component. Values are in mA.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
33%	4.08	4.34	4.57	3.55	7.07	4.72	1.37	5.1	----
66%	3.83	4.31	4.20	2.35	4.82	3.90	0.94	5.1	----
100%	3.19	2.72	3.28	2.27	6.83	3.66	1.82	5.3	----

Source: Author

Table 5-III - TyTest with real equipment normalized error analysis for DC component. Values are in mA.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
33%	3.04	3.45	3.48	3.43	1.78	3.04	0.72	5.0	0.234
66%	2.69	2.88	3.63	2.30	2.24	2.75	0.56	5.0	0.162
100%	3.42	3.51	3.61	3.25	3.44	3.44	0.13	5.0	0.030

Source: Author

Table 5-IV - TyTest with CHIL normalized error analysis for DC component. Values are in mA.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
33%	4.55	4.54	4.41	4.52	3.00	4.20	0.67	0.6	0.100
66%	3.62	3.84	4.08	3.45	3.87	3.77	0.24	0.2	0.026
100%	2.06	2.21	2.16	2.12	2.06	2.12	0.06	0.1	0.292

Source: Author

5.2.2 Harmonics and total harmonic distortion

For the individual harmonic distortion measurements, the normalized errors for each harmonic are smaller than 1 for the TyTest with real equipment but higher than 1 for the TyTest with CHIL as shown in Tables 5-V to 5-VII. As mentioned in the previous section, this is due to the waveform difference between the CHIL and PHIL applications.

In the total harmonic distortion test the results are also not compliant for CHIL but compliant for PHIL platform, as shown in Table 5-VIII to 5-X. Despite that at a first look the results having a small relative difference between them, with 1.528 % in the accredited laboratory and 1.364% in the CHIL testbed, as the expanded uncertainty for this measurement is small, the normalized error is still higher than 1 and so, the measurements are not equivalent.

For these tests, the converter model is not good enough to reproduce the real equipment behavior in a way that they can be considered “equal” and so, the CHIL test is not suitable to replace the real equipment testing.

Improvements in the model can be made to improve the fidelity of the simulation, especially regarding the switches and gate drivers, that are not present in the H6 simulation due to HIL model limitations. Other non-idealities can also be implemented, like the grid simulator own harmonic content or the interaction between the inverter and grid/PV simulators, as both are switching converters. A better modeling of passive components can also be performed, components like capacitors and inductors that are only modeled considering their capacitance or inductance but not the ESR, the coupling factor or other parameters that are also present in real components should be modeled too.

Despite the test results showing that the CHIL and PHIL testing are not equivalent in this case, the results can still be used in a pre-certification context, providing a good indication of the test results but not assuring that the results will be the same when tested in the real laboratory.

Table 5-V - Accredited laboratory (reference) NE analysis for harmonic distortion. Values are in %.

Harm. index	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
2	0.452	0.443	0.480	0.491	0.502	0.474	0.0253	0.044	----
3	0.976	0.974	0.971	0.942	0.941	0.961	0.0177	0.057	----
4	0.194	0.192	0.198	0.190	0.197	0.194	0.0033	0.044	----
5	0.498	0.506	0.502	0.490	0.491	0.497	0.0069	0.053	----
6	0.089	0.091	0.085	0.083	0.083	0.086	0.0036	0.04	----
7	0.355	0.356	0.351	0.360	0.357	0.356	0.0033	0.052	----
8	0.111	0.108	0.106	0.102	0.107	0.107	0.0033	0.041	----
9	0.360	0.371	0.353	0.351	0.349	0.357	0.0090	0.053	----
10	0.070	0.068	0.068	0.061	0.065	0.066	0.0035	0.037	----
11	0.319	0.325	0.319	0.321	0.318	0.320	0.0028	0.040	----
12	0.111	0.113	0.108	0.106	0.109	0.109	0.0027	0.039	----
13	0.304	0.309	0.301	0.303	0.301	0.304	0.0033	0.039	----
14	0.056	0.054	0.054	0.054	0.058	0.055	0.0018	0.037	----
15	0.259	0.261	0.256	0.260	0.259	0.259	0.0019	0.039	----
16	0.061	0.060	0.063	0.060	0.067	0.062	0.0029	0.038	----
17	0.252	0.253	0.252	0.256	0.254	0.253	0.0017	0.037	----
18	0.046	0.046	0.046	0.044	0.046	0.046	0.0009	0.037	----
19	0.229	0.233	0.230	0.231	0.231	0.231	0.0015	0.037	----
20	0.058	0.054	0.056	0.052	0.057	0.055	0.0024	0.038	----
21	0.196	0.197	0.194	0.198	0.197	0.196	0.0015	0.037	----
22	0.071	0.069	0.068	0.066	0.069	0.069	0.0018	0.038	----
23	0.184	0.183	0.183	0.186	0.185	0.184	0.0013	0.037	----
24	0.069	0.068	0.068	0.065	0.068	0.068	0.0015	0.038	----
25	0.170	0.171	0.169	0.170	0.167	0.169	0.0015	0.037	----
26	0.065	0.063	0.064	0.062	0.066	0.064	0.0016	0.038	----
27	0.158	0.158	0.155	0.159	0.156	0.157	0.0016	0.037	----
28	0.063	0.062	0.063	0.061	0.064	0.063	0.0011	0.037	----
29	0.146	0.148	0.146	0.147	0.146	0.147	0.0009	0.037	----
30	0.060	0.058	0.059	0.057	0.061	0.059	0.0016	0.037	----
31	0.143	0.142	0.142	0.143	0.142	0.142	0.0005	0.037	----
32	0.062	0.059	0.060	0.059	0.061	0.060	0.0013	0.037	----
33	0.130	0.129	0.131	0.132	0.131	0.131	0.0011	0.037	----

Source: Author

Table 5-VI – TyTest with real equipment NE analysis for harmonic distortion. Values are in %.

Harm. index	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
2	0.442	0.458	0.449	0.468	0.449	0.453	0.0100	0.034	0.367
3	0.978	0.967	0.954	0.950	0.965	0.963	0.0111	0.045	0.030
4	0.191	0.181	0.171	0.182	0.196	0.184	0.0095	0.034	0.177
5	0.497	0.493	0.489	0.488	0.486	0.490	0.0043	0.045	0.100
6	0.089	0.086	0.085	0.084	0.090	0.087	0.0025	0.034	0.008
7	0.360	0.362	0.362	0.358	0.354	0.359	0.0035	0.045	0.049
8	0.114	0.110	0.110	0.110	0.124	0.114	0.0060	0.034	0.129
9	0.365	0.359	0.359	0.353	0.356	0.359	0.0044	0.045	0.026
10	0.069	0.070	0.067	0.066	0.070	0.068	0.0017	0.032	0.038
11	0.321	0.323	0.326	0.320	0.322	0.322	0.0022	0.034	0.034
12	0.117	0.113	0.114	0.112	0.127	0.117	0.0062	0.032	0.144
13	0.307	0.307	0.307	0.306	0.308	0.307	0.0008	0.034	0.063
14	0.059	0.058	0.057	0.059	0.064	0.059	0.0028	0.032	0.080
15	0.260	0.262	0.263	0.258	0.259	0.260	0.0019	0.034	0.026
16	0.062	0.064	0.060	0.065	0.071	0.064	0.0042	0.032	0.043
17	0.255	0.254	0.257	0.254	0.252	0.254	0.0019	0.032	0.019
18	0.048	0.048	0.045	0.047	0.052	0.048	0.0025	0.032	0.045
19	0.230	0.233	0.234	0.231	0.227	0.231	0.0027	0.032	0.006
20	0.059	0.059	0.057	0.058	0.066	0.060	0.0034	0.032	0.085
21	0.198	0.198	0.199	0.198	0.194	0.197	0.0021	0.032	0.017
22	0.071	0.069	0.068	0.069	0.076	0.071	0.0035	0.032	0.042
23	0.186	0.186	0.186	0.186	0.183	0.185	0.0015	0.032	0.023
24	0.069	0.068	0.067	0.069	0.077	0.070	0.0041	0.032	0.054
25	0.172	0.171	0.172	0.170	0.169	0.171	0.0012	0.032	0.031
26	0.067	0.064	0.064	0.067	0.074	0.067	0.0038	0.032	0.062
27	0.159	0.159	0.159	0.158	0.156	0.158	0.0014	0.032	0.023
28	0.065	0.065	0.062	0.065	0.070	0.065	0.0029	0.032	0.059
29	0.148	0.146	0.148	0.146	0.144	0.146	0.0016	0.032	0.004
30	0.060	0.059	0.059	0.061	0.066	0.061	0.0028	0.032	0.038
31	0.143	0.145	0.145	0.143	0.140	0.143	0.0021	0.032	0.014
32	0.063	0.063	0.062	0.062	0.069	0.064	0.0028	0.032	0.072
33	0.132	0.132	0.132	0.132	0.127	0.131	0.0020	0.032	0.007

Source: Author

Table 5-VII – TyTest with CHIL NE analysis for harmonic distortion. Values are in %.

Harm. index	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
2	0.453	0.461	0.460	0.452	0.453	0.456	0.0041	0.004	0.406
3	1.145	1.163	1.154	1.143	1.149	1.151	0.0078	0.007	3.306
4	0.066	0.066	0.067	0.064	0.065	0.066	0.0014	0.001	2.923
5	0.375	0.369	0.369	0.368	0.366	0.370	0.0034	0.003	2.407
6	0.015	0.015	0.015	0.018	0.018	0.016	0.0017	0.002	1.753
7	0.255	0.261	0.260	0.256	0.258	0.258	0.0027	0.002	1.883
8	0.024	0.022	0.024	0.024	0.024	0.024	0.0009	0.001	2.029
9	0.124	0.128	0.127	0.121	0.123	0.124	0.0029	0.003	4.381
10	0.034	0.034	0.034	0.032	0.033	0.033	0.0009	0.001	0.895
11	0.109	0.114	0.113	0.109	0.110	0.111	0.0022	0.002	5.233
12	0.016	0.015	0.016	0.020	0.020	0.017	0.0024	0.002	2.355
13	0.100	0.106	0.104	0.100	0.103	0.103	0.0025	0.002	5.138
14	0.025	0.026	0.026	0.021	0.022	0.024	0.0023	0.002	0.839
15	0.116	0.120	0.119	0.112	0.113	0.116	0.0038	0.003	3.652
16	0.036	0.035	0.036	0.041	0.041	0.038	0.0028	0.002	0.640
17	0.097	0.103	0.100	0.096	0.098	0.099	0.0025	0.002	4.169
18	0.018	0.018	0.018	0.021	0.021	0.019	0.0017	0.002	0.716
19	0.095	0.099	0.097	0.092	0.093	0.095	0.0028	0.003	3.660
20	0.020	0.021	0.020	0.019	0.019	0.020	0.0006	0.001	0.939
21	0.099	0.104	0.102	0.100	0.100	0.101	0.0021	0.002	2.572
22	0.029	0.028	0.029	0.026	0.027	0.028	0.0011	0.001	1.070
23	0.090	0.094	0.093	0.087	0.087	0.090	0.0031	0.003	2.542
24	0.039	0.039	0.040	0.040	0.040	0.039	0.0006	0.001	0.741
25	0.090	0.093	0.092	0.087	0.088	0.090	0.0026	0.002	2.143
26	0.031	0.032	0.031	0.033	0.033	0.032	0.0010	0.001	0.846
27	0.086	0.089	0.089	0.085	0.086	0.087	0.0017	0.002	1.897
28	0.024	0.024	0.024	0.026	0.027	0.025	0.0014	0.001	1.018
29	0.083	0.086	0.085	0.082	0.082	0.083	0.0019	0.002	1.704
30	0.022	0.021	0.021	0.021	0.022	0.021	0.0005	0.000	1.020
31	0.079	0.083	0.081	0.077	0.078	0.080	0.0023	0.002	1.697
32	0.019	0.019	0.019	0.020	0.020	0.019	0.0008	0.001	1.106
33	0.077	0.080	0.079	0.075	0.076	0.078	0.0020	0.002	1.432

Source: Author

Table 5-VIII – Accredited laboratory NE analysis for total harmonic distortion. Values are in %.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
10%	16.905	17.087	16.880	16.901	17.401	17.035	0.2211	0.256	----
20%	9.487	9.564	9.524	9.526	9.539	9.528	0.0279	0.038	----
30%	5.812	5.805	5.817	5.793	5.829	5.811	0.0134	0.025	----
50%	3.011	3.007	3.001	3.040	3.023	3.016	0.0155	0.027	----
75%	1.865	1.844	1.844	1.829	1.846	1.846	0.0128	0.025	----
100%	1.528	1.533	1.530	1.515	1.516	1.524	0.0093	0.023	----

Source: Author

Table 5-IX – TyTest with real equipment NE analysis for total harrmonic distortion. Values are in %.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
10%	16.752	16.880	16.926	16.992	17.012	16.912	0.1039	0.256	0.476
20%	9.573	9.676	9.509	9.583	9.491	9.566	0.0730	0.038	0.895
30%	5.837	5.843	5.846	5.836	5.830	5.838	0.0063	0.025	0.843
50%	3.038	3.008	3.013	3.020	3.025	3.021	0.0116	0.027	0.132
75%	1.851	1.845	1.842	1.843	1.835	1.843	0.0058	0.025	0.075
100%	1.532	1.526	1.514	1.513	1.520	1.521	0.0081	0.023	0.112

Source: Author

Table 5-X – TyTest with CHIL NE analysis for total harrmonic distortion. Values are in %.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
10%	10.764	11.362	11.357	11.357	11.375	11.243	0.2677	0.310	18.245
20%	8.094	8.073	8.078	8.103	8.068	8.083	0.0149	0.026	44.806
30%	7.274	7.269	7.277	7.283	7.257	7.272	0.0098	0.023	47.017
50%	2.128	2.118	2.151	2.131	2.138	2.133	0.0123	0.025	28.058
75%	1.595	1.605	1.582	1.606	1.599	1.597	0.0098	0.023	8.068
100%	1.364	1.385	1.376	1.359	1.365	1.370	0.0105	0.023	4.910

Source: Author

5.2.3 Fixed power factor

Tables 5-XI to 5-XIII shows the test results for fixed power factor, the results of the PHIL comparison are compliant for all power levels, while the CHIL results are compliant only for power levels above 20% of the inverter nominal power. This is also a consequence of the waveform difference already mentioned, but in this case the impact is higher when the output current is small. Considering that Inmetro ordinances only consider power levels above 20%

for inverter pass/fail criteria, the test can still be used for certification purposes, but results can also be improved with a better modeling of the inverter.

Table 5-XI – Accredited laboratory NE analysis for fixed power factor. Values are dimensionless.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
10%	0.774	0.773	0.775	0.771	0.769	0.772	0.0024	0.012	----
20%	0.935	0.943	0.936	0.961	0.961	0.947	0.0130	0.019	----
30%	0.988	0.988	0.988	0.988	0.988	0.988	0.0000	0.012	----
50%	0.987	0.988	0.987	0.987	0.988	0.987	0.0005	0.012	----
75%	0.985	0.985	0.985	0.985	0.985	0.985	0.0000	0.012	----
100%	0.992	0.992	0.992	0.992	0.992	0.992	0.0000	0.012	----

Source: Author

Table 5-XII – TyTest with real equipment NE analysis for fixed power factor. Values are dimensionless.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
10%	0.779	0.778	0.777	0.778	0.780	0.778	0.0011	0.012	0.348
20%	0.935	0.935	0.935	0.935	0.935	0.935	0.0000	0.012	0.539
30%	0.987	0.987	0.987	0.987	0.987	0.987	0.0000	0.012	0.059
50%	0.985	0.984	0.985	0.984	0.984	0.984	0.0005	0.012	0.177
75%	0.985	0.985	0.985	0.985	0.985	0.985	0.0000	0.012	0.000
100%	0.992	0.992	0.992	0.992	0.992	0.992	0.0000	0.012	0.000

Source: Author

Table 5-XIII – TyTest with CHIL NE analysis for fixed power factor. Values are dimensionless.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
10%	0.844	0.842	0.842	0.842	0.842	0.842	0.0011	0.001	5.646
20%	0.983	0.983	0.983	0.983	0.983	0.983	0.0002	0.000	1.866
30%	0.996	0.996	0.996	0.996	0.996	0.996	0.0000	0.000	0.699
50%	0.994	0.994	0.994	0.994	0.994	0.994	0.0000	0.000	0.521
75%	0.990	0.991	0.992	0.991	0.991	0.991	0.0007	0.001	0.499
100%	1.000	1.000	1.000	1.000	1.000	1.000	0.0000	0.000	0.633

Source: Author

5.2.4 Frequency level for overfrequency disconnection

In the frequency level for overfrequency disconnection measurement the results are compliant for all measured points, both in PHIL and CHIL as shown in tables 5-XIV to 5-XVI. For this test the power measurement is not relevant, only the disconnection level (62 Hz in all platforms) but the power level was also measured because due to the active power control feature, while the frequency rises the inverter must reduce its active power and even this behavior is the same in all platforms, showing a good compliance between the CHIL and PHIL platforms with the accredited laboratory.

Table 5-XIV – Accredited laboratory NE analysis for overfrequency threshold. Values are in W

Grid freq. (Hz)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
60.0	1498	1499	1499	1496	1494	1497	2.2	6.3	----
60.1	1497	1499	1495	1495	1496	1496	1.7	6.3	----
60.2	1499	1499	1495	1496	1498	1497	1.8	6.3	----
60.3	1499	1499	1498	1497	1497	1498	1.1	6.1	----
60.4	1499	1499	1495	1495	1498	1497	2.0	6.4	----
60.5	1499	1499	1497	1498	1496	1498	1.5	6.2	----
60.6	1437	1456	1458	1456	1438	1449	10.2	13.2	----
60.7	1390	1399	1402	1405	1403	1400	6.0	9.2	----
60.8	1338	1326	1349	1345	1344	1340	9.0	12.0	----
60.9	1273	1280	1269	1276	1271	1274	4.5	7.9	----
61.0	1209	1212	1211	1215	1205	1211	3.8	7.4	----
61.1	1142	1148	1146	1155	1143	1147	5.1	8.4	----
61.2	1096	1104	1093	1092	1098	1097	4.9	8.3	----
61.3	1027	1035	1034	1034	1031	1032	3.4	7.2	----
61.4	973	972	980	983	975	977	4.7	8.1	----
61.5	913	906	908	915	921	913	6.0	9.2	----
61.6	841	837	838	847	840	841	3.9	7.5	----
61.7	765	775	762	775	778	771	7.1	10.2	----
61.8	706	700	695	709	710	704	6.4	9.5	----
61.9	653	653	640	664	642	650	9.7	12.7	----
62.0	0.00	0.00	0.00	0.00	0.00	0.0	0.0	6.0	----

Source: Author

Table 5-XV – TyTest with real equipment NE analysis for overfrequency threshold. Values are in W

Grid freq. (Hz)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
60.0	1498	1498	1499	1499	1497	1498	0.8	6.1	0.049
60.1	1499	1498	1497	1499	1499	1499	0.9	6.1	0.181
60.2	1498	1498	1499	1499	1499	1499	0.6	6.0	0.091
60.3	1499	1499	1499	1499	1499	1499	0.3	6.0	0.035
60.4	1499	1499	1498	1498	1497	1498	0.7	6.1	0.079
60.5	1498	1498	1499	1499	1497	1498	0.7	6.1	0.009

60.6	1462	1474	1446	1471	1472	1465	11.7	14.8	0.781
60.7	1401	1408	1412	1408	1406	1407	4.3	7.8	0.573
60.8	1343	1348	1350	1350	1344	1347	3.2	7.1	0.450
60.9	1280	1288	1284	1287	1282	1284	3.1	7.0	0.932
61.0	1208	1214	1211	1219	1213	1213	4.2	7.7	0.171
61.1	1153	1153	1158	1161	1158	1157	3.3	7.1	0.883
61.2	1097	1108	1107	1102	1100	1103	4.8	8.1	0.479
61.3	1029	1039	1039	1042	1037	1037	4.7	8.1	0.442
61.4	983	988	988	990	984	986	2.9	6.9	0.896
61.5	918	923	923	915	924	920	4.1	7.6	0.615
61.6	846	850	852	840	850	848	4.6	8.0	0.572
61.7	777	782	779	783	789	782	4.8	8.2	0.784
61.8	710	721	709	723	720	717	6.4	9.5	0.930
61.9	657	670	659	672	670	666	6.8	9.9	0.905
62.0	0	0	0	0	0	0	0.0	6.0	0.000

Source: Author

Table 5-XVI TyTest with CHIL NE analysis for overfrequency threshold. Values are in W

Grid freq. (Hz)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
60.0	1496	1494	1494	1495	1495	1495	0.8	0.7	0.453
60.1	1495	1494	1495	1490	1495	1494	2.4	2.2	0.461
60.2	1494	1491	1494	1496	1492	1493	2.0	1.7	0.685
60.3	1495	1494	1494	1495	1492	1494	1.2	1.1	0.719
60.4	1494	1494	1494	1497	1493	1494	1.4	1.2	0.521
60.5	1496	1495	1495	1494	1493	1494	1.2	1.1	0.599
60.6	1457	1459	1426	1459	1457	1452	14.4	12.9	0.118
60.7	1400	1409	1386	1400	1390	1397	9.0	8.1	0.244
60.8	1333	1317	1327	1332	1329	1328	6.4	5.7	0.994
60.9	1270	1265	1261	1268	1266	1266	3.5	3.2	0.991
61.0	1215	1200	1209	1214	1212	1210	6.1	5.4	0.129
61.1	1153	1141	1140	1152	1151	1147	6.3	5.6	0.005
61.2	1098	1085	1091	1094	1086	1091	5.3	4.8	0.668
61.3	1029	1016	1015	1035	1030	1025	9.0	8.1	0.718
61.4	972	961	965	972	970	968	4.9	4.4	0.984
61.5	912	901	905	911	908	907	4.5	4.0	0.577
61.6	839	823	834	833	839	833	6.6	5.9	0.808
61.7	761	757	761	765	765	762	3.5	3.2	0.932
61.8	695	686	692	695	702	694	5.8	5.2	0.931
61.9	652	626	644	638	638	639	9.4	8.4	0.754
62.0	0	0	0	0	0	0	0.0	0.0	0.000

Source: Author

5.2.5 Disconnection time for overfrequency disconnection

For the disconnection time for overfrequency, the test results of both platforms are compliant with the accredited laboratory, as shown in Tables 5-XVII to 5-XIX. This is another example of small uncertainty measurement that is still compliant between the platforms, showing that for some functions like protection and grid support/utility features the CHIL and PHIL tests have a good match with the real laboratory and so, could be used to certify the equipment.

Table 5-XVII – Accredited laboratory NE analysis for disconnection time for overfrequency. Values are in ms.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
100%	75.93	75.34	79.02	79.60	76.43	77.3	1.9	1.7	----

Source: Author

Table 5-XVIII - TyTest with real equipment NE analysis for disconnection time for overfrequency. Values are in ms.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
100%	75.33	79.35	79.22	75.98	76.32	77.2	1.9	1.7	0.010

Source: Author

Table 5-XIX - TyTest with CHIL NE analysis for disconnection time for overfrequency. Values are in ms.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
100%	79.58	76.31	75.82	76.68	79.70	77.6	1.9	1.7	0.149

Source: Author

5.2.6 Voltage level for undervoltage disconnection

In the voltage level for undervoltage disconnection all points are compliant. The only important measurement for the pass/fail criteria of this test is the voltage level at which the inverter disconnected, 175.5V_{rms} in both platforms and the accredited laboratory. However, even the power reduction due to output current limitation is the same between the platforms, which indicates a good match between the simulated model and the real equipment, as shown in Tables 5-XX to 5-XXII.

Table 5-XX Accredited laboratory NE analysis for low voltage threshold. Values are in W

Grid Volt. (V_{rms})	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
193.5	1502	1500	1501	1500	1503	1501.2	1.3	6.2	----
192.5	1503	1500	1502	1502	1500	1501.4	1.3	6.2	----
191.5	1503	1503	1501	1500	1502	1501.8	1.3	6.2	----
190.5	1500	1500	1503	1502	1500	1501.0	1.4	6.2	----
189.5	1502	1503	1502	1500	1499	1501.2	1.6	6.3	----
188.5	1503	1501	1499	1500	1501	1500.8	1.5	6.2	----
187.5	1502	1502	1502	1503	1500	1501.8	1.1	6.1	----
186.5	1502	1503	1500	1502	1501	1501.6	1.1	6.1	----
185.5	1496	1495	1492	1496	1498	1495.4	2.2	6.5	----
184.5	1484	1485	1484	1487	1484	1484.8	1.3	6.2	----
183.5	1482	1479	1479	1481	1478	1479.8	1.6	6.3	----
182.5	1473	1470	1475	1464	1470	1470.3	4.2	7.7	----
181.5	1463	1462	1467	1469	1456	1463.6	5.1	8.4	----
180.5	1444	1462	1450	1452	1457	1453.0	7.0	10.1	----
179.5	1446	1449	1447	1455	1442	1447.8	4.9	8.3	----
178.5	1440	1453	1440	1442	1429	1440.6	8.6	11.6	----
177.5	1436	1427	1436	1428	1428	1431.3	4.5	7.9	----
176.5	1436	1420	1410	1419	1431	1423.1	10.4	13.5	----
175.5	0	0	0	0	0	0.0	0.0	6.0	----

Source: Author

Table 5-XXI TyTest with real equipment NE analysis for low voltage threshold. Values are in W

Grid Volt. (V_{rms})	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
193.5	1500	1500	1499	1500	1498	1499.6	0.8	6.1	0.185
192.5	1499	1501	1499	1499	1499	1499.3	0.8	6.1	0.240
191.5	1500	1499	1501	1499	1500	1499.7	0.9	6.1	0.247
190.5	1497	1498	1500	1498	1499	1498.4	0.8	6.1	0.296
189.5	1499	1500	1498	1500	1500	1499.4	1.1	6.1	0.204
188.5	1500	1499	1499	1499	1500	1499.2	0.7	6.0	0.184
187.5	1500	1499	1498	1499	1498	1498.6	0.6	6.0	0.367
186.5	1499	1500	1500	1498	1499	1499.3	0.6	6.0	0.271
185.5	1493	1496	1496	1499	1497	1496.2	2.1	6.5	0.086
184.5	1490	1485	1485	1491	1485	1487.1	3.0	6.9	0.249
183.5	1476	1471	1476	1480	1471	1474.9	3.9	7.5	0.497
182.5	1475	1473	1476	1465	1470	1471.7	4.4	7.9	0.127
181.5	1465	1462	1464	1471	1459	1464.4	4.6	8.0	0.069
180.5	1447	1461	1450	1455	1457	1454.0	5.7	8.9	0.074
179.5	1446	1451	1448	1453	1444	1448.4	3.8	7.5	0.054

178.5	1437	1450	1437	1445	1429	1439.4	8.2	11.2	0.074
177.5	1435	1429	1434	1426	1427	1430.5	4.0	7.6	0.073
176.5	1433	1418	1412	1420	1434	1423.3	9.8	12.8	0.011
175.5	0	0	0	0	0	0.0	0.0	6.0	0.000

Source: Author

Table 5-XXII TyTest with CHIL NE analysis for low voltage threshold. Values are in W

Grid Volt. (V_{rms})	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
193.5	1505	1502	1501	1498	1505	1502	2.9	6.9	0.108
192.5	1500	1500	1503	1501	1500	1501	1.3	6.2	0.069
191.5	1506	1500	1501	1502	1501	1502	2.3	6.6	0.022
190.5	1498	1497	1501	1504	1502	1500	2.9	6.9	0.065
189.5	1505	1501	1500	1499	1498	1501	2.7	6.8	0.065
188.5	1504	1503	1500	1502	1499	1502	2.1	6.5	0.089
187.5	1502	1500	1499	1500	1501	1500	1.1	6.1	0.161
186.5	1503	1504	1500	1499	1498	1501	2.6	6.7	0.088
185.5	1496	1494	1490	1496	1495	1494	2.5	6.7	0.129
184.5	1483	1483	1483	1486	1483	1484	1.3	6.2	0.137
183.5	1485	1476	1482	1483	1475	1480	4.4	7.9	0.040
182.5	1472	1470	1474	1463	1468	1469	4.2	7.7	0.092
181.5	1464	1459	1468	1469	1455	1463	6.0	9.2	0.032
180.5	1443	1460	1448	1453	1460	1453	7.6	10.7	0.014
179.5	1444	1449	1450	1458	1442	1449	6.3	9.5	0.064
178.5	1437	1455	1438	1441	1429	1440	9.6	12.6	0.047
177.5	1438	1424	1434	1425	1427	1430	6.0	9.2	0.115
176.5	1436	1420	1410	1419	1434	1424	11.1	14.1	0.031
175.5	0	0	0	0	0	0	0.0	6.0	0.000

Source: Author

5.2.7 Disconnection time for undervoltage disconnection

In the disconnection time for undervoltage test both platform modes and the accredited laboratory have compliant results (normalized error <1). In the same way as the frequency test, the mean value of the three platforms is close with less than 1ms of difference. Between the tests, the standard deviation is almost the same in the platform and the accredited laboratory and considering that the uncertainty is less than 1.5% of the mean value, the results can be considered solid, as shown in Tables 5-XXIII to 5-XXV.

Table 5-XXIII – Accredited laboratory NE analysis for disconnection time for undervoltage. Values are in ms.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
100%	143.6	147.6	147.2	144.1	145.6	145.6	1.8	2.1	----

Source: Author

Table 5-XXIV - TyTest with real equipment NE analysis for disconnection time for undervoltage. Values are in ms.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
100%	148.6	144.6	146.0	143.2	145.9	145.7	2.0	2.3	0.016

Source: Author

Table 5-XXV - TyTest with CHIL NE analysis for disconnection time for undervoltage. Values are in ms.

Power Level	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
100%	143.2	146.8	142.7	146.4	145.5	144.9	1.9	2.2	0.228

Source: Author

5.2.8 Rate of change of frequency supportability

This test cannot be entirely performed in this inverter. As mentioned in the last section, the equipment is not configured with the new Inmetro ordinance and so, at 57.5 Hz it disconnects from the grid. However, before the 57.5 Hz its behavior is compliant in both platform modes and the accredited laboratory, as shown in Tables 5-XXVI to 5-XXVIII. It only disconnects from the grid because during the first part of the test the grid frequency is reduced below 57.5 Hz, which trigger the low frequency protection and not a RoCoF protection.

Even knowing that the inverter would not pass this test, it is important to show the results, as the platform must also be compliant with the tests that inverters will fail.

Table 5-XXVI - Accredited laboratory (reference) NE analysis for RoCoF. Values are in W.

Time (s)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
0	1501	1502	1504	1505	1504	1502.7	1.6	6.3	----
0.1	1502	1503	1502	1500	1501	1501.3	1.1	6.1	----
0.2	1501	1499	1500	1502	1500	1500.4	1.1	6.1	----
0.3	1502	1500	1501	1499	1499	1500.5	1.3	6.2	----
0.4	1502	1500	1499	1501	1500	1500.0	1.1	6.1	----
0.5	1502	1500	1502	1500	1501	1500.6	1.0	6.1	----
0.6	1503	1505	1503	1504	1506	1504.0	1.3	6.2	----
0.7	1499	1501	1502	1502	1501	1501.5	1.2	6.2	----

0.8	1502	1504	1505	1503	1503	1503.8	1.1	6.1	----
0.9	1502	1500	1500	1499	1497	1499.5	1.8	6.4	----
1	1501	1499	1501	1501	1500	1500.5	0.9	6.1	----
1.1	1502	1501	1501	1501	1501	1501.0	0.4	6.0	----
1.2	1503	1502	1502	1501	1500	1501.3	1.1	6.1	----
1.3	1501	1501	1503	1504	1504	1502.4	1.5	6.3	----
1.4	1501	1499	1500	1500	1498	1499.6	1.1	6.1	----
1.5	1502	1503	1502	1500	1501	1501.6	1.1	6.1	----
1.6	1501	1501	1499	1501	1503	1500.6	1.4	6.2	----
1.7	1501	1501	1500	1500	1498	1500.2	1.2	6.2	----
1.8	1501	1499	1497	1498	1499	1498.8	1.5	6.2	----
1.9	1502	1502	1502	1504	1504	1502.5	1.1	6.1	----
2	1501	1501	1502	1502	1500	1501.1	0.8	6.1	----
2.1	1500	1500	1500	1498	1496	1498.5	1.8	6.3	----
2.2	1502	1501	1500	1498	1496	1499.1	2.4	6.6	----
2.3	1497	1495	1497	1495	1493	1495.7	1.7	6.3	----
2.4	0	0	0	0	0	0	0.0	6.0	----

Source: Author

Table 5-XXVII – TyTest with real equipment NE analysis for RoCoF. Values are in W.

Time (s)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
0	1501	1502	1502	1500	1502	1500.9	0.9	6.1	0.206
0.1	1502	1504	1504	1504	1503	1503.1	0.9	6.1	0.208
0.2	1502	1503	1505	1503	1505	1503.6	1.3	6.2	0.367
0.3	1504	1504	1504	1503	1501	1503.5	1.3	6.2	0.343
0.4	1502	1503	1501	1501	1500	1501.0	1.1	6.1	0.115
0.5	1500	1499	1499	1500	1500	1499.2	0.5	6.0	0.163
0.6	1504	1505	1505	1503	1501	1503.4	1.7	6.3	0.068
0.7	1500	1498	1500	1502	1504	1501.3	2.3	6.6	0.022
0.8	1504	1502	1501	1502	1502	1502.6	1.1	6.1	0.138
0.9	1501	1503	1505	1503	1501	1502.5	1.7	6.3	0.335
1	1502	1503	1504	1502	1504	1503.1	1.0	6.1	0.301
1.1	1504	1503	1504	1504	1506	1504.0	1.1	6.1	0.349
1.2	1504	1506	1506	1506	1508	1505.7	1.4	6.2	0.503
1.3	1499	1501	1500	1498	1497	1498.8	1.6	6.3	0.407
1.4	1501	1501	1502	1501	1502	1501.4	0.5	6.0	0.209
1.5	1503	1501	1501	1499	1499	1500.6	1.7	6.3	0.114
1.6	1501	1501	1500	1498	1497	1499.0	1.8	6.4	0.180
1.7	1501	1499	1499	1499	1497	1499.2	1.4	6.2	0.114
1.8	1499	1499	1497	1498	1500	1498.6	1.1	6.1	0.023
1.9	1504	1502	1500	1502	1502	1501.7	1.4	6.2	0.092
2	1500	1500	1499	1499	1497	1498.9	1.2	6.2	0.254

2.1	1502	1501	1501	1501	1501	1500.9	0.4	6.0	0.274
2.2	1503	1503	1505	1503	1502	1502.9	1.1	6.1	0.421
2.3	1498	1498	1499	1499	1501	1499.3	1.2	6.2	0.408
2.4	1501	1502	1502	1500	1502	1500.9	0.9	6.1	0.206

Source: Author

Table 5-XXVIII – TyTest with CHIL NE analysis for RoCoF. Values are in W.

Time (s)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
0	1498	1500	1499	1499	1501	1499.8	1.1	6.1	0.334
0.1	1498	1500	1502	1500	1499	1500.2	1.5	6.2	0.133
0.2	1498	1500	1498	1496	1497	1497.3	1.5	6.2	0.347
0.3	1498	1496	1498	1499	1499	1497.5	1.2	6.2	0.341
0.4	1498	1497	1495	1495	1495	1495.5	1.4	6.2	0.511
0.5	1497	1498	1498	1497	1495	1496.9	1.2	6.2	0.422
0.6	1497	1495	1498	1500	1501	1498.1	2.4	6.6	0.656
0.7	1498	1499	1501	1499	1497	1498.8	1.5	6.2	0.307
0.8	1498	1497	1499	1498	1498	1498.0	0.7	6.1	0.672
0.9	1499	1501	1502	1504	1506	1502.5	2.7	6.8	0.329
1	1499	1498	1496	1498	1500	1498.3	1.5	6.2	0.245
1.1	1498	1500	1498	1497	1497	1497.7	1.2	6.2	0.387
1.2	1498	1500	1501	1503	1501	1500.3	1.8	6.4	0.113
1.3	1497	1498	1496	1496	1496	1496.2	0.9	6.1	0.712
1.4	1497	1495	1497	1498	1500	1497.0	1.8	6.4	0.297
1.5	1498	1496	1494	1494	1495	1495.3	1.7	6.3	0.724
1.6	1498	1497	1498	1500	1502	1498.9	2.0	6.4	0.194
1.7	1497	1496	1496	1496	1495	1496.1	0.7	6.1	0.471
1.8	1497	1498	1498	1498	1499	1498.1	0.7	6.1	0.078
1.9	1500	1500	1500	1499	1501	1499.9	0.7	6.1	0.302
2	1500	1501	1499	1498	1497	1498.9	1.6	6.3	0.259
2.1	1498	1497	1499	1497	1495	1497.0	1.5	6.2	0.174
2.2	1498	1497	1499	1498	1499	1498.0	0.8	6.1	0.122
2.3	1497	1496	1498	1500	1499	1498.4	1.6	6.3	0.305
2.4	1498	1500	1499	1499	1501	1499.8	1.1	6.1	0.334

Source: Author

5.2.9 Active power control in overfrequency

Considering the Inmetro ordinance n°140/2022 and the new frequency limits, this inverter also cannot fully complete the test. When the grid frequency reach 62 Hz the inverter disconnects from the grid. However, from 60 Hz to 62 Hz its behavior is compliant, as this test already exists in the older Inmetro ordinance n°004/2011, where the equipment is approved.

During the test, the PHIL is compliant with accredited laboratory, the EUT reduces its power according to the frequency level in the same way in both tests. However, for the CHIL testing, the equipment stabilizes at lower power levels than it achieved in the accredited laboratory for the same frequency level, a difference of about 30 W or 2% of the EUT nominal power. This difference is enough to make the results between CHIL and the accredited laboratory not compliant.

Further investigating this difference, it was discovered that a series of factors were causing it. First, the ordinance configured in the equipment demands it to reduce the output power at a rate of 40%/Hz, so a 2% difference is equivalent to 0.05 Hz difference between the CHIL and the laboratory. Second, the laboratory grid simulator has a configuration where it only applies a voltage or frequency step at the beginning of the waveform cycle, while the CHIL simulation does not have this limitation, it applies the frequency step at any moment. Third, this small difference, applying the step at the beginning or at the middle of a cycle, makes the EUT frequency algorithm to have a small spike in its measurement. And as the ordinance also demands the EUT to keep the lowest power level reached for at least 5 minutes, it kept its reduced power level during the entire test.

Table 5-XXIX – Accredited laboratory (reference) NE analysis for active power control in overfrequency. Values are in W.

Grid Freq. (Hz)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
60	1500	1499	1501	1498	1503	1500.2	1.9	6.4	----
60.2	1501	1498	1497	1501	1502	1499.8	2.2	6.5	----
60.5	1500	1497	1502	1497	1503	1499.8	2.8	6.8	----
61	1219	1222	1218	1221	1218	1219.6	1.8	6.4	----
61.5	920	919	918	922	922	920.2	1.8	6.3	----
62	0	0	0	0	0	0.0	0.0	6.0	----
62.5	0	0	0	0	0	0.0	0.0	6.0	----
62	0	0	0	0	0	0.0	0.0	6.0	----
61.5	0	0	0	0	0	0.0	0.0	6.0	----

61	0	0	0	0	0	0.0	0.0	6.0	----
60.5	0	0	0	0	0	0.0	0.0	6.0	----
60.2	0	0	0	0	0	0.0	0.0	6.0	----
60.0	0	0	0	0	0	0.0	0.0	6.0	----

Source: Author

Table 5-XXX – TyTest with real equipment NE analysis for active power control in overfrequency. Values are in W.

Grid Freq. (Hz)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
60	1502	1500	1501	1502	1498	1500.6	1.7	6.3	0.045
60.2	1502	1498	1498	1500	1502	1500.0	2.0	6.4	0.022
60.5	1499	1499	1500	1497	1501	1499.2	1.5	6.2	0.065
61	1220	1219	1218	1221	1222	1220.0	1.6	6.3	0.045
61.5	920	921	918	919	918	919.2	1.3	6.2	0.113
62	0	0	0	0	0	0.0	0.0	6.0	0.000
62.5	0	0	0	0	0	0.0	0.0	6.0	0.000
62	0	0	0	0	0	0.0	0.0	6.0	0.000
61.5	0	0	0	0	0	0.0	0.0	6.0	0.000
61	0	0	0	0	0	0.0	0.0	6.0	0.000
60.5	0	0	0	0	0	0.0	0.0	6.0	0.000
60.2	0	0	0	0	0	0.0	0.0	6.0	0.000
60.0	0	0	0	0	0	0.0	0.0	6.0	0.000

Source: Author

Table 5-XXXI – TyTest with CHIL NE analysis for active power control in overfrequency. Values are in W.

Grid Freq. (Hz)	1	2	3	4	5	Mean	Std. Dev.	Unc.	N.E.
60	1501	1501	1503	1498	1501	1500.8	1.8	6.3	0.067
60.2	1500	1502	1501	1502	1498	1500.6	1.7	6.3	0.088
60.5	1500	1497	1502	1497	1498	1498.8	2.2	6.5	0.106
61	1192	1192	1192	1194	1192	1192.4	0.9	6.1	3.090
61.5	889	891	891	891	890	890.4	0.9	6.1	3.388
62	0	0	0	0	0	0.0	0.0	6.0	0.000
62.5	0	0	0	0	0	0.0	0.0	6.0	0.000
62	0	0	0	0	0	0.0	0.0	6.0	0.000
61.5	0	0	0	0	0	0.0	0.0	6.0	0.000
61	0	0	0	0	0	0.0	0.0	6.0	0.000
60.5	0	0	0	0	0	0.0	0.0	6.0	0.000
60.2	0	0	0	0	0	0.0	0.0	6.0	0.000
60.0	0	0	0	0	0	0.0	0.0	6.0	0.000

Source: Author

6 CONCLUSION

As for the conclusion of this work, some points must be highlighted. Considering the proposed test classification, it is a good way to determine the extension and reliability of the tests performed in each equipment, but it can still be improved. Specially the "external environment" should have criteria, in each country or region, to determine what is a representative model of the grid to be used in EHIL Level 2 where complex models are employed. The MHIL can also benefit from pre-defined models of communication and a definition of common commands or communication protocols to be tested and how those commands will be performed as well as the performance criteria for the inverter response. The Brazilian Inmetro ordinances, both n°004 and n°140, already define a series of standardized commands and the performance criteria, but do not define a standard protocol or how the inverter will receive such commands. This way, they are not very useful for the system, as each inverter can have its own protocol. Also, the Inmetro ordinances only says that the inverter must have "external control" and do not define it, allowing a simple wireless switch to be considered an external control. Those things should be standardized and the classification of the inverters according to the proposed classification, especially about the management system, could help the electrical system operators to know the capabilities of the inverters prior to installing them into the grid.

The implemented IBR testbench fulfilled its objectives and now can be further utilized to test inverters in different conditions, including precertification and maybe even full certifications in the future. The measurement algorithms were tested and compared to the measurements of a commercial, high precision, power analyzer (LMG670 from Zimmer) and are considered compliant. It is an improvement compared to the traditional measurement algorithms used by the HIL604. Even being offline algorithms, they allow for a better measurement of the model variables and allow the precertification and certification tests to be performed in any level of the development, even a fully simulated stage (CHIL 0 and PHIL 0).

The algorithms implemented to reproduce the certification process of an accredited laboratory inside HIL environment were tested and are considered compliant with the conventional laboratory in terms of procedure and how variables are measured, with standardized measurement algorithms, test protocols and uncertainty analysis, allowing for all levels of the THIL environment testing.

There is still room to improve the THIL category as the uncertainty analysis of the HIL environment is still a challenge and there is nothing in literature about this theme, being an area of further development. The implementation of such routines to allow a fully standardized testing environment, equivalent to an accredited laboratory, can also be a challenge and needs a convergence from all HIL simulator manufacturers to implement such algorithms in their systems. Considering the PHIL application, it can be even more difficult as in addition to all matters pointed for a conventional HIL simulation, the compatibility of the simulator with the power supply can be a factor that demands attention and can impact in test results. As seen in the active power control in overfrequency test results, even a small feature from any of the power supplies employed in the simulation, the moment at which the frequency degree is applied in this case, can alter the test results and be the difference between a pass or fail result.

The comparison between an accredited laboratory results, used as reference, and the results of the same tests, performed in CHIL and PHIL environment, shows that the HIL simulation can be a powerful tool to simplify and reduce the costs of a HIL certification. In most of the tests, through a statistical analysis of the normalized error between the measurements, they are considered compliant and equivalent. This way, the HIL process can be used in substitution to the conventional certification process for many tests, especially for high cost and/or high-power equipment, which tests would be expensive and difficult to find laboratories with infrastructure to perform them.

Yet, the HIL simulation cannot be considered a magical solution or something that will immediately change how certification process are conducted around the world. As showed in some tests, especially for power quality purposes, the model of the simulated equipment has a big impact on the results and even small alterations between the simulated and the real equipment can cause significative differences in the results. There is still the problem of validating the HIL model, as it is necessary to assure that the model being tested is representative enough of the product that will be commercialized.

However, even with the issues pointed out and the challenges that still need to be overcome, HIL can be really useful not just for precertification or development purposes, but also for certification of equipment, maybe not alone but as a complementary tool, allowing tests that a conventional testing laboratory cannot perform without risks of due to time or cost limitation but it will certainly be the future of product certification.

6.1 FUTURE WORK

Product certification utilizing hardware-in-the-loop is still a novel research trend, this work contributes to the area and to answers some of the questions, but also arise new ones. Some of the open topics that should be further investigated are:

- **HIL Model validation:** This is one of the most important topics that need to be investigated and regulated. To create mechanisms to allow companies to model their inverters and perform certification tests on such models at the same time it is assured that the models used to certify the product are representative of the commercialized inverters.
- **Inverter modeling techniques and "fidelity factor" definition:** Models can be more or less representative of the real system depending on the desired purpose. The definition of a "fidelity factor" that a model must fulfill to be used in a certification process and how this factor is calculated is also in important matter to HIL certification process.
- **Improvement on the external environment:** As mentioned in the classification proposal, the MHIL Level 2 utilizes complex models to represent the grid. Such models also need to be defined, ideally for each country, but it is necessary to evaluate the impacts of such models on inverter testing and how to define them.
- **Further studies on what can be tested and new tests:** As HIL testing opens a lot of possibilities related to what can be tested and at what level, including things that conventional laboratories cannot test due to security or economic concerns. It is important to define new tests and evaluate the relevance of them.

6.2 PUBLICATIONS

During the doctoral period, a series of papers were published, as shown in Table 6-I. In addition to the ones in the table, a new paper will be submitted with the final results and analysis.

Table 6-I - List of papers during the doctoral period

Title	**Situation**	**Magazine/Conference**	**Qualis**	**Reference**
Management of operation and maintenance practices in photovoltaic plants: Key performance indicators	Published	International Journal of Energy Research	A1	(REDISKE et al., 2022)
Strategies to deal with ground faults in grid-connected transformerless photovoltaic converters with battery energy storage system	Published	Brazilian Journal of Power Electronics	A4	(VIZZOTTO BELLINASO et al., 2019)
Improved Methodology for Testing the Compliance of Residual Current Detection of Non-Isolated Grid-Connected Photovoltaic Inverters	Recommended for publication	Brazilian Journal of Power Electronics	A4	----

Hardware-in-the-Loop Low Voltage Fault Ride Through Tests of Commercial Photovoltaic Inverters	Published	2021 Brazilian POWER Electronics Conference (COBEP)	----	(MENEGAZZO et al., 2021)
Standards for Interconnecting Distributed Energy Resources with Electric Power System: Current scenario and challenges	Published	12_{th} Seminar on Power Electronics and Control (SEPOC)	----	(MOCCELLIN et al., 2019)
Automação do circuito de carga CA para teste de anti-ilhamento em power-hardware-in-the-loop	Published	7° Congresso Brasileiro de Geração Distribuída	----	(PITON et al., 2022)
Plataforma de desenvolvimento e testes automatizados para inversores baseado em hardware-in-the-loop	Published	7° Congresso Brasileiro de Geração Distribuída	----	(MARQUIORO DE FREITAS et al., 2022)
Pré-certificação do firmware de inversores fotovoltaicos de acordo com a norma brasileira NBR16150 através de hardware-in-the-loop	Published	VIII Congresso Brasileiro de Energia Solar	----	(FERNANDO RISSOTTO MENEGAZZO et al., 2020)

Source: Author

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APPENDIX

The uncertainty calculation used in the accredited laboratory is based on 4 parameters, as shown in Figure 0-1, the definition of each uncertainty source is as follows.

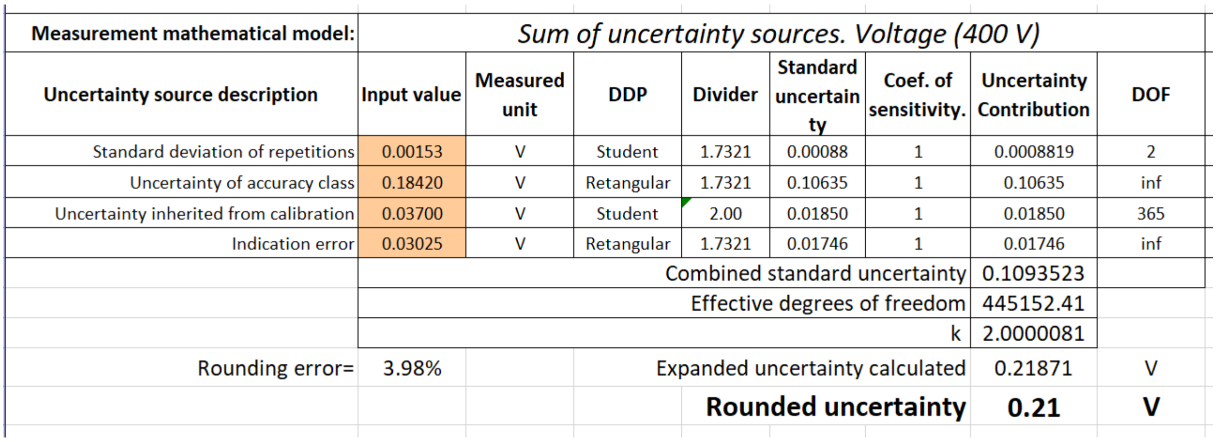
Standard deviation of repetitions: Is the uncertainty associated with the standard deviation from a series of repeated measurements on the same point.

Uncertainty of accuracy class: Is the uncertainty associated with the measurement equipment itself, declared by the manufacturer in the equipment manual/datasheet.

Uncertainty inherited from calibration: Is the uncertainty associated with the calibration procedure utilized by the calibration laboratory.

Indication error: Is the error detected in the calibration certificate. This value can be ignored if the equipment is adjusted during the calibration procedure or if this value is manually adjusted in the measurement registers.

Figure 0-1 – Example of uncertainty calculation for voltage measurements in the range of 400 Vrms



Measurement mathematical model:	*Sum of uncertainty sources. Voltage (400 V)*							
Uncertainty source description	**Input value**	**Measured unit**	**DDP**	**Divider**	**Standard uncertainty**	**Coef. of sensitivity.**	**Uncertainty Contribution**	**DOF**
Standard deviation of repetitions	0.00153	V	Student	1.7321	0.00088	1	0.0008819	2
Uncertainty of accuracy class	0.18420	V	Retangular	1.7321	0.10635	1	0.10635	inf
Uncertainty inherited from calibration	0.03700	V	Student	2.00	0.01850	1	0.01850	365
Indication error	0.03025	V	Retangular	1.7321	0.01746	1	0.01746	inf
	Combined standard uncertainty						0.1093523	
	Effective degrees of freedom						445152.41	
	k						2.0000081	
Rounding error=	3.98%		Expanded uncertainty calculated				0.21871	V
				Rounded uncertainty			**0.21**	**V**

Source: Author