Evaluation of Interoperable Distributed Energy Resources to IEEE 1547.1 Using SunSpec Modbus, IEEE 1815, and IEEE 2030.5

JAY JOHNSON1, (Senior Member, IEEE), BOB FOX2, (Member, IEEE), KUDRAT KAUR2, AND JITHENDAR ANANDAN3

1Sandia National Laboratories, Renewable and Distributed Systems Integration, Albuquerque, NM 87185, USA
2SunSpec Alliance, San Jose, CA 95117, USA
3Electric Power Research Institute, Knoxville, TN 37932, USA

Corresponding author: Jay Johnson (jjohns2@sandia.gov)

This work was supported by the “Accelerating Systems Integration Standards II (ACCEL II)” Project funded by the U.S. Department of Energy Solar Energy Technologies Office under Grant DE-EE0034497. Sandia National Laboratories is a Multimission Laboratory Managed and Operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under Contract DE-NA0003525.

ABSTRACT The American distributed energy resource (DER) interconnection standard, IEEE Std. 1547, was updated in 2018 to include standardized interoperability functionality. As state regulators begin ratifying these requirements, all DER—such as photovoltaic (PV) inverters, energy storage systems (ESSs), and synchronous generators—in those jurisdictions must include a standardized SunSpec Modbus, IEEE 2030.5, or IEEE 1815 (DNP3) communication interface. Utilities and authorized third parties will interact with these DER interfaces to read nameplate information, power measurements, and alarms as well as configure the DER settings and grid-support functionality. In 2020, the certification standard IEEE 1547.1 was revised with test procedures for evaluating the IEEE 1547-2018 interoperability requirements. In this work, we present an open-source framework to evaluate DER interoperability. To demonstrate this capability, we used four test devices: a SunSpec DER Simulator with a SunSpec Modbus interface, an EPRI-developed DER simulator with an IEEE 1815 interface, a Kitu Systems DER simulator with an IEEE 2030.5 interface, and an EPRI IEEE 2030.5-to-Modbus converter. By making this test platform openly available, DER vendors can validate their implementations, utilities can spot check communications to DER equipment, certification laboratories can conduct type testing, and research institutions can more easily research DER interoperability and cybersecurity. We indicate several limitations and ambiguities in the communication protocols, information models, and the IEEE 1547.1-2020 test protocol which were exposed in these evaluations in anticipation that the standards-development organizations will address these issues in the future.

INDEX TERMS Distributed energy resource, smart grid, interoperability, certification, IEEE std. 1547.1, communication, interconnection.

I. INTRODUCTION

Around the world, Distributed Energy Resource (DER) grid codes and interconnection standards have been evolving to include new grid-support functions. These standards often include functionality to provide voltage regulation (e.g., fixed power factor, voltage-reactive power, voltage-active power, and active power-reactive power functions), frequency response (frequency-active power or frequency-droop), and voltage and frequency ride-through capabilities [1]–[3]. Historically, these capabilities are enabled during the manufacturing or commissioning process and left to operate autonomously for the life of the equipment. While some standards have included ranges of adjustability for the functions—such as in California Rule 21 [4] and the Australian/New Zealand interconnection standard AS/NZS 4777 [5], [6]–the US interconnection standard, IEEE 1547-2018 [7], is the first to require DER equipment include ranges of adjustability and mandate DER devices include a standardized communication interface. This interface is designed to enable grid operators...
to read DER measurements and adjust settings and operating modes in near real-time.

Communications-enabled DER provide a wide range of benefits to grid operators. Transmission and distribution system operators have better visibility into distribution networks and can optimize DER settings according to schedules or real-time needs. There have been many studies that show the advantages of using DER Management Systems (DERMS) to configure the operations of fleets of DER devices. For example, carefully tuned voltage-reactive power (volt-var) curves or power factor set points can increase feeder hosting capacity [8] and support voltage on unbalanced feeders [9].

Communication-enabled DER also allow for new voltage regulation optimization techniques—e.g., Particle Swarm Optimization and Extremum Seeking Control—to be developed to set DER reactive power set points to minimize voltage deviations and circuit losses [10]. At the bulk system level, it is also possible to select frequency-watt parameters to provide fast frequency reserves [11], [12] and wide-area damping [13].

DER communications will also open up markets to provide third-party virtual power plants (VPPs) or aggregation services. In the United States, Federal Energy Regulatory Commission (FERC) Order 2222 [14] was passed in September 2020 which allows DER aggregations to participate in regional wholesale markets. In combination with DER interoperability functions, the FERC order will pave the way for VPP players in Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) wholesale markets in the U.S. There has been substantial research in different VPP approaches to use the DER active power and curtailment set points to provide transmission services. As an example, Castillo et al. designed a stochastic risk aversion-based rolling horizon optimization framework to bid into day-ahead scheduling and real-time dispatch markets [15]. Others investigated VPP optimization using chance-constrained methodologies [16], robust optimization [17], and stochastic programming [18] to meet load or generation needs.

In order to provide the aforementioned grid services, DER equipment must operate and communicate as expected. Unfortunately, it is challenging to verify DER equipment is functioning in accordance with grid codes and standards [19]—taking weeks if not months to perform all the experiments. In the last decade, evaluating DER equipment has been the source of significant academic interest and corporate investment. In the U.S. and Canada, DER equipment must be listed in accordance with regional requirements where it is installed. In most states, the requirements are harmonized to IEEE 1547-2003. The step-by-step test procedure for evaluating DER equipment to IEEE 1547 requirements is documented in IEEE 1547.1, but Nationally Recognized Testing Laboratories (NRTLs) certify DER compliance using Underwriters Laboratories (UL) 1741 [20]—which heavily references IEEE 1547.1 but provides greater testing detail in some key areas. UL 1741 was used to certify DER to IEEE 1547-2013; UL 1741 Supplement SA was added in 2016 to certify equipment to California Rule 21 and Hawaii Rule 14; and UL 1741 Supplement SB will certify DER to IEEE 1547-2018/IEEE 1547.1-2020. Since the development of UL 1741 Supplement SA added ranges of adjustment to the test procedure, it was no longer practical to manually certify equipment to the standards, and automated test beds started to emerge.

While there are proprietary test beds at NRTLs and DER vendor test facilities, the SunSpec Alliance and Sandia National Laboratories created an open-source, automated compliance testing software package called the System Validation Platform in 2014 [21], [22]. This software package has been further refined by an international network of research laboratories known as the Smart Grid International Research Facility Network (SIRFN), which operates under the International Smart Grid Action Network (ISGAN) International Energy Agency (IEA) Technology Collaboration Programme (TCP). This group has collaborated to write test logic to automate multiple test procedures. To date, some of the laboratory results include:

- **Compliance Protocol**: A pre-standardization Sandia-developed test procedure for IEC TR 61850-90-7 [23], [24]
  - connect/disconnect, active power curtailment, and power factor [25]
  - connect/disconnect, active power curtailment, power factor, reactive power-priority volt-var [26]

- **Compliance Protocol**: A SIRFN-developed test procedure for ESS devices [27]
  - active power, fixed power factor, volt-var, and frequency-watt [28]

- **Compliance Protocol**: UL 1741 SA
  - volt-var and specified power factor [29]
  - normal ramp rate, soft start ramp rate, specified power factor, volt-var, and frequency-watt [30]

- **Compliance Protocol**: IEEE 1547.1-2020
  - constant power factor, volt-var, frequency-droop, and volt-watt [31]
  - limit active power, constant reactive power, active power-reactive power (watt-var), and prioritization of grid-support functions [32]
  - voltage phase-angle change ride-though [33]
  - voltage ride-through, frequency ride-through, and rate of change of frequency (ROCOF) ride-through

These experiments were each executed by manually adjusting the DER settings through graphical user interfaces, proprietary Modbus interfaces, or 100-Series SunSpec Modbus Models—none of which were compliant to the IEEE 1547-2018 requirements. However, with the approval of IEEE 1547.1-2020, each of the IEEE 1547.1 compliance tests must now be conducted by adjusting the parameters with one of the IEEE 1547-mandated interfaces: SunSpec Modbus, IEEE 1815 (DNPs), or IEEE 2030.5. Each of the protocols have specific information models associated with the IEEE 1547 functionality, as shown in Table 1, which expose...
DER nameplate, configuration, monitoring, and control mode information.

While some DER devices may include a DNP3 or IEEE 2030.5 interface natively, Modbus is currently the prevailing technology on the market. However, Modbus does not include any encryption or authentication, so it is not intended to leave DER facility premises and will likely only communicate very far distances to a IEEE 2030.5 or DNP3 gateway or converter—such as a DER bolt-on module like that demonstrated in a California Solar Initiative project led by EPRI [35]. Using a converter, the DER will be able to connect to utility or aggregator systems through the public internet with standardized cybersecurity protections.

In this work, we validate the interoperability of multiple DER simulators using the information models in Table 1 in accordance with the IEEE 1547.1 compliance test protocol. This process exposed a number of errors, ambiguities, and issues with the test protocol, information models, and DER simulator implementations. These findings have been relayed back to the appropriate standards-making bodies and stakeholders. This paper represents the first detailed investigation of these information models using the DER interoperability certification procedure and is the first to demonstrate the IEEE 1547 communication protocols. The remainder of the paper is structured as follows: Section 2 describes the methodology used to conduct the experiments; Section 3 provides detailed results of the experiments; Section 4 summarizes the standards development recommendations; and Section 5 concludes the paper with the major findings from this work.

### TABLE 1. Information models associated with each of the IEEE 1547 communication protocols.

| Protocol         | Information Model for IEEE 1547 Functionality                                                                 |
|------------------|-------------------------------------------------------------------------------------------------------------|
| Modbus           | 700-Series SunSpec Modbus Model Definitions [36]                                                          |
| IEEE 1815        | DNP3 Application Note [37]                                                                                  |
| IEEE 2030.5      | Common Smart Inverter Profile (CSIP) [38]                                                                  |

### II. EXPERIMENTAL APPROACH

The SVP was designed as a highly versatile platform for automating certification experiments. Now, more than eight years in development, it includes a wide range of abstraction layers and equipment drivers. The abstraction layers are used to expose different classes of drivers in the GUI so the same testing logic (scripts) can be used to run experiments at different laboratories by only changing the test parameters in the script [22], [39]. Current abstraction layers included in the SVP Energy Lab repository [40] are AC/grid simulators, DC/PV simulators, DER, battery simulators, data acquisition systems, and gensets, switches, and loads. Using this software, Sandia created an IEEE 1547.1 interoperability certification script [41] that automates the evaluation of DER communications for nameplate, configuration, and setting information. This script also provided a means to spot-check the communications required to run all the electrical tests that can be configured via the communication port.

Executing a full IEEE 1574.1 interoperability compliance test for a given communication protocol is challenging because it requires verification of the entire information model. The test procedure is shown in Table 2. To certify a device to any of the protocols, in addition to verifying the measurement points by adjusting the grid simulator settings or DER operating modes, the DER must be evaluated for the management functions (volt-reactive power, freq-droop, etc.) using the specified communication protocol. The pass/fail criteria for those tests is the same as the management function tests which evaluate the electrical characteristics of the DER. In order to automate and accelerate IEEE 1547.1 testing, the SVP was updated to include drivers for SunSpec Modbus via pySunSpec2 [42], IEEE 1815, and IEEE 2030.5. To conduct the nameplate, configuration, and monitoring information tests, a JOP.py SVP script was created. Additional IEEE 1547.1 SVP scripts were also created to evaluate the interoperability and electrical functionality of the management functions, as shown in the final column of Table 3.

Sandia, SunSpec, EPRI, Kitu Systems, and SIRFN labs collaborated to create the testing scripts and DER simulators required to evaluate the conformance tests and information models. The SVP test environment used for these evaluations is shown in Figure 1. The SVP was connected to four DER end-point simulators which each used an IEEE 1547-mandated protocol:

- **SunSpec DER**: A SunSpec-constructed DER emulator that ingests a JSON file to create a SunSpec-compliant device with all of the 700-Series Models. This device did not include a power system or power electronics simulation capability—only a state-based representation of a SunSpec-compliant DER device. The SVP interacted with this DER simulator using the pySunSpec2 python package.

- **IEEE 1815 DER**: The EPRI DER Simulator version 1.0.6 with a DNP3 interface included a partial implementation of the DNP3 Application Note (App Note) AN2018-001. This simulator is a windows executable with the ability to run the power electronics simulation with irradiance, grid voltage, and grid frequency temporal profiles loaded from CSV files [43]. To communicate DNP3 commands to the EPRI simulator, a windows-based DNP3 Master agent was instantiated by the SVP. The DNP3 agent included a TCP server and associated backend API which would configure interactions with DNP3 outstations. The SVP sent HTTP JSON client requests to the DNP3 Master agent server to get Analog Input (AI) or Binary Input (BI) values from the EPRI DER Simulator outstation, or write Analog Output (AO) or Binary Output (BO) values to the outstation.

- **IEEE 2030.5 DER #1**: The Kitu Systems IEEE 2030.5 client with DER simulation capabilities. This client was built on a Raspberry Pi single board computer

---

1 MODBUS/TCP Security does provide these security capabilities but is not commonly used. See [34] for more details.
with an IEEE 2030.5 CSIP information model with an optional DER simulator. The private keys for the Kitu Client were used to communicate to the device using an IEEE 2030.5 server developed by SunSpec. This server configured default settings (as opposed to scheduled behaviors) and was a standalone application from which the Kitu client retrieved information at fixed poll rates.

- IEEE 2030.5 DER #2: A IEEE 2030.5-to-Modbus converter developed by EPRI that interfaced with the EPRI DER Simulator. This converter ran as an executable on Ubuntu 20.04.2 LTS with a configurable poll rates. The converter was also configured to connect to the SunSpec IEEE 2030.5 server as shown in Figure 1.

In the case of the IEEE 2030.5 experiments, the SunSpec server was used because it allowed the greatest flexibility and visibility in debugging and viewing client-server errors and messages. A range of other client-server topologies could have been investigated—and should be in the future to ensure true interoperability. For instance, the Kitu Client and EPRI converter could also connect to a Kitu IEEE 2030.5 Server, the IEEE 2030.5 Test Tools from QualityLogic, or other commercial IEEE 2030.5 servers. To perform the interoperability experiments with that equipment, the SVP would need the ability to update server configurations and retrieve client data from the Kitu Systems NorthGate Server API or QualityLogic test environment.

An added complication with IEEE 2030.5 testing was provisioning the SVP with the client certificate and private key to establish the Transport Layer Security Version 1.2 (TLS 1.2) session with the server. The Common Smart Inverter Profile (CSIP) defines a specific cipher suite (TLS_ECDHE_ECDSA_WITH_AES_128_CCM_8) to perform asymmetric encryption of IEEE 2030.5 exchanges [44]. In order to establish the connection and interact within the Public Key Infrastructure (PKI) ecosystem, the IEEE 2030.5 server was configured with the server certificate, server private key, and root certificate in Privacy Enhanced Mail (PEM) files. The server made the TLS connection with OpenSSL to the Kitu and EPRI clients using those PEM files, the certificate and private key of the client, and the cipher specifications.

It should also be noted that the IEEE 1547.1 testing is not a comprehensive interoperability test sequence. It is designed to verify a basic level of functionality to demonstrate the DER communication interface is connected appropriately to the electrical control and measurement capabilities of the DER. In order to fully validate the communication capabilities of DER, a separate certification program has been established by the SunSpec Alliance for IEEE 2030.5 clients and servers.
SunSpec Modbus devices, and IEEE 1815 masters and outstations [46]. In the program, vendors submit their products to one of the SunSpec Authorized Test Labs (ATLs) for compliance certification. Those labs verify the full communication functionality of the devices and send the trace files to SunSpec for final certification validation. For instance, in the case of the Modbus devices, this process verifies that single registers can be read/written, multiple adjacent holding registers can be read/written using a single request, and multiple non-adjacent holding registers can be read/written in multiple requests [47]; and in the case of IEEE 2030.5, the program verifies the security features (e.g., appropriate cipher suites, certificate encoding, establishing valid TLS 1.2 connections, etc.), uses the HTTP protocol, checks the function sets (time, event handling, event priorities, etc.), and verifies that all the IEEE 1547-mandated functions can be acquired from the server and are implemented in the client [48]. These experiments are not included in the IEEE 1547.1 test procedure.

III. RESULTS

Working with these prototype DER devices, the first hands-on assessment of the IEEE 1547.1 interoperability tests were conducted. Unfortunately, not all the functionality was included in these devices (e.g., statuses, alarms, operational states, etc. we’re not present in the EPRI simulator), so not all the functionality was evaluated for each of the protocols/DER simulators. To execute the experiments, a DER 1547 abstraction layer was created and read and write methods were built for the drivers for IEEE 2030.5 (der1547_20305.py), IEEE 1815 (der1547_dnp3.py), and SunSpec Modbus (der1547_sunspec.py). The following section presents the results from the experiments. Errors and ambiguities in the test and communication protocols were identified for feedback to the standards working groups.

Each of the DER simulators and associated communication tools were instantiated at the beginning of the IEEE 1547 interoperability tests. In the case of the SunSpec Modbus, a JSON mapping of a SunSpec Modbus device was imported by the pySunSpec2 Python package and this SunSpec object was used for all the interactions. This object did not include a power electronics model so the measurements were static values included in the JSON data file.

For the IEEE 1815 experiments, the SVP used an operating system bash shell command to start the DNP3 Agent with variables to indicate the Agent IP address and Outstation IP address (both use the 127.0.0.1 loopback address since the SVP, DNP3 Agent, and EPRI DER Simulator are all on the same Windows 10 machine), the Agent and Outstation IP port, Outstation local address, Master local address, and request ID. The EPRI Simulator was also started with a system command from Python and pywinauto was used to interface with the GUI. The DER nameplate capacity information was preloaded as a CSV in the Windows GUI. At start up, the SVP enabled the DERMS mode in the EPRI Simulator and the DNP3 Agent connected to the outstation and read the AI and BI points in the device. Then, the SVP commenced the IEEE 1547.1 test sequence with the EPRI Simulator outstation using the DNP3 Agent API to issue read/write commands to the device.
For the IEEE 2030.5 testing, the IEEE 2030.5 Server was started on port 9443 for the Kitu experiments and port 8443 for the EPRI converter experiments. The clients were then initialized and communicated to the server by getting /sep2/dcap, creating a resource tree with dcap, tm, der, edev, fsa, derp, dc, denc, dderc, rsp, upt, and mup paths for the given Short Form Device Identifier (SFDI). The SVP communicated to the SunSpec server API via an HTTP API on the loopback IP address. Initially, there were challenges communicating with the EPRI converter because the server was closing the HTTP connection between messages and the client expected the connection to remain open for the duration of the experiments. Since a TCP connection can be closed for many reasons outside of the control of the endpoints, it is important to ensure communication failures are recoverable. This highlights some of the interoperability challenges that exist when testing with a single client or server—there will be different use cases that are not represented by the IEEE 1547.1 requirements.

A. NAMEPLATE DATA TEST

The nameplate data provides information about the DER device. The IEEE 1547.1 test procedure requires the tester to read the values for each of the nameplate data points and compare them against the manufacturer-provided values.

1) SunSpec MODBUS

The nameplate data is included in SunSpec Common Model 1 and DERCapacity Model 702, as shown in Table 4. In the case of the simulated SunSpec-compliant DER, the IEEE 1547-mandated points were read as anticipated. Notably, there are additional nameplate data points included in SunSpec Model 702, added based on the needs of the stakeholders in the SunSpec Alliance Modbus Working Group, but these were not required for IEEE 1547 certification.

2) IEEE 1815

With the exception of Manufacturer, Model, Serial Number, and Version Data, the DNP3 App Note includes AI and BI points for all the Nameplate data points as shown in Table 4 and aligned with IEEE 1547.1 and App Note Table 63. Manufacturer, Model, Serial Number, and Version Data are optional Device Attribute Objects in point number 0 of object group 0. So in practice, the master can read Device Attributes – Device serial number at Group 0 Variation 248, Device Attributes – Device manufacturer’s product name and model at Group 0 Variation 250, and Device Attributes – Device manufacturer’s name at Group 0 Variation 248 with point index 0, though the EPRI Simulator did not include this functionality. In fact, the DNP3 App Note requires only a DNP3 Level 2 (DNP3-L2) device so some DERMS masters may not have the ability to read this class object data. Therefore, it is recommended to move these values to AI points in the DNP3 Application Note.

Not all the other data points were included in the EPRI DER Simulator either, e.g., Active power rating at specified over-excited power factor, Abnormal operating performance category, and some of the Supported control mode functions returned null, but the DNP3 driver and DNP3 Agent successfully returned numerical and string data and reporting null data points to the user, demonstrating the ability of the SVP and DNP3 Agent to complete the IEEE 1547.1 Nameplate Data Test.

3) IEEE 2030.5

The Kitu Client was configured with a 600-second poll rate and the EPRI converter with a 60-second poll rate, after which they retrieved the control resources associated with the client from the server. The SVP configured the topological and DER resources in the server using the SunSpec backend API in order to establish the client-server connection and program IEEE 2030.5 settings. The information pushed to the server was nameplate information, monitoring data, and status/alarm information. This information was stored in the server and pulled into the SVP via the API. Each class of resources includes a poll rate, so the monitoring data could be updated at a quicker rate than status information, for example. The DER nameplate information is POSTed to the server a single time after GETting down the end device resource locations from the server. The SVP gets the DERList link based on the SFDI and Long Form Device Identifier (LFDI), finds the DeviceInformation and DERCapability links, and then reads the nameplate points. The DERCapability Link and Resource are shown in Fig. 7 with the DERSettings and DERStatus points.

The paradigm for testing a IEEE 2030.5 client is much different than Modbus and DNP3 because the SVP is not directly reading or writing data on the DER. The SVP is configuring the server and then waiting for the client to interact with it. As a result, there are much longer test times because the SVP must wait (up to the resource poll rate) for the client to exchange data with the server.

B. CONFIGURATION DATA TEST

For the configuration information tests in IEEE 1547.1 the following parameters are read and the DER behavior is measured through a data acquisition system:

- Active power rating at unity power factor (nameplate active power rating)
- Apparent power maximum rating
- Reactive power injected maximum rating
- Reactive power absorbed maximum rating
- For ESS, active power charge maximum rating
- For ESS, apparent power charge maximum rating

These parameters are set to 80% of the initial value, re-verified with the data acquisition system, and returned to 100% of the initial value to be verified a final time. The pass/fail indicates that the values should match the configuration data. Adding an allowable tolerance on the accuracy of these points would be useful in the future. The Supported control mode functions are also verified to operate as expected.
when enabling and disabling each of the management (grid-support) functions; although no specifics are provided on how to do this, leaving it to the interpretation of the test engineer on how to perform the experiment. Adding more detail in IEEE 1547.1 to that test case would be helpful to ensure all the experiments are conducted in the same manner.

In IEEE 1547.1, the SunSpec, DNP3, and IEEE 2030.5-specific tests state that the nameplate points are to be overwritten for the configuration information data tests. This is a poor practice, and SunSpec Modbus and IEEE 2030.5 have created settings points so that the nameplate data is never overwritten. There are also typos in IEEE 1547.1 mislabeling IEEE 2030.5 nameplate and configuration information test section titles (Sections 6.8.2.1 and 6.8.2.2), which should be cleaned up in the next revision.

1) SunSpec MODBUS
Using pySunSpec2 to interact with the setting points in the DERCapacity Model produced the intended changes in the SunSpec Models. Since this DER simulator did not include a power simulation, there was no way to independently verify the DER operations were changed with these updates. In the future, this will need to be verified for DER devices when undergoing IEEE 1547.1 tests.

2) IEEE 1815
As stated above, the IEEE 1547.1 standard states the tests should use the same data points for configuration information as the nameplate data points. In the case of DNP3, this is not possible because nameplate data are AI and BI points, as indicated in Table 63 of the DNP3 Application Note. As a result, there are no DNP3 outputs (DER inputs) that permit changing the nameplate information. The DNP3 App Note and IEEE 1547.1 should be updated with AO and BO points to adjust the nameplate values. Or, preferably, there should be a completely new set of AO/BO and AI/BI points that represent the device settings—similar to the approach used in SunSpec Modbus and IEEE 2030.5. This way the nameplate DNP3 information can never be changed. This is a significant gap in the DNP3 information model that will need to be updated to allow DER devices to be tested to the IEEE 1547.1 requirements.

3) IEEE 2030.5
While IEEE 1547.1 states that the DERCapability Resource should be used to make configuration data changes on the client-side and IEEE 2030.5 Appendix A states that HTTP GET/HEAD and PUT are mandatory for DERCapability, it is preferred to use DERSettings to update the configuration parameters in the client. As shown in Figure 7, DERSettings includes setMaxW, setMaxVA, setMaxVar, setMaxVarNeg, setMinPFOverExcited, setMinPFUnderExcited, setMaxChargeRateW, setMaxChargeRateVA, and modelsEnabled which allows the SVP to communicate the configuration changes to the client/DER via the server. An example XML exchange to make this update from the server is shown at the bottom of Fig. 2.

Generally, the client will PUT their DERCapability and DERSettings to the server to inform the server of the DER nameplate ratings and settings. DERCapability and

| Nameplate Data | DNP3 | IEEE 2030.5 | SunSpec Modbus |
|----------------|------|-------------|----------------|
| Active power rating at unity power factor (nameplate active power rating) | A14 | DERCapability:: rtgMaxW | 702.WMaxRtg |
| Active power rating at specified over-excited power factor | A16-A17 | DERCapability:: rtgOverExcitedW | 702.WOverExtRtg |
| Specified over-excited power factor | A18 | DERCapability:: rtgOverExcitedPF | 702.WOverExtRtg |
| Active power rating at specified under-excited power factor | A19-A110 | DERCapability:: rtgUnderExcitedW | 702.WUndExtRtg |
| Specified under-excited power factor | A11 | DERCapability:: rtgUnderExcitedPF | 702.WUndExtRtg |
| Apparent power maximum rating | A14 | DERCapacity:: rtgMaxVA | 702.VMaxRtg |
| Normal operating performance category | A22 | DERCapacity:: rtgNormalCategory | 702.NorOpCatRtg |
| Abnormal operating performance category | A23 | DERCapacity:: rtgAbnormalCategory | 702.AbnOpCatRtg |
| Reactive power injected maximum rating | A12 | DERCapability:: rtgMaxVar | 702.VarMaxInjRtg |
| Reactive power absorbed maximum rating | A13 | DERCapability:: rtgMaxVarNeg | 702.VarMaxAbsRtg |
| Reactive power change maximum rating | A15 | DERCapability:: rtgMaxChargeRateW | 702.WChgRateMaxRtg |
| Apparent power change maximum rating | A15 | DERCapability:: rtgMaxChargeRateVA | 702.VChgRateMaxRtg |
| AC voltage nominal rating | A129-A130 | DERCapability:: rtgVNom | 702.VNomRtg |
| AC voltage maximum rating | A13 | DERCapacity:: rtgMaxV | 702.VMaxRtg |
| AC voltage minimum rating | A12 | DERCapacity:: rtgMinV | 702.VMinRtg |
| Supported control mode functions | B131-B151 | DERCapability:: modesSupported | 702.CtrlModes |
| Reactive susceptance that remains connected to the Area EPS in the cease to energize and trip state | A21 | DERCapability:: rtgReactivesusceptance | 702.ReactSusceptRtg |

Manufacturer | DeviceInformation:: mID | 1.Ms |
Model | DeviceInformation:: mModel | 1.MD |
Serial number | DeviceInformation:: mSerNum | 1.SN |
Version | DeviceInformation:: swVer, DeviceInformation:: swVer | 1.Vr |
**Fig. 2.** The client-server interaction to gather nameplate information and to update the client settings.

*DERSettings* are not meant for the server to make changes to these values on the client. Instead, in the case of the Kitu system, there was a subset of client “settings” that a server can change on the client. These changeable settings are mapped to a *DefaultDERControl* (e.g., *setGradW*, *setSoftGradW*, and Enter Service settings). If the server sets any of these *DefaultDERControls*, the client will change its *DERSettings* and put the new values to the server. During the tests, the server *DERSettings* configuration was updated with the new *DERSettings* data and read back using the API; however, it was much more difficult to evaluate if the client picked up these settings or taken affect. The IEEE 1547.1 test requires that the test lab verify “the value reported matches the behavior of the DER measured through independent test equipment separate from the DER interface”. To do this, the SVP is designed to adjust the settings, wait for the poll rate, read back the setting in the server and then independently check the power measurement using a data acquisition system. It is not clear how to verify supported modes, other than to run electrical tests which would indicate their operation when enabled and...
disabled—a time intensive and difficult task that is not defined in IEEE 1547.1.

C. MONITORING INFORMATION TEST

The IEEE 1547.1 monitoring information tests are designed to verify the DER can measure and report grid conditions, internal states, and alarm statuses. The tests set the DER to two operating points shown in Table 6, measured the value after at least 30 seconds, and verify the reported values match the operation conditions. The pass/fail criteria in 6 states the values should be within the allowable accuracies for each of the measurements in IEEE 1547 Table 3. The test procedure does not indicate how to produce the operating points, so it may be helpful for the IEEE committee to clarify this in the future. For instance, if testing a PV inverter, it would be possible to produce the active power setpoints be either changing the DC input to the EUT or commanding the DER to an active power curtailment mode. While it may be beneficial to use external sources to produce these operating points as to not rely on DER controls to validate the monitoring information, to produce the reactive power setpoints, a reactive power mode will need to be used. Oddly, in the general IEEE 1547.1 interoperability testing section for monitoring (Section 6.6.2) does not include the Operational State of Charge (SoC) that is in the protocol-specific requirements in Sections 6.8.1.3, 6.8.2.3, and the DNP3 App Note Table 63, shown in the monitoring data points in Table 5.

There is poor alignment between the information models in terms of data points or naming conventions for DER states and alarms. The reported data required for the Operational State test is an on/off indication; the connection status data must report a connected/disconnected state, and only a single alarm is required for the Alarm Status. There is no direct mapping between the information models shown in the comparison of SunSpec Modbus 701.Alm, the DNP3 App Note Alarms in B10-B19, and the IEEE 2030.5 CSIP alarms from the bit-mapped resource, DERStatus:alarmStatus, as shown in Table 7. As a result, it is very difficult to create a communication protocol agnostic test for the alarms. Currently, the grid voltage in the IOP test is set to 1.25 * \( V_{nom} \) which will cause a high voltage alarm for SunSpec and IEEE 2030.5 devices, but it is not clear what, if any, alarms will be raised on a DNP3 device. Poor harmonization between the information models also makes creating an EUT abstraction layer difficult because all alarm names have to be supported. Non-harmonization issues like this are also present with many other parameters. For instance, the Operational State and Connection Status in the SunSpec Modbus Models are binary, IEEE 2030.5 CSIP Connection Status options include Connected, Available, Operating, Test, and Fault/Error and Operational State options are Not applicable/Unknown, Off, Operational mode, and Test mode, whereas the DNP3 App Note contains 15 Connection Status/Operational State points. For testing purposes, these status/state options were converted to a binary value to autonomously issue pass or fail results for the monitoring tests.

1) SunSpec MODBUS

The SunSpec Modbus simulator did not include a power electronics simulation, inter-register logic/state machine, or have the ability to measure a power system, but these experiments were conducted to demonstrate the test sequence. To test active power measurements, the Limit Active Power (LAP) function was used to create the two test conditions. Constant Reactive Power (CRP) was used to test the two reactive power monitoring points—although the SVP test script does offer the option to test with Constant Power Factor (CPF). In creating the test script, it was discovered the Injected/Absorbed indications in Reactive Power (Injected) and Reactive Power (Absorbed) operating points were ambiguous and could indicate the active power direction or the excitation of the reactive power. It was assumed to be the latter. The voltage, frequency, operation state, connection status, and alarm status were measured and manually verified to reflect the state of the DER simulator.

2) IEEE 1815

The DNP3 interface on the EPRI DER Simulator demonstrated the ability to monitor active power, reactive power, voltage, frequency, and connection status. The active power was verified using LAP; reactive power was inspected using CPF; and the connection status checked with a connect/disconnect command written to BO5. The DNP3 voltage and frequency monitoring points were confirmed by manually adjusting the voltage and frequency sliders on the DER Simulator GUI. The operational state and alarms were not implemented in the DER Simulator, so those DNP3 points and associated call in the DNP3 driver could not be validated.

3) IEEE 2030.5

Using the MirrorMeterReading XML schema in Fig. 3, the IEEE 1547.1 measurements points were transferred to the IEEE 2030.5 server. This action was completed at the meter post rate defined in the client. This occurred at 300 second update rates for the Kuit client and 60 seconds for the EPRI client. The SVP queried the server every second until the server was updated to a monitoring information value within the permitted range. This process took much longer than the DNP3 and SunSpec Modbus tests because of the added time waiting for the client to send a measurement update.

D. MANAGEMENT INFORMATION TESTS

The management information tests cover the management functions included in Table 3: constant power factor, voltage-reactive power, active power-reactive power, constant reactive power, voltage-active power, voltage trip, frequency trip, frequency droop, enter service and cease to energize and trip, limit maximum active power. These are the functions that include adjustable settings in IEEE 1547-2018. To test them, the test sequences from the electrical type tests were repeated using the standardized interface to communicate the settings to the EUT. Originally, there was no mechanism
to enable or disable the anti-islanding functionality of the DER in the information models, which is required for the IEEE 1547.1 Unintentional Islanding type tests. In the model review process, SunSpec adopted the Anti-Islanding Enable (AntiIslEna) point in the DER AC Controls Model. It is recommended this point also be added to IEEE 1815 and IEEE 2030.5 because it will provide a standardized means to conduct Unintentional Islanding experiments.

The SIRFN community is working to construct the IEEE 1547.1 tests as described in the Introduction and listed in Table 3, but it was desired to spot-check these functions in the interoperability SVP script in order to assess if there were any issues with the information models or DER simulators. The following experiments were conducted:

- **Constant Power Factor (CPF):** SVP enabled the function and set PF to 0.90 injecting, -0.90, absorbing, and 0.85 injecting, then checked the reactive power changes, and disabled the function.

- **Active Power-Reactive Power (WV) Mode:** SVP set $P = -P' = \{0.2, 0.5, 1.0\}$ pu and $Q = -Q' = \{0.0, 0.0, -0.44\}$ pu %WMax, followed by $P = -P' = \{0.1, 0.6, 1.0\}$ pu and $Q = -Q' = \{0.0, -0.1, -0.25\}$ pu %WMax points, read them back, and disabled the function.

- **Voltage-Reactive Power (VV) Mode:** SVP enabled $V = \{0.95, 0.99, 1.01, 1.05\}$ pu, $Q = \{1.0, 0.0, 0.0, -1.0\}$ pu %VarMax and then $V = \{0.93, 0.98, 1.02, 1.08\}$ pu, $Q = \{0.3, 0.0, 0.0, -0.5\}$ pu %VarMax points, read back the VV settings, and disabled the function.

- **Constant Reactive Power (CRP) Mode:** SVP enabled the function and set the CRP limit to 25%, 59%, 87%, and 45% of nameplate injection and absorption capacities, checked the reactive power monitoring point for changes, and disabled the function.

- **Voltage-Active Power (VV) Mode:** enabling $V = \{1.03, 1.05\}$ pu, $P = \{1.0, 0.2\}$ pu and $V = \{1.05, 1.08\}$ pu, $P = 1.0, 0.5$ pu points, reading back the settings. Disabling the function.

- **Voltage Trip (VT):** SVP set two groups of $\{V_{\text{high}}\ \text{pu}, \ t_{\text{high}}\ \text{S}\}$ and $\{V_{\text{low}}\ \text{pu}, t_{\text{low}}\ \text{S}\}$ curve points to the EUT and read them back. Group 1: $V_{\text{high}} = \{1.10, 1.20\}$, $t_{\text{high}} = \{13.0, 0.16\}$, $V_{\text{low}} = \{0.88, 0.50\}$, $t_{\text{low}} = \{21.0, 2.0\}$. Group 2: $V_{\text{high}} = \{1.17, 1.25\}$, $t_{\text{high}} = \{15.0, 1.20\}$, $V_{\text{low}} = \{0.86, 0.55\}$, $t_{\text{low}} = \{20.0, 3.0\}$

- **Frequency Trip (FT):** SVP set two groups of $\{f_{\text{high}}\ \text{Hz}, \ t_{\text{high}}\ \text{S}\}$ and $\{f_{\text{low}}\ \text{Hz}, t_{\text{low}}\ \text{S}\}$ points and read them back. Group 1: $f_{\text{high}} = \{61.8, 62.0\}$, $t_{\text{high}} = \{384.0, 0.5\}$, $f_{\text{low}} = \{59.2, 58.5\}$, $t_{\text{low}} = \{299.0, 5.0\}$. Group 2: $f_{\text{high}} = \{61.5, 63.8\}$, $t_{\text{high}} = \{100.0, 10.0\}$, $f_{\text{low}} = \{59.6, 57.8\}$, $t_{\text{low}} = \{299.0, 5.0\}$

- **Frequency Droop (FD):** SVP issued $\Delta f_{\text{OF}} = \Delta f_{\text{UF}} = 0.02$ Hz, $k_{\text{OF}} = k_{\text{UF}} = 0.05$ and $\Delta f_{\text{OF}} = \Delta f_{\text{UF}} = 0.036$ Hz, $k_{\text{OF}} = k_{\text{UF}} = 0.08$ parameters, reading them back, and disabled the function.

- **Enter Service (ES) and Cease to Energize and Trip:** SVP enabled the mode with $V_{\text{low}} = 0.917$ pu, $V_{\text{high}} = 1.05$ pu, $f_{\text{low}} = 59.5$ Hz, $f_{\text{high}} = 60.1$ Hz, 300 s Random Delay, Delay, and Ramp Period; and $V_{\text{low}} = 0.88$ pu, $V_{\text{high}} = 1.06$ pu, $f_{\text{low}} = 59.9$ Hz, $f_{\text{high}} = 61.0$ Hz, 600 s Random Delay, 1 s Delay, and 1000 s Ramp Period. Note: the test criteria is for Enter Service electrical type testing, which does not include any trip testing, so this should be relabeled as to not indicate that it is a trip test.
TABLE 6. Monitoring information test operating points and criteria per IEEE 1547.1.

| Monitoring information parameter | Operating Point A | Operating Point B | Criteria |
|----------------------------------|------------------|------------------|----------|
| Active Power                     | 20% to 30% of DER “active power rating at unity power factor.” | 90% to 100% of DER “active power rating at unity power factor.” | Reported values match test operating conditions within the accuracy requirements specified in Table 3 in IEEE Std 1547-2018. |
| Reactive Power (Injected)        | 20% to 30% of DER “reactive power injected maximum rating.” | 90% to 100% of DER “reactive power injected maximum rating.” | Reported values match test operating conditions within the accuracy requirements specified in Table 3 in IEEE Std 1547-2018. |
| Reactive Power (Absorbed)        | 20% to 30% of DER “reactive power absorbed maximum rating.” | 90% to 100% of DER “reactive power absorbed maximum rating.” | Reported values match test operating conditions within the accuracy requirements specified in Table 3 in IEEE Std 1547-2018. |
| Voltage(s)                       | At or below 0.90 × (ac voltage nominal rating). | At or above 1.08 × (ac voltage nominal rating). | Reported values match test operating conditions within the accuracy requirements specified in Table 3 in IEEE Std 1547-2018. |
| Frequency                        | At or below 57.2 Hz. | At or above 61.6 Hz. | Reported values match test operating conditions within the accuracy requirements specified in Table 3 in IEEE Std 1547-2018. |
| Operational State                | On: Conduct this test while the DER is generating. | Off: If supported by the DER. | Reported Operational State matches the device present condition for on and off states. |
| Connection Status                | Connected: Conduct this test while the DER is generating. | Disconnected: Conduct this test while permit service is disabled. | Reported Connection Status matches the device present connection condition. |
| Alarm Status                     | Has alarms set. | No alarms set. | Reported Alarm Status matches the device present alarm condition for alarm and no alarm conditions. |

TABLE 7. Alarms in the SunSpec Modbus, IEEE 1815, and IEEE 2030.5 information models.

| SunSpec Modbus 701.Alarm | IEEE 1815 B10-19 | IEEE 2030.5 DER.Status:alarmStatus |
|--------------------------|------------------|-----------------------------------|
| • Ground Fault           | • System Commu-   | • Over Current                    |
|                          | nication Error    | • Over Voltage                    |
| • DC Over Voltage        | • System Has Prior-| • Under Voltage                   |
|                          | ity 1 Alarms      | • Over Frequency                  |
| • AC Disconnect Open     | • System Has Prior-| • Under Frequency                 |
|                          | ity 2 Alarms      | • Voltage Imbalance               |
| • DC Disconnect Open     | • System Has Prior-| • Current Imbalance               |
|                          | ity 3 Alarms      | • Local Emergency                 |
| • Grid Disconnect        | • Storage State   | • Remote Emergency                |
|                          | of Charge at Max-| • Low Input Power                 |
| • Cabinet Open           | imum. Maximum     | • Phase Rotation                  |
| • Manual Shutdown        | Usable State of  |                                |
| • Over Temperature       | Charge reached.   |                                |
| • Frequency Above Limit  | • Storage State   |                                |
| • Frequency Under Limit  | of Charge is Too |                                |
|                          | High. Maximum     | • Storage State of Charge is Deple-|
| • AC Voltage Above Limit | Reserve Percentage | ted: Minimum Usable State of Charge|
|                          | (of usable capacity) reached. | Reached. |
| • AC Voltage Under Limit | • Storage State   | • Storage Internal Temperature is |
|                          | of Charge is Too | Too High                           |
| • Blown String Fuse On In-| Low. Minimum      | • Storage External (Ambient) Tempe-|
|                           | Reserve Percentage| rature is Too High                  |
| • Under Temperature      | (of usable capacity) reached. | • Storage External (Ambient) Tempe-|
| • Generic Memory Or Commu-| • Storage State   | rature is Too High                  |
|                         | nication Error    | • Storage State of Charge is Deple-|
| • Hardware Test Failure  | (Internal)        | ted: Minimum Usable State of Charge|
| • Manufacturer Alarm     | • System Commu-   | Reached.                           |

- **Limit Maximum Active Power (LAP):** SVP enabled the function and set the limit to 25%, 59%, 87%, and 45% of nameplate %WMax capacity, checked the active power monitoring point for changes, and disabled the function.

Results and discussion are provided below for each of the protocols.

1) **SunSpec MODBUS**

While completing these experiments, the SunSpec Modbus 700-Series Models were in TEST status and actively being updated by the committee so it was relatively straightforward to report suggested changes and have those modifications made quickly. In this process, a range of issues at the SunSpec model definition, pySunSpec2, SVP Dashboard, and SVP-levels were resolved. Some Modbus points were added and removed. There were missing labels for some points. Scaling/rounding issues were fixed. Point names, data types, units, and enumerations were changed. After these modifications, the SunSpec models and DER simulator functioned as expected during the management function spot checks. Each of the settings and management function parameters were able to be written and read back effectively. To help see the Modbus parameter and interact with DER equipment, the SunSpec Alliance has created a windows program called the SVP Dashboard that allows a user to quickly read a SunSpec Modbus map from a device and make changes to the parameters using a web browser. A screen shot of this tool with the voltage-reactive power model displayed is shown in Fig. 4. Since the SVP Dashboard was constructed
FIGURE 3. Elements of the IEEE 2030.5 XML schema for MirrorMeter used for monitoring information tests.

using the pySunSpec2 Python library like the SVP driver, the python object interactions were the same with the simulated DER. Both of these tools will need to be tested against physical DER devices that have Modbus TCP and Modbus RTU implementations to confirm the full functionality in the future. Using the SVP to automate the IOP experiments, the nameplate, configuration, monitoring, and management experiments were completed in 3 minutes 24 seconds, with a 1 second delay between write and read test steps.

2) IEEE 1815

As described before, not all the IEEE 1547-2018 functionality was included in the EPRI DER Simulator, but it did include many of the grid-support functions. The spot check on CPF confirmed that in DER generating mode overexcited and underexcited PF values could be configured and read back from the DER using the DNP3 interface. To change DNP3 curve-based functions, first the Curve Edit Selector (AI328/AO244) was used to select the curve, set the Curve Mode Type, e.g., VV, VW, etc. (AI329/AO245), number of points (AI330/AO246), the X and Y Units (AI331/AO247, AI332/AO248), and then read/write up to 100 curve point values. The Volt-Var curve index was written to AO217 to indicate which curve should be used when the function was enabled with BO29. This process was performed to store the curve. While it may be necessary for production devices to write specific curves for each of the functions, for the IEEE 1547.1 testing, all the functions used curve index 1, so that implementation errors could be quickly identified. Although, testing the storing and recalling capabilities of the DER would be necessary to certify the device for DNP3 App Note compliance.

VV, WV, CRP, VW, FW, and LAP tests were successful. During the LAP experiments, a packet capture was performed on the loopback interface using Npcap and Wireshark, as shown in Figure 5. The communication between the SVP and the DNP3 Agent were filtered out of the figure to just show the DNP3 traffic between the DNP3 Agent on port 11949 and the DNP3 outstation on port 20000. Packet 395 sets the active power level of the DER to 25% by writing AO88. There is a scaling factor in the DER that converted the 250 value to 25. Packet 435 was the direct operate command which writes a 1 to BO17 to enable the LAP function. The measured active power (AI537) and the Limit Active Power Mode setting (BI69) were requested from the outstation in packet 509, and returned to the master in packet 511. The AO writes set the active power level to 59%, 87% and 45% in packets 629, 880, and 951. The active power measurements from AI537 occur after each change. After issuing each of the active power curtailment commands, the EPRI DER simulator reduces the power output, which is reflected in the GUI and in the measured power point. A screenshot of the DER EPRI Simulator GUI interface after setting the 45% LAP command is shown in Figure 6. The vertical yellow line labeled Wmax in the Active-Reactive Power (P-Q) plane represents the LAP reduction in power. This simulated device was configured to represent a 250 kW PV inverter, so the 45% curtailment changed the power output to 112.5 kW, even though there was 100% DC power input available to it.

3) IEEE 2030.5

In the case of the IEEE 2030.5 spot checks, the SunSpec Server API interface was used to issue a number of changes to the Kitu and EPRI clients. For these experiments the default settings in DefaultDERControl (dderc) were changed for each of the management information points (e.g., grid-support function parameters) in the SunSpec Server. The settings were then read back from the server. This is not a sufficient experiment to confirm the client or DER has updated the settings—but there is no way to do this with the current
IEEE 2030.5 protocol. Fortunately the IEEE 1547.1 test procedure requires the electrical tests for each of these modes, to show that the client effectively updates operations. But grid operators will have to assume that the client has updated its control settings in the field. Additionally, there is no clear way to “disable” an operating mode in IEEE 2030.5. The only option is to set the control points to None, but it is ambiguous whether the client will disable that control mode or leave the default settings running in those cases.

4) GRID OPERATIONS

In addition to testing challenges, there are also a number of operational concerns that were identified through the Management Information Tests. These issues are the result of permitting multiple valid IEEE 1547-2018 interoperability implementations. From the perspective of the grid operator, they would like to send a single command to all devices and have a deterministic response. However, the optionality of some of the Management Information parameters currently makes this impossible. Two examples of this are:

- Do all DER devices need to support six points to create the \( P/Q \) and \( P'/Q' \) \( \text{WV} \) curves? In the case of a mix of four- and two-quadrant DER devices, the grid operator would want to send a single command that would include the \( P'/Q' \) points, but this command may be rejected by DER without storage. Therefore, it is
FIGURE 5. A packet capture of the DNP3 LAP experiment. AO88 is the active power curtailment value, BO17 is the limit active power enable/disable point, and AI537 is the active power measurement point.

recommends that all DER equipment support those points and, for those that do not include storage, $P'/Q'$ points are ignored.

- DER devices historically do not support all the reactive power units (e.g., %WMax, %VarMax, %VarAval, or %VAMax) and will generate an exception if they are commanded into those modes. In fact, defining reactive power as a percentage of nameplate apparent power (%VAMax) is currently not an option in DNP3 or IEEE 2030.5, despite being the units used to define the curves in IEEE 1547 and California Electric Rule 21. If this practice were to continue, for a grid operator to send desired WV or VV operating mode to a nonhomogeneous collection of DER devices, they would first need to query all DER to know what units are supported, translate the set points according to those units, and send that data to the equipment. The use of %VarMax, while common in the inverter industry, is especially problematic because some devices may have different injection and absorption reactive power nameplate ratings or produce different levels of reactive power than required by the standard (i.e., 44% of VAMax for IEEE 1547 Category B equipment) which would likely produce unexpected and nonuniform responses from DER equipment. To promote operational clarity and interoperability, it is recommended that all the communication standards include %VAMax reactive power units and IEEE 1547 be updated with language requiring DER to support %VAMax, at minimum.

IV. STANDARD REVISION RECOMMENDATIONS

These experiments revealed a number of issues, limitations, and ambiguities with the IEEE 1547.1 test procedure and the information models. The requirements for listing products to IEEE 1547.1 are being refined in the American National Standards Institute (ANSI)-approved test procedure, UL 1741 Supplement SB, which was published September 28, 2021. UL 1741 provides additional guidance for test engineers and Nationally Recognized Test Laboratories (NRTLs) to conduct the IEEE 1547.1 type tests in order
to list DER products. The following recommendations were provided to the committee for inclusion in UL 1741 SB and updates to future updates to IEEE 1547.1.

In addition to multiple typographical errors, there were several issues identified in the IEEE 1547 base standard, IEEE 1547.1 test protocol, the DER communication protocols, and associated information models. The following items are suggested for review by the standards development organizations and associated writing committees:

- **IEEE 1547.1-2020**
  - The Configuration Data Tests should use settings points for each of the protocols, not the DER nameplate points. Nameplate data should never be overwritten.
  - Add a procedure for testing the Supported control mode functions in the Configuration Data Test.
  - Indicate how the values are to be changed and clarify an allowable tolerance on the accuracy of the results in the Configuration Data Test.
  - It is not clear that the DNP3 management information tests required that the electrical experiments are done in accordance with IEEE 1547.1 Clause 5.
  - Explicitly state if Operational State of Charge (SoC) is in the Monitoring Information Tests.
  - Indicate how to generate the Monitoring Information Test Operating Points.

- **IEEE 1547-2018**
  - The standard should be updated to clarify what curves DER devices support in order to promote broad interoperability. This includes mandating DER equipment support six points that represent the P/Q and P′/Q′ IEEE 1547 WV curves.
  - IEEE 1547 should be updated to require DER include a preferred, standardized unit for reactive power, preferably %VA_{Max}, in order to reduce the complexity of grid operator systems and minimize the chances of misoperation.

- **General Information Model Recommendations**
  - There is poor alignment between the information models for DER states and alarms, e.g., SunSpec Modbus 701.Alrn, the DNP3 App Note Alarms in BI0-BI9, and the IEEE 2030.5 CSIP alarms from the bit-mapped resource, DERStatus:alarmStatus. The standards development organization should work to harmonize the DER states and alarms.
  - **SunSpec Modbus**
    - Through the course of this research, a number of issues were identified in the SunSpec
FIGURE 7. Elements of the IEEE 2030.5 XML schema for the DER SubscribableResource used for nameplate data and configuration data tests; [a..b] indicates there can be between a and b elements.

Modbus 700-series models and pySunSpec2. This work was performed while the SunSpec models were in TEST status, so those issues could be logged as GitHub issues, and brought to the committee for revision. These included missing points, naming conventions, selection of data types, problems with scale factors, etc. Each were addressed by the SunSpec Models Working Group before going to APPROVED status in April 20, 2021.

- **IEEE 1815**
  - The DNP3 App Note should add Manufacturer, Model, Serial Number, and Version Data to the AI points.
  - The DNP3 information model should to be updated with AO and BO setting points to adjust the configuration data in IEEE 1547.1.
  - Add Anti-Islanding Enable/Disable point.
  - Add %VAMax to list of optional reactive power units.
IEEE 2030.5

- IEEE 2030.5 simply adopts allowed HTTP/HTTPS layer usage patterns for client-server interactions, but clearly indicating that there should be no expectation that sessions will persist would be helpful for improving interoperability. Some implementations may open a session and continue to use that session for multiple GET/POST/PUTs, whereas other implementations may open/close a session for each GET/POST/PUT. Clients and servers must be able to handle any allowed usage pattern.
- There is no clear IEEE 2030.5 mechanism to disable controls.
- There is no visibility into the operating mode of the client/DER. Adding a means to check on the current operating conditions of the client would help support interoperability testing.
- Add Anti-Islanding Enable/Disable point.
- Add %VAMax to list of optional reactive power units.

V. CONCLUSION

The DER and power industry is undergoing a monumental transition with the adoption of the interoperability requirements in IEEE Std. 1547-2018. All devices entering American market sectors will soon be required to have a standardized SunSpec Modbus, IEEE 1815 (DNP3), or IEEE 2030.5 communication interface. In order to prepare for type testing DER devices to the IEEE 1547.1 conformance requirements and providing recommendations back to the standards development organizations, a new IEEE 1547.1 interoperability script and associated communication drivers were created for the System Validation Platform (SVP). This test script was executed against DER simulators running each of the protocols. In this process, the team unearthed multiple issues with the IEEE 1547.1 test procedure, the information models, pySunSpec2, and the DER simulators running each of the protocols. These issues have been raised with the appropriate companies and committees to address these concerns and streamline the roll-out of advanced inverters. The SVP can also be used by DER vendors and nationally recognized testing laboratories to efficiently complete these experiments, thereby reducing the costs for developing these new products and listing them to the revised IEEE 1547.1 standard.

ACKNOWLEDGMENT

The authors would like to thank the contributions of the Smart Grid International Research Facility Network (SIRFN) test protocols test team for continuously working to improve the System Validation Platform (SVP), Sheldon Crow for revising and improving pySunSpec2, The Kitu Systems team for supporting the research project, and the IEEE 1547.1 Interoperability Task Group leadership for discussing the recommendations presented within this article.

REFERENCES

[1] R. Bründlinger, “European codes & guidelines for the application of advanced grid support functions of inverters,” in Proc. PV Syst. Symp. PV Distrib. Syst. Modeling Workshop (Sandia/EPRI), Santa Clara, CA, USA, May 2014.
[2] R. Bründlinger, “Advanced smart inverter and der functions requirements in newest European grid codes and future trends,” Tech. Rep., SolarCanada, Toronto, ON, Canada, Dec. 2015. [Online]. Available: https://www.researchgate.net/publication/299645392_Advanced_smart_inverter_andDER_functions_Requirements_in_latest_European_Grid_Codes_and_future_trends
[3] J. Johnson, S. Gonzalez, and A. Ellis, “Sandia der interoperability test protocols; relationship to grid codes and standards,” in Proc. IEEE Int. Conf. Standards Smart Grid Ecosystem, Bangalore, India, Mar. 2014, pp. 1–7.
[4] California Public Utilities Commission. (2018). Electric Rule No. 21 Generating Facility Interconnections. [Online]. Available: https://www.cpuc.ca.gov/rule21/
[5] Grid Connection of Energy Systems Via Inverters Installation Requirements, Standard AS/NZS 4777.1, Standards Australia, 2016.
[6] Grid Connection of Energy Systems Via Inverters Inverter Requirements, Standard AS/NZS 4777.2, Standards Australia, 2015.
[7] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems, IEEE Std 1547-2018, IEEE, 2018, pp. 1–138.
[8] J. Seuss, M. J. Reno, R. J. Broderick, and S. Grijalva, “Improving distribution network PV hosting capacity via smart inverter reactive power support,” in Proc. IEEE Power Energy Soc. General Meeting, Jul. 2015, pp. 1–5.
[9] J. Seuss, M. J. Reno, R. J. Broderick, and R. G. Harley, “Evaluation of reactive power control capabilities of residential PV in an unbalanced distribution feeder,” in Proc. IEEE 40th Photovoltic Spec. Conf. (PVSC), Jun. 2014, pp. 2094–2099.
[10] A. Summers, J. Johnson, R. Darbali-Zamora, C. Hansen, J. Anandan, and C. Showalter, “A comparison of DER voltage regulation technologies using real-time simulations,” Energies, vol. 13, no. 14, p. 3562, Jul. 2020.
[11] J. Neely, J. Johnson, J. Delhotal, S. Gonzalez, and M. Lave, “Evaluation of PV frequency-watt function for fast frequency reserves,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), Mar. 2016, pp. 1926–1933.
[12] J. Johnson, J. C. Neely, J. J. Delhotal, and M. Lave, “Photovoltaic frequency–watt curve design for frequency regulation and fast contingency reserves,” IEEE I. Photovolt., vol. 6, no. 6, pp. 1611–1618, Nov. 2016.
[13] J. C. Neely, J. Johnson, R. T. Elliott, and R. H. Byrne, “Structured optimization for parameter selection of frequency-watt grid support functions for wide-area damping,” Int. J. Distrib. Energy Resour. Smart Grids, DERlibs/SIRFN Special Issue Pre-standardisation Activities Grid Integr. DERs, vol. 11, no. 1, pp. 69–94, 2015.
[14] Department of Energy Federal Energy Regulatory Commission. (2020). Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators. [Online]. Available: https://www.ferc.gov/sites/default/files/2020-09/1_0.pdf
[15] A. Castillo, J. Flicker, C. W. Hansen, J. Watson, and J. Johnson, “Stochastic optimisation with risk aversion for virtual power plant operations: A rolling horizon control,” IET Gener., Transmiss. Distrib., vol. 13, no. 11, pp. 2063–2076, Jun. 2019.
[16] H. Zhang, Z. Hu, E. Munsing, S. J. Moura, and Y. Song, “Data-driven chance-constrained regulation capacity offering for distributed energy resources,” IEEE Trans. Smart Grid, vol. 10, no. 3, pp. 2713–2725, May 2019.
[17] A. Baringo and L. Baringo, “A stochastic adaptive robust optimization model for a virtual power plant based on stochastic programming,” IEEE Trans. Power Syst., vol. 32, no. 5, pp. 3492–3504, Sep. 2017.
[18] H. Pandžić, J. M. Morales, A. J. Conejo, and J. Kuzle, “Offering model for a virtual power plant based on stochastic programming,” Appl. Energy, vol. 105, pp. 282–292, May 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261913000044
[19] R. Bründlinger, T. Strasser, G. Lauss, A. Hoke, S. Chakraborty, G. Martin, B. Kroposki, J. Johnson, and E. de Jong, “Lab tests: Verifying that smart grid power converters are truly smart,” IEEE Power Energy Mag., vol. 13, no. 2, pp. 30–42, Feb. 2015.
[20] Inverters, Converters, Controllers and Interconnection System Equipment for use With Distributed Energy Resources, Standard UL 1741, Underwriters Laboratories, 2016.
[21] SunSpec Alliance. (2020). OpenSVP. Accessed: Oct. 22, 2020. [Online]. Available: https://github.com/sunspec/svp
[22] J. Johnson and B. Fox, “Automating the Sandia advanced interoperability test protocols,” in Proc. 40th IEEE PVSC, Denver, CO, USA, Jun. 2014, pp. 8–13.

[23] J. Johnson, S. Gonzalez, M. E. Ralph, A. Ellis, and R. Broderick, “Test protocols for advanced inverter interoperability functions–appendices,” Sandia Nat. Laboratories, Albuquerque, NM, USA, Tech. Rep. SAND2013–9875, 2013.

[24] J. Johnson, S. Gonzalez, M. E. Ralph, A. Ellis, and R. Broderick, “Test protocols for advanced inverter interoperability functions–main document,” Sandia Nat. Laboratories, Albuquerque, NM, USA, Tech. Rep. SAND2013–9880, 2013.

[25] J. Johnson, R. Bründlinger, C. Uregro, and R. Alonso, “Collaborative development of automated advanced interoperability certification test protocols for PV smart grid integration,” in Proc. Eur. Photovoltaic Sol. Energy Conf. Exhib. (PVSEC), Amsterdam, The Netherlands, 2014, pp. 1–7.

[26] J. B. Ahn, J. I. Lee, J. Johnson, and J. H. Bae, “Test results for advanced inverter functions based-on IEC 61850–90–7,” in Proc. 5th Asia-Pacific Forum Renew. Energy (AFORE), Jeju, South Korea, 2015, pp. 1–13.

[27] M. Verga, R. Lazzari, J. Johnson, D. Rosewater, C. Messner, and J. Hashimoto, “SIRFN draft test protocols for advanced battery energy storage system interoperability functions,” ISGAN Annex Discuss. Paper, Int. Smart Grid Action Netw., Tech. Rep., 2016.

[28] D. M. Rosewater, J. T. Johnson, M. Verga, R. Lazzari, C. Messner, K. Johannes, J. Hashimoto, and K. Otani, “International development of energy storage interoperability test protocols for photovoltaic integration,” in Proc. EU PVSEC, Hamburg, Germany, 2015, pp. 1–11.

[29] J. Johnson, E. Apablaza-Arancibia, N. B. M. Turiotte, A. Prieur, R. Ablinger, R. Bründlinger, T. Moore, R. Heidari, J. Hashimoto, and C. Cho, “International development of a distributed energy resource test platform for electrical and interoperability certification,” in Proc. IEEE 7th World Conf. Photovoltaic Energy Convers. (WCPEC) Joint Conf. 48th IEEE PVSC, 28th PVSEC 34th EU (PVSEC), Jun. 2018, pp. 2492–2497.

[30] J. Johnson, R. Ablinger, R. Bründlinger, B. Fox, and J. Flicker, “Interconnection standard grid-support function evaluations using an automated hardware-in-the-loop testbed,” IEEE J. Photovolt., vol. 8, no. 2, pp. 565–571, Mar. 2018.

[31] N. Ninad, E. Apablaza-Arancibia, M. Bui, J. Johnson, S. Gonzalez, W. Son, C. Cho, J. Hashimoto, K. Otani, R. Bründlinger, and R. Ablinger, “Development and evaluation of open-source IEEE 1547.1 test scripts for improved solar integration,” in Proc. 36th Eur. Photovoltaic Sol. Energy Conf. Exhib. (PVSEC), Marseille, France, Sep. 2019, pp. 952–957.

[32] N. Ninad, E. Apablaza-Arancibia, M. Bui, J. Johnson, S. Gonzalez, R. Darbali-Zamora, C. Cho, W. Son, J. Hashimoto, K. Otani, and R. Bründlinger, “PV inverter grid support function assessment using open-source IEEE1547.1 test package,” in Proc. 47th IEEE Photovoltaic Spec. Conf. (PVSC), Jun. 2020, pp. 1138–1144.

[33] R. Darbali-Zamora, J. Johnson, N. S. Gurule, M. J. Reno, N. A. Ninad, and E. Apablaza-Arancibia, “Evaluation of photovoltaic inverters under balanced and unbalanced voltage phase angle jump conditions,” in Proc. 47th IEEE Photovoltaic Spec. Conf. Jun. 2020, pp. 1562–1569.

[34] SIREN/STC/Security Psswrd-2/Asccesion, Standard MB-TCP-Security-v21_2018-07-24, Modbus Organization, Inc., 2018.

[35] B. Seal, T. Tansy, B. Fox, A. Pochiraju, J. Johnson, J. Henry, F. Cleveland, W. Colavecchio, T. P. Zgona, S. Hassell, B. Lydic, G. Lum, J. Sharp, C. Tschendel, E. Smith, T. Vargas, D. Hinds, J. McDonald, and S. Robles, “Final report for CSI RD&D solicitation #4 standard communication interface and certification test program for smart inverters,” Electr. Power Res. Inst., Knoxville, TN, USA, Tech. Rep., Jun. 2016.

[36] SunSpec DER Information Model, Test Status, SunSpec Alliance, San Jose, CA, USA, 2020.

[37] DN3 Profile for Communications with Distributed Energy Resources (DERs), Version 2018-08-22, DN3.org, DNP Application Note AN2018-08-22, 2018.

[38] Common Smart Inverter Profile: IEEE 2030.5 Implementation Guide for Smart Inverters, Version 2.1, San Jose, CA, USA, 2018.

[39] J. Johnson and A. Summers, “Automating RT-Lab PHIL experiments to conduct der interconnection conformance tests, parametrized fault experiments, and cybersecurity research,” in Proc. 12th Conf. Real-Time Simul. (RTS), Jun. 2020, pp. 18–19.

[40] SVP Energy Lab. Accessed: Oct. 22, 2020. [Online]. Available: https://github.com/jayatsandia/svp_energy_lab/

[41] IEEE 1547.1 Scripts. Accessed: Oct. 22, 2020. [Online]. Available: https://github.com/jayatsandia/svp_1547.1

[42] SunSpec Alliance. (2020). PySunspec2. Accessed: Oct. 22, 2020. [Online]. Available: https://github.com/sunspec/pysunspec2

[43] B. Ealey, “Overview of EPRI’s DER simulation tool for emulating smart solar inverters and energy storage systems on communication networks: An overview of EPRI’s distributed energy resource simulator,” EPRI, Nashville, TN, USA, Tech. Rep. 300213622, 2018.

[44] J. Obert, P. Cordova, J. Johnson, G. Lum, T. Tansy, M. Pala, and R. Ih, “Recommendations for trust and encryption in der interoperability standards,” Sandia Nat. Laboratories, Albuquerque, NM, USA, Tech. Rep. SAND2019-1490, Feb. 2019.

[45] SunSpec Test PKI Certificates: Application Note, SunSpec Alliance, San Jose, CA, USA, 2019.

[46] SunSpec Alliance. San Jose, CA, USA. SunSpec Certified Registry. Accessed: Dec. 22, 2020. [Online]. Available: https://sunspec.org/certified-registry/

[47] Test Specification for IEEE 1547-2018/SunSpec: Modbus (in Development), SunSpec Alliance, San Jose, CA, USA, 2020.

[48] SunSpec Common Smart Inverter Profile (CSIP) Conformance Test Procedures, Revision 1.2, SunSpec Alliance, San Jose, CA, USA, 2019.

JAY JOHNSON (Senior Member, IEEE) received the B.S. degree in mechanical engineering from the University of Missouri–Rolla, in 2006, and the M.S. degree in mechanical engineering from the Georgia Institute of Technology, in 2009. He is currently a Principal Member of Technical Staff with the Sandia National Laboratories and leads several multidisciplinary renewable energy research projects focused on power system interoperability, control, optimization, and cybersecurity. He is also the Co-Convenor of the SunSpec/Sandia Distributed Energy Resource (DER) cybersecurity workgroup and is investigating cyber-hardening technologies for photovoltaic systems, electric vehicle chargers, wind energy sites, and microgrids.

BOB FOX (Member, IEEE) received the B.A. degree in economics from the University of California at Los Angeles, Los Angeles, in 1983. He is currently a Principal Engineer at SunSpec Alliance, where he leads standards and software development. He actively works on harmonization of information models across DER related standards. He is also a working group participant on IEEE 2030.5, the Vice Chair for IEEE 1547-2018 leading the interoperability content, and the Co-Leader for IEEE 1547.1 interoperability content. He is also a Key Contributor to software tools that facilitate the integration and testing of DER interoperability functionality, such as the System Validation Platform.

KUDRAK KAUR received the B.Tech. degree in computer science in India, in 2013, and the M.S. degree in computer science from Washington State University (WSU), in 2016. She is currently a Software Engineer at Sunspec Alliance. While at WSU, she took part in research related to cyber security in smart grids and working with a smart city testbed. She is currently involved in the DER Connect Project, working with the University of California at San Diego, San Diego, USA.

JITHENDAR ANANDAN received the B.E. degree in electronics and instrumentation engineering from Anna University, Chennai, India, in 2013, and the M.S. degree in computer science from Texas A&M University–Commerce, Commerce, TX, USA, in 2017. He is currently an Engineer/Scientist III with the DER Integration Team, Electric Power Research Institute, Knoxville, TN, USA. He leads several research projects on distributed energy resources management systems (DERMS), communication architectures for DER integration and grid-edge control systems and is also the lead architect for EPRI’s SPIDER testbed. His research interests include information and communication technologies with an emphasis on standards and interoperability for distributed energy resources. ** *