Design and Evaluation of SunSpec-Compliant Smart Grid Controller with an Automated Hardware-in-the-Loop Testbed

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***Abstract*—With increasing penetrations of inverter-based, renewable energy resources on electrical grids around the world, new distributed energy resource (DER) interconnection and interoperability requirements are designed to address emerging power system operator needs. Inverter-based power conversion systems are capable of communicating with grid operators, providing voltage and frequency support, and supporting the grid during faults. However, with the rapidly changing landscape of disparate codes and standards, DER vendors are under pressure to quickly and reliably update the interoperability and electrical capabilities of their equipment for different jurisdictions. To help vendors meet these requirements, we introduce an approach for the concurrent development of controls and application software through a controller hardware-in-the-loop (CHIL) testbed integrated with an automated testing platform. This system can also be used by standards development organizations to rapidly draft, refine, and finalize inter-connection and interoperability requirements. This methodology has many advantages over traditional power laboratory testing including (a) validating advanced inverter grid support functions without expensive power laboratory equipment; (b) executing certification tests to verify controller operation prior to hardware integration; (c) and enabling quick firmware or test protocol design iterations.**

Keywords—Systems integration, grid integration, inverter design, advanced grid-support functions, controller hardware-in-the-loop, DER interoperability

INTRODUCTION

Recently, DER interconnection and interoperability codes and standards around the world are being revised to provide grid operators with tools for providing frequency, voltage, and protection services [1]-[3]. This rapid evolution is driven by grid operator needs as greater penetrations of distributed renewable energy (RE) resources are displacing traditional thermal generation. The widespread adoption and distributed nature of DER is causing voltage regulation challenges for distribution circuits [4]; greater frequency deviations due to reduced inertia in power systems [5]; and new protection challenges from fuse, relay, and circuit breaker desensitization [6]. In order to maintain safe, stable power system, DER must actively participate in grid operations.

DER can provide grid services through programmable autonomous functions and commanded actions. Many of these functions were described in an EPRI report [7] and later formalized in IEC Technical Report 61850-90-7 [8]—soon to be standardized in IEC 61850-7-420 [9]. Many of these same functions—or variations on them—have been required in Europe [2]-[3], and more recently in California and Hawaii in the U.S. The U.S. national interconnection standard, IEEE Std. 1547 [10], is currently undergoing a full revision to add many of these functions and interoperability requirements. With the addition of these requirements, there are two emerging needs: (a) equipment vendors must redesign their equipment to meet new grid standards by systematically validating DER performance and (b) standards development organizations (SDOs) must establish certification protocols (e.g., IEEE 1547.1 [11] and UL 1741 [12]) to list equipment.

To address these near-term industry needs, Sandia National Laboratories, Austrian Institute of Technology (AIT), SunSpec Alliance, and Typhoon HIL are collaborating to introduce a new approach for rapid development of DER controls, and interoperability and interconnection protocols. This approach expands previous power systems research on DER grid-support function evaluations under the International Smart Grid Action Network (ISGAN) Smart Grid

International Research Facility Network (SIRFN) [14]-[15] and integrates test automation software from a Sandia-SunSpec-SIRFN development project [16]-17] with the AIT Smart Grid Converter (SGC) development and controller hardware-in-the-loop (CHIL) research platform [18]-[20]. This methodology provides key benefits over traditional power laboratory testing, including:

- Validating smart inverter grid-support functions without expensive power laboratory equipment, but instead using low-voltage benchtop equipment,
- Executing certification tests to verify controller operation prior to hardware integration,
- Allowing quick design iterations of the communication system to provide interoperability to a range of equipment and standards, and
- Quickly refining SDO draft interconnection and interoperability codes and standards prior to publication.

One of the goals of this project is to provide institutions in emerging economies, universities, and utilities with a low-cost, low-voltage platform for conducting DER grid-support research. As emerging economies begin to integrate higher penetrations of renewables, there will be a need to establish DER requirements to provide grid support functions. This platform will enable SDO members the ability to develop, evaluate, and finalize interconnection, interoperability, and certification standards.

In this paper, the design and use of a smart inverter CHIL (Si-CHIL) platform consisting of an integrated SunSpec-compliant server, smart grid controller, CHIL hardware/software system, and automated test platform is presented. Then the testing methodology along with results of a number of advanced grid-support functions including connect/disconnect, active power curtailment, fixed power factor, reactive power, volt-var, and frequency-watt are provided.

LABORATORY TESTBED CONFIGURATION

The hardware setup used for the design and validation of the advanced smart grid converter is shown in Fig. 1. The testbed consists of the real-time simulation system (Typhoon HIL 602) and simulation software, AIT SGC (sometimes shortened to ASGC), SunSpec Modbus server, and a Windows computer to automate the tests.

The HIL 602 unit provides a real-time µs resolution simulation of the converter power stage, the AC power grid and the solar array and connects to the Smart Grid Converter Controller through analog and digital inputs and outputs (I/Os), representing grid voltages, currents and Insulated-Gate Bipolar Transistor (IGBT) Pulse Width Modulation (PWM) signals. The AIT SGC represents the grid-connected PV inverter providing a broad range of advanced grid support capabilities. The equipment under test (EUT) modes and settings—ASGC, in this case—were accessed through a dedicated communications processor running a SunSpec Modbus TCP server that handles the low-level communication with the ASGC via a secured binary protocol. Figure 2 shows the internal layout of the HIL Connect and the connectivity features. The AIT SGC HIL Connect is comprised of the SGC Controller, which is powered by a Real Time Operating System (RTOS) running on a Digital Signal Processor (DSP), and a Field-Programmable Gate Array (FPGA) connected to the DSP via an External Memory Interface (EMIF) bus capable of Gbit/s cluster-synchronization for various values across a multiple SGC controllers via the Power Link. A valid SunSpec client request is processed by the communication processor and sent to the DSP. The DSP communicates via a low-level binary Inter-Processor Communication (IPC) protocol with the SunSpec Modbus server, an ARM-based communication processor.

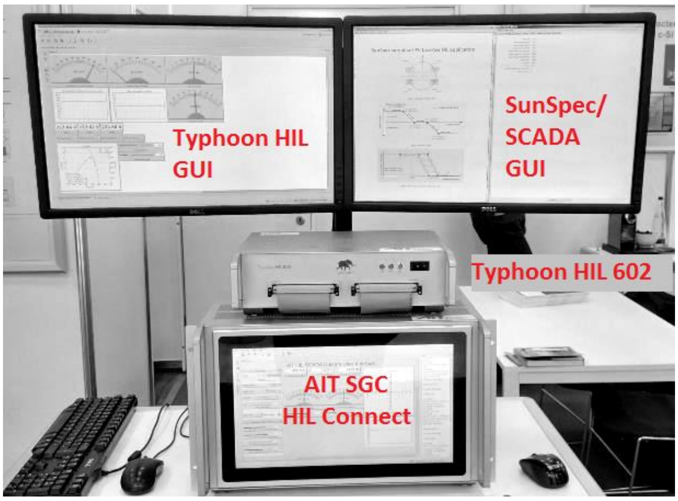

Fig. 1. Si-CHIL test setup with Typhoon HIL 602 simulator and AIT SGC HIL Connect integrating the ASGC components and a SunSpec/supervisory control and data acquisition (SCADA) graphical user interface (GUI).

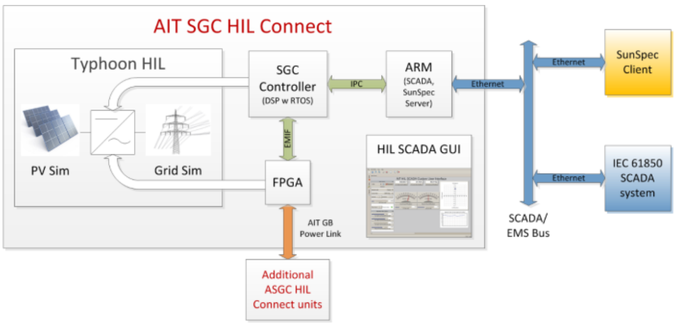

Fig. 2. Layout of the AIT SGC HIL Connect test system.

To fully implement automated tests, the SunSpec System Validation Platform (SVP) was utilized as a central control platform. The SVP is a versatile automated certification platform that allows the test sequences to be scripted through abstraction layers to test equipment and EUTs using the Python programming language. The abstraction layers allow identical test logic to be executed for different test equipment/EUTs, e.g., with actual PV inverters or simulated inverters through the use of CHIL. In this case, the SVP was used to automate the testing sequence by issuing commands to adjust AC grid and PV parameters in the CHIL simulation environment, capture data from the simulation, and adjust the functional modes and settings in the EUT. The SVP communicated to the HIL simulator through a USB connection using the Typhoon HIL Application Program Interface (API) and the EUT settings were changed via SunSpec Modbus TCP over Ethernet as shown in Fig. 3.

The EUT was a 34.5 kW device with full four-quadrant capabilities. In these tests, only positive active power operation was witnessed because and no storage was present. The DC power was provided by simulated PV array with P_{mp} = 36.24 kW at 1000 W/m^2. The EUT response to different SunSpec settings was initially assessed using the Typhoon HIL Control Center and the SunSpec Dashboard [21] to determine the EUT functional limitations (e.g., minimum and maximum grid frequency and voltage) and available grid support functions. These limitations where observed when conducting the automated experiments.

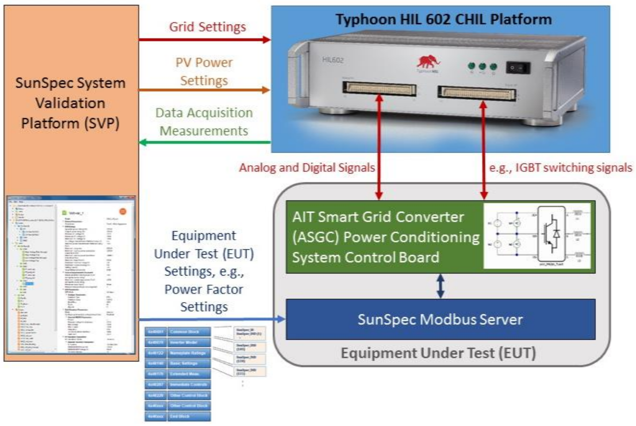

Fig. 3. Si-CHIL test configuration for automated grid-support function testing.

EXPERIMENTAL RESULTS

The Si-CHIL setup is capable of testing the EUT compliance to any number of grid codes and standards using the SVP. For this work, simple experiments were scripted to evaluate the grid-support capabilities of the EUT. Data was collected from the Typhoon HIL through the Typhoon HIL Python API every 200 ms from analog signals representing the AC and DC current and voltage, and from calculated CHIL channels including root mean square (RMS) AC power, RMS reactive power, and power factor. In the experiments, the PV power was adjusted by setting the simulated PV irradiance level, and the grid voltage and frequency were changed for all three single-phase voltage sources simultaneously via the Typhoon API.

A. Connect/Disconnect

The connect/disconnect function (IEC 61850-90-7 INV1) isolates the DER from the grid. Typically, isolation is created by gate blocking the H-bridge semiconductor switches, but it could also be accomplished by actuating a contactor to provide galvanic isolation.

To evaluate the EUT, five disconnect and five connect commands were issued to the Modbus Server at 15 second intervals. The results are shown in Fig. 4. As can be seen, the disconnect command was acted upon in less than 1 second. However, the connect command took longer, ~5 seconds, while the EUT resynchronized with the grid and began to output power. Then the power increased for another ~5 seconds as the maximum power point tracker (MPPT) moved to the PV maximum power point (MPP).

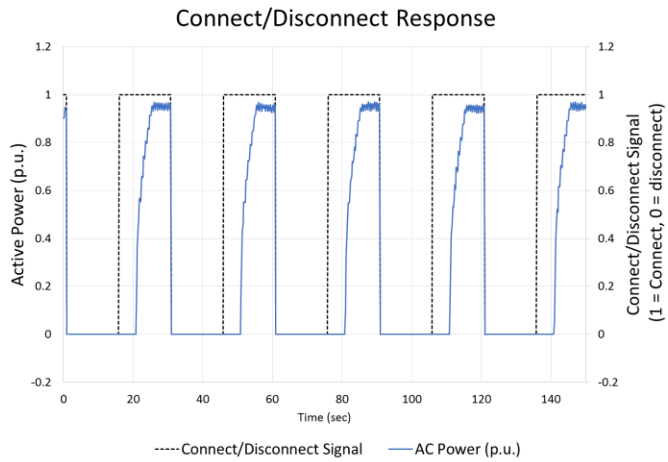

Fig. 4. EUT response from five disconnect and five connect commands.

B. Active Power Curtailment

The curtailment function (IEC 61850-90-7 INV2) is used to reduce the DER output to typically provide voltage regulation or ensure circuit protection. The PV irradiance was set to 1000 W/m^2 and EUT was commanded three times to change active power from 10% to 100% to 10% output at 10% increments. The settings were issued at 3 second intervals. As can be seen in Fig. 5, the EUT tracks the signal well except at the MPP where device efficiency prevents the DER from reaching nameplate power.

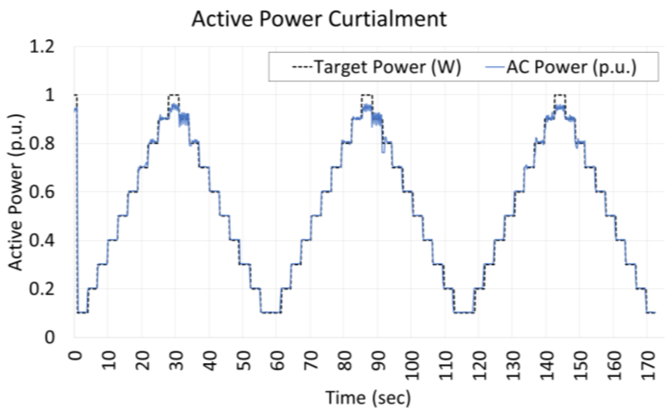

Fig. 5. Active power of the EUT when operating in the curtailment mode.

C. Fixed Power Factor

The fixed power factor (PF) function (IEC 61850-90-7 INV3), or cos(ϕ) (assuming small distortion), is used to inject or absorb reactive power for voltage regulation. Power factors every 30º were issued to the EUT while the PV irradiance was set to 100, 250, 450, 600, 750, 900, and 1000 W/m^2. After a 2 second settling time, the active and reactive power were recorded and plotted in Fig. 6. As can be seen in the P-Q plane, the EUT accurately provided the PF setting while maximizing the active power output of the EUT and maintaining the apparent power limit of the device, represented by the outside circle in the figure.

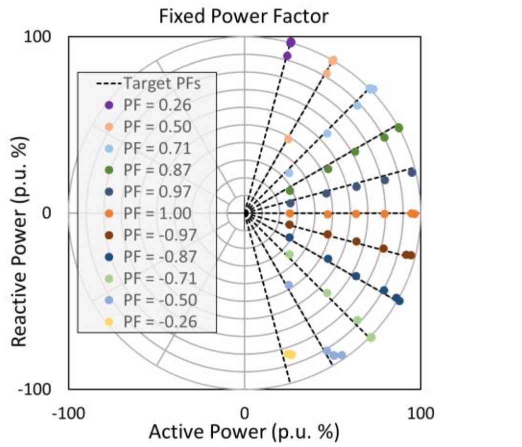

Fig. 6. Fixed power factor results for seven different PV irradiance levels.

D. Reactive Power

Another voltage regulation function is a commanded reactive power mode. This function can set the reactive power in units of maximum active power (WMax), maximum reactive power (VArMax), or available reactive power (VArAval)—where active power is not curtailed. The PV irradiance was set to 20 points between 100 and 1000 W/m^2 for seven reactive power settings. For this EUT, the WMax and VArMax values were both 34500, so the results of these functions were very similar, as seen in Figs. 7 and 8. In the case of setting the reactive power as a function of %VArAval, the reactive power was reduced at higher irradiances to avoid active power curtailment, shown in Fig. 9.

E. Volt-Var

The volt-var function, or Q(V), is an autonomous DER mode that is designed for autonomous voltage regulation based on the local EUT grid voltage measurements. Two different VV curves were programmed into the EUT using the SunSpec parameters and tested at 100 voltage points for three different irradiance levels (200, 600, and 1000 W/m^2). There was close alignment of the EUT reactive power output and the target for the two VV curves, as shown in Figs. 10 and 11. The slight horizontal shift in the curve is thought to be due to calibration and measurement accuracy of the lab setup.

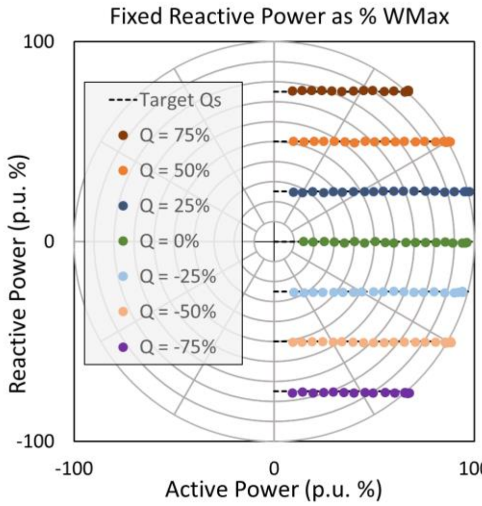

Fig. 7. Seven commanded reactive power settings (WMax).

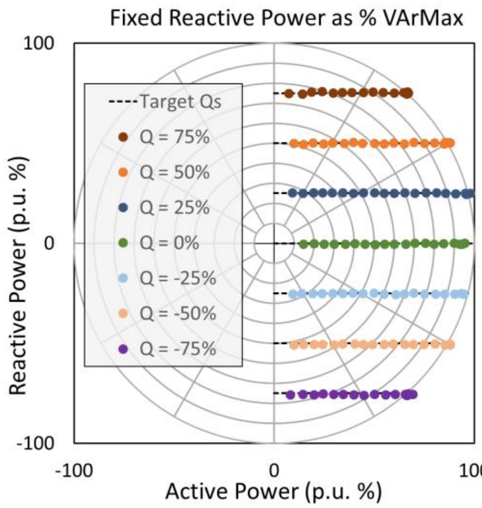

Fig. 8. Seven commanded reactive power settings (VArMax).

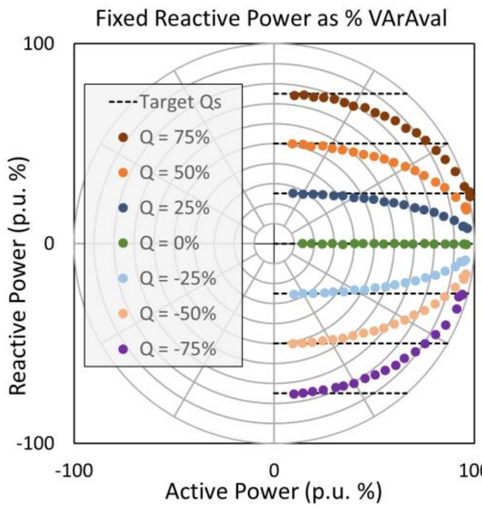

Fig. 9. Seven commanded reactive power settings (VArAval).

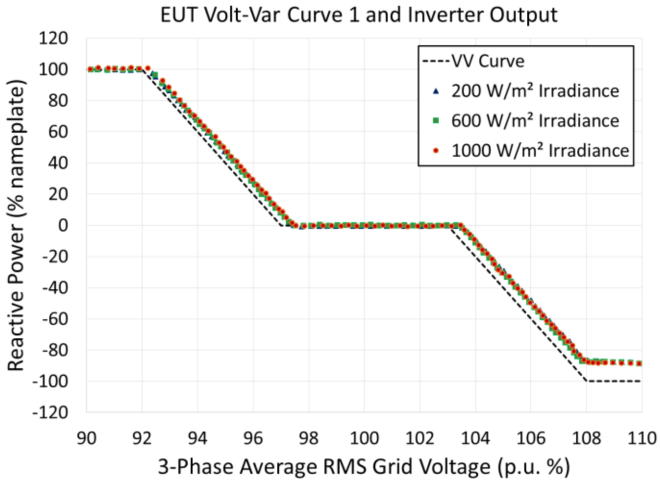

Fig. 10. Volt-Var behavior of the EUT for Curve 1.

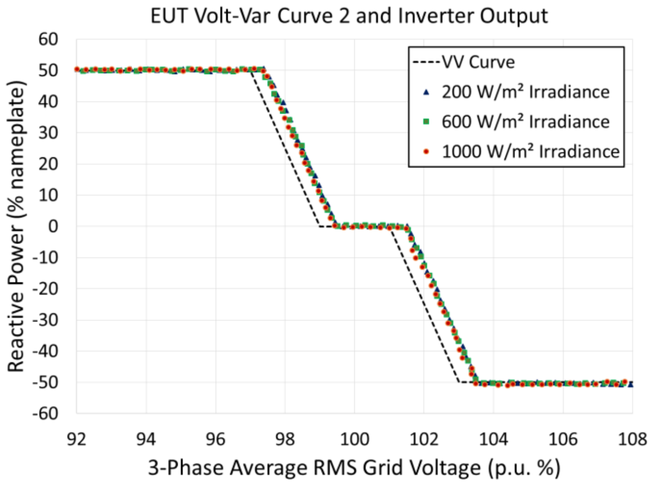

Fig. 11. Volt-Var behavior of the EUT for Curve 2.

F. Frequency-Watt Function

The frequency-watt, FW, or P(f) function is used to support bulk system balancing. The EUT autonomously changes its active power output based on local grid frequency measurements. For instance, in Germany and Austria, VDE-AR-N 4105 requires a 40%/Hz reduction in PV power above 50.2 Hz [22]. Per IEC 61850-90-7 and SunSpec models, these functions can be programmed either as a parameterized curve or a pointwise function—as was the case for this EUT. To characterize the device FW behavior, the grid frequency was increased to 50.5, 51.0, and 52.0 Hz from f_{nom} to determine the influence of hysteresis. The frequency profile was generated with 0.05 Hz steps and 1 sec settling times. For this demonstration, the EUT power was measured through the frequency profile with the FW function enabled and disabled. As shown in Fig. 12, the active power was reduced based on the FW curve when the function was enabled. The effect of the hysteresis is also shown in the figure with arrows indicating the direction of the frequency change.

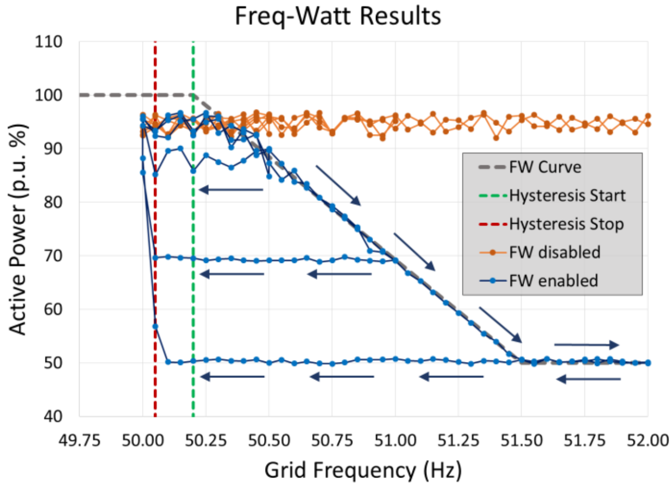

Fig. 12. FW behavior with the hysteresis loop indicated with arrows.

G. Discussion

As shown by the CHIL experiments, test protocols can be quickly scripted and automated using the SunSpec SVP. The EUT was capable of enabling and adjusting a range of advanced grid support functions. The combination of the SVP and CHIL platforms would be particularly useful for testing EUTs to certification protocols requiring a number of operating modes and/or settings. This capability reduces the burden on test engineers by automating the experiments and data collection, while still validating the functionality of the EUT early in the design process. Furthermore, coupling the interoperability (i.e., communications) tests with the electrical behavior testing would be effective for certifying the equipment for both sets of requirements. In this case, the EUT was shown to properly understand and update its behavior when receiving standardized SunSpec Modbus commands. Additional communications protocols such as IEEE 2030.5, DNP3, or IEC 61850 could be easily substituted in the SunSpec SVP to validate other communication protocols.

Conclusions

Sandia, AIT, SunSpec, and Typhoon-HIL collaborated to create an automated smart inverter controller hardware-in-the-loop testbed. This platform and associated capabilities enables users to:

1. Complete certification experiments with limited power system hardware, e.g., no grid simulator, PV simulator, data acquisition system, RLC loads, etc.
2. Test large EUT controllers prior to integration with power equipment.
3. Accelerate the DER design cycle for interconnection and interoperability compliance.
4. Create optimized testing protocols for certification standards.

Sandia and SunSpec are releasing the SVP testing code in an online repository [23] for DER vendors, Nationally Recognized Testing Laboratories (NRTLs), and other interested parties. It is the intention of the this team to provide the integrated certification platform to academic and research institutions around the world—especially in emerging economies, where access to power equipment may be limited. One possible outcome is Si-CHIL users can develop and refine interconnection and interoperability certification standards using the results from the integrated platform.

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