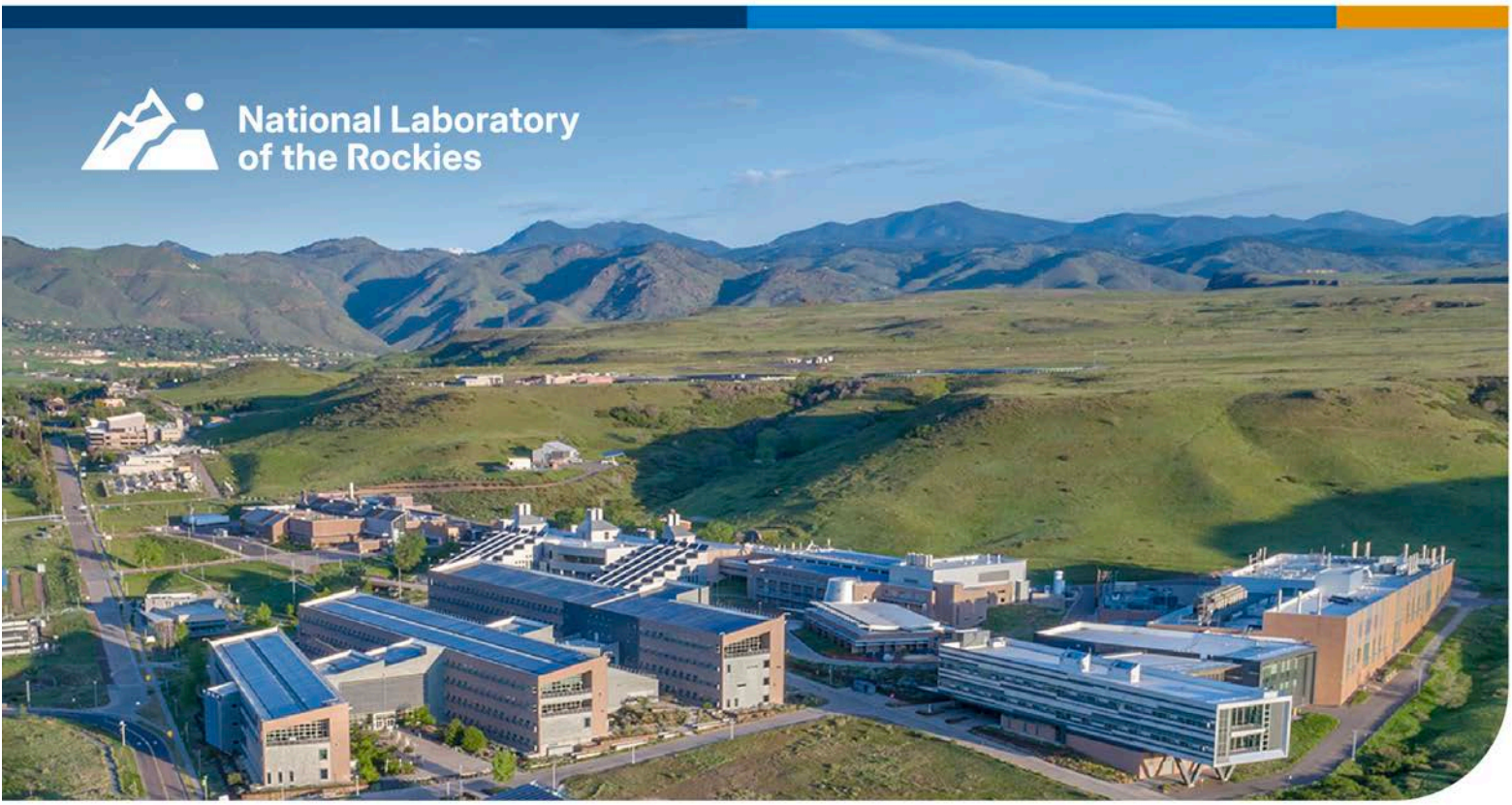

V2XConnect: Harmonizing the Landscape of Bidirectional Charging Codes, Standards, and Communication Protocols

Yukihiro Hatagishi, Pranav Gadamsetty, Saroj Shinde, and Jesse Bennett

National Laboratory of the Rockies

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

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List of Acronyms

AC	alternating current
DC	direct current
DER	distributed energy resource
EV	electric vehicle
EVSE	electric vehicle supply equipment
F/D	frequency droop
IEEE	Institute of Electrical and Electronics Engineers
OCPP	Open Charge Point Protocol
OpenADR	Open Automated Demand Response
PCC	point of common coupling
PCS	power control system
PEL	power export limiting
PIL	power import limiting
PV	photovoltaics
URI	Uniform Resource Identifier
V2B	vehicle to building
V2G	vehicle to grid
V2X	vehicle to everything
V/Q	voltage-reactive power
V/W	voltage-active power

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Table of Contents

Introduction **1**
1 Bidirectional Charging Overview **2**
1.1 Applications 2
1.1.1 V2G 2
1.1.2 V2B 2
1.2 Topologies and Hardware Requirements 3
1.2.1 V2X AC 3
1.2.2 V2X DC 3
2 Interconnection Codes and Industry Standards **4**
2.1 IEEE 1547 5
2.2 SAE J3072 7
2.3 UL 1741SC 9
2.4 UL 3141 10
3 Communication and Control Requirements **13**
3.1 Diverse Landscape 13
3.2 Key Protocols of Interest 15
3.2.1 OCPP 16
3.2.2 SunSpec Modbus 19
3.2.3 IEEE 2030.5 21
3.3 Additional Considerations 24
4 Site Harmonization Development **25**
Conclusion **30**
References **31**
Appendix A. List of Relevant Industry Standards and Grid Codes **33**
Appendix B. List of OCPP 2.1 Fields for IEEE 1547 Functions **36**
B.1 List of OCPP 2.1 Fields for V/W Control per IEEE 1547 36
B.2 List of OCPP 2.1 Fields for V/Q Control per IEEE 1547 37

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List of Figures

Figure 1. V2X applications 2
Figure 2. V2X AC and DC EVSE hardware requirements 3
Figure 3. Bidirectional charging standards landscape 5
Figure 4. V/Q curve [1] 7
Figure 5. Overview of SAE J3072 handshake 8
Figure 6. Oversight: interrupting an EV not following IEEE 1547 9
Figure 7. EV and EVSE coordination concept 10
Figure 8. Overview of PCS Coordination 11
Figure 9. Inverter communication protocol distribution 14
Figure 10. Market breakdown of nonproprietary inverter communication protocol options 15
Figure 11. Modbus server: client 20
Figure 12. Example class diagram [2] 22
Figure 13. Chain of URIs 23
Figure 14. Convoluted communication paths 25
Figure 15. Simplified communication paths with gateway 26
Figure 16. Impact of impedance between PCC and point of DER connection 27
Figure 17. Flex service/interconnection [20] 27
Figure 18. PCS gateway with prioritization 29

List of Tables

Table 1. IEEE 1547 Functional and Minimum Capability Requirements 6
Table 2. UL 3141 PCS Functional Requirements 11
Table 3. UL 3141 to OCPP 2.1 Mapping for Key Remote Control Signals 18
Table 4. Key Charging Profile Purposes 18
Table 5. UL 3141 to OCPP 2.1 Mapping for Key Smart Charging Signals 19
Table 6. SunSpec Modbus Register Map (Except V/Q)[a] 20
Table 7. Example Models for IEEE 1547 21
Table 8. Example Use Cases 28
Table A-1. Relevant Industry Standards and Grid Codes 33
Table B-1. IEEE 1547 to OCPP 2.1 Mapping for V/W 36
Table B-2. IEEE 1547 to OCPP 2.1 Mapping for V/Q 37

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Introduction

The utility grid is constantly evolving with new generation sources and diverse loads from backup generators, backup batteries, rooftop photovoltaics (PV), and flexible charging loads. Each of these technologies presents consumers with an opportunity to work with their local utility to promote grid stability, reliability, and affordability. Through a wide range of programs, utilities are incentivizing the use of these resources to benefit the grid. However, especially for devices with inverters that supply power back to the grid, it is important that these assets comply with local grid codes to ensure human safety, power quality, and grid reliability. As technology expands, individual sites—such as homes, buildings, or campuses with a single point of common coupling (PCC)—are increasing the number of assets providing grid services. These multi-asset sites will require solutions to ensure a cohesive response to grid codes, while navigating the expanding landscape of communication protocols necessary for coordination with each asset.

One of the most promising new technologies that falls under this grid asset landscape is the bidirectional electric vehicle (EV) coupled with bidirectional electric vehicle supply equipment (EVSE) [1]. Bidirectional charging has multiple different topologies and applications. It is a great opportunity for consumers to leverage the value of their EV battery during dwell periods when the vehicle is not needed for driving. Additionally, bidirectional EVs and EVSE are most valuable when their use is coordinated with the grid and optimized for all stakeholders through the use of communication protocols and certifications. This communication ensures all transportation needs can be met, while providing beneficial grid services and complying with all necessary grid codes.

This report introduces the technologies that enable bidirectional charging and how these systems operate. It then outlines the necessary interconnection codes and industry standards that govern the operations of grid-tied inverters, including those in bidirectional charging. Implementing multiple assets at a site presents a key challenge in the complex landscape of communication protocols and proprietary systems designed to coordinate these assets. Finally, in Section 4 we propose a single gateway solution to harmonize these communications between all assets across an entire site for a cohesive response to grid codes and utility programs that is flexible enough to support a range of market options.

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1 Bidirectional Charging Overview

As electrification evolves, it is clear that EVs present a value proposition that expands beyond transportation services: flexibility as an energy resource. The dense traction batteries that store the majority of electricity needed to operate the vehicle present opportunities for flexible charging or even the ability to act as a generation source. Bidirectional charging leverages the energy stored in an EV battery and discharges that energy for use outside the vehicle. The following sections outline different bidirectional charging applications, generically referred to as vehicle to everything (V2X), as well as the different topologies that can enable V2X solutions.

1.1 Applications

V2X applications are primarily defined by the intended use of the discharged energy. There are a wide range of V2X applications, as highlighted in Figure 1, from the simplest direct power from the vehicle to individual loads (V2L) (most common in power outlets around the vehicle) to some of the most complex solutions for off-grid island mode requiring grid-forming capabilities. This report focuses on two applications—vehicle to grid (V2G) and vehicle to building (V2B)—that both require a sustained grid connection but have energy objectives that are grid-centric and building-centric, respectively.

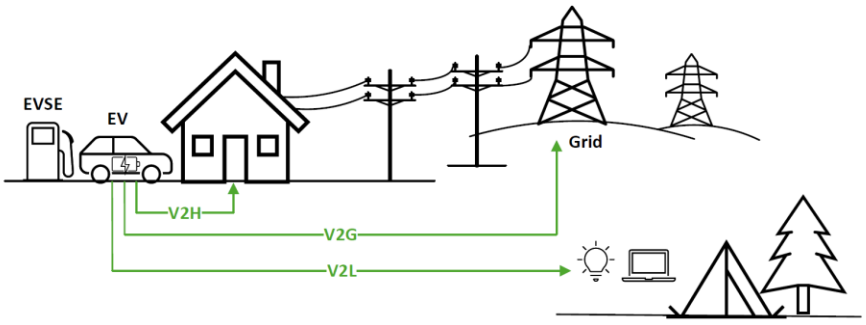

Figure 1. V2X applications

1.1.1 V2G

V2G applications focus on objectives that are developed from utility programs and often require direct communications to or from utility systems. In these applications, the EV battery is scheduled to serve as a utility energy asset, and remuneration is generally provided to the vehicle owner for the grid services provided. The most common grid services provided from this application are demand response and frequency support, but future programs could enable more precise objectives that benefit distribution systems in addition to bulk power supply. Two key considerations that must be supported for these applications are the source of utility communication signals and the optimization of EV charging and discharging in coordination with transportation and grid objectives.

1.1.2 V2B

V2B applications focus on objectives that are in coordination with site needs and constraints during normal operations with a sustained connection to the local utility. In these applications the EV battery is scheduled to serve as a site energy asset and is generally designed to reduce the need for capacity investments or mitigate costly operating expenses. The most common site

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objectives are to either enforce a net power ceiling to avoid overloading service equipment (often limited at the PCC) or optimize the site power profile to mitigate costly demand charges or peak energy pricing. Two key considerations that must be supported for these applications are centralized optimization and communication to all site assets (typically across multiple communication protocols) and the forecasting of loads and generation sources to schedule optimized operations of all energy assets.

1.2 Topologies and Hardware Requirements

In addition to the different applications, there are also different V2X topologies with unique hardware requirements for each. These topologies are defined by the form of power that is transferred between the EV and EVSE. Similar to the two conventional charging topologies, V2X AC passes alternating-current (AC) power from the vehicle's onboard charger to the EVSE, while V2X DC passes direct-current (DC) power directly from the EV battery to the EVSE, before the EVSE must invert this DC power to an AC power output for use on the grid. Each of these topologies is outlined in Figure 2, with more details on each outlined below.

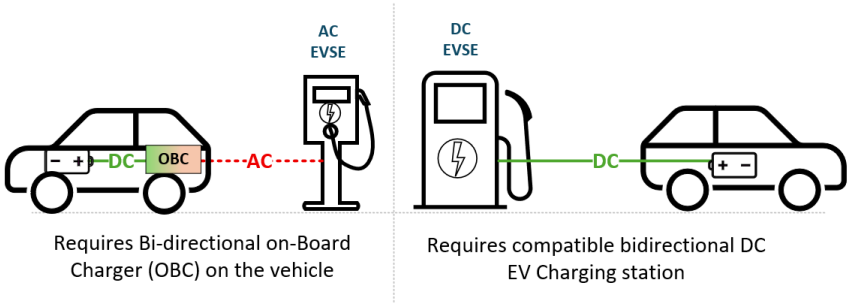

Figure 2. V2X AC and DC EVSE hardware requirements

1.2.1 V2X AC

V2X AC charging provides a more economic approach to extract energy from an EV battery for building or grid services. The most common architecture for this approach is for the onboard charger that supports AC charging to also have conventional inverter capabilities that convert DC power from the battery to AC power for discharging off the vehicle. This approach includes much of the bidirectional hardware within the EV and simplifies the complementary off-vehicle hardware that must be installed to facilitate. However, this simplified architecture does add some complication for grid interconnections with the advent of a mobile inverter. This situation is unique, compared to conventional systems with permanently installed grid-connected inverters.

1.2.2 V2X DC

V2X DC charging provides a more conventional approach to supply power for building or grid services. The most common architecture for this approach is for DC EVSE to have bidirectional charging capabilities that may supply or extract DC power directly to or from the EV battery. This approach requires adaptations to conventional EV hardware designs, but must be supported with more robust charging infrastructure capable of inverting DC power to AC power for exporting to the grid. However, additional hardware requirements for V2X DC, compared to V2X AC, result in a more conventional grid interconnection, with a permanently installed grid-connected inverter at the point of interconnection.

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2 Interconnection Codes and Industry Standards

As commercial and residential sites consider new energy technologies to support growing loads, many will consider the use of distributed energy resources (DERs). A DER is a combination of devices that can export power to the grid or local loads following the grid code, leveraging energy storage or power generation. Some examples include battery energy storage systems, natural gas generators, PV panels, and bidirectional EVSE. Examples of key DER elements are AC to DC converters (namely inverters) and gateways (i.e., communication controllers).

Although these DER assets could be intended to either support site loads or provide grid services, most applications will still operate in a grid-connected environment. Therefore, in order to maintain power quality and reliability, these devices must be approved for interconnection by the utility. The approval process differs across utilities. For example, the California Public Utilities Commission (CPUC) uses a process called Rule 21[2] with different implementations for each investor-owned utility under CPUC's jurisdiction.[1] Rule 21 offers fast-track review to facilitate the approval process, with one of the criteria being listing to UL 1741SB [3] to verify the DER is "suitable" for grid interconnection.

UL 1741SB defines conformance test requirements to verify compliance with IEEE 1547-2018 [4]. It is one of the criteria for residential DERs under Rule 21 fast-track review. However, some circumstances, such as V2G AC, involve a grid-connected inverter that is mobile, such as in the EV, and not permanently installed. In these circumstances, the alternate certification is UL 1741SC. This certification is for the EVSE, which will be designed to verify the connected EV contains an inverter that is designed and tested per the automotive standard, namely SAE J3072 [4]. SAE J3072 outlines the IEEE 1547 performance requirements for an EV's inverter and is the foundation for UL 1741SC's verification process.

In addition to IEEE 1547, some sites with energy assets may be subject to power import and export limits to maintain grid reliability and stability. UL 3141 [6] is a safety and performance standard that defines the functionality for a power control system(PCS) to meet these power import and export limits across a site of energy assets. Although these requirements are separate from IEEE 1547, it is important to understand that a site may be subject to both standards.

As highlighted in Figure 3, all energy assets at a site connected to the grid must comply with the requirements of IEEE 1547 to maintain grid reliability and stability. However, the certification process for the testing to ensure these devices will support those requirements are different for stationary and mobile DERs, requiring UL 1741SB and UL 1741SC, respectively. This figure also highlights UL 3141 requirements that will be placed on the meter and supported by a site PCS.

[1] Each investor-owned utility has its own version of Rule 21.

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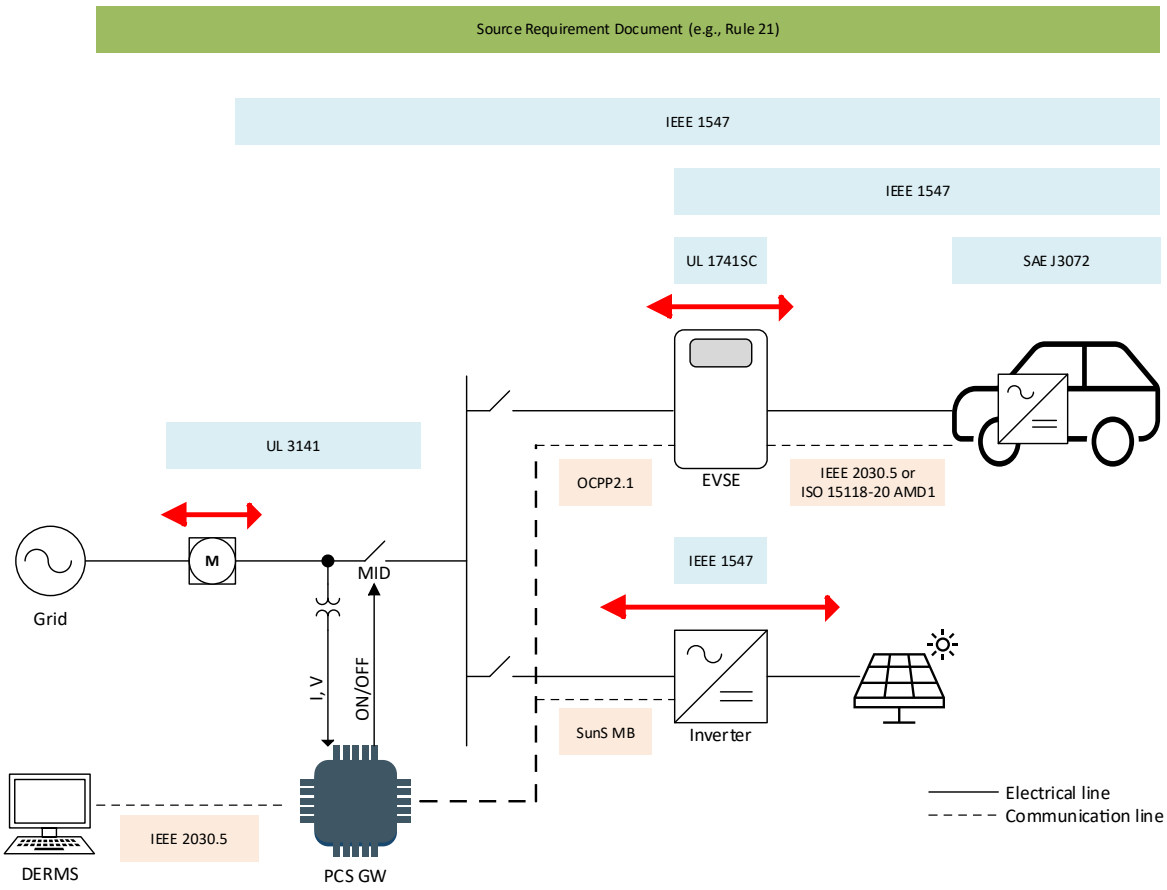

Figure 3. Bidirectional charging standards landscape

2.1 IEEE 1547

One of the most commonly referenced standards for technical grid interconnection requirements is IEEE 1547, which is the standard that sets forth technical requirements for DERs intended to be interconnected to the distribution system.[2] In order to maintain power quality and system reliability, utilities often require any DER to comply with the functional and minimum capability requirements summarized in Table 1.

[2] For bulk system interconnection, IEEE 2800 applies.

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Table 1. IEEE 1547 Functional and Minimum Capability Requirements

Requirement Type [a]	Description	Example Requirements
Enter service	Through this requirement, a DER verifies that the grid is in the condition for the DER to export power. The condition includes but is not limited to grid voltage and the permission to operate.	Permit service, enter service ramp
Voltage and frequency support	These sets of requirements define how a DER determines the amount of active and reactive power to output. Some are constant and others are autonomous (i.e., based on a piecewise linear curve).	Voltage-reactive power (V/Q), frequency droop (F/D), constant power factor
Power quality	This defines a DER's output current quality to reduce the impact to the grid voltage quality.	Current distortion, DC current
Response to abnormal conditions	These sets of requirements define necessary response to abnormal voltage and/or frequency conditions, such as undervoltage. Because those conditions are typically triggered by an incident on the grid, the expectation is to withstand for a moment and then trip.	Voltage trip and ride-through, anti-islanding
Communication interoperability	This sets forth what data need to be available for a utility to read and write, and list of protocols to be implemented.	Information model, required protocol

[a] This does not intend to fully align with IEEE 1547's clauses.

Most of the requirements specified in this standard need to be met at the reference point of applicability. In a small site with a small DER, such as a rooftop solar system at a small residential home, the reference point of applicability can be at the point of DER connection. Otherwise, the reference point of applicability is at the PCC, which is typically at the meter. This has created a challenge to large sites, as each DER needs to be able to capture AC voltage and frequency at the meter, requiring additional wiring, logic, and/or communication.

The functions described above can have different settings to accommodate different needs across the locations and utilities. For example, in V/Q, a DER monitors AC voltage (at the reference point of applicability) and adjusts its reactive power autonomously, following the prescribed piecewise linear curve (see Figure 4 for an example curve). As illustrated, V/Q function can be configured with different points, allowing the utility to tailor the response.

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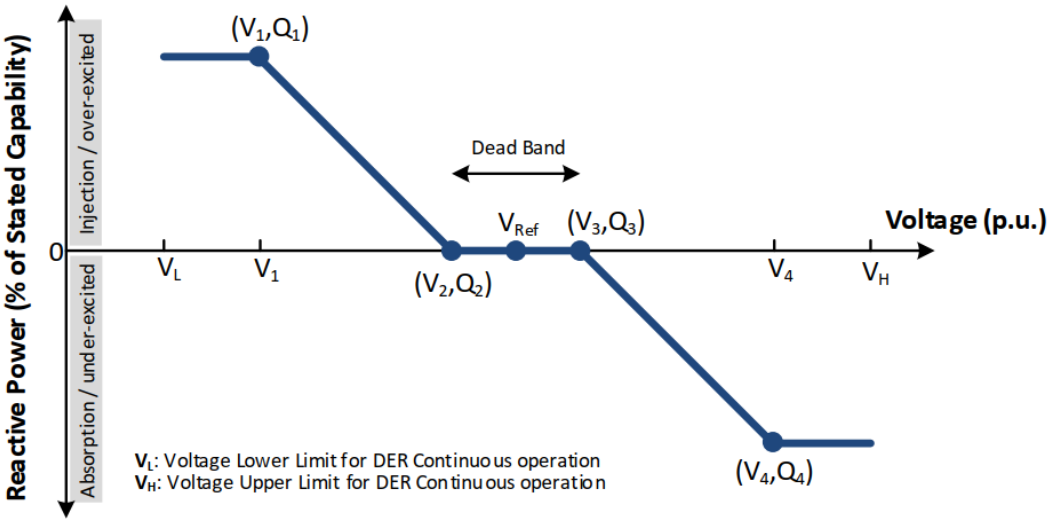

Figure 4. V/Q curve [1]

Different models of DERs have their own nameplate and configurations, such as maximum active power. These are expected to be read and/or written by the utility and/or the DER operator. To facilitate interoperability, IEEE 1547 also establishes the requirements for data exchange, data model, and protocol.

For the protocol requirement, per Clause 10.7 in IEEE 1547:2018 and Table 41 in the same document, either of the following three communication protocols is required to be *implemented* at minimum:[3]

- DNP3 [7] over Ethernet.
- SunSpec Modbus [8] over Ethernet or RS-485.
- IEEE 2030.5 [9] over Ethernet.

Additional protocols, including proprietary ones and other physical layers, are permitted as long as both the following conditions are met:

1. At least one of the three communication protocols mentioned above is implemented.
2. A mutual agreement with the utility has been established.

Note that the protocol requirements in IEEE 1547 apply at the utility interface to communicate with the utility for IEEE 1547 compliance purposes. The protocols and physical layers used for communication within the DER and site are out of scope of this standard and are consequently not constrained by the standard. The proposed single gateway solution outlined in Section 4 will be responsible for meeting these communication requirements set forth in IEEE 1547.

2.2 SAE J3072

A unique element for V2G AC charging is the separation of the permanently grid-connected asset, the EVSE, and the inverter that will provide AC power, which is inside the EV. This scenario requires a pair of devices designed to work in harmony. All EVs intended for

[3] This does not preclude other protocols being used. This is simply a minimum implementation requirement.

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performing V2G AC with *any* EVSE must comply with SAE J3072, which is complementary to the requirement that EVSE be listed to UL 1741SC. Note that today's V2G DC systems in the market include the inverter within the permanently installed EVSE, so UL 1741SC is not necessary.

At its heart, SAE J3072 requires the EV to comply with IEEE 1547 and the compliance to be evaluated by UL 1741SB. Therefore, the SAE J3072-compliant EV is comparable to a stationary DER that is compliant with IEEE 1547.

SAE J3072 also addresses the mobile nature of EVs. In other words, an EV can be connected to different locations with different limits (such as maximum active power) and/or different configurations for IEEE 1547 requirements (such as V/Q curve points as described in Section 2.1.) The coordination and hence the adjustment is defined in the standard, also referred to as "J3072 handshake." Notably, as described in Figure 5, the EVSE verifies that the EV's model number (i.e., ISMN) is included in the "authorized EV list." To date, the list does not exist. Only after a successful handshake can the EVSE authorize the EV to discharge. The EVSE is required to prevent the EV from discharging otherwise.

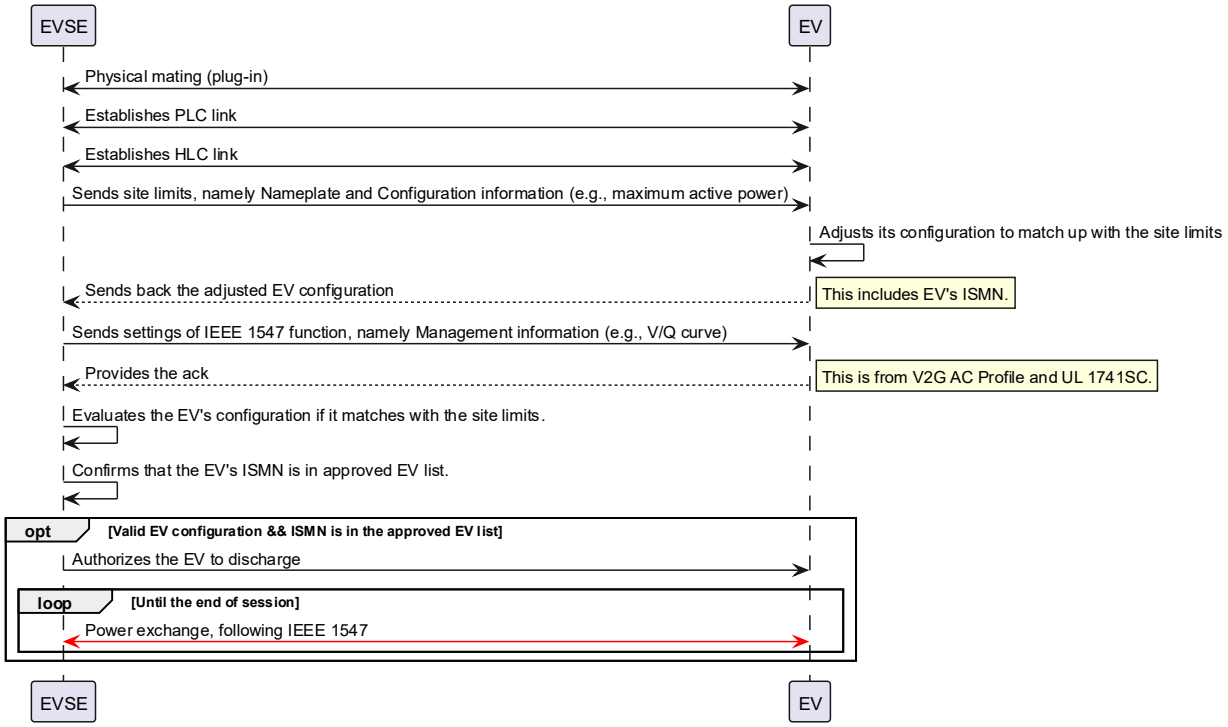

Figure 5. Overview of SAE J3072 handshake

SAE J3072 defines possible protocols to be used for the standard: IEEE 2030.5 and SunSpec Modbus. While ISO 15118-20 [10] is *acknowledged* in the standard, it highlights that ISO 15118-20 does not support SAE J3072. To date, there is an ongoing revision to the standard to add ISO 15118-20 Amendment 1 to the list of protocols.

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2.3 UL 1741SC

While an SAE J3072-compliant EV is in principle compliant with IEEE 1547 and is evaluated by UL 1741SB, it may not be listed. Listing has been utilized in interconnection approval processes and in this situation requires UL 1741SC to address the gap and allow for the bidirectional charging system to interconnect to the grid.

UL 1741SC is applicable to an AC EVSE intending to perform V2G AC along with an SAE J3072-compliant EV. Besides referencing existing EVSE standards, it includes a concept called oversight. The objective of oversight is to support the grid safety by:

- Performing voltage and frequency trip as defined in IEEE 1547.[4]
- Performing trip against line-to-neutral overvoltage.[5]
- Preventing unauthorized discharge, aligning with SAE J3072.

As the EVSE only has a contactor to disconnect the EV from the grid, a trip will require opening the contactor. To reduce the likelihood of breaking under load, oversight requires the EVSE to ride-through (i.e., not trip) until a certain duration (e.g., 60 ms) before clearing time.

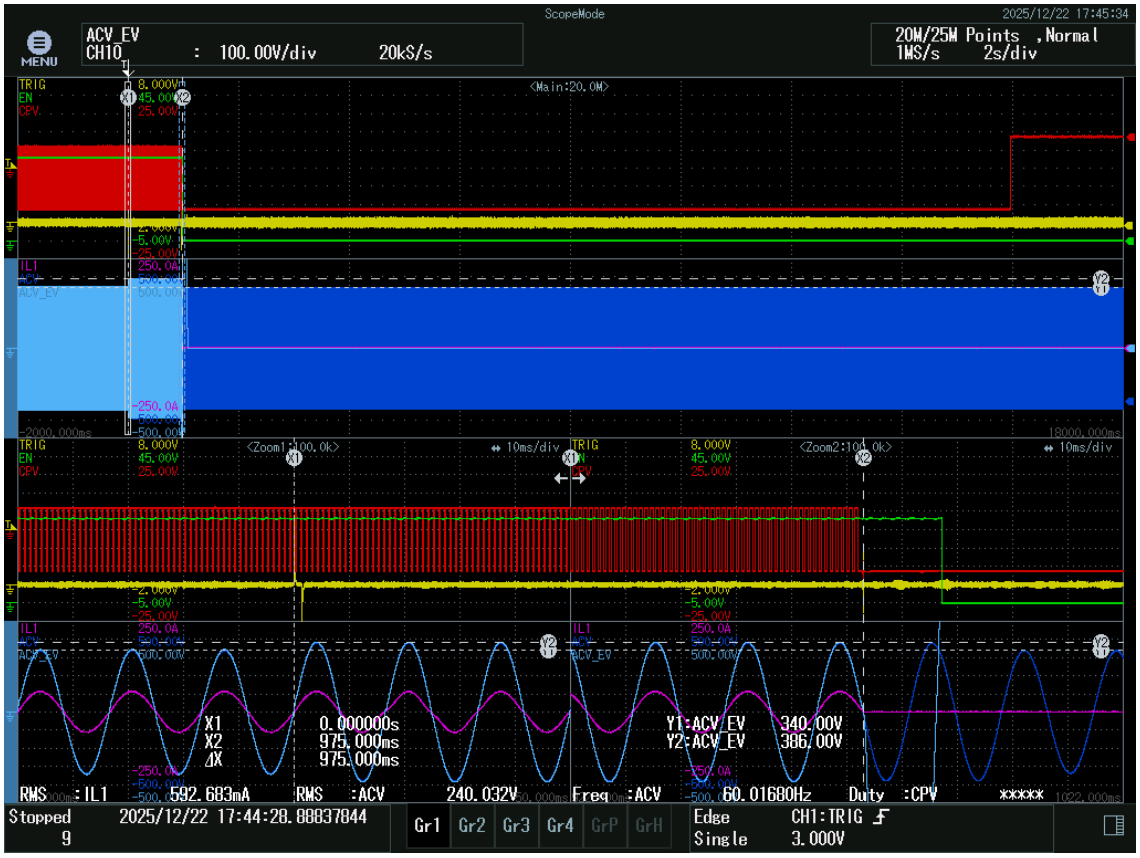

Figure 6. Oversight: interrupting an EV not following IEEE 1547

[4] SAE J3072-compliant EVs also perform voltage and frequency trip, as required by IEEE 1547.
[5] Level 2 AC charging does not have neutral connection between the EVSE and EV.

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However, as a DER complying with IEEE 1547, an EV can trip barely before the clearing time. Therefore, the extended ride-through requirement to the EVSE still leaves the chance of breaking under load, and hence a harmonization between SAE J3072 is needed. Requiring EVs to trip beforehand (i.e., shortening the clearing time from IEEE 1547) will make sure that the EV trips before the EVSE does. The example is illustrated in Figure 7.

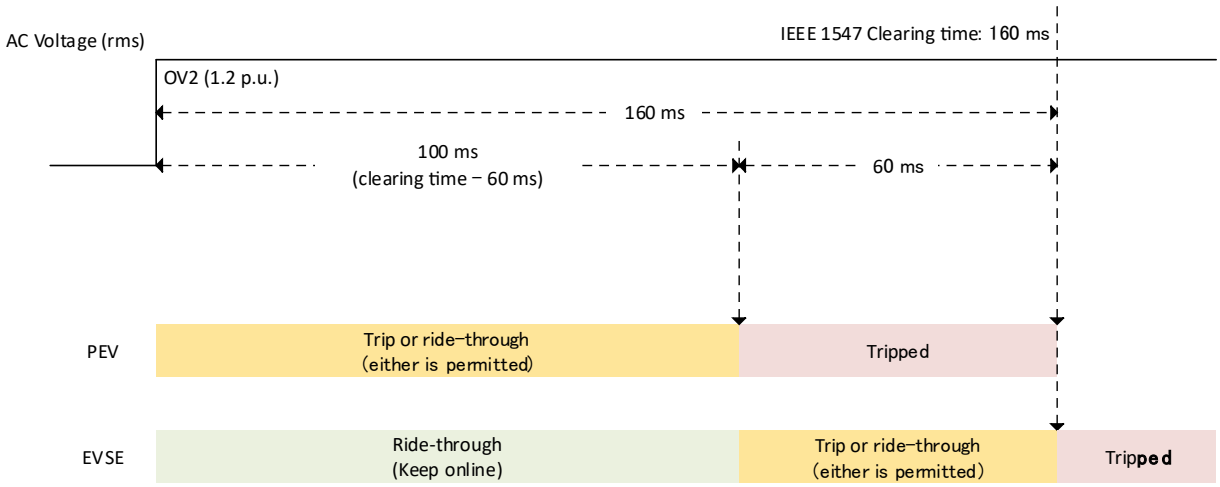

Figure 7. EV and EVSE coordination concept

2.4 UL 3141

In addition to IEEE 1547, some utilities require systems to comply with power import and export limits to support grid capacity constraints. UL 3141 is a safety and performance standard that defines requirements for a PCS used in DER installations. The standard was developed to address the increasing complexity of DER-integrated electrical systems and evolving grid constraints that impose limits on power import and export at a PCC. A PCS is a system consisting of one or more devices that actively monitor, limit, and control current or power on conductors or bus bars as set forth by UL 3141. PCS functionality can be implemented for both single-source and multisource electrical systems (as shown in Table 2) and is intended to ensure safe, predictable operation under normal and dynamic grid conditions. Note that this document uses the terms PCS and PCS controller interchangeably outside this section, except where otherwise specified.

UL 3141 defines multiple PCS functional categories, each addressing specific control and protection objectives, as defined in Table 2.

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Table 2. UL 3141 PCS Functional Requirements

Category	Description
Power import limiting (PIL)/ power export limiting (PEL) PCS	Designed to manage power exchange at the point of interconnection such as PCC.
Multisource PCS	Bus bar overload control: Provides overload protection for monitored bus bars within panelboards. Feeder conductor overload control: Provides overload protection for controlled feeders and/or to service conductors. Branch conductor overload control: Provides overload protection for branch conductors between panelboards and connected sources or loads.
Single-source PCS	Designed to provide overload protection through load management when only a single source of supply is present.

Loads or sources with PCS functionality that act as active protective devices are considered part of the PCS. Figure 8 shows a brief overview of the PCS system for PEL/PIL PCS as an example.

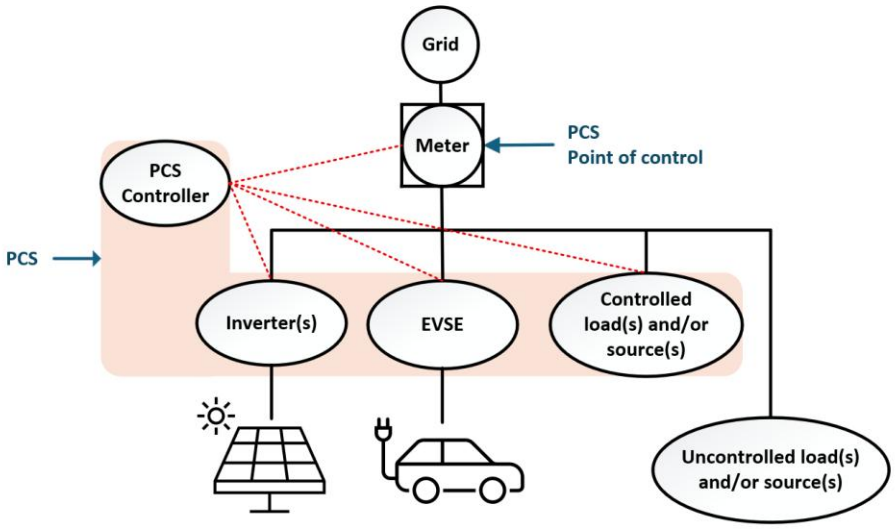

Figure 8. Overview of PCS Coordination

These PCS functional categories collectively can control power flow between DERs, local electrical systems, and the grid. UL 3141 defines several key architectural and safety-related constraints for PCS. For example, the PCS controller responsible for overload protection is required to be located on-site, and reliance on cloud-based or web-dependent overload control is not permitted. For PIL and PEL control functions only, PCS control settings may be adjusted remotely by permission of the utility. While UL 3141 specifies the file format for scheduling import and export, it does not impose a specific communication protocol. In the event of a communication failure, the PCS must transition to a safe state that maintains overload protection and enforces defined power limits. In addition, manufacturers are required to clearly list all devices like external current sensors, PCS controllers, controllable loads, and inverters for proper operation of PCS.

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Testing and Performance Framework:

UL 3141 provides a structured, testable framework for evaluating PCS functionality. Testing is designed to verify that a PCS can accurately and safely provide overload protection and control import and export of power to the grid with the following key testing categories:

- General and normal operating tests: Verify that when a control command or step change is applied, the PCS responds within a defined time (typically ≤30 seconds, with some conditional exceptions) and maintains power or current at the testpoint (such as PCC) within ±7.5% of the set point.
- Step-change tests: Evaluate PCS response to sudden changes at the testpoint (such as PCC) in load or generation, including load increases or decreases and rapid changes in DER output (e.g., PV inverter ramping).
- Single-source PCS tests: Confirm correct overload protection and import/export limiting when only one source of supply is present.
- Multisource PCS tests: Assess PCS coordination across multiple interacting sources, ensuring limits are maintained without instability or unintended overload.

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3 Communication and Control Requirements

As mentioned in Section 2.1, IEEE 1547 defines the technical requirements for interconnection of DERs with the grid. Employing relevant communication protocols plays a crucial role in enabling the desired interaction with a DER and supporting necessary grid benefits. Hence, IEEE 1547 requires at least one of the following protocols to be implemented at minimum:

- DNP3 over Ethernet.
- SunSpec Modbus over Ethernet or RS-485.
- IEEE 2030.5 over Ethernet.

The standard also allows the use of additional communication protocols, including proprietary ones if there is a mutual agreement with the utility. The use of industry standard protocols enables a more open market environment for consumers, while the option for proprietary systems enables a more customized solution space allowing for the development of additional functionality. This results in a diverse set of market options, limiting interoperability, and potentially benefiting from a solution that communicates across multiple protocols.

A market study was performed to investigate the landscape of communication protocols supported by inverters currently in production. The list of inverters for this study was compiled from multiple sources including, but not limited to:

1. UL-listed inverters in UL's Product iQ database.
2. Approved smart inverter list from PPL Electric Utilities [11]
3. SunSpec Alliance contributing members [12].

3.1 Diverse Landscape

A total of 751 inverters from 50 companies have been analyzed in this study. This list comprises PV inverters, battery inverters, microinverters, and bidirectional converters (including chargers). Figure 9 shows the distribution of models that support nonproprietary communication protocols versus proprietary ones.

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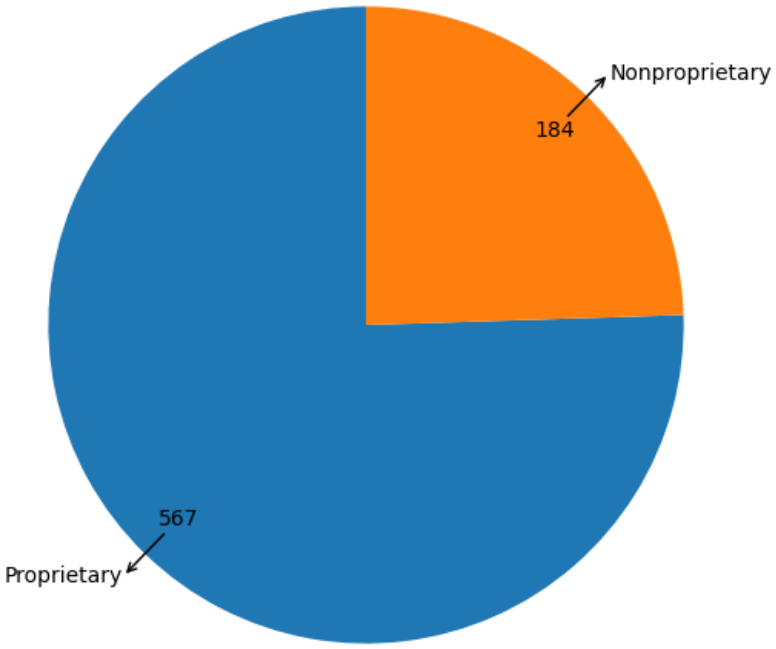

Figure 9. Inverter communication protocol distribution

This shows that the vast majority of inverters currently in the market only support proprietary communication protocols, with just 184 models supporting at least one nonproprietary protocol. The study also reveals that SunSpec Modbus and IEEE 2030.5 are the most popular nonproprietary communication protocols. In addition to these two, four nonproprietary protocols outside of the three required by IEEE 1547 are also supported by inverters. These are Open Charge Point Protocol (OCPP) 1.6j [13], Open Automated Demand Response (OpenADR) [14], Process Field Network (Profinet), and Process Field Bus (Profibus), in decreasing order of popularity according to the market study. The distribution of number of inverter models supporting each of these six nonproprietary protocols is shown in Figure 10.

OCPP 1.6j is a popular communication protocol with increasing adoption across EVSE. OpenADR is an open communications data model designed to facilitate demand response events initiated by a utility upon customer-side equipment such as a smart thermostat, water heater, solar/inverter system, lighting control, or industrial control. Profibus is a widely used, vendor-independent, serial-based industrial protocol, while Profinet is the modern version of Profibus based on industrial Ethernet. These two protocols are designed for communication in automation, supporting a wide array of devices like drives, motors, input/output devices, sensors, robots, and actuators.

Due to the differing motivation behind the definition of these six nonproprietary protocols, there is no straightforward way to harmonize these communications. This is further exacerbated by the 45 distinct proprietary communication protocols used by the 567 models mentioned in Figure 9.

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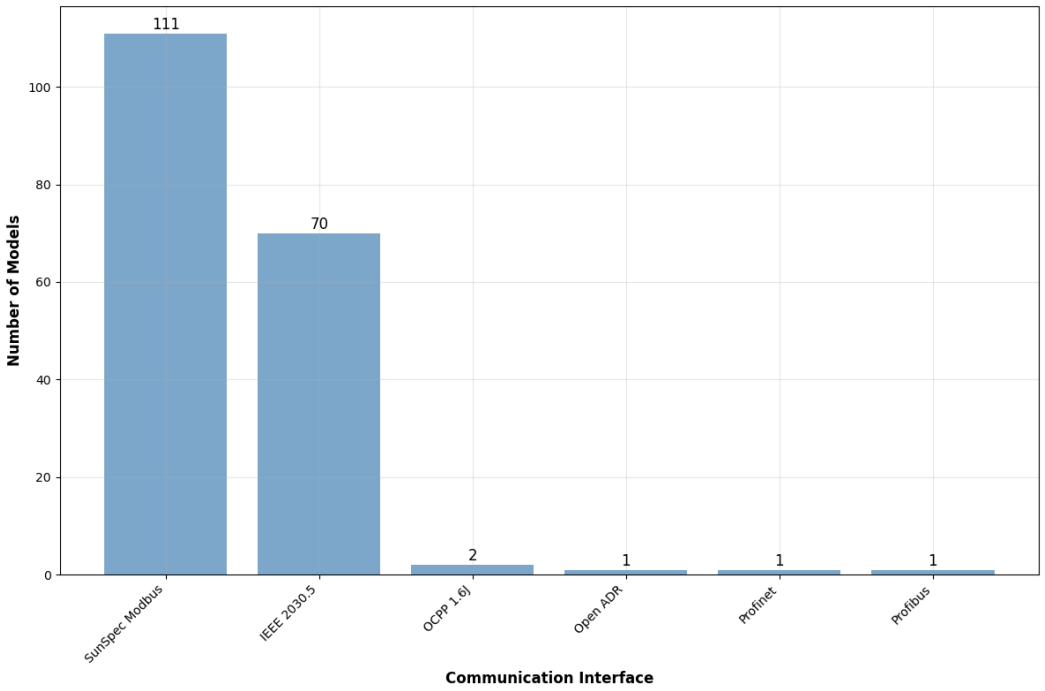

Figure 10. Market breakdown of nonproprietary inverter communication protocol options

The sheer number of distinct proprietary communication protocols adds complexity in achieving interoperability across all inverter models in the market due to the volume of specific translations required. Thus, for any single gateway that needs to perform translations and coordinate multiple types of DER assets, using a limited set of popular nonproprietary communication protocols is the most optimal option.

3.2 Key Protocols of Interest

The market study shows that SunSpec Modbus and IEEE 2030.5, which also form part of the minimum required protocols per IEEE 1547, have the highest adoption rate of all nonproprietary protocols. In addition to these two protocols supported by stationary DERs (PV and battery inverters), OCPP 1.6 is a popular communication protocol used by EVSE to communicate with a charge station management system or aggregator.

The newest version of this protocol, OCPP 2.1 [15], which was released in 2025, introduces key messages and functional blocks such as bidirectional power transfer and DER control. These enable exchange of crucial information such as nameplate information, power settings, and parameter settings, thereby unlocking IEEE 1547 support. In contrast to OCPP 1.6, OCPP 2.1 also establishes native support for ISO 15118-2 [16] and ISO 15118-20 [17], which are popular protocols used for EV-to-EVSE communications. Additionally, in-site communication is beyond the scope of IEEE 1547 (explained in Section 2.1). Hence, leveraging OCPP 2.1 is a reasonable choice to facilitate communication between the gateway and the EVSE for DER control and between the charge station management system and EVSE for managed charging.

Thus, these three communication protocols, namely OCPP 2.1, SunSpec Modbus, and IEEE 2030.5, have been chosen to consolidate the interactions of multiple types of DER assets via the

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single gateway solution. Each of these three protocols and their path to support IEEE 1547 are described in further detail in the following sections.

3.2.1 OCPP

OCPP is an open communications protocol developed by the Open Charge Alliance to enable interactions between EVSE and the charge station management system. This protocol is designed to be vendor agnostic and hence enables communication interoperability between any EVSE manufacturer and relevant EV charging stakeholders. In the context of this report, OCPP will enable the PCS gateway to coordinate with EVSE in compliance with IEEE 1547, while OCPP may also be used for separate charge station management system objectives, such as access control and charge session status metrics.

Released in 2015, OCPP 1.6 is the most widely deployed OCPP standard but lacks a few useful features required to fully support IEEE 1547. On top of the smart charging capabilities defined in OCPP 1.6, OCPP 2.0.1 introduced more capabilities such as frequency support and local load balancing in addition to native support for bidirectional charging and ISO 15118-2 communications with the EV. OCPP 2.1 added native support for ISO 15118-20 enabling V2X, and crucially, new functional blocks called "DER Control" and "Energy Management System" explicitly enabling support for energy management using DERs. These additions in OCPP 2.0.1 and OCPP 2.1 enable compatibility with IEEE 1547. OCPP 2.1 Edition 1 is now officially published as an IEC standard, IEC 63584-210: 2025 [18]. This section serves as an overview of the protocol functionality in reference to its incorporation as part of a single gateway solution.

OCPP 2.1 describes the following message field definitions that can be used for supporting IEEE 1547 functions:

- *SetDERControl*: This message is designed to communicate DER control settings such as voltage trip curves, frequency trip curves, reactive power curves and parameters, active power curves, and frequency droop, among other parameters. These settings can also be scheduled using the "start time" and "duration" fields.
- *ClearDERControl*: This message allows the charge station operator to clear any default and/or previously set DER controls settings in any EVSE.
- *GetDERControl*: This message enables the charge station operator to retrieve currently active DER settings of any EVSE. The EVSE then uses the *ReportDERControl* message to respond with the details of the currently active DER settings.
- *ReportDERControl*: EVSE uses this message in response to a *GetDERControl* message initiated by the charge station operator to communicate its currently active DER settings.
- *NotifyDERAlarm*: This message is used by the EVSE to inform the charge station operator of any grid event that has caused a fault. Additional information like DER control type and the type of grid event that caused this fault is also included as part of this message. An "ended" flag can be used by the EVSE to inform the charge station operator that this fault alarm has ended.
- *NotifyDERStartStop*: This message is used by the EVSE to communicate which DER control is taking over and what caused it. Similarly, this message is also used to indicate when this event ends with an "ended" flag.

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- *DataTransfer:* This message can be used by either EVSE or the charge station operator to initiate a vendor-specific information exchange. This message requires vendor-specific implementation on both the EVSE and charge station operator.

All messages in OCPP 2.1 are designed in a request/response pair format in which each message's "request" can be initiated by the EVSE, charge station management system, or both. Some of the fields in each message's field structure are defined as "optional." This means that, in practice, some of the fields in a specific message can be omitted by the sender. OCPP 2.1 defines the information embedded within each of its message's structure while considering the constraints/limitations that arise from a request/response-based communication format.

OCPP Response to IEEE 1547

OCPP 2.1 has smart charging, bidirectional power transfer, and DER control functional blocks in addition to the messages described above, with the intention to support IEEE 1547 functions such as voltage-active power (V/W) and V/Q. Table B-1 and Table B-2 provide a detailed mapping of OCPP 2.1 message fields to IEEE 1547 parameters for these two functions. These two functions have been used in this report as an example to depict OCPP 2.1's mapping with IEEE 1547.

Additionally, OCPP 2.1 only defines the message structure but does not impose any requirements on the protocol's implementation, with the protocol allowing the use of some message fields to be optional. OCPP 2.1 defines a prescribed sequence of information exchange for various use cases and scenarios, but this description is limited to primary stakeholders only. As a result, clarifying the practical challenges associated with implementation of interaction between the EV charging stakeholders using OCPP2.1 to satisfy IEEE 1547 requirements is crucial for designing a robust gateway solution.

Thus, implementation of interaction between the EV charging stakeholders using OCPP 2.1 to satisfy IEEE 1547 requirements and the associated practical challenges will need to be clarified.

OCPP Response to UL 3141

OCPP 2.1 does not directly specify the PCS requirements addressed in UL 3141. However, it provides standardized communication mechanisms that can be used by a PCS to exchange control commands, limits, and measurement data necessary to execute and verify power control functions such as control of power import and export or protection against overload conditions within a power system. The following bullet points describe information/messages that can be used to support functions relevant to UL 3141.

- Remote control: OCPP 2.1 supports remote transaction control, allowing the PCS to start or stop a transaction remotely. This capability aligns with UL 3141 scenarios such as PIL, PEL, and overload protection for monitored bus bars. Table 3 lists some key signals.

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Table 3. UL 3141 to OCPP 2.1 Mapping for Key Remote Control Signals

Key Signals	Description
RequestStartTransaction	Enables controlled restoration of charging once PCS constraints are lifted.
RequestStopTransaction	Allows immediate reduction of load during overload or grid constraint conditions.
TransactionEvent	Provides traceable evidence that remote control actions were executed.

- Smart charging: The smart charging functionality in OCPP 2.1 offers standardized mechanisms that allow the PCS to influence the charging current or power delivered by a charging station. It supports control at various levels—charging station, EVSE, or site—allowing management over total energy consumption across individual stations or groups of stations. OCPP 2.1 includes internal, central, local, and external smart charging topologies, which makes it suitable for PCS-based overload protection. Key functionalities of smart charging in OCPP 2.1 enable PCS to:
    - Limit total import and/or export power.
    - Delay or reduce charging during peak conditions.
    - Coordinate constraints from grid, transformer, or bus bar limits.

  Charging power or current is controlled by sending time-dependent energy transfer limits to a charging station. These limits are defined in a *ChargingProfile*, which specifies power or current limits and may include start times and durations at the charging station or EVSE level. Some of the key charging profile purposes relevant to UL 3141 are mentioned in Table 4.

Table 4. Key Charging Profile Purposes

Key Signals	Description
ChargingStationMaxProfile	Defines the maximum allowable power for a charging station, which could provide site-level overload protection.
ChargingStationExternalConstraints	Representing limits imposed by a PCS, typically derived from grid, transformer limitations, or bus bar protection logic and could support UL 3141 import/export control objectives.
LocalGeneration	Describes locally available generation that offsets grid import. This supports PCS logic when managing net import power and coordinating local generation resources.

Table 5 identifies some key OCPP 2.1 signals used to support implementation of the charging profiles described above.

OCPP 2.1 also introduces smart charging operation modes, which define whether a charging set point is fixed or dynamically updated by the PCS. These operation modes,

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along with charging profile stacking, define clear control authority for charging set points and limits, ensuring grid-imposed power constraints are enforced over secondary charging objectives.

Table 5. UL 3141 to OCPP 2.1 Mapping for Key Smart Charging Signals

Key Signals	Description
SmartChargingAvailable	Indicates availability of smart charging functionality.
SetChargingProfile	Used to define charging power or current limits for specific EVSE or the entire charging station over a defined time period.
ClearChargingProfile	Removes previously applied charging profiles, allowing charging power to return to normal operation once PCS constraints are cleared.
GetChargingProfiles	Retrieves active charging profiles from the charging station for verification or diagnostics purposes.
NotifyChargingLimit	Sent by the charging station to indicate that a charging limit has been applied. This signal can be used to confirm activation of PCS constraints.
ClearedChargingLimit	Indicates that a previously applied charging limit has been removed.
GetCompositeSchedule	Requests the effective charging schedule calculated by the charging station by combining all active charging profiles, external constraints, and local limits. This signal provides evidence that PCS-defined limits are correctly enforced in the presence of multiple control sources.

Although UL 3141 does not mandate a specific communication protocol, OCPP 2.1 provides a comprehensive and standardized set of control, monitoring, and reporting mechanisms that can be used to implement and demonstrate PCS functionality. Through smart charging and remote control, OCPP 2.1 supports import/export power control and overload protection, aligning with the objectives of UL 3141. These capabilities can support cohesive response to both UL 3141 and IEEE 1547 requirements. With OCPP 2.1 and the following complementary protocols, a gateway will be able to coordinate all site energy assets with dynamic grid constraints.

3.2.2 SunSpec Modbus

SunSpec Modbus is one of three protocol options that is required to be implemented at minimum per IEEE 1547 and hence supports the compliance of a DER to IEEE 1547. SunSpec Modbus is a protocol based on Modbus to exchange data. The physical layer can be Ethernet (and hence Transmission Control Protocol/Internet Protocol [TCP/IP] can be used) or RS-485 per IEEE 1547. In Modbus, a device holding data (information) such as operational settings (e.g., V/Q curve), measured values, and nameplate information is called a server. A client makes requests to read and/or write to those pieces of information. Typically, a DER becomes the server, and an upstream device such as the gateway becomes the client. This is illustrated in Figure 11.

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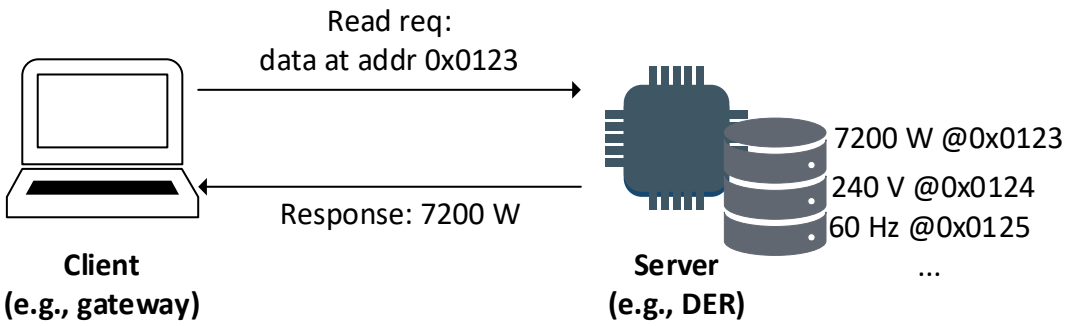

Figure 11. Modbus server: client

A client specifies an address or a series of addresses to read the intended data or write a value (or values) to update the data. Typically, data is 2 or 4 bytes, and the address is 4 bytes, allowing smaller payload. Additionally, Modbus's header is numeric-based, and hence the total data length is compact. Therefore, Modbus (SunSpec Modbus) is ideal for in-device and in-site communication. Indeed, Modbus can be found in factory automation.

While Modbus is a standardized protocol to exchange data (information), the information model, also known as register map, is not standardized. Therefore, the register map is up to the vendor of the device, causing interoperability problems between Modbus devices.

SunSpec Modbus was developed to solve the interoperability issue by defining the information model (i.e., register map) to support compliance with IEEE 1547. An example of a register map describing parameter-address-value type-value pairs is shown in Table 6.

Table 6. SunSpec Modbus Register Map (V/Q Excerpted)[a]

Address	Name	Value	Type
40394	ID	705	uint16
40395	L	163	uint16
40396	Ena	0	enum16
…			
40409	Crv[0].ActPt	4	uint16
40410	Crv[0].DeptRef	3	enum16
…			
40419	Crv[0].Pt[0].V	92	uint16
40420	Crv[0].Pt[0].Var	44	int16
40421	Crv[0].Pt[1].V	98	uint16
40422	Crv[0].Pt[1].Var	0	int16

[a] This is an example of actual implementation and appears different from SunSpec Modbus information model available from SunSpec.

A set of data is grouped to form a meaningful dataset, called a model. In SunSpec Modbus, each model corresponds to a group of IEEE 1547 requirements (e.g., functional requirement), such as V/Q. Each model is distinguished by the model ID. Table 7 lists example models for IEEE 1547.

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Table 7. Example Models for IEEE 1547

ID	Mapping to IEEE 1547	Description
701	Monitoring information	Provides electrical readings captured by the DER
702	Nameplate and configuration information	Provides the DER's nameplate and configurable ratings, such as maximum active power
703	Management information – enter service	Settings for enter service for the DER
704	Management information – misc.	Settings for miscellaneous functions for the DER, such as active power set point
705	Management information – V/Q	Settings for V/Q for the DER
…	…	…

For example, an upstream device (i.e., client) such as the gateway can initiate a read request to collect operational information of the DER that can be found on ID 702 in Table 7. It can also make a write request to provide active power set point. With the aforementioned compactness of the payload, SunSpec Modbus allows the upstream to control DERs in real time. Nonetheless, SunSpec Modbus does not offer aggregation of devices, and hence is more suitable for controlling on-site devices. Because an on-site gateway is the front end for the utility, and communication within the site is handled by the gateway, it will alleviate the need for aggregation from the utility's perspective.

3.2.3 IEEE 2030.5

IEEE 2030.5 is another of three protocols required to be implemented at minimum per IEEE 1547 and hence supports the compliance of a DER with IEEE 1547. For IEEE 1547-related information, it adopts generator sign convention[6] as IEEE 1547 does. To date, Rule 21 requires IEEE 2030.5 by default to communicate with the local utility.

IEEE 2030.5 uses RESTful protocol to exchange data. One known example of such a protocol is HTTP. Unlike SunSpec Modbus, a DER acts as a client and an upstream device, such as the gateway, and a DER management system acts as a server. Thereby, a DER initiates the request to get settings (i.e., HTTP GET), such as active power set point, V/Q curve, and maximum active power, and pushes (HTTP PUT or POST) the update on the up-to-date settings and/or operational information such as measured values.

Considering the above, it is not straightforward to change the settings such as active power set point, as the timing to GET the setting is up to the client. To address the issue, IEEE 2030.5 defines the minimum polling requirement and offers a Subscription/Notification mechanism where the client exposes its end point (i.e., Uniform Resource Identifier [URI]) so that the server sends the notification over a new TCP link with a separate Transport Layer Security (TLS) session.

[6] For example, information related to smart charging (e.g., *FlowReservationRequest*) uses a positive value to indicate charging.

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IEEE 2030.5 uses Extensible Markup Language (XML) or Efficient XML Interchange (EXI) to exchange information (i.e., the presentation layer). XML data consists of one or more individual data fields, namely element and attribute. This corresponds to Modbus's register map, and like the register map, XML needs defined framework (i.e., information model) for interoperability. The schema defines the information model and is based on an object model. An example class diagram of IEEE 2030.5 is shown in Figure 12.

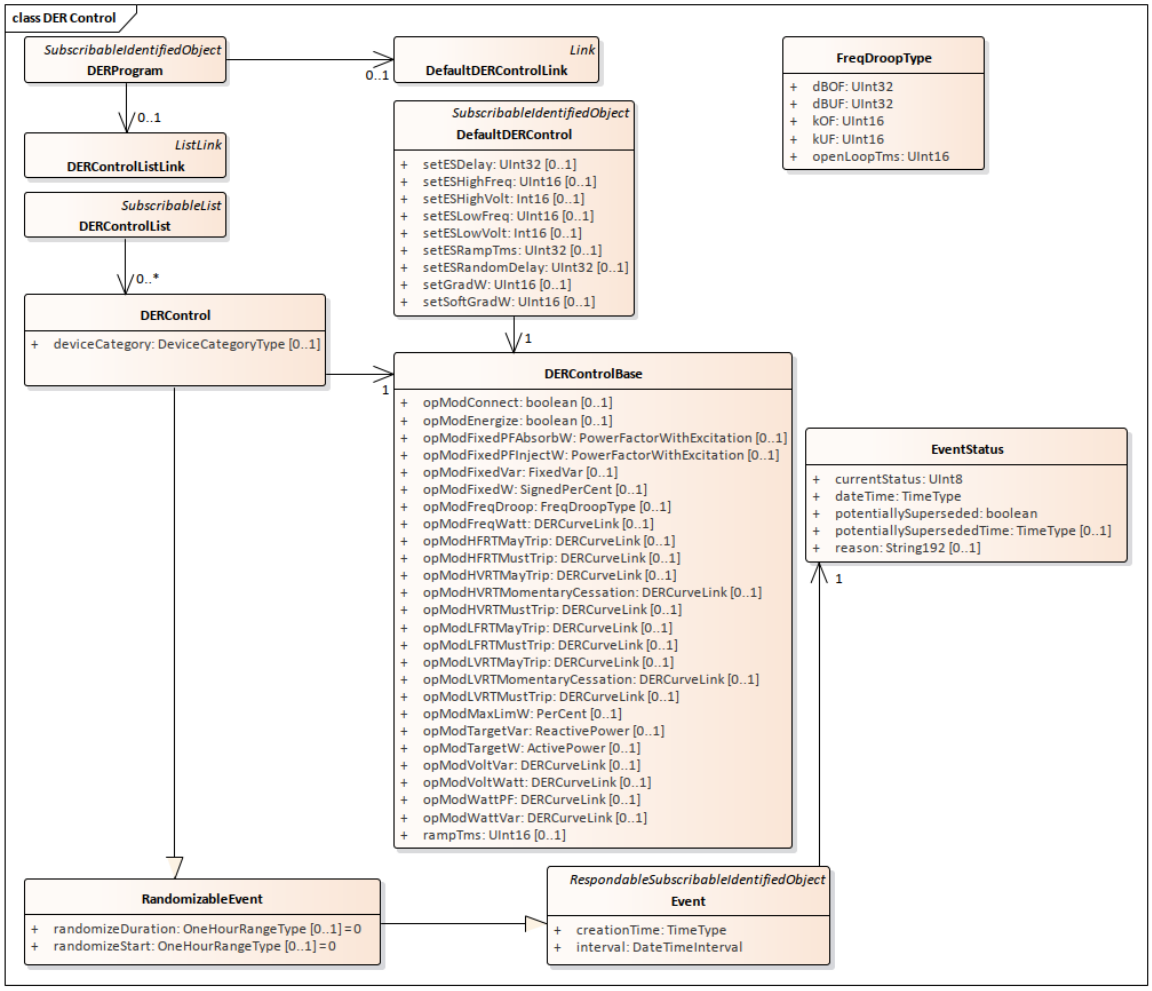

Figure 12. Example class diagram [2]

As a web-based technology, XML data is referred to as a resource. A dedicated URI exists for each resource to access the resource for reading or writing. Indeed, there are many elements and attributes in IEEE 2030.5 that provide a URI to another resource. The resource then may include another URI, forming a chain of URIs, as illustrated in Figure 13.

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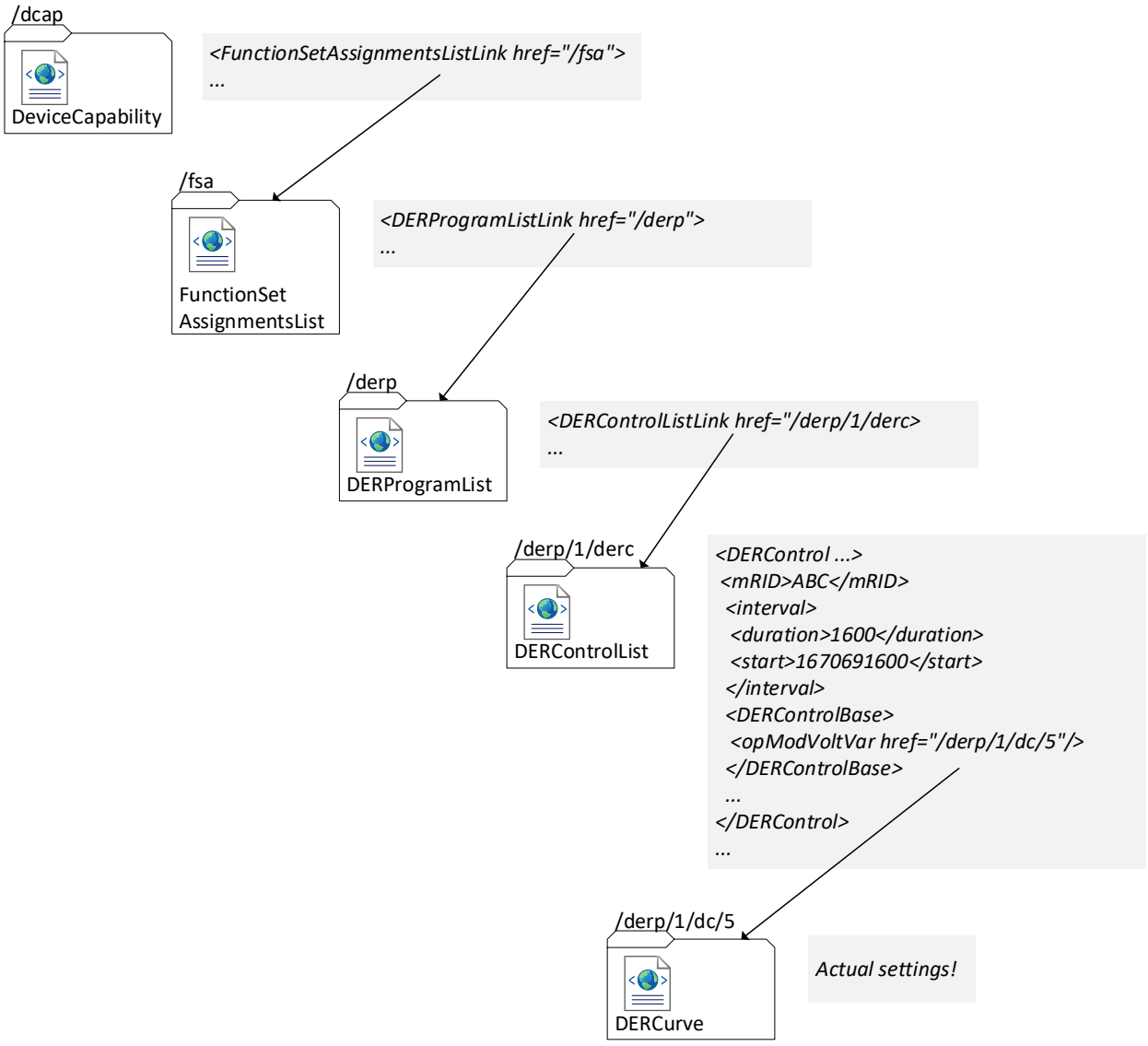

Figure 13. Chain of URIs

Figure 13 is an example of the chain to acquire a list of DERControls and then the setting for V/Q. A DERControl is a container to carry settings for each group of IEEE 1547 requirements (e.g., V/Q). Again, the element within a DERControl may be just a URI (e.g., DERControl, DERControlBase.opModVoltVar for V/Q), and following the chain, the necessary settings are retrieved.

IEEE 2030.5 also introduces and leverages events. Each DERControl has start time and duration. This allows scheduling of each function ahead of time, including active power set point.

While there is complexity in implementation, with the features mentioned above, IEEE 2030.5 is versatile. Indeed, IEEE 2030.5 covers time of use, managed charging, demand response of diverse asset types (e.g., pool), aggregation (with the latest version), and so on. To support the interoperability of IEEE 2030.5 devices, SunSpec developed a profile called Common Smart Inverter Profile, which is planned to be transitioned into IEEE 2030.5.1 [19].

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3.3 Additional Considerations

While this section has demonstrated that the set of communication protocols chosen can facilitate the required interaction, there are some additional implementation-related aspects that need to be addressed:

1. IEEE 1547, IEEE 2030.5, and SunSpec Modbus are all based on generator sign convention. In contrast, OCPP 2.1, ISO 15118-2, and ISO 15118-20 are based on load sign convention.
2. The communication protocols mentioned so far are application-level protocols. These need to be used on top of underlying protocols (e.g., WebSocket, HTTP[S], TCP, serial) depending on the chosen network architecture.
3. In addition to translating information from one protocol to another, the sequence of communication also forms a crucial part of enabling interaction across different protocols via the gateway.

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4 Site Harmonization Development

As identified earlier, there are multiple communication protocols used in the market with unique capabilities to coordinate DER with utility interconnection requirements. This diverse set of options becomes problematic when there are different asset types installed across a single site. For example, in a residential setup, rooftop solar can be combined with energy storage (e.g., a battery system or V2X-capable EV) to increase resilience and lower electricity bills. These scenarios with multiple assets and different communication protocols create a challenging environment for a single site to meet objectives such as IEEE 1547 and UL 3141. An example of this convoluted framework using different protocols and communication paths is displayed in Figure 14.

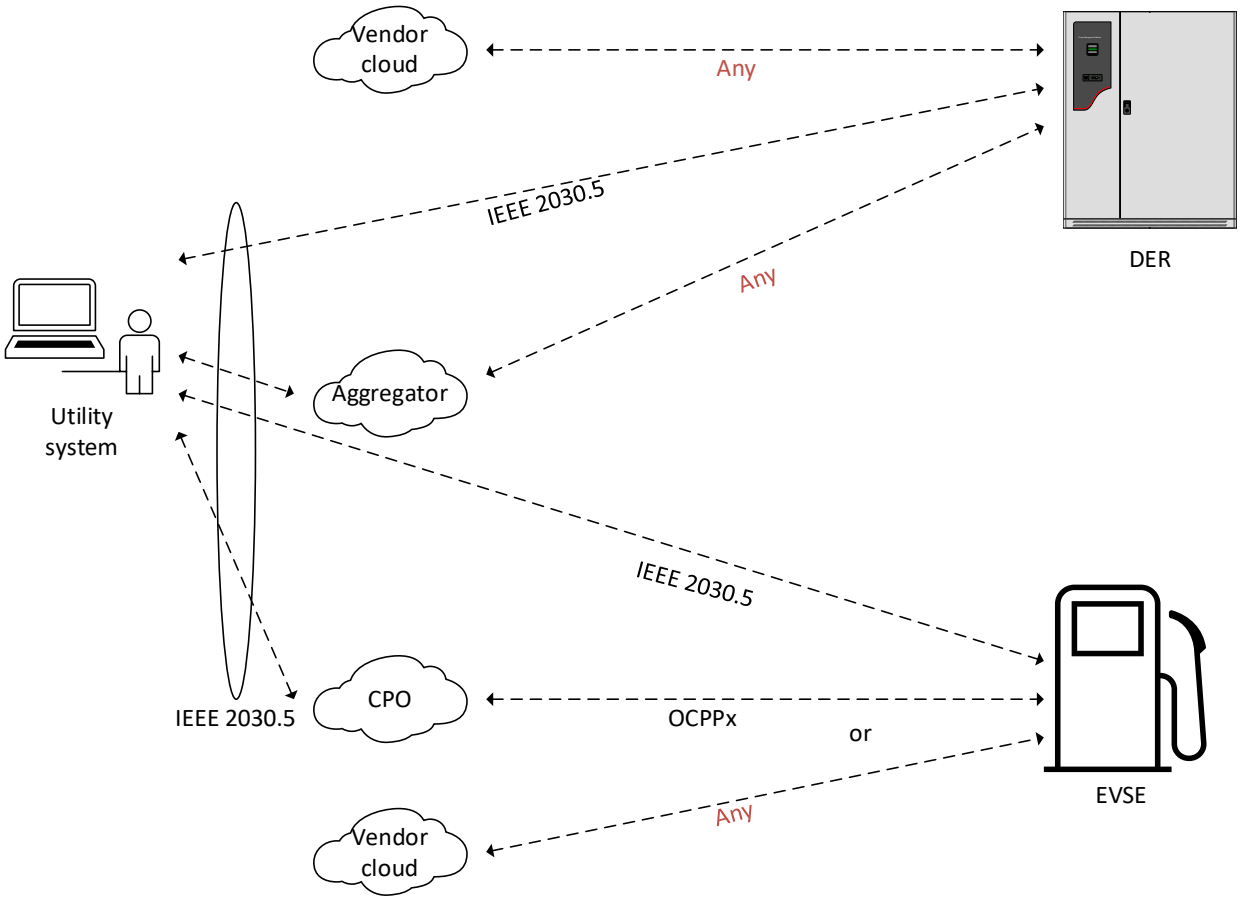

Figure 14. Convoluted communication paths

However, a gateway that serves as a centralized communication controller can simplify the communication paths and lower the overall cost of the system installation and operation. This gateway will coordinate diverse site assets to develop a cohesive response to UL 3141 and IEEE 1547, as outlined in Figure 15.

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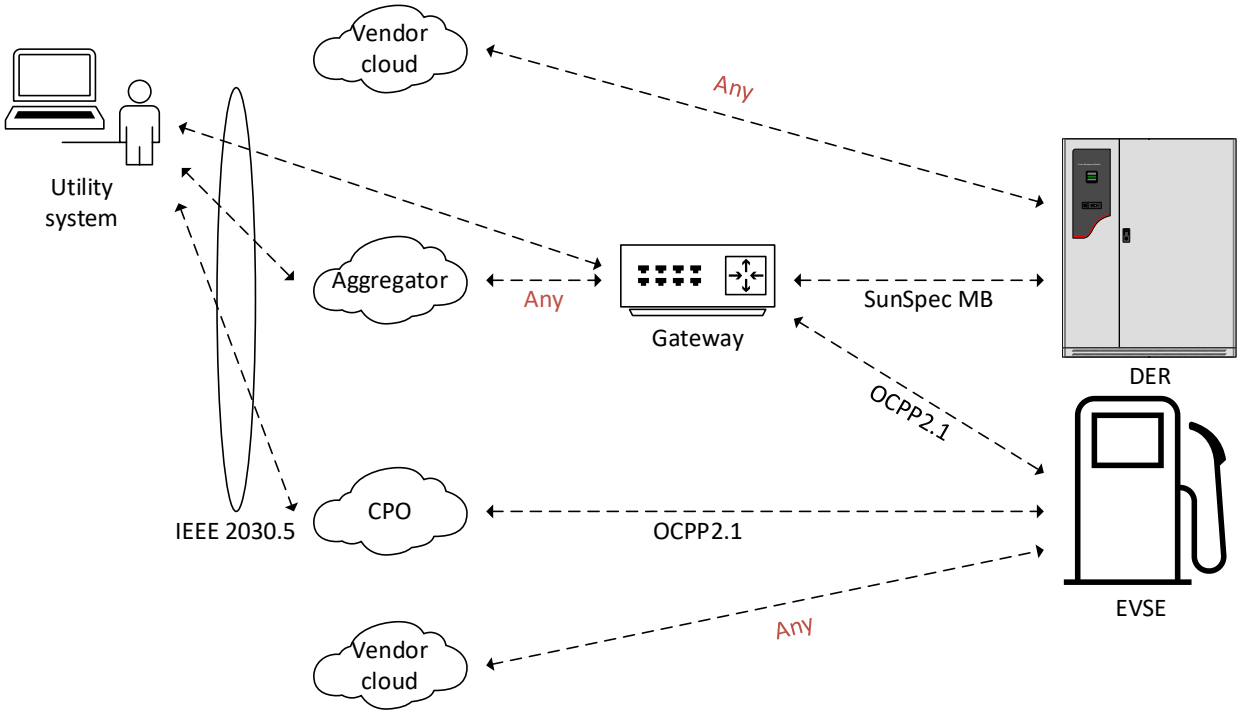

Figure 15. Simplified communication paths with gateway

The core gateway functionality necessary to support this solution is the translation of different protocols and bundling of communication paths. The gateway must support industry-adopted standards to avoid vendor lock-in, as non-standardized protocols (i.e., proprietary protocols) require a proxy from the vendor of the DER.[7] Note that the proxy also facilitates communication with the utility.

Beyond diverse communication paths, having multiple DERs at a site typically requires each DER to comply with IEEE 1547 requirement at the PCC, as described in Section 2.1. This can be met by an additional wiring to the DER from the PCC and/or communication channel to the DER to inform the AC voltage measured by a device at the PCC. However, in V2X this is problematic, as the wiring is limited by the EV connector. Figure 16 briefs this issue.

[7] This does not preclude the vendor from communicating directly to their devices.

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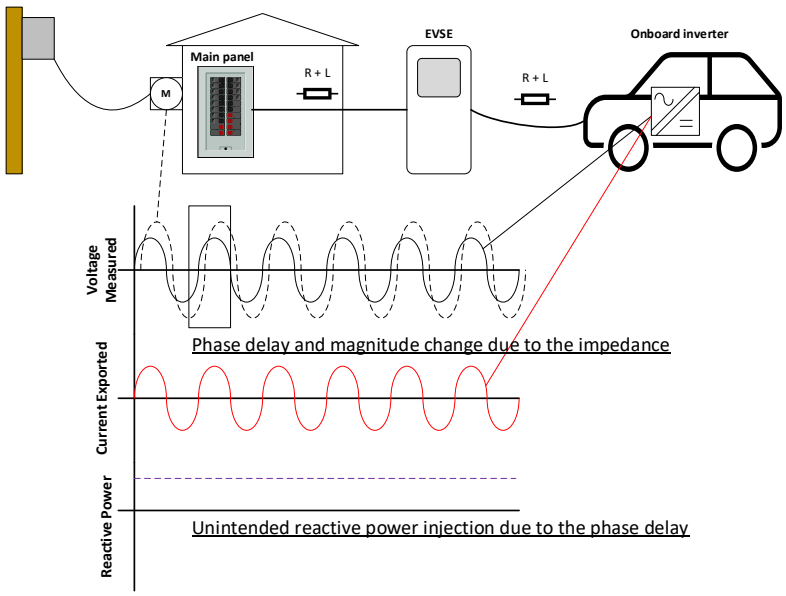

Figure 16. Impact of impedance between PCC and point of DER connection

Similarly, for a flex service/interconnection, the utility may instruct the site to limit the amount of export/import of active power at the PCC during an operation (Figure 17).

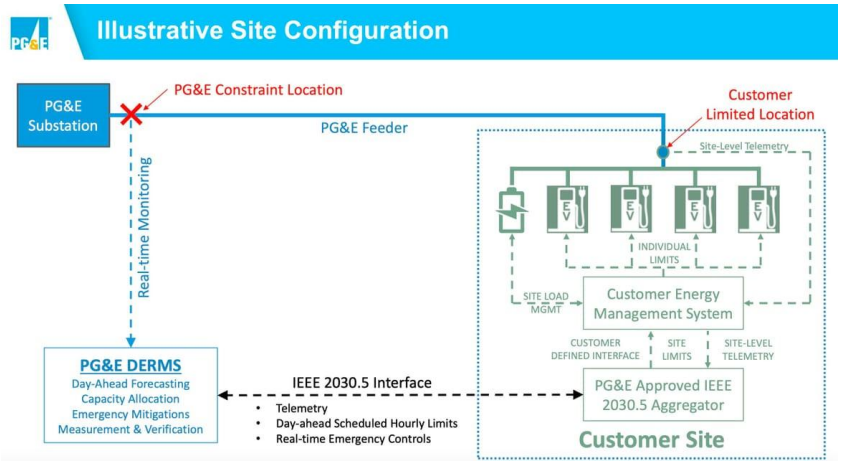

Figure 17. Flex service/interconnection [20]

The PEL/PIL PCS introduced in Section 2.4 can be leveraged to address those two. Indeed, PEL/PIL is to address the limit at the PCC. Adding an ability to measure AC voltage at the PCC also enables the PCS to be a proxy to the AC voltage measurement for DERs.

As identified, the measured AC voltage needs to be communicated to the DERs for compliance with IEEE 1547. Additionally, the limit for flex service/interconnection is communicated by the utility. This calls out the need of having the "gateway" function described earlier into the PCS, namely PCS gateway. With those combined features, the PCS gateway will:

- Monitor the active power at the PCC and instruct one or more DERs for desired active power to meet flex service/interconnection (PCS PEL/PIL function).

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- Monitor the AC voltage at the PCC for the DERs to comply with IEEE 1547 requirements.
- Translate IEEE 2030.5 messages from the utility into the protocols that the DERs use (i.e., SunSpec Modbus, IEEE 2030.5, and OCPP 2.1) as identified in Section 3 to exchange:
    - The utility's dynamic limit for flex service/interconnection with the utility.
    - Settings for IEEE 1547 functional requirements, such V/Q curve with the DERs.
    - AC voltage at the PCC with the DERs.

While these functionalities complement each other, there can be multiple active power set points and/or limits that originate from different purposes. There are many sources beyond flex service/interconnection-originated limit and IEEE 1547 requirements; the site or one or more DERs may provide bulk system service, or PV can charge batteries during the day, including EVs, and use the charged energy at night to reduce the electricity purchase. Those different objectives need to be prioritized and harmonized. Notably, under IEEE 1547, active power is modulated only during abnormal voltage or frequency conditions. The resulting active power set point/limit is momentary and hence it does not influence active power during normal conditions.

The "harmonized" active power limit and/or set point needs to be provided to individual DERs.[8] The allocation of those also needs to be computed.

As the central information hub, the PCS gateway understands the grid's needs and each DER's needs, including requested state of charge of a battery (including EVs).

The National Laboratory of the Rockies has extensively researched smart charge management—an algorithm that harmonizes the needs for a large load and a local distribution system (i.e., mitigating overcurrent at an overhead transformer), referencing EVs as an example of such a load. This can support flex service, as it controls large loads to maintain the active power level below the utility desired limit. Regardless of the limit level, smart charge management generates set points for each DER. Hence, PCS and smart charge management complement each other to generate an active power set point that can apply to normal conditions, and PCS can override or limit the active power when necessary. Table 8 provides an example use cases that the smart-charge-management-integrated PCS gateway supports.

Table 8. Example Use Cases

#	Description	PCS Gateway Response
01	Normal condition; no limit	PCS gateway may respond to any external signal.[a]
02	Normal condition; import limit	PCS gateway performs load balancing (i.e., increase of generation and/or decrease of consumption). If charging power is curtailed, PCS gateway performs smart charge management to distribute the curtailment per the logic.
03	Overfrequency; no limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D.[b]

[8] Inverters for some energy resources, such as a PV inverter, generate active power at the most efficient point, and hence do not need a set point, whereas a stationary battery system needs an explicit set point.

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#	Description	PCS Gateway Response
04	Overfrequency; import limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D.[c] If the import limit is not met, PCS gateway instructs non-DER energy assets to decrease the load (e.g., charging power of EVs in *charging session*).
05	Normal condition; export limit	PCS gateway performs load balancing (i.e., decrease of generation and/or increase of consumption).
06	Underfrequency; no limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D.[b]
07	Overvoltage; no limit	PCS gateway provides PCC voltage to individual DERs and monitors that the active power at the PCC follows IEEE 1547 V/W (i.e., under the active power limit constrained by the V/W requirement).
08	Underfrequency and/or overvoltage; export limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D and/or V/W. If both are active, PCS gateway honors lesser (stricter) limit.[d] If the export limit is not met, PCS gateway instructs non-DER energy assets to increase the load.

[a] External signal refers to any non-utility constraint-related signals such as aggregator's request.

[b] Individual DERs following IEEE 1547 meet the intent.

[c] If PCS gateway does not interrupt individual DERs from performing IEEE 1547 F/D, the intent is met, provided note b.

[d] This aligns with the prioritization requirement in IEEE 1547.

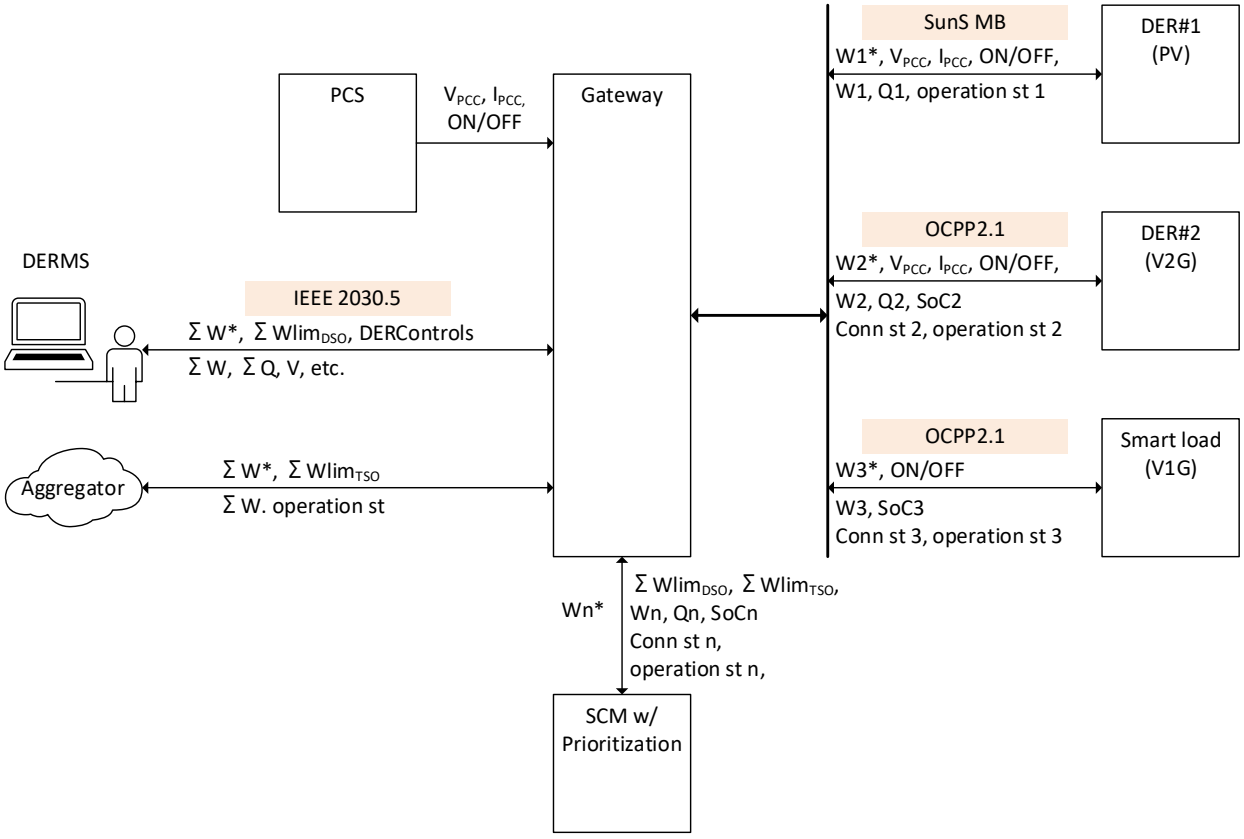

Figure 18. PCS gateway with prioritization

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Conclusion

As site loads continue to grow in size the incentive and need for flexible local energy assets will expand. These energy assets have the potential to benefit both site and grid operations, but must comply with grid codes and interconnection requirements. Due to the diverse landscape of energy assets, grid requirements, and coordination protocols, a new PCS gateway will be needed to navigate this landscape and ensure a cohesive site response to local utility and on-site facility needs. The National Lab of the Rockies is developing these technologies to simplify installation of energy assets for consumers, as well as considering new coordination opportunities that will expand UL 3141 PEL/PIL to support distribution capacity limitations.

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Appendix A. List of Relevant Industry Standards and Grid Codes

Table A-1. Relevant Industry Standards and Grid Codes

Standard	Title	Description
IEEE 1547	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces	This is the base standard that sets forth technical requirements for grid interconnection. The requirements include voltage supports, such as volt-var (V/Q), and response to abnormalities, such as voltage ride-through and trip. A DER needs to be designed to at least meet the requirements defined therein.
IEEE 1547.1	Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces	This provides the conformance test procedure (i.e., type test) for a DER that is intended to comply with IEEE 1547. Although the test procedure is detailed, there are typos and inaccuracies within the document that led to the development of UL 1741SB.
P1547.10	Recommended Practice for Distributed Energy Resources (DER) Gateway Platforms	This document will be a recommended practice for DER gateway that can be added between an IEEE 1547-conformant DER (i.e., a DER with utility communication interface) for a variety of upstream entities to leverage the DER.
UL 1741	Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources	Main body of UL 1741 sets forth the product safety requirements, such as insulation and flammability. This document also includes tests for such safety features, including abnormal conditions (e.g., short circuit and rain shower).
UL 1741SA	SUPPLEMENT SA – GRID SUPPORT UTILITY INTERACTIVE EQUIPMENT	This document is a supplement (annex) of UL 1741. This served as an interim functional requirement document until IEEE 1547-2018 was published and test requirement document until IEEE 1547.1-2020 was published. The functions defined in this document were referred to as smart inverter functions. This is to be superseded by IEEE 1547-2018, IEEE 1547.1-2020, and UL 1741SB.
UL 1741SB	SUPPLEMENT SB – GRID SUPPORT UTILITY-INTERACTIVE INVERTERS AND CONVERTERS BASED UPON IEEE 1547-2018 and IEEE 1547.1-2020	This document serves as the conformance test for IEEE 1547-2018. While IEEE 1547.1-2020 exists for the purpose, this document corrects the inaccuracies therein and also serves as the certification pathway for DERs.

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Standard	Title	Description
UL 1741SC	Supplement SC for AC Bidirectional Electric Vehicle Supply Equipment (BEVSE) / Interconnection Systems Equipment (ISE) for EVs with SAE J3072 Bidirectional Onboard Inverters	This document species the requirements for AC EVSE intended to operate with an SAE J3072-conformant EV to operate as a DER (i.e., V2G AC).
UL 3141	Power Control Systems	In some conditions (e.g., residential battery energy storage systems under Rule 21), the site is prohibited from exporting back to the grid. Even beyond, the site may be required to limit the power export (PEL) and even import (PIL) to facilitate interconnection/service agreement to address dynamic hosting capacity. UL 3141 defines requirements of devices used in this purpose, namely PCS, that operates to meet PEL and PIL requirements that may or may not be dynamic.
IEEE 2030.5	Smart Energy Profile Application Protocol	This document defines data and messages primarily intended for smart grid. This also sets forth implementation requirement. The base communication layer is HTTP(S). IEEE 2030.5 is one of the three protocols that are identified in IEEE 1547 that need to be supported by a DER.
P2030.5.1	Standard for Common Smart Inverter Profile of IEEE Std 2030.5	This document serves as the guideline to implement IEEE 2030.5 (though normative) and provides conformance test procedure for the standard.
IEEE 2030.7	Standard for the Specification of Microgrid Controllers	This document provides functional requirement for a microgrid. It does so by providing different scenarios that trigger the transition from grid-connected mode to islanded mode. Given each microgrid is different, this standard stays high level as opposed to IEEE 1547.
IEEE 2030.8	Standard for the Testing of Microgrid Controllers	This defines test requirements for a microgrid controller intended to meet IEEE 2030.7.
UL 3001	Distributed Energy Resource Systems	This document details the components within a microgrid, such as a transfer switch, to make a microgrid testable for UL certification. Inherently, this document references many other existing UL standards and establishes test procedure for voltage quality.
SunSpec Modbus	SunSpec Information Model	This document defines Modbus register map (information layer) for smart grid, including DERs for Modbus to be interoperable among the devices. SunSpec Modbus is one of the three protocols identified in IEEE 1547 that need to be supported by a DER.

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Standard	Title	Description
IEEE 1815.2		This document defines DNP3 points for smart grid (by following IEC 61850 data model) and supporting IEEE 1547 compliance in interoperable way. DNP3 is one of the three protocols identified in IEEE 1547 that need to be supported by a DER.
OpenADR		This document defines data and messages primarily intended for automated demand response. The base communication layer is HTTP. While the latest version is intended to support DER functions, IEEE 1547 does not acknowledge the protocol.
NFPA70		This document addresses electrical installations for residential, commercial, and industrial building and/or site. Adoption of this is up to local state authority having jurisdiction, but this covers a wide range of topics including EV charging installation, PCS (EMS in the document), and DER.
SAE J3072	Interconnection Requirements for Onboard, Grid Support Inverter Systems	This SAE document defines functional requirements for EVs intended to interconnect with the grid using an onboard charger (i.e., V2G AC).
IEEE 2800	Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems	This document defines functional requirements for inverter-based resources (active power source plus inverter) interconnecting with bulk system.

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Appendix B. List of OCPP 2.1 Fields for IEEE 1547 Functions

B.1 List of OCPP 2.1 Fields for V/W Control per IEEE 1547

Table B-1. IEEE 1547 to OCPP 2.1 Mapping for V/W

IEEE 1547 Parameter	OCPP 2.1 Field	Description
V/W mode enable	SetDERControlRequest: controlType = VoltWatt	En/disabling of V/W
Voltage points [9](x)	SetDERControlRequest: curve: {curveData[n]: x}	V/W curve's n-th point (x)
Active power points (y)	SetDERControlRequest: curve: {yUnit, curveData[n]: y}	V/W curve's n-th point (y)
Open loop response time	SetDERControlRequest: curve: responseTime	Time to reach 90% of new active power target calculated based on V/W curve points

[9] V/W curve is described to have two points in IEEE 1547. However, it doesn't preclude from having different number of points.

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B.2 List of OCPP 2.1 Fields for V/Q Control per IEEE 1547

Table B-2. IEEE 1547 to OCPP 2.1 Mapping for V/Q

IEEE 1547 Parameter	OCPP 2.1 Field	Description
V/Q mode enable	SetDERControlRequest: controlType = VoltVar	En/disabling of V/Q
VRef	SetDERControlRequest: curve: reactivePowerParams: vRef	V/Q's voltage reference (only applies to V/Q)
Autonomous VRef adjustment enable	SetDERControlRequest: curve: reactivePowerParams: autonomousVRefEnable	En/disabling of autonomously adjusting VRef
VRef adjustment time constant	SetDERControlRequest: curve: reactivePowerParams: autonomousVRefTimeConstant	Time constant for adjusting VRef
Voltage points[10] (x)	SetDERControlRequest: curve: {curveData[n]: x}	V/Q curve's n-th point (x)
Reactive power points (y)	SetDERControlRequest: curve: {yUnit, curveData[n]: y}	V/Q curve's n-th point (y)
Open loop response time	SetDERControlRequest: curve: responseTime	Time to reach 90% of new reactive power target calculated based on V/Q curve points

[10] V/Q curve is described to have four points in IEEE 1547. However, it doesn't preclude from having different number of points.

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List of Acronyms

AC	alternating current
DC	direct current
DER	distributed energy resource
EV	electric vehicle
EVSE	electric vehicle supply equipment
F/D	frequency droop
IEEE	Institute of Electrical and Electronics Engineers
OCPP	Open Charge Point Protocol
OpenADR	Open Automated Demand Response
PCC	point of common coupling
PCS	power control system
PEL	power export limiting
PIL	power import limiting
PV	photovoltaics
URI	Uniform Resource Identifier
V2B	vehicle to building
V2G	vehicle to grid
V2X	vehicle to everything
V/Q	voltage-reactive power
V/W	voltage-active power

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Table of Contents

Introduction **1**
1 Bidirectional Charging Overview **2**
1.1 Applications 2
1.1.1 V2G 2
1.1.2 V2B 2
1.2 Topologies and Hardware Requirements 3
1.2.1 V2X AC 3
1.2.2 V2X DC 3
2 Interconnection Codes and Industry Standards **4**
2.1 IEEE 1547 5
2.2 SAE J3072 7
2.3 UL 1741SC 9
2.4 UL 3141 10
3 Communication and Control Requirements **13**
3.1 Diverse Landscape 13
3.2 Key Protocols of Interest 15
3.2.1 OCPP 16
3.2.2 SunSpec Modbus 19
3.2.3 IEEE 2030.5 21
3.3 Additional Considerations 24
4 Site Harmonization Development **25**
Conclusion **30**
References **31**
Appendix A. List of Relevant Industry Standards and Grid Codes **33**
Appendix B. List of OCPP 2.1 Fields for IEEE 1547 Functions **36**
B.1 List of OCPP 2.1 Fields for V/W Control per IEEE 1547 36
B.2 List of OCPP 2.1 Fields for V/Q Control per IEEE 1547 37

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List of Figures

Figure 1. V2X applications 2
Figure 2. V2X AC and DC EVSE hardware requirements 3
Figure 3. Bidirectional charging standards landscape 5
Figure 4. V/Q curve [1] 7
Figure 5. Overview of SAE J3072 handshake 8
Figure 6. Oversight: interrupting an EV not following IEEE 1547 9
Figure 7. EV and EVSE coordination concept 10
Figure 8. Overview of PCS Coordination 11
Figure 9. Inverter communication protocol distribution 14
Figure 10. Market breakdown of nonproprietary inverter communication protocol options 15
Figure 11. Modbus server: client 20
Figure 12. Example class diagram [2] 22
Figure 13. Chain of URIs 23
Figure 14. Convoluted communication paths 25
Figure 15. Simplified communication paths with gateway 26
Figure 16. Impact of impedance between PCC and point of DER connection 27
Figure 17. Flex service/interconnection [20] 27
Figure 18. PCS gateway with prioritization 29

List of Tables

Table 1. IEEE 1547 Functional and Minimum Capability Requirements 6
Table 2. UL 3141 PCS Functional Requirements 11
Table 3. UL 3141 to OCPP 2.1 Mapping for Key Remote Control Signals 18
Table 4. Key Charging Profile Purposes 18
Table 5. UL 3141 to OCPP 2.1 Mapping for Key Smart Charging Signals 19
Table 6. SunSpec Modbus Register Map (Except V/Q)[a] 20
Table 7. Example Models for IEEE 1547 21
Table 8. Example Use Cases 28
Table A-1. Relevant Industry Standards and Grid Codes 33
Table B-1. IEEE 1547 to OCPP 2.1 Mapping for V/W 36
Table B-2. IEEE 1547 to OCPP 2.1 Mapping for V/Q 37

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Introduction

The utility grid is constantly evolving with new generation sources and diverse loads from backup generators, backup batteries, rooftop photovoltaics (PV), and flexible charging loads. Each of these technologies presents consumers with an opportunity to work with their local utility to promote grid stability, reliability, and affordability. Through a wide range of programs, utilities are incentivizing the use of these resources to benefit the grid. However, especially for devices with inverters that supply power back to the grid, it is important that these assets comply with local grid codes to ensure human safety, power quality, and grid reliability. As technology expands, individual sites—such as homes, buildings, or campuses with a single point of common coupling (PCC)—are increasing the number of assets providing grid services. These multi-asset sites will require solutions to ensure a cohesive response to grid codes, while navigating the expanding landscape of communication protocols necessary for coordination with each asset.

One of the most promising new technologies that falls under this grid asset landscape is the bidirectional electric vehicle (EV) coupled with bidirectional electric vehicle supply equipment (EVSE) [1]. Bidirectional charging has multiple different topologies and applications. It is a great opportunity for consumers to leverage the value of their EV battery during dwell periods when the vehicle is not needed for driving. Additionally, bidirectional EVs and EVSE are most valuable when their use is coordinated with the grid and optimized for all stakeholders through the use of communication protocols and certifications. This communication ensures all transportation needs can be met, while providing beneficial grid services and complying with all necessary grid codes.

This report introduces the technologies that enable bidirectional charging and how these systems operate. It then outlines the necessary interconnection codes and industry standards that govern the operations of grid-tied inverters, including those in bidirectional charging. Implementing multiple assets at a site presents a key challenge in the complex landscape of communication protocols and proprietary systems designed to coordinate these assets. Finally, in Section 4 we propose a single gateway solution to harmonize these communications between all assets across an entire site for a cohesive response to grid codes and utility programs that is flexible enough to support a range of market options.

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1 Bidirectional Charging Overview

As electrification evolves, it is clear that EVs present a value proposition that expands beyond transportation services: flexibility as an energy resource. The dense traction batteries that store the majority of electricity needed to operate the vehicle present opportunities for flexible charging or even the ability to act as a generation source. Bidirectional charging leverages the energy stored in an EV battery and discharges that energy for use outside the vehicle. The following sections outline different bidirectional charging applications, generically referred to as vehicle to everything (V2X), as well as the different topologies that can enable V2X solutions.

1.1 Applications

V2X applications are primarily defined by the intended use of the discharged energy. There are a wide range of V2X applications, as highlighted in Figure 1, from the simplest direct power from the vehicle to individual loads (V2L) (most common in power outlets around the vehicle) to some of the most complex solutions for off-grid island mode requiring grid-forming capabilities. This report focuses on two applications—vehicle to grid (V2G) and vehicle to building (V2B)—that both require a sustained grid connection but have energy objectives that are grid-centric and building-centric, respectively.

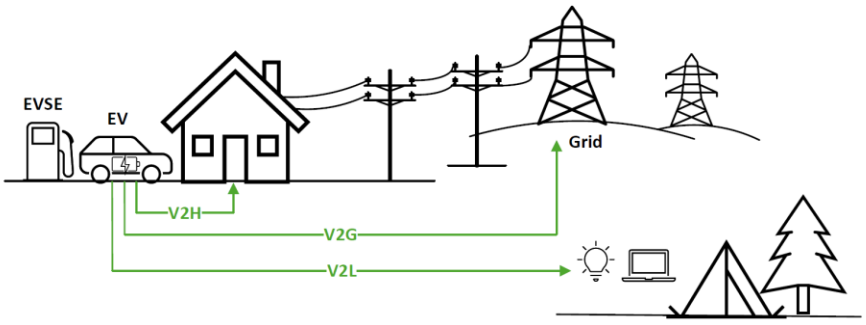

Figure 1. V2X applications

1.1.1 V2G

V2G applications focus on objectives that are developed from utility programs and often require direct communications to or from utility systems. In these applications, the EV battery is scheduled to serve as a utility energy asset, and remuneration is generally provided to the vehicle owner for the grid services provided. The most common grid services provided from this application are demand response and frequency support, but future programs could enable more precise objectives that benefit distribution systems in addition to bulk power supply. Two key considerations that must be supported for these applications are the source of utility communication signals and the optimization of EV charging and discharging in coordination with transportation and grid objectives.

1.1.2 V2B

V2B applications focus on objectives that are in coordination with site needs and constraints during normal operations with a sustained connection to the local utility. In these applications the EV battery is scheduled to serve as a site energy asset and is generally designed to reduce the need for capacity investments or mitigate costly operating expenses. The most common site

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objectives are to either enforce a net power ceiling to avoid overloading service equipment (often limited at the PCC) or optimize the site power profile to mitigate costly demand charges or peak energy pricing. Two key considerations that must be supported for these applications are centralized optimization and communication to all site assets (typically across multiple communication protocols) and the forecasting of loads and generation sources to schedule optimized operations of all energy assets.

1.2 Topologies and Hardware Requirements

In addition to the different applications, there are also different V2X topologies with unique hardware requirements for each. These topologies are defined by the form of power that is transferred between the EV and EVSE. Similar to the two conventional charging topologies, V2X AC passes alternating-current (AC) power from the vehicle's onboard charger to the EVSE, while V2X DC passes direct-current (DC) power directly from the EV battery to the EVSE, before the EVSE must invert this DC power to an AC power output for use on the grid. Each of these topologies is outlined in Figure 2, with more details on each outlined below.

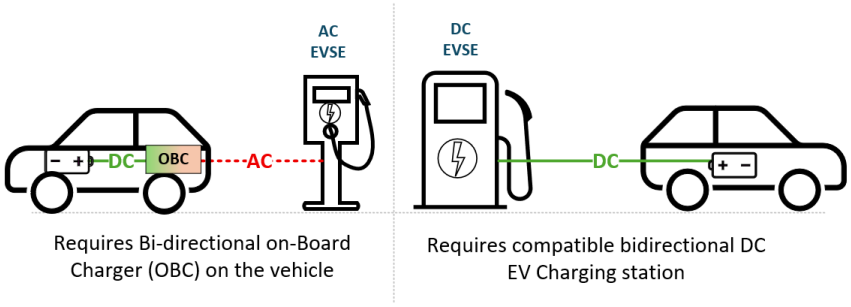

Figure 2. V2X AC and DC EVSE hardware requirements

1.2.1 V2X AC

V2X AC charging provides a more economic approach to extract energy from an EV battery for building or grid services. The most common architecture for this approach is for the onboard charger that supports AC charging to also have conventional inverter capabilities that convert DC power from the battery to AC power for discharging off the vehicle. This approach includes much of the bidirectional hardware within the EV and simplifies the complementary off-vehicle hardware that must be installed to facilitate. However, this simplified architecture does add some complication for grid interconnections with the advent of a mobile inverter. This situation is unique, compared to conventional systems with permanently installed grid-connected inverters.

1.2.2 V2X DC

V2X DC charging provides a more conventional approach to supply power for building or grid services. The most common architecture for this approach is for DC EVSE to have bidirectional charging capabilities that may supply or extract DC power directly to or from the EV battery. This approach requires adaptations to conventional EV hardware designs, but must be supported with more robust charging infrastructure capable of inverting DC power to AC power for exporting to the grid. However, additional hardware requirements for V2X DC, compared to V2X AC, result in a more conventional grid interconnection, with a permanently installed grid-connected inverter at the point of interconnection.

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2 Interconnection Codes and Industry Standards

As commercial and residential sites consider new energy technologies to support growing loads, many will consider the use of distributed energy resources (DERs). A DER is a combination of devices that can export power to the grid or local loads following the grid code, leveraging energy storage or power generation. Some examples include battery energy storage systems, natural gas generators, PV panels, and bidirectional EVSE. Examples of key DER elements are AC to DC converters (namely inverters) and gateways (i.e., communication controllers).

Although these DER assets could be intended to either support site loads or provide grid services, most applications will still operate in a grid-connected environment. Therefore, in order to maintain power quality and reliability, these devices must be approved for interconnection by the utility. The approval process differs across utilities. For example, the California Public Utilities Commission (CPUC) uses a process called Rule 21[2] with different implementations for each investor-owned utility under CPUC's jurisdiction.[1] Rule 21 offers fast-track review to facilitate the approval process, with one of the criteria being listing to UL 1741SB [3] to verify the DER is "suitable" for grid interconnection.

UL 1741SB defines conformance test requirements to verify compliance with IEEE 1547-2018 [4]. It is one of the criteria for residential DERs under Rule 21 fast-track review. However, some circumstances, such as V2G AC, involve a grid-connected inverter that is mobile, such as in the EV, and not permanently installed. In these circumstances, the alternate certification is UL 1741SC. This certification is for the EVSE, which will be designed to verify the connected EV contains an inverter that is designed and tested per the automotive standard, namely SAE J3072 [4]. SAE J3072 outlines the IEEE 1547 performance requirements for an EV's inverter and is the foundation for UL 1741SC's verification process.

In addition to IEEE 1547, some sites with energy assets may be subject to power import and export limits to maintain grid reliability and stability. UL 3141 [6] is a safety and performance standard that defines the functionality for a power control system(PCS) to meet these power import and export limits across a site of energy assets. Although these requirements are separate from IEEE 1547, it is important to understand that a site may be subject to both standards.

As highlighted in Figure 3, all energy assets at a site connected to the grid must comply with the requirements of IEEE 1547 to maintain grid reliability and stability. However, the certification process for the testing to ensure these devices will support those requirements are different for stationary and mobile DERs, requiring UL 1741SB and UL 1741SC, respectively. This figure also highlights UL 3141 requirements that will be placed on the meter and supported by a site PCS.

[1] Each investor-owned utility has its own version of Rule 21.

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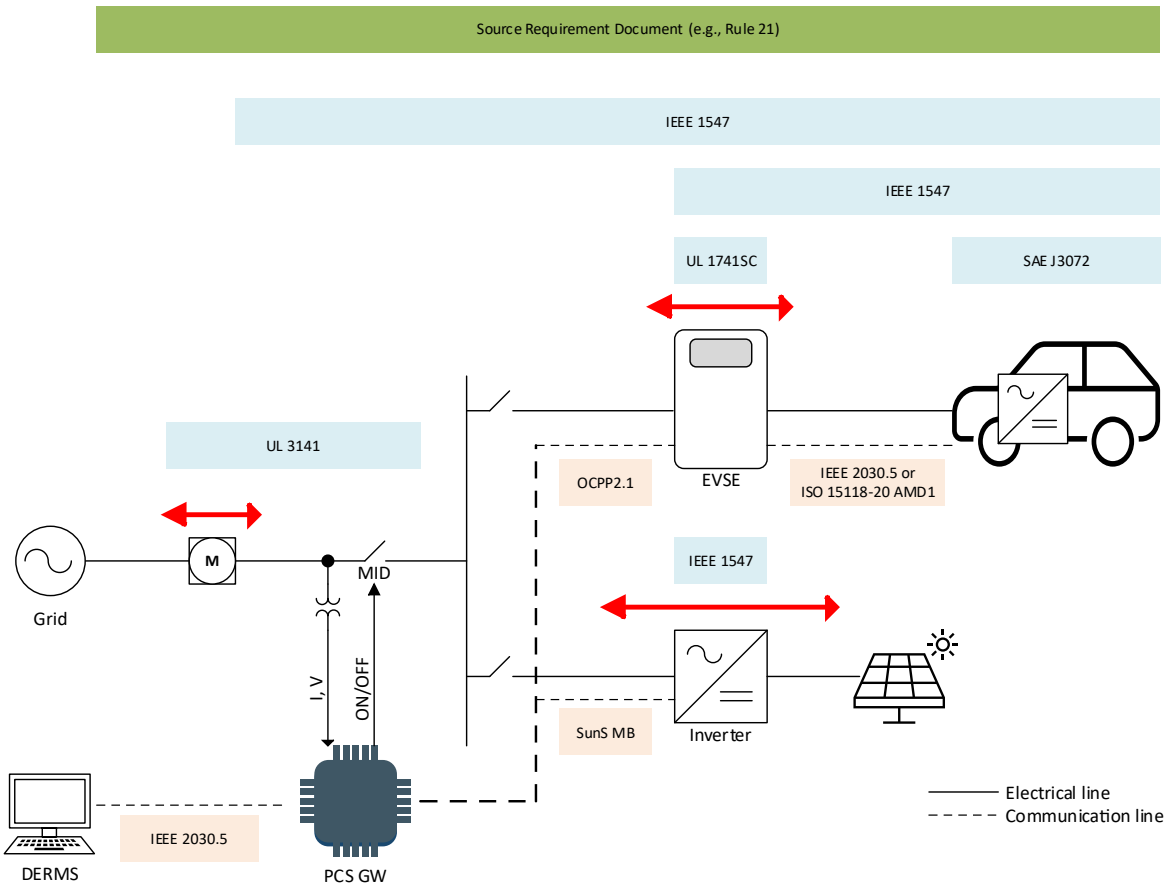

Figure 3. Bidirectional charging standards landscape

2.1 IEEE 1547

One of the most commonly referenced standards for technical grid interconnection requirements is IEEE 1547, which is the standard that sets forth technical requirements for DERs intended to be interconnected to the distribution system.[2] In order to maintain power quality and system reliability, utilities often require any DER to comply with the functional and minimum capability requirements summarized in Table 1.

[2] For bulk system interconnection, IEEE 2800 applies.

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Table 1. IEEE 1547 Functional and Minimum Capability Requirements

Requirement Type [a]	Description	Example Requirements
Enter service	Through this requirement, a DER verifies that the grid is in the condition for the DER to export power. The condition includes but is not limited to grid voltage and the permission to operate.	Permit service, enter service ramp
Voltage and frequency support	These sets of requirements define how a DER determines the amount of active and reactive power to output. Some are constant and others are autonomous (i.e., based on a piecewise linear curve).	Voltage-reactive power (V/Q), frequency droop (F/D), constant power factor
Power quality	This defines a DER's output current quality to reduce the impact to the grid voltage quality.	Current distortion, DC current
Response to abnormal conditions	These sets of requirements define necessary response to abnormal voltage and/or frequency conditions, such as undervoltage. Because those conditions are typically triggered by an incident on the grid, the expectation is to withstand for a moment and then trip.	Voltage trip and ride-through, anti-islanding
Communication interoperability	This sets forth what data need to be available for a utility to read and write, and list of protocols to be implemented.	Information model, required protocol

[a] This does not intend to fully align with IEEE 1547's clauses.

Most of the requirements specified in this standard need to be met at the reference point of applicability. In a small site with a small DER, such as a rooftop solar system at a small residential home, the reference point of applicability can be at the point of DER connection. Otherwise, the reference point of applicability is at the PCC, which is typically at the meter. This has created a challenge to large sites, as each DER needs to be able to capture AC voltage and frequency at the meter, requiring additional wiring, logic, and/or communication.

The functions described above can have different settings to accommodate different needs across the locations and utilities. For example, in V/Q, a DER monitors AC voltage (at the reference point of applicability) and adjusts its reactive power autonomously, following the prescribed piecewise linear curve (see Figure 4 for an example curve). As illustrated, V/Q function can be configured with different points, allowing the utility to tailor the response.

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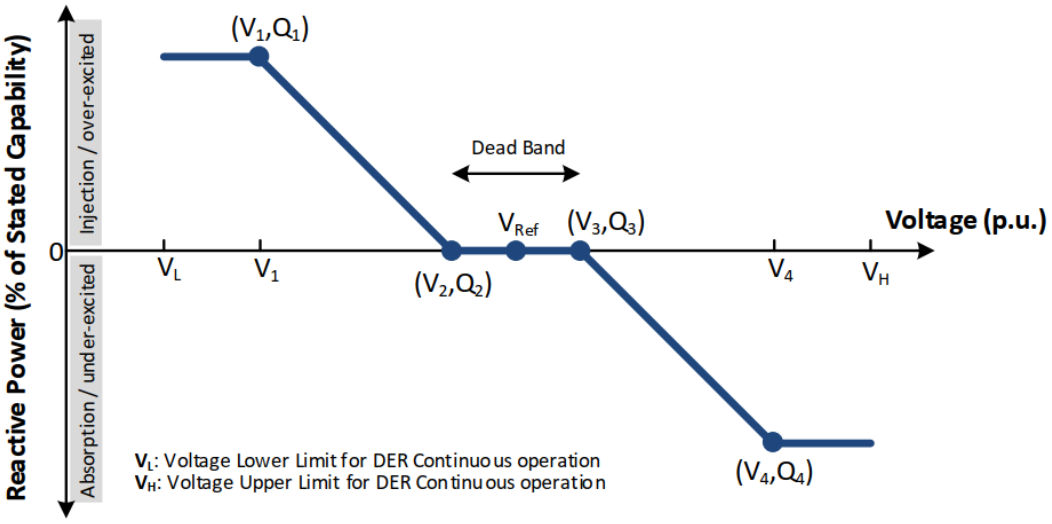

Figure 4. V/Q curve [1]

Different models of DERs have their own nameplate and configurations, such as maximum active power. These are expected to be read and/or written by the utility and/or the DER operator. To facilitate interoperability, IEEE 1547 also establishes the requirements for data exchange, data model, and protocol.

For the protocol requirement, per Clause 10.7 in IEEE 1547:2018 and Table 41 in the same document, either of the following three communication protocols is required to be *implemented* at minimum:[3]

- DNP3 [7] over Ethernet.
- SunSpec Modbus [8] over Ethernet or RS-485.
- IEEE 2030.5 [9] over Ethernet.

Additional protocols, including proprietary ones and other physical layers, are permitted as long as both the following conditions are met:

1. At least one of the three communication protocols mentioned above is implemented.
2. A mutual agreement with the utility has been established.

Note that the protocol requirements in IEEE 1547 apply at the utility interface to communicate with the utility for IEEE 1547 compliance purposes. The protocols and physical layers used for communication within the DER and site are out of scope of this standard and are consequently not constrained by the standard. The proposed single gateway solution outlined in Section 4 will be responsible for meeting these communication requirements set forth in IEEE 1547.

2.2 SAE J3072

A unique element for V2G AC charging is the separation of the permanently grid-connected asset, the EVSE, and the inverter that will provide AC power, which is inside the EV. This scenario requires a pair of devices designed to work in harmony. All EVs intended for

[3] This does not preclude other protocols being used. This is simply a minimum implementation requirement.

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performing V2G AC with *any* EVSE must comply with SAE J3072, which is complementary to the requirement that EVSE be listed to UL 1741SC. Note that today's V2G DC systems in the market include the inverter within the permanently installed EVSE, so UL 1741SC is not necessary.

At its heart, SAE J3072 requires the EV to comply with IEEE 1547 and the compliance to be evaluated by UL 1741SB. Therefore, the SAE J3072-compliant EV is comparable to a stationary DER that is compliant with IEEE 1547.

SAE J3072 also addresses the mobile nature of EVs. In other words, an EV can be connected to different locations with different limits (such as maximum active power) and/or different configurations for IEEE 1547 requirements (such as V/Q curve points as described in Section 2.1.) The coordination and hence the adjustment is defined in the standard, also referred to as "J3072 handshake." Notably, as described in Figure 5, the EVSE verifies that the EV's model number (i.e., ISMN) is included in the "authorized EV list." To date, the list does not exist. Only after a successful handshake can the EVSE authorize the EV to discharge. The EVSE is required to prevent the EV from discharging otherwise.

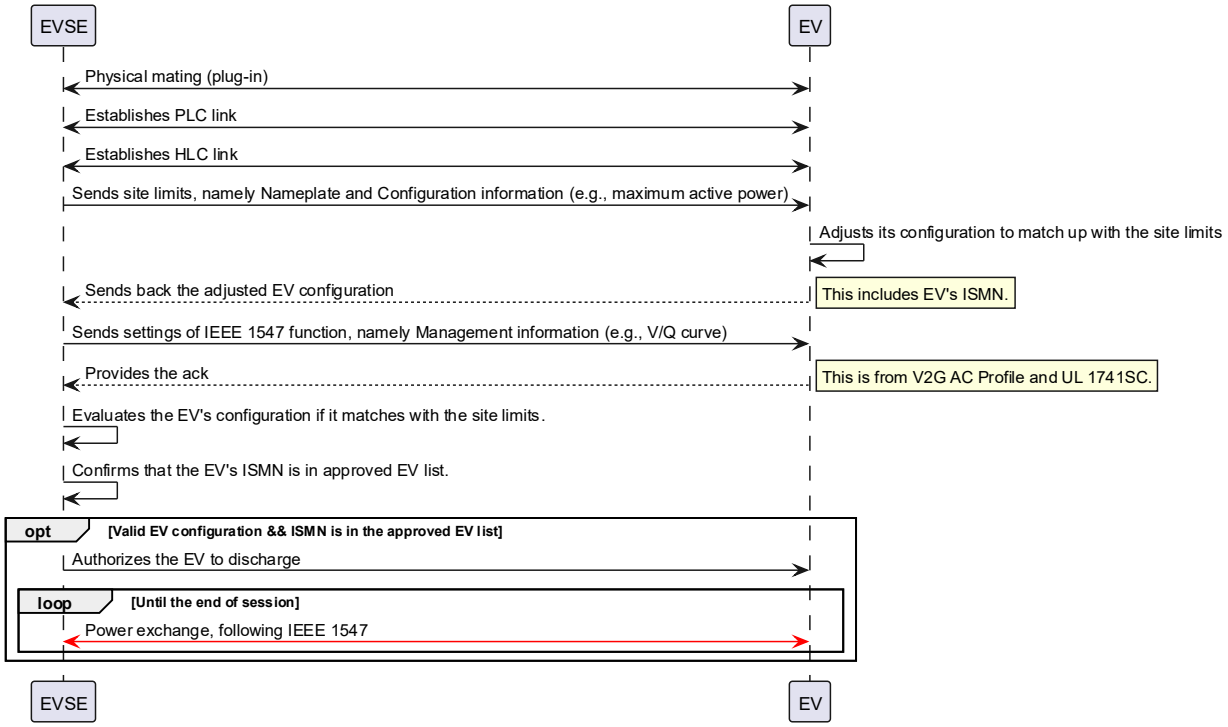

Figure 5. Overview of SAE J3072 handshake

SAE J3072 defines possible protocols to be used for the standard: IEEE 2030.5 and SunSpec Modbus. While ISO 15118-20 [10] is *acknowledged* in the standard, it highlights that ISO 15118-20 does not support SAE J3072. To date, there is an ongoing revision to the standard to add ISO 15118-20 Amendment 1 to the list of protocols.

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2.3 UL 1741SC

While an SAE J3072-compliant EV is in principle compliant with IEEE 1547 and is evaluated by UL 1741SB, it may not be listed. Listing has been utilized in interconnection approval processes and in this situation requires UL 1741SC to address the gap and allow for the bidirectional charging system to interconnect to the grid.

UL 1741SC is applicable to an AC EVSE intending to perform V2G AC along with an SAE J3072-compliant EV. Besides referencing existing EVSE standards, it includes a concept called oversight. The objective of oversight is to support the grid safety by:

- Performing voltage and frequency trip as defined in IEEE 1547.[4]
- Performing trip against line-to-neutral overvoltage.[5]
- Preventing unauthorized discharge, aligning with SAE J3072.

As the EVSE only has a contactor to disconnect the EV from the grid, a trip will require opening the contactor. To reduce the likelihood of breaking under load, oversight requires the EVSE to ride-through (i.e., not trip) until a certain duration (e.g., 60 ms) before clearing time.

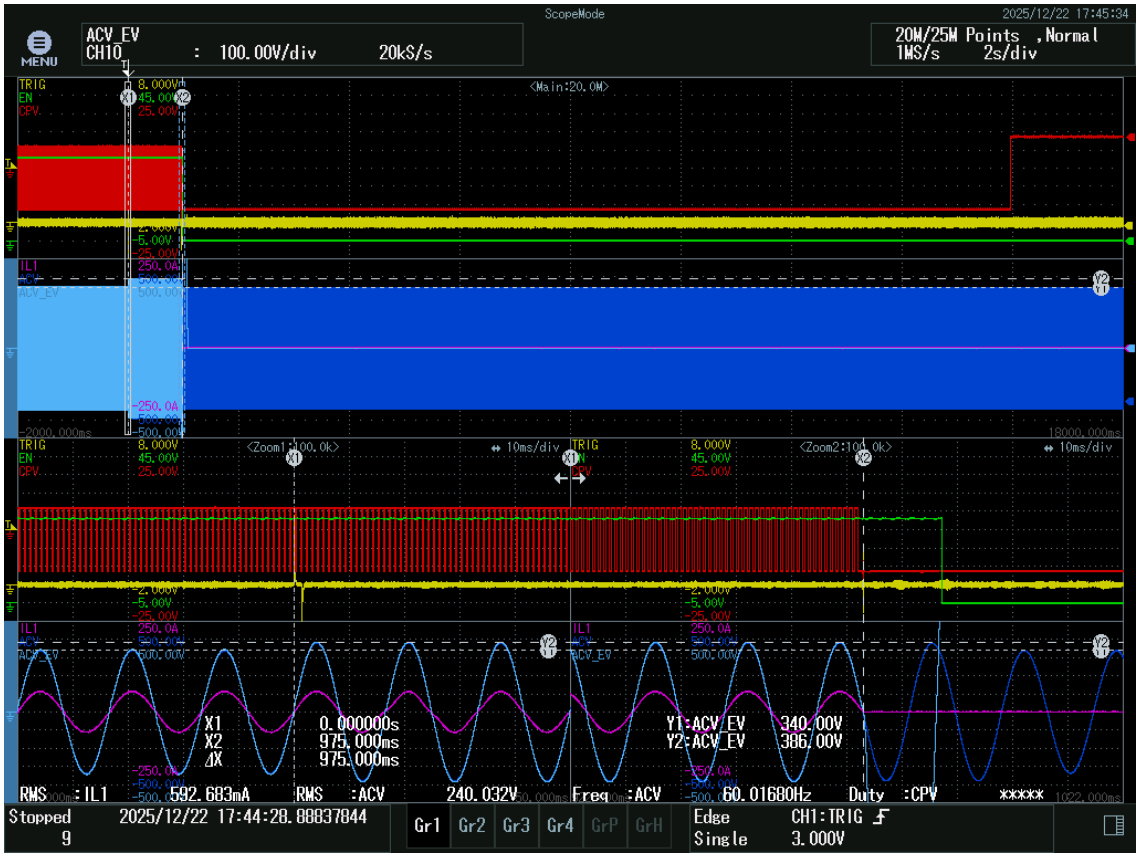

Figure 6. Oversight: interrupting an EV not following IEEE 1547

[4] SAE J3072-compliant EVs also perform voltage and frequency trip, as required by IEEE 1547.
[5] Level 2 AC charging does not have neutral connection between the EVSE and EV.

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However, as a DER complying with IEEE 1547, an EV can trip barely before the clearing time. Therefore, the extended ride-through requirement to the EVSE still leaves the chance of breaking under load, and hence a harmonization between SAE J3072 is needed. Requiring EVs to trip beforehand (i.e., shortening the clearing time from IEEE 1547) will make sure that the EV trips before the EVSE does. The example is illustrated in Figure 7.

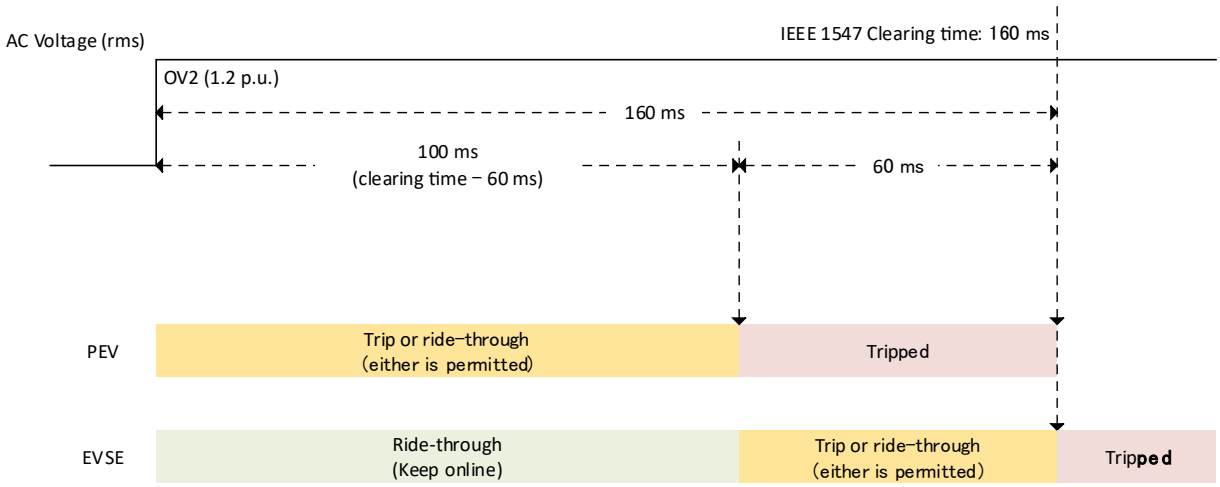

Figure 7. EV and EVSE coordination concept

2.4 UL 3141

In addition to IEEE 1547, some utilities require systems to comply with power import and export limits to support grid capacity constraints. UL 3141 is a safety and performance standard that defines requirements for a PCS used in DER installations. The standard was developed to address the increasing complexity of DER-integrated electrical systems and evolving grid constraints that impose limits on power import and export at a PCC. A PCS is a system consisting of one or more devices that actively monitor, limit, and control current or power on conductors or bus bars as set forth by UL 3141. PCS functionality can be implemented for both single-source and multisource electrical systems (as shown in Table 2) and is intended to ensure safe, predictable operation under normal and dynamic grid conditions. Note that this document uses the terms PCS and PCS controller interchangeably outside this section, except where otherwise specified.

UL 3141 defines multiple PCS functional categories, each addressing specific control and protection objectives, as defined in Table 2.

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Table 2. UL 3141 PCS Functional Requirements

Category	Description
Power import limiting (PIL)/ power export limiting (PEL) PCS	Designed to manage power exchange at the point of interconnection such as PCC.
Multisource PCS	Bus bar overload control: Provides overload protection for monitored bus bars within panelboards. Feeder conductor overload control: Provides overload protection for controlled feeders and/or to service conductors. Branch conductor overload control: Provides overload protection for branch conductors between panelboards and connected sources or loads.
Single-source PCS	Designed to provide overload protection through load management when only a single source of supply is present.

Loads or sources with PCS functionality that act as active protective devices are considered part of the PCS. Figure 8 shows a brief overview of the PCS system for PEL/PIL PCS as an example.

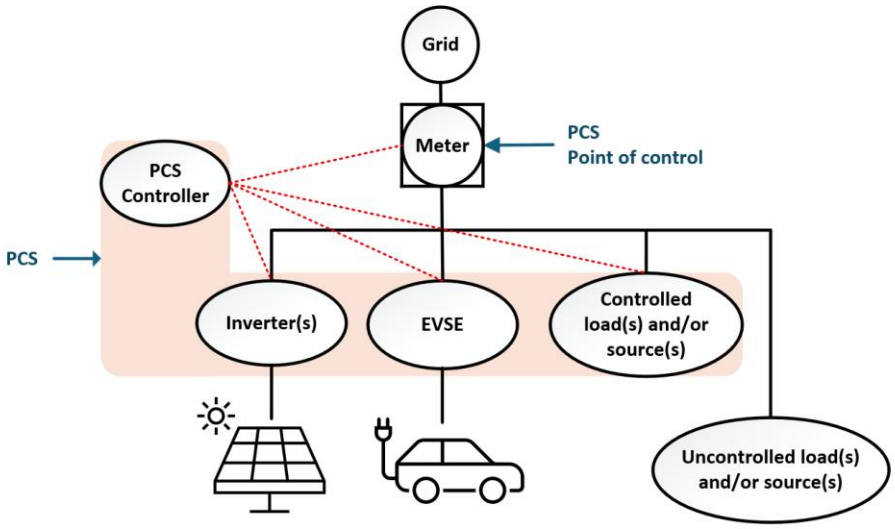

Figure 8. Overview of PCS Coordination

These PCS functional categories collectively can control power flow between DERs, local electrical systems, and the grid. UL 3141 defines several key architectural and safety-related constraints for PCS. For example, the PCS controller responsible for overload protection is required to be located on-site, and reliance on cloud-based or web-dependent overload control is not permitted. For PIL and PEL control functions only, PCS control settings may be adjusted remotely by permission of the utility. While UL 3141 specifies the file format for scheduling import and export, it does not impose a specific communication protocol. In the event of a communication failure, the PCS must transition to a safe state that maintains overload protection and enforces defined power limits. In addition, manufacturers are required to clearly list all devices like external current sensors, PCS controllers, controllable loads, and inverters for proper operation of PCS.

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Testing and Performance Framework:

UL 3141 provides a structured, testable framework for evaluating PCS functionality. Testing is designed to verify that a PCS can accurately and safely provide overload protection and control import and export of power to the grid with the following key testing categories:

- General and normal operating tests: Verify that when a control command or step change is applied, the PCS responds within a defined time (typically ≤30 seconds, with some conditional exceptions) and maintains power or current at the testpoint (such as PCC) within ±7.5% of the set point.
- Step-change tests: Evaluate PCS response to sudden changes at the testpoint (such as PCC) in load or generation, including load increases or decreases and rapid changes in DER output (e.g., PV inverter ramping).
- Single-source PCS tests: Confirm correct overload protection and import/export limiting when only one source of supply is present.
- Multisource PCS tests: Assess PCS coordination across multiple interacting sources, ensuring limits are maintained without instability or unintended overload.

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3 Communication and Control Requirements

As mentioned in Section 2.1, IEEE 1547 defines the technical requirements for interconnection of DERs with the grid. Employing relevant communication protocols plays a crucial role in enabling the desired interaction with a DER and supporting necessary grid benefits. Hence, IEEE 1547 requires at least one of the following protocols to be implemented at minimum:

- DNP3 over Ethernet.
- SunSpec Modbus over Ethernet or RS-485.
- IEEE 2030.5 over Ethernet.

The standard also allows the use of additional communication protocols, including proprietary ones if there is a mutual agreement with the utility. The use of industry standard protocols enables a more open market environment for consumers, while the option for proprietary systems enables a more customized solution space allowing for the development of additional functionality. This results in a diverse set of market options, limiting interoperability, and potentially benefiting from a solution that communicates across multiple protocols.

A market study was performed to investigate the landscape of communication protocols supported by inverters currently in production. The list of inverters for this study was compiled from multiple sources including, but not limited to:

1. UL-listed inverters in UL's Product iQ database.
2. Approved smart inverter list from PPL Electric Utilities [11]
3. SunSpec Alliance contributing members [12].

3.1 Diverse Landscape

A total of 751 inverters from 50 companies have been analyzed in this study. This list comprises PV inverters, battery inverters, microinverters, and bidirectional converters (including chargers). Figure 9 shows the distribution of models that support nonproprietary communication protocols versus proprietary ones.

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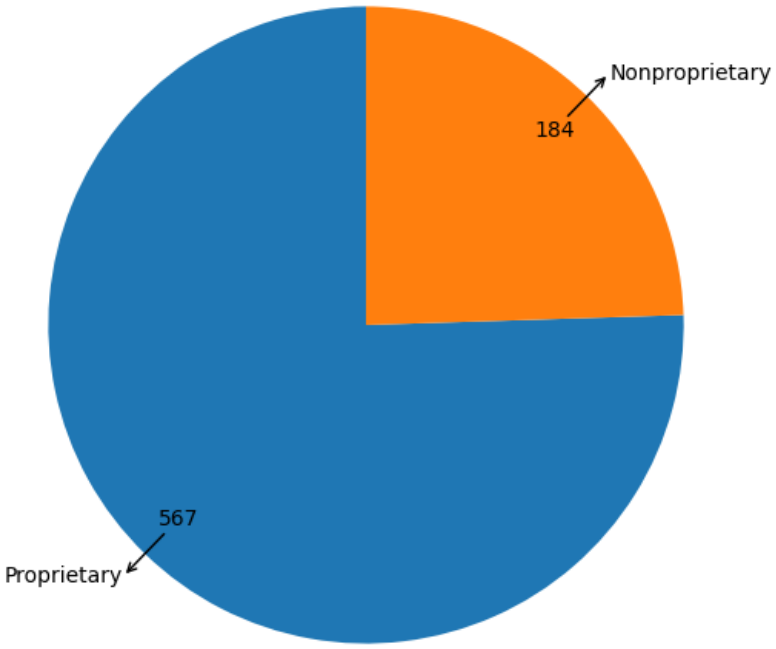

Figure 9. Inverter communication protocol distribution

This shows that the vast majority of inverters currently in the market only support proprietary communication protocols, with just 184 models supporting at least one nonproprietary protocol. The study also reveals that SunSpec Modbus and IEEE 2030.5 are the most popular nonproprietary communication protocols. In addition to these two, four nonproprietary protocols outside of the three required by IEEE 1547 are also supported by inverters. These are Open Charge Point Protocol (OCPP) 1.6j [13], Open Automated Demand Response (OpenADR) [14], Process Field Network (Profinet), and Process Field Bus (Profibus), in decreasing order of popularity according to the market study. The distribution of number of inverter models supporting each of these six nonproprietary protocols is shown in Figure 10.

OCPP 1.6j is a popular communication protocol with increasing adoption across EVSE. OpenADR is an open communications data model designed to facilitate demand response events initiated by a utility upon customer-side equipment such as a smart thermostat, water heater, solar/inverter system, lighting control, or industrial control. Profibus is a widely used, vendor-independent, serial-based industrial protocol, while Profinet is the modern version of Profibus based on industrial Ethernet. These two protocols are designed for communication in automation, supporting a wide array of devices like drives, motors, input/output devices, sensors, robots, and actuators.

Due to the differing motivation behind the definition of these six nonproprietary protocols, there is no straightforward way to harmonize these communications. This is further exacerbated by the 45 distinct proprietary communication protocols used by the 567 models mentioned in Figure 9.

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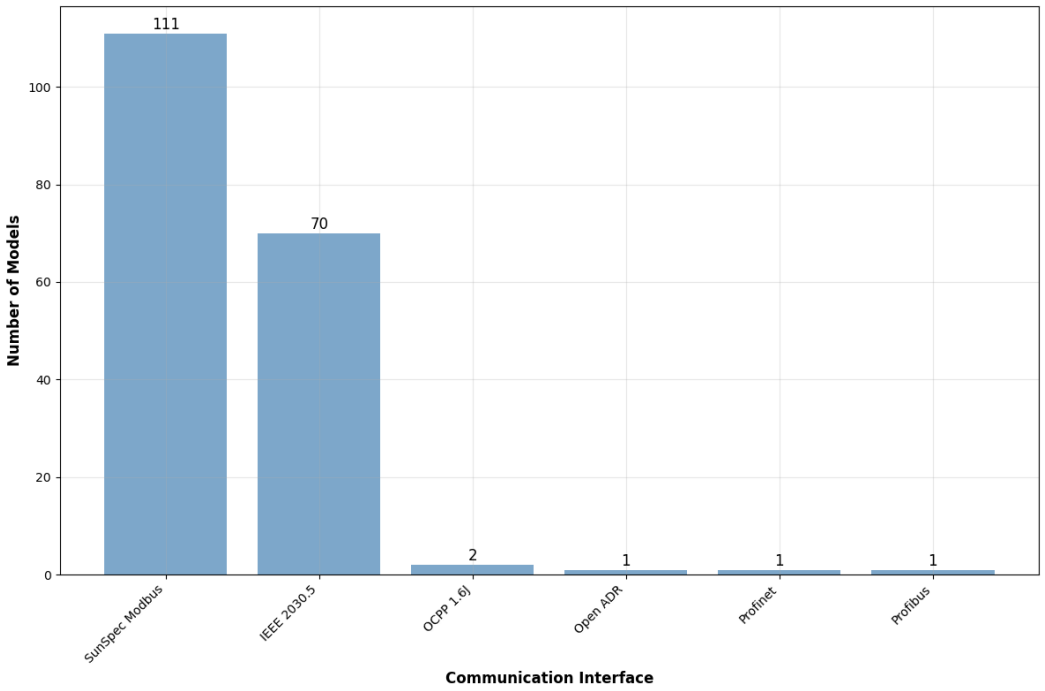

Figure 10. Market breakdown of nonproprietary inverter communication protocol options

The sheer number of distinct proprietary communication protocols adds complexity in achieving interoperability across all inverter models in the market due to the volume of specific translations required. Thus, for any single gateway that needs to perform translations and coordinate multiple types of DER assets, using a limited set of popular nonproprietary communication protocols is the most optimal option.

3.2 Key Protocols of Interest

The market study shows that SunSpec Modbus and IEEE 2030.5, which also form part of the minimum required protocols per IEEE 1547, have the highest adoption rate of all nonproprietary protocols. In addition to these two protocols supported by stationary DERs (PV and battery inverters), OCPP 1.6 is a popular communication protocol used by EVSE to communicate with a charge station management system or aggregator.

The newest version of this protocol, OCPP 2.1 [15], which was released in 2025, introduces key messages and functional blocks such as bidirectional power transfer and DER control. These enable exchange of crucial information such as nameplate information, power settings, and parameter settings, thereby unlocking IEEE 1547 support. In contrast to OCPP 1.6, OCPP 2.1 also establishes native support for ISO 15118-2 [16] and ISO 15118-20 [17], which are popular protocols used for EV-to-EVSE communications. Additionally, in-site communication is beyond the scope of IEEE 1547 (explained in Section 2.1). Hence, leveraging OCPP 2.1 is a reasonable choice to facilitate communication between the gateway and the EVSE for DER control and between the charge station management system and EVSE for managed charging.

Thus, these three communication protocols, namely OCPP 2.1, SunSpec Modbus, and IEEE 2030.5, have been chosen to consolidate the interactions of multiple types of DER assets via the

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single gateway solution. Each of these three protocols and their path to support IEEE 1547 are described in further detail in the following sections.

3.2.1 OCPP

OCPP is an open communications protocol developed by the Open Charge Alliance to enable interactions between EVSE and the charge station management system. This protocol is designed to be vendor agnostic and hence enables communication interoperability between any EVSE manufacturer and relevant EV charging stakeholders. In the context of this report, OCPP will enable the PCS gateway to coordinate with EVSE in compliance with IEEE 1547, while OCPP may also be used for separate charge station management system objectives, such as access control and charge session status metrics.

Released in 2015, OCPP 1.6 is the most widely deployed OCPP standard but lacks a few useful features required to fully support IEEE 1547. On top of the smart charging capabilities defined in OCPP 1.6, OCPP 2.0.1 introduced more capabilities such as frequency support and local load balancing in addition to native support for bidirectional charging and ISO 15118-2 communications with the EV. OCPP 2.1 added native support for ISO 15118-20 enabling V2X, and crucially, new functional blocks called "DER Control" and "Energy Management System" explicitly enabling support for energy management using DERs. These additions in OCPP 2.0.1 and OCPP 2.1 enable compatibility with IEEE 1547. OCPP 2.1 Edition 1 is now officially published as an IEC standard, IEC 63584-210: 2025 [18]. This section serves as an overview of the protocol functionality in reference to its incorporation as part of a single gateway solution.

OCPP 2.1 describes the following message field definitions that can be used for supporting IEEE 1547 functions:

- *SetDERControl*: This message is designed to communicate DER control settings such as voltage trip curves, frequency trip curves, reactive power curves and parameters, active power curves, and frequency droop, among other parameters. These settings can also be scheduled using the "start time" and "duration" fields.
- *ClearDERControl*: This message allows the charge station operator to clear any default and/or previously set DER controls settings in any EVSE.
- *GetDERControl*: This message enables the charge station operator to retrieve currently active DER settings of any EVSE. The EVSE then uses the *ReportDERControl* message to respond with the details of the currently active DER settings.
- *ReportDERControl*: EVSE uses this message in response to a *GetDERControl* message initiated by the charge station operator to communicate its currently active DER settings.
- *NotifyDERAlarm*: This message is used by the EVSE to inform the charge station operator of any grid event that has caused a fault. Additional information like DER control type and the type of grid event that caused this fault is also included as part of this message. An "ended" flag can be used by the EVSE to inform the charge station operator that this fault alarm has ended.
- *NotifyDERStartStop*: This message is used by the EVSE to communicate which DER control is taking over and what caused it. Similarly, this message is also used to indicate when this event ends with an "ended" flag.

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- *DataTransfer:* This message can be used by either EVSE or the charge station operator to initiate a vendor-specific information exchange. This message requires vendor-specific implementation on both the EVSE and charge station operator.

All messages in OCPP 2.1 are designed in a request/response pair format in which each message's "request" can be initiated by the EVSE, charge station management system, or both. Some of the fields in each message's field structure are defined as "optional." This means that, in practice, some of the fields in a specific message can be omitted by the sender. OCPP 2.1 defines the information embedded within each of its message's structure while considering the constraints/limitations that arise from a request/response-based communication format.

OCPP Response to IEEE 1547

OCPP 2.1 has smart charging, bidirectional power transfer, and DER control functional blocks in addition to the messages described above, with the intention to support IEEE 1547 functions such as voltage-active power (V/W) and V/Q. Table B-1 and Table B-2 provide a detailed mapping of OCPP 2.1 message fields to IEEE 1547 parameters for these two functions. These two functions have been used in this report as an example to depict OCPP 2.1's mapping with IEEE 1547.

Additionally, OCPP 2.1 only defines the message structure but does not impose any requirements on the protocol's implementation, with the protocol allowing the use of some message fields to be optional. OCPP 2.1 defines a prescribed sequence of information exchange for various use cases and scenarios, but this description is limited to primary stakeholders only. As a result, clarifying the practical challenges associated with implementation of interaction between the EV charging stakeholders using OCPP2.1 to satisfy IEEE 1547 requirements is crucial for designing a robust gateway solution.

Thus, implementation of interaction between the EV charging stakeholders using OCPP 2.1 to satisfy IEEE 1547 requirements and the associated practical challenges will need to be clarified.

OCPP Response to UL 3141

OCPP 2.1 does not directly specify the PCS requirements addressed in UL 3141. However, it provides standardized communication mechanisms that can be used by a PCS to exchange control commands, limits, and measurement data necessary to execute and verify power control functions such as control of power import and export or protection against overload conditions within a power system. The following bullet points describe information/messages that can be used to support functions relevant to UL 3141.

- Remote control: OCPP 2.1 supports remote transaction control, allowing the PCS to start or stop a transaction remotely. This capability aligns with UL 3141 scenarios such as PIL, PEL, and overload protection for monitored bus bars. Table 3 lists some key signals.

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Table 3. UL 3141 to OCPP 2.1 Mapping for Key Remote Control Signals

Key Signals	Description
RequestStartTransaction	Enables controlled restoration of charging once PCS constraints are lifted.
RequestStopTransaction	Allows immediate reduction of load during overload or grid constraint conditions.
TransactionEvent	Provides traceable evidence that remote control actions were executed.

- Smart charging: The smart charging functionality in OCPP 2.1 offers standardized mechanisms that allow the PCS to influence the charging current or power delivered by a charging station. It supports control at various levels—charging station, EVSE, or site—allowing management over total energy consumption across individual stations or groups of stations. OCPP 2.1 includes internal, central, local, and external smart charging topologies, which makes it suitable for PCS-based overload protection. Key functionalities of smart charging in OCPP 2.1 enable PCS to:
    - Limit total import and/or export power.
    - Delay or reduce charging during peak conditions.
    - Coordinate constraints from grid, transformer, or bus bar limits.

  Charging power or current is controlled by sending time-dependent energy transfer limits to a charging station. These limits are defined in a *ChargingProfile*, which specifies power or current limits and may include start times and durations at the charging station or EVSE level. Some of the key charging profile purposes relevant to UL 3141 are mentioned in Table 4.

Table 4. Key Charging Profile Purposes

Key Signals	Description
ChargingStationMaxProfile	Defines the maximum allowable power for a charging station, which could provide site-level overload protection.
ChargingStationExternalConstraints	Representing limits imposed by a PCS, typically derived from grid, transformer limitations, or bus bar protection logic and could support UL 3141 import/export control objectives.
LocalGeneration	Describes locally available generation that offsets grid import. This supports PCS logic when managing net import power and coordinating local generation resources.

Table 5 identifies some key OCPP 2.1 signals used to support implementation of the charging profiles described above.

OCPP 2.1 also introduces smart charging operation modes, which define whether a charging set point is fixed or dynamically updated by the PCS. These operation modes,

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along with charging profile stacking, define clear control authority for charging set points and limits, ensuring grid-imposed power constraints are enforced over secondary charging objectives.

Table 5. UL 3141 to OCPP 2.1 Mapping for Key Smart Charging Signals

Key Signals	Description
SmartChargingAvailable	Indicates availability of smart charging functionality.
SetChargingProfile	Used to define charging power or current limits for specific EVSE or the entire charging station over a defined time period.
ClearChargingProfile	Removes previously applied charging profiles, allowing charging power to return to normal operation once PCS constraints are cleared.
GetChargingProfiles	Retrieves active charging profiles from the charging station for verification or diagnostics purposes.
NotifyChargingLimit	Sent by the charging station to indicate that a charging limit has been applied. This signal can be used to confirm activation of PCS constraints.
ClearedChargingLimit	Indicates that a previously applied charging limit has been removed.
GetCompositeSchedule	Requests the effective charging schedule calculated by the charging station by combining all active charging profiles, external constraints, and local limits. This signal provides evidence that PCS-defined limits are correctly enforced in the presence of multiple control sources.

Although UL 3141 does not mandate a specific communication protocol, OCPP 2.1 provides a comprehensive and standardized set of control, monitoring, and reporting mechanisms that can be used to implement and demonstrate PCS functionality. Through smart charging and remote control, OCPP 2.1 supports import/export power control and overload protection, aligning with the objectives of UL 3141. These capabilities can support cohesive response to both UL 3141 and IEEE 1547 requirements. With OCPP 2.1 and the following complementary protocols, a gateway will be able to coordinate all site energy assets with dynamic grid constraints.

3.2.2 SunSpec Modbus

SunSpec Modbus is one of three protocol options that is required to be implemented at minimum per IEEE 1547 and hence supports the compliance of a DER to IEEE 1547. SunSpec Modbus is a protocol based on Modbus to exchange data. The physical layer can be Ethernet (and hence Transmission Control Protocol/Internet Protocol [TCP/IP] can be used) or RS-485 per IEEE 1547. In Modbus, a device holding data (information) such as operational settings (e.g., V/Q curve), measured values, and nameplate information is called a server. A client makes requests to read and/or write to those pieces of information. Typically, a DER becomes the server, and an upstream device such as the gateway becomes the client. This is illustrated in Figure 11.

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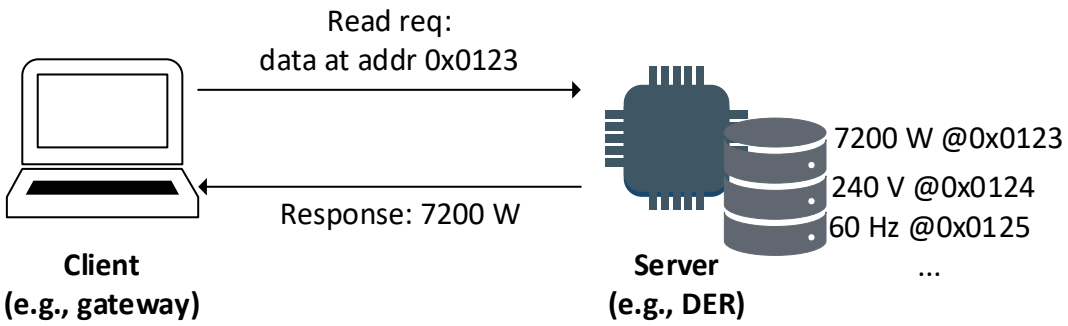

Figure 11. Modbus server: client

A client specifies an address or a series of addresses to read the intended data or write a value (or values) to update the data. Typically, data is 2 or 4 bytes, and the address is 4 bytes, allowing smaller payload. Additionally, Modbus's header is numeric-based, and hence the total data length is compact. Therefore, Modbus (SunSpec Modbus) is ideal for in-device and in-site communication. Indeed, Modbus can be found in factory automation.

While Modbus is a standardized protocol to exchange data (information), the information model, also known as register map, is not standardized. Therefore, the register map is up to the vendor of the device, causing interoperability problems between Modbus devices.

SunSpec Modbus was developed to solve the interoperability issue by defining the information model (i.e., register map) to support compliance with IEEE 1547. An example of a register map describing parameter-address-value type-value pairs is shown in Table 6.

Table 6. SunSpec Modbus Register Map (V/Q Excerpted)[a]

Address	Name	Value	Type
40394	ID	705	uint16
40395	L	163	uint16
40396	Ena	0	enum16
…			
40409	Crv[0].ActPt	4	uint16
40410	Crv[0].DeptRef	3	enum16
…			
40419	Crv[0].Pt[0].V	92	uint16
40420	Crv[0].Pt[0].Var	44	int16
40421	Crv[0].Pt[1].V	98	uint16
40422	Crv[0].Pt[1].Var	0	int16

[a] This is an example of actual implementation and appears different from SunSpec Modbus information model available from SunSpec.

A set of data is grouped to form a meaningful dataset, called a model. In SunSpec Modbus, each model corresponds to a group of IEEE 1547 requirements (e.g., functional requirement), such as V/Q. Each model is distinguished by the model ID. Table 7 lists example models for IEEE 1547.

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Table 7. Example Models for IEEE 1547

ID	Mapping to IEEE 1547	Description
701	Monitoring information	Provides electrical readings captured by the DER
702	Nameplate and configuration information	Provides the DER's nameplate and configurable ratings, such as maximum active power
703	Management information – enter service	Settings for enter service for the DER
704	Management information – misc.	Settings for miscellaneous functions for the DER, such as active power set point
705	Management information – V/Q	Settings for V/Q for the DER
…	…	…

For example, an upstream device (i.e., client) such as the gateway can initiate a read request to collect operational information of the DER that can be found on ID 702 in Table 7. It can also make a write request to provide active power set point. With the aforementioned compactness of the payload, SunSpec Modbus allows the upstream to control DERs in real time. Nonetheless, SunSpec Modbus does not offer aggregation of devices, and hence is more suitable for controlling on-site devices. Because an on-site gateway is the front end for the utility, and communication within the site is handled by the gateway, it will alleviate the need for aggregation from the utility's perspective.

3.2.3 IEEE 2030.5

IEEE 2030.5 is another of three protocols required to be implemented at minimum per IEEE 1547 and hence supports the compliance of a DER with IEEE 1547. For IEEE 1547-related information, it adopts generator sign convention[6] as IEEE 1547 does. To date, Rule 21 requires IEEE 2030.5 by default to communicate with the local utility.

IEEE 2030.5 uses RESTful protocol to exchange data. One known example of such a protocol is HTTP. Unlike SunSpec Modbus, a DER acts as a client and an upstream device, such as the gateway, and a DER management system acts as a server. Thereby, a DER initiates the request to get settings (i.e., HTTP GET), such as active power set point, V/Q curve, and maximum active power, and pushes (HTTP PUT or POST) the update on the up-to-date settings and/or operational information such as measured values.

Considering the above, it is not straightforward to change the settings such as active power set point, as the timing to GET the setting is up to the client. To address the issue, IEEE 2030.5 defines the minimum polling requirement and offers a Subscription/Notification mechanism where the client exposes its end point (i.e., Uniform Resource Identifier [URI]) so that the server sends the notification over a new TCP link with a separate Transport Layer Security (TLS) session.

[6] For example, information related to smart charging (e.g., *FlowReservationRequest*) uses a positive value to indicate charging.

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IEEE 2030.5 uses Extensible Markup Language (XML) or Efficient XML Interchange (EXI) to exchange information (i.e., the presentation layer). XML data consists of one or more individual data fields, namely element and attribute. This corresponds to Modbus's register map, and like the register map, XML needs defined framework (i.e., information model) for interoperability. The schema defines the information model and is based on an object model. An example class diagram of IEEE 2030.5 is shown in Figure 12.

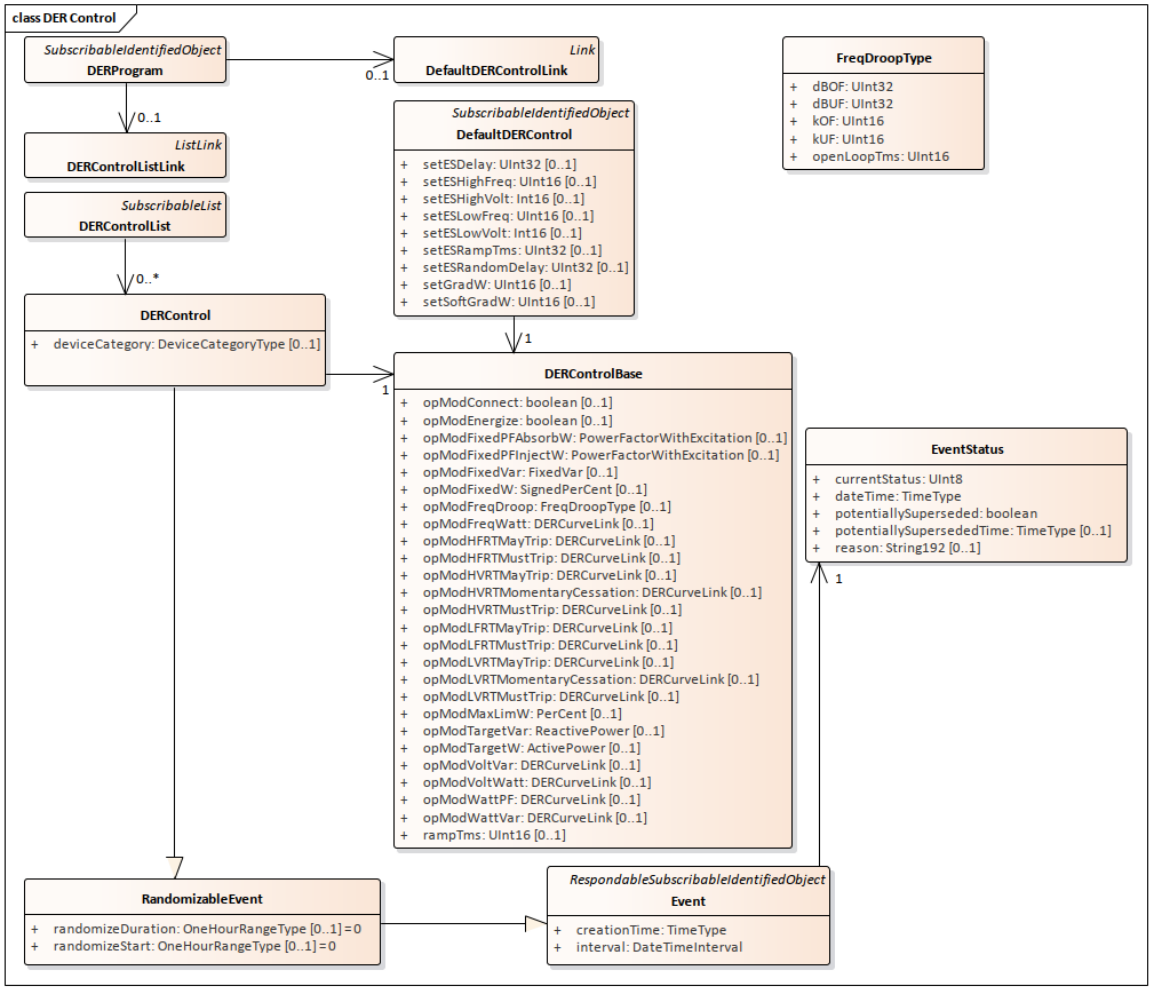

Figure 12. Example class diagram [2]

As a web-based technology, XML data is referred to as a resource. A dedicated URI exists for each resource to access the resource for reading or writing. Indeed, there are many elements and attributes in IEEE 2030.5 that provide a URI to another resource. The resource then may include another URI, forming a chain of URIs, as illustrated in Figure 13.

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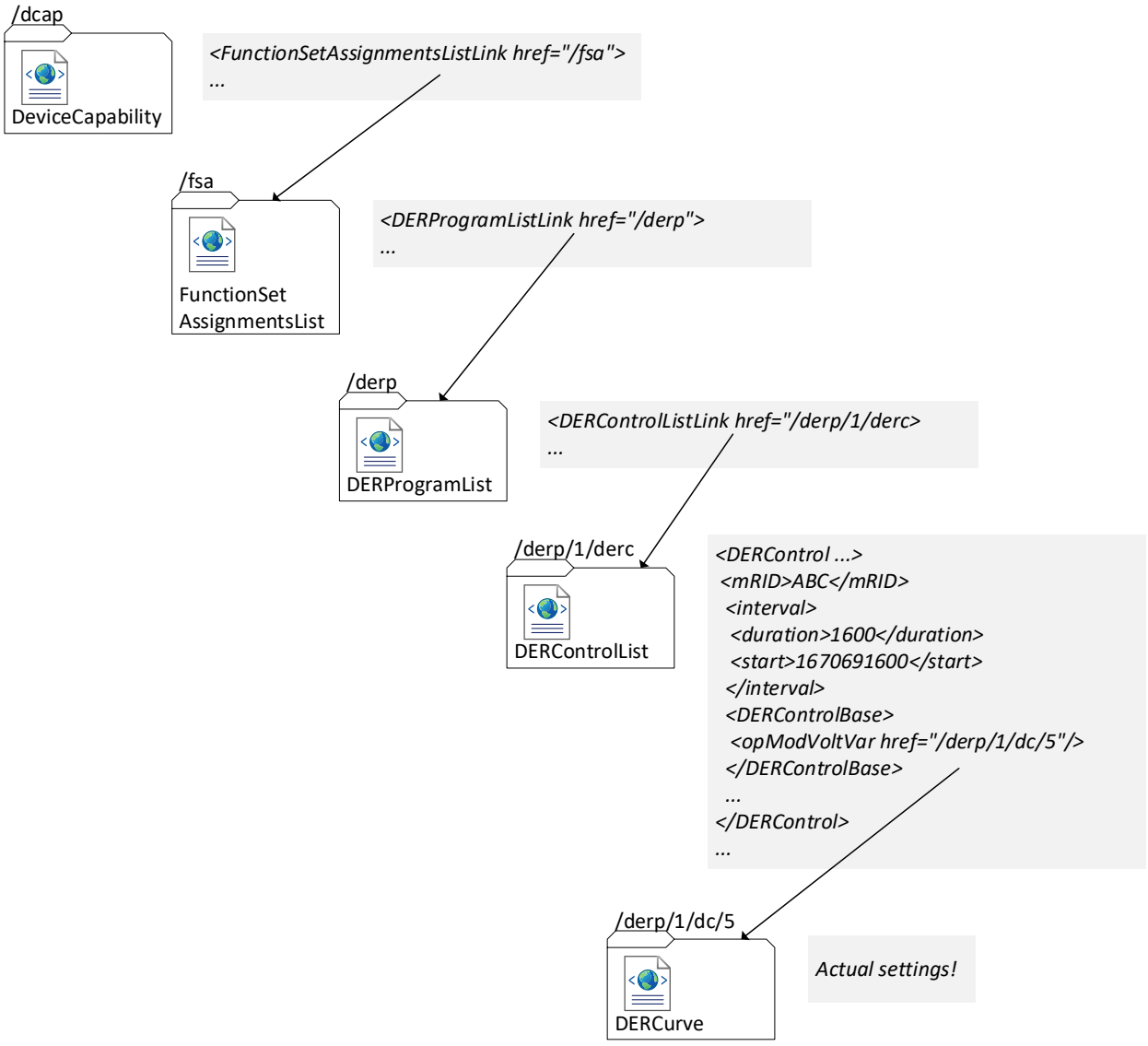

Figure 13. Chain of URIs

Figure 13 is an example of the chain to acquire a list of DERControls and then the setting for V/Q. A DERControl is a container to carry settings for each group of IEEE 1547 requirements (e.g., V/Q). Again, the element within a DERControl may be just a URI (e.g., DERControl, DERControlBase.opModVoltVar for V/Q), and following the chain, the necessary settings are retrieved.

IEEE 2030.5 also introduces and leverages events. Each DERControl has start time and duration. This allows scheduling of each function ahead of time, including active power set point.

While there is complexity in implementation, with the features mentioned above, IEEE 2030.5 is versatile. Indeed, IEEE 2030.5 covers time of use, managed charging, demand response of diverse asset types (e.g., pool), aggregation (with the latest version), and so on. To support the interoperability of IEEE 2030.5 devices, SunSpec developed a profile called Common Smart Inverter Profile, which is planned to be transitioned into IEEE 2030.5.1 [19].

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3.3 Additional Considerations

While this section has demonstrated that the set of communication protocols chosen can facilitate the required interaction, there are some additional implementation-related aspects that need to be addressed:

1. IEEE 1547, IEEE 2030.5, and SunSpec Modbus are all based on generator sign convention. In contrast, OCPP 2.1, ISO 15118-2, and ISO 15118-20 are based on load sign convention.
2. The communication protocols mentioned so far are application-level protocols. These need to be used on top of underlying protocols (e.g., WebSocket, HTTP[S], TCP, serial) depending on the chosen network architecture.
3. In addition to translating information from one protocol to another, the sequence of communication also forms a crucial part of enabling interaction across different protocols via the gateway.

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4 Site Harmonization Development

As identified earlier, there are multiple communication protocols used in the market with unique capabilities to coordinate DER with utility interconnection requirements. This diverse set of options becomes problematic when there are different asset types installed across a single site. For example, in a residential setup, rooftop solar can be combined with energy storage (e.g., a battery system or V2X-capable EV) to increase resilience and lower electricity bills. These scenarios with multiple assets and different communication protocols create a challenging environment for a single site to meet objectives such as IEEE 1547 and UL 3141. An example of this convoluted framework using different protocols and communication paths is displayed in Figure 14.

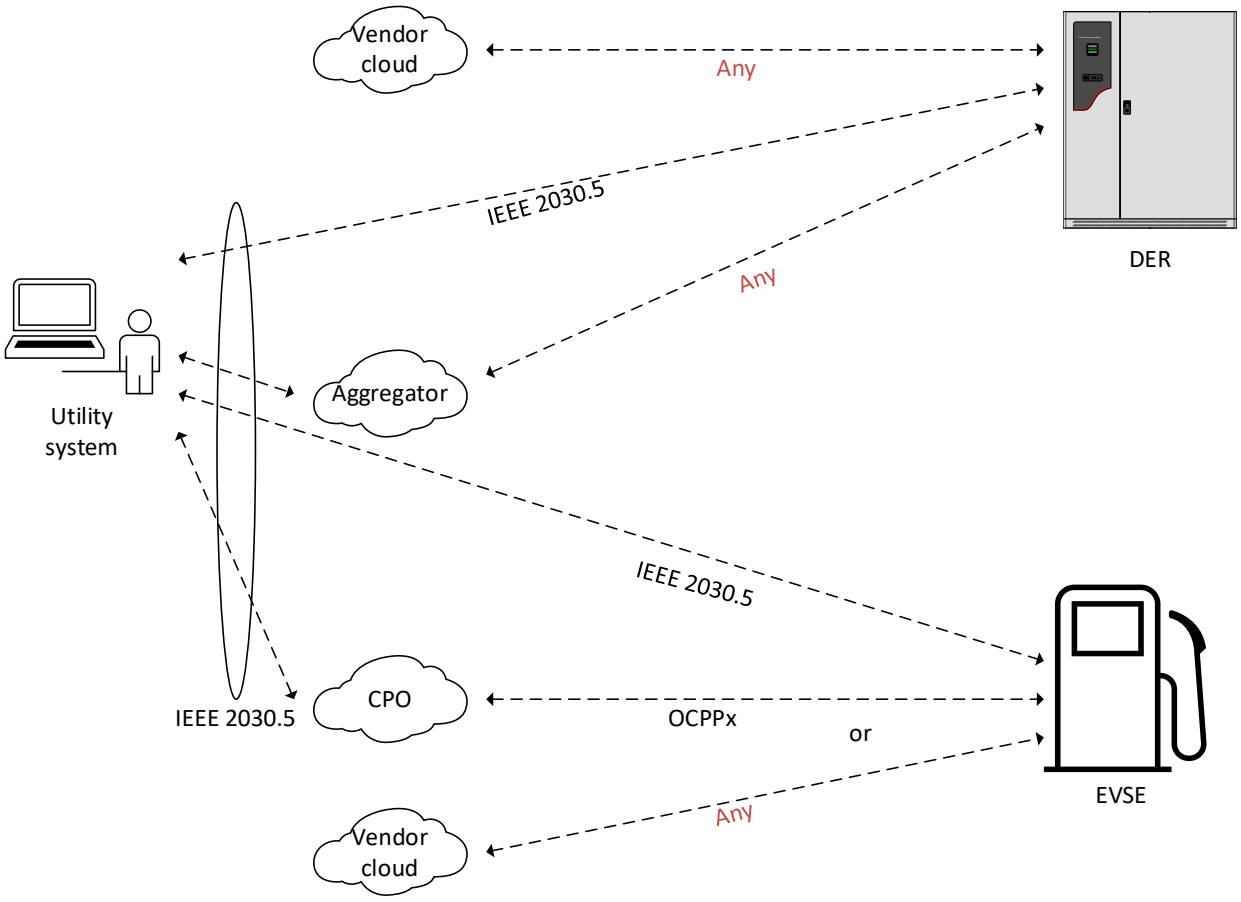

Figure 14. Convoluted communication paths

However, a gateway that serves as a centralized communication controller can simplify the communication paths and lower the overall cost of the system installation and operation. This gateway will coordinate diverse site assets to develop a cohesive response to UL 3141 and IEEE 1547, as outlined in Figure 15.

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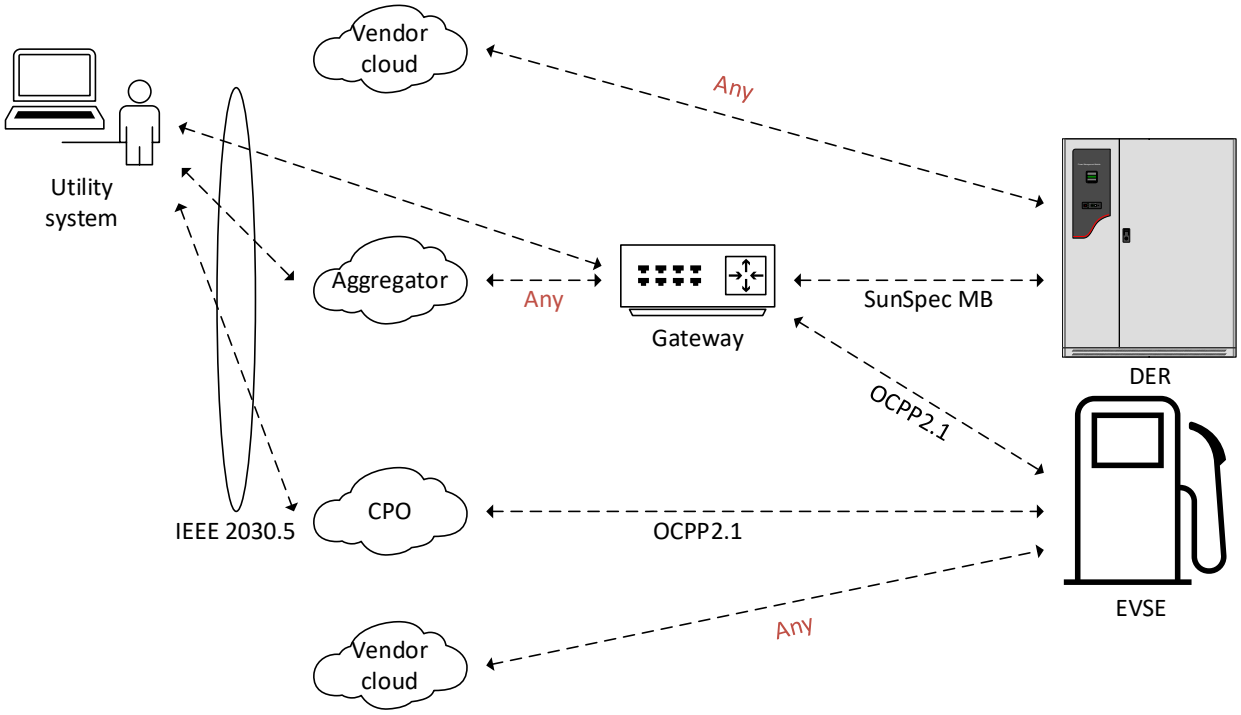

Figure 15. Simplified communication paths with gateway

The core gateway functionality necessary to support this solution is the translation of different protocols and bundling of communication paths. The gateway must support industry-adopted standards to avoid vendor lock-in, as non-standardized protocols (i.e., proprietary protocols) require a proxy from the vendor of the DER.[7] Note that the proxy also facilitates communication with the utility.

Beyond diverse communication paths, having multiple DERs at a site typically requires each DER to comply with IEEE 1547 requirement at the PCC, as described in Section 2.1. This can be met by an additional wiring to the DER from the PCC and/or communication channel to the DER to inform the AC voltage measured by a device at the PCC. However, in V2X this is problematic, as the wiring is limited by the EV connector. Figure 16 briefs this issue.

[7] This does not preclude the vendor from communicating directly to their devices.

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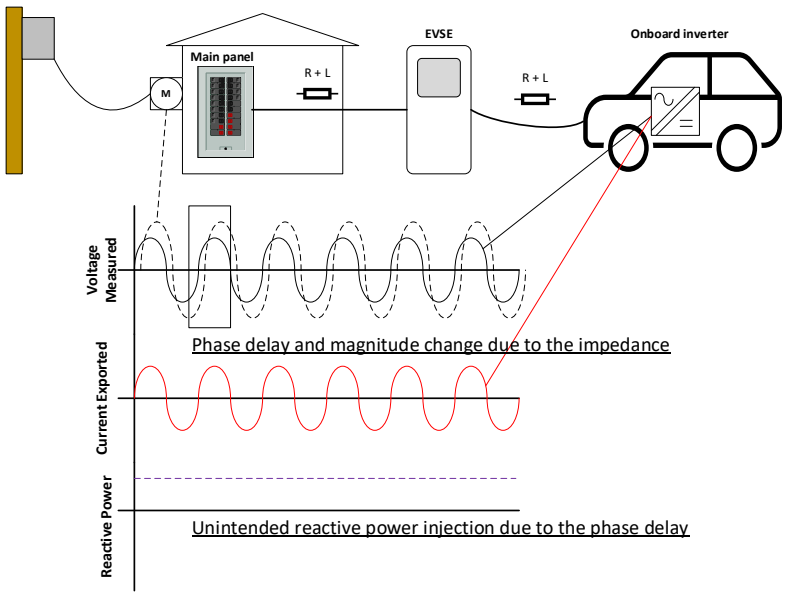

Figure 16. Impact of impedance between PCC and point of DER connection

Similarly, for a flex service/interconnection, the utility may instruct the site to limit the amount of export/import of active power at the PCC during an operation (Figure 17).

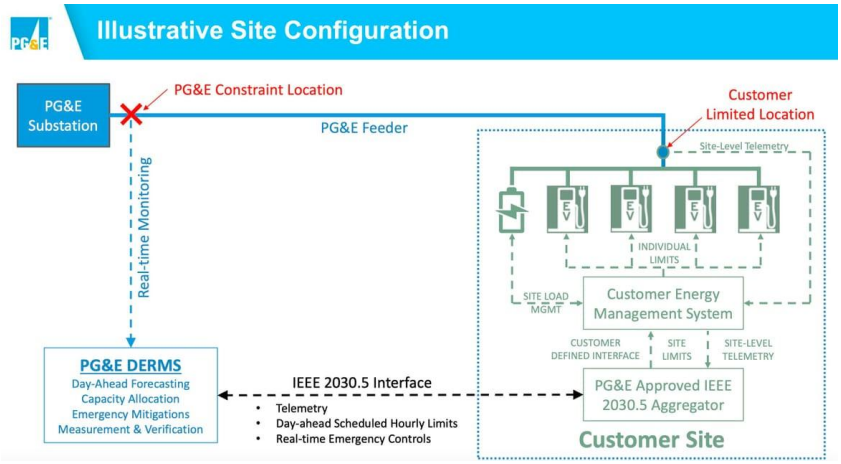

Figure 17. Flex service/interconnection [20]

The PEL/PIL PCS introduced in Section 2.4 can be leveraged to address those two. Indeed, PEL/PIL is to address the limit at the PCC. Adding an ability to measure AC voltage at the PCC also enables the PCS to be a proxy to the AC voltage measurement for DERs.

As identified, the measured AC voltage needs to be communicated to the DERs for compliance with IEEE 1547. Additionally, the limit for flex service/interconnection is communicated by the utility. This calls out the need of having the "gateway" function described earlier into the PCS, namely PCS gateway. With those combined features, the PCS gateway will:

- Monitor the active power at the PCC and instruct one or more DERs for desired active power to meet flex service/interconnection (PCS PEL/PIL function).

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- Monitor the AC voltage at the PCC for the DERs to comply with IEEE 1547 requirements.
- Translate IEEE 2030.5 messages from the utility into the protocols that the DERs use (i.e., SunSpec Modbus, IEEE 2030.5, and OCPP 2.1) as identified in Section 3 to exchange:
    - The utility's dynamic limit for flex service/interconnection with the utility.
    - Settings for IEEE 1547 functional requirements, such V/Q curve with the DERs.
    - AC voltage at the PCC with the DERs.

While these functionalities complement each other, there can be multiple active power set points and/or limits that originate from different purposes. There are many sources beyond flex service/interconnection-originated limit and IEEE 1547 requirements; the site or one or more DERs may provide bulk system service, or PV can charge batteries during the day, including EVs, and use the charged energy at night to reduce the electricity purchase. Those different objectives need to be prioritized and harmonized. Notably, under IEEE 1547, active power is modulated only during abnormal voltage or frequency conditions. The resulting active power set point/limit is momentary and hence it does not influence active power during normal conditions.

The "harmonized" active power limit and/or set point needs to be provided to individual DERs.[8] The allocation of those also needs to be computed.

As the central information hub, the PCS gateway understands the grid's needs and each DER's needs, including requested state of charge of a battery (including EVs).

The National Laboratory of the Rockies has extensively researched smart charge management—an algorithm that harmonizes the needs for a large load and a local distribution system (i.e., mitigating overcurrent at an overhead transformer), referencing EVs as an example of such a load. This can support flex service, as it controls large loads to maintain the active power level below the utility desired limit. Regardless of the limit level, smart charge management generates set points for each DER. Hence, PCS and smart charge management complement each other to generate an active power set point that can apply to normal conditions, and PCS can override or limit the active power when necessary. Table 8 provides an example use cases that the smart-charge-management-integrated PCS gateway supports.

Table 8. Example Use Cases

#	Description	PCS Gateway Response
01	Normal condition; no limit	PCS gateway may respond to any external signal.[a]
02	Normal condition; import limit	PCS gateway performs load balancing (i.e., increase of generation and/or decrease of consumption). If charging power is curtailed, PCS gateway performs smart charge management to distribute the curtailment per the logic.
03	Overfrequency; no limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D.[b]

[8] Inverters for some energy resources, such as a PV inverter, generate active power at the most efficient point, and hence do not need a set point, whereas a stationary battery system needs an explicit set point.

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#	Description	PCS Gateway Response
04	Overfrequency; import limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D.[c] If the import limit is not met, PCS gateway instructs non-DER energy assets to decrease the load (e.g., charging power of EVs in *charging session*).
05	Normal condition; export limit	PCS gateway performs load balancing (i.e., decrease of generation and/or increase of consumption).
06	Underfrequency; no limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D.[b]
07	Overvoltage; no limit	PCS gateway provides PCC voltage to individual DERs and monitors that the active power at the PCC follows IEEE 1547 V/W (i.e., under the active power limit constrained by the V/W requirement).
08	Underfrequency and/or overvoltage; export limit	PCS gateway monitors that the active power at the PCC follows IEEE 1547 F/D and/or V/W. If both are active, PCS gateway honors lesser (stricter) limit.[d] If the export limit is not met, PCS gateway instructs non-DER energy assets to increase the load.

[a] External signal refers to any non-utility constraint-related signals such as aggregator's request.

[b] Individual DERs following IEEE 1547 meet the intent.

[c] If PCS gateway does not interrupt individual DERs from performing IEEE 1547 F/D, the intent is met, provided note b.

[d] This aligns with the prioritization requirement in IEEE 1547.

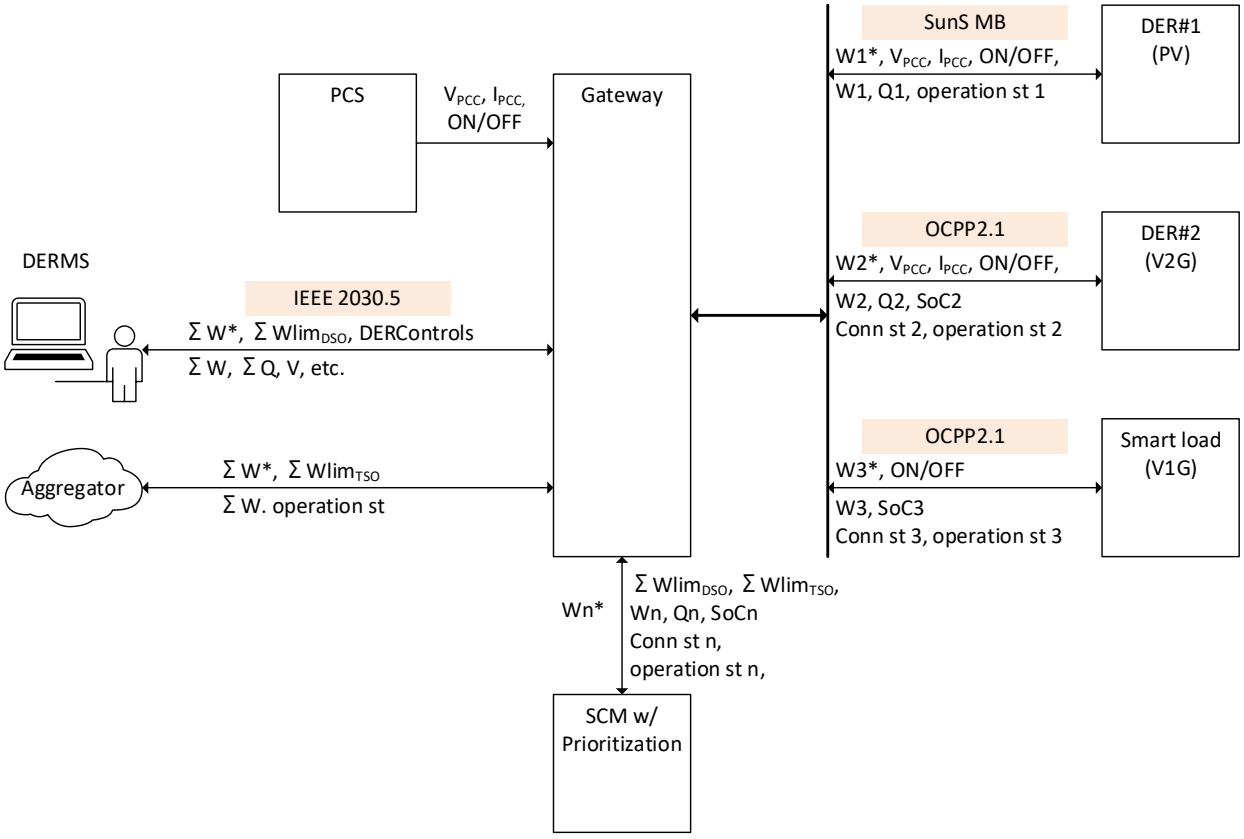

Figure 18. PCS gateway with prioritization

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Conclusion

As site loads continue to grow in size the incentive and need for flexible local energy assets will expand. These energy assets have the potential to benefit both site and grid operations, but must comply with grid codes and interconnection requirements. Due to the diverse landscape of energy assets, grid requirements, and coordination protocols, a new PCS gateway will be needed to navigate this landscape and ensure a cohesive site response to local utility and on-site facility needs. The National Lab of the Rockies is developing these technologies to simplify installation of energy assets for consumers, as well as considering new coordination opportunities that will expand UL 3141 PEL/PIL to support distribution capacity limitations.

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Appendix A. List of Relevant Industry Standards and Grid Codes

Table A-1. Relevant Industry Standards and Grid Codes

Standard	Title	Description
IEEE 1547	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces	This is the base standard that sets forth technical requirements for grid interconnection. The requirements include voltage supports, such as volt-var (V/Q), and response to abnormalities, such as voltage ride-through and trip. A DER needs to be designed to at least meet the requirements defined therein.
IEEE 1547.1	Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces	This provides the conformance test procedure (i.e., type test) for a DER that is intended to comply with IEEE 1547. Although the test procedure is detailed, there are typos and inaccuracies within the document that led to the development of UL 1741SB.
P1547.10	Recommended Practice for Distributed Energy Resources (DER) Gateway Platforms	This document will be a recommended practice for DER gateway that can be added between an IEEE 1547-conformant DER (i.e., a DER with utility communication interface) for a variety of upstream entities to leverage the DER.
UL 1741	Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources	Main body of UL 1741 sets forth the product safety requirements, such as insulation and flammability. This document also includes tests for such safety features, including abnormal conditions (e.g., short circuit and rain shower).
UL 1741SA	SUPPLEMENT SA – GRID SUPPORT UTILITY INTERACTIVE EQUIPMENT	This document is a supplement (annex) of UL 1741. This served as an interim functional requirement document until IEEE 1547-2018 was published and test requirement document until IEEE 1547.1-2020 was published. The functions defined in this document were referred to as smart inverter functions. This is to be superseded by IEEE 1547-2018, IEEE 1547.1-2020, and UL 1741SB.
UL 1741SB	SUPPLEMENT SB – GRID SUPPORT UTILITY-INTERACTIVE INVERTERS AND CONVERTERS BASED UPON IEEE 1547-2018 and IEEE 1547.1-2020	This document serves as the conformance test for IEEE 1547-2018. While IEEE 1547.1-2020 exists for the purpose, this document corrects the inaccuracies therein and also serves as the certification pathway for DERs.

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Standard	Title	Description
UL 1741SC	Supplement SC for AC Bidirectional Electric Vehicle Supply Equipment (BEVSE) / Interconnection Systems Equipment (ISE) for EVs with SAE J3072 Bidirectional Onboard Inverters	This document species the requirements for AC EVSE intended to operate with an SAE J3072-conformant EV to operate as a DER (i.e., V2G AC).
UL 3141	Power Control Systems	In some conditions (e.g., residential battery energy storage systems under Rule 21), the site is prohibited from exporting back to the grid. Even beyond, the site may be required to limit the power export (PEL) and even import (PIL) to facilitate interconnection/service agreement to address dynamic hosting capacity. UL 3141 defines requirements of devices used in this purpose, namely PCS, that operates to meet PEL and PIL requirements that may or may not be dynamic.
IEEE 2030.5	Smart Energy Profile Application Protocol	This document defines data and messages primarily intended for smart grid. This also sets forth implementation requirement. The base communication layer is HTTP(S). IEEE 2030.5 is one of the three protocols that are identified in IEEE 1547 that need to be supported by a DER.
P2030.5.1	Standard for Common Smart Inverter Profile of IEEE Std 2030.5	This document serves as the guideline to implement IEEE 2030.5 (though normative) and provides conformance test procedure for the standard.
IEEE 2030.7	Standard for the Specification of Microgrid Controllers	This document provides functional requirement for a microgrid. It does so by providing different scenarios that trigger the transition from grid-connected mode to islanded mode. Given each microgrid is different, this standard stays high level as opposed to IEEE 1547.
IEEE 2030.8	Standard for the Testing of Microgrid Controllers	This defines test requirements for a microgrid controller intended to meet IEEE 2030.7.
UL 3001	Distributed Energy Resource Systems	This document details the components within a microgrid, such as a transfer switch, to make a microgrid testable for UL certification. Inherently, this document references many other existing UL standards and establishes test procedure for voltage quality.
SunSpec Modbus	SunSpec Information Model	This document defines Modbus register map (information layer) for smart grid, including DERs for Modbus to be interoperable among the devices. SunSpec Modbus is one of the three protocols identified in IEEE 1547 that need to be supported by a DER.

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Standard	Title	Description
IEEE 1815.2		This document defines DNP3 points for smart grid (by following IEC 61850 data model) and supporting IEEE 1547 compliance in interoperable way. DNP3 is one of the three protocols identified in IEEE 1547 that need to be supported by a DER.
OpenADR		This document defines data and messages primarily intended for automated demand response. The base communication layer is HTTP. While the latest version is intended to support DER functions, IEEE 1547 does not acknowledge the protocol.
NFPA70		This document addresses electrical installations for residential, commercial, and industrial building and/or site. Adoption of this is up to local state authority having jurisdiction, but this covers a wide range of topics including EV charging installation, PCS (EMS in the document), and DER.
SAE J3072	Interconnection Requirements for Onboard, Grid Support Inverter Systems	This SAE document defines functional requirements for EVs intended to interconnect with the grid using an onboard charger (i.e., V2G AC).
IEEE 2800	Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems	This document defines functional requirements for inverter-based resources (active power source plus inverter) interconnecting with bulk system.

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Appendix B. List of OCPP 2.1 Fields for IEEE 1547 Functions

B.1 List of OCPP 2.1 Fields for V/W Control per IEEE 1547

Table B-1. IEEE 1547 to OCPP 2.1 Mapping for V/W

IEEE 1547 Parameter	OCPP 2.1 Field	Description
V/W mode enable	SetDERControlRequest: controlType = VoltWatt	En/disabling of V/W
Voltage points [9](x)	SetDERControlRequest: curve: {curveData[n]: x}	V/W curve's n-th point (x)
Active power points (y)	SetDERControlRequest: curve: {yUnit, curveData[n]: y}	V/W curve's n-th point (y)
Open loop response time	SetDERControlRequest: curve: responseTime	Time to reach 90% of new active power target calculated based on V/W curve points

[9] V/W curve is described to have two points in IEEE 1547. However, it doesn't preclude from having different number of points.

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B.2 List of OCPP 2.1 Fields for V/Q Control per IEEE 1547

Table B-2. IEEE 1547 to OCPP 2.1 Mapping for V/Q

IEEE 1547 Parameter	OCPP 2.1 Field	Description
V/Q mode enable	SetDERControlRequest: controlType = VoltVar	En/disabling of V/Q
VRef	SetDERControlRequest: curve: reactivePowerParams: vRef	V/Q's voltage reference (only applies to V/Q)
Autonomous VRef adjustment enable	SetDERControlRequest: curve: reactivePowerParams: autonomousVRefEnable	En/disabling of autonomously adjusting VRef
VRef adjustment time constant	SetDERControlRequest: curve: reactivePowerParams: autonomousVRefTimeConstant	Time constant for adjusting VRef
Voltage points[10] (x)	SetDERControlRequest: curve: {curveData[n]: x}	V/Q curve's n-th point (x)
Reactive power points (y)	SetDERControlRequest: curve: {yUnit, curveData[n]: y}	V/Q curve's n-th point (y)
Open loop response time	SetDERControlRequest: curve: responseTime	Time to reach 90% of new reactive power target calculated based on V/Q curve points

[10] V/Q curve is described to have four points in IEEE 1547. However, it doesn't preclude from having different number of points.

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