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A Review of Distributed Wind Interconnection Technology and Standards

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ABSTRACT

The objectives of this report are to discuss the uniqueness of power converters in distributed wind (DW), identify challenges in complying with existing standards, prioritize technological innovations to facilitate interconnection of DW energy systems, and, where necessary, propose potential clarifications or revisions to standards. This report evaluates IEEE 1547-2018, IEEE 1547.1-2020, and UL 1741 SB standards and their implications for DW. A standards review and interviews of DW industry stakeholders were conducted to identify challenges in the application of current standards to DW. The study concludes with a combination of recommendations of pathways towards facilitating DW product commercialization and DW interconnection, which draws on participation from multiple stakeholders in the space. These solutions can continue to be explored to improve DW standards compliance, improve the applicability of the standards to DW, reduce certification testing barriers, and ensure the safe and reliable operation of DW energy resources and electric power systems.

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EXECUTIVE SUMMARY

Distributed energy resources can be interconnected and interoperated with the main distribution grid. Standards publishing organizations, such as IEEE and UL have relevant standards including IEEE 1547-2018, IEEE 1547.1-2020, and UL 1741, which collectively contain technical criteria, performance testing requirements and methods, and certification tests for DER interconnection. Authorities having jurisdiction, such as public utilities commissions and grid infrastructure owner-operators (e.g., utilities) can adopt and enforce requirements from these standards.

A review of DW industry perspectives was conducted. Incorporating viewpoints from other stakeholders such as standards publishers, utilities, regulatory bodies, and authorities having jurisdiction, will be prioritized in future work. These industry stakeholders, particularly those involved in wind turbine and product design, manufacturing, installation, and maintenance, described the challenges of complying with the standard requirements. The requirements are viewed as technically difficult for wind energy equipment to achieve because of characteristics like the variability of wind turbine output and high inertia of wind systems. The certification process is seen as prohibitively time-consuming and costly, largely because of recently added requirements for advanced capabilities such as voltage and frequency ride-through and unintentional islanding protection. There are few available testing platforms for wind energy equipment, leaving manufacturers with few options for in-house testing before participating in the official certification process, which can take months and may cost hundreds of thousands of dollars. Industry stakeholders have also expressed that it is difficult to keep up with requirements, which are constantly being updated, sometimes before or shortly after the previous requirements have finally been achieved. Overall, these challenges have made achieving compliance and certification unfeasible and unattractive to some manufacturers, who perceive the process of designing and certifying a compliant wind energy interconnection device as economically risky. At the time of publication of this report, there are no wind energy inverters, converters, or controllers that are certified to the most recent version of the UL 1741 certification tests (Supplement B).

Based on these industry perspectives, there are actions various stakeholders may take to address the identified barriers to commercialization for DW interconnection products. Standards organizations may consider using input from industry and utilities to clarify how to apply current requirements to wind energy technology. They may also consider creating supplements, exemptions, or standards specific to wind energy interconnection, to tune modes, setpoints, and parameters in the current standards to wind energy characteristics. Additionally, DW industry interviewees mentioned that authorities having jurisdiction may elect to adopt different versions of standards for wind energy until the market is able to catch up to other more established DERs, like the distributed solar energy industry. For example, the authority may allow DW interconnection project developers to comply with general UL 1741 requirements rather than the most recently UL 1741 SB requirements. Finally, respondents emphasized the role of research institutions in improving DW interconnection outcomes. National laboratories can review standards and the current environment of DER interconnection to pinpoint barriers and causes and facilitate conversations between industry stakeholders and developers. Researchers can help test devices under development, as well as develop and refine testing platforms for manufacturers to conduct their own unofficial testing before initiating the certification process. Sandia National Laboratories already conducts power hardware-in-the-loop testing for inverters and other products. There are also already testing platforms such as Sandia National Laboratories' open source System Validation Platform and DER Security Corp's commercially available LabTest tool. These platforms are currently well-developed for solar systems and can continue to be expanded for use with wind energy inputs.

ACRONYMS AND TERMS

Acronym/Term	Definition
AC	alternating current
ACP	American Clean Power
AHJ	authority having jurisdiction
AWEA	American Wind Energy Association
CAN	control area network
CIP	Competitiveness Improvement Project
CPUC	California Public Utilities Commission
DC	direct current
DER	distributed energy resource
DERMS	distributed energy resource management system
DSP	digital signal processor
DTT	direct transfer trip
DW	distributed wind
EMI	electromagnetic interference
EPS	electric power system
EUT	equipment under test
FPGA	field programmable gate array
FRT	frequency ride-through
FW(C)	frequency-watt (control)
GFOV	ground fault overvoltage
HIL	hardware-in-the-loop
i2X^{TM}	Interconnection Innovation e-Xchange
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IOU	investor-owned utility
ISE	interconnection system equipment
LC(L)	inductor-capacitor(-inductor)
L/H FRT	low/high frequency ride-through
L/H VRT	low/high voltage ride-through
LROV	load rejection overvoltage
LVRT	low-voltage ride-through
MPPT	maximum power point tracking
OEM	original equipment manufacturer
PCS	Power Control System

Acronym/Term	Definition
PF	power factor
PLL	phase-locked loop
PMSG	permanent magnet synchronous generator
PV	photovoltaic
PWM	pulse-width modulation
RR	ramp rate
SA/SB	Supplement A / Supplement B
SCADA	Supervisory Control and Data Acquisition
SG	synchronous generator
SIWG	Smart Inverter Working Group
SMJU	Small Multi-Jurisdictional Utilities
SVP	System Validation Platform
UI	unintentional islanding
UIWG	Unintentional Islanding Working Group
UL	Underwriters’ Laboratory
VAr	reactive power
Volt-VAr or Q(V)	volt-ampere reactive
Volt-Watt or VW	voltage-active power
VPP	virtual power plant
VSI	voltage source inverter
VRT	voltage ride-through
VVC	volt-var control
Watt-VAr	power-reactive power

1. INTRODUCTION

Distributed energy systems (DERs) refer to energy generation or storage installations that may be interconnected with the distribution system infrastructure of the main electrical grid. Distributed wind (DW) falls into this category of technology [1]. Currently, DW deployment in the United States lags behind distributed solar, which is a comparable intermittent energy generation technology. Several factors may contribute to the disparity between DW and distributed solar deployment such as the siting and space requirements, place-based resource availability of solar insolation compared to wind penetration, and local public perception of each technology.

One major consideration of distributed energy generation development that often disproportionately impedes DW development is the regulatory landscape for DERs and interconnection projects. Various authorities having jurisdiction (AHJs) across the country that may include federal, state, and municipal regulators, have adopted standard compliance requirements for distribution grid interconnection projects. Specifically, many of these regulators require distribution system interconnection projects to adhere to one or more of the following standards:

- **IEEE 1547-2018:** Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces [2]
- **IEEE 1547.1-2020:** IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces [3]
- **UL 1741:** Standards for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources (and associated Supplement SA and Supplement SB documents) [4]

These testing and performance standards, which are written to ensure safe and reliable integration of DER generators into the main grid, are written in technology-agnostic terms. However, because of the differences in solar and wind energy generation architectures, they tend to pose greater financial and logistical challenges to DW projects, as described by stakeholder engagement and feedback, particularly from DW project developers and interconnection applicants. Recent research and work in this space, for example through working groups and state utility commissions, has begun to explore alternative requirements such as wind-specific guidance to improve outcomes for DW projects.

In this report, we provide a technical overview of wind energy generator power converters, and their distinguishing features compared to other common DERs. These considerations were used to review the IEEE 1547-2018, IEEE 1547.1-2020, and UL 1741 standards and their potential limitations for DW energy systems, including through the lens of stakeholders who have experienced these challenges in practice. Insights from the technical overview, gap analysis of the standards, and stakeholder feedback were used to develop a set of recommendations and revisions for DW interconnection guidance.

2. POWER ELECTRONIC COMPONENTS OF A DISTRIBUTED WIND ENERGY SYSTEM

The power converter and conversion stages in DW are unique from other DERs. In this section we review common system architectures. These diagrams will be important for providing context in subsequent sections, for discussions of challenges for DW developers in meeting the standards, technical differences between DW and distributed solar, and technology improvement recommendations.

2.1. Main Electrical Components

A DW system uses a series of power electronic components to convert variable frequency, variable AC voltage from the turbine into grid compatible power, while ensuring protection, stability, and power quality [5]. A generic schematic showing the flow of electricity through the components downstream of a wind turbine generator is shown in Figure 2-1.

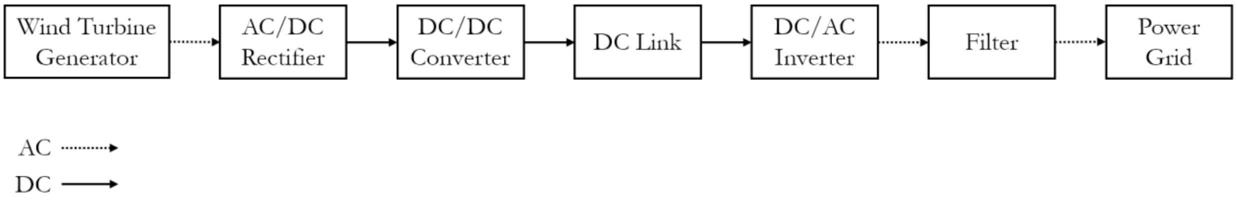

Figure 2-1. Generic Schematic of Wind Turbine Electrical Components.

There are four different types of wind turbine generator (WTG) technologies, with increasing control capabilities. Type I WTGs are direct-connected induction asynchronous generators, or stall-operated turbines, that are directly connected to the grid with no converter [6]; they generally use three-phase induction generators and supply reactive power using local power factor correction capacitors. Type I WTGs are mostly used for small WTs. Type II WTGs use wound-rotor induction machines with a variable resistor in the rotor circuit to provide control over the power output [6]. Commercial Type II WTGs are currently rarely used. Type III WTGs are wound-rotor induction machines, also called doubly fed induction generators (DFIGs) that contain a AC-DC-AC converter in the rotor circuit [6]. Type III WTGs make up a large portion of the WTs that are currently connected to the grid. Type IV WTGs are also considered to have "full inverters," with an AC-DC-AC converter. The converter decouples the machine frequency from the grid frequency and can handle non-sinusoidal outputs [6]. Type IV WTGs are becoming increasingly common in the market. Type IV WTGs will be the main focus of this report, with some mention of other generator types as is necessary.

2.1.1. AC/DC Rectifier Stage

The generator variable-frequency AC output is converted to DC using a controlled three-phase rectifier, often implemented as an active converter to allow for bidirectional power flow and precise control of generator torque. This stage enables DC maximum power point tracking (MPPT) and maintains generator efficiency over varying wind speed conditions.

Wind turbine rectifiers can either be passive or active. Figure 2-2(a) illustrates a DW power conversion topology with passive rectification. This topology uses a passive diode-based rectifier to convert variable-frequency AC from the generator into DC, followed by a DC/DC converter to regulate voltage, and then a DC/AC inverter to produce grid-compatible AC. This topology does not typically enable control over generator-side current and is most common in small to medium DW turbines with permanent magnet generators. Figure 2-2(b) illustrates a DW power conversion topology with active rectification. This configuration uses an active rectifier stage to convert generator AC to DC with full control over current and voltage, followed by an inverter to produce grid-tied AC voltage [7]. This allows variable speed control for DW turbines with synchronous generators (SG) or permanent magnet synchronous generators (PMSG) [8].

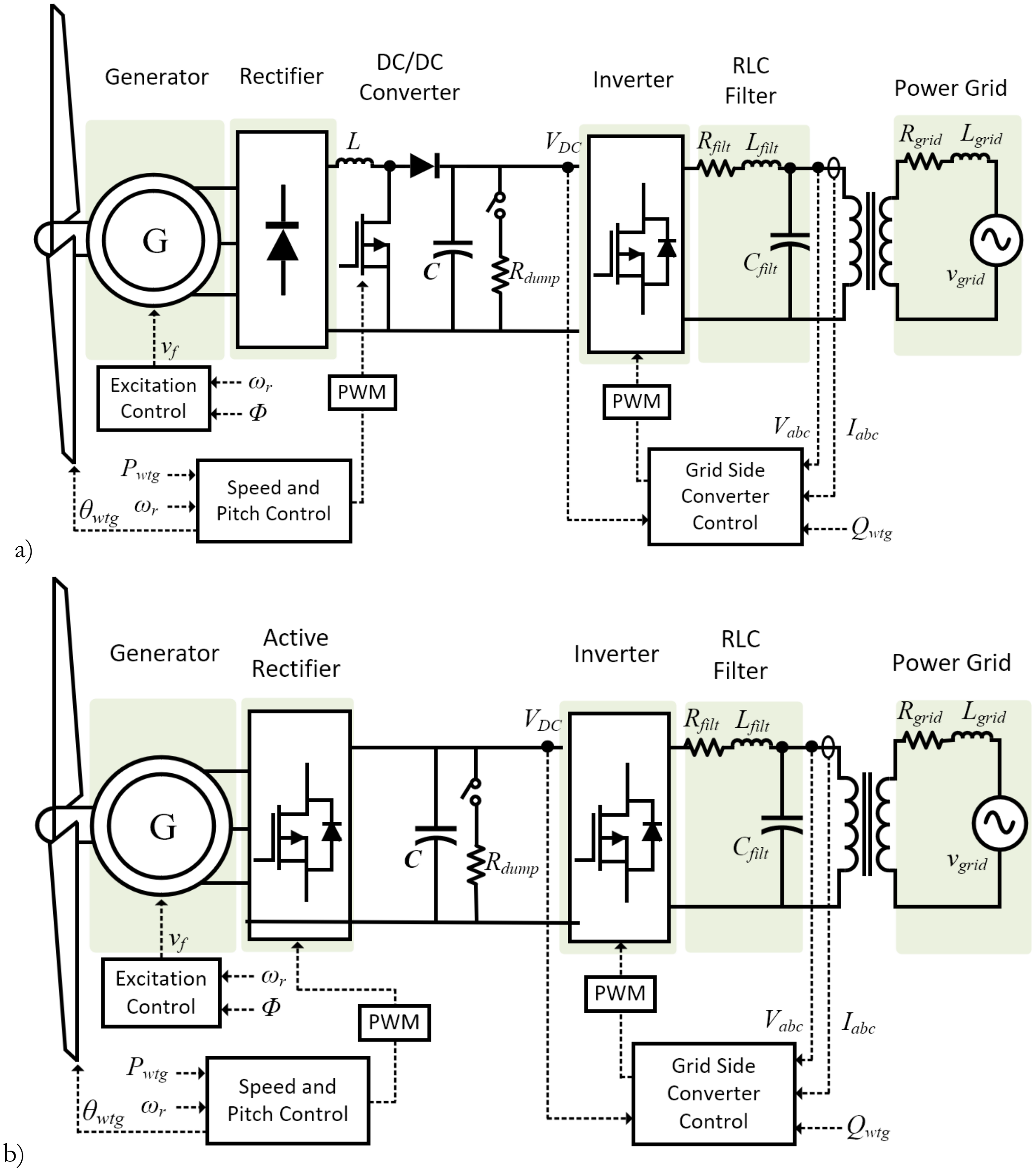

Figure 2-2: Diagram of the Conversion Stages of Two Different DW Power Converter Topologies for a Type IV WTG. (a) Passive Rectifier. (b) Active Rectifier.

Small and medium DW generators tend to use passive rectifiers due to their relative simplicity, but active rectifiers may present an opportunity to improve efficiency and performance as wind energy technology progresses [9].

2.1.2. DC/DC Converter Stage

A DC/DC converter regulates the DC voltage and implements MPPT by adjusting the operating point of the wind turbine. Depending on the system design, boost, buck, or buck-boost topologies may be used. In most cases this type of DC/DC converter stage is required when passive rectification is employed.

2.1.3. DC Link

This intermediate energy storage stage consists of capacitors that smooth the DC voltage and decouples the dynamics between the generator-side and grid-side converters. It ensures voltage stability and allows transient energy buffering during power fluctuations. The DC link is a stand-alone stage in active rectification and the output stage of a DC/DC converter in passive rectification. Coordination between the generator and the grid-side converter stage is required to ensure the energy stored in the DC link does not exceed the voltage threshold.

2.1.4. DC/AC Inverter Stage

The inverter converts DC power to grid-synchronized AC using a voltage source inverter (VSI). It provides control overactive/reactive power, voltage/frequency, and supports low-voltage ride-through (LVRT) and other grid code requirements. Inverters can be controlled to be grid-following, in which the inverter uses its terminal voltage as a reference, or grid-forming, in which the inverter has an internal reference [10]. Most inverters connected to the grid today are grid-following.

2.1.5. Filters

To minimize harmonic distortion and electromagnetic interference (EMI), a combination of inductor-capacitor (LC) or inductor-capacitor-inductor (LCL) filters are installed at the inverter output. These filters are tuned to attenuate switching-frequency harmonics and ensure compliance with standards like IEEE 1547 and IEC 61000 standards.

2.2. Other Components

2.2.1. Diversion and Dump Loads

In scenarios where the grid cannot accept additional power, diversion (dump) loads act as a safety mechanism to absorb excess energy. These are resistive loads connected to the DC link or AC output of the inverter via controllable relays or solid-state switches, preventing over-voltage conditions by maintaining load balance. These devices are common in small wind systems.

2.2.2. Crowbar Circuits

Crowbars provide fault protection for the generator and power electronics during overvoltage or over-current events. The crowbar is typically a thyristor or diode-based circuits that short-circuits the generator terminals or bypasses the DC link to rapidly dissipate energy and prevent damage. This capability is especially critical for PMSGs, where fault conditions can be destructive due to longer recovery times than other generator types like doubly fed induction generators (DFIGs) [11].

2.2.3. Control and Communication

The converter's controller manages the operation of all converter stages, implements MPPT, coordinates grid interaction, and executes protection logic. The following list summarizes some parameters that can be controlled in wind turbine power converters to optimize system performance:

1. **Pitch:** Adjusts the angle of the blades to control aerodynamic power. It is used to limit power output in high winds or optimize efficiency and it is common in medium-to-large turbines. Most small DW turbines do not incorporate pitch controls.
2. **Speed:** Maintains the rotor speed within optimal range to ensure efficiency and protect components. It is typically achieved through generator loading or pitch control.
3. **Torque:** Regulates generator torque to maximize power capture, especially in variable-speed turbines. This type of control enables MPPT to operate the generator at its maximum power point.
4. **Yaw:** Rotates the turbine nacelle to face the wind direction. For large scale wind turbines, active yaw is employed, using motors and sensors, while small-scale wind turbines use passive yaw, relying on the wind turbines tail fins to adjust position.
5. **Furling:** Mechanical safety system that turns the rotor or entire nacelle out of the wind during high wind events to prevent excess generator speed. This approach is common in small-scale turbines and can also be used in the absence of yaw and pitch controls.

In addition to internal controls, some communication with external systems may be required. Some examples of external control systems include microgrid controllers, supervisory control and data acquisition (SCADA), distributed energy resource management systems (DERMS) and virtual power plants (VPP). Communication with these can be supported via protocols such as Modbus, DNP3, controller area network (CAN), or Ethernet. Communication with external relays to enable direct transfer trip (DTT) can also be enabled for external protection.

2.3. Differences Between Solar and Wind Power Converters

Solar PV and DW systems have fundamentally different electrical and operational characteristics, which means off-the-shelf inverters for PV that may be more easily tailored to published standards are not well-suited for DW applications. This distinction is important when evaluating regulations and standards that may be more accommodating to PV than DW electrical architecture.

Wind turbine generators produce variable-frequency AC output, so rectification is required; PV inherently produces DC and does not require rectification. Maximum power point tracking (MPPT) control in wind turbines can involve many interacting variables with significantly differing time constants, including the machine's inertial response. PV MPPT involves a single variable (e.g., the PV voltage), and the PV array itself has essentially no inertial response (the "inertia" that must be considered in PV MPPT is primarily in the converter's DC link). Wind turbines are dynamic rotating machines that depend on factors including shaft speed, torque, and blade aerodynamics, so they require advanced converter control algorithms to coordinate both mechanical and electrical behavior that PV does not require.

Figure 2-3 shows a simplified electrical diagram for the flow of electricity from a solar PV generator to the electric grid; fundamental differences can be observed between this figure and the DW architecture shown in Figure 2-2.

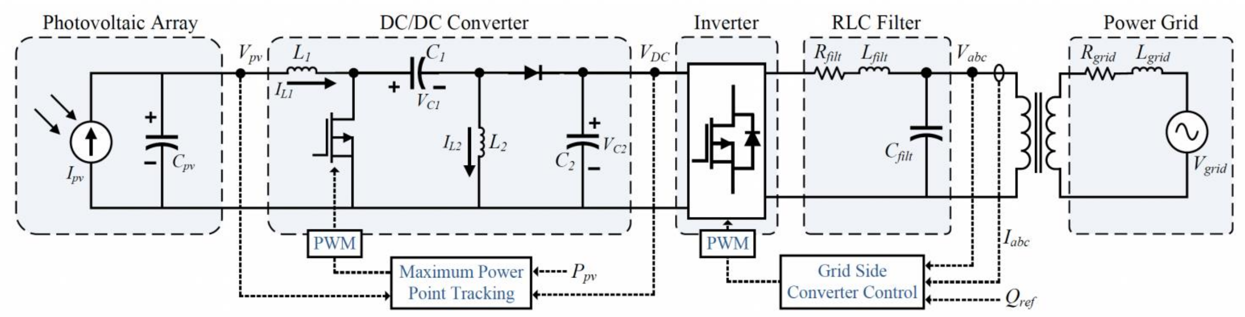

Figure 2-3. Diagram of a Solar PV Power Converter.

3. REVIEW OF MAJOR DER INVERTER STANDARDS

The IEEE 1547 standards (IEEE 1547-2018 and IEEE 1547.1-2020) and UL 1741 standards all occupy different roles within the overall regulatory landscape for DER interconnection. The IEEE 1547 series provides performance and testing standards that can be used to ensure that DERs can be safely and sufficiently interconnected and interoperated with the main grid. UL 1741 is a certification test for specific interconnection equipment (e.g., inverters, converters, charge controllers) that uses IEEE 1547 requirements as target criteria.

3.1. IEEE 1547 Series

As mentioned, the IEEE 1547 standards are performance and testing requirements for a DER interconnected with the main grid. They are used as baseline criteria for the specific product certification tests described in UL 1741.

3.1.1. IEEE 1547-2018

IEEE 1547-2018 provides an overview of requirements and criteria for a DER interconnected to the distribution infrastructure of a main electrical power system (EPS); the scope of these conditions includes the DER itself, the operational interface between the DER and the grid, and general properties to be monitored and maintained throughout the lifetime of the interconnected system. The general requirements section establishes the criteria for the performance, operation, testing, safety, and maintenance of the interconnection. Some highlights of IEEE 1547-2018 grid functionality requirements are provided below.

1. **Active Voltage Support:** Active voltage support is categorized in this standard by reactive power performance categories A and B, which describe the required reactive power capabilities during normal grid conditions. Performance Category A requires constant power factor, constant reactive power, and voltage-reactive power (volt-VAR) capabilities. Performance Category B requires those capabilities, plus active-reactive power (watt-VAR) and voltage-active power (volt-Watt) capability. The flow chart in IEEE 1547-2018 Annex B.4.3.2, Figure B.2, contains additional details [2].
2. **Response to Area EPS Abnormal Conditions:** Response to area EPS abnormal conditions specifies how DERs should respond to abnormal voltage and frequency conditions. The abnormal performance categories are named Categories I, II, and III: minimal bulk power system reliability requirements, additional voltage ride-through capability, and power quality and system overload support, respectively. Generally, DW falls under Category I.
3. **Power Quality:** Power quality addresses issues such as harmonic distortion, flicker, and DC injection, while islanding provides guidelines for preventing unintentional islanding, where a portion of the grid continues to be powered by DERs even when disconnected from the main grid.

IEEE 1547-2018 defines a DER as an electric power source that is not directly connected to a bulk power system and provides examples of DERs that include PV and wind turbines. IEEE 1547-2018 describes interconnection requirements such as allowable voltage and frequency ranges for entering service and general interoperability, reactive and active power control requirements, parameter limits for synchronization, and a requirement that necessitates detection and tripping of the system within 2 seconds of the formation of an unintentional island.

IEEE 1547-2018 provides examples of test methods and procedures that can be used to verify performance of the DER and its supporting equipment. These tests include type tests, production tests, commissioning tests, and periodic tests, which are detailed further in IEEE 1547.1-2020.

3.1.2. IEEE 1547.1-2020

IEEE 1547.1-2020 provides the detailed test procedures and methods that can be used to ensure that the performance requirements discussed in IEEE 1547-2018 are being met by a particular system. For example, IEEE 1547-2018 specifies the requirement to prevent unintentional islanding (UI), while IEEE 1547.1-2020 describes test methods that can be used to confirm that the system is adequately accomplishing this level of protection, including test circuit configurations for testing voltage and frequency trip settings, voltage-active and voltage-reactive power settings, and frequency-droop settings.

Overall, the tests in IEEE 1547.1-2020 can be used to ensure safe operation, reliability and conformance with recommended performance metrics enumerated in IEEE 1547-2018. The major test categories are described below.

1. **Type Tests:** These tests are the most comprehensive set of tests and focus on a representative sample of a DER system or subsystem in a lab to certify the entire product line. These tests examine different functionalities including response to abnormal grid conditions, grid support functions, interoperability and communications, and power quality and reconnection behavior; to ensure compliance with performance, safety, and reliability criteria before the DER is deployed in the field.
    a. Response to abnormal grid condition testing is focused on ensuring predictability and safety during grid disturbances, which prioritize safety and stability. These include voltage trip tests (both over and undervoltage), frequency trip tests (over and undervoltage), ride-through capability (low and high voltage; low and high frequency), and anti-islanding.
    b. Grid support function testing ensures grid reliability and stability during all operating conditions, through verification of smart functions which allow the DER to support grid voltage and frequency stability. These tests include voltage support (or reactive power control including volt-var control, constant power factor control, volt-watt control), and frequency regulation (or active power control including frequency-watt).
    c. Interoperability and communications testing ensures that the DER can communicate with the utility control systems.
    d. Power quality and reconnection behavior testing are critical for ensuring safe and reliable integration of DERs into the grid. These include enter service and reconnect tests, and power quality (testing harmonics, DC injection, and flicker).
2. **Production Tests (Factory Tests):** These tests are simpler to perform on every DER unit as it comes off the production line to ensure consistency in manufacturing. Key tests include verification of grid support function settings, basic over/undervoltage and over/under frequency trip checks, and checking the active/reactive power control functions.
3. **Commissioning Tests (On-Site Tests):** These tests are performed on the fielded DER system to verify that the DER system is correctly installed, configured, and interacting properly with the grid. Key tests include visual inspection (wiring, disconnects, nameplate info), cease to energize verification, interoperability verification, and settings verification (to ensure all utility-required settings have been correctly programmed into the DER device).

Figure 3-1 illustrates different experimental testing setups that can be used depending on the testing procedure. Figure 3-1(a) illustrates a DC-source-based setup, utilizing a programmable DC source emulates the DC link side for testing the DC/AC inverter stage. This setup is commonly used for isolated inverter compliance testing, including UL 1741 SB and IEEE 1547. Figure 3-1(b) illustrates an AC-source-based setup, utilizing a programmable AC simulator which replicates the generator AC output, enabling evaluation of the passive rectifier and inverter stage. This setup enables testing the full DW power conversion stages under controllable AC conditions. Figure 3-1(c) illustrates a full-system setup with dynamometer, utilizing a wind turbine emulator (motor and generator) which replicates realistic electromechanical behavior, allowing testing of the complete AC/DC and DC/AC power conversion stages under dynamic operating conditions. This approach replicates real-world wind turbine operation and supports full system performance validation including controls (MPPT, torque controls, speed controls, etc.) and transient behavior.

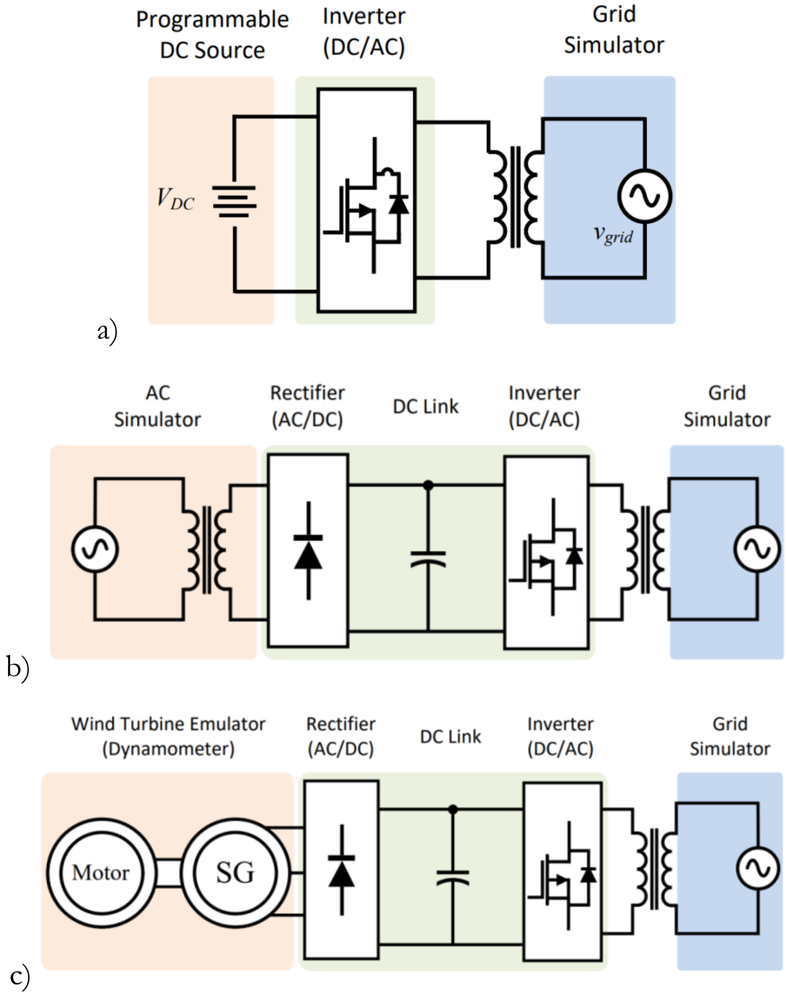

Figure 3-1. Experimental Testing Setups for DW Power Converter Validation. (a) Programmable DC Simulator. (b) Programmable AC Simulator. (c) Dynamometer.

In order to implement these experimental testing platforms, the following hardware equipment is typically required:

1) **Programmable DER prime-mover simulator (AC simulator, PV Simulator, or Battery Emulator):** A programmable or controllable source can provide input power to the

converter. A controllable DC source is typically used for testing PV inverters, which allows replicating the PV panels dynamics. Some programmable DC sources are designed to specifically replicate the dynamic voltage and current behavior of solar PV panels (PV simulator) and batteries (battery emulator). Some commercial examples of programmable DC sources include AMETEK TerraSAS, Cinergia, Regatron, Chroma DC Power Supplies and NH Research 9300.

2) **Grid Simulator (Programmable Grid Source):** A grid simulator has the ability to emulate various grid conditions, including voltage sags, frequency deviations, and phase imbalances. In order to properly replicate grid conditions, grid simulators must support programmable frequency and voltage variations, provide fast transitions for dynamic tests and have a three-phase output with independent phase control. For more complex testing, an external control through an external analog signal allows replicating more dynamics than the front panel. Grid simulators must support bidirectional power flow. Some examples of commercially available grid simulators include AMETEK TerraSAS, Pacific Power Source, and the Chroma A61500 series.
3) **Wind Turbine Emulator (Dynamometer):** A wind turbine emulator is able to emulate the mechanical input of a wind turbine rotor under controlled conditions [12]. In order to replicate the dynamic wind turbine behavior, a wind turbine emulator must be able to control speed and torque. Common, commercially available wind turbine emulator platforms include dSPACE Smart Energy Lab with dynamometer integration and the OPAL-RT HIL, motor drive, and dynamometer setup.
4) **Programmable Load Bank (AC or DC):** Load banks have the ability to simulate load on the system, allowing testing under resistive, capacitive and inductive dynamics. Programmable loads are useful for functional testing and efficiency validation. Unintentional islanding tests may be performed using a programmable load bank to emulate different grid impedances when islanding conditions occurs. Some examples of programmable load banks include the Keysight DC Electronic Load and the Chroma DC Electronic Load.
5) **Real-Time Simulator or Hardware-in-the-Loop System (for Advanced Testing):** Utilizing a real-time controller or Hardware-in-the-Loop (HIL) allows emulating dynamic grid conditions and control systems. This approach also allows emulating different load conditions, eliminating the need of a programmable load bank. HIL is most commonly used for advanced fault ride-through (FRT) or phase jump conditions that cannot be easily replicated with a stand-alone grid simulator. Examples of commercially available real-time simulators include OPAL-RT, Typhoon HIL, Speedgoat, and dSPACE.
6) **Measurement and Data Acquisition System:** For all experimental testing, measurement and data acquisition systems are employed to accurately measure voltage, current, frequency, power factor, and harmonics. In order for these systems to effectively capture the inverters dynamics, it is required they measure high-accuracy RMS and harmonics. Typical examples of commercially available measurement devices include the Yokogawa WT5000, Hioki Power Analyzers, and NI cDAQ.
7) **Testing Automation Software:** Utilizing a testing automation software allows automating interconnection procedures like UL 1741 SB and IEEE 1547.1 by controlling laboratory equipment such as grid simulators, programmable DC sources, HIL platforms, and data acquisition systems. This approach reduces execution time for repetitive sequence tests such as voltage ride-through (VRT), frequency ride-through (FRT), volt-var (VVC)/freq-watt (FWC) response, and anti-islanding tests. DERSec provides a commercially available software known as LabTest and Sandia offers its open-source tool called the System Validation Platform (SVP) [13]. The DERSec tool was recently updated to further improve

testing of DW converters with the IEEE 1547-2018 standards, including adding more extensive simulator backend options like AC and DC simulation and incorporating automatic startup operation functionality for AC and DC simulators [14].

3.2. UL 1741

UL 1741 is a standard describing requirements for equipment that includes inverters, converters, charge controllers, and interconnection system equipment (ISE) used in islanded or grid-connected EPS. It states that it is harmonized with, and meant to supplement, the IEEE 1547 series of standards; throughout the document, it mentions, adds to, revises, and provides optional or mandatory alternatives to the tests discussed in IEEE 1547.1. UL 1741 includes sections covering topics such as construction (general practices for how electrical components and housing should be physically constructed and protected), performance (e.g., temperature limits, overcurrent protection, grounding impedance, voltage surge, calibration, rain and testing), rating (which types of equipment and systems must be rated, and to which metrics), manufacturing tests (e.g., dielectric voltage-withstand test), and production tests (references IEEE 1547 tests). Notably, the major sections explicitly provide this host of construction, performance, and test requirements for specific equipment that includes generic inverters and converters, charge controllers, AC modules and PV modules with integrated electronics, and rapid shutdown equipment.

The first edition of UL 1741, published in 1999, was only applicable to PV generator technology, but the second and third editions, published in 2020 and 2021 respectively, expanded applicability to general distributed energy resources, which implicitly includes wind energy generators.

3.2.1. UL 1741 Supplements

UL 1741 includes Supplement A (Grid Support Utility Interactive Equipment) and Supplement B (Grid Support Utility-Interactive Inverters and Converters Based Upon IEEE 1547-2018 and IEEE 1547.1-2020), also referred to as UL 1741 SA and UL 1741 SB, respectively. Both supplements provide equipment tests for UL certification, with UL 1741 SA being more general and UL 1741 SB being more updated and current. UL 1741 SA was the initial supplement published to cover grid interactive functions not included in IEEE 1547-2003. UL 1741 SB was subsequently published to provide a more extensive certification test series, in conjunction with IEEE 1547.1-2020 and in accordance with IEEE 1547-2018. UL 1741 SA includes the following tests:

- **Anti-Islanding and UI Protection:** Ensures that unintentional islanding can be detected by the equipment under test (EUT), and that the system can be shut down within a specified timeframe.
- **Low and High Voltage Ride-Through:** Ensures the system can continue functioning when abnormal voltages are experienced.
- **Low and High Frequency Ride-Through:** Ensures the system can continue functioning when abnormal frequencies are experienced.
- **Normal and Soft Start Ramp Rate:** Confirms that inverter can accommodate normal and soft start ramp rates.
- **Volt-Var Mode:** Verifies that inverters have adequate voltage stabilizing capabilities.

There are also optional certification tests included in UL 1741 SA, such as the for the frequency-watt and volt-watt functions.

UL 1741 SB includes tests for more interconnection equipment and DER system capabilities. This supplement discusses performance requirements for the DER and interconnection equipment, including requirements for testing based on IEEE 1547.1-2020 (such as verification that the system can reach steady-state operation), confirmation of the system's tripping functionalities, and acceptable data formatting for reporting test results. The type tests in UL 1741 SB, some of which are repeated from UL 1741 SA, include:

- **Temperature Stability Test:** This test clarifies parameters to be used with IEEE 1547.1-2020 test for ensuring that the EUT, whether an inverter or power converter, is able to accurately measure temperature across its full operating temperature range.
- **Tests for Response to Voltage Disturbances:** This category of tests adjusts and references parameters from IEEE 1547.1-2020 tests, which include over- and under-voltage tripping and low- and high-voltage ride-through testing. These tests are meant to provide test ranges and response times to ensure that the system can ride through very brief voltage fluctuations outside of expected ranges, but that the system is also able to trip when those fluctuations occur for longer periods.
- **Tests for Response to Frequency Disturbances:** This category of tests is similar to the tests for response to voltage disturbances, except for frequency setpoints. This category of tests adjusts and references parameters from IEEE 1547-2018 guidance and IEEE 1547.1-2020 tests, which include over- and under-frequency tripping and low- and high-frequency ride-through testing.
- **Voltage Phase-Angle Change Ride-Through Test:** This test is based on an IEEE 1547.1-2020 test and is a way to check that the system is able to ride through abnormal voltage conditions.
- **Tests for Interconnection Integrity:** This category of tests refers to the performance metrics and testing methods from the IEEE 1547.1-2020, IEEE 37.90.2, and IEC 61000-4-3 standards, and includes determination of system protection from radiated EMI and ability of the system to withstand surges.
- **Unintentional Islanding Requirements:** The UI requirements include balanced generation to load testing, powerline conducted permissive signal testing, and reverse or minimum import active-power flow testing. These tests are meant to ensure that the DER system has adequate tripping capabilities to prevent UI.
- **Voltage Regulation:** These requirements include a constant power factor (PF) test, various voltage-reactive power (Volt-VAr) tests, power-reactive power (Watt-VAr) mode tests, constant reactive power (VAr) tests, and voltage-active power (Volt-Watt) mode tests.
- **Frequency Support:** These tests, which reference IEEE 1547.1-2020, include frequency-watt testing for frequency droop above and below the nominal frequency.
- **Test for Prioritization of DER Responses:** This section of UL 1741 SB prioritizes UI functionality in the DER equipment.
- **Limitation of Overvoltage Contribution:** These tests, which include a ground fault overvoltage (GFOV) and load rejection overvoltage (LROV) test, specify the relevant requirements from IEEE 1547-2018 and IEEE 1547.1-2020 and clarifies responsibilities for reporting results.

- **Interoperability Tests:** These tests refer to the requirements in IEEE 1547-2018 and IEEE 1547.1-2020 that are used to ensure compatibility between equipment from different manufacturers when used in distribution grid interconnection applications. The interoperability tests include configuration information testing, monitoring information testing, and management information testing. This section provides specific parameters for use with products like SunSpec Modbus and DNP3 software. This section also refers to IEEE 2030.5 as a foundation for the included requirements.

3.3. UL 3141

UL 3141 is a certification standard for Power Control Systems (PCSs). A PCS is a device or system that monitors the output of power sources and regulates or limit current or power within predefined limits, and thus has a key role in ensuring safety; it may be comprised of components such as a charge controller or inverter [15]. UL 3141 is mentioned here for completeness because PCSs will be a part of most DW installations, but a detailed discussion of UL 3141 is beyond the scope of this document.

4. PRACTICAL APPLICATION OF INVERTER STANDARDS TO DISTRIBUTED WIND

4.1. California Rule 21

AHJs across the country have adopted the IEEE 1547 and UL 1741 standards as criteria for certification and approval of DER systems. Notably, the main regulatory structure for grid interconnection in California is for the California Public Utilities Commission (CPUC) to determine general requirements to include in Electric Rule 21 (Interconnection Tariff), and for investor-owned utilities (IOUs) to be responsible for incorporating those requirements into their versions of the tariff for the projects under their jurisdiction. A summary timeline of proceedings and decisions from throughout the history of Rule 21 is provided in Appendix B, along with descriptions of the potential implications of each of the decisions on DW interconnection project development in general.

The main IOUs serving a large number of customers are Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E), while the smaller utilities, also referred to as Small Multi-Jurisdictional Utilities (SMJUs), include Bear Valley Electric (BVE) and Liberty Utilities. Each utility is required by the CPUC to establish and oversee its own version of the Rule 21 Tariff, taking direction from the overall Rule 21 requirements instituted by the CPUC.

Rule 21 was established as a technology-agnostic interconnection regulation, with specific mention of wind turbine and synchronous generator technology in some of the utilities' Rule 21 documentation. Many of the rulings and decisions made since its inception in 1982 have impacted, or been impacted by feedback from, DW project development. A timeline and more detailed descriptions of each ruling and decision is provided in Appendix B, but certain aspects and their implications for DW interconnection projects are highlighted here. Note that "R" refers to a CPUC ruling or proceeding, while "D" refers to a decision.

R.11-09-011 was opened in 2011 to address issues such as long timelines, high costs, and low transparency or insight into the distribution infrastructure and interconnection point characteristics. These are pain points that have been brought up by multiple DW developers: in many places across the country, approving interconnection to the grid requires assessments and possibly infrastructure upgrades. These requirements can lead to long wait times, prohibitively high costs (especially when a single interconnection customer bears the responsibility of the entire upgrade cost, even when benefits are shared between multiple customers), and sparse accessible or publicly available information about the distribution grid that makes it difficult to design a DER system to the parameters of the existing system [16]. A series of decisions in R.11-09-011 was used to address these issues. In terms of improving approval times, D.12-09-018 provided a fast track application option for smaller projects, while D.14-04-003 required the large IOUs to establish a Distribution Group Study Process to cluster studies for customers intending to interconnect at the same or nearby locations, which could each reduce customer wait times in the interconnection queue. Additionally, the Distribution Group Study Process could help share the study and upgrade costs amongst multiple customers, so an individual customer is not burdened by a potentially prohibitively high cost. D.16-06-052 was another decision in the ruling that began a pilot study for instituting a cost envelope, which was also used to keep costs within a certain upper bound. These efforts directly helped address or create the foundation to address these major challenges faced by DW developers.

Several decisions in R.11-09-011 were also impactful to DW developers in that they presented a new challenge to project feasibility. While this ruling was open, the CPUC inaugurated the Smart Inverter Working Group (SIWG). Following the recommendations of this working group, D.14-12-035 required DER inverters to be "smart" and certified to UL 1741; at the time of the ruling, UL 1741 SA was the relevant certification. The inverter capability requirements included functionality like voltage and frequency ride-through, while D.16-06-052 later added other advanced grid support functions and communications requirements. This decision led to DW challenges that continue to persist; namely, technical difficulty in achieving certification for wind turbines that are described more fully below, resulting in long timelines and high costs for DW manufacturers and project developers.

R.17-07-007 was opened in 2017 to revisit the DER interconnection rules and regulations and make necessary revisions. Decisions in this ruling improved the transparency of information useful for interconnection applicants. D.19-03-013 required IOUs to increase applicant access to information, such as any queued generation projects adjacent to the proposed project and potential network upgrades needed. D.20-09-035 and D.22-04-003 required the major IOUs and the SMJUs, respectively, to host workshops for current and prospective interconnection customers describing the interconnection application portals, to increase information-sharing with project applicants. In this ruling, the CPUC also continued work to understand different cost-sharing models for infrastructure upgrades and benefit outcomes. In this ruling, D.20-09-035 kept up to date with smart inverter and interconnection equipment standards by allowing Rule 21 revisions based on recent updates made to IEEE 1547-2018 and IEEE 1547.1-2020. In 2021, D.21-06-002 also established the Unintentional Islanding Working Group (UIWG) to understand and analyze different anti-islanding methods at the distribution level.

The IEEE and UL standards are explicitly interwoven into this regulation, with Rule 21 considered a Source Requirement Document that is meant to be used in conjunction with UL 1741 (which in turn references and complements the IEEE 1547 series of standards) [17]. The purpose of these standards and certifications is to ensure that the DER is interconnected and interoperated with the main grid safely, especially in regard to unintentional islanding.

The past and current CPUC proceedings demonstrate efforts to address interconnection challenges and update guidance as technology matures and the state of the grid infrastructure changes. The California utilities use this overall guidance to inform and continue revising their own versions of Rule 21.

4.1.1. California Rule 21 at the Utility Level

The Rule 21 Tariff for each IOU provides a summary of the required type tests for inverters, smart inverters before 2022, and the updated guidance for smart inverters from 2022 onwards; there are also required type tests for synchronous and induction generators. The requirements between IOUs are mostly consistent, with slight variability. The required type tests for PG&E, SCE, and SDG&E are shown in Table 4-1 as examples.

Table 4-1. Smart Inverter Functionality Requirements for Major California IOUs.

Type Test	Standard	PG&E	SCE	SDG&E
Utility Interaction	UL 1741-39, 40	x	x	x
Utility Compatibility[1]	UL 1741-46	x	x	x
Dielectric Voltage Withstand	IEEE 1547.1-2005, 5.8.2	x	x	x
Harmonic Distortion	IEEE 1547.1-2020, 5.12	x	x	x
DC Injection	IEEE 1547.1-2020, 5.9	x	x	x
DC Injection	IEEE 1547.1-2020	x	x	x
Abnormal Tests	UL 1741-47	x	x	x
Loss of Control Circuit	UL 1741-47.8	x	x	x
Short Circuit	UL 1741-47.3	x	x	x
Load Transfer	UL 1741-47.7	x	x	x
Surge Withstand Capability	Utility Rule L.3.e[2]	x	x	
Non-Export[3]	Utility Rule 21 L.3.c[2]	x	x	x
Synchronization[4]	Utility Rule 21 L.3.f[2]	x	x	x
Anti-Islanding	UL 1741SB–SB3	x	x	
L/H VRT	UL 1741SB–SB3	x	x	x
L/H FRT	UL 1741SB–SB3	x	x	x
Normal and Soft-Start Ramp Rate	UL 1741SB–SB3	x	x	x
Specified Power Factor	UL 1741SB–SB3	x	x	x
Volt/Var Mode	UL 1741SB–SB3	x	x	x
Frequency-Watt	UL 1741SB–SB3	x	x	x
Volt-Watt	UL 1741SB–SB3	x	x	x
Constant Reactive Power	UL 1741SB–SB3	x	x	
Disable Permit Service	UL 1741SB–SB3	x	x	x
Limit Active Power	UL 1741SB–SB3	x	x	x
Markings and Instructions	UL 1741SB–SB3	x	x	x

These are the most up to date requirements at the time of publication of this report, with some of the requirements replacing previous requirements from earlier versions of standards. For example, previous inverter capabilities were mainly required to be compliant with IEEE 1547.1 standards, and smart inverters were required to have their advanced grid functions be certified to UL 1741 SA, while the current smart inverters are required to be certified to the most recent tests in UL 1741 SB. In accordance with the precedent set in Rule 21 Decision D.14-12-035, the smart inverter requirements apply to the development of new DERs, and CPUC does not require that existing DERs that were interconnected and interoperated before 2022 replace their inverters with UL 1741 SB compliant inverters either during their working lives or at their end-of-life [18].

The main challenges faced by DW developers lie with the UL 1741 SB certification requirements, as well as additional assessments not captured in Table 4-1. Feedback from DW product manufacturers and project developers will be discussed in more detail in the next section. The overarching finding from this feedback is that the UL 1741 certifications are more technically difficult, expensive, and

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[1] Required testing to IEEE 1547 and IEEE 1547.1

[2] Specified rule in Rule 21 documentation for each utility

[3] Required only for non-export designation if desired

[4] Required for self-excited induction generators and inverters that operate as voltage sources when connected to distribution provider's distribution or transmission system

time-consuming to achieve for wind energy product manufacturers than solar energy product managers. In addition, PG&E in particular requires a specific anti-islanding screening test, and DERs that do not pass are required to install a direct transfer trip (DTT) device to automatically isolate the generation section of the DER. This requirement has been reported as costly and potentially increasingly infeasible with greater DER generation on the grid [19]. The CPUC UIWG focused on understanding and recommending alternatives to this direct transfer trip (DTT) technology, but many of them are early stage and not yet ready for deployment [19].

Other states besides California have similar workflows and regulatory landscapes, with a combination of state regulators and utilities overseeing the requirements for DER interconnection customers; DERs in other states are also beholden to similar standards and certification tests. For example, the New York State Public Service Commission calls out UL 1741 as the necessary certification for inverter-based systems within a certain hosting capacity range [16]. In addition, the NY-based utility National Grid reiterates and reinforces IEEE 1547 compliance as well as UL 1741 SB certification [16].

While there may be slight differences in how each state PUC or other regulatory body handles regulation and compliance with certain DER standards, these examples highlight how a combination of regulators such as at the state government level and the utility level have in practice adopted the IEEE and UL standards.

4.2. Technical Challenges for Distributed Wind Power Converters in Achieving Compliance with Interconnection Standards

As mentioned previously, DW turbines face several challenges in meeting the requirements of the newest standards, especially as they continue to be updated. One major challenge is that new standards require time and investment by original equipment manufacturers (OEMs) to develop certifiable and certified products.

Converters designed to allow DW to meet the requirements of IEEE Std 1547.1-2020 may be more expensive than comparably sized inverters for PV. Reasons for this include:

- Wind energy systems have significant rotational inertia. making it difficult for the systems to rapidly adjust active power to comply with over/undervoltage and over/underfrequency trip requirements in IEEE 1547.1 [20].
- IEEE 1547.1 also requires low/high voltage requirement tests (L/H VRT) that involve maintaining pre-disturbance current levels while riding through a fault event export [20].
- The DER must be able to limit active power in certain scenarios, which may be challenging for wind systems to achieve [20].

In addition to these requirements imposed by the standard, other requirements are imposed by the nature of the generators in wind turbines themselves. For example, when wind speeds change quickly, a wind turbine may produce considerably more than its rated power for several seconds, depending on the mechanical mechanisms used to regulate the machine speed [20].

A converter designed to enable a Type IV (full-converter) DW system to meet these requirements must be able to absorb or export the difference in current and power between the output of the machine and the injection to the grid during the transient conditions. Achieving this will impact the design of the converter's DC link: it may require larger DC link elements, additional DC link elements (potentially including additional power conversion stages), or external equipment like dump loads (which can absorb excess power but cannot provide additional power or current). A PV inverter does not require this, so it could be expected that a DW converter that conforms to IEEE 1547-2018 would be more expensive than a similarly sized 1547-conforming inverter for PV.

Finally, the interoperability models required by IEEE 1547-2018, such as SunSpec Modbus, do not include certain setpoints that would be desirable for wind energy generator technology. For example, [20]. the list of alarms included in SunSpec Modbus series 700 does not include things like oil pressure and temperature, and the information model does not include provisions for such things as blade pitch and turbine yaw angle, all of which are important for DW [20]. Expanding the information models in IEEE 2030.5, SunSpec Modbus, and DNP3 (the three protocols that IEEE 1547 includes) to more inclusively incorporate wind-specific internal states and operational capabilities would facilitate the ability of DW to achieve conformity with IEEE 1547 [20].

In UL 1741, there are some PV-specific guidelines and parameters, including a section for AC modules and PV modules with integrated electronics [4]. This section calls out PV-specific standards, including sections of UL 1703 (Flat-Plate Photovoltaic Modules and Panels), UL 61730 (Photovoltaic [PV] Module Safety Qualification), UL 3730 (Photovoltaic Junction Boxes), and IEC 60904-0 (Photovoltaic Devices) [4]. The standard does not have similar guidance for wind energy technology, but safe DW wind energy development may benefit from more studies and potentially the establishment of testing methods and performance criteria geared towards wind energy converters and other interconnection equipment for wind energy applications.

4.3. DW Product and Project Developer Response to Regulatory Requirements

To more thoroughly understand the challenges and barriers to interconnection and compliance of DW with the IEEE and UL standards in practice, the Sandia team engaged stakeholders in the DW industry in a series of interviews and surveys to capture a wide range of perspectives and identify common concerns. Industry experts were consulted to provide their technical expertise and practical experience, ensuring that the proposed solutions were both feasible and effective. These industry stakeholders included experts from the Distributed Wind Energy Association (DWEA), Bergey Windpower Co., Northern Power Systems, Buffalo Renewables Inc., Windurance, Matric Group, RE Innovations, and XFlow Energy. We also communicated with some researchers at the National Laboratory of the Rockies who are subject matter experts in DW project implementation. Some experts were engaged at the 2025 DWEA Meeting.

The interviewees were primarily manufacturers of DW products that would benefit from more lenient standards due to simpler hardware, software, and lower testing costs. Therefore, their input may have some bias towards reduced regulations for their company's benefit. The scope of these interviews did not include other important stakeholders in the space, such as regulators, utilities, other grid infrastructure owner-operators, or standards publishers. Nonetheless, this summary of DW industry stakeholder input helps provide an understanding of their perspective of the challenges and priorities in developing and bringing new DW energy products to market and ultimately developing DW projects.

The following questions were used to facilitate the discussions and capture input.

- **Question 1:** What are the main challenges you face in your DW products or research?
- **Question 2:** What DW energy technologies are most important to enabling safe and reliable growth of DW interconnection with other DERs and EPS?

- **Question 3:** What research opportunities are there to better integrate DW with battery storage and PV solar?
- **Question 4:** What parts of the IEEE 1547 and 1547.1 standards are difficult to meet or add significant cost to your product?
- **Question 5:** What recommendations would you make for improving the IEEE and UL standards to better accommodate DW energy systems?

The Sandia team has consistent contact and informal engagements with various DW OEMs and industry stakeholders, which has also contributed insight into the overall current interconnection landscapes and perspectives that were gathered in these interviews. For example, we used correspondence with DWEA members as well as review of the current California Rule 21 proceeding 25-08-004 and opening statements by DW stakeholders to supplement this review.

The DW industry engagement responses described several overarching themes that are summarized below.

4.3.1. Current State of DW Interconnection Equipment in Development and on the Market

At the time of the publication of the report, there are no wind turbine inverters or converters that are compliant with and certified to all the standard requirements (including IEEE 1547-2018, IEEE 1547.1-2020, and UL 1741 and either of its supplements).

Some OEMs reported working towards IEEE and UL standard compliance and certification, while others discussed an overall sentiment of the requirements being difficult, prohibitively costly, and time-consuming to achieve to justify pursuing certification for their products. The OEMs in this latter category may see the requirements as technologically irrelevant or unfeasible for wind or may not feel they are in a regulatory landscape where the importance of complying with the requirements is emphasized. In practice, this sentiment in some cases leads to the continued development of non-compliant and uncertified wind inverters, with regulators and/or utilities ultimately having the final say in rejecting projects that use this uncertified equipment. OEM buy-in of standards compliance and certification is crucial for DW developers to be able to successfully move forward with their interconnection projects.

Some OEMs did report current work on various stages of the development and certification process. For example, Windurance reported a focus on research and development for controls, storage and inverter integration, and modular and scalable power converter packages; they are also working towards receiving UL 1741 SA and SB certification for their DW power converters. However, as mentioned, neither these inverters nor others currently being developed and tested by other manufacturers, have achieved certification under the current standards yet.

In addition, separate from the discussion about compliant and certified products, the DW stakeholders discussed other aspects of the current wind energy interconnection equipment that are also relevant to the discussion of capabilities and functions. For example, some manufacturers see current wind turbine inverters as being unable to reach their full potential in terms of grid support and control functionalities. Even smart inverters and converters, which can control the wind turbines they support, are unable to fully control a system, especially if there are multiple DERs connected within a system that can work together to respond to loads and disturbances, such as solar power or batteries. In practice, many DW users (e.g., residential and agricultural customers) need the wind energy to be able to stand in when there are issues with other primary energy types such as diesel and gas, and to be able to work with other DERs in the system. Current inverters may not have the communication capabilities yet to be able to work with other DER inverters within the same system. This sentiment was shared for multiple types of devices, including inverters, converters, controllers, and variable frequency drive devices.

Many respondents expressed that DW interconnection projects lag behind distributed solar interconnection projects, with the opinion that the inherent variability of wind requires more technically complex interconnection equipment that ends up being more expensive.

4.3.2. Current Challenges

Many of the interviewed OEMs expressed that achieving compliance and certification of DW products to interconnection standards is technically, financially, and temporally difficult for OEMs to achieve.

From a technical standpoint, some of the system response requirements in the IEEE and UL standards were described as difficult for WTGs to achieve, similar to the discussion in Section 4.2. Not all parameters in the standards are seen as relevant to WTG operational characteristics. Large systems with high inertia and associated slow response times were described as especially difficult to control in the ways required by the standards. The ramp rates in the standards were noted as being not well-suited for wind turbines, with timing and excess power dumping controls mentioned as challenging to control. Respondents also brought up that the standard communications requirements may be specifically difficult to achieve for DW in particular. The last major difficulty mentioned in this stakeholder engagement exercise was anti-islanding: respondents discussed that the previously used technologies of protective relays and automatic shutdowns/disconnects were much easier to implement compared to the UL 1741 SA and SB anti-islanding requirements. However, all these technical difficulties are ultimately possible to overcome, though at the cost of other constraints such as financial, time, and effort resources.

Certifications are time-consuming to achieve, especially if products fail in initial testing attempts and require iteration and re-testing. This time-consuming process often means that, shortly after certifications are achieved, standards and requirements are updated, and manufacturers are then beholden to new and possibly more stringent targets. The process is also costly from factors such as labor, time, and contracting of testing, since the testing must be completed by entities with certain qualifications, such as the Nationally Recognized Testing Laboratory (NRTL). This process is especially difficult for small OEMs who may not have the personnel, time, or financial resources to pursue this rigorous cycle of development and testing. For larger OEMs, the process may be unattractive from a profit standpoint, since other technologies like solar inverters may have more immediate financial benefit due to their more established status in the market. This perspective was shown by the discontinuation of the Windy Boy inverter manufactured by SMA America [21] – at the time it was commercially available, this inverter was certified to the standards that were published at the time (although not necessarily to the versions of these standards used at the time of publication of this report). SMA America discontinued this inverter to pursue the more profitable solar inverter market. Currently, OEMs perceive entering the market for certified wind energy interconnection equipment as risky because it is so small, resulting in few units, higher costs per unit, and low customizability – the commercialized products are compatible with few very specific power ratings and grid connection types.

As described, additional correspondence with, and feedback gathered from, stakeholders outside of the described interview process, provided more context for the practical challenges of the current state of DW interconnection regulation from the perspective of DW product OEMs. For example, as part of the California Rule 21 Proceeding R.25-08-004 (still ongoing as of the publication of this report), DWEA expressed concerns about the application of UL 1741 SB to DW. In their opening comments on the proceeding, DWEA stated that requiring inverter certification with UL 1741 SB is potentially too stringent for DW systems, which are mostly installed in rural areas and do not impact the grid as much as other DER technologies for which UL 1741 SB requirements may be more appropriate [22]. Additionally, the letter indicates that there is a burden on DW manufacturers and the DW industry as a whole because of the need to develop bespoke inverters that pass the certification tests, which requires long timeframes and often results in high product costs [22]. Indeed, at the time of publication of this report, no DW power converter has yet been fully certified to the IEEE 1547-2018 and UL 1741 SB 3rd Edition standards. The letter also postulates that UL 1741 SB compliance may be "overkill" for DW systems, especially small ones, with the evidence of the existing small wind systems that have been interconnected and interoperating with the California grid without being certified to this supplement [22]. These systems may have been interconnected before the publication of UL 1741 SB but may be compliant with the standards that were relevant at the time of installation [22]. Thus, DWEA suggests a removal of the requirement for UL 1741 SB certification, while maintaining the UL 1741 requirements [22].

Foundation Windpower also provided opening comments on the proceeding, focusing on the PG&E requirement for DW projects that have failed an initial anti-islanding screening to install anti-islanding equipment, with DTT and SCADA utility-operated reclosers being two major compliant technologies [23]. As also discussed by the UIWG, a requirement for DTT installation may delay projects substantially and carry prohibitively high costs. The UIWG found that these additional UI mitigations may cost over $1 million, with Foundation Windpower reporting costs over $2 million [19]. Foundation Windpower, similar to the DWEA reasoning that UL 1741 SB certification is "overkill," states that anti-islanding mitigations may add unnecessary costs for the unlikely (and historically absent) event of UI.

The UIWG identified several alternative UI mitigation methods, including synchrophasors (or phasor measurement units), bulk system timing reference, cellular wireless DTT, and power line carriers [19]. However, these technologies are still in various stages of research and development, and their technological and financial viability has yet to be proven in practice. The UIWG also presented insurance as a non-technological anti-islanding mitigation tool, but this finding has not yet been reflected in California Rule 21.

Currently in California, the CPUC requires that DW installations must comply with the same inverter efficiency testing protocols used for PV and battery energy assets; there is no option for waiving these requirements for small system sizes or other reasons. These requirements are described and documented using the CEC Power and Efficiency Inverter Form. In September 2025, DWEA formally requested that the CEC exempt small wind turbines from this requirement if they are already certified to either the AWEA 9.1-2009 (American Wind Energy Association Small Wind Turbine Performance and Safety Standard) or ACP-101-1-2021 (The Small Wind Turbine Standard).

4.3.3. Recommendations from the Perspective of the Interviewees

Interviewees presented potential solutions to the challenges they discussed. It is important to note again, however, that the major stakeholder group we engaged with in this review was made up of DW developers and manufacturers, and that these perspectives do not necessarily reflect those of other key stakeholders such as regulators and grid infrastructure owner-operators.

Several respondents expressed interest in using interconnection equipment certified for use with solar systems, for wind energy applications. Many of these inverters are already certified and are already available on the market, which makes them less expensive than bespoke wind turbine inverters. There still remain technical and regulatory barriers to this course of action. For example, it is not yet conclusive if solar inverters can be made compatible with WTG power input. There are some efforts to achieve compatibility using low current MPPT PV inputs between the WTG and the PV inverter, although other respondents expressed that this solution may not be feasible.

From a standards and regulatory standpoint, even if this pathway were proven to be technologically sound, it is not explicitly clear if using a wind energy generator input with certified solar inverters would be permissible without further performance testing of the system as a whole. Again, the UL 1741 certifications are for specific interconnection devices, but they are meant to support the overall system performance requirements set in the IEEE 1547 standards. The generation sources for the certified solar interconnection products were likely emulating solar energy generation input, which would indicate that further testing with an input emulating wind energy generation would likely be necessary. However, respondents expressed that more clear expectations and requirements would help clarify this area of interest. For example, explicitly stating if non-solar inputs can be used with inverters certified with solar energy inputs would be helpful. Additionally, stakeholders would find it valuable if technical support and guidance for using non-solar inputs with solar inverters were provided, such as guidance related to input voltage ranges for testing. Exploring streamlined or accelerated testing pathways for using certified equipment for different generation input types (i.e., understanding if not all tests in the standards would be needed when using a different energy input source with a certified interconnection device) would be valuable.

Other developers are still interested in developing and commercializing equipment certified for wind energy generation, and they also have perspectives on how review and revision of existing standards and regulations can help support this development. One proposed avenue was to clarify the practical application of current standards to wind energy within the established regulatory framework, through something like a supplement to IEEE 1547 and 1547.1. A task group of UL 6142, a standard for small wind turbine systems, supported this recommendation over creating completely separate wind energy interconnection standards. Another request was to roll back current requirements, for example, from UL 1741 SA and SB certification to just UL 1741 compliance, until wind energy capacity on the grid is high enough for the DW interconnection product market to catch up to the standards [22].

Other developers expressed a preference for the development of guidance and standards specific to wind energy, rather than only using technology-agnostic standards. For example, some respondents proposed identifying and codifying possible exemptions from standards, especially for small DW projects. The idea of developing either additional standards specific to wind energy or adding supplemental documentation for existing standards with operating modes and setpoints more relevant to wind energy, was also brought up. Largely, these suggestions were because several OEMs expressed perspectives that current standards may not apply well to wind energy technologies, especially small capacity turbines. Some manufacturers brought up their preference for the previous methods of managing voltage or frequency fluctuations, which mainly involved shutting down the system, over the anti-islanding capability requirements. The rationale for this preference was that some interview respondents felt that this previous allowance was more relevant to small wind turbine systems that may not need to be able to ride through fluctuations and fault events.

4.3.4. Stakeholder Responsibility for DW Project Outcome Improvement

Another theme identified throughout this engagement process was that of the responsibility of the various stakeholders involved in DW product and project development. Interview respondents discussed the role of industry and research institutions, such as national laboratories.

All respondents were industry stakeholders, and they presented an overview of the current initiatives in the DW product manufacturing and project development space. For example, as discussed, some OEMs are conducting research and development to understand the technical requirements regarding if and how solar inverters can be used with wind energy generation inputs. Other stakeholders in the general DW industry space are conducting research into the DER interconnection process in order to present possible alternative solutions, with safety and equity being specific priorities called out by one interviewee. The need for collaboration between wind turbine OEMs and interconnection product OEMs was also discussed, with emphasis on understanding constraints and gaps related to the interconnection of wind systems with current utility grids.

Interview participants also talked about how national laboratories can support efforts to improve DW interconnection outcomes by reviewing and synthesizing current standards and performance testing requirements. Rigorous review of these standards by a non-industry, non-regulator institution can help pinpoint the causes and details of the tests and specifications that are currently difficult to achieve for DW projects. National laboratories are also well positioned to provide recommendations, technical assistance, and other support to facilitate DW development and interconnection. One example of efforts in this space is the Competitiveness Improvement Project (CIP), which is a funding opportunity hosted by the Department of Energy and the National Laboratory of the Rockies [24]. The CIP provides financial support to small and medium wind turbine manufacturers to build out their design, manufacturing, and testing capabilities, to help keep up with the fast-changing standards and requirements [24]. Overall, through the mention of the interplay between stakeholders and their unique roles, these interviews emphasized the importance of gaining a holistic understanding of perspectives from all stakeholders involved in DW interconnection (e.g., utilities, regulators, and DW industry stakeholders). A comprehensive review of stakeholder perspectives can help contribute to a solution that would satisfy all stakeholders and factor in multiple priorities, including safety and economic opportunity. The Sandia team plans for future work include talking with other stakeholders not reached in the engagement efforts described in this report.

National laboratories have also provided, and will continue to provide, technical input and recommendations for improvement of interconnection processes and outcomes through the Department of Energy's Interconnection Innovation e-Xchange (i2X^{TM}) program [25]. Through this initiative, research institutions provide a roadmap of priorities and actions for improvement of DER interconnection processes, with themes that include improving transparency of grid information relevant to interconnection projects, mitigating long wait times in the interconnection queue, and supporting the economic landscape for DW interconnection products [26].

5. RECOMMENDATIONS

The recommendations in this section, which are meant to improve outcomes of DW interconnection projects overall, fall into two categories. First, a potentially more accessible and feasible opportunity is for regulators stakeholders, standards publishers, and other participants in policy development to re-evaluate current requirements that may adversely affect DW interconnections to determine which are fully necessary, and whether adjustments could be made that still meet the system-level requirements but are more within the range of current DW capability. Second, we present possibilities for making changes to DW technologies to bring them closer to compliance with current codes and standards.

5.1. Regulatory Recommendations

As discussed, there are multiple stakeholders in the regulatory space, including AHJs like federal regulators, state PUCs, and utilities, as well as organizations that publish standards like IEEE and UL. Professional organizations that represent DW project developers and owner-operators, such as DWEA, are also instrumental in providing constant feedback regarding practical regulation compliance and recommendations or requests for revision of regulations. Coordination between these stakeholders may be useful in the efforts to improve DW project outcomes. Several recommendations are included in the following sections.

5.1.1. Provide Support to Address DW Barriers to Adoption

Regulatory bodies and research institutions like national laboratories can provide valuable support to address challenges and barriers brought by key stakeholders. For example, CPUC opens rulings and allows stakeholders such as utilities and project developers to discuss their respective challenges, concerns, and viewpoints. Further, the CPUC has created working groups to specifically research and find potential solutions to some of the stakeholder concerns that have emerged in recent years, including the Smart Inverter Working Group and the Unintentional Islanding Working Group. The UIWG in particular provided insight into different potential solutions for the PG&E anti-islanding requirements (that largely result in costly DTT installation); most of these solutions were underdeveloped at the time of publication of the UIWG Final Report. The CPUC can continue to explore these solutions from a research and development perspective, which could help potentially increase options for DW developers trying to interconnect to PG&E infrastructure and make their projects more viable. In an opening statement for the currently-open CPUC proceeding R-25-08-004, Foundation Windpower requested that the CPUC revisit the UIWG findings and more deeply explore the DTT alternatives presented in the UIWG final report [23]. PUCs in other states can also use working group models to support different groups of stakeholders and work towards improvement of DW project outcomes while also balancing the needs of utilities.

National laboratories like Sandia can review gaps in the current interconnection process and gather a holistic understanding of all stakeholder perspectives to effectively address pain points in DW interconnection. National laboratories and other research institutions can also help interpret and facilitate performance and certification testing for OEMs. For example, as mentioned in Section 3.1.2, Sandia has developed the SVP to provide open-source simulations for DER product performance testing. Currently, the SVP is well-developed for solar system applications [27], and Sandia plans to continue updating the SVP for wind energy interconnection equipment and inputs. Making this resource available to manufacturers could improve timelines and costs during development of products, since they would be able to perform preliminary testing and iterate on their products immediately rather than having to send products for official certification testing without having confidence that they will pass. National laboratories have also historically conducted testing research on interconnection products, which takes the burden off of OEMs to undergo the official testing process. For example, Sandia recently tested the UI mitigation performance of an off-the-shelf protective relay with a Type I wind turbine input source [28]. National laboratories can continue to conduct performance testing in a research context outside of the official testing avenues.

5.1.2. *Explore Recommendations to Develop and Adopt an Interconnection Certification or Supplement Specific to Distributed Wind*

To address the current stakeholder concerns and feasibility challenges faced by DW developers in working towards inverter compliance with the UL 1741 SB requirements, development of a UL 1741 supplement specific to wind energy may improve outcomes while maintaining the safety and integrity of existing regulations. This initiative would largely be the decision of standards publishers like IEEE and UL. AHJs could then review these certification tests and elect to adopt or not adopt them.

For example, codified exemptions from some of the requirements in the IEEE and UL standards for small capacity wind systems and interconnection equipment could potentially be made, based on the feedback from stakeholders described in this report. In particular, the DW industry interviews suggested that exempting grid-connected power converters with capacities less than 500 kVA from needing interoperability and communication interfaces may help manufacturer and DW developer timelines without introducing negative effects; interview respondents expressed the view that communication may have little benefit to the grid at low capacity levels anyway. Again, this view of exempting small wind systems or wind energy as a whole from current requirements largely belongs to the DW industry stakeholders and would possibly not have strong support (or would even face opposition) from utilities and other grid infrastructure owner-operators. Therefore, open dialogue between stakeholders with different roles in the DER interconnection process, such as the dialogue currently happening in the ongoing CPUC proceeding, would help understand the needs, pain points, and root causes of each stakeholder. Research institutions such as national laboratories can then help support this dialogue with their technical and testing capabilities and review of requirements to supplement these discussions.

5.1.3. *Offer Non-Technical UI Protection Options*

The Foundation Windpower opening statements for California Rule 21 proceeding 25-08-004 mentioned offering non-technical UI protection options as an alternative to requiring implementation of anti-islanding devices in the system, such as insurance [23].

5.2. Technical Recommendations

There are some technical recommendations that are focused on either passing performance and certification tests with current DW interconnection equipment or on manufacturing certifiable equipment itself. These recommendations are mostly focused on DW product manufacturers.

5.2.1. *Upgrading Power Converters*

To meet the current IEEE 1547 standards in active power support, voltage ride-through, and frequency ride-through, innovation is required. The following technologies are proposed as a list of potential solutions to enable more successful deployment of DW. Note that some of these recommendations are specific to the interconnection equipment (advanced power converters), while others refer to performance and engineering of the DER as a whole.

1. **Advanced Power Converters:** Upgrading to advanced power converters with more rapid reactive power support and ride-through capabilities can help DW provide autonomous grid stability. Advanced power converters should provide autonomous voltage-watt and voltage-var control. The major challenge of advanced power converters for DW is that wind and the associated generator speed variability can result in fluctuating voltages. Research should be prioritized for power electronics and technology that enable variable voltage operation such as STATCOMs, energy storage, and diversion load controllers. Innovations in this technology space will eliminate the need for grid operators to manage many small DERs.
2. **Grid-Friendly Rotor Design:** There is an opportunity to design high capacity factor or low specific power (W/m^2) DW turbines that reduce power variability due to changes in wind speed. This makes wind turbines operate in a steady output regime by designing larger rotors for a given generator size. The strategy is to produce relatively large rotor swept areas per generator capacity, specific powers below 200 W/m2. Vertical axis wind turbines (VAWTs) can also have more constant power output for DW installed around buildings and other wind obstructions where highly turbulent airflow patterns exist to remove the losses due to flow alignment and yawing for horizontal axis wind turbines.
3. **Enhanced Control Systems:** Implementing more sophisticated control systems that can dynamically respond to grid conditions will improve the frequency-watt and voltage-watt grid services capability of DW. Example control systems include aerodynamic and mechanical systems to decouple power output from current wind conditions. Specific implementations include blade pitch or tip brakes that are coupled with feedback to advanced power converters.
4. **DC Bus DW Farm:** The variability in power output from a wind farm is generally lower than that of an individual turbine, primarily because wind speed coherence diminishes over distance [29]. As a result, it may be worthwhile to investigate the potential for DW farms to share a single power inverter at their point of interconnection. This approach would involve connecting the outputs of multiple turbines, first rectifying them to direct current (DC), and then combining them into a single, high-capacity power converter. By adopting this strategy, the number of required power converters is reduced and the variability in the overall output of the DW farm is decreased.
5. **Full Converter Testing:** Current IEEE 1547.1-2020 test procedures often use a DC source to simulate the generator side, omitting critical dynamics present in wind systems. We recommend explicitly supporting full converter testing, including the AC generator interface, DC/DC stage (if present), and inverter. This enables testing of the complete power conversion chain under dynamic wind conditions and better evaluates the interaction between generator torque control, DC link behavior, and grid services. Full testing provides a more realistic performance characterization and prevents compliance gaps during field operation.
6. **Integrating Unintentional Islanding Detection into Converter Logic:** DW systems rely on external relays or DTT for anti-islanding protection, which increases cost and complexity, especially for small systems. We recommend supporting converters that incorporate built-in unintentional islanding detection, such as active frequency/power

perturbation schemes, eliminating the need for external protection devices. This not only reduces system cost and commissioning time but also enhances resilience in areas with limited communications infrastructure.

7. **Standardized Testing Platform:** A standardized testing platform tailored to DW (e.g., PHIL bench with open-source configurations) would provide a consistent, validated method for manufacturers and test labs. This platform should include configurable models for turbine dynamics, grid scenarios, and fault events as defined in IEEE 1547.1. Leveraging shared reference test benches (e.g., Sandia's System Validation Platform or open-source Simulink/OPAL-RT libraries) will reduce cost and testing time, improve reproducibility, and help small OEMs achieve certification more efficiently.
8. **Under-Frequency/Frequency-Droop Functionality:** An argument could be made for removing the under-frequency frequency-droop functionality for wind systems given the dynamics of the prime mover. The Pre-Disturbance Dispatch Level is the power at which the device exits the freq-droop deadband. For wind systems, 99% of the time this will be the maximum power the converter can produce (Pavl) and therefore will only operate in the over-frequency case. However, if an active power curtailment function is enabled, Ppre ≠ Pavl, and hence the device will need to "up-reg" to try to produce more power. In a high IBR future, every little bit of active power support is going to be needed in order to keep the power system stable to voltage and frequency transients.

Overall, multiple stakeholders will be integral in supporting these challenges. The research community for wind energy and DER interconnection standards and testing can help work on improving testing platforms and making them accessible and usable for actual wind energy products, for example. Researchers may include PUC-formed working group members, who may be industry experts, regulators, and independent researchers such as from national laboratories and universities. Researchers, such as those from national laboratories and other institutions outside of the DW industry, grid infrastructure, and regulatory landscape, can continue to play a part in generally testing wind converter hardware and simulating tests. These efforts can help work towards alleviating burdens such as time, effort, and money, for DW product and project developers.

6. CONCLUSIONS

Addressing DW interconnection challenges requires a multifaceted approach that combines regulatory review and technological innovation. The key proposed solutions in the regulatory landscape include review of current adoption of standards for DERs by AHJs and consideration of usage of standards whose compliance has been challenging and potentially overly strict for DW development. Additionally, revising language in standards like IEEE 1547-2018, IEEE 1547.1-2018, and UL 1741, to more explicitly and specifically include considerations for wind energy, may help these standards be more usable by AHJs and DW developers. Publishing a certification test for wind turbines, or even just including more wind-specific language and/or exemptions, may also help. The key proposed technical solutions are to utilize the hardware testing emulation support and automation from Sandia to streamline compliance verification and to implement power controls via software or hardware. Together, these recommendations aim to overcome technical barriers, reduce costs, and enable broader deployment of DW systems, ultimately supporting a more resilient energy grid.

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[52] D. Jantz, "Distributed Generation Protection Requirements." Pacific Gas and Electric Company, Feb. 15, 2023. [Online]. Available: https://www.pge.com/assets/pge/docs/about/doing-business-with-pge/094681.pdf

APPENDIX A. SUMMARY OF IEEE 1547-2018 FOR HIGH-PENETRATION DER SCENARIOS

IEEE 1547-2018 has undergone several revisions to keep up with technological advancements and evolving grid requirements. The most recent version, IEEE 1547-2018, includes updates to address high-penetration DER scenarios and enhanced grid support functionalities. These updates are designed to enhance grid stability, reliability, and interoperability as the number of DERs, such as wind turbines, solar panels, and energy storage systems increases. Some new high penetration DER requirements include: Voltage regulation requires reactive power control for DERs to provide reactive power support to help regulate voltage levels on the grid. This can be achieved through various control modes such as constant power factor, constant reactive power, voltage-reactive power (Volt-VAR) control, and active power-reactive power (Watt-VAR) control. Active power control for DERs can also be required to adjust their active power output in response to grid conditions, such as reducing output during over-frequency events. Voltage and frequency ride-through capabilities are now essential for distributed energy resources (DERs) to remain connected and operational during short-term voltage disturbances. Voltage ride-through (VRT) helps maintain grid stability during events such as faults or sudden load changes, while frequency ride-through (FRT) ensures that DERs stay connected during frequency deviations, thereby supporting grid stability during fluctuations. Additionally, power quality is addressed through stricter limits on harmonic distortion to prevent adverse effects on the grid, along with flicker requirements aimed at minimizing impacts on sensitive equipment. Communication and interoperability requirements ensure that DERs can effectively 20 interact with utility control systems and other grid components, supporting protocols such as IEEE 2030.5 (Smart Energy Profile 2.0) and IEEE 1815 (DNP3). This interoperability facilitates seamless operation with various grid management systems and other DERs, enabling coordinated control. Standardized testing and verification procedures outlined in IEEE 1547.1-2020 ensure that DERs meet the performance and safety standards established in IEEE 1547-2018. Grid support functions, including frequency-watt control and voltage-watt control, require DERs to adjust their power output in response to frequency changes and reduce output to prevent over-voltage situations, respectively, thereby enhancing overall grid stability.

APPENDIX B. CALIFORNIA RULE 21 HISTORY RELATING TO DISTRIBUTED WIND DEVELOPMENT

California's recent, ongoing, and planned DW deployments [30] and established regulatory structure for DW interconnection projects contribute to its value as a case study for practical applications of interconnection standards to DW technology. Many of the correspondences between Sandia researchers and DW industry stakeholders are focused on application of standards in California, although there are distinct efforts in many states related to DW interconnection.

Table B-1 below provides a timeline of overall proceedings and decisions made for Rule 21 by the CPUC from 1982 until the time of publication of this report, with specific attention to rulemaking activities that would or did have an impact on DW development. For context, the IEEE 1547 and UL 1741 standards that are referenced in Rule 21 are also included in the timeline.

Table B-1. Timeline of California Rule 21 Proceedings and Decisions and Publications of Relevant Standards, Color-Coded by Standard or Rule 21 Proceeding

Date	Document	Rule or Decision	Description	Source
1982	Rule 21	N/A	• CPUC adopted original iteration of Rule 21 to establish practices for interconnection of generating facilities, including renewables	[31]
May 7, 1999	UL 1741	N/A	• Initial publication of UL 1741 (Edition 1) • Scope expressly covered only PV systems	[32]
October 21, 1999	Rule 21	R.99-10-025	• Opened proceeding to create policies for distributed generation deployment in CA	[31]
November 2, 2000	Rule 21	D.00-11-001	• Adopted Rule 21 language from the California Energy Commission • Required main CA IOUs (PG&E, SDG&E, SCE) to adopt Interconnection Application Form and Agreement o Applicable to DERs, including wind • Required main CA IOUs to adopt Model Tariff language o Includes requirements for distributed generators to operate within interconnection / distribution system normal voltage ranges o Requires distributed generator to be able to detect and respond to abnormal voltages via tripping • Gave other IOUs the option to adopt Model Tariff language or provide justification for non-applicability	[33]
December 21, 2000	Rule 21	D.00-12-037	• Approved language from D.00-11-001	[34]
April 17, 2003	Rule 21	D.03-04-060	• Closed R.99-10-025 proceeding	[35]
July 28, 2003	IEEE 1547-2003	N/A	• Publication of first standard of IEEE 1547 series • Scope covered technical specifications and testing considerations for interconnection of distribution-level generators	[36]

July 1, 2005	IEEE 1547.1-2005	N/A	• Publication of first version of IEEE 1547.1 • Scope covered type, production, and commissioning tests to prove conformance of interconnection equipment and DER with IEEE 1547 standards	[37]
September 22, 2011	Rule 21	R.11-09-011	• Opened to review policies and consider revisions in the interest of timely, non-discriminatory, cost-effective, and transparent interconnection processes	[31]
February 13, 2013	Rule 21		• Establishment of Smart Inverter Working Group (SIWG)	[31]
September 20, 2012	Rule 21	D.12-09-018	• Required main IOUs to separate interconnection applications into either a "Fast Track" or "Detailed Study" category depending on size and energy exporting needs	[38]
April 16, 2014	Rule 21	D.14-04-003	• Required main IOUs to incorporate Distribution Group Study Process into Rule 21 to do clustered analyses for multiple generators at a single interconnection point	[39]
December 18, 2014	Rule 21	D.14-12-035	• Implemented Phase 1 of SIWG recommendations o Instructed main IOUs to require smart inverters (UL 1741 SA certified) for new interconnecting generators and to Rule 21 encourage (but not require) smart inverters for replaced inverters o Pertained to autonomous functions such as voltage and frequency ride-through	[18]
June 23, 2016	Rule 21	D.16-06-052	• Established cost envelope pilot policy to reduce interconnection cost uncertainty and financial burden on single DER developer/stakeholder • Implemented Phase 2 of SIWG recommendations o Pertained to communication functionality such as monitoring, controls, and cybersecurity • Implemented Phase 3 of SIWG recommendations o Pertained to additional mandatory and optional functionality such as limitations on maximum active power and scheduling of DER modes • Closed R.11-09-011 proceeding	[40]
September 8, 2016	UL 1741 SA	N/A	• Publication of UL 1741 SA to start the UL Advanced Inverter Testing and Certification Program	[17]
July 13, 2017	Rule 21	R.17-07-007	• Opened to revisit rules and regulations for DER interconnection to electric distribution systems of large IOUs	[31]
April 6, 2018	IEEE 1547-2018	N/A	• Publication of IEEE 1547-2018 • Scope was expanded to include interoperability (in addition to interconnection) • Scope was expanded to increase required DER grid support functionality and capabilities (more advanced)	[2]

April 5, 2020	Rule 21	D.19-03-013	• Expanded screening exemption for small net energy metering facilities by increasing facility size threshold • Required utilities to increase relevant interconnection information access for future interconnection project developers (e.g., currently queued generation projects adjacent to proposed project, comparisons for pre-project base-case and post-project base-case loading, potential network upgrades needed)	[41]
May 21, 2020	IEEE 1547.1-2020	N/A	• Publication of revision of IEEE 1547.1-2020 • Scope was expanded to cover more advanced grid support capabilities (such as smart inverter functionality) • Updated to accompany 2018 version of IEEE 1547	[3]
July 23, 2020	Rule 21	D.20-07-040	• Made corrections to D.19-03-013	[31]
September 16, 2020	UL 1741	N/A	• Publication of revision of UL 1741 (Edition 2) • Scope expanded to include all distributed energy resources	[42]
September 24, 2020	Rule 21	D.20-09-035	• Allowed for changes to default settings of inverters • Allowed for Rule 21 revisions based on updates to IEEE 1547-2018 and IEEE 1547.1-2020 standards • Required main IOUs to host workshops describing updates to their interconnection application portals to improve transparency for existing and new interconnection customers	[43]
April 7, 2021	Rule 21	R.11-09-011	• Reopened R.11-09-011 to revisit Rule 21 exemption allowing all Net Energy Metering (NEM) Generating Facilities to interconnect to the grid	[31]
January 21, 2021	Rule 21	D.21-01-027	• Made corrections to D.20-09-035	[43]
June 4, 2021	Rule 21	D.21-06-002	• Established Unintentional Islanding Working Group (UIWG) to study distribution-level anti-islanding methods • Required main IOUs to analyze interconnection cost data to report on grid upgrade costs (e.g., payment by single applicants whose upgrades do not benefit subsequent interconnection customers vs. distributed payments by ratepayers whose upgrades do benefit subsequent interconnection customers)	[44]
September 28, 2021	UL 1741 (including SB)	N/A	• Publication of revision of UL 1741 (Edition 3) • Supplement B added to expand functionalities and capabilities for grid interconnection equipment for product testing and certification requirements	[4]
April 7, 2022	Rule 21	D.22-04-003	• Small Multi-Jurisdictional Utilities (SMJUs) (Bear Valley Electric Service, Liberty Utilities, PacifiCorp) required to host workshops with prospective interconnection applicants to communicate updated information about their interconnection portals • SMJUs encouraged to participate in SIWG	[45]
April 8, 2022	Rule 21	D.22-04-001	• Made corrections to D.20-09-035	[46]

July 14, 2022	Rule 21	D.22-07-001	• Limited NEM exemption to small facilities (≤ 1 MW)	[47]
June 8, 2023	Rule 21	D.23-06-005	• Required main IOUs to report collected telemetry data from interconnected customers to CAISO • Closed R.11-09-011 proceeding	[48]
December 23, 2024	Rule 21	D.24-12-034	• Closed R.17-07-007 proceeding	[49]
August 20, 2025	Rule 21	R.25-08-004	• Opened to update and address evolving technologies and status of the grid and its interconnected projects (as part of ongoing requests stated in D.24-12-034 and D.21-06-002)	[31]

APPENDIX C. DIRECT TRANSFER TRIP BACKGROUND

Enhancements in anti-islanding protection have introduced advanced methods for detecting and preventing unintentional islanding, where a portion of the grid continues to be powered by DERs when disconnected from the main grid. These improvements include more robust detection methods and faster response times. DTT, as shown in Figure C-1, is an alternative to anti-islanding detection schemes. It uses an isolation device (recloser, breaker, or switch) to remove the distributed generator, prompting the breaker to open and the generator to be taken offline [50], [51]. When a fault is detected on the grid (typically by substation relays), a trip signal is sent directly to the DER's protective relay or breaker. This trip ensures that the DER does not continue to energize a faulted or islanded section of the grid, which could pose safety risks to utility personnel and equipment. DTT is especially important in systems where conventional anti-islanding detection may not be sufficient, such as in systems with high DER penetration or critical infrastructure. Some utilities like PG&E already require DTT as part of their interconnection requirements [52].

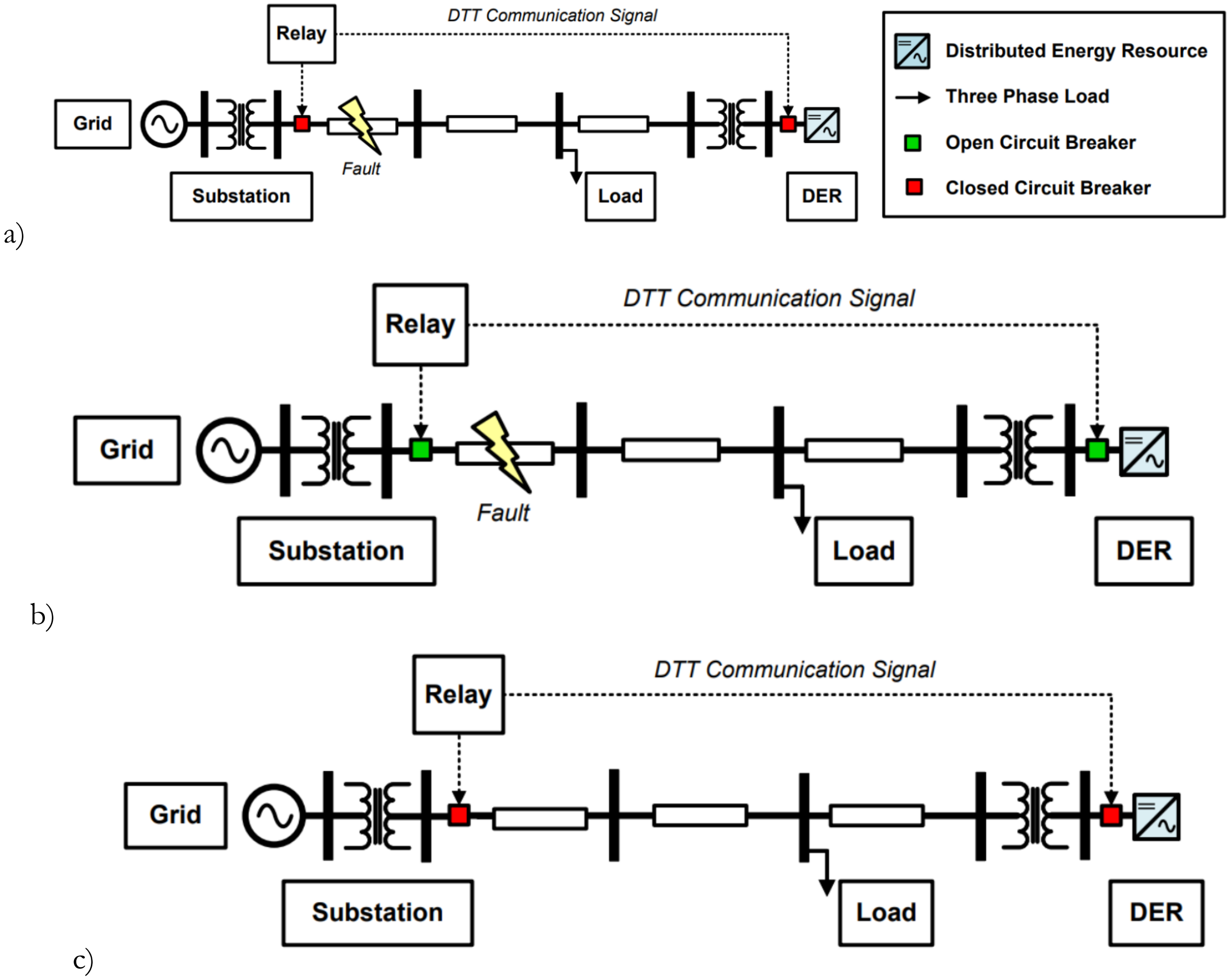

Figure C-1: Sequence of operations in a DTT scheme for DER disconnection during a fault event. (a) A fault occurs on the distribution feeder between the substation and the load. The relay detects the fault. (b) The relay initiates a DTT signal to the DER, opening the DER-side breaker to prevent unintentional islanding. (c) The fault is cleared, and the DER remains isolated until reclosure criteria are met.

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