HIL-based certification for converter controllers: Advantages, challenges and outlooks

(Invited Paper)

Henrique Magnago, Henrique Figueira, Ognjen Gagrica, Dusan Majstorovic
Typhoon Hil, Inc.
Novi Sad, Serbia
(henrique.magnago, henrique.figueira, ognjen.gagrica, dusan)@typhoon-hil.com

***Abstract*—Hardware in the Loop (HIL) testing is widely used in automotive, aerospace, and robotics. However, the use of HIL in power electronics is still in its early stages of expansion due to the growing need for advanced grid support functions of distributed energy resources (DER) and microgrids. This paper presents the advantages, challenges, and outlooks of HIL-based certification for converter controllers. It will cover the types of existing HIL tests, the HIL base certification of controllers, and finally, some examples of industry use cases that successfully employ HIL from product development to pre-certification and certification.**

***Index Terms*—Distributed energy resources, Hardware-in-the-loop, power electronics, product development, certification**

I. INTRODUCTION

Hardware in the loop (HIL) test methodology is widely applied in automotive [1], [2], aerospace [3], [4] and robotics [5], [6]. In the last decade we observed accelerated HIL adoption for power electronics and microgrid applications; mainly driven by significant deployment of inverter-based distributed energy resources (DERs). DER proliferation brought the idea that they should take an active role to perform ancillary functionalities such as supporting grid stability, power quality, and reliability despite simply feeding power into the electric grid, [7]. Those functionalities are usually referred to as advanced grid support (AGS). To achieve this goal in a coordinated way, some revisions of standards and grid codes included requirements for DER to deliver extra grid supporting functions [8], [9], [10], [11], [12]. Also, the grid support capability does not apply for DER alone but also for microgrids that could contain different power sources, storage systems, and high priority loads, for instance. In this case, there is an extra effort to achieve this goal due to costs to design, deploy and test a microgrid.

Furthermore, DER can autonomously respond to grid demands of providing reactive/active power support, withstand under/over voltage ride through, etc. In this scenario, the complexity of requirements the manufacturers have to comply with will increase depending on how many markets they will be selling a specific product, [13]. Each market has regional requirements that usually demand product configuration case-by-case and a final test from an accredited laboratory. However, it is recurrent the interactions between the product manufacturer and the testing laboratory until the converter controller complies with the requirement of each standard. Regarding the microgrid's higher complexity, there is a risk in the final commissioning stage when deploying in the field. Integration of different sources requires careful configuration and intense testing to avoid unwanted interactions among the devices under all operating scenarios, [14].

Moreover, advancements in FPGA and CPU technologies paved the way towards real-time simulators for fast dynamic systems such as power electronics, where it is necessary to have real-time simulation time steps in the sub-microsecond range. Fig. 1 contains the different testbed platforms available and the trade-off between test fidelity and test coverage. The test fidelity represents how accurate the testbed reflects the behavior of the deployed system and the test coverage represents the range of test conditions that can be safely executed. The traditional development procedure consists of employing a simulation tool, building the prototype, and performing limited and full power laboratory tests. The simulation tool has good test coverage flexibility but provides limited test fidelity, [15]. HIL testing can be deployed to increase test fidelity while maintaining high test coverage. In the power electronics field, for example, the power stage could be simulated in real-time, while the controller remains the same as it will be if embedded in the real system. This type of HIL methodology is called controller hardware-in-the-loop (C-HIL). If the equipment under test (EUT) is a full-size, full-power converter, it has to be interfaced with the real-time simulation through high power amplifiers. This system is called power hardware-in-the-

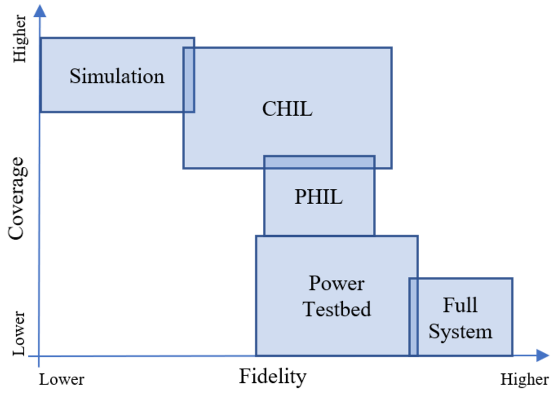

Fig. 1. Comparison between testbed types, adapted from [15].

978-1-6654-0187-6/21/$31.00

loop (PHIL). PHIL is used where a full-power component of a system has to be tested within the larger system, for example. The next possible testbed would be the power testbed. This testing type has a higher test fidelity but also has the drawback of reduced test coverage, once the test is limited to the test bench equipment and laboratory operators' knowledge. Finally, the full system test has the highest test fidelity and the lowest test coverage. This type of test represents the real system test in the final installation point, a wind turbine in its final power plant, for example. Recently, some studies were conducted to review the traditional certification process to include HIL-based tests as part of the certification testing, [16]. Also, the power electronics industry increasingly applies HIL in the product development cycle, starting from early research to pre-certification testing.

In this scenario, to reduce the time and cost to deploy a DER or a microgrid, C-HIL testing can be applied to test controllers, protections, and AGS. The C-HIL scheme can provide a broad test coverage, similar to a computational simulation, and test fidelity, close to PHIL or a power testbed, if the models are well validated. This paper will present some use cases that apply C-HIL-base certification for converters controllers from laboratories and industry. It will further address some highlights of the HIL-based certification advantages, challenges, and future outlook, and finally, a conclusion.

II. USE CASES

This section presents some use cases that apply HIL-based testing capable of certifying converter controllers.

A. *Austrian Institute of Technology and Sandia National Laboratories*

The first use case [7] is a partnership between the Austrian Institute of Technology (AIT) and the Sandia National Laboratories (Sandia). They developed C-HIL testing for rapid and concurrent development of converter controls for interconnection standards, Fig. 2. This C-HIL testbed platform applies the Typhoon HIL602 (already updated by Typhoon HIL604) integrated with the SunSpec System Validation Platform (SVP) and the Equipment Under Test (EUT) for testing UL 1741 SA requirements [8].

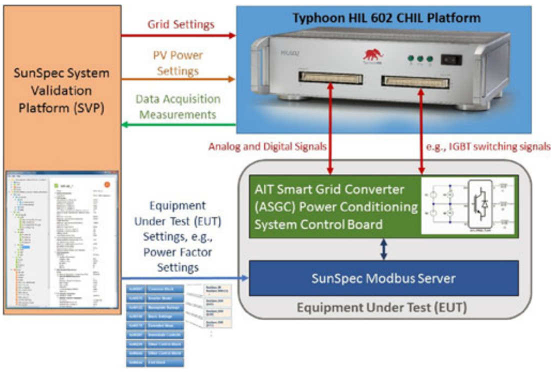

Fig. 2. AIT and Sandia C-HIL testing, [7].

In this application, the EUT represents a two-quadrant 34.5-kW grid-tie PV inverter that can provide a broad range of AGS. The EUT operating modes and settings are controlled by the smart grid controller via SunSpec Modbus Server. The SVP was designed as UL 1741 SA [8] control center. Thus the SVP enables portability of the test sequences, capability of autonomous testing, and reduction of configuration time.

Fig. 3 shows the power factor (PF) test results. This function requires a change in the power factor value settings in three different power levels, and each of these power factor values is measured three times. The black dashed lines in the active–reactive power (P–Q) plane indicate the target power factors, the red dashed lines indicate boundary levels, and the four colored markers represent the EUT output for each of the PF levels. The EUT accurately reached the PF target within the passing bounds in all but three tests at PF=-0.20, [7].

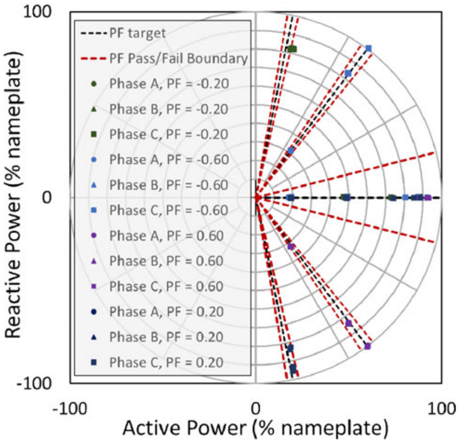

Fig. 3. PF test results on a P-Q plane, [7].

Fig. 4 shows the frequency-watt (FW) test. This function is designed to support bulk system operation in the case of high generation or load tripping. The function is typically programmed to only reduce power in over-frequency scenarios for PV systems in order to prevent system instability. The black dashed lines indicate the target output power, the red dashed lines indicate boundary levels, and the three colored markers represent the EUT output, [7]. Again the results from C-HIL testing are inside the expected boundaries.

B. *Austrian Institute of Technology*

The second use case is from AIT. They developed a C-HIL testing for pre-certification of grid code compliance for solar inverters, [17]. The platform consists of software automating the test procedures (called Pre-Cert Toolbox) running in the Typhoon HIL602 (already updated by Typhoon HIL604), an EUT in form of the converter controller board connected to a digital real-time simulation system and a simulation model of the power stage, grid and DC sources, Fig. 5.

The fidelity of the simulation is mainly determined by the time resolution of the model and the accurate representation of electrical components (IGBT switches, magnetic, loads, etc). Each of these aspects needs to be considered to ensure realistic

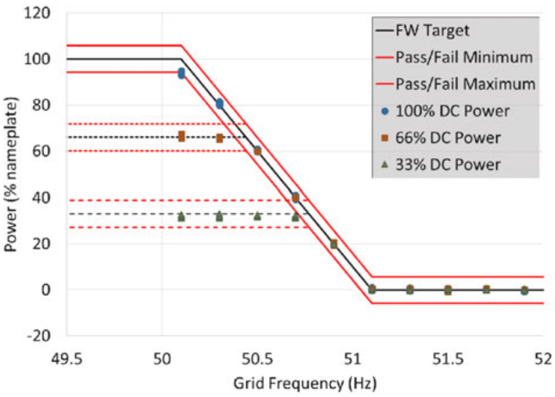

Fig. 4. EUT Frequency-Watt response, [7].

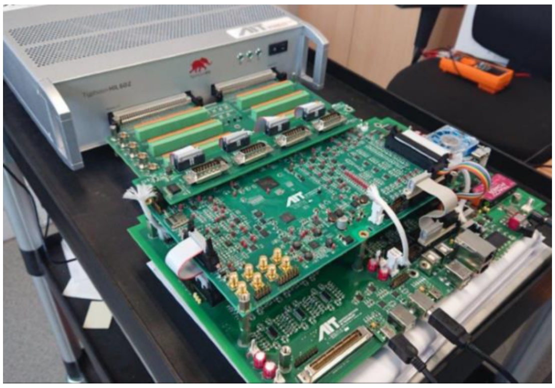

Fig. 5. View of the converter controller board connected to Typhoon HIL via an interface board, [17].

behavior and accurate results from the C-HIL testbed. The C-HIL testbed implements the full set of test items defined in widely used test specifications in Europe as VDE 0124-100 [11] and FGW TR3 [12].

The C-HIL results were compared with the traditional power testbed. In the traditional test, the converter controller board is connected to the DC-AC 34.5 kVA, 3-phase 4 wire, neutral-point-clamped inverter with IGBT switches, Fig. 6.

Fig. 7 shows the comparison of the measured response from C-HIL and real laboratory testing for the frequency-watt (FW) test. The complete sequence is repeated for two active power levels, 100% and 50% of the rated power (Pn). Fig. 8 shows the comparison of the measured response from C-HIL and real laboratory testing for the Under-Voltage Ride Through Test (UVRT). Both tests were performed using a procedure defined in FGW TR3, [12], where the converter controller was programmed to provide the required reactive current Ib according to the grid voltage drop as defined in [18].

In both cases, Fig. 7 and 8, it is possible to verify the correlation of the results, both in steady-state and transient behavior. This validates the model, hence results from C-HIL will very likely e reproduced in the power laboratory.

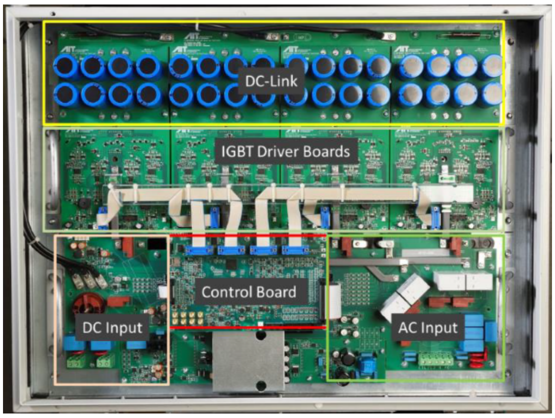

Fig. 6. View of the full-scale inverter (34.5 kVA DC-AC) showing DC link (yellow), IGBT power boards (light green), control board (red), DC input (white) and AC input boards (green), [17].

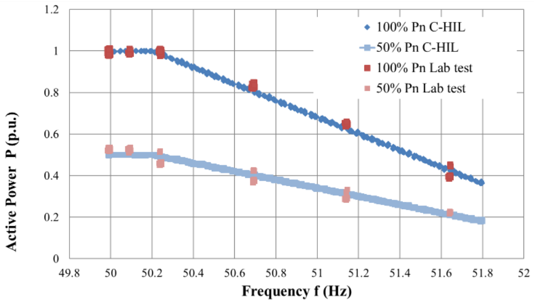

Fig. 7. Comparison of the results from C-HIL and power testbed for Frequency-Watt, [17].

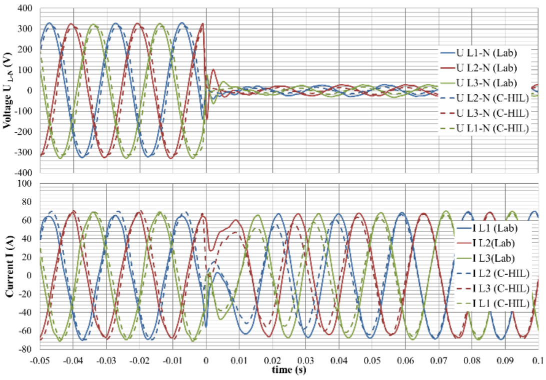

Fig. 8. Comparison of the results from C-HIL vs power testbed for a transient UVRT, [17].

C. Hitachi ABB Power Grids

The third use case is the microgrid and controller test by Hitachi ABB e-mesh solution. The e-mesh solution is a digital concept that allows the management of distributed energy resources from the converter level through the microgrid system [19]. The battery storage system for this application could be up to 1 MW, [20] and by applying Typhoon HIL604 C-HIL testbed in the e-mesh environment it is possible to better design the microgrid and converter controller to cover the desired needs in the early stage of the development of the project. Before the C-HIL methodology, it was usual to do on-site testing. However, that implies a limited time frame to run the tests and a limited number of test cases that can be executed. In the C-HIL testing, it is possible to simulate some specific conditions, such as a grid disconnection event, and pre-certificate the controllers, [21]. In this way, it is possible to verify the response of converters controllers and monitor the response of the battery energy storage system to keep the grid alive with limited disturbances, Fig. 9.

Another great benefit of using C-HIL is to automate all the necessary tests. By doing so, it becomes easy and inexpensive to run all the required tests and receive a full report before sending the converter to the certification laboratory. It allows the company to run pre-certification tests, fix any issues in the converter firmware, and run all the tests again to guarantee that the new firmware version did not cause unexpected errors in other operating conditions.

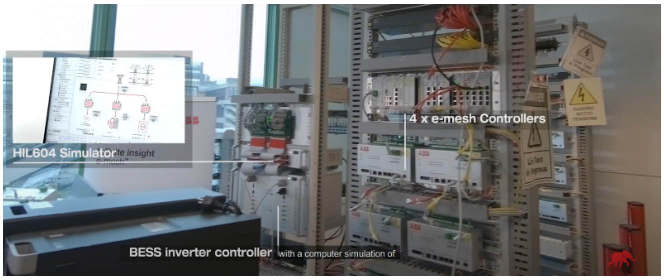

Fig. 9. E-mesh C-HIL testing, [21].

D. EPC Power

The fourth use case is the converter controller test by EPC Power. The EPC Power laboratory infrastructure allows the development and testing of power electronics converters on the megawatts scale. However, the power testbed operation time is expensive, time-consuming, hazardous for humans and adjacent equipment. To overcome these issues it was developed a C-HIL testbed with the Typhoon HIL602 (already updated by Typhoon HIL604), the interface board, and the converter controller board running the same inverter software like the one in the final product, Fig. 10, [22]. Additionally, the C-HIL testbed allowed control engineers to develop the firmware in parallel to the hardware team, reducing the development time by at least 6 weeks. After the hardware was done, it was possible to test the converter with full power within a couple of days.

An exciting development case was troubleshooting a resonance issue with the output filter of the inverter against a specific grid impedance. The resonance did not occur in the pure simulation software, but only in the full system commissioning. When the parameters were loaded and tested using the C-HIL testbed the same resonance appeared allowing its mitigation, [22].

Regarding the certification tests, the C-HIL testing allows the pre-certification of the converter controller before going to the traditional laboratory power testbed. For instance, the anti-islanding tests that consume a third of the total traditional test time can be performed in a couple of minutes when using the C-HIL testbed. The UL 1741 SA certification of the 375 kW and 500 kW inverter was initially performed on the C-HIL testbed. After the satisfactory performance of the controller, full power tests were performed, following the standard procedure, where no changes to the firmware were necessary, [22].

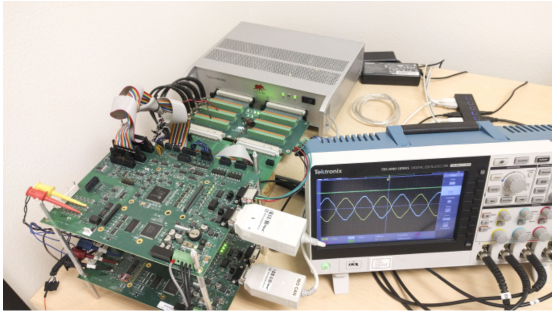

Fig. 10. EPC Power C-HIL testing, [22].

E. Schneider Electric

The fifth use case is the converter controller testing by Schneider Electric. The Schneider laboratory infrastructure allows the development and testing of power electronics hybrid inverters for residential storage. Like the previous use case, Schneider Electric also experienced the setback when developing a converter controller for different standards and markets. The certification process was time-consuming, expensive, thus, a C-HIL testbed was built. The testbed comprised Typhoon HIL602+, the interface board, and the converter controller boards. This platform can perform pre-certification tests and speed up development. Fig. 11 shows the example of an anti-islanding C-HIL schematic diagram for controller pre-certification. They also created an automated test execution environment so every time the firmware is updated, a full regression test is performed on C-HIL testbed. Finally, the C-HIL application was expanded to test different microgrid configurations often encountered in the field [23].

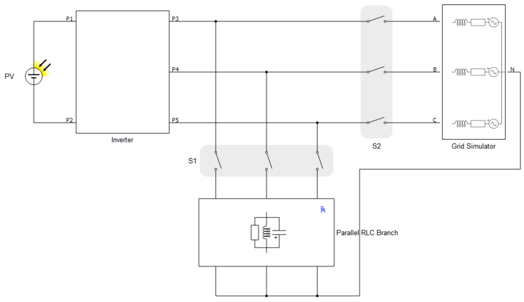

Fig. 11. Example of C-HIL testing for anti-islanding.

III. ADVANTAGES, CHALLENGES AND OUTLOOK

This section address the advantages, challenges, and outlooks from the point of view of testing laboratory and industry.

A. Advantages

The advantages of the HIL-based approach over traditional power testbeds are remarkable, not only for testing laboratories but also for the industry. The common advantages between both would be: It is possible to reduce the infrastructure needs for testing, reduce the time needed for testing, there is no risk of damaging any equipment, it is possible to achieve test conditions that are not feasible in the field or the laboratory, and updating the firmware is inexpensive if needed. It also will allow the flexibility to operate a range of systems (single-phase, three-phase, etc), different rated power, and advanced grid support functions. The testing laboratory will have a well-defined, repeatable, standardized test procedure with minimal chances for human error. It also will be able to expand the test coverage they can offer for other standards, grid codes, and application-specific requirements. The industry will be able to evaluate control logic and interoperability interfaces prior to integration with hardware, perform a quick check of project changes, and speed up the development of products even with different standards and grid codes.

B. Challenges

Regarding the general challenges, it is possible to highlight that this is a new tool for most laboratories and industries. Thus it will require an initial investment in equipment and training. However, the main challenge would be to change the culture of testing or developing products. Also, the controller-simulator interface would need to be validated and perhaps even certified due to the profound impact on test results it might have.The testing laboratory will have to develop a way to validate the C-HIL model to ensure that the obtained results are trustworthy. It could be performed with a benchmark between the real vs C-HIL test in a well-defined set of key operation points, for instance. In the same way, the industry will have to develop a methodology to create the converter/microgrid model to be validated and tested in the C-HIL testbed.

C. Outlook

The outlook for this technology in the field of power electronics, microgrids, and power systems is to become widely adopted by testing laboratories and the industry. Several studies from testing laboratories and experiences from the industry already validated numerous benefits of applying HIL-based pre-certification for converter controllers in several applications, from converter-level to the microgrid-level. However, even without the C-HIL based certification being included in the traditional certification process, the industry use cases have demonstrated how helpful it is in shortening and streamlining the certification process by providing means of running accredited laboratory-grade tests in-house. Once the C-HIL test technology becoming well-adapted, the standard bodies could provide traditional standard documents together with the required testing code. It would simplify the process of grid code compliance testing, nudging the academia to develop new control strategies able to bring additional grid support capabilities.

IV. CONCLUSION

The HIL testing methodology is widely used in many areas such as robotics, automotive, and aerospace. Recent advancements in FPGA technology allowed the creation of real-time simulators for fast dynamic systems necessary for power electronics. Additionally, the increasing presence of DER connected to the electric grid and their capability of performing AGS lead to standards and grid codes revisions to include extra grid support functions. In this scenario, the complexity of requirements manufacturers have to comply with increases depending on which markets they are selling a product. Therefore, HIL-based testing provides a highly effective solution for converter control verification against an ever-increasing number of grid code requirements. It also allows seamless, risk-free test automation, ensuring repeatability of the test procedure and regression testing.

This paper presented several examples where C-HIL pre-certification of converter controllers was implemented with success. The examples covered certification laboratories and industries. They confirmed that the HIL-based certification and pre-certification can improve the DER development process, enhancing quality, and reducing costs and time-to-market. Thus, this technology should be considered as part of the traditional certification process. Most of the use cases were listed as early generation HIL simulators that still showed a satisfactory level of fidelity. Meanwhile, the setups were updated to the latest generation devices able to provide results that are even closer to the actual field measurements.

The main advantages of HIL-based product certification are the ability to reduce the infrastructure needs for testing, the time needed for testing, the risk of damaging the equipment, and the possibility to achieve test conditions that are not feasible in a tests laboratory. Complete HIL-based product certification also requires additional steps in the industrial process, such as models and interface validation, which might be a challenge, changing the culture of testing or developing products and validating the C-HIL model, the simulation interface, for example, could be a challenge. Further, some studies from testing laboratories and experiences from the industry already validate the benefits of applying HIL-based pre-certification for converter controllers. The applications covered the converters controller, as well as microgrids with several converters. Nevertheless, the presented examples confirm that benefits significantly outweigh the added effort and we expect accelerated adoption from both, become increasingly adopted from the testing laboratories and the industry.

ACKNOWLEDGMENT

The authors would like to acknowledge Austrian Institute of Technology, Hitachi ABB Power Grids, EPC Power, and Schneider Electric Solar for the technical development cited in this paper.

REFERENCES

[1] A. Genic, C. Mayet, M. Almeida, A. Bouscayrol, and N. Stojkov, “EMR-Based Signal-HIL Testing of an Electric Vehicle Control,” in *2017 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2017, pp. 1–6.

[2] K. Algarny, A. S. Abdelrahman, and M. Youssef, “A novel platform for power train model of electric cars with experimental validation using real-time hardware in-the-loop (HIL): A case study of GM Chevrolet Volt 2nd generation,” in *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2018, pp. 3510–3516.

[3] M. Amin and G. A. Abdel Aziz, “A Hardware-in-the-Loop Realization of a Robust Discrete-Time Current Control of PMa-SynRM for Aerospace Vehicle Applications,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 2, pp. 936–945, 2019.

[4] R. Rodrigues, A. Murilo, R. V. Lopes, and L. C. G. D. Souza, “Hardware in the Loop Simulation for Model Predictive Control Applied to Satellite Attitude Control,” *IEEE Access*, vol. 7, pp. 157 401–157 416, 2019.

[5] M. De Stefano, H. Mishra, A. M. Giordano, R. Lampariello, and C. Ott, “A Relative Dynamics Formulation for Hardware- in-the-Loop Simulation of On-Orbit Robotic Missions,” *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 3569–3576, 2021.

[6] A. Peiret, F. González, J. Kövecses, M. Teichmann, and A. Enzenhoefer, “Model-Based Coupling for Co-Simulation of Robotic Contact Tasks,” *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 5756–5763, 2020.

[7] J. Johnson, R. Ablinger, R. Bruendlinger, B. Fox, and J. Flicker, “Interconnection Standard Grid-Support Function Evaluations Using an Automated Hardware-in-the-Loop Testbed,” *IEEE Journal of Photovoltaics*, vol. 8, no. 2, pp. 565–571, 2018.

[8] “UL 1741 SA - Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources,” *UL 1741 SA-2021*, 2021.

[9] “IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces,” *IEEE Std. 1547.1-2020*, pp. 1–282, 2020.

[10] “Photovoltaic (PV) systems - Characteristics of the utility interface,” *IEC Std. 62727-2004*, pp. 1–23, 2004.

[11] “DIN VDE V 0124-100 - Grid Integration of Generator Plants - Low-voltage - Test requirements for Generator Units to be Connected to and Operated in Parallel With Low-voltage Distribution Networks,” *DIN VDE V 0124-100-2020*, 2020.

[12] “FGW TG 3 – Determination of the Electrical Characteristics of Power Generating Units and systems, Storage Systems as well for their Components in medium-, high- and extra-high voltage grids,” *FGW TG 3-2018*, 2018.

[13] V. S. Zeni, L. Munaretto, H. Chaves, N. C. Dal Pont, V. F. Gruner, and G. Finamor, “Hardware-In-the-Loop Simulation of Smart Hybrid Inverter: A comparison of online simulation and practical results,” in *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, 2020, pp. 2005–2009.

[14] J. Wang, Y. Song, W. Li, J. Guo, and A. Monti, “Development of a Universal Platform for Hardware In-the-Loop Testing of Microgrids,” *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2154–2165, 2014.

[15] “IEEE Standard for the Testing of Microgrid Controllers,” *IEEE Std. 2030.8-2018*, pp. 1–42, 2018.

[16] T. Jersch, “DyNaLab Update: Meeting Industry Needs and Standardization & HIL Grid Cop: Generator and Converter Testing,” *5th Annual International Workshop on Grid Simulator Testing of Energy Systems and Wind Turbine Powertrains*, 2018.

[17] J. Bründlinger, Roland ans Stöckl, Z. Miletic, R. Ablinger, F. Leimgruber, J. Johnson, and J. Shi, “Pre-Certification of Grid Code Compliance for Solar Inverters with an Automated Controller-Hardware-in-the-Loop Test Environment,” in *Solar Integration Workshop*, 2018.

[18] “Vorabversion der VDE-AR-N 4110 Technische Regeln für den Anschluss von Kundenanlagen an das Mittelspannungsnetz und deren Betrieb (TAR Mittelspannung),” *VDE-FNN*, 2018.

[19] (2020) Infinite insight e-mesh. [Online]. Available: https://search.abb.com/library/Download.aspx?DocumentID=4CAE000717&LanguageCode=en&DocumentPartId=A4-web&Action=Launch

[20] (2021) Infinite insight e-mesh. [Online]. Available: PS1000 utility-grade power conversion system, Available in: https://search.abb.com/library/Download.aspx?DocumentID=4CAE000825&LanguageCode=en&DocumentPartId=A4-web&Action=Launch

[21] (2021) Industry Spotlight: Hitachi ABB Power Grids E-mesh Solutions - Part 1. [Online]. Available: https://info.typhoon-hil.com/blog/industry-spotlight-hitachi-abb-power-grids-e-mesh-solutions-part-1

[22] (2018) Industry Spotlight: Ryan Smith, EPC Power. [Online]. Available: https://info.typhoon-hil.com/blog/industry-spotlight-qa-ryan-smith-from-epc-power

[23] (2019) Build A Better Microgrid Series — HIL Tested Schneider Solar Systems. [Online]. Available: https://www.typhoon-hil.com/videos/case-studies/episode-2-build-a-better-microgrid-series-hil-tested-schneider-solar-systems/